

RV32IC Pipelined implementation

Computer Architecture

Fall 2024

The American University in Cairo

Aly Elaswad 900225517

Ismail Sabry 900222002

Supervised by Dr. Cherif Salama

Project Description:

The femtoRV32 project involves implementing a pipelined RISC-V processor (RV32I) in Verilog for the Nexys A7 FPGA. It supports all 42 user-level RV32I instructions, excluding ECALL, EBREAK, PAUSE, FENCE, and FENCE.TSO, with ECALL treated as a halting instruction and the others as no-ops. The processor uses a single-ported memory for both instructions and data, with a 2-cycle instruction issue to handle memory access hazards. The project includes hazard handling, test cases, and bonus features like compressed instruction support and a test program generator. The final deliverables include Verilog code, test programs, and this report detailing the design and testing process.

Problems and solutions:

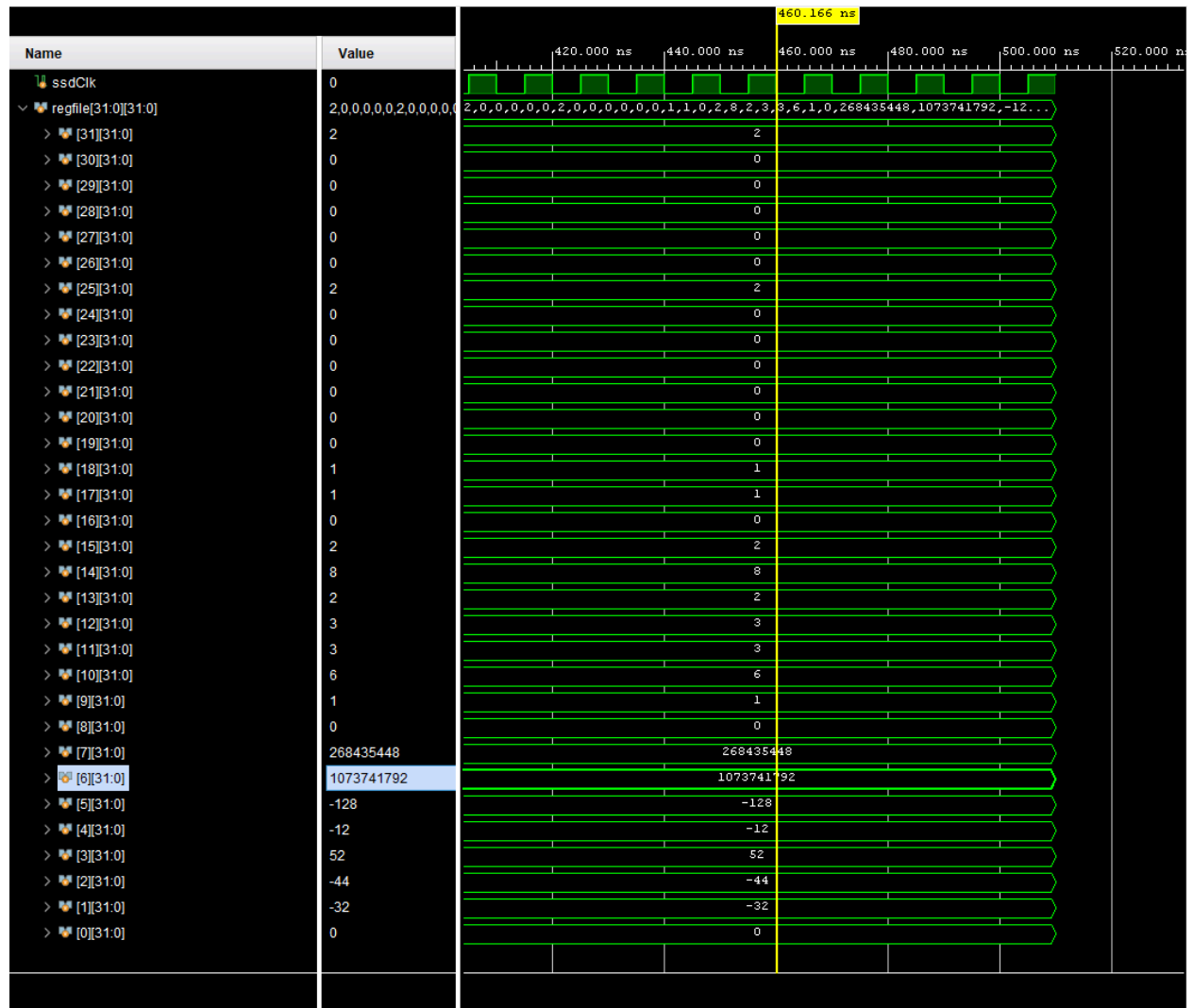
The single memory was the most challenging part to implement since it takes distinct data and instructions and puts them in the same port, we just had to differentiate them by fetching one at a positive edge and the other at a negative edge. It also forced us to accept the trade off and make our program has an average CPI of 2 to handle the structural hazards that came with this. Changing from our code that was implemented in the lab was also a bit challenging since there was different hazards and stages handled in the lab that we no longer needed such as forwarding from the MEM/WB stage.

Test Cases:

Testing all I instructions

```
addi x1,x0,-32
addi x2,x0,44
addi x31,x0,2
addi x25,x0,2
add x2,x2,x1
sub x2,x1,x2
xor x3,x2,x1
or x4,x3,x1
and x5,x4,x1
sll x5,x5,x25
srl x6,x5, x25
sra x7,x6,x25
slt x8,x7,x25
sltu x9,x8,x25
addi x10,x9,5
xori x11, x10,5
ori x12,x11,2
andi x13,x12,2
slli x14,x13,2
srli x15,x14,2
srai x16,x15,2
slti x17,x16,2
```

Waveform Output:



Benchmark Output

Init Value	Register	Decimal	Hex	Binary
0	x0 (zero)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x1 (ra)	-32	0xffffffffe0	0b111111111111111111111111111110000
<input type="text" value="0"/>	x2 (sp)	-44	0xffffffffd4	0b111111111111111111111111111101000
<input type="text" value="0"/>	x3 (gp)	52	0x00000034	0b000000000000000000000000000010100
<input type="text" value="0"/>	x4 (tp)	-12	0xfffffffff4	0b111111111111111111111111111110100
<input type="text" value="0"/>	x5 (t0)	-128	0xffffffff80	0b11111111111111111111111111110000000
<input type="text" value="0"/>	x6 (t1)	1073741792	0x3fffffe0	0b0011111111111111111111111111100000
<input type="text" value="0"/>	x7 (t2)	268435448	0x0ffffff8	0b00001111111111111111111111111000
<input type="text" value="0"/>	x8 (s0/fp)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x9 (s1)	1	0x00000001	0b000000000000000000000000000000001
<input type="text" value="0"/>	x10 (a0)	6	0x00000006	0b000000000000000000000000000000110
<input type="text" value="0"/>	x11 (a1)	3	0x00000003	0b000000000000000000000000000000011
<input type="text" value="0"/>	x12 (a2)	3	0x00000003	0b000000000000000000000000000000011
<input type="text" value="0"/>	x13 (a3)	2	0x00000002	0b000000000000000000000000000000010
<input type="text" value="0"/>	x14 (a4)	8	0x00000008	0b0000000000000000000000000000001000
<input type="text" value="0"/>	x15 (a5)	2	0x00000002	0b000000000000000000000000000000010
<input type="text" value="0"/>	x16 (a6)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x17 (a7)	1	0x00000001	0b000000000000000000000000000000001
<input type="text" value="0"/>	x18 (s2)	1	0x00000001	0b000000000000000000000000000000001
<input type="text" value="0"/>	x19 (s3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x20 (s4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x21 (s5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x22 (s6)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x23 (s7)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x24 (s8)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x25 (s9)	2	0x00000002	0b000000000000000000000000000000010
<input type="text" value="0"/>	x26 (s10)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x27 (s11)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x28 (t3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x29 (t4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x30 (t5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x31 (t6)	2	0x00000002	0b000000000000000000000000000000010

Testing store and load instructions

```
li x1,0x7f7f4f2
```

```
li x2,0x7f1
```

```
li x9,4
```

```
sw x1,0(x0)
```

```
sw x2,0(x9)
```

```
lw x5,4(x0)
```

```
lb x6,6(x0)
```

```
lbu x7,5(x0)
```

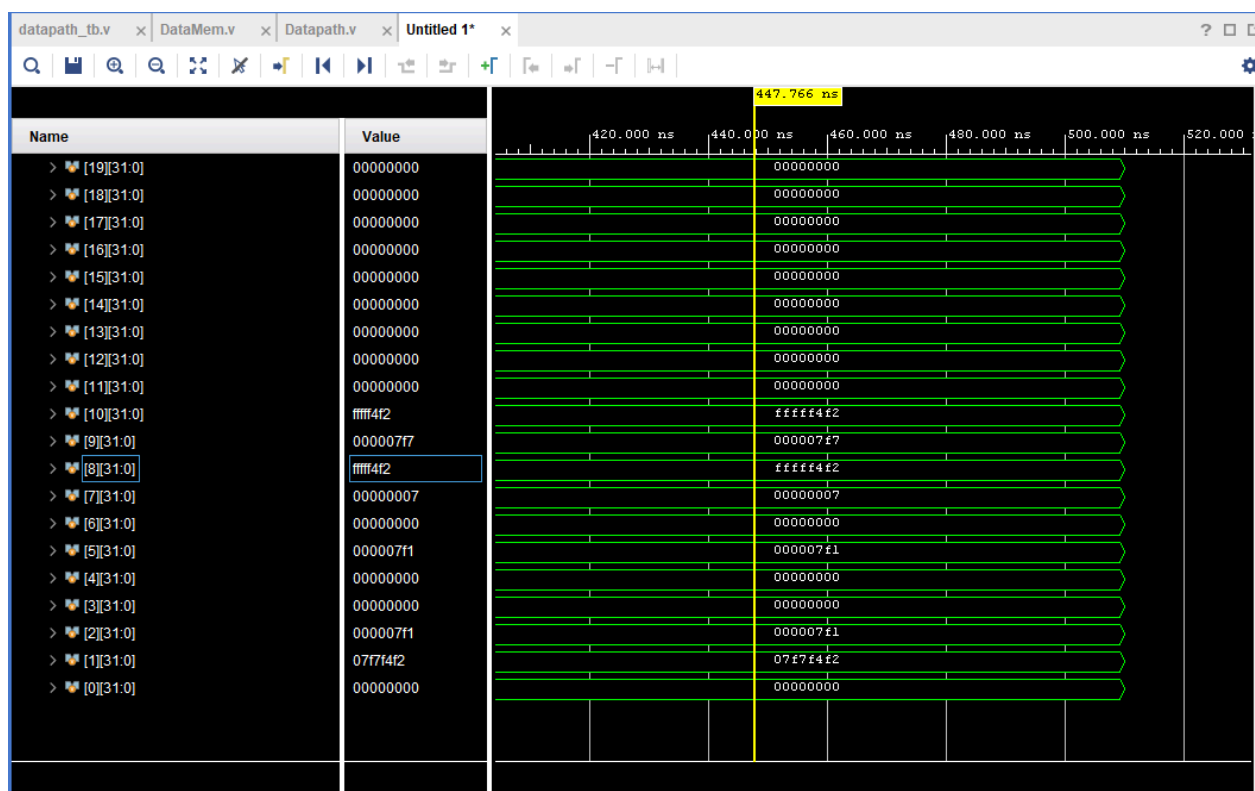
```
lh x8,0(x0)
```

```
lhu x9,2(x0)
```

```
sh x1, 2(x0)
```

```
lh x10, 2(x0)
```

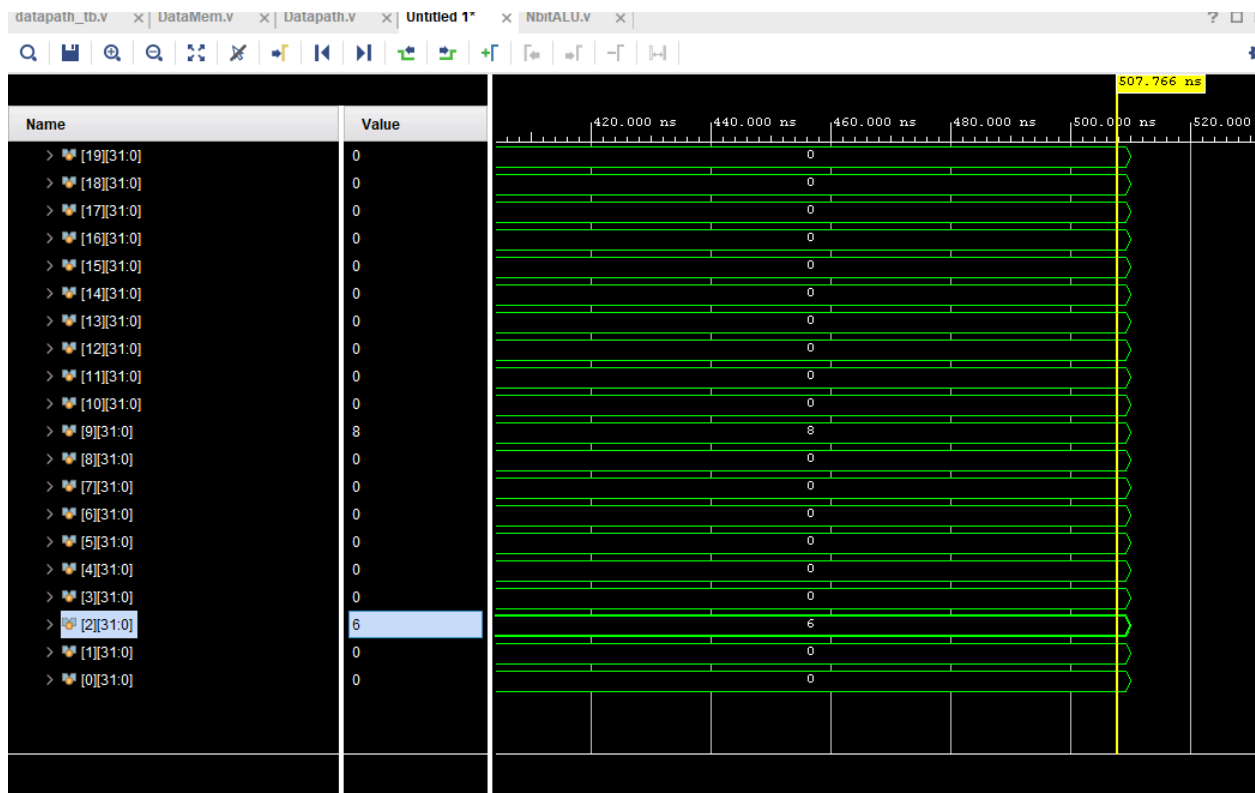
Waveform Output:



Testing Branch instructions

```
beq x0,x1,8
addi x1,x1,4
blt x1,x2,8
addi x2,x2,6
bge x2,x1,8
addi x3,x3,5
bne x2,x3,8
addi x10,x10,10
addi x9,x9,8
```

Waveform Output:

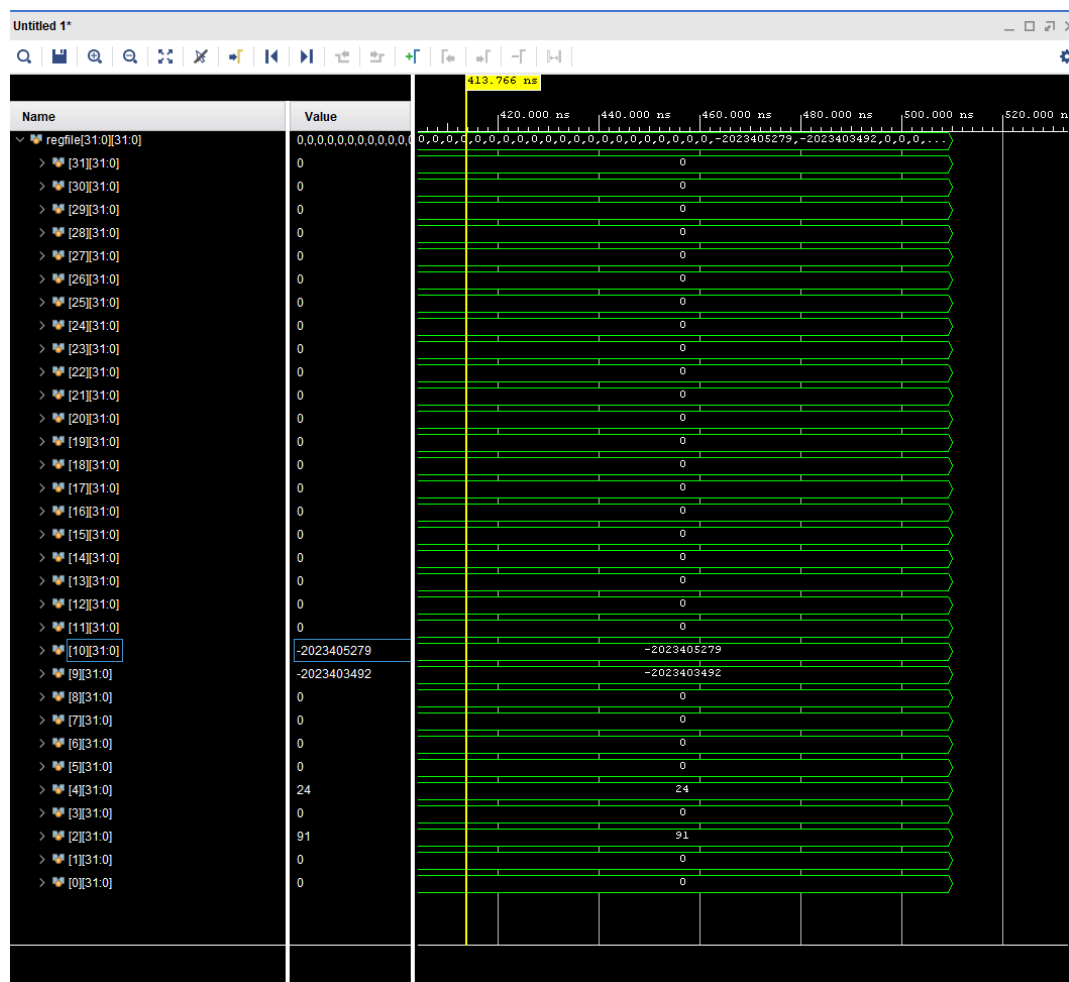


Benchmark Output:

Init Value	Register	Decimal	Hex	Binary
0	x0 (zero)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x1 (ra)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x2 (sp)	6	0x00000006	0b00000000000000000000000000000110
<input type="text" value="0"/>	x3 (gp)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x4 (tp)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x5 (t0)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x6 (t1)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x7 (t2)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x8 (s0/fp)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x9 (s1)	8	0x00000008	0b00000000000000000000000000001000
<input type="text" value="0"/>	x10 (a0)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x11 (a1)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x12 (a2)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x13 (a3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x14 (a4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x15 (a5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x16 (a6)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x17 (a7)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x18 (s2)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x19 (s3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x20 (s4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x21 (s5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x22 (s6)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x23 (s7)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x24 (s8)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x25 (s9)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x26 (s10)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x27 (s11)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x28 (t3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x29 (t4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x30 (t5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x31 (t6)	0	0x00000000	0b00000000000000000000000000000000

Testing JAL,JALR,AUIPC,LUI

```
lui x10,0x87655
addi x10,x10,10
jal x0,8
addi x10,x0,53
addi x2,x0,91
jalr x4,x0,28
addi x5,x0,20
auipc x9,0x87655
```



Benchmark:

Init Value	Register	Decimal	Hex	Binary
0	x0 (zero)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x1 (ra)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x2 (sp)	91	0x0000005b	0b00000000000000000000000000001011011
<input type="text" value="0"/>	x3 (gp)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x4 (tp)	24	0x00000018	0b000000000000000000000000000011000
<input type="text" value="0"/>	x5 (t0)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x6 (t1)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x7 (t2)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x8 (s0/fp)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x9 (s1)	-2023403492	0x8765501c	0b10000111011001010101000000011100
<input type="text" value="0"/>	x10 (a0)	-2023403510	0x8765500a	0b1000011101100101010100000001010
<input type="text" value="0"/>	x11 (a1)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x12 (a2)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x13 (a3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x14 (a4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x15 (a5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x16 (a6)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x17 (a7)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x18 (s2)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x19 (s3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x20 (s4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x21 (s5)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x22 (s6)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x23 (s7)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x24 (s8)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x25 (s9)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x26 (s10)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x27 (s11)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x28 (t3)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x29 (t4)	0	0x00000000	0b00000000000000000000000000000000
<input type="text" value="0"/>	x30 (t5)	0	0x00000000	0b00000000000000000000000000000000

Datapath:

Notes:
All necessary shifts have been made in the imm gen

