CS385 – CPU Project

Robert Rotaru, Bryan Bigelow, Anthony Cerritelli

# Progress Report 3

## Task Format

**Task**

* Subtask – [Contributor 1], [Contributor 2], etc.

## Tasks

**16-Bit Test Program**

* Assembly – Tony
* Binary – Tony

**Pipelining**

* IF – Tony
* ID – Tony, Bryan
* EX – Tony

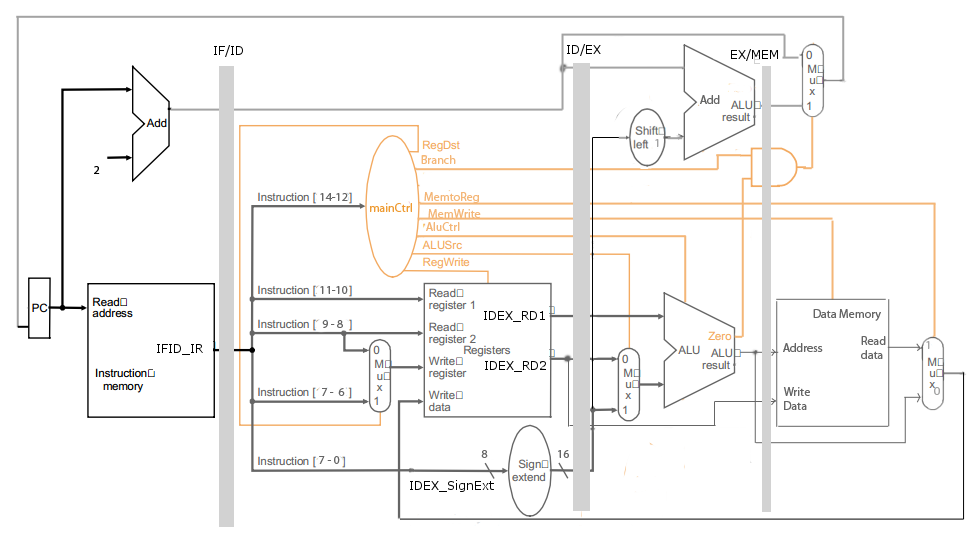
**Diagrams**

* Single-Cycle Path – Bryan
* Internals – Bryan

**Report** - Robert Rotaru, Bryan Bigelow, Anthony Cerritelli

## Diagrams

**Single-Cycle Datapath**



**Internals**



## Source Code

/\* CS 385 - Semester Project - Progress Report 3

Authors:

Robert Rotaru

Bryan Bigelow

Anthony Cerritelli

Content:

16-bit MIPS CPU in Verilog

All source code and project work can be found on GitHub at:

https://github.com/rrotaru/CS385-CPU

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/\*\*\* Multiplexers \*\*\*/

module mux2x1(A,B,select,OUT);

input A,B,select;

output OUT;

wire x,y;

and g1(x,A,~select),

g2(y,B,select);

or g3(OUT,x,y);

endmodule

module mux4x1(i0,i1,i2,i3,select,O);

input i0,i1,i2,i3;

input [1:0] select;

output O;

wire w,x,y,z;

and g1(w,i0,~select[1],~select[0]),

g2(x,i1,~select[1],select[0]),

g3(y,i2,select[1],~select[0]),

g4(z,i3,select[1],select[0]);

or g5(O,w,x,y,z);

endmodule

module mux16Bit4x1(i0, i1, i2, i3, select, O);

input [15:0] i0, i1, i2, i3;

input [1:0] select;

output [15:0] O;

mux4x1 mux0(i0[0], i1[0], i2[0], i3[0], select, O[0]),

mux1(i0[1], i1[1], i2[1], i3[1], select, O[1]),

mux2(i0[2], i1[2], i2[2], i3[2], select, O[2]),

mux3(i0[3], i1[3], i2[3], i3[3], select, O[3]),

mux4(i0[4], i1[4], i2[4], i3[4], select, O[4]),

mux5(i0[5], i1[5], i2[5], i3[5], select, O[5]),

mux6(i0[6], i1[6], i2[6], i3[6], select, O[6]),

mux7(i0[7], i1[7], i2[7], i3[7], select, O[7]),

mux8(i0[8], i1[8], i2[8], i3[8], select, O[8]),

mux9(i0[9], i1[9], i2[9], i3[9], select, O[9]),

mux10(i0[10], i1[10], i2[10], i3[10], select, O[10]),

mux11(i0[11], i1[11], i2[11], i3[11], select, O[11]),

mux12(i0[12], i1[12], i2[12], i3[12], select, O[12]),

mux13(i0[13], i1[13], i2[13], i3[13], select, O[13]),

mux14(i0[14], i1[14], i2[14], i3[14], select, O[14]),

mux15(i0[15], i1[15], i2[15], i3[15], select, O[15]);

endmodule

module mux2bit2x1(A,B,select,OUT);

input [1:0] A,B;

input select;

output [1:0] OUT;

mux2x1 mux1(A[0], B[0], select, OUT[0]),

mux2(A[1], B[1], select, OUT[1]);

endmodule

module mux16bit2x1(A, B, select, OUT);

input [15:0] A,B;

input select;

output [15:0] OUT;

mux2x1 mux1(A[0], B[0], select, OUT[0]),

mux2(A[1], B[1], select, OUT[1]),

mux3(A[2], B[2], select, OUT[2]),

mux4(A[3], B[3], select, OUT[3]),

mux5(A[4], B[4], select, OUT[4]),

mux6(A[5], B[5], select, OUT[5]),

mux7(A[6], B[6], select, OUT[6]),

mux8(A[7], B[7], select, OUT[7]),

mux9(A[8], B[8], select, OUT[8]),

mux10(A[9], B[9], select, OUT[9]),

mux11(A[10], B[10], select, OUT[10]),

mux12(A[11], B[11], select, OUT[11]),

mux13(A[12], B[12], select, OUT[12]),

mux14(A[13], B[13], select, OUT[13]),

mux15(A[14], B[14], select, OUT[14]),

mux16(A[15], B[15], select, OUT[15]);

endmodule

/\*\*\* 16-bit D flip flop \*\*\*/

module D\_16\_Flip\_flop(D,CLK,Q);

input [15:0] D;

input CLK;

output [15:0] Q;

D\_flip\_flop f0(D[0], CLK, Q[0]),

f1(D[1], CLK, Q[1]),

f2(D[2], CLK, Q[2]),

f3(D[3], CLK, Q[3]),

f4(D[4], CLK, Q[4]),

f5(D[5], CLK, Q[5]),

f6(D[6], CLK, Q[6]),

f7(D[7], CLK, Q[7]),

f8(D[8], CLK, Q[8]),

f9(D[9], CLK, Q[9]),

f10(D[10], CLK, Q[10]),

f11(D[11], CLK, Q[11]),

f12(D[12], CLK, Q[12]),

f13(D[13], CLK, Q[13]),

f14(D[14], CLK, Q[14]),

f15(D[15], CLK, Q[15]);

endmodule

module D\_flip\_flop(D,CLK,Q);

input D,CLK;

output Q;

wire CLK1, Y;

not not1 (CLK1,CLK);

D\_latch D1(D,CLK, Y),

D2(Y,CLK1,Q);

endmodule

module D\_latch(D,C,Q);

input D,C;

output Q;

wire x,y,D1,Q1;

nand nand1 (x,D, C),

nand2 (y,D1,C),

nand3 (Q,x,Q1),

nand4 (Q1,y,Q);

not not1 (D1,D);

endmodule

/\*\*\* 16-bit register source code \*\*\*/

module reg\_file (rr1,rr2,wr,wd,regwrite,rd1,rd2,clock);

input [1:0] rr1,rr2,wr;

input [15:0] wd;

input regwrite,clock;

output [15:0] rd1,rd2;

wire [15:0] q1, q2, q3;

// registers

D\_16\_Flip\_flop r1 (wd,c1,q1);

D\_16\_Flip\_flop r2 (wd,c2,q2);

D\_16\_Flip\_flop r3 (wd,c3,q3);

// output port

mux16Bit4x1 mux1 (16'b0,q1,q2,q3,rr1,rd1),

mux2 (16'b0,q1,q2,q3,rr2,rd2);

// input port

decoder dec(wr[1],wr[0],w3,w2,w1,w0);

and a (regwrite\_and\_clock,regwrite,clock);

and a1 (c1,regwrite\_and\_clock,w1),

a2 (c2,regwrite\_and\_clock,w2),

a3 (c3,regwrite\_and\_clock,w3);

endmodule

module decoder (S1,S0,D3,D2,D1,D0);

input S0,S1;

output D0,D1,D2,D3;

not n1 (notS0,S0),

n2 (notS1,S1);

and a0 (D0,notS1,notS0),

a1 (D1,notS1, S0),

a2 (D2, S1,notS0),

a3 (D3, S1, S0);

endmodule

/\*\*\* ALU and arithmetic source code \*\*\*/

module halfadder (S,C,x,y);

input x,y;

output S,C;

xor (S,x,y);

and (C,x,y);

endmodule

module fulladder (S,C,x,y,z);

input x,y,z;

output S,C;

wire S1,D1,D2;

halfadder HA1 (S1,D1,x,y),

HA2 (S,D2,S1,z);

or g1(C,D2,D1);

endmodule

// 1-bit ALU for bits 0-14

module ALU1 (a,b,binvert,op,less,carryin,carryout,result);

input a,b,less,carryin,binvert;

input [1:0] op;

output carryout,result;

wire sum, a\_and\_b, a\_or\_b, b\_inv;

not not1(b\_inv, b);

mux2x1 mux1(b,b\_inv,binvert,b1);

and and1(a\_and\_b, a, b);

or or1(a\_or\_b, a, b);

fulladder adder1(sum,carryout,a,b1,carryin);

mux4x1 mux2(a\_and\_b,a\_or\_b,sum,less,op[1:0],result);

endmodule

// 1-bit ALU for the most significant bit

module ALUmsb (a,b,binvert,op,less,carryin,carryout,result,sum);

input a,b,less,carryin,binvert;

input [1:0] op;

output carryout,result,sum;

wire sum, a\_and\_b, a\_or\_b, b\_inv;

not not1(b\_inv, b);

mux2x1 mux1(b,b\_inv,binvert,b1);

and and1(a\_and\_b, a, b);

or or1(a\_or\_b, a, b);

fulladder adder1(sum,carryout,a,b1,carryin);

mux4x1 mux2(a\_and\_b,a\_or\_b,sum,less,op[1:0],result);

endmodule

module ALU (op,a,b,result,zero);

input [15:0] a;

input [15:0] b;

input [2:0] op;

output [15:0] result;

output zero;

wire c1,c2,c3,c4,c5,c6,c7,c8,c9,c10,c11,c12,c13,c14,c15,c16;

ALU1 alu0 (a[0], b[0], op[2], op[1:0],set,op[2],c1, result[0]);

ALU1 alu1 (a[1], b[1], op[2], op[1:0],0, c1, c2, result[1]);

ALU1 alu2 (a[2], b[2], op[2], op[1:0],0, c2, c3, result[2]);

ALU1 alu3 (a[3], b[3], op[2], op[1:0],0, c3, c4, result[3]);

ALU1 alu4 (a[4], b[4], op[2], op[1:0],0, c4, c5, result[4]);

ALU1 alu5 (a[5], b[5], op[2], op[1:0],0, c5, c6, result[5]);

ALU1 alu6 (a[6], b[6], op[2], op[1:0],0, c6, c7, result[6]);

ALU1 alu7 (a[7], b[7], op[2], op[1:0],0, c7, c8, result[7]);

ALU1 alu8 (a[8], b[8], op[2], op[1:0],0, c8, c9, result[8]);

ALU1 alu9 (a[9], b[9], op[2], op[1:0],0, c9, c10,result[9]);

ALU1 alu10 (a[10],b[10],op[2], op[1:0],0, c10, c11,result[10]);

ALU1 alu11 (a[11],b[11],op[2], op[1:0],0, c11, c12,result[11]);

ALU1 alu12 (a[12],b[12],op[2], op[1:0],0, c12, c13,result[12]);

ALU1 alu13 (a[13],b[13],op[2], op[1:0],0, c13, c14,result[13]);

ALU1 alu14 (a[14],b[14],op[2], op[1:0],0, c14, c15,result[14]);

ALUmsb alu15 (a[15],b[15],op[2], op[1:0],0, c15, c16,result[15],set);

or or1(or01, result[0],result[1]);

or or2(or23, result[2],result[3]);

nor nor1(zero,or01,or23);

endmodule

module branchCtrl (BranchOp, Zero, BranchOut);

input [1:0] BranchOp;

input Zero;

output BranchOut;

wire not\_Zero, w1, w2;

not G1(not\_Zero, Zero);

and G2(w1, BranchOp[0], Zero),

G3(w2, BranchOp[1], not\_Zero);

or G4(BranchOut, w1, w2);

endmodule

/\*\*\* 16-bit CPU control source code \*\*\*/

module mainCtrl (op, ctrl);

input [3:0] op;

output reg [9:0] ctrl;

always @(op) case (op)

// RegDst, AluSrc, MemtoReg, RegWrite, MemWrite, BNE, BEQ, AluCtrl

4'b0000: ctrl <= 10'b1001000010; // ADD 1 0 0 1 0 0 0 010

4'b0001: ctrl <= 10'b1001000110; // SUB 1 0 0 1 0 0 0 110

4'b0010: ctrl <= 10'b1001000000; // AND 1 0 0 1 0 0 0 000

4'b0011: ctrl <= 10'b1001000001; // OR 1 0 0 1 0 0 0 001

4'b0100: ctrl <= 10'b0101000010; // ADDI 1 0 0 1 0 0 0 010

4'b0101: ctrl <= 10'b0111000010; // LW 0 1 1 1 0 0 0 010

4'b0110: ctrl <= 10'b0100100010; // SW X 1 X 0 1 0 0 010

4'b0111: ctrl <= 10'b1001000111; // SLT 1 0 0 1 0 0 0 111

4'b1000: ctrl <= 10'b0000001110; // BEQ X 0 X 0 0 0 1 110

4'b1001: ctrl <= 10'b0000010110; // BNE X 0 X 0 0 1 0 110

endcase

endmodule

//module CPU (clock, WD, IR);

module CPU (clock, PC, IFID\_IR, IDEX\_IR, WD);

input clock;

output [15:0] PC, IFID\_IR, IDEX\_IR, WD;

initial begin

// Program with nop's - no hazards

IMemory[0] = 16'b0100000100001111; // addi $t1, $0, 15 ($t1 = 15)

IMemory[1] = 16'b0100001000000111; // addi $t2, $0, 7 ($t1 = 7)

IMemory[2] = 16'b0000000000000000; // nop

IMemory[3] = 16'b0010011011000000; // and $t3, $t1, $t2 ($t3 = 7)

IMemory[4] = 16'b0000000000000000; // nop

IMemory[5] = 16'b0001011110000000; // sub $t2, $t1, $t3 ($t2 = 8)

IMemory[6] = 16'b0000000000000000; // nop

IMemory[7] = 16'b0011101110000000; // or $t2, $t2, $t3 ($t2 = 15)

IMemory[8] = 16'b0000000000000000; // nop

IMemory[9] = 16'b0000101111000000; // add $t3, $t2, $t3 ($t3 = 22)

IMemory[10] = 16'b0000000000000000; // nop

IMemory[11] = 16'b0111111001000000; // slt $t1, $t3, $t2 ($t1 = 0)

IMemory[12] = 16'b0111101101000000; // slt $t1, $t2, $t3 ($t1 = 1)

end

/\*

initial begin

// Program without nop's - wrong results

IMemory[0] = 16'b0100000100001111; // addi $t1, $0, 15 ($t1 = 15)

IMemory[1] = 16'b0100001000000111; // addi $t2, $0, 7 ($t1 = 7)

IMemory[2] = 16'b0010011011000000; // and $t3, $t1, $t2 ($t3 = 7)

IMemory[3] = 16'b0001011110000000; // sub $t2, $t1, $t3 ($t2 = 8)

IMemory[4] = 16'b0011101110000000; // or $t2, $t2, $t3 ($t2 = 15)

IMemory[5] = 16'b0000101111000000; // add $t3, $t2, $t3 ($t3 = 22)

IMemory[6] = 16'b0111111001000000; // slt $t1, $t3, $t2 ($t1 = 0)

IMemory[7] = 16'b0111101101000000; // slt $t1, $t2, $t3 ($t1 = 1)

end

\*/

// Pipeline stages

// IF

wire [15:0] PCplus2, NextPC;

reg[15:0] PC, IMemory[0:1023], IFID\_IR, IFID\_PCplus2;

ALU fetch (3'b010, PC, 16'b10, NextPC, Unused);

// ID

reg [15:0] IDEX\_IR; // For monitoring the pipeline

wire [9:0] Control;

reg IDEX\_RegDst, IDEX\_AluSrc, IDEX\_MemtoReg, IDEX\_RegWrite, IDEX\_MemWrite;

reg [1:0] IDEX\_Branch;

reg [2:0] IDEX\_AluCtrl;

wire [15:0] RD1, RD2, SignExtend, WD;

reg [15:0] IDEX\_RD1, IDEX\_RD2, IDEX\_SignExt, IDEXE\_IR;

reg [1:0] IDEX\_rt, IDEX\_rd;

reg\_file rf (IFID\_IR[11:10], IFID\_IR[9:8], WR, WD, IDEX\_RegWrite, RD1, RD2, clock);

mainCtrl main (IFID\_IR[15:12], Control);

assign SignExtend = {{8{IFID\_IR[7]}},IFID\_IR[7:0]};

// EXE

wire [15:0] B, AluOut;

wire [1:0] WR;

ALU exec (IDEX\_AluCtrl, IDEX\_RD1, B, AluOut, Zero);

// assign B

mux16bit2x1 muxB (IDEX\_RD2, IDEX\_SignExt, IDEX\_AluSrc, B);

// assign WR

mux2bit2x1 muxWR (IDEX\_rt, IDEX\_rd, IDEX\_RegDst, WR);

// assign WD

//assign WD = AluOut;

mux16bit2x1 muxWD (AluOut, AluOut, IDEX\_MemtoReg, WD);

initial begin

PC = 0;

end

// Running the pipeline

always @(negedge clock) begin

// Stage 1 - IF

PC <= NextPC;

IFID\_IR <= IMemory[PC>>1];

// Stage 2 - ID

IDEX\_IR <= IFID\_IR; // For monitoring the pipeline

{IDEX\_RegDst, IDEX\_AluSrc, IDEX\_MemtoReg, IDEX\_RegWrite, IDEX\_MemWrite, IDEX\_Branch, IDEX\_AluCtrl} <= Control;

IDEX\_RD1 <= RD1;

IDEX\_RD2 <= RD2;

IDEX\_SignExt <= SignExtend;

IDEX\_rt <= IFID\_IR[9:8];

IDEX\_rd <= IFID\_IR[7:6];

// Stage 3 - EX

// No transfers needed here - on negedge WD is written into register WR

end

endmodule

/\*\*\* CPU testing source code \*\*\*/

module test();

reg clock;

//wire [15:0] WD,IR;

wire [15:0] PC, IFID\_IR, IDEX\_IR, WD;

CPU test\_cpu(clock, PC, IFID\_IR, IDEX\_IR, WD);

always #1 clock = ~clock;

initial begin

$display ("time\tPC\tIFID\_IR\t\t\tIDEX\_IR\t\t\tWD");

$monitor ("%2d\t%3d\t%b\t%b\t%d", $time,PC,IFID\_IR,IDEX\_IR,WD);

clock = 1;

#29 $finish;

end

endmodule

## Testing

/\* Compiling and simulation

with nops:

C:\Users\User\git\forks\CS385-CPU\Source Files\Progress Report 3>vvp out

time PC IFID\_IR IDEX\_IR WD

0 0 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

1 2 0100000100001111 xxxxxxxxxxxxxxxx X

3 4 0100001000000111 0100000100001111 15

5 6 0000000000000000 0100001000000111 7

7 8 0010011011000000 0000000000000000 0

9 10 0000000000000000 0010011011000000 7

11 12 0001011110000000 0000000000000000 0

13 14 0000000000000000 0001011110000000 8

15 16 0011101110000000 0000000000000000 0

17 18 0000000000000000 0011101110000000 15

19 20 0000101111000000 0000000000000000 0

21 22 0000000000000000 0000101111000000 22

23 24 0111111001000000 0000000000000000 0

25 26 0111101101000000 0111111001000000 0

27 28 xxxxxxxxxxxxxxxx 0111101101000000 1

29 30 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

without nops:

C:\Users\User\git\forks\CS385-CPU\Source Files\Progress Report 3>vvp out

time PC IFID\_IR IDEX\_IR WD

0 0 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx x

1 2 0100000100001111 xxxxxxxxxxxxxxxx x

3 4 0100001000000111 0100000100001111 15

5 6 0010011011000000 0100001000000111 7

7 8 0001011110000000 0010011011000000 X

9 10 0011101110000000 0001011110000000 x

11 12 0000101111000000 0011101110000000 X

13 14 0111111001000000 0000101111000000 x

15 16 0111101101000000 0111111001000000 X

17 18 xxxxxxxxxxxxxxxx 0111101101000000 X

19 20 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

21 22 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

23 24 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

25 26 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

27 28 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

29 30 xxxxxxxxxxxxxxxx xxxxxxxxxxxxxxxx X

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