**Milestone 04**

**Design Document**

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# Description of Registers Available

There are sixteen registers total.

There are eight “t” registers, which are temporary variables. These registers can be overwritten at any time and do not need to be backed up on the stack. They are also used as parameters for functions. For example, if there is a function funct1(num0, num1, num2), num0 would be stored in $t0, num1 would be in $t1, and num2 would be in $t2.

There are four “s” registers. These registers must be backed up before use and restored after use. “S” registers are general purpose and can be used at any time.

There are two “v” registers. These registers function exactly like t registers, in that they don’t need to be backed up and can be used for general purposes. However, whenever a function is called, the v registers will contain the return value of the function. The $v0 register is also the display register. This is the final output number and will be displayed to the user.

There is one “at” register. This register is special use for when the compiler needs to split a pseudo-instruction into multiple instructions. This register may not be used in normal code.

There is one “ra” register. This register is for the return address of a function. When a function is called, jal automatically saves PC counter into the $ra register. The program counter is then changed to the address of the function. $ra is a reserved register and may not be used for general purpose needs. $ra must be backed up on the stack before calling a function and restored after the call is complete.

There is one “dp” register. This register keeps track of the data stack, where we can store variables (see register conventions). $dp functions as a second stack, very similarly to the stack $sp keeps track of. The value of $dp at the beginning and end of a function must match.

*Table 1 Register address*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| REGCODE | 00 | 01 | 10 | 11 |
| 00 | t0 | t1 | t2 | t3 |
| 01 | t4 | t5 | t6 | t7 |
| 10 | s0 | s1 | v0 | v1 |
| 11 | s2 | at | ra | dp |

# English description of each machine language instruction format

R-type -- regular instruction format with two 4-bit register (r1 and r2), 1-bit memory-load-option-code (LM), and a 3-bit cc. Most of the time, instructions of this format will perform general operations with the values in r1 and r2, like add and or, and stores the result into r1. If one wants to use the CC, please refer to the later explanation on cc. If LM is 1, then it would perform the operation with Mem[R[r2]] instead of R[r2], so just go to memory to load value.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| op(4) | r1(4) | r2(4) | LM(1) | CC(3) |

I-type -- immediate instruction format with one 4-bit register (r1) and 8-bit immediate value (imm). It performs a general operation of values in r1 and imm and stores it into r1.

|  |  |  |
| --- | --- | --- |
| op(4) | r1(4) | imm(8) |

J-Type -- jump instruction format takes up 2 instructions (32 bits). If jop is set to 1 then the second instruction contains a 16 bit address and when it goes to that address, it also links by setting $ra to be PC. If jop is set to 0, then it will only go to that address.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| op(4) | $ra | unused(4) | jop(1) | CC(3) |

|  |
| --- |
| address(16) |

### Explanation of Condition Code (CC)

All R, B, and J type instructions use a three-bit condition code. This three-bit code specifies one of the following:

*Table 2 Conditional Code (CC)*

|  |  |  |
| --- | --- | --- |
| **explanation** | **CC** | **condition** |
| greater than | 100 | > |
| greater than or equal | 110 | >= |
| less than | 001 | < |
| less than or equal | 011 | <= |
| equal | 010 | = |
| not equal | 101 | != |
| always execute | 111 | True |

How condition code work:

There is a three-bit flag register inside our CPU, which stores the last comparison result. The only cmd that would update flag register is cmp.

cmp $t0 $t1

In the above example, cmp would subtract $t0 and $t1 and set flag bits depending on the result. Three bits of flag represent negative (smaller than), zero (equal), positive (bigger than) respectively. Only one bit of those flags can be 1 since $t0 - $t1 can only be negative number, zero or positive number.

Whenever an instruction is executed (except I-type, without CC), we compare those condition bits and flag bits. Similarly, three CC bits represent negative (smaller than), zero (equal), positive (bigger than). As shown in the table above, if the flag bit indicate that the last comparison satisfies the condition, this instruction is going to be executed, otherwise, it is going to be skipped.

This cool feature enables us to do short ‘if’ statement without branches. We can do a compare and then skip instruction that we do not want to execute. Instruction skipped would take only two cycles, so a pretty efficient way to do single line ‘if’.

Take, for example, the following python code:

|  |  |
| --- | --- |
| if $t0 > $t1 :  B1  B2…  elif $t0 == $t1:  E1  else:  S1. | cmp $t0, $t1  B1 …… , 100  B2 …… , 100  E1 …… , 010  S1 …… , 001 |

For short if statements of no more than 2 instructions, CC can save the trouble multiple branches have by simply skipping over certain instructions. For one single line if, this is even better. However, there is one restriction for CC. I-type instruction cannot take advantage of CC.

By default, the condition code is 111 if it is not specified in the instruction, so these instructions are always going to be executed.

# English Description of Each Instruction and Semantics

## Real Instructions:

add -- adds a register and either a value from another register or a value from memory together and stores the value in the first register. This is an R-type instruction. All R-type can have optional condition code at its end.

add $r1, $r2 add $r1, ($r2) add $r1, $r2, 110

addi -- adds a register to an immediate value and stores the result in the register. This is an I-type instruction.

addi $r1, imm (immediate is 8 bits)

sto -- takes the value in a register and then stores it in memory at a specified address. That address is either from a register or a location in memory. This is an R-type instruction.

sto $r1, $r2 sto $r1, ($r2) sto $r1, $r2, 100

lui -- takes the immediate value and places it in the upper portion of whatever register specified. This is an I-type instruction.

lui $r1, 8-bit immediate

sub -- takes a register and subtracts either a value from another register or memory from it and stores the value in the register. This is an R-type instruction.

sub $r1, $r2 sub $r1, ($r2) sub $r1, $r2, 100

cmp -- takes a register and another register or a value from memory and compares their values. It then sets the three flag bits to show whether the first register is smaller (100), equal (010), or greater (001) than the second. This is an R-type instruction, so it also takes CC. We can optional skip cmp, so we can do multiple comparison in a row.

cmp $r1, $r2 cmp $r1, ($r2) cmp $r1, $r2, 100

cp -- takes one register and copies its value into a different register in the format of destination register, source register. This is an R-type instruction.

cp $r1, $r2 cp $r1, ($r2) cp $r1, $r2, 100

cpi -- initializes a register with an immediate value. This is an I-type instruction.

cpi $r1, imm (immediate is 8 bits)

and -- ands a register and either a value from another register or memory together and stores the value in the first register. This is an R-type instruction.

and $r1, $r2 and $r1, ($r2) and $r1, $r2, 100

xor -- takes a register value and another register or a value from memory, xors them together, and stores the new value in the first register. This is an R-type instruction.

xor $r1, $r2 xor $r1, ($r2) xor $r1, $r2, 100

push -- decrements the stack pointer register and then stores the value in the register in the stack. This is an R-type instruction.

push $r1 push $r1, 100

pop -- loads the value from the stack at the location of the stack pointer into the register and then increments the stack pointer. This is an R-type instruction.

pop $r1 pop $r1, 100

or -- Ors a register and either a value from another register or memory together and stores the value in the first register. This is an R-type instruction.

or $r1, $r2 or $r1, ($r2) or $r1, $r2, 100

jr -- takes the value in a register and jumps to that instruction number. This is an R-type instruction.

jr $r1 jr $r1, 010

jl -- jumps conditionally to a label. It has the same opcode as jal, but with a flag bit(LM) = 0 to discriminate them. This is a J-type and takes 4 bytes memory.

jl label jl label, 010

jal -- jumps conditionally to a label and link. It has the same oncode as jl, but with a flag bit(jop) = 1 to discriminate them. Apart from setting the PC to new address, it also sets $ra to old PC address. jal is usually used to do function calls. This is a J-type and takes 4 bytes memory.

jal label jal label, 001

## Pseudo Instructions:

andi -- ands a value from a register and an eight bit immediate and puts the value into the source register.

andi $r1, imm (8 bit immediate)

cpi $at, imm (8 bit immediate)

and $r1, $at

ori -- ors a value from a register and an eight bit immediate and puts the value into the source register.

ori $r1, imm (8 bit immediate)

cpi $at, imm (8 bit immediate)

or $r1, $at

xori -- xors a value from a register with an eight bit immediate and puts the value in the source register.

xori $r1, imm (8 bit immediate)

cpi $at, imm (8 bit immediate)

xor $r1, $at

clear -- sets a register to have a value of zero.

clear $r1

cpi $r1, 0

addi (big) -- adds a 16 bit immediate to a value in a register.

addi $r1, imm (16 bit immediate)

lui $at, upper immediate

cpi $at, lower immediate

add $r1, $at

cpi (big) -- sets a register to a 16 bit immediate value.

cpi $r1, imm (16 bit immediate)

lui $r1, upper immediate

cpi $r1, lower immediate

cmpi -- compares a value from a register with an immediate value.

cmpi $r1, imm (8 bit immediate)

cpi $at, immediate

cmp $r1, $at

cmpi (big) -- compares a value from a register with an immediate value.

cmpi $r1, imm (16 bit immediate)

lui $at, upper immediate

cpi $at, lower immediate

cmp $r1, $at

beq -- branches to a label if two registers are equal.

beq $r1, $r2, label

cmp $r1, $r2

jl label, 010

bne -- branches to a label if two registers are not equal.

bne $r1, $r2, label

cmp $r1, $r2

jl label, 101

blt -- branches if the first register is less than the second register.

blt $r1, $r2, label

cmp $r1, $r2

jl label, 100

bgt -- branches if the first register is greater than the second register

bgt $r1, $r2, label

cmp $r1, $r2

jl label, 001

ble -- branches if the first register is less than or equal to the second register

ble $r1, $r2, label

cmp $r1, $r2

jl label, 110

bge -- branches if the first register is greater than or equal to the second register

bge $r1, $r2, label

cmp $r1, $r2

jl label, 011

# Explanation of Register Conventions

In general purpose assembly, the t and v registers may be used. However, these values are potentially destroyed whenever a function call is made, so their values must be saved on the stack or into an s register. The t registers are also used as parameters for function calls, starting with the lowest t register first. If more than eight parameters are needed, they are to be stored on the stack. The v registers are used as output from functions.

The s registers may be used in general purpose assembly code as well, but they must be backed up before use and restored after use. In exchange, their value is guaranteed across function calls.

The at register is for the compiler’s use only. When pseudo-instructions are changed into a set of regular instructions, if a temporary variable is needed, at is to be used. It is very important that at is not used for general purpose programming.

The ra register is for the return address of a function only. If it is ever changed, it must be backed up first and restored afterward. This allows for the nesting of function calls. For example, if main calls add(), and add() calls sub(), add() must back up the ra value from main and restore it after the sub() call has finished. Additionally, any t or v registers that hold important values must be backed up or their values will be lost.

**We separate the regular stack into a data stack and a procedure stack.** The procedure stack keeps track of return address and restored ‘s’ and ‘t’ registers while the data stack keeps track of arrays and other data that needs a reference. **No pointer is allowed to point to any address within the procedure stack.** This design prohibits buffer overflow attacks because return address and any array will be in two different stacks and no one can modify return addresses in the procedure stack.

There are two separate stack pointers for data stack and procedure stack -- $dp and $sp.

**$dp keeps track of the data stack.** Sometimes we need to allocate a big chunk of local memory for an array or object. We can decrement $dp to allocate appropriate amount of data. Then the value of $dp would be the pointer to the data chunk we just allocated. For example, to initialize an array of chars with size of 20 --

|  |  |
| --- | --- |
| char[] a = new char[20];  …  return .... | addi $dp, -20  cp $t0, $dp # $t0 points to the new array  ……  addi $dp, 20 # free memory before end this function |

For other times, we might want a reference to some data, and pass it to another function (similar to the idea of objects). Again, we can decrement $dp to allocate the appropriate amount of memory and then get a pointer to that data. For example, pass reference in C program --

|  |  |
| --- | --- |
| char a = 20;  ...  func( &a )  a = a + 1  ...  return | cpi $t1, 20  addi $dp, -1  sto $t1, $dp  cp $s0, $dp # now $s0 is address of variable a  ...  cp $t0, $s0 # pass the address of a as parameter  call func  addi $t0, ($s0) # restore possible changed value of a  ... # from the data stack.  addi $dp, 1 |

Note that value might have changed during the function call, so it is necessary to restore its value from data stack after the function call. Except global variables, all addressable memory (array, struct, object) created inside a function must be stored in the data stack.

Therefore, all pointers in the program have to point somewhere within data stack or heap.

We have a procedure stack pointer($sp) register besides those sixteen registers, but not accessible through assembly. It keeps track of the procedure stack, which is only used to backup and restore register for procedure calls. We hide $sp form programmers, so there will never be a pointer to somewhere in procedure stack. Therefore, no programmer will be able to change data in procedure stack. Attacks like buffer overflow can never exist in our processor, because the input data are in the data stack, while the return address is in the procedure stack. Furthermore, to protect that data, our memory is supposed to throw a segment fault if anybody tries to modify data in the procedure stack.

Another advantage of having push and pop is that they are fast. For MIPS, every function call needs to increment and decrement stack pointer and then backup data one by one. Our ‘push’ and ‘pop’ write and read data as well as update the stack pointer, but takes the same amount of time with real memory. With fake memory, it is possible to take even less time than ‘add’.

# Assembly Language Translation Rule

For each instruction in the Assembly language, first translate the name of the instruction to an opcode using this table. All instruction format except I-type would have 3 bits conditional code (CC) at the end. If not specified with the assembly, those three bits is going to be 111 defaultly.

*Table 3 op code*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| OPCODE | 00 | 01 | 10 | 11 |
| 00 | add [R] | addi [I] | sto [R] | lui [I] |
| 01 | sub [R] | cmp [R] | cp [R] | cpi [I] |
| 10 | and [R] | xor [R] | push [R] | pop [R] |
| 11 | or [R] | (blank) | jr [R] | jl/jal [J] |

After the first four bits are determined, the rest of the instruction is determined based on what type of instruction it is.

If it’s an R type:

Translate the two register names into register codes and append them. If the second

register had parenthesis around it symbolizing a retrieve from memory, then the next bit (LM) is one. Otherwise, it is zero. The last three bits are condition code (CC) used to decide whether to skip this R-type instruction or not.

opcode (4) + r1 (4) + r2 (4) + LM (1) + CC(3)

If it’s an I Type:

The next four bits are the register address. After that is an eight bit immediate. I-Type is the only type without CC.

opcode (4) + r1 (4) + imm(8)

If it’s a J Type:

Its machine code takes 4 bytes instead of 2 bytes as others. The first 2-byte has 4-bit opcode at front and 3-bit CC code at end. If it is jr, then the last fourth bit(LM) is set to be 0. If it’s jr, then LM is set to 1 and second register slot(r2[11-8]) should be the register address of $ra to simplify hardware implementation. The second 2-byte contains the new address to jump to.

jl jal

opcode (4) + unused(8) + 0 + imm(3) opcode (4) + unused(4) + 1110($ra) + 1 + imm(3)

address(16) address(16)

# Example Assembly Language programs

## Euclid’s Algorithm

|  |  |  |  |
| --- | --- | --- | --- |
| **Address** | **Assembly code** | **Binary Representation** | **Comments** |
| 0x0000 | \_\_\_relPrime: | \_\_relPrime: |  |
| 0x0004 | push $ra | 1010111000000111 | # store $ra on the stack |
| 0x0008 | push $s0 | 1010100000000111 | # store old $s0 on the stack |
| 0x000c | push $s1 | 1010100100000111 | # store old $s1 on the stack |
| 0x0010 | cp $s0, $t0 | 0110100000000111 | # put argument to a s register |
| 0x0014 | cpi $s1, 2 | 0111100100000010 | # int m = 2; |
| 0x0018 | WHILE1: | WHILE1: |  |
| 0x001c | cp $t0, $s0 | 0110000010000111 | # put variables into argument registers |
| 0x0020 | cp $t1, $s1 | 0110000110010111 |  |
| 0x0024 | jl \_\_gcd | 1111000000000111  0000000001010000 | # call function gcd |
| 0x0028 | addi $s1, 1 | 0001100100000001 | # m = m + 1; |
| 0x002c | cpi $at, 1 | 0111110100000001 | # check to see if the output is not 1 |
| 0x0030 | cmp $v0, $at | 0101101011010111 |  |
| 0x0034 | jl WHILE1, 101 | 1111000000000101 | # loop if return value != 1 |
| 0x0038 |  | 0000000000011000 |  |
| 0x003c | cp $v0, $s1 | 0110101010010111 | # set retValue = m |
| 0x0040 | pop $s1 | 1011100100000111 | # restore previous $s1 |
| 0x0044 | pop $s0 | 1011100000000111 | # restore previous $s0 |
| 0x0048 | pop $ra | 1011111000000111 | # restore previous $ra |
| 0x004c | jr $ra | 1110111000000111 | # return m |
| 0x0050 | \_\_gcd: | \_\_gcd: |  |
| 0x0054 | cpi $t7, 0 | 0111011100000000 | # create a zero for comparisons |
| 0x0058 | cmp $t0, $t7 | 0101000001110111 | # check if a == 0 |
| 0x005c | cp $v0, $t1, 010 | 0110101000010010 | # if a == 0, set retValue = b |
| 0x0060 | jr $ra, 010 | 1110111000000010 | # if a == 0, return b |
| 0x0064 | cmp $t1, $t7 | 0101000101110111 | # checks if b !=0 |
| 0x0068 | jl RET, 010 | 1111000000000010 | # skip the while loop if b == 0 |
|  |  | 0000000010000100 |  |
| 0x006c | WHILE2: | WHILE2: |  |
| 0x0070 | cmp $t0, $t1 | 0101000000010111 | # check if a > b |
| 0x0074 | sub $t0, $t1, 001 | 0100000000010001 | # a = a - b; if a > b |
| 0x0078 | sub $t1, $t0, 110 | 0100000100000110 | # b = b - a; if a <= b |
| 0x007c | cmp $t1, $t7 | 0101000101110111 | # check if b != 0 |
| 0x0080 | jl WHILE2, 101 | 1111000000000101 | # loop if b != 0 |
|  |  | 0000000001101100 |  |
| 0x0084 | RET: | RET: |  |
| 0x0088 | cp $v0, $t0 | 0110101000000111 | # set retValue = a |
| 0x008c | jr $ra, jr | 1110111000000111 | # return a |

## Assembly Language Fragments for difficult instructions

|  |  |
| --- | --- |
| \_clear $t0  sub $t0, $t0 | 0100000000000111 |
| \_beq $t1, $t2, label  cp $at, $t1  sub $at, $t2  jl label, 101 | 0110110100010111  0100110100100111  1111000000000101  (label) |
| \_blt $t1, $t2, label  cp $at, $t1  sub $at, $t2  jl label, 100 | 0110110100010111  0100110100100111  1111000000000100  (label) |
| \_ble $t1, $t2, label  cp $at, $t1  sub $at, $t2  jl label, 110 | 0110110100010111  0100110100100111  1111000000000110  (label) |
| \_addi(big) $t1, big  lui $at, upperbig  cpi $at, lowerbig  add $t1, $at | 0011110100000000  0111110100000000  0000000111010000 |
| \_li(big) $t1, big  lui $t1, upperbig  cpi $t1, lowerbig | 0011000100000000  0111000100000000 |
| \_cp(big) $t1, (big)  lui $t1, upperbig  cpi $t1, lowerbig | 0011000100000000  0111000100000000 |

# RTL Details

For all instruction except I-type, they might be skipped if flag does not match condition code. In cycle 2, flag register compares condition code (CC) and flag bits and output perform bit into control. When perform is 1, it signals that flag bit satisfies CC and this instruction is going to be executed, otherwise, the control is going to skip this instruction and starts the next one.

For most R-type instruction except push and pop, if LM = 1, there is an extra cycle between Cycle 2 and Cycle 3 to load memory. If LM = 0, there will not be LM cycle. All of those magic happen inside control, which has LMC input from datapath. This extra cycle is in the red box in the RLT below. After this extra cycle, everything else works exactly the same.

*Table 4 RTL first half*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Calculations | cmp | sto | cp | jr | jl | jal |
| Cycle 1 | IR = Mem[PC]  PC += 1 | | | | | | |
| Cycle 2 | A = R[IR[11:8]]  B = R[r2] | | | | | PC += 1  B = Mem[PC] | |
| LM cycle | B = Mem[B] | | | | |  | |
| Cycle 3 | ALUO= A op B | flag = sign(A – B) | Mem[B] = A | R[IR[11:8]] = B | PC = B | | PC = B  R[IR[11:8]] = PC |
| Cycle 4 | R[IR[11:8]] = ALUO |  |  |  |  |  |  |

*Table 5 RTL second half*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | addi | lui | cpi | push | pop |
| Cycle 1 | IR = Mem[PC]  PC += 2 | | | | |
| Cycle 2 | A = R[r1]  B = R[r2] | R[r1] = Upper(imm) | R[r1] = SignExtend(imm) | $sp -= 2 | B = Mem[$sp] |
| Cycle 3 | ALUO = A + Sign(imm) |  |  | Mem[$sp] = A | R[r1] = B  $sp +=2 |
| Cycle 4 | R[r1] = ALUO |  |  |  |  |

# RTL Testing methods

For all instructions, besides the jumps and branches, make sure pc was incremented by 2 in all cases.

*Table 6 RTL Testing*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Instruction | Opcode | Testing method | | |
| addi | 0001 | addi $t0, 5  Assume $t0= 6. The expected value of $t0 after the execution should be 11 |  |  |
| lui | 0011 | lui $t0, 0xff  The expected value of $t0 after the execution should be 1111 1111 0000 0000 regardless of what was previously in $t0 |  |  |
| cpi | 0111 | cpi $r1, 0xff  The expected value of $r1 is 0000 0000 1111 1111 |  |  |
| sto | 0010 | sto $r1, $r2  If $r1 is 0xffff and $r2 = 0x0022, then the memory at 0x0022 will be 0xffff after the execution | sto $r1, ($r2)  If $r1 is 0xffff and $r2 is 0x0001, then the value at the address specified by what is at 0x0001 in memory will be 0xffff | sto $r1, $r2, 100  If the cc is true, then the instruction will be executed |
| cp | 0110 | cp $r1, $r2  if $r2=0x0033 initially, then after the execution, $r1 should be 0x0033 | cp $r1, ($r2)  if $r2=0x0112 and the value at 0x0112 in memory is 12, after execution, $r1 should be 12. | cp $r1, $r2, 100  if the cc is true, then the instruction will be executed, use the initial conditions from the first column |
| add | 0000 | add $r1, $r2  input: $r1 = 0x0002, $r2= 0x0003  check that $r1 = 0x0005 after execution | add $r1, ($r2)  input: $r1 = 0x0003, $r2=0x0002  Assume value at 0x0002 in memory = 0x0004  check that $r1=0x0007 | add $r1, $r2, 110  if the flag does not match CC, make sure the add was not done, otherwise do previous. Use initial conditions from first test column. |
| sub | 0100 | sub $r1, $r2  input: $r1 = 0x0003, $r2= 0x0002  check that $r1 = 0x0001 after execution | sub $r1, ($r2)  input: $r1 = 0x0003, $r2=0x0002  Assume value at 0x0002 in memory = 0x0001  check that $r1=0x0002 | sub $r1, $r2, 100  if the flag does not match CC, make sure the add was not done, otherwise do previous. Use initial conditions from first test column. |
| cmp | 0101 | cmp $r1, $r2  if $r1=0x0002=$r2, check to make sure the value in the flag register equals 010 after the comparison | cmp $r1, ($r2)  if $r1=0x0002, $r2=0x0014, and the value at 0x0014 in memory is 0x0001, make sure the flag value is for greater than | cmp $r1, $r2, 100  if the flag does not match CC, make sure the value in the flag register was unchanged. otherwise do previous |
| and | 1000 | and $r1, $r2  input: $r1 = 0x0003, $r2= 0x0005  check that $r1 = 0x0001 after execution | and $r1, ($r2)  input: $r1 = 0x0003, $r2=0x0002  Assume value at 0x0002 in memory = 0x0004  check that $r1=0x0000 | and $r1, $r2, 100  if the flag does not match CC, make sure the value in $r1 is unchanged, otherwise do previous. Use initial conditions from first test column. |
| xor | 1001 | xor $r1, $r2  input: $r1 = 0x0003, $r2= 0x0005  check that $r1 = 0x0004 after execution | xor $r1, ($r2)  input: $r1 = 0x0003, $r2=0x0002  Assume value at 0x0002 in memory = 0x0006  check that $r1=0x0002 | xor $r1, $r2, 100  if the flag does not match CC, make sure the value in $r1 is unchanged, otherwise do previous. Use initial conditions from first column |
| or | 1100 | or $r1, $r2  input: $r1 = 0x0003, $r2= 0x0005  check that $r1 = 0x0007 after execution | or $r1, ($r2)  input: $r1 = 0x0003, $r2=0x0003  Assume value at 0x0002 in memory = 0x0006  check that $r1=0x0007 | or $r1, $r2, 100  if the flag does not match CC, make sure the value in $r1 is unchanged, otherwise do previous. Use initial conditions from first column |
| push | 1010 | push $r1  Value of stack register is 0x0004 initially. Check whether the value in the register is now 0x0006.  if $r1 is initially 4  Check if Mem[stack register] = 4 |  | push $r1, 100  if the flag does not match CC, make sure stack pointer register is not incremented, otherwise do previous. Use intitial conditions from first column |
| pop | 1011 | pop $r1  Value of stack register is 0x0004 initially. Check whether the value in the register is now 0x0002.  if Mem[stack register] = 4 initially, check if $r1=4. |  | pop $r1, 100  if the flag does not match CC, make sure stack pointer register is not decremented, otherwise do previous. Use intitial conditions from first column |
| jr | 1110 | jr $r1  check the PC if it is the same value as $r1 |  | jr $ra, 010  if the flag does not match CC, then PC should be PC+2 |
| jal | 1111 | jal label  if this is instruction 0x0202 and the label is |  | jal label, 010  if the flag does not match CC, then PC should be PC+2 |
| jl | jl label  check the PC to make sure the branch was executed, PC = PC + 2 |  | jl label, 100  if the cc is true, make sure the branch was executed. make sure the branch was executed. |

# Connections of the Datapath Components:

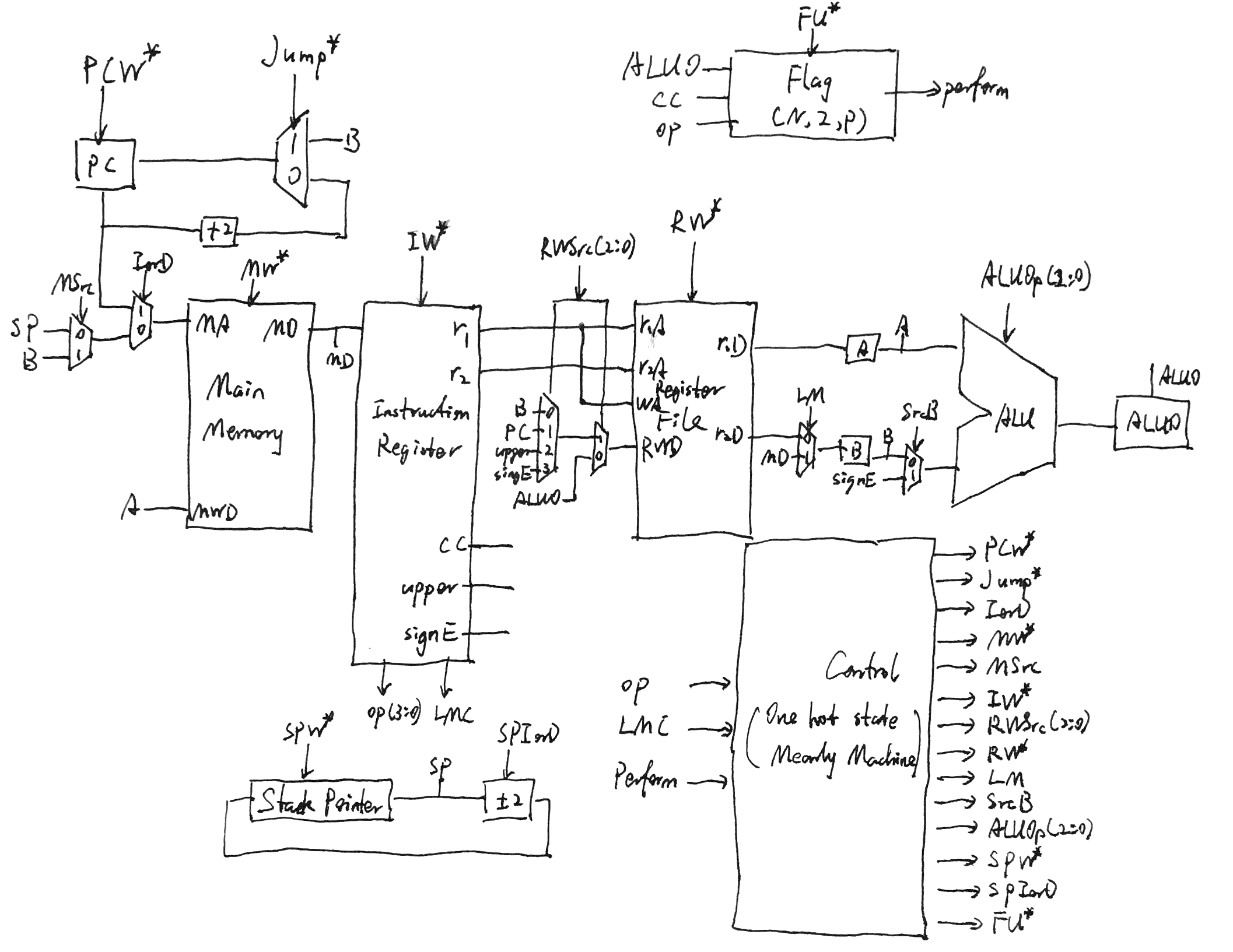
*Table 7 Connections of Datapath Components*

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type of component | Name | Inputs | | | | | Outputs | | | |
|  | 0 | 1 | 2 | 3 | **Control Signal** | 0 | 1 | 2 | **Control Input** |
| Mux | MSrcMux | SP | B |  |  | **MSrc** | MDAddr |  |  |  |
| PCMux | PC+2 | B |  |  | **Jump** | newPC |  |  |  |
| RWSrcMux | ALUO | SpeRWD |  |  | **RWSrc(0)** | RWD |  |  |  |
| SrcBMux | B | signE |  |  | **SrcB** | ALUBin |  |  |  |
| LMMux | r2D | MD |  |  | **LM** | Bin |  |  |  |
| IorDMux | MDAddr | PC |  |  | **IorD** | MA |  |  |  |
| RWSrcMux2 | B | PC | upper | signE | **RWSrc(1:0)** | SpeRWD |  |  |  |
| Memory/ Register | Memory | MA | MWD |  |  | **MW** | MD |  |  |  |
| Register File | r1A | r2B | RWD |  | **RW** | R1D | R2D |  |  |
| A | r1D |  |  |  |  | A |  |  |  |
| B | Bin |  |  |  |  | B |  |  |  |
| ALUO | ALUOut |  |  |  |  | ALUO |  |  |  |
| PC | newPC |  |  |  | **PCW** | PC |  |  |  |
| Instruction register | MD |  |  |  | **IW** | r1 | r2 | CC | **Op** |
| upper | signE |  | **LMC** |
| Stack Pointer | newSP |  |  |  | **SPW** | SP |  |  |  |
| Flag | ALUO | CC | Op |  | **FU** |  |  |  | **perform** |
| ALU/  Adder | ALU | A | ALUBin |  |  | **ALUOp** | ALUOut |  |  |  |
| SPAdder | SP |  |  |  | **SPIorD** | newSP |  |  |  |
| PCAdder | PC |  |  |  |  | PC+2 |  |  |  |

# Datapath Design Diagram

All signals with arrows into block are control signals, while all arrows out of blocks are input to control.

*Figure Datapath implementation diagram*



# Description of Datapath Components

Note for text in *Italic*: RESET control to initialize our datapath, and modification necessary due to Xilinx’s limitation of 14-bit address is described above, but not yet implemented yet. We will work on those updates in next milestone.

*Table 8 Datapath components Desriptions*

|  |  |  |
| --- | --- | --- |
| Type of component | Name | Description |
|
| Mux | MSrcMux | Memory source mux indicates whether pop or branch is used, then select the correct memory location then send it to the main memory. It takes three inputs: SP, the stack pointer; B, the output from the register file; and the MSrc bit from the control. This MUX outputs the address of memory read or write. |
| PCMux | The jump mux is used to determine the address of next instruction, it could be PC+1, or the jumping address in the B register. This mux is controlled by jump signal, it uses the PC+1 by default, when jump is called, it is set to 1, and set PC to the address that is stored in the B register |
| SrcBMux | SrBMux controls the second input of the ALU, it could be either from the sign extension when Lui is used, or from register B when R type, J type instructions is called. This mux is controlled by SrcB signal, when using R type instruction, it will send out the result from B register to the ALU, else it will take the. |
| LMMux | LM determine the input of the B register, if R type instruction is used, it will take the register regFile(3-6) value, else it will use the value from memory data. It needs three inputs: r2D, which is the data from the second register; MD, which is data taken from memory; and the LM bit from the control. Rw is the control bit, 0 for R2D and 1 for signE. |
| IorDMux | Instruction or data determine if the datapath is moving on to the next instruction in memory, jump to a specific instruction or doing push/pop to alter the stack in the memory. The mux takes three inputs: PC, which is is the value of the program counter, or the value from MSrc. This MUX outputs either the PC, so that the Main Memory can retrieve that instruction; sp, so that main memory can get that information off of the stack; or B, which would be if an R-type instruction accessed memory to get the value. |
| RWSrcMux2 | The regWrite source mux is used when register write needs value besides ALUO. Only a few instruction would use it--  If cp is used, it will select B(0); If lui is used, then it will select the value from upper(2); if cpi is used, it will select immediate from signE(3); if jal is used, it will select PC(1) to write into $ra. The output of the result will be used to prepare to write into the register file. |
| RWSrcMux | This mux is used when the instruction need to write in a register, it will use ALUO when arithmetic operation needed to be performed in the instruction, otherwise it will use the result from RWSrcMux2. |
| Memory/  Register | Main Memory | Memory stores instruction data, each instruction is 2 bytes, and it can only be accessed by chunk of 16 bits. It takes four inputs: MRA, which reads the specified address; MWA, which chooses a specified memory location to write to; MWD writes the specified data to the address specified in MWA; and the MW control bit. The output of this memory block is MD, memory data, which is the data from the memory address specified in MRA.  *In actually implementation, Xilinx can only generate a 14-bit memory, so we decide to throw the 13 and 12 bit of our memory. Memory should throw an exception if MA[13]|MA[12] is not 0.*  *Also, to protect procedure stack from malicious access, memory would also throw an segment fault if MA is bigger than $sp.* |
| Register File | The Register File can read and write data to 16 bits registers that used in assembly, each register is represented by a 4 bit number. The file takes four inputs: r1A, which is the address of $r1; r2A, which is the address of $r2, RWD, which is the value to write to the address specified in r1A; and the RW control whether to write or not. The output of this register is r1D, which is the data at r1A, and r2D, which is the data value at r2A.  R1D and r2D would output data as soon as address appear at r1A or r2D, but it only write data at rising edge of clock when RW = 1. The newly written data should appeared at r1D immediately after write. |
| A | A is a register that temporarily stores the value of Reg[IR[11-8]] . The input and output are both the value of $r2. This register holds data between cycles. It is used in R-type, I-type, and its result is stored into the main memory when push and sto is called. |
| B | B is a register that temporarily stores the value of Reg[IR[11-8]] or read data from memory. Its data can be used to update PC for jump, write into register file for cp and specify memory address for sto and LM cycle. This register holds data between cycles. |
| ALUO | This is a register that temporarily stores the result of the ALU. |
| PC | This is a register that store the current location of current instruction in the main memory. It can be updated through jump with value from B. |
| Instruction register | The instruction register reads the data coming out of the memory, and spits out a single instruction. The CC is used in R, J, and J type instructions. They are specified in the assembly code. r1(8-11) and r2(4-7) are both outputted as the register’s addresses specified in the instruction. It outputs LMC and Op to control.  It also outputs upper, the immediate used for lui, and signE, the immediate used for cpi and addi. |
| Stack Pointer | It takes the control bit SPW (stack pointer write) so the user can push and pop. It also take the input of an updated stack pointer that was either incremented or decremented by 1. It outputs the stack pointe.  *Since no programmer is able to access it, it would have a RESET control, to initialize STACK Pointer to 0xf3ff – the top address of our stack.* |
| Flag | This flag register takes the input from ALU output, CC code, and Op code. The flag determines whether this instruction needs more than 2 cycle. It has one output Perform to control unit, which will determine whether control unit would cut this instruction and start fetch next instruction in the following cycle.  For non I-type instruction, at cycle 2, flag compares CC and flag bit and output Perform = 1 if they match. The rest of instruction is skipped when they don’t match and Perform = 0. (See condition code specification in previous section for when CC matches flag).  So a skipped instruction only takes 2 cycles.  For I-type instruction, flag cannot perform CC since I-type instruction does not even have CC bit, I-type instruction is always executed. In this case, Perform would be 1 if this I-type instruction would needs more than two cycle, eg. addi; Perform would be 0 if this I-type instruction is finished after cycle 2, eg cpi, lui. In other word, when Op = 0001(addi), Perform is always 1, and when Op = 0111(cpi) or 0011(lui), Perform is always 0.  Flag bit would be updated when FU is 1 according to output of ALU result. It would store the sign of ALU result in 3 bits—N(negative), Z(zero), P(positive).  Note that Flag does not get take input from ALUO, but the directly output of ALU (ALUOut in the component table), so updating can be perform in the same cycle of ALU calculation. |
| ALU/Adder | ALU | ALU reads inputs from SrcA and SrcB, then computes the result according to ALUOp (the ALU operation code). The output of the ALU is written into ALUO, which might be written back to register file later. |
| SPAdder | This adder increments or decrements the value of SP by 1 depending on the control signal from SPIorD.  *Since Xilinx implementation can only contain 14-bit address, SPAdder would ignore SP[13] and SP[12] in addition and always output 0 for them.* |
| PCAdder | This is an adder that increments the PC by 1 and send the result to the PCMux.  *Since Xilinx implementation can only contain 14-bit address, PCAdder would ignore SP[13] and SP[12] in addition and always output 0 for them.* |

# Testing of Each Component

*Table 9 Component testing*

|  |  |
| --- | --- |
| Component | test |
| 16bits\_2to1 mux | Set the following:  A = 0xa; B = 0xc; op = 0;  output = 0xa  A = 0xa; B = 0xc; op = 1;  output = 0xc  if the output of the mux is correct in both cases, then the mux is working correctly. |
| 16bits\_4to1 mux | Assume A,B,C,D, and op are inputs into the mux and op is the control. Set the following:  A=0xa;B=0x2;C=0xb;D=0xc;op=11;  output = 0xc  A=0xa;B=0x2;C=0xb;D=0xc;op=10;  output = 0xb  A=0xa;B=0x2;C=0xb;D=0xc;op=01;  output = 0x2  A=0xa;B=0x2;C=0xb;D=0xc;op=00;  output = 0xa  If the outputs are all correct, then the mux works correctly. |
| Main memory | Memory read: assume the memory has only one instruction:  Instruction 0x0000  Input: IorD=1, MW = 0  output:0x0 |
| Memory write:  Input: MW=1, A = 0xffff  result: mem[A] =0xffff |
| Register File | Input: RA1 = 4'b0010, RWD = 16'h1425, RW = 1  wait after one rising clock edge  Input RA1 = 4'b0100, RWD = 16'h77ED, RW = 1  wait after one rising clock edge  Input: r1A = 0010 , r2A = 1000, $t2 = 0x1425, $s0 = 0x77ed  check if r1D = 1425, r2D =0x77ed  if it does, then register write and read both works |
| ALU | Assume A, B, and op (control) are the inputs into the ALU for all the ALU tests  Add tests:  Set the following: (P + P = P)  A=0xa; B=0xb; op = (000)  Output: ALU0 = 0x15  Set the following: (N + P = P)  A=0xfff6; B=0xb; op = (000)  Output: ALU0 = 0x0001  Set the following: (N + P = N)  A=0xa; B=0xfff5; op = (000)  Output: ALU0 = 0xffff  Set the following: (N + N = N)  A=0xfff6; B=0xfff5; op = (000)  Output: ALU0 = 0xffeb  Set the following: P + P = overflow  A=0x0001; B=0x7fff; op = (000)  Output: ALU0 =0x8000 Overflow = 1  Set the following: N + N = overflow  A=0x8000; B=0x8000; op = (000)  Output: ALU0 = 0x0 Overflow = 1  Set the following:  A=0x0; B=0x0; op = (000)  Output: ALU0 = 0x0  If all 7 cases product the correct output, ALU add works correctly. |
| ALU tests  Subtraction tests:  Set the following: (P - P = P)  A=0xb; B=0xa; op = (010)  Output: ALU0 = 0x1  Set the following: (P - P = 0)  A=0xb; B=0xb; op = (010)  Output: ALU0 = 0x0  Set the following: (N - P = N)  A=0xfff5; B=0xb; op = (010)  Output: ALU0 = 0xffeb  Set the following: (N - N = N)  A=0xfff5; B=0xfff6; op = (010)  Output: ALU0 = 0xffff  Set the following: P - P = N  A=0xa; B=0xb; op = (010)  Output: ALU0 = 0xffff  Set the following: N - P = overflow  A=0x7fff; B=0xffff; op = (010)  Output: ALU0 = 0x8000 Overflow = 1  Set the following: N - N = P  A=0xfff6; B=0xfff5; op = (010)  Output: ALU0 = 1  If all 7 cases product the correct output, ALU sub works correctly. |
| use the following inputs to check to make sure or’s correct outputs are produced:  input: A=(1001 0010 0000 0000) B =(0000 0111 1001 1111);  op = (110)  output: ALUO = (1001 0111 1001 1111)  input: A= 0xffff B = 0xffff; op = (110)  output: ALUO = 0xffff  input: A= 0 B = 0; op = (110)  output: ALUO = 0  input: A = 0 B= 0xffff; op = (110)  output: ALUO= 0xffff  if all 4 test cases produce the correct output, the ALU works correctly for or. |
| use the following inputs to check to make sure xor’s correct outputs are produced:  input: A=(1001 0010 0000 0000) B =(0000 0111 1001 1111);  op = (101)  output: ALUO = (1001 0101 1001 1111)  input: A= 0xffff B = 0xffff; op = (101)  output: ALUO = 0  input: A= 0 B = 0; op = (101)  output: ALUO = 0  input: A = 0 B=0xffff; op = (101)  output: ALUO= 0xffff  if all 4 test cases produce the correct output, the ALU works correctly for xor. |
| use the following inputs to check to make sure and’s correct outputs are produced:  input: A=(1001 0010 0000 0000) B =(0000 0111 1001 1111);  op = (100)  output: ALUO = (0000 0010 0000 0000)  input: A= 0xffff B = 0xffff; op = (100)  output: ALUO = 0xffff  input: A= 0 B = 0; op = (100)  output: ALUO = 0  input: A = 0 B= 0xffff; op = (100)  output: ALUO= 0  if all 4 test cases produce the correct output, the ALU works correctly for and. |
| Instruction Register (r1, r2, CC)  (signE)  (upper) | Input instruction add $t0, $t4; 0000 0000 0100 0111;  check if op is 0000, r1 is 0000, r2 is 0100, CC is 111. |
| Input first half of jl label , 010; 1111 1110 0000 1010;  check if op is 1111, CC is 010. |
| Input instruction addi $t3, -2; 0001 0011 1111 1101;  check if op is 0001, r1 is 0011, signE is 0xfffe |
| Input instruction lui $s2, 5; 0011 1100 0000 0101;  check if op is 0011, r1 is 1100, upper is 0x0500, |
| Flag | input: CC = 101, op = 0000, Flag bits [N,Z,P] = 100, FU = 0  check if output (perform) is 1  input: CC = 111, op = 0100, Flag bits [N,Z,P] = 010, FU = 0  check if output is 1  input: CC = 001, op = 1100, Flag bits [N,Z,P] = 010, FU = 0  check if output is 0  input: CC = 001, op = 0001, Flag bits [N,Z,P] = 010, FU = 0  check if output is 0 (immediate type always output 0) |
| Flag(update) | input: ALUO = 0x ffff, FU = 1  check if [N,Z,P] = 100 after a rising clock cycle.  input: ALUO = 0x 0020, FU = 1  check if [N,Z,P] = 001 after a rising clock cycle.  input: ALUO = 0x 0000, FU = 1  check if [N,Z,P] = 010 after a rising clock cycle. |
| PC adder | input: PC = 0x0006  check if output is 0x0007  input: PC = 0xffff  check if output is 0x0000  input: PC = 0xfffe  check if output is 0xffff |
| SP adder | input: SP = 0x0006 IoD=1  check if output is 0x0007  input: SP = 0x0000 IoD=0 check if output is 0xffff  input: SP = 0x0001 IoD=0  check if output is 0x0000  input: SP = 0xffff IoD=1  check if output is 0x0000 |

# Integration Tests

Note: “x” symbolizes any value. All hex values are preceded by “0x”. Everything else is in binary.

|  |  |  |  |
| --- | --- | --- | --- |
| Set of Components | Inputs | Outputs | Tests |
| PC + Memory + IR | PC, IW | R1, R2, CC, LMC, Op, Upper, signE | Initial state: Mem[PC] = 0x4111, IW = 1  Expected Output: R1=0x0, R2=0x1, CC=001, LMC=0, Op=0x4, Upper=0x1100, signE=0x0011  Initial state: Mem[PC] = 0x8eb8, IW = 1  Expected Output: R1=1110, R2=1011, CC=000, LMC=1, Op=1000, Upper=0xb800, signE=0xffb8 |
| SP + PC + Memory | PC, SP, B, MSrc, MW, A | MD | Input: Mem[0xa0aa] = 0x0022, SP = 0xa0aa, MSrc=0, IorD=0, SP=0x00F2, MW=0,  Expected Output: MD=0x0022  Input: Mem[0x00F3] = 0x0744,  SP=0x00F3, MSrc=0, IorD=0, MW=1, A=0x0044  Expected Output: MD=0x0744 first,  After clock edge MD=0x0044  Input: B=0x00F3, A=0xFF00, MW=1, IorD=1, MSrc = 1;  Output: Check memory at 0x00F3 is 0xFF00 |
| RF + ALU | R1A, R2B, RWD, RW, ALUOp, LM, SrcB, MD | ALUO, Overflow | Assume $0 holds 0x0004  Assume $1 holds 0x0002  Input: R1A=0x0, R2B=0x1, RWD=0000, RW=1, ALUOp=010, LM=0, SrcB=0, MD=x  Expected Output: ALUO=0x0002, Overflow=0  Assume $0 holds 0x0000  Assume $1 holds 0x0000  Input: R1A=0x0, R2B=0x1, RWD=0000, RW=1, ALUOp=000, LM=1, SrcB=0, MD=0x0000  Expected Output: ALUO=0x0000, Overflow=0  Assume $0 holds 0x0004  Assume $1 holds 0x0004  Input: R1A=0x0, R2B=0x1, RWD=0000, RW=1, ALUOp=000, LM=0, SrcB=1, MD=x  Expected Output: ALUO=0x0008, Overflow=0  Assume $0 holds 0xFFFE  Assume $1 holds 0x0002  Input: R1A=0x0, R2B=0x1, RWD=0x0, RW=1, ALUOp=000, LM=0, SrcB=0, MD=x  Expected Output: ALUO=0x0001, Overflow=1 |
| IR + Flag | MD, ALUout, FU\* | LMC, Upper, Perform | Input: MD=0x1001, ALUout=0x0002, FU\*=0  Expected Output: LMC=0, Upper=0x02, Perform=1  Input: MD=0x0010, ALUout=0x0000, FU\*=1  Expected Output: LMC=0, Upper=0x10, Perform=1  Input: MD=0x04015, ALUout=0x0000, FU\*=0  Expected Output: LMC=0, Upper=0x15, Perform=0 |
| IR + RF | MD, B, PC, RWSrc, ALUO | R1D, R2D, Op, LMC | Assume $0 holds 0x0000  Assume $1 holds 0x0000  Input: MD=0x0007, B=x, PC=x, RWSrc=000, ALUO=0x0000  Expected Output: R1D=0x0001, R2D=0x0001, Op=111, LMC=0  Assume $0 holds 0x0000  Assume Mem[$1] holds 0x0008  Input: MD=0x001F, B=0x421, PC=x, RWSrc=000, ALUO=0x0008  Expected Output: R1D=0x0000, R2D=0x0008, Op=111, LMC=1  Assume $0 holds 0x0002  Input: MD=0xE017, B=0x0000, PC=x, RWSrc=000, ALUO=x  Expected Output: R1D=0x0002, R2D=x, Op=1110, LMC=0  Assume $0 holds 0x0000  Assume $1 holds 0x0000  Input: MD=0xD017, B=0x0000, PC=x, RWSrc=000, ALUO=0  Expected Output: R1D=0x0001, R2D=0x0002, Op=1101, LMC=0 |
| ALU + Flag | A, B, CC, Op, FU, ALUOp, Flag\* | ALUO, Perform | Input: A=0x0008, B=0x0001, CC=011, ALUOp=010, Op=1, FU=0, Flag\*=001  Expected Output: ALUO=0x0007, Perform=1  Input: A=0x0001, B=0x0001, CC=010, ALUOp=000, Op=0010, FU=0, Flag\*=001  Expected Output: ALUO=0x0002, Perform=0  Input: A=0x0000, B=0x0008, CC=111, ALUOp=010, Op=0101, FU=1, Flag\*=100  Expected Output: ALUO=0xFFF9, Perform=1 |
| PC+adder+mux | PC, B,Jump, PW\* | PC | Input:PC = 0, B = 12, Jump = 1, PW\*=1  Expected Output: PC = 1  Input: PC = 0, B = 12, Jump = 0, PW\*=1  Expected Output: PC = 12 |
| Reg+ALU+MM | MW, A,B, SrcB, ALUop, ALUO, SP | ALUO, MM | Input: MW = 0, A = 0x1, B = 0x1, SrcB = 0, ALUOp = add, ALUO = ---, SP = 32  Expected output: ALUO = 0x10, Main Memory(32) = Main Memory(32)  Input: MW = 1, A = 0x10, B = 0x1, SrcB = 0, ALUOp = sub, ALUP = --- , SP =32  Expected output: ALUO = 0x1, Main Memory(32) = 0x1 |
| SP+ addder | SPW, SPIorD, SP | SP | Input: SPW = 1, SPIorD = 1, SP = 10  Expected output: SP = 11  Input = SPW = 1, SPlorD = 0, SP = 11  Expected output: SP = 10 |

# Ideas for Xilinx implementation

Xilinx provide many useful components like 1-bit mux’s and 16-bit flip flops.

16-bit 2\_1mux takes two 16-bit bus (A and B) and a select bit (S). It outputs A when S = 0 , B when S = 1. We can simply take 16 1-bit built-in mux and wire each bit.

16-bit 4\_1mux takes four 16-bit bus (D0, D1, D2 and D3) and two select bit (S0 and S1). We can just take three 16-bit 2\_1 mux and cascade them into 4\_1 mux.

Instruction register is just a 16-bit register with many different outputs. All outputs such as r1, r2, CC, Upper and sign Extended are certain bits of the instruction and can be formed with just many buf. We don’t even need gates inside Instruction register at all.

Register file is just a group of 16 16-bit registers. r1D and r2D are outputs of two 16-bit 16\_1mux (built with 16 1-bit 16\_1 mux). Each 16-bit register’s D takes values from RWD and EN takes decode a decoded bit from r1 respectively.

ALU will be implemented with Verilog with cases. It takes advantage of Verilog’s ability to do multi-bits design. With “case switch”, we can describe the output of ALU given specific input, and Verilog magic comes into play and generate corresponded hardware. We can do an overflow check after we have the results. There are still a few means that we can improve our ALU right now. See Design Journal for more details.

Flag is implemented with Verilog. It only takes a few lines.

# Control signals

We have 14 control signals and 3 inputs into datapath.

Note PCW, MW, IW, RW, SPW, FU have a “\*” in the table. This “\*” specified that those signals control write into register. These write signals always matter. If not specified, these wright control has to be 0. In contrast, other control signal can sometimes be don’t care.

Furthermore, “When it matter?” column specifies the condition to make each control signal matter. Only when condition in this column is met, we care about this control signal and it can produce specified results. If those conditions are not met, we don’t care about this control signal in this case. Those “don’t care” cases introduce more design flexibility for control unit.

*Table 10 Control signals*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Control signals | Description | When it matters? | on ( = 1 ) | off ( = 0 ) |
| PCW\* (PC Write) | Controls if the PC register can be overwritten with a new value. | Always | PC is updated | PC is unchanged |
| Jump | Controls whether PC’s new value will be the next instruction or the address from a jump. | PCW = 1 | PC jumps to a new address stored in B right now | PC will increment 2. |
| MW\* (Memory Write) | Controls whether the datapath can write to the memory block during a store. | Always | Memory will write data. |  |
| IorD (Instruction or Data) | Controls whether or not the next line read from the Instruction Register should be treated as an address or instruction. | IW = 1  or LM = 1  or MW = 1 | Memory reads an instruction from Mem[PC] (MW and IorD should never be on at the same time) | Memory reads or writes data at address specified by MSrc. |
| MSrc (Memory address source) | Controls which address memory is reading or writing data. | IorD = 0 and  (IW = 1  or LM = 1  or MW = 1) | Memory reads or write data at address of B | Memory reads or write data at address of SP. |
| IW\* (Instruction Write) | Controls whether or not the Instruction Register can be overwritten by loading from memory. | Always | Instruction register loads memory from memory | Instruction register remains unchanged. ( when IorD = 0, IW should never be 1 ) |
| RW\* (Register Write) | Controls whether or not the register block can be written to. | Always | Write into register file | Register file remains unchanged |
| LM (Load Memory) | Controls where B register is going to load memory from -- memory or register. | When we need to use B next cycle | Load data from memory into B register at address specified by MSrc. (IorD should always be 0 when LM = 1) | Load data from register into B at address r1.  B = R[r1] |
| RWSrc(0) (Register Write Source) | Controls if data is written from a special source. | RW = 1 | Write data into register file from some special source from B, PC, signE, upper | Write ALUO into register file at address r1.  R[r1] = ALUO |
| RWSrc(2:1) (Register Write Source) | Controls what data should be written into the register file. | RW = 1 and  RWSrc(0) = 1 | Select data to write into register file as  00 -- B ; 01 -- PC ; 10 -- upper ; 11 -- signE | |
| SrcB (Source B) | Controls which input should be the B input into the ALU. | When we need ALUO next cycle | use B as the second source of ALU, otherwise | use sign-extended immediate as the second source of ALU |
| ALUOp(2:0) (ALU Operation) | Controls which operation the ALU does on A and B. | ALU does following operation on A and B  00x -- add ; 01x -- subtract ;  100 -- and ; 101 -- xor ;  110 -- or ;  (We don’t know what ALU will do if ALUOp is not included above.)  (We might decide to add more operations later) | |
| SPW\* (Stack Pointer Write) | Controls whether or not the stack pointer should be updated. | Always | write and update the stack pointer depending on SPIorD | stack pointer remains the same |
| SPIorD (Stack Pointer Increment or Decrement) | Controls whether to increment or decrement the stack pointer based on the instruction. | SPW = 1 | increment SP by 2 | decrement SP by 2 |
| FU\* (Flag Update) | Controls whether or not the control code should be updated based on the value of ALUO. | Always | Update flag bits based on sign of data in ALUO | ALUO remains the same |

# Control signals for RTL for each possible cycle

As explained above, there might be an extra cycle between cycle 2 and cycle 3 for loading memory (box in red) for certain instructions if LM = 1.

The following two tables show the control signals for each cycles in RTL.

For control signals that are not specified in a particular cycle, they have to be 0 if there is a (\*) sign in the control signals table above, otherwise we don’t care about its value.

*Table 11 Control signals of RTL first half*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Calculations | cmp | sto | cp | jr | jl | jal |
| Cycle 1 | IW  IorD = 1  PCW  Jump = 0 | | | | | | |
| Cycle 2 | LM = 0 | | | | | PCW  LM = 1  IorD = 1 | |
| LM cycle | LM = 1 | | | | |  | |
| Cycle 3 | SrcB = 0  ALUOp = op | SrcB = 0  ALUOp = (A - B) | MW  IorD = 0  MSrc = 1 | RW  RWSrc = 001 | PCW  Jump = 1 | | PCW  Jump = 1  RW  RWSrc = 011 |
| Cycle 4 | RW  RWSrc = xx0 | FU |  |  |  |  |  |

*Table 12 Control signals for RTL second half*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | addi | lui | cpi | push | pop |
| Cycle 1 | IW  IorD = 1  PCW | | | | |
| Cycle 2 | LM = 0 | RW  RWSrc = 101 | RW  RWSrc = 111 | SPW  SPIorD = 0 | LM = 1  IorD = 0  MSrc = 0 |
| Cycle 3 | SrcB = 1  ALUOp = (A + B) |  |  | MW  IorD = 0  MSrc = 0 | SPW  SPIorD = 1 |
| Cycle 4 | RW  RWSrc = xx0 |  |  |  |  |

# State transition diagram

Table 3 State Transition

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| State | Perform | op | | | | instruct | Next State | |
| op(0) | op(1) | op(2) | op(3) | LMC = 0 | LMC = 1 |
| State 1: Read instruction | x | x | x | x | x | any inst | 2 |  |
| State 2:  Decode / load register value / write immediate | 0 | x | x | x | x | any inst | 1 | 1 |
| 1 | 0 | 0 | x | x | R-type calc | 4 | 3 |
| 1 | 1 | 0 | 0 | 0 | addi | 4 | 4 |
| 1 | 1 | 0 | 1 | 0 | cmp | 4 | 3 |
| 1 | 1 | 0 | 0 | 1 | xor | 4 | 3 |
| 1 | 0 | 1 | 0 | 0 | sto | 5 | 3 |
| 1 | 0 | 1 | 1 | 0 | cp | 6 | 3 |
| 1 | 0 | 1 | 0 | 1 | push | 5 | 6 |
| 1 | 0 | 1 | 1 | 1 | jr | 7 | 3 |
| 1 | 1 | 1 | 0 | 0 | lui | 1 | 1 |
| 1 | 1 | 1 | 1 | 0 | cpi | 1 | 1 |
| 1 | 1 | 1 | 0 | 1 | pop | 8 | 8 |
| 1 | 1 | 1 | 1 | 1 | jl/jal | 7 | 7 |
| State 3:  Load memory data | 1 | x | 0 | x | x |  | 4 | - |
| 1 | 0 | 1 | 0 | 0 | sto | 5 | - |
| 1 | 0 | 1 | 1 | 0 | cp | 6 | - |
| 1 | 0 | 1 | 1 | 1 | jr | 7 | - |
| State 4:  Calculations | 1 | 1 | 0 | 1 | 0 | cmp | 1 | - |
| - | - | - | - | - |  | 9 | - |
| State 5: memory write | 1 | 0 | 1 | 0 | 0 | sto | 1 | - |
| 1 | 0 | 1 | 0 | 1 | push | 1 | - |
| State 6: cp | 1 | 0 | 1 | 1 | 0 | cp | 1 | - |
| State 7: jump | 1 | 0 | 1 | 1 | 1 | jr | 1 | - |
| 1 | 1 | 1 | 1 | 1 | jl | 1 | - |
| 1 | 1 | 1 | 1 | 1 | jal | 1 | - |
| State 8: pop | 1 | 1 | 1 | 0 | 1 | pop | 1 | - |
| State: 9 Register Write | 1 | 0 | 0 | x | x | R-Type inst | 1 | - |
| 1 | 1 | 0 | 0 | 0 | addi | 1 | - |
| 1 | 1 | 0 | 0 | 1 | xor | 1 | - |

# State “bubbles”

Table 14 State Bubbles for each instruction

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Calc | cmp | sto | cp | jr | jl | jal | addi | lui | cpi | | push | pop |
| Cycle 1 | State 1:  Read instruction | | | | | | | | | | | | |
| Cycle 2 | State 2:  Decode / load register value / write immediate | | | | | | | | | | | | |
| LM cycle | State 3:  Load memory data | | | | |  | | | | | | | |
| Cycle 3 | State 4:  Calculations | | State 5:  memory write | State 6:  cp | State 7:  jump | | | State 4:  Calculations |  |  | State 5:  memory write | | State 8:  pop |
| Cycle 4 | State: 9  Register Write |  |  |  |  |  |  | State: 9  Register Write |  |  |  | |  |

Figure: The above chart shows the state for each instruction. Each instruction has states that within the same column. State 3 is optional and only used in R type instructions -- if the LM bit is set to true, then State 3 is used, else it is skipped. For example, calculation with load memory has state 1, 2, 3, 4, and 9, calculation without load memory will have states 1,2,4 and 9. For other instructions like Jal, it will have states 1, 2 and 7.

# Control Signal output

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| State | Instruction | OP | LMC | Perform | Output |
| 1 | add | 0000 | x | 1 | PCW=1, Jump=0, IorD=1, IW=1 |
| addi | 0001 | x | 1 |
| sto | 0010 | x | 1 |
| lui | 0011 | x | 1 |
| sub | 0100 | x | 1 |
| cmp | 0101 | x | 1 |
| cp | 0110 | x | 1 |
| cpi | 0111 | x | 1 |
| and | 1000 | x | 1 |
| xor | 1001 | x | 1 |
| push | 1010 | x | 1 |
| pop | 1011 | x | 1 |
| or | 1100 | x | 1 |
| jr | 1110 | x | 1 |
| jl/jal | 1111 | x | 1 |
| any | xxxx | x | 0 | IorD = 0 |
| 2 | any | xxxx | x | 0 | IorD = 0 |
| add | 0000 | 0 | 1 | LM = 0 |
| addi | 0001 | 0 | 1 |
| sto | 0010 | 0 | 1 |
| sub | 0100 | 0 | 1 |
| cmp | 0101 | 0 | 1 |
| cp | 0110 | 0 | 1 |
| and | 1000 | 0 | 1 |
| xor | 1001 | 0 | 1 |
| or | 1100 | 0 | 1 |
| jr | 1110 | 0 | 1 |
| any R-Type | xxxx | 0 | 0 | LM = 0, SPW = 1, SPIorD = 0 |
| push | 1010 | x | 1 | LM = 0, SPW = 1, SPIorD = 0 |
| x | 0 | LM = 0, SPW = 0, SPIorD = 0, RW = 0 |
| pop | 1011 | x | 1 | PCW=1, LM=1, IorD=1 |
| x | 0 | PCW=0, LM=0, IorD=1, RW = 0 |
| jl/jal | 1111 | x | 1 | PCW=1, LM=1, IorD=1 |
| x | 0 | PCW=0, LM=0, IorD=1, RW = 0 |
| lui | 0011 | x | 1 | RW = 1, RWSrc = 101 |
| x | 0 | RW = 0, RWSrc = 101 |
| cpi | 0111 | x | 1 | RW = 1, RWSrc = 111 |
| x | 0 | RW = 0, RWSrc = 111 |
| 3 | add | 0000 | 1 | 1 | LM = 1, IorD = 0, MSrc = 1 |
| addi | 0001 | 1 | 1 |
| sto | 0010 | 1 | 1 |
| sub | 0100 | 1 | 1 |
| cmp | 0101 | 1 | 1 |
| cp | 0110 | 1 | 1 |
| and | 1000 | 1 | 1 |
| xor | 1001 | 1 | 1 |
| or | 1100 | 1 | 1 |
| jr | 1110 | 1 | 1 |
| r-type | xxxx | 1 | 0 | LM = 0, IorD = 0, MSrc = 1, RW = 0 |
| 4 | add | 0000 | x | 1 | SrcB = 0 ALUOp = 000 |
| addi | 0001 | x | 1 | SrcB = 1 ALUOp = 000 |
| sub | 0100 | x | 1 | SrcB = 0 ALUOp = 010 |
| and | 1000 | x | 1 | SrcB = 0 ALUOp = 100 |
| or | 1100 | x | 1 | SrcB = 0 ALUOp = 110 |
| cmp | 0100 | x | 1 | SrcB = 0, ALUOp = 010, FU = 1 |
| all of above | xxxx | x | 0 | SrcB = 0, ALUOp = op, FU = 0, RW = 0, LM = 0 |
| 5 | sto | 0010 | x | 1 | MW = 1, IorD = 0, MSrc = 1 |
| 0 | MW = 0, IorD = 0, MSrc = 1 |
| 6 | cp | 0110 | x | 1 | RW=1, RWSrc=001 |
| 0 | RW=0, RWSrc=001 |
| 7 | jr | 1110 | x | 1 | Jump = 1, PCW = 1 |
| 0 | Jump = 1, PCW = 0 |
| jl | 1111 | x | 1 | Jump = 1, PCW = 1 |
| 0 | Jump = 1, PCW = 0 |
| jal | x | 1 | Jump: 1, RW: 1, RWSrc: 011, PCW: 1 |
| 0 | Jump: 1, RW: 0, RWSrc: 011, PCW: 0 |
| 8 | pop | 1011 | x | 1 | RW = 1, RWSrc = 001, IorD = 0, MSrc = 0 |
| 0 | RW = 1, RWSrc = 001, IorD = 0, MSrc = 0 |
| 9 | add | 0000 | x | 1 | RW = 1, RWSrc = xx0 |
| sub | 0100 | x | 1 |
| and | 1000 | x | 1 |
| xor | 1001 | x | 1 |
| or | 1100 | x | 1 |
| addi | 0001 | x | 1 |
| add | 0000 | x | 0 | RW = 0, RWSrc = xx0 |
| sub | 0100 | x | 0 |
| and | 1000 | x | 0 |
| xor | 1001 | x | 0 |
| or | 1100 | x | 0 |
| addi | 0001 | x | 0 |

Figure above shows the tests if the control works correctly when op code is given. The first column shows the state of the current process, second column shows the instruction is running, third column is the operation code. LMC is only used in state 2, 3, it indicates if memory access is needed at this stage. Perform is used to decides whether the instruction will be executed or not. The output column shows the expected control signal generated from the state.

# Control Unit Xilinx implementation design

Control Unit will be a one-hot mealy state machine, so as long we has the state diagram draw we can directly implement it intuitively. Our Control Unit will be a mealy machine, so our output depends not only on the state but also the input, so each instruction can start to do different work at cycle 2. Number of cycle can be reduced. In our project, we implement two Control unit, one with behavior level Verilog, which is easier to implement, and another with register-transfer level Verilog, which takes full use of “don’t cares” states and maximize performance. The latter is harder, because we would need to draw K-Maps and find the optimal gate design manually. The former is easier and serves as a backup plan. See design Journal for more details about control unit implementation and testing.

# Control Unit Testing

Control unit testing would involve running all combination of Op, LMC and Perform in the state diagram, and check its control signal output and state transition to the above table. All cases would be tested exclusively. However, it would be pretty tedious to type all cases done, so we create another module ControlUnitTester to help us.

ControlUnitTester module takes state, input to controls and output corresponding control signals and next state. For control signals that can be don’t care, ControlUnitTester would output an extra bit to specify whether this signal is “don’t care”. ControlUnitTester is implemented simply by copying every states in FSM. As long as programmer do not make typo, it would be correct. ControlUnitTester is all logic gates without storage, and serves as a standard answer producer machine. **In test bench, we can run ControlUnit with specified input combination for multiply cycles and check its output and transition to ControlUnitTester.** The checking also cover the case of “don’t care”. In actual code, for example, “MSrc” is the output from ControlUnit, and is compared with the standard answer “MSrca” from ControlUnitTester. If they equal or “MSrca” indicates “don’t care”, then “MSrce” is going to be 1 to indicate that “MSrc” pass the test in this case. If any control signal do not pass the test, “error” would be high. Sometimes, our FSM would transit to some impossible state, with all control signals to be “don’t care”. We do not want to miss those errors, so ControlUnitTester also output an “error” bit to signal that the combination of input and states is not supposed to happen.