VE370 Intro to Computer Organization

Project 2 (Individual)
Single cycle processor

Written by

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1 Introduction

A single cycle processor features completing one whole instruction in one clock cycle. The processor in this project supports functions including

- The memory-reference instructions load word (lw) and store word (sw)
- The arithmetic-logical instructions add, addi, sub, and, andi, or, and slt
- The jumping instructions branch equal (beq), branch not equal (bne), and jump (j)

A basic structure of a single cycle processor will look like Figure 1

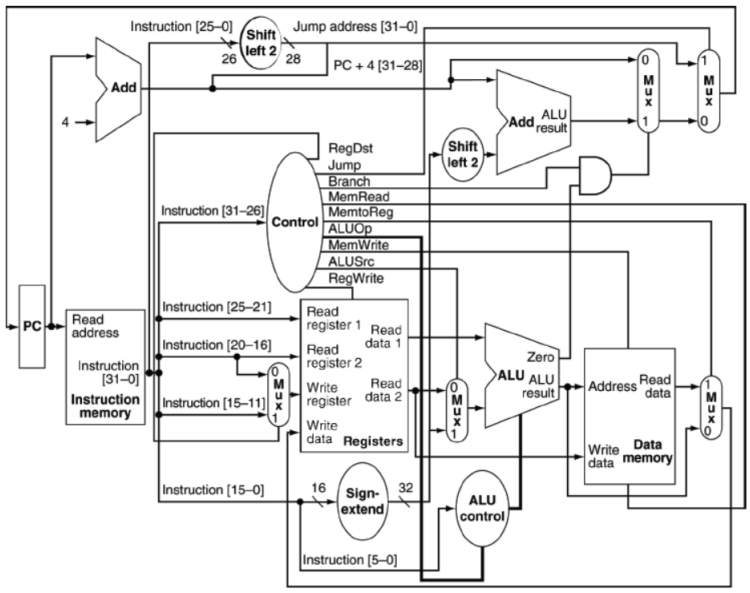

Figure 1: Single cycle implementation of MIPS architecture

However this architecture won't support all the instruction mentioned above. After adding some units, we come up with the schematic below (Fig2), which is generated by Vivado RTL Analysis.

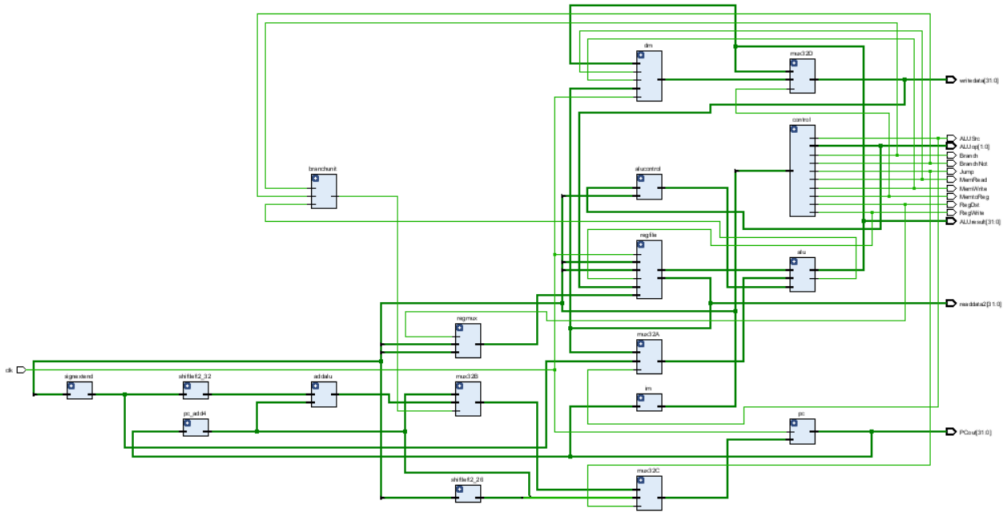

Figure 2: Single cycle processor schematic

2 Simulation Result

Mainly we use the instruction sequence below to test our processor.

```
00100000 00001000 00000000 00100000 //addi $t0, $zero, 0x20 0
00100000 00001001 00000000 00110111 //addi $t1, $zero, 0x37 4
00000001 00001001 10000000 00100100 //and $s0, $t0, $t1 8
00000001 00001001 10000000 00100101 //or $s0, $t0, $t1 c
10101100 00010000 00000000 00000100 //sw $s0, 4($zero) 10
10101100 00001000 00000000 00001000 //sw $t0, 8($zero) 14
00000001 00001001 10001000 00100000 //add $s1, $t0, $t1 18
00000001 00001001 10010000 00100010 //sub $s2, $t0, $t1 1c
00010010 00110010 00000000 00001001 //beq $s1, $s2, error0 20
10001100 00010001 00000000 00000100 //lw $s1, 4($zero) 24
00110010 00110010 00000000 01001000 //andi $s2, $s1, 0x48 28
00010010 00110010 00000000 00001001 //beq $s1, $s2, error1 3c
10001100 00010011 00000000 00001000 //lw $s3, 8($zero) 40
00010010 00010011 00000000 00001010 //beq $s0, $s3, error2 44
00000010 01010001 10100000 00101010 //slt $s4, $s2, $s1 (Last) 48
00010010 10000000 00000000 00001111 //beq $s4, $0, EXIT 4c
00000010 00100000 10010000 00100000 //add $s2, $s1, $0
00001000 00000000 00000000 00001110 //j Last
00100000 00001000 00000000 00000000 //addi $t0, $0, 0(error0)
00100000 00001001 00000000 00000000 //addi $t1, $0, 0
00001000 00000000 00000000 00011111 //j EXIT
00100000 00001000 00000000 00000001 //addi $t0, $0, 1(error1)
00100000 00001001 00000000 00000001 //addi $t1, $0, 1
00001000 00000000 00000000 00011111 //j EXIT
00100000 00001000 00000000 00000010 //addi $t0, $0, 2(error2)
00100000 00001001 00000000 00000010 //addi $t1, $0, 2
00001000 00000000 00000000 00011111 //j EXIT
00100000 00001000 00000000 00000011 //addi $t0, $0, 3(error3)
```

```
00100000 00001001 00000000 00000011 //addi $t1, $0, 3
00001000 00000000 00000000 00011111 //j EXIT
```

Our program starts at 0ns, logic low, and each clock cycle takes 20ns. The first 20ns is skipped to avoid hazard. Every time an instruction is loaded, the instant time, the PC address, and contents of some registers are displayed. Together with the given sequence of instructions, we'll explain what is happening as well as verify the results.

2.1 Memory-reference instructions

2.1.1 sw

The fifth instruction sw $s0, 4($zero) save s0=0x37 into mem[1]

```
Time:                   90, CLK=0, PC=00000010
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  100, CLK=1, PC=00000010
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.1.2 lw

In the later instruction lw $s1, 4($zero) this piece of memory is load to s1. Now s1 change to 0x37.

```
Time:                  190, CLK=0, PC=00000024
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  200, CLK=1, PC=00000024
[$s0] = 00000037, [$s1] = 00000037, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2 Arithmetic-logical instructions

2.2.1 addi

The first insturction addi $t0, $zero, 0x20 assign t0 to 0+0x20=0x20.

```
Time:                   10, CLK=0, PC=00000000
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000000
[$t1] = 00000000, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                   20, CLK=1, PC=00000000
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000000, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2.2 add

The instruction add $s1, $t0, $t1 will make s1 equal to t0+t1. As we see, s1 change from original value 0 to 0x57.

```
Time:                  130, CLK=0, PC=00000018
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  140, CLK=1, PC=00000018
[$s0] = 00000037, [$s1] = 00000057, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2.3 sub

The instruction sub $s2, $t0, $t1 make s2 equal to t0-t1. We see s2=0x20-0x37=0xE9.

```
Time:                  150, CLK=0, PC=0000001c
[$s0] = 00000037, [$s1] = 00000057, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
```

```
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  160, CLK=1, PC=0000001c
[$s0] = 00000037, [$s1] = 00000057, [$s2] = fffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2.4 and

The instruction and $s0, $t0, $t1 makes s0 equal to t0 & t1, which is 100000_2 & $110111_2 = 100000_2 =$ 0x20.

```
Time:                   50, CLK=0, PC=00000008
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                   60, CLK=1, PC=00000008
[$s0] = 00000020, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2.5 andi

The instruction $s2, $s1, 0x48 makes s2=$00110111_2$ & 01001000_2 =0x0.

```
Time:                  210, CLK=0, PC=00000028
[$s0] = 00000037, [$s1] = 00000037, [$s2] = fffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  220, CLK=1, PC=00000028
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
```

```
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2.6 or

The instruction or $s0, $t0, $t1 makes s0= 100000_2 — 110111_2 = 110111_2= 0x37.

```
Time:                    70, CLK=0, PC=0000000c
[$s0] = 00000020, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                    80, CLK=1, PC=0000000c
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.2.7 slt

The instruction slt $s4, $s2, $s1 set s4 to 1 because s2 is smaller than s1.

```
Time:                   290, CLK=0, PC=00000038
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                   300, CLK=1, PC=00000038
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.3 Jumping instructions

2.3.1 j

The instruction j Last goes back to slt $s4, $s2, $s1 (Last). We can see the machine code of j instruction is 00001000 00000000 00000000 00001110. The last 26 bits with two

0 added to the end gives us the jump destination, that is 38, exactly the address of slt.

```
Time:                  360, CLK=1, PC=00000044
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  370, CLK=0, PC=00000038
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

2.3.2 beq and bne

The instruction beq $s1, $s2, error0 doesn't jump because s1 s2 are not equal. I change this instruction to bne $s0,$t1, error0, it gives the same result since s0 equals t1 .

```
Time:                  170, CLK=0, PC=00000020
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  180, CLK=1, PC=00000020
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

The instruction beq $s4, $0, EXIT execute the jump since s4=0. Change this instruction to bne $s0, $s3, EXIT, it gives the same results since s0!=s3.

```
Time:                  400, CLK=1, PC=0000003c
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  410, CLK=0, PC=00000130
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
```

```
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

3 Peer evaluation

•	contribution	description
Hanyun Zhao(me)	5	connecting wires; debug; report
Yuchuan Tian	5++	connecting wires; debug; report; implementation
Qinzhe Yang	5	all other units in pipeline; report
Jinyuan Chen	5	forwarding unit, hazard detection; report

4 Apendix

```
module PC(clk,in, out);
input clk;
input [31:0]in;
output reg [31:0]out;

initial begin
    out=32'b11111111111111111111111111111100 ; //not from 0
       x00400000?
    //out=32'b0;
end

always@(posedge clk)begin
    out=in;
end

endmodule



module inst_mem(readaddr,instruction);
input [31:0]readaddr;
output [31:0] instruction;
reg [31:0]mem[127:0]; //size 128 words

//instruction load from where?

//initial begin
//$readmemb("C:/Users/Administrator/Desktop/VE370/Projects/
   project2/InstructionMem_for_P2_Demo.txt",mem);
```

```
28 //end
29 initial begin
30 //demo no bonus
31 //mem[0]=32'b00100000000010000000000000100000; //addi $t0, $zero,
      0x20
32 //mem[1]=32'b00100000000010010000000000110111 ;//addi $t1, $zero,
      0x37
33 //mem[2]=32'b00000001000010011000000000100100; //and $s0, $t0, $t1
34 //mem[3]=32'b00000001000010011000000000100101; //or $s0, $t0, $t1
35 //mem[4]=32'b10101100000100000000000000000100; //sw $s0, 4($zero)
36 //mem[5]=32'b10101100000100000000000000001000; //sw $t0, 8($zero)
37 //mem[6]=32'b00000001000010011000100000100000; //add $s1, $t0, $t1
38 //mem[7]=32'b00000001000010011001000000100010; //sub $s2, $t0, $t1
39 //mem[8]=32'b00100000000010000000000000100000; //addi $t0, $zero,
      0x20
40 //mem[9]=32'b00100000000010000000000000100000; //addi $t0, $zero,
      0x20
41 //mem[10]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
42 //mem[11]=32'b00010010001100100000000000010010; //beq $s1, $s2,
      error0
43 //mem[12]=32'b10001100000100010000000000000100; //lw $s1, 4($zero)
44 //mem[13]=32'b00110010001100100000000001001000; //andi $s2, $s1, 0
      x48
45 //mem[14]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
46 //mem[15]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
47 //mem[16]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
48 //mem[17]=32'b00010010001100100000000000001111; //beq $s1, $s2,
      error1
49 //mem[18]=32'b10001100000100110000000000001000; //lw $s3, 8($zero)
50 //mem[19]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
51 //mem[20]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
52 //mem[21]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
53 //mem[22]=32'b00010010000100110000000000001101; //beq $s0, $s3,
      error2
54 //mem[23]=32'b00000010010100011010000000101010; //slt $s4, $s2,
      $s1 (Last)
55 //mem[24]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
56 //mem[25]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
57 //mem[26]=32'b00100000000010000000000000100000; //addi $t0, $zero,
       0x20
```

```
58 //mem[27]=32'b00010010100000000000000000001111; //beq $s4, $0,
       EXIT
59 //mem[28]=32'b00000010001000001001000000100000; //add $s2, $s1, $0
60 //mem[29]=32'b00001000000000000000000000010111; //j Last
61 //mem[30]=32'b00100000000010000000000000000000;//addi $t0, $0, 0(
       error0)
62 //mem[31]=32'b00100000000010010000000000000000; //addi $t1, $0, 0
63 //mem[32]=32'b00001000000000000000000000111111; //j EXIT
64 //mem[33]=32'b00100000000010000000000000000001; //addi $t0, $0, 1(
       error1)
65 //mem[34]=32'b00100000000010010000000000000001; //addi $t1, $0, 1
66 //mem[35]=32'b00001000000000000000000000111111; //j EXIT
67 //mem[36]=32'b00100000000010000000000000000010; //addi $t0, $0, 2(
       error2)
68 //mem[37]=32'b00100000000010010000000000000010; //addi $t1, $0, 2
69 //mem[38]=32'b00001000000000000000000000111111; //j EXIT
70 //mem[39]=32'b00100000000010000000000000000011; //addi $t0, $0, 3(
       error3)
71 //mem[40]=32'b00100000000010010000000000000011; //addi $t1, $0, 3
72 //mem[41]=32'b00001000000000000000000000111111; //j EXIT
73
74 //*************************
75 //bonus test
76 mem[0]=32'b00100000000010000000000000100000; //addi $t0, $zero, 0
       x20
77 mem[1]=32'b00100000000010010000000000110111 ;//addi $t1, $zero, 0
       x37
78 mem[2]=32'b00000001000010011000000000100100; //and $s0, $t0, $t1
79 mem[3]=32'b00000001000010011000000000100101; //or $s0, $t0, $t1
80 mem[4]=32'b10101100000010000000000000000100; //sw $s0, 4($zero)
81 mem[5]=32'b10101100000010000000000000001000; //sw $t0, 8($zero)
82 mem[6]=32'b00000001000010011000100000100000; //add $s1, $t0, $t1
83 mem[7]=32'b00000001000010011001000000100010; //sub $s2, $t0, $t1
84 mem[8]=32'b00010010001100100000000000001001; //addi $t0, $zero, 0
       x20
85 mem[9]=32'b10001100000100010000000000000100; //addi $t0, $zero, 0
       x20
86 mem[10]=32'b00110010001100100000000001001000; //addi $t0, $zero, 0
       x20
87 mem[11]=32'b00010010001100100000000000001001; //beq $s1, $s2,
       error0
88 mem[12]=32'b10001100000100110000000000001000; //lw $s1, 4($zero)
89 mem[13]=32'b00010010000100110000000000001010; //andi $s2, $s1, 0
       x48
90 mem[14]=32'b00000010010100011010000000101010; //addi $t0, $zero, 0
       x20
91 mem[15]=32'b00010010100000000000000000001111; //addi $t0, $zero, 0
       x20
92 mem[16]=32'b00000010001000001001000000100000; //addi $t0, $zero, 0
       x20
```

```
93  mem[17]=32'b00001000000000000000000000001110; //beq $s1, $s2,
        error1
94  mem[18]=32'b00100000000010000000000000000000; //lw $s3, 8($zero)
95  mem[19]=32'b00100000000010010000000000000000; //addi $t0, $zero, 0
        x20
96  mem[20]=32'b00001000000000000000000000011111; //addi $t0, $zero, 0
        x20
97  mem[21]=32'b00100000000010000000000000000001; //addi $t0, $zero, 0
        x20
98  mem[22]=32'b00100000000010010000000000000001; //beq $s0, $s3,
        error2
99  mem[23]=32'b00001000000000000000000000011111; //slt $s4, $s2, $s1
        (Last)
100 mem[24]=32'b00100000000010000000000000000010; //addi $t0, $zero, 0
        x20
101 mem[25]=32'b00100000000010010000000000000010; //addi $t0, $zero, 0
        x20
102 mem[26]=32'b00001000000000000000000000011111; //addi $t0, $zero, 0
        x20
103 mem[27]=32'b00100000000010000000000000000011; //beq $s4, $0, EXIT
104 mem[28]=32'b00100000000010010000000000000011; //add $s2, $s1, $0
105 mem[29]=32'b00001000000000000000000000011111; //j Last
106
107
108 end
109 assign  instruction=mem[readaddr/4];
110
111
112 endmodule
113
114
115
116
117 module Control(opcode,RegDst,Jump,Branch,MemRead,MemtoReg,ALUop,
        MemWrite,ALUSrc,RegWrite,BranchNot);
118 //branchnot is for bne
119 input [5:0]opcode;
120 output reg RegDst,Jump,Branch,MemRead,MemtoReg,MemWrite,ALUSrc,
        RegWrite,BranchNot;
121 output reg [1:0] ALUop;
122
123 initial begin
124     RegDst=1'b0;
125     Jump=1'b0;
126     Branch=1'b0;
127     MemRead=1'b0;
128     MemtoReg=1'b0;
129     MemWrite=1'b0;
130     ALUSrc=1'b0;
131     RegWrite=1'b0;
```

```
132     BranchNot=1'b0;
133     ALUop=2'b00;
134 end
135
136 always@(opcode) begin
137     case (opcode)
138         6'b000000:begin  //R type
139             ALUop=2'b10;RegDst=1'b1;Jump=1'b0;Branch=1'b0;MemRead
                    =1'b0;MemtoReg=1'b0;
140             MemWrite=1'b0;ALUSrc=1'b0;RegWrite=1'b1;BranchNot=1'b0
                    ;
141         end
142
143          6'b100011:begin //lw
144             ALUop=2'b00;RegDst=1'b0;Jump=1'b0;Branch=1'b0;MemRead
                    =1'b1;MemtoReg=1'b1;
145             MemWrite=1'b0;ALUSrc=1'b1;RegWrite=1'b1;BranchNot=1'b0
                    ;
146         end
147
148         6'b101011:begin //sw
149             ALUop=2'b00;RegDst=1'b0;Jump=1'b0;Branch=1'b0;MemRead
                    =1'b0;MemtoReg=1'b0;
150             MemWrite=1'b1;ALUSrc=1'b1;RegWrite=1'b0;BranchNot=1'b0
                    ;
151         end
152
153         6'b001000:begin //addi
154             ALUop=2'b00;RegDst=1'b0;Jump=1'b0;Branch=1'b0;MemRead
                    =1'b0;
155             MemtoReg=1'b0;MemWrite=1'b0;ALUSrc=1'b1;RegWrite=1'b1;
                    BranchNot=1'b0;
156         end
157
158         6'b001100:begin //andi
159             ALUop=2'b11;RegDst=1'b0;Jump=1'b0;Branch=1'b0;MemRead
                    =1'b0;MemtoReg=1'b0;
160             MemWrite=1'b0;ALUSrc=1'b1;RegWrite=1'b1;BranchNot=1'b0
                    ;
161         end
162
163         6'b000100:begin //beq
164             ALUop=2'b01;RegDst=1'b0;Jump=1'b0;Branch=1'b1;MemRead
                    =1'b0;MemtoReg=1'b0;
165             MemWrite=1'b0;ALUSrc=1'b0;RegWrite=1'b0;BranchNot=1'b0
                    ;
166         end
167
168         6'b000101:begin //bne
```

```
169             ALUop=2'b01;RegDst=1'b0;Jump=1'b0;Branch=1'b0;MemRead
                    =1'b0;MemtoReg=1'b0;
170             MemWrite=1'b0;ALUSrc=1'b0;RegWrite=1'b0;BranchNot=1'b1
                    ;
171         end
172
173         6'b000010:begin //j
174             ALUop=2'b00;RegDst=1'b0;Jump=1'b1;Branch=1'b0;MemRead
                    =1'b0;MemtoReg=1'b0;
175             MemWrite=1'b0;ALUSrc=1'b0;RegWrite=1'b0;BranchNot=1'b0
                    ;
176         end
177
178     endcase
179 end
180
181 endmodule
182
183
184
185
186 module Regfile(clk, readreg1, readreg2, writereg, writedata,
       readdata1, readdata2,regwrite);
187 input clk,regwrite;
188 input[4:0]readreg1,readreg2,writereg;
189 input[31:0] writedata;
190 output reg[31:0] readdata1,readdata2;
191 reg [31:0] regs[0:31];
192
193 //read is neg, write is pos??
194
195 //always@(posedge clk) begin
196 //    readdata1<=regs[readreg1];
197 //    readdata2<=regs[readreg2];
198 //end
199
200 integer i;
201 initial begin
202     for (i = 0; i < 32; i = i + 1)
203         regs[i] = 32'b0;
204 end
205
206 always@(*)begin
207  readdata1=regs[readreg1];
208 readdata2=regs[readreg2];
209
210 end
211 always@(negedge clk) begin
212     if(regwrite) begin
213         regs[writereg]<=writedata;
```

```
214     end
215 end
216
217 always @ (posedge clk or negedge clk) begin
218     $display("[$s0] = %h, [$s1] = %h, [$s2] = %h", regs[16], regs
            [17], regs[18]);
219     $display("[$s3] = %h, [$s4] = %h, [$s5] = %h", regs[19], regs
            [20], regs[21]);
220     $display("[$s6] = %h, [$s7] = %h, [$t0] = %h", regs[22], regs
            [23], regs[8]);
221     $display("[$t1] = %h, [$t2] = %h, [$t3] = %h", regs[9], regs
            [10], regs[11]);
222     $display("[$t4] = %h, [$t5] = %h, [$t6] = %h", regs[12], regs
            [13], regs[14]);
223     $display("[$t7] = %h, [$t8] = %h, [$t9] = %h", regs[15], regs
            [24], regs[25]);
224     //$display("[$zero]=%h",regs[0]);
225 end
226
227 endmodule
228
229
230
231
232
233 module RegMux(RegDst,reg1,reg2,dst);
234 input RegDst;
235 input [4:0]reg1,reg2;
236 output [4:0]dst;
237
238 assign dst=RegDst?reg2:reg1;
239 endmodule
240
241
242
243
244
245
246 module SignExtend(in, out);
247 input [15:0]in;
248 output [31:0] out;
249
250 assign out={{16{in[15]}},in[15:0]};
251
252 endmodule
253
254
255
256
257 module ALUcontrol(funct,ALUop,alufunction);
```

```
input [5:0]funct;
input [1:0]ALUop; //how many bits is enough? why not just
   providing opcode?
output reg [3:0]alufunction;


always@(funct or ALUop) begin
    case (ALUop)
        2'b00:alufunction=4'b0010;//add
        2'b01:alufunction=4'b0110;//sub
        2'b11:alufunction=4'b0000;//and
        2'b10:begin
            case(funct)
                6'b100000:alufunction=4'b0010;//add
                6'b100010:alufunction=4'b0110;//sub
                6'b100100:alufunction=4'b0000;//and
                6'b100101:alufunction=4'b0001;//or
                6'b101010:alufunction=4'b0111;//slt
            endcase
            end
     endcase
end

endmodule









module Mux32(sel,data1,data2,data);
input sel;
input [31:0]data1, data2;
output [31:0]data;

assign data=sel?data2:data1;
endmodule









module ALU(result,zero,a,b,operation);
input [31:0]a,b;
output  zero;
output reg [31:0]result;//when a reg is needed?
input [3:0]operation;

assign zero=((a-b)==0);
```

```
307
308 initial begin
309     result=32'b0;
310 end
311 always@(a or b or operation) begin
312     case(operation)
313         4'b0010://add
314         result=a+b;
315
316         4'b0110://sub
317         result=a-b;
318
319         4'b0000://and
320         result=a & b;
321
322         4'b0001://or
323         result=a | b;
324
325         4'b0111://slt
326         result=(a<b)?1:0;
327
328     endcase
329 end
330
331 endmodule
332
333
334
335
336
337 module BranchUnit(Branch,BranchNot,zero,branchcontrol);
338 input Branch,BranchNot,zero;
339 output reg branchcontrol;
340 initial begin
341     branchcontrol=0;
342 end
343
344 always@(Branch or BranchNot or zero) begin
345
346     if(Branch==1) begin
347         if(zero==1) branchcontrol=1;
348         else branchcontrol=0;
349     end
350     else if (BranchNot==1) begin
351         if(zero==0) branchcontrol=1;
352         else branchcontrol=0;
353     end
354     else branchcontrol=0;
355
356     if(Branch==1 && BranchNot==1) branchcontrol=0; //error
```

```
357
358 end
359 endmodule
360
361
362
363
364
365
366 module Shiftleft2_26bit(instruction,j_addr);
367 input [25:0]instruction;
368 output [27:0]j_addr;
369
370 assign j_addr=instruction<<2;
371 endmodule
372
373 module Shiftleft2_32bit(signeximm,addaluop2);
374 input [31:0]signeximm;
375 output [31:0]addaluop2;
376
377 assign addaluop2=signeximm<<2;
378 endmodule
379
380
381
382
383 module PC_ADD4(PC,newPC);
384 input [31:0]PC;
385 output [31:0]newPC;
386
387 assign newPC=PC+4;
388
389 endmodule
390
391
392
393
394
395 module Shiftleft2_26bit(instruction,j_addr);
396 input [25:0]instruction;
397 output [27:0]j_addr;
398
399 assign j_addr=instruction<<2;
400 endmodule
401
402 module Shiftleft2_32bit(signeximm,addaluop2);
403 input [31:0]signeximm;
404 output [31:0]addaluop2;
405
406 assign addaluop2=signeximm<<2;
```

```
endmodule




module Add_ALU(newPC,imm,b_addr);
input [31:0]newPC;
input [31:0]imm;
output [31:0]b_addr;

assign b_addr=newPC+(imm<<2);
endmodule




module DataMemory(clk,Address,Writedata,Readdata,MemWrite,MemRead)
    ;
input MemWrite,MemRead,clk;
output reg [31:0]Readdata;
input [31:0]Address;
input [31:0]Writedata;
reg [31:0] storage [31:0];

initial begin
storage[0]=32'b0;
storage[1]=32'b0;
storage[2]=32'b0;
storage[3]=32'b0;
storage[4]=32'b0;
storage[5]=32'b0;
storage[6]=32'b0;
storage[7]=32'b0;
storage[8]=32'b0;
storage[9]=32'b0;
storage[10]=32'b0;
storage[11]=32'b0;
storage[12]=32'b0;
storage[13]=32'b0;
storage[14]=32'b0;
storage[15]=32'b0;
storage[16]=32'b0;
storage[17]=32'b0;
storage[18]=32'b0;
storage[19]=32'b0;
storage[20]=32'b0;
```

```
456 storage[21]=32'b0;
457 storage[22]=32'b0;
458 storage[23]=32'b0;
459 storage[24]=32'b0;
460 storage[25]=32'b0;
461 storage[26]=32'b0;
462 storage[27]=32'b0;
463 storage[28]=32'b0;
464 storage[29]=32'b0;
465 storage[30]=32'b0;
466 storage[31]=32'b0;
467 end
468
469 always@(MemRead or MemWrite or Address or Writedata) begin
470 //always@(negedge clk) begin
471     if(MemRead==1) Readdata=storage[Address/4];
472     else if (MemWrite==1) storage[Address/4]=Writedata;
473 end
474
475 endmodule
476
477
478
479
480
481
482 module singlecycle(clk,PCout,readdata2,writedata,RegDst,Jump,
       Branch,MemRead,MemtoReg,ALUop,MemWrite,ALUSrc,RegWrite,
       BranchNot,ALUresult);
483 input clk;
484 output [31:0]PCout;
485 //wire[31:0] PCin,PCout;//the input and output of PC
486 wire[31:0] PCin;//the input and output of PC
487 PC pc(clk,PCin,PCout);
488
489 wire [31:0]instruction;
490 inst_mem im(PCout,instruction);
491
492 output RegDst,Jump,Branch,MemRead,MemtoReg,MemWrite,ALUSrc,
       RegWrite,BranchNot;
493 output [1:0] ALUop;
494 Control control(instruction[31:26],RegDst,Jump,Branch,MemRead,
       MemtoReg,ALUop,MemWrite,ALUSrc,RegWrite,BranchNot);
495
496 wire [4:0]writereg;
497 output [31:0]writedata;
498 wire [31:0] readdata1;
499 output [31:0]readdata2;
500 Regfile regfile(clk,instruction[25:21],instruction[20:16],writereg
       ,writedata,readdata1,readdata2,RegWrite);
```

```
501 //clk, readreg1, readreg2, writereg, writedata, readdata1,
       readdata2,regwrite
502
503 RegMux regmux(RegDst,instruction[20:16],instruction[15:11],
       writereg);
504
505 wire[31:0]signeximm;
506 SignExtend signextend(instruction[15:0], signeximm);
507
508 wire [3:0]aluoperation;
509 ALUcontrol alucontrol(instruction[5:0],ALUop,aluoperation);
510
511 wire [31:0] operand1, operand2;//operand1 seems unused because
       readdata1 directly connected to ALU
512 Mux32 mux32A(ALUSrc,readdata2,signeximm,operand2);
513
514 wire zero;
515 output [31:0] ALUresult;
516 ALU alu(ALUresult,zero,readdata1,operand2,aluoperation);
517
518 wire branchcontrol;
519 BranchUnit branchunit(Branch,BranchNot,zero,branchcontrol);
520
521 wire[31:0] addaluop1,addaluop2;
522 Shiftleft2_32bit shiftleft2_32(signeximm,addaluop2);
523
524 wire [31:0]PCplus4;
525 PC_ADD4 pc_add4(PCout,PCplus4);
526
527 wire [27:0]jumpaddr;
528 Shiftleft2_26bit shiftleft2_26(instruction[25:0],jumpaddr);
529
530 wire [31:0]b_addr;//branch addr
531 Add_ALU addalu(PCplus4,addaluop2,b_addr);
532
533 wire [31:0]branchornextaddr;
534 Mux32 mux32B(branchcontrol,PCplus4,b_addr,branchornextaddr);
535
536
537 Mux32 mux32C(Jump,branchornextaddr,{PCplus4[31:28],jumpaddr
       [27:0]},PCin);
538
539 wire [31:0] Readdata;
540 DataMemory dm(clk,ALUresult,readdata2,Readdata,MemWrite,MemRead);
541
542 Mux32 mux32D(MemtoReg,ALUresult,Readdata,writedata);
543
544 endmodule
545
546
```

```
547
548
549
550
551
552 //************************Testbench
553 module singlecyclesim;
554 reg clk;
555 wire [31:0]PCout;
556 wire [31:0]readdata2;
557 wire [31:0]writedata;
558 wire RegDst,Jump,Branch,MemRead,MemtoReg,MemWrite,ALUSrc,RegWrite,
       BranchNot;
559 wire [1:0]ALUop;
560 wire [31:0]ALUresult;
561 singlecycle sc(clk,PCout,readdata2,writedata,RegDst,Jump,Branch,
       MemRead,MemtoReg,ALUop,MemWrite,ALUSrc,RegWrite,BranchNot,
       ALUresult);
562 integer count;
563 initial begin
564 //    #0 clk=0; count=1;$display("Time:%d, CLK=%d, PC=%h
       ",0,0,00000000);
565  #0 clk=1; count=1;$display("Time:%d, CLK=%d, PC=%h",0,0,00000000)
       ;
566 end
567 always #10 clk=~clk;
568 always #10
569 begin
570     $display("Time:%d, CLK=%d, PC=%h",$time,clk,PCout);
571     count=count+1;
572 end
573
574
575 initial #1000 $stop;
576 endmodule
```

Simulation output

```
1  Time:           0, CLK=           0, PC=00000000
2  [$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
3  [$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
4  [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000000
5  [$t1] = 00000000, [$t2] = 00000000, [$t3] = 00000000
6  [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
7  [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
8  Time:                  10, CLK=0, PC=00000000
9  [$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
10 [$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
11 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000000
```

```
[$t1] = 00000000, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  20, CLK=1, PC=00000000
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000000, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  30, CLK=0, PC=00000004
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000000, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  40, CLK=1, PC=00000004
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  50, CLK=0, PC=00000008
[$s0] = 00000000, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  60, CLK=1, PC=00000008
[$s0] = 00000020, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  70, CLK=0, PC=0000000c
[$s0] = 00000020, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  80, CLK=1, PC=0000000c
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
```

```
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                   90, CLK=0, PC=00000010
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  100, CLK=1, PC=00000010
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  110, CLK=0, PC=00000014
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  120, CLK=1, PC=00000014
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  130, CLK=0, PC=00000018
[$s0] = 00000037, [$s1] = 00000000, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  140, CLK=1, PC=00000018
[$s0] = 00000037, [$s1] = 00000057, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  150, CLK=0, PC=0000001c
[$s0] = 00000037, [$s1] = 00000057, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
```

```
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 160, CLK=1, PC=0000001c
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 170, CLK=0, PC=00000020
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 180, CLK=1, PC=00000020
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 190, CLK=0, PC=00000024
[$s0] = 00000037, [$s1] = 00000057, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 200, CLK=1, PC=00000024
[$s0] = 00000037, [$s1] = 00000037, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 210, CLK=0, PC=00000028
[$s0] = 00000037, [$s1] = 00000037, [$s2] = ffffffe9
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                 220, CLK=1, PC=00000028
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

```
Time:                  230, CLK=0, PC=0000002c
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  240, CLK=1, PC=0000002c
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  250, CLK=0, PC=00000030
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000000, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  260, CLK=1, PC=00000030
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  270, CLK=0, PC=00000034
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  280, CLK=1, PC=00000034
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  290, CLK=0, PC=00000038
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  300, CLK=1, PC=00000038
```

```
212 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
213 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
214 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
215 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
216 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
217 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
218 Time:                 310, CLK=0, PC=0000003c
219 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
220 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
221 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
222 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
223 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
224 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
225 Time:                 320, CLK=1, PC=0000003c
226 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
227 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
228 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
229 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
230 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
231 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
232 Time:                 330, CLK=0, PC=00000040
233 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000000
234 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
235 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
236 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
237 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
238 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
239 Time:                 340, CLK=1, PC=00000040
240 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
241 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
242 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
243 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
244 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
245 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
246 Time:                 350, CLK=0, PC=00000044
247 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
248 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
249 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
250 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
251 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
252 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
253 Time:                 360, CLK=1, PC=00000044
254 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
255 [$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
256 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
257 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
258 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
259 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
260 Time:                 370, CLK=0, PC=00000038
261 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
```

```
[$s3] = 00000020, [$s4] = 00000001, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  380, CLK=1, PC=00000038
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  390, CLK=0, PC=0000003c
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  400, CLK=1, PC=0000003c
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  410, CLK=0, PC=00000130
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  420, CLK=1, PC=00000130
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  430, CLK=0, PC=00000134
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  440, CLK=1, PC=00000134
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
```

```
312 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
313 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
314 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
315 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
316 Time:                  450, CLK=0, PC=00000138
317 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
318 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
319 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
320 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
321 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
322 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
323 Time:                  460, CLK=1, PC=00000138
324 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
325 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
326 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
327 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
328 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
329 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
330 Time:                  470, CLK=0, PC=0000013c
331 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
332 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
333 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
334 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
335 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
336 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
337 Time:                  480, CLK=1, PC=0000013c
338 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
339 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
340 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
341 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
342 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
343 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
344 Time:                  490, CLK=0, PC=00000140
345 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
346 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
347 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
348 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
349 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
350 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
351 Time:                  500, CLK=1, PC=00000140
352 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
353 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
354 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
355 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
356 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
357 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
358 Time:                  510, CLK=0, PC=00000144
359 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
360 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
361 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
```

```
362 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
363 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
364 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
365 Time:                  520, CLK=1, PC=00000144
366 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
367 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
368 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
369 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
370 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
371 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
372 Time:                  530, CLK=0, PC=00000148
373 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
374 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
375 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
376 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
377 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
378 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
379 Time:                  540, CLK=1, PC=00000148
380 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
381 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
382 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
383 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
384 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
385 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
386 Time:                  550, CLK=0, PC=0000014c
387 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
388 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
389 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
390 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
391 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
392 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
393 Time:                  560, CLK=1, PC=0000014c
394 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
395 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
396 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
397 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
398 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
399 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
400 Time:                  570, CLK=0, PC=00000150
401 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
402 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
403 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
404 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
405 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
406 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
407 Time:                  580, CLK=1, PC=00000150
408 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
409 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
410 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
411 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
```

```
412 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
413 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
414 Time:                  590, CLK=0, PC=00000154
415 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
416 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
417 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
418 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
419 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
420 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
421 Time:                  600, CLK=1, PC=00000154
422 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
423 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
424 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
425 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
426 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
427 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
428 Time:                  610, CLK=0, PC=00000158
429 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
430 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
431 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
432 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
433 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
434 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
435 Time:                  620, CLK=1, PC=00000158
436 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
437 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
438 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
439 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
440 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
441 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
442 Time:                  630, CLK=0, PC=0000015c
443 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
444 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
445 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
446 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
447 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
448 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
449 Time:                  640, CLK=1, PC=0000015c
450 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
451 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
452 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
453 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
454 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
455 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
456 Time:                  650, CLK=0, PC=00000160
457 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
458 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
459 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
460 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
461 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
```

```
462 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
463 Time:                  660, CLK=1, PC=00000160
464 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
465 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
466 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
467 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
468 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
469 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
470 Time:                  670, CLK=0, PC=00000164
471 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
472 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
473 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
474 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
475 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
476 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
477 Time:                  680, CLK=1, PC=00000164
478 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
479 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
480 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
481 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
482 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
483 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
484 Time:                  690, CLK=0, PC=00000168
485 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
486 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
487 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
488 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
489 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
490 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
491 Time:                  700, CLK=1, PC=00000168
492 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
493 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
494 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
495 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
496 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
497 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
498 Time:                  710, CLK=0, PC=0000016c
499 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
500 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
501 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
502 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
503 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
504 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
505 Time:                  720, CLK=1, PC=0000016c
506 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
507 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
508 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
509 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
510 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
511 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

```
Time:                  730, CLK=0, PC=00000170
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  740, CLK=1, PC=00000170
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  750, CLK=0, PC=00000174
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  760, CLK=1, PC=00000174
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  770, CLK=0, PC=00000178
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  780, CLK=1, PC=00000178
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  790, CLK=0, PC=0000017c
[$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
[$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
[$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
[$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
[$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
[$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
Time:                  800, CLK=1, PC=0000017c
```

```
562 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
563 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
564 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
565 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
566 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
567 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
568 Time:                  810, CLK=0, PC=00000180
569 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
570 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
571 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
572 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
573 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
574 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
575 Time:                  820, CLK=1, PC=00000180
576 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
577 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
578 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
579 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
580 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
581 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
582 Time:                  830, CLK=0, PC=00000184
583 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
584 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
585 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
586 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
587 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
588 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
589 Time:                  840, CLK=1, PC=00000184
590 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
591 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
592 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
593 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
594 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
595 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
596 Time:                  850, CLK=0, PC=00000188
597 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
598 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
599 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
600 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
601 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
602 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
603 Time:                  860, CLK=1, PC=00000188
604 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
605 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
606 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
607 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
608 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
609 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
610 Time:                  870, CLK=0, PC=0000018c
611 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
```

```
612 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
613 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
614 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
615 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
616 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
617 Time:                  880, CLK=1, PC=0000018c
618 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
619 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
620 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
621 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
622 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
623 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
624 Time:                  890, CLK=0, PC=00000190
625 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
626 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
627 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
628 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
629 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
630 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
631 Time:                  900, CLK=1, PC=00000190
632 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
633 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
634 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
635 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
636 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
637 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
638 Time:                  910, CLK=0, PC=00000194
639 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
640 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
641 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
642 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
643 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
644 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
645 Time:                  920, CLK=1, PC=00000194
646 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
647 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
648 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
649 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
650 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
651 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
652 Time:                  930, CLK=0, PC=00000198
653 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
654 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
655 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
656 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
657 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
658 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
659 Time:                  940, CLK=1, PC=00000198
660 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
661 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
```

```
662 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
663 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
664 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
665 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
666 Time:                  950, CLK=0, PC=0000019c
667 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
668 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
669 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
670 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
671 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
672 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
673 Time:                  960, CLK=1, PC=0000019c
674 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
675 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
676 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
677 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
678 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
679 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
680 Time:                  970, CLK=0, PC=000001a0
681 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
682 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
683 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
684 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
685 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
686 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
687 Time:                  980, CLK=1, PC=000001a0
688 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
689 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
690 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
691 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
692 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
693 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
694 Time:                  990, CLK=0, PC=000001a4
695 [$s0] = 00000037, [$s1] = 00000037, [$s2] = 00000037
696 [$s3] = 00000020, [$s4] = 00000000, [$s5] = 00000000
697 [$s6] = 00000000, [$s7] = 00000000, [$t0] = 00000020
698 [$t1] = 00000037, [$t2] = 00000000, [$t3] = 00000000
699 [$t4] = 00000000, [$t5] = 00000000, [$t6] = 00000000
700 [$t7] = 00000000, [$t8] = 00000000, [$t9] = 00000000
```

Figure 3: Simulation waveform