Darío Caballero Polo

HAZARD ELIMINATION

ONARISC-V321 5-STAGE PIPELINED CPU



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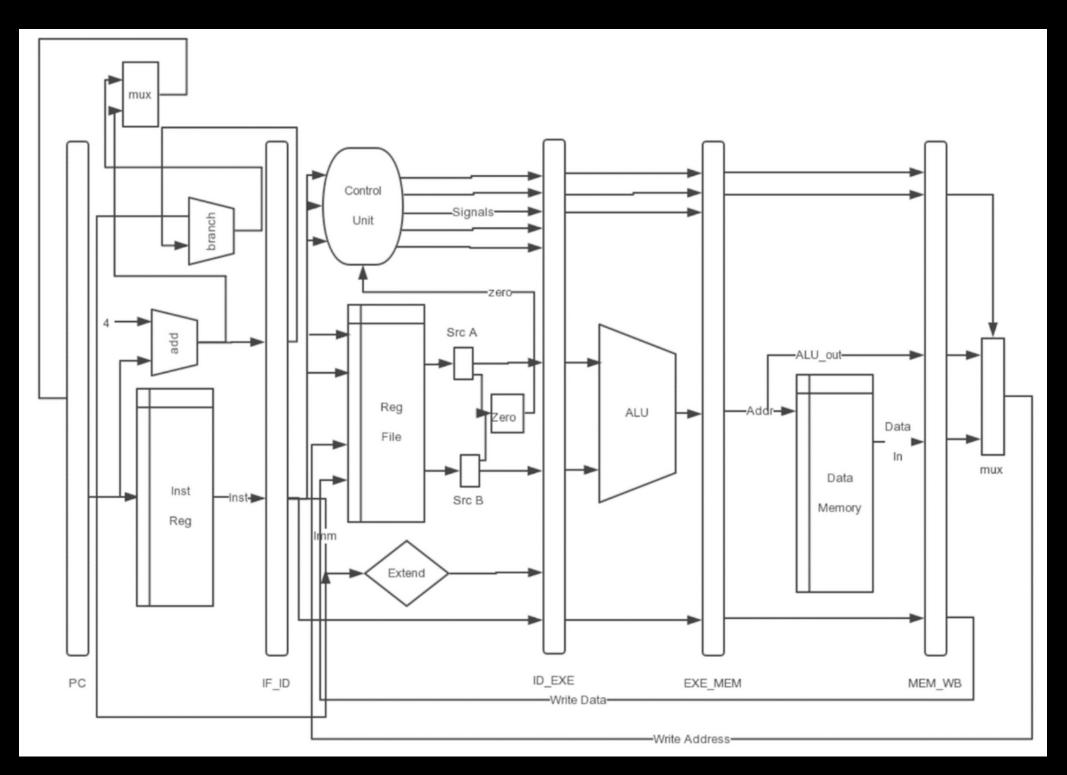


Introduction

Improve CPI of RISC-V32i 5-stage Pipelined CPU

Eliminate data & control stalls





Related works

Linfeng Du RISC-V32i 5-stage Pipelined

Programmed in Verilog



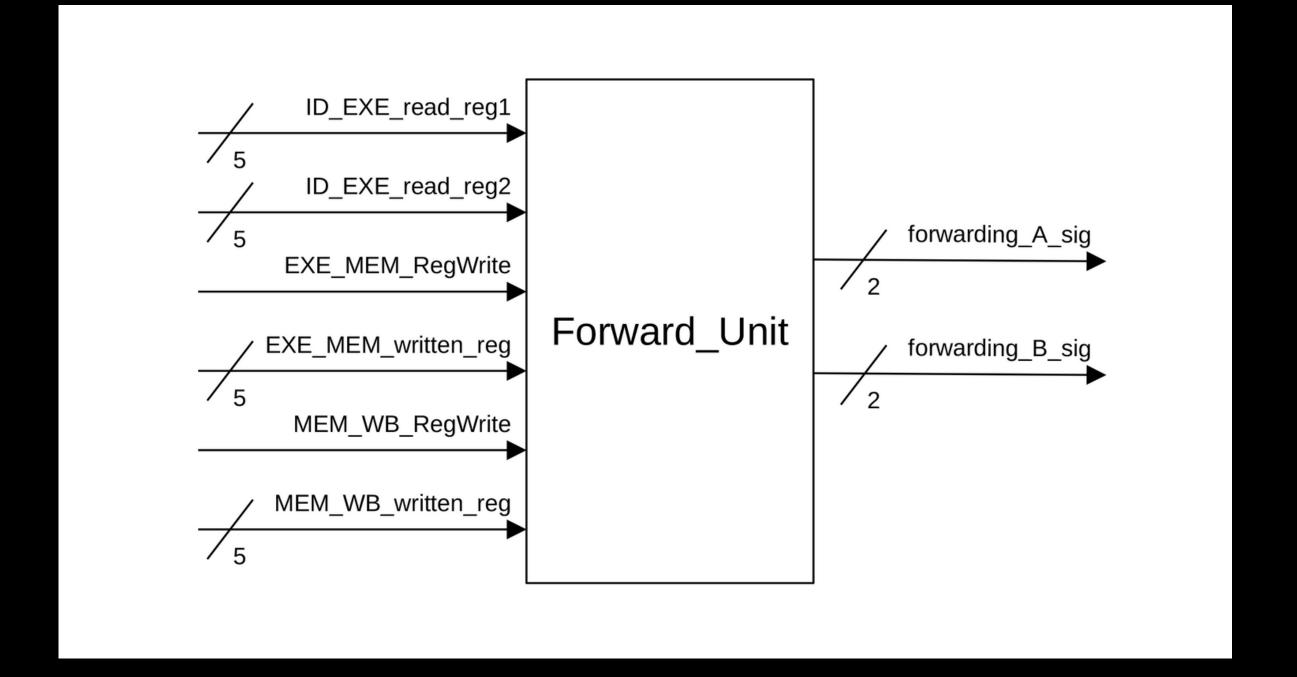
Methods

Data Forwarding

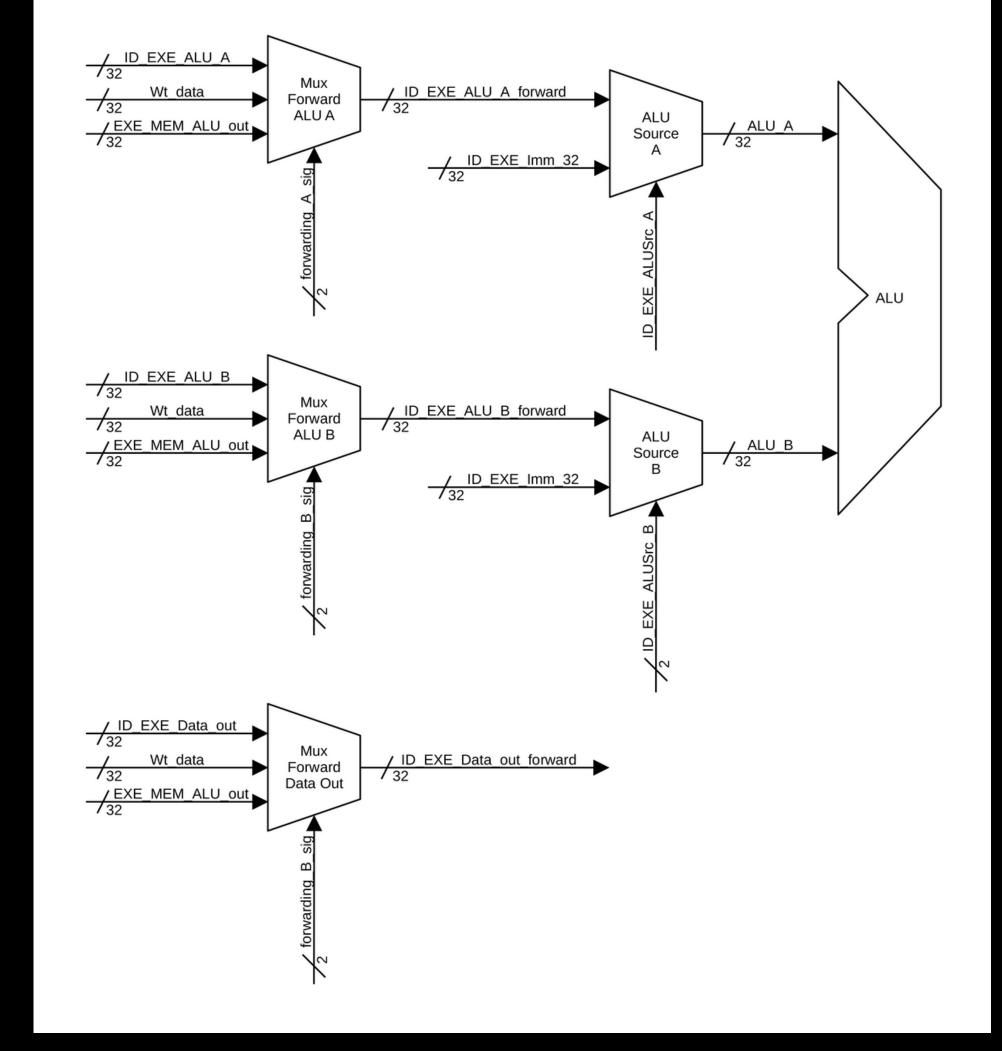
Branch Prediction



Forward Unit

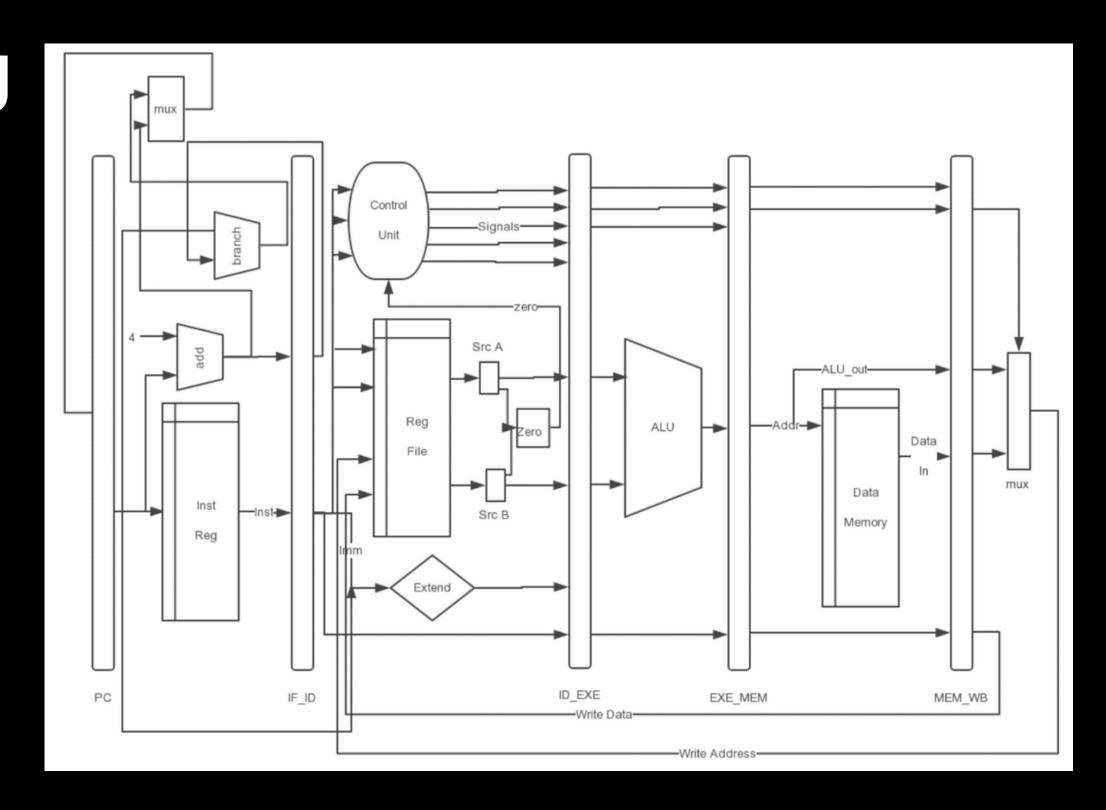


Multiplexing

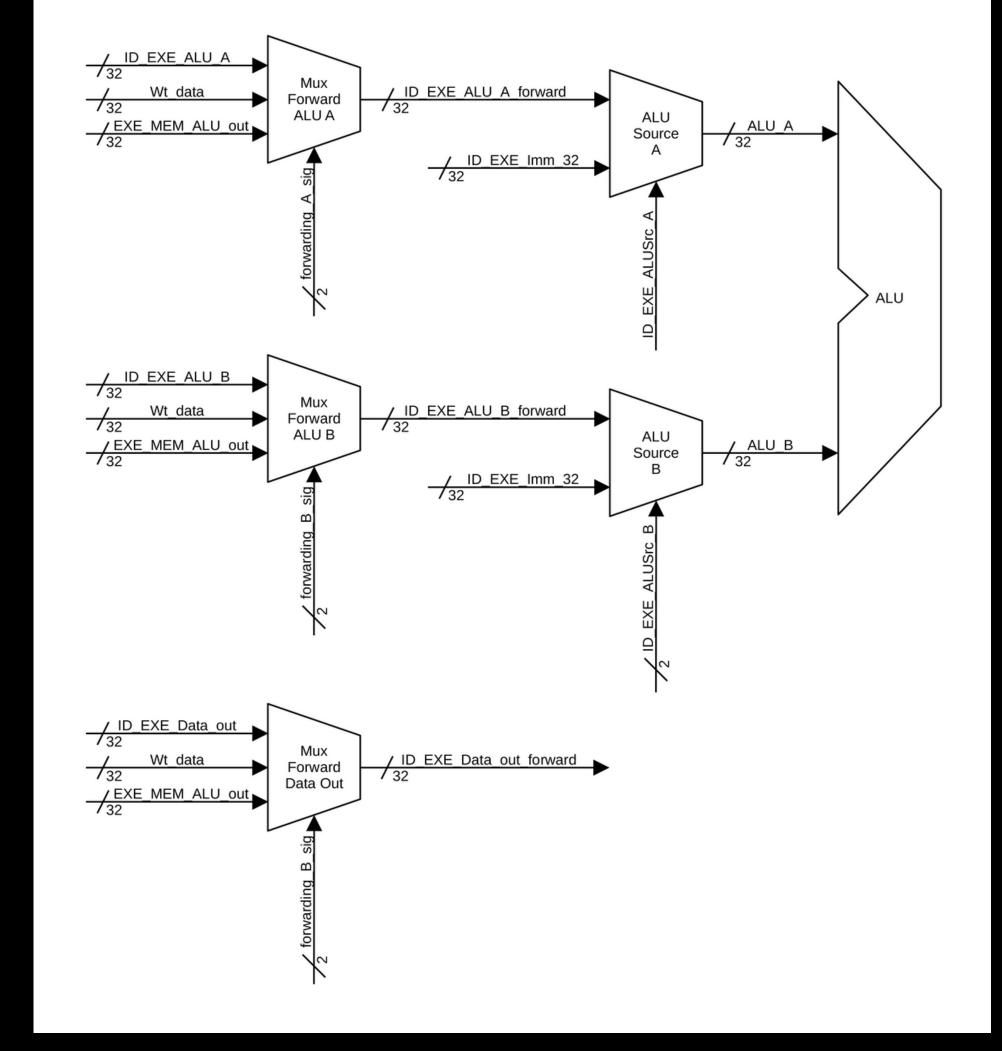




Multiplexing



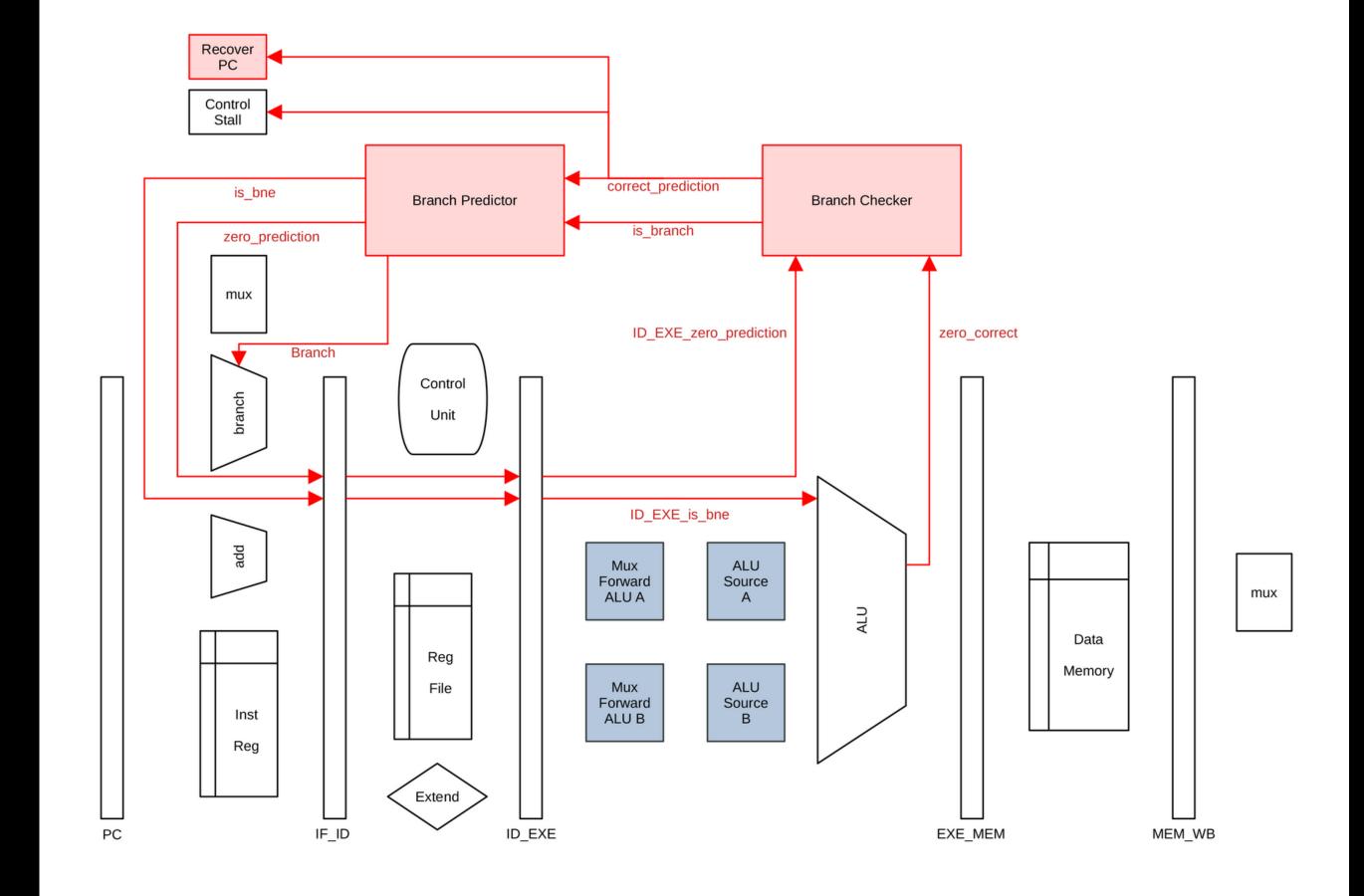
Multiplexing





Branch Prediction

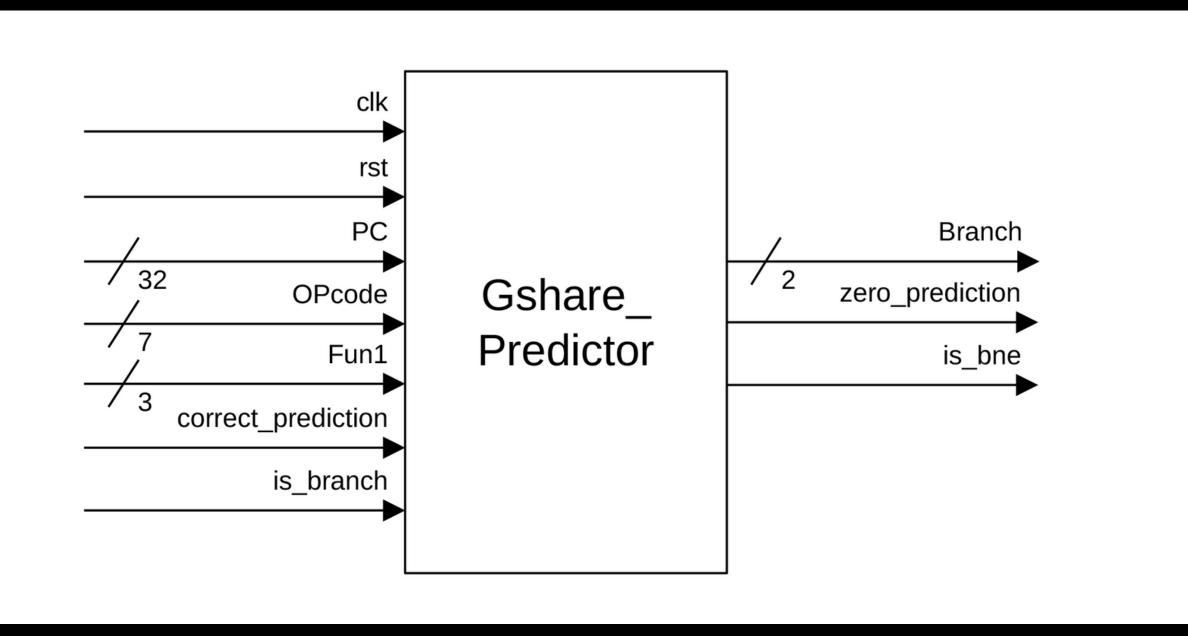
Overall Pipeline





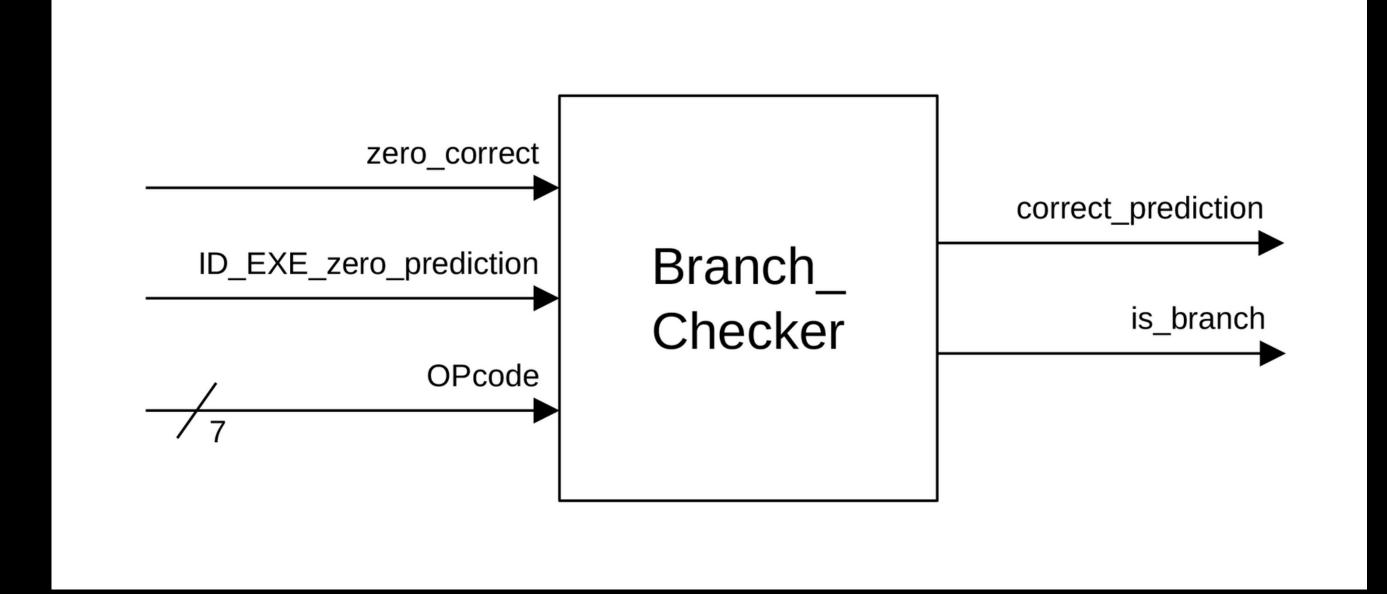
Branch Prediction

Branch Predictor



Branch Prediction

Branch Checker



Evaluation

Data Forwarding

Branch Prediction



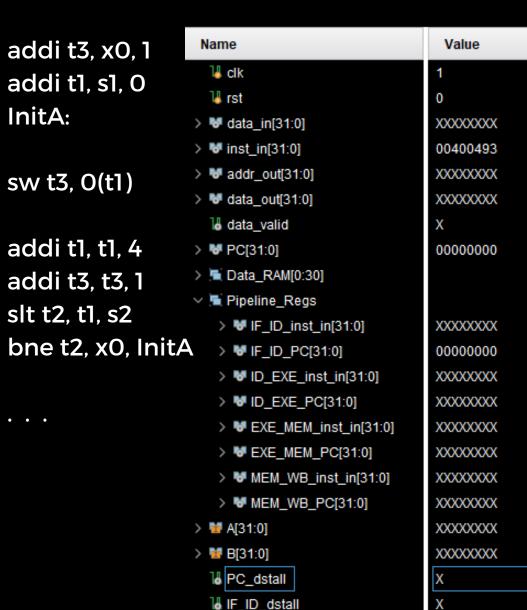
Vec Mul.asm:

addi s1, x0, 4 addi s2, s1, 40

addi s3, s2, 40

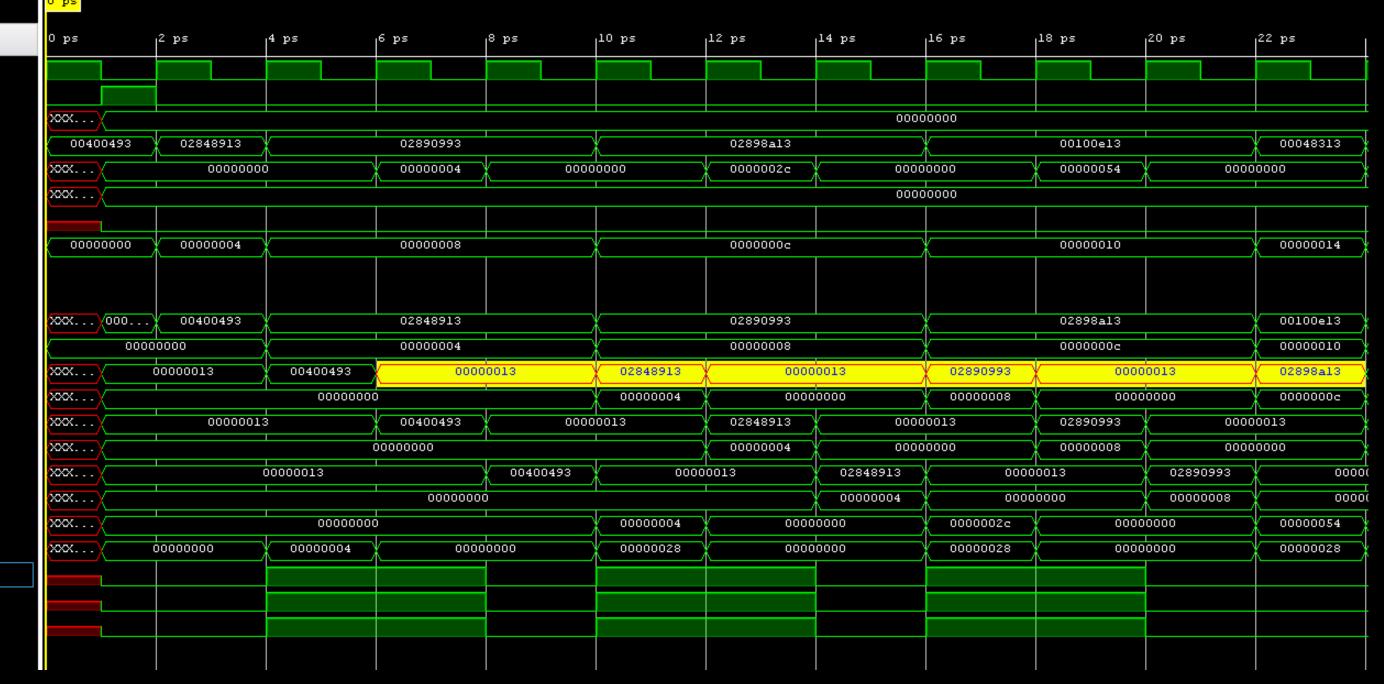
addi s4, s3, 40

addi t1, s1, 0 InitA: sw t3, O(t1) addi t1, t1, 4 addi t3, t3, 1



ID EXE dstall

Before Data Forwarding





Vec_Mul.asm:

After Data Forwarding

addi s1, x0, 4 addi s2, s1, 40

addi s3, s2, 40

addi s4, s3, 40

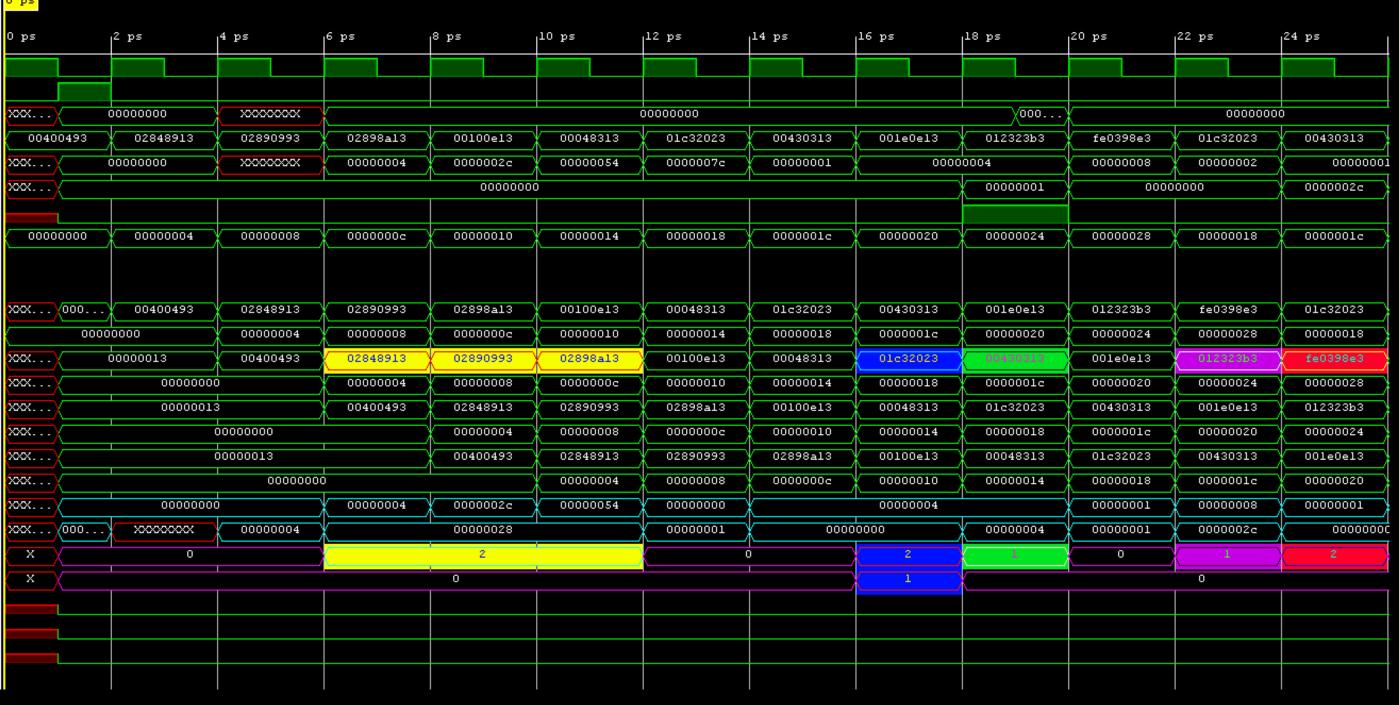
addi t3, x0, 1 addi t1, s1, 0 InitA:

sw t3, O(t1)

addi t1, t1, 4 addi t3, t3, 1 slt t2, t1, s2 bne t2, x0, Init/

. .

| | | | 0 |
|------------|----------------------|------------|-----------|
| Name | | Value | 0 |
| ¼ clk | | 1 | |
| 🛚 rst | | 0 | |
| > 😽 data_ | in[31:0] | XXXXXXXXXX | x |
| > 😽 inst_i | in[31:0] | 00400493 | \subset |
| > 😽 addr_ | _out[31:0] | XXXXXXXXXX | x |
| > 😽 data_ | out[31:0] | XXXXXXXXX | x |
| ¼ data_ | valid | Х | |
| > W PC[3 | 1:0] | 00000000 | |
| > 🗏 Data | _RAM[0:30] | | |
| V 🗏 Pipel | ine_Regs | | |
| > 😽 IF | ID_inst_in[31:0] | XXXXXXXXX | x |
| > 😽 IF | F_ID_PC[31:0] | 00000000 | C |
| > 😽 [[| D_EXE_inst_in[31:0] | XXXXXXXXX | X |
| > 😽 🛭 | D_EXE_PC[31:0] | XXXXXXXXX | X |
| > 😽 E | XE_MEM_inst_in[31:0] | XXXXXXXXX | X |
| > 😽 E | XE_MEM_PC[31:0] | XXXXXXXXXX | X |
| > 161 M | IEM_WB_inst_in[31:0] | XXXXXXXXXX | X |
| > 161 M | IEM_WB_PC[31:0] | XXXXXXXXXX | × |
| > 👹 A[31: | 0] | XXXXXXXXXX | x |
| > 👹 B[31: | 0] | XXXXXXXXXX | × |
| > 👹 forwa | rding_A_sig[1:0] | Х | \subset |
| > 👹 forwa | rding_B_sig[1:0] | Х | |
| ™ PC_c | Istall | Х | |
| ¼ IF_ID | _dstall | Χ | |
| ¹⊌ ID_E | XE_dstall | X | |
| | | | |

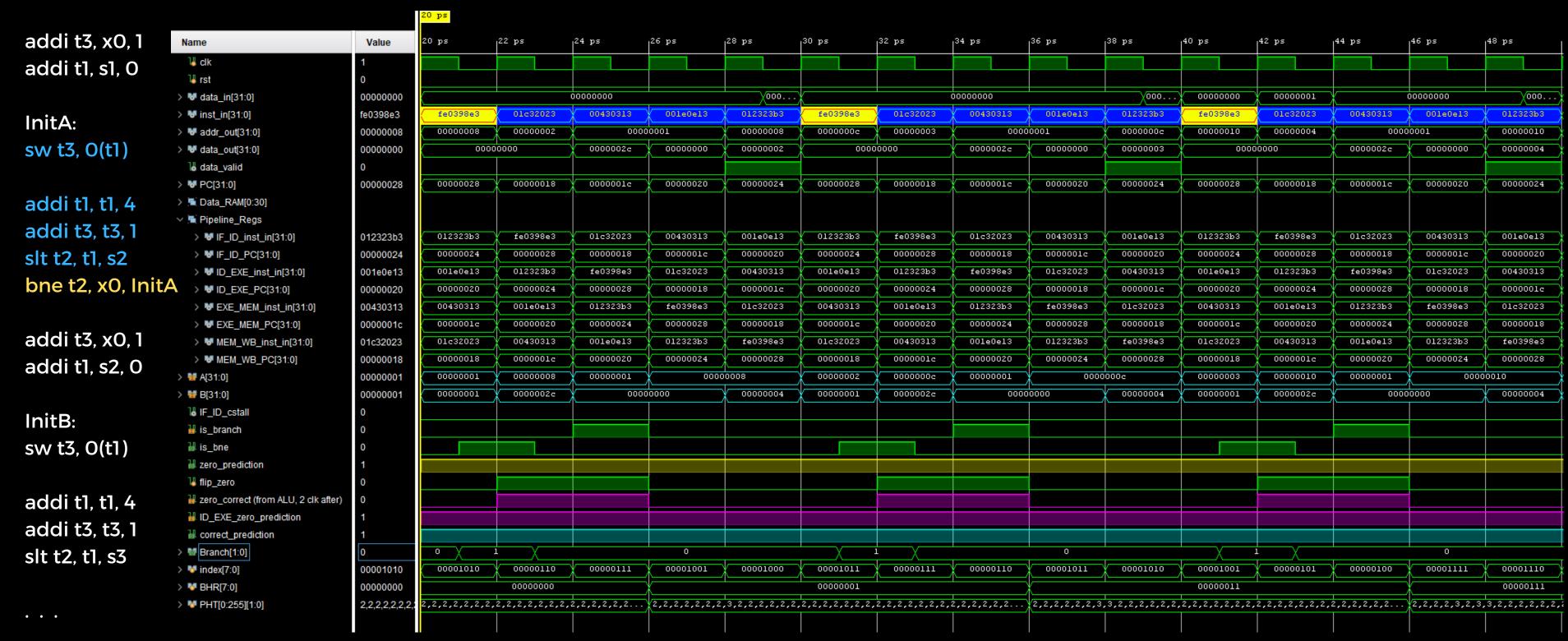




Vec_Mul.asm:

. . .

Correct Branch Prediction





Vec_Mul.asm:

. . .

addi t3, x0, 1 addi t1, s1, 0

InitA: sw t3, O(t1)

addi t1, t1, 4 addi t3, t3, 1 slt t2, t1, s2 bne t2, x0, InitA

addi t3, x0, 1 addi t1, s2, 0

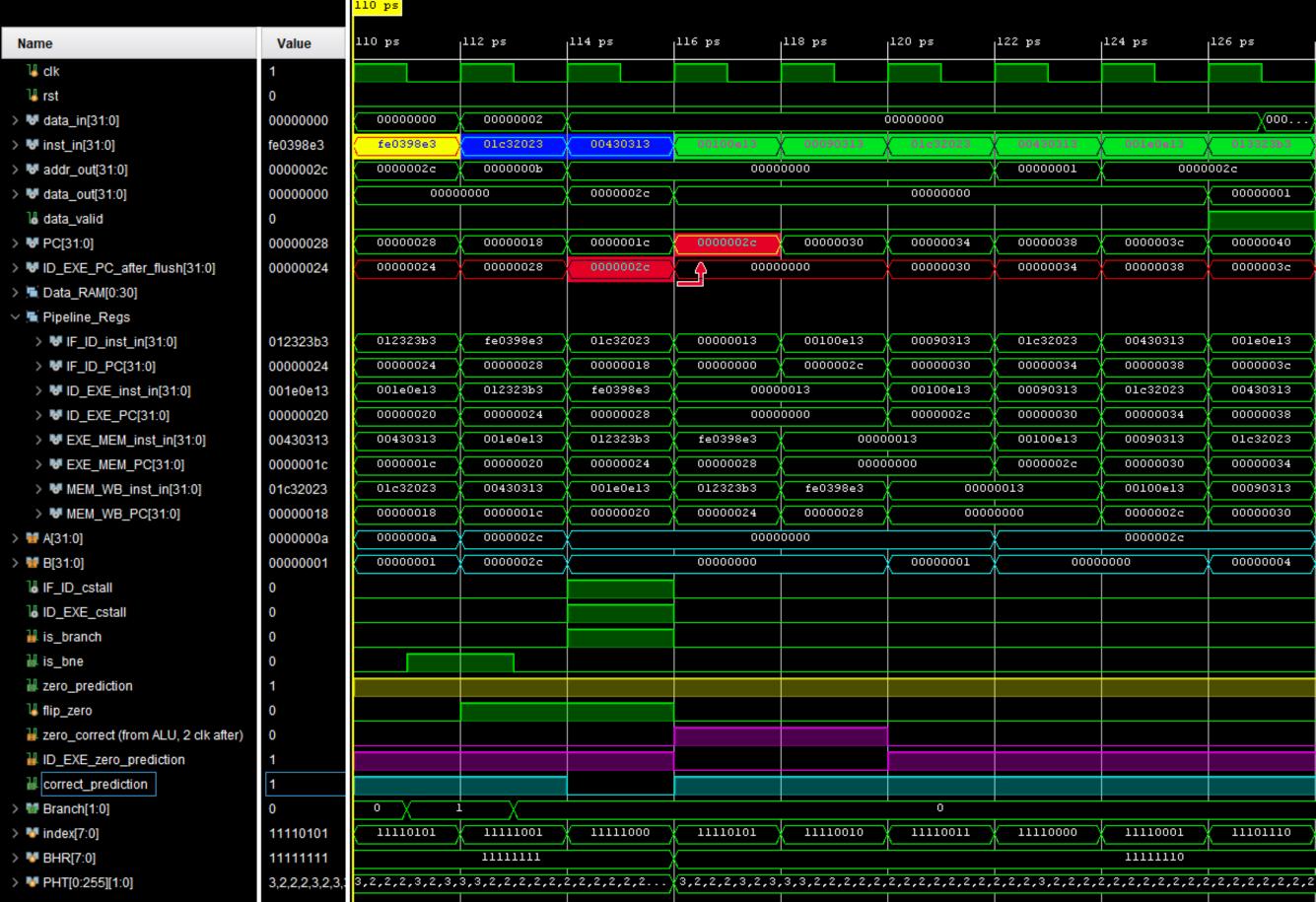
InitB: sw t3. O(t1)

addi t1, t1, 4 addi t3, t3, 1 slt t2, t1, s3

. . .



Incorrect Branch Prediction



```
Jacobi-1d.asm:
                                                                                    JAL instruction
jal ra, init array // 0b0000ef
jal ra, kernel // 008000ef
jal ra, continue // Od8000ef
                                             Name
                                                                          Value

↓ clk

                                             🛂 rst
kernel:
                                                                                                                                                                               00000000
                                                                                               00000000
                                                                                                              XXXXXXXXXX
                                            > W data_in[31:0]
                                                                         XXXXXXXX
addi t4, s0, -1// fff40e93
                                                                         00a00413
                                                                                      00a00413
                                                                                                  00500493
                                                                                                               20000913
                                            > W inst_in[31:0]
addi t0. x0. 0
                                                                                                                           0000000a
                                            > W addr_out[31:0]
                                                                          XXXXXXXXX
                                                                                               00000000
                                                                                                              XXXXXXXXX
                                                                                                                                       00000005
                                                                                                                                                   00000200
                                                                                                                                                                00000300
                                                                                                                                                                                  00000000
                                                                         XXXXXXXX
                                            > W data_out[31:0]
k loop t:
                                              data valid
                                                                                                  00000004
                                                                                                               00000008
                                                                                                                           0000000c
                                                                                      00000000
                                                                                                                                       00000010
                                                                                                                                                   00000000
                                                                                                                                                                000000c4
                                                                                                                                                                            000000c8
                                                                                                                                                                                        000000cc
addi t1. x0. 1
                                            > W PC[31:0]
                                            > W ID_EXE_PC_after_flush[31:0]
                                                                          XXXXXXXXX
                                                                                                  XXXXXXXXXX
                                                                                                               00000004
                                                                                                                           00000008
                                                                                                                                       0000000c
                                                                                                                                                   00000010
                                                                                                                                                                00000014
                                                                                                                                                                            000000c4
                                                                                                                                                                                        000000c8
                                            > Mate | Data | RAM[0:30]
k_loop_i1:
                                            Pipeline_Regs
addi t2. t1. -1
                                                                                                  00a00413
                                                                                                               00500493
                                                                                                                           20000913
                                                                                                                                       30000993
                                                                                                                                                                00000293
                                                                                                                                                                            00090el3
                                                                                                                                                                                        00098e93
                                                                          XXXXXXXXX
                                                                                   XXX...\000..
                                                                                                                                                   0b0000ef
                                              > W IF ID inst in[31:0]
                                                                                                               00000004
                                                                                                                           00000008
                                                                                                                                                                                        000000c8
                                                                                            00000000
                                                                                                                                       0000000c
                                                                                                                                                   00000010
                                                                                                                                                                000000c0
                                                                                                                                                                            000000c4
                                              > W IF_ID_PC[31:0]
                                              > W ID_EXE_inst_in[31:0]
                                                                                                               00a00413
                                                                                                                           00500493
                                                                                                                                       20000913
                                                                                                                                                    30000993
                                                                                                                                                                0b0000ef
                                                                                                                                                                            00000293
                                                                                                                                                                                        00090el3
                                                                          XXXXXXXXX
init array:
                                                                                                     00000000
                                                                                                                           00000004
                                                                                   XXX.
                                                                                                                                       00000008
                                                                                                                                                   0000000c
                                                                                                                                                                00000010
                                                                                                                                                                            000000c0
                                                                                                                                                                                        000000c4
                                              > W ID_EXE_PC[31:0]
                                                                          XXXXXXXX
addi t0, x0, 0 // t0: i // 00000293
                                                                                                     00000013
                                               > W EXE MEM inst in[31:0]
                                                                          XXXXXXXXX
                                                                                                                           00a00413
                                                                                                                                       00500493
                                                                                                                                                   20000913
                                                                                                                                                                30000993
                                                                                                                                                                            0b0000ef
                                                                                                                                                                                        00000293
addi t3, s2, 0 // addr of A
                                                                                                            00000000
                                               > W EXE_MEM_PC[31:0]
                                                                          XXXXXXXXX
                                                                                   XXX...
                                                                                                                                       00000004
                                                                                                                                                   00000008
                                                                                                                                                                0000000c
                                                                                                                                                                            00000010
                                                                                                                                                                                        000000c0
addi t4, s3, 0 // addr of B
                                                                                                            00000013
                                                                                                                                       00a00413
                                                                                                                                                   00500493
                                                                                                                                                                20000913
                                                                                                                                                                            30000993
                                                                                                                                                                                        0b0000ef
                                              > W MEM_WB_inst_in[31:0]
init loop i:
                                                                                                                  00000000
                                                                                                                                                   00000004
                                                                                                                                                                            0000000c
                                                                                                                                                                                        00000010
                                              > W MEM WB PC[31:0]
                                                                          XXXXXXXXX
                                                                                                                                    00000000
                                                                                                                                                                                        00000200
                                            > W A[31:0]
                                                                          XXXXXXXXX
addi t1, t0, 2 // data for A[i]
                                            > W B[31:0]
                                                                          XXXXXXXXX
                                                                                                                                                   00000300
                                                                                                                                                                                  00000000
sw t1, O(t3) // A[i] = i + 2
                                              IF_ID_cstall
addi t1, t1, 1 // data for B[i]
                                              is branch
sw t1, O(t4) // B[i] = i + 3
                                              ₩ is_bne
addi t3. t3. 4

↓ flip zero

addi t4. t4. 4
                                              Jacob zero correct (from ALU, 2 clk after)
addi t0. t0. 1
                                              ID EXE zero prediction
bne t0, s0, init_loop_i // fe8292e3
                                              // 00008067
jalr x0, ra, 0
                                            > M Branch[1:0]
                                                                                      00000000
                                                                                                  00000001
                                                                                                              00000010
                                                                                                                           00000011
                                                                                                                                       00000100
                                                                                                                                                   00110000
                                                                                                                                                               00110001
                                                                                                                                                                            00110010
                                                                                                                                                                                        00110011
                                            > W index[7:0]
                                                                         00000000
                                            > 😽 BHR[7:0]
          香港科技大學
                                                                                     2.2.2.2.2.2
                                            > W PHT[0:255][1:0]
                                              is_first_jalr
          THE HONG KONG
                                              IF_ID_is_first_jalr
          UNIVERSITY OF SCIENCE
```

AND TECHNOLOGY

00000200

00000040

000000cc

00228313

000000cc

00098e93

000000c8

00090el3

000000c4

00000293

000000c0

00000300

00110100

00000300

000000d4

00000040

006e2023

00000040

00228313

000000cc

00098e93

000000c8

00090e13

000000c4

00000000

00110101

00000002

85000000

00000044

00130313

000000d4

006e2023

00000040

00228313

000000cc

00098e93

000000c8

00000200

00000000

00110110

```
Jacobi-1d.asm:
jal ra, init array // 0b0000ef
jal ra, kernel // 008000ef
jal ra, continue // 0d8000ef
kernel:
addi t4, s0, -1// fff40e93
addi t0. x0. 0
k_loop_t:
addit1.x0.1
k_loop_i1:
addi t2. t1. -1
init array:
addi t0. x0. 0 // t0: i // 00000293
addi t3, s2, 0 // addr of A
addi t4, s3, 0 // addr of B
init loop i:
addi t1, t0, 2 // data for A[i]
sw t1, O(t3) // A[i] = i + 2
addi t1, t1, 1 // data for B[i]
sw t1, O(t4) // B[i] = i + 3
addi t3. t3. 4
addi t4. t4. 4
addi t0. t0. 1
bne t0, s0, init loop i // fe8292e3
                    // 00008067
jalr x0, ra, 0
        香港科技大學
        THE HONG KONG
        UNIVERSITY OF SCIENCE
         AND TECHNOLOGY
```

Name

↓ clk

🛂 rst

> W data_in[31:0]

> W inst_in[31:0]

> W addr_out[31:0]

> W data_out[31:0]

data valid

> Tota_RAM[0:30]

V Pipeline Regs

> W ID_EXE_PC_after_flush[31:0]

> **W** IF_ID_inst_in[31:0]

> W ID EXE inst in[31:0]

> W EXE MEM inst in[31:0]

> W MEM_WB_inst_in[31:0]

zero correct (from ALU, 2 clk after)

ID EXE zero prediction

> W EXE MEM PC[31:0]

> W MEM WB PC[31:0]

> W IF_ID_PC[31:0]

> W ID EXE PC[31:0]

PC[31:0]

> W A[31:0]

> W B[31:0]

IF_ID_cstall

zero_prediction

is_branch

is_bne

flip zero

> W Branch[1:0]

> W index[7:0]

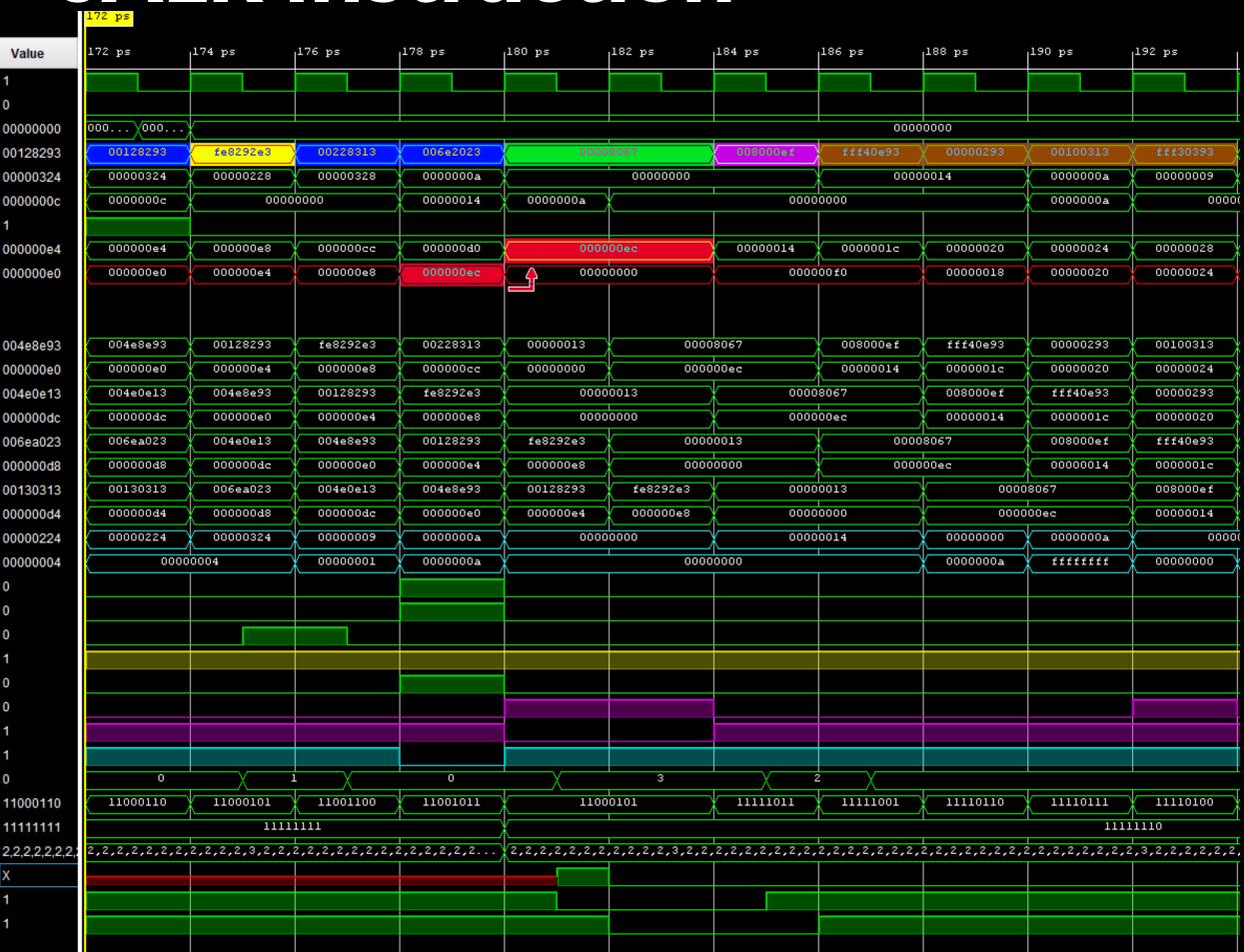
> W BHR[7:0]

> W PHT[0:255][1:0]

IF ID is first jair

IF_cstall

JALR instruction



Overall Speedup

| | Non-optimized | Optimized | Speedup |
|-----------|----------------------|-----------|---------|
| Vec_Mul | 850 clk | 462 clk | 1.840 |
| Jacobi-1d | $3585 \mathrm{clk}$ | 1748 clk | 2.051 |

Conclusions

Significant improvement ~ x2 Speedup

Follow up: Superscalar architecture CPI < 1



THANKS FOR LISTENING

ANY QUESTIONS?

