

流水线MIPS处理器实验报告

项目设计

本项目完成了一个主频为102.6MHz的流水线结构的MIPS处理器，并利用此处理器和所编写的冒泡排序算法，将128个32bit的无符号随机数进行排序，并利用BCD7显示排序算法所需的时钟周期数。下面将详细介绍项目原理。

项目原理

流水线结构

本项目采用MIPS五级流水线结构，使用4个寄存器存放相关数据和信号。下面是各级流水线的功能简述。

IF级

IF级的主要功能包括PC的更新、读取Instruction Memory获取指令、将之后所需数据写入IF/ID流水线寄存器等。

ID级

ID级的主要功能包括控制信号、部分转发信号的生成、寄存器堆的读取、立即数的扩展、将之后所需数据写入ID/EX流水线寄存器等。

EX级

EX级的主要功能包括ALU的运算、分支控制信号的生成、部分转发信号的生成、将之后所需数据写入EX/MEM流水线寄存器等。

MEM级

MEM级的主要功能包括对Data Memory中的数据进行读写操作、对外设进行控制操作、将之后所需数据写入MEM/WB流水线寄存器等。

WB级

WB级的主要功能包括写入寄存器堆、冒险检测等。

转发单元

本项目在ID级和EX级分别实现了转发单元。值得一提的是，在理论课程中我们只针对EX级的转发重点进行了讲解，但是在编写CPU的过程中我发现，如果使用之前单周期大作业中的Register File，则会出现“先写后读”的情况，这与理论课中所讲的寄存器堆先读后写有所区别，因此需要在ID阶段增加额外的转发单元；此外，由于jr、jalr指令在ID阶段需要用到Rs寄存器，因此也要在该阶段增加转发。因此，ID阶段的转发主要完成的是上述两个功能。而EX阶段的转发便与理论课中所讲相同，即需要得到来自EX/MEM、MEM/WB寄存器的转发。

两个转发单元相关代码如下：

```
module IDforward(  
    IF_ID_Rs, ID_EX_Rd, EX_MEM_Rd, EX_MEM_RegWrite, ID_EX_RegWrite, forward  
);  
input [4:0] IF_ID_RS;
```

```

input [4:0] ID_EX_Rd;
input [4:0] EX_MEM_Rd;
input EX_MEM_RegWrite;
input ID_EX_RegWrite;
output [1:0] forward;

assign forward = ID_EX_RegWrite && (ID_EX_Rd != 5'b00000) && (IF_ID_RS ==
ID_EX_Rd)? 2'b11:
                EX_MEM_RegWrite && (EX_MEM_Rd != 5'b00000) && (IF_ID_RS ==
EX_MEM_Rd) ? 2'b10:
                2'b00;

endmodule

```

```

module EX_forward(
    MEM_WB_RegWrite, EX_MEM_RegWrite, ID_EX_RS, MEM_WB_Rd, EX_MEM_Rd, forward
);
input MEM_WB_RegWrite;
input EX_MEM_RegWrite;
input [4:0] ID_EX_RS;
input [4:0] MEM_WB_Rd;
input [4:0] EX_MEM_Rd;
output [1:0] forward;

assign forward = (MEM_WB_RegWrite && MEM_WB_Rd != 5'b00000 && MEM_WB_Rd ==
ID_EX_RS) && (EX_MEM_Rd != ID_EX_RS || ~EX_MEM_RegWrite) ? 2'b01:
/*&& (EX_MEM_Rd != ID_EX_RS || ~EX_MEM_RegWrite)*/
                EX_MEM_RegWrite && EX_MEM_Rd != 5'b00000 && EX_MEM_Rd ==
ID_EX_RS ? 2'b10:
                2'b00;

endmodule

```

load and use冒险单元

load and use 冒险主要发生在如下情况：

- 1、ID阶段的指令需要用到前一条指令的EX或MEM结果
- 2、ID阶段的指令需要用到前第二条指令的MEM结果
- 3、EX阶段的指令需要用到前一条指令的MEM阶段的结果

处理load and use 冒险的相关代码如下：

```

module LoadAndUse(
    ID_EX_MemRead, EX_MEM_MemRead, EX_Rd, ID_RS, ID_Rt, EX_MEM_Rd, PCSrc, Stall
);
input ID_EX_MemRead;
input EX_MEM_MemRead;
input [4:0] EX_Rd;
input [4:0] ID_RS;
input [4:0] ID_Rt;
input [4:0] EX_MEM_Rd;
input [2:0] PCSrc;

```

```

    output Stall;

    wire EX_Stall, MEM_Stall;

    assign EX_Stall = (ID_EX_MemRead) && (EX_Rd != 5'b00000) && ((EX_Rd == ID_RS)
    || (EX_Rd == ID_Rt));
    assign MEM_Stall = (EX_MEM_MemRead) && (EX_MEM_Rd != 5'b00000) && (EX_MEM_Rd
    == ID_RS);
    assign Stall = EX_Stall || (PCSrc == 3'b010 && MEM_Stall);

endmodule

```

分支信号单元

本模块的功能为产生分支信号，该分支信号产生后主要有两个作用，第一是控制PC的跳转，第二是当分支跳转发生时，flush掉IF/ID和ID/EX寄存器。相关代码如下：

```

module BranchCtrl(Branch, BranchOp, i_1, i_2, ctrl);

input Branch;
input [2:0] BranchOp;
input [31:0] i_1;
input [31:0] i_2;
output ctrl;

reg ans;

assign ctrl = ans && Branch;

always @(*)
begin
    case(BranchOp)
        3'b001:
            ans = i_1[31];
        3'b010:
            ans = ~(i_1 == i_2);
        3'b011:
            ans = i_1[31] || ~|i_1;
        3'b100:
            ans = ~(i_1[31] || ~|i_1);
        default:
            ans = (i_1 == i_2);
    endcase
end

endmodule

```

控制信号产生单元

本模块的功能为通过解码 `Instruction`，产生对应的控制信号，同时考虑中断和异常。相关代码如下：

```

module Control(
    OpCode, Funct, PCSrc, RegDst, ExtOp, LuOp, Branch, BranchOp, ALUOp, ALUSrc1,
    ALUSrc2, MemRead, MemWrite, MemToReg, RegWrite, IRQ, Exception
);

```

```

input [5:0] OpCode;
input [5:0] Funct;
input IRQ;
output [2:0] PCSrc;
output [1:0] RegDst;
output ExtOp;
output LuOp;

output Branch;
output [2:0] BranchOp;
output [3:0] ALUOp;
output ALUSrc1;
output ALUSrc2;

output MemRead;
output MemWrite;

output [1:0] MemToReg;
output RegWrite;
output Exception;

assign PCSrc = //IRQ, exception
    IRQ ? 3'b011:
    Exception ? 3'b100:
    (OpCode == 6'h02 || OpCode == 6'h03)? 3'b001:
    ((OpCode == 0 && Funct == 6'h08) || (OpCode == 0 && Funct == 6'h09))?
3'b010:

    3'b000;
assign Branch =
    ~IRQ && (OpCode == 6'h01 || (OpCode >= 6'h04 && OpCode <= 6'h07))?
1'b1:
    1'b0;
assign BranchOp[2:0] =
    (OpCode == 6'h01) ? 3'b001://bltz
    (OpCode == 6'h05) ? 3'b010://bne
    (OpCode == 6'h06) ? 3'b011://blez
    (OpCode == 6'h07) ? 3'b100://bgtz
    3'b000;//beq
assign ALUOp[2:0] = //???
    (OpCode == 6'h00)? 3'b010: //R, jr, jalr
    (OpCode == 6'h04)? 3'b001: //andi
    (OpCode == 6'h0c)? 3'b100: //ori
    (OpCode == 6'h0a || OpCode == 6'h0b)? 3'b101://slti or sltiu
    3'b000; //addi, addiu, ...
assign ALUOp[3] = OpCode[0];

assign ALUSrc1 =
    (OpCode == 6'h00 && (Funct == 6'h00 || Funct == 6'h02 || Funct ==
6'h03))? 1'b1:
    1'b0;
assign ALUSrc2 = ~(OpCode == 6'h00 || OpCode == 6'h04);
assign MemRead =
    (OpCode == 6'h23) && ~(IRQ || Exception);
assign MemWrite =
    (OpCode == 6'h2b) && ~(IRQ || Exception);
assign MemToReg =
    (IRQ || Exception) ? 2'b11:

```

```

        (OpCode == 6'h23)? 2'b01://mem out
        (OpCode == 6'h03 || (OpCode == 0 && Funct == 6'h09))? 2'b10://pc
        2'b00;//alu out
    assign ExtOp =
        (OpCode == 6'h0c || OpCode == 6'h0d)? 1'b0://without ori
        1'b1;
    assign LuOp =
        (OpCode == 6'h0f)? 1'b1:
        1'b0;
    assign RegDst[1:0] = //???
        (IRQ || Exception) ? 2'b11:
        (OpCode == 6'h03) ? 2'b10:
        (OpCode == 6'h23 || OpCode == 6'h0f || OpCode == 6'h08 || OpCode ==
6'h09 || OpCode == 6'h0c || OpCode == 6'h0a || OpCode == 6'h0b)? 2'b00:
        2'b01;
    assign RegWrite = IRQ || Exception ||
        ~(OpCode == 6'h2b || Branch || OpCode == 6'h02 || (OpCode == 0 &&
Funct == 6'h08));

    assign Exception = ~((OpCode == 6'h00 && ((Funct >= 6'h20 && Funct <= 6'h27)
|| Funct == 6'h2a ||
        Funct == 6'h2b || Funct == 6'h08||Funct == 6'h09 ||
Funct == 6'h00 ||
        Funct == 6'h02 || Funct == 6'h03)) || ((OpCode >= 6'h01
&& OpCode <= 6'h0d) ||
        (OpCode == 6'h23 || OpCode == 6'h2b || OpCode ==
6'h0f)));

endmodule

```

异常和中断

本模块可判别的异常为“未定义指令”，可判别的中断为“定时器中断”，下面讲述其原理。

当PC[31]为1时，程序处于内核态，此时不应该发生异常或中断；当PC[31]为0时，程序处于普通态，此时可以处理异常和中断。

异常：Control 模块生成 Exception 信号，Exception 信号控制PC进入 0x80000008，程序进入异常处理部分（本项目汇编代码的异常处理部分为死循环）。

中断：Timer 时钟的 TL 计数到 0xffffffff 时，TH 中的值被加载到 TL，同时产生中断信号，PC进入 0x80000004，程序进入中断处理部分（本项目汇编代码的中断处理部分为先求出排序所用的周期数，再通过查找表的方法将其后四位译码，最后将其传输给BCD模块，使得结果能够显示在7段数码管上，具体代码见测试的汇编程序部分）。

由于我没有将Timer外设写在单独的模块里，这里便截取部分timer的更新逻辑代码，相关代码如下：

```

always @(posedge reset or posedge clk)
    if(reset)
        begin
            SysTick <= 32'h00000000;
            TL_next <= 32'h00000000;
            TCON_next <= 3'b000;
        end
    else
        begin
            SysTick <= SysTick + 1'b1;
        end
    end

```

```

    if(TCON[0])
    begin

        if(TL==32'hffffffff)
        begin
            TL_next <= TH;

            if(TCON[1])
            TCON_next[2] <= 1'b1;
            else
            TCON_next <= TCON;
        end
        else
        begin
            TL_next <= TL + 1'b1;
            TCON_next <=TCON;
        end
    end
end
end

```

七段数码管

本模块使用了上学期实验三频率计中自己实现的数码管相关代码，但是值得一提的是，本模块删去了之前代码中的译码部分，只保留了输出结果的部分，对16进制数进行译码的工作需由中断处理程序完成。本模块相关代码如下：

```

module BCD7(scan_clk, din0, din1, din2, din3, dout, AN, bcd_en);
    input scan_clk;
    input [7:0] din0;
    input [7:0] din1;
    input [7:0] din2;
    input [7:0] din3;
    input bcd_en;
    output [7:0] dout;
    output reg [3:0] AN;
    //reg [7:0] temp;
    reg [1:0]c_state = 2'b00, n_state = 2'b00;
    reg [7:0] douttemp = 7'b0;
    reg [3:0] dintemp;
    assign dout = douttemp;
    always @(posedge scan_clk)
        c_state <= n_state;
    always @(*)
    begin
        if(bcd_en)
        begin
            case(c_state)
                2'b00:
                begin
                    AN <= 4'b1000;
                    n_state <= 2'b01;
                    douttemp <= din0;
                end
                2'b01:
                begin
                    AN <= 4'b0100;
                    n_state <= 2'b10;

```

```

        douttemp <= din1;
    end
    2'b10:
    begin
        AN <= 4'b0010;
        n_state <= 2'b11;
        douttemp <= din2;
    end
    2'b11:
    begin
        AN <= 4'b0001;
        n_state <= 2'b00;
        douttemp <= din3;
    end
endcase
end
end
endmodule

```

其余主要模块基本使用或微调了单周期大作业中提供的代码，这里为了功能的完整性，也一并列举出来，但不再详解其原理。

ALU Control

本模块使用了单周期的相关代码，生成了ALU控制信号，相关代码如下：

```

module ALUControl(ALUOp, Funct, ALUctl, Sign);
    input [3:0] ALUOp;
    input [5:0] Funct;
    output reg [4:0] ALUctl;
    output Sign;

    parameter aluAND = 5'b00000;
    parameter aluOR  = 5'b00001;
    parameter aluADD = 5'b00010;
    parameter aluSUB = 5'b00110;
    parameter aluSLT = 5'b00111;
    parameter aluNOR = 5'b01100;
    parameter aluXOR = 5'b01101;
    parameter aluSLL = 5'b10000;
    parameter aluSRL = 5'b11000;
    parameter aluSRA = 5'b11001;

    assign Sign = (ALUOp[2:0] == 3'b010)? ~Funct[0]: ~ALUOp[3];

    reg [4:0] aluFunct;
    always @(*)
        case (Funct)
            6'b00_0000: aluFunct <= aluSLL;
            6'b00_0010: aluFunct <= aluSRL;
            6'b00_0011: aluFunct <= aluSRA;
            6'b10_0000: aluFunct <= aluADD;
            6'b10_0001: aluFunct <= aluADD;
            6'b10_0010: aluFunct <= aluSUB;
            6'b10_0011: aluFunct <= aluSUB;
            6'b10_0100: aluFunct <= aluAND;
            6'b10_0101: aluFunct <= aluOR;

```

```

        6'b10_0110: aluFunct <= aluXOR;
        6'b10_0111: aluFunct <= aluNOR;
        6'b10_1010: aluFunct <= aluSLT;
        6'b10_1011: aluFunct <= aluSLT;
        default: aluFunct <= aluADD;
    endcase

    always @(*)
        case (ALUOp[2:0])
            3'b000: ALUctl <= aluADD;
            3'b001: ALUctl <= aluSUB;
            3'b100: ALUctl <= aluAND;
            3'b101: ALUctl <= aluSLT;
            3'b010: ALUctl <= aluFunct;
            default: ALUctl <= aluADD;
        endcase

endmodule

```

ALU

本模块使用了单周期的相关代码，实现了ALU操作，相关代码如下：

```

module ALU(in1, in2, ALUctl, Sign, out, zero);
    input [31:0] in1, in2;
    input [4:0] ALUctl;
    input Sign;
    output reg [31:0] out;
    output zero;

    assign zero = (out == 0);

    wire ss;
    assign ss = {in1[31], in2[31]};

    wire lt_31;
    assign lt_31 = (in1[30:0] < in2[30:0]);

    wire lt_signed;
    assign lt_signed = (in1[31] ^ in2[31])?
        ((ss == 2'b01)? 0: 1): lt_31;

    always @(*)
        case (ALUctl)
            5'b00000: out <= in1 & in2;
            5'b00001: out <= in1 | in2;
            5'b00010: out <= in1 + in2;
            5'b00110: out <= in1 - in2;
            5'b00111: out <= {31'h00000000, Sign? lt_signed: (in1 < in2)};
            5'b01100: out <= ~(in1 | in2);
            5'b01101: out <= in1 ^ in2;
            5'b10000: out <= (in2 << in1[4:0]);
            5'b11000: out <= (in2 >> in1[4:0]);
            5'b11001: out <= ({32{in2[31]}}, in2) >> in1[4:0];
            default: out <= 32'h00000000;
        endcase
endmodule

```



```
endmodule
```

Memory

本模块借鉴单周期的相关代码，实现了 Instruction Memory 和 Data Memory，其中 Instruction Memory 中储存了带有中断和异常的排序汇编程序，Data Memory 中储存了128个32位无符号数。相关代码如下：

Instruction Memory:

```
module InstructionMemory(Address, Instruction);
    input [31:0] Address;
    output reg [31:0] Instruction;
    always @(*)
        case (Address[9:2])

            8'd0: Instruction <= 32'h08000003;
            8'd1: Instruction <= 32'h0800002b;
            8'd2: Instruction <= 32'h0800008c;
            8'd3: Instruction <= 32'h3c114000;
            8'd4: Instruction <= 32'h22310014;
            8'd5: Instruction <= 32'h8e320000;
            8'd6: Instruction <= 32'h24100000;
            8'd7: Instruction <= 32'h20080080;
            8'd8: Instruction <= 32'h0c00000a;
            8'd9: Instruction <= 32'h0800000e;
            8'd10: Instruction <= 32'h20090000;
            8'd11: Instruction <= 32'h0128502a;
            8'd12: Instruction <= 32'h1540000d;
            8'd13: Instruction <= 32'h03e00008;
            8'd14: Instruction <= 32'h8e330000;
            8'd15: Instruction <= 32'h0272a022;
            8'd16: Instruction <= 32'h3c114000;
            8'd17: Instruction <= 32'h20120003;
            8'd18: Instruction <= 32'hae320008;
            8'd19: Instruction <= 32'h2415fff0;
            8'd20: Instruction <= 32'hae350000;
            8'd21: Instruction <= 32'h2413ffff;
            8'd22: Instruction <= 32'hae330004;
            8'd23: Instruction <= 32'h08000017;
            8'd24: Instruction <= 32'h21290001;
            8'd25: Instruction <= 32'h0800000b;
            8'd26: Instruction <= 32'h212bffff;
            8'd27: Instruction <= 32'h000b5880;
            8'd28: Instruction <= 32'h020b6020;
            8'd29: Instruction <= 32'h000b5882;
            8'd30: Instruction <= 32'h8d8d0000;
            8'd31: Instruction <= 32'h8d8e0004;
            8'd32: Instruction <= 32'h01cd782b;
            8'd33: Instruction <= 32'h0160c02a;
            8'd34: Instruction <= 32'h1700fff5;
            8'd35: Instruction <= 32'h11e0fff4;
            8'd36: Instruction <= 32'h01cd6826;
            8'd37: Instruction <= 32'h01cd7026;
            8'd38: Instruction <= 32'h01cd6826;
            8'd39: Instruction <= 32'had8d0000;
```

```
8'd40: Instruction <= 32'had8e0004;
8'd41: Instruction <= 32'h216bffff;
8'd42: Instruction <= 32'h0800001b;
8'd43: Instruction <= 32'h3c104000;
8'd44: Instruction <= 32'hae000008;
8'd45: Instruction <= 32'h24100190;
8'd46: Instruction <= 32'h240c000f;
8'd47: Instruction <= 32'h028c4024;
8'd48: Instruction <= 32'h0014a102;
8'd49: Instruction <= 32'h028c4824;
8'd50: Instruction <= 32'h0014a102;
8'd51: Instruction <= 32'h028c5024;
8'd52: Instruction <= 32'h0014a102;
8'd53: Instruction <= 32'h028c5824;
8'd54: Instruction <= 32'h21040000;
8'd55: Instruction <= 32'h0c000043;
8'd56: Instruction <= 32'h20880000;
8'd57: Instruction <= 32'h21240000;
8'd58: Instruction <= 32'h0c000043;
8'd59: Instruction <= 32'h20890000;
8'd60: Instruction <= 32'h21440000;
8'd61: Instruction <= 32'h0c000043;
8'd62: Instruction <= 32'h208a0000;
8'd63: Instruction <= 32'h21640000;
8'd64: Instruction <= 32'h0c000043;
8'd65: Instruction <= 32'h208b0000;
8'd66: Instruction <= 32'h08000084;
8'd67: Instruction <= 32'h00006020;
8'd68: Instruction <= 32'h108c001f;
8'd69: Instruction <= 32'h218c0001;
8'd70: Instruction <= 32'h108c001f;
8'd71: Instruction <= 32'h218c0001;
8'd72: Instruction <= 32'h108c001f;
8'd73: Instruction <= 32'h218c0001;
8'd74: Instruction <= 32'h108c001f;
8'd75: Instruction <= 32'h218c0001;
8'd76: Instruction <= 32'h108c001f;
8'd77: Instruction <= 32'h218c0001;
8'd78: Instruction <= 32'h100c001f;
8'd79: Instruction <= 32'h218c0001;
8'd80: Instruction <= 32'h108c001f;
8'd81: Instruction <= 32'h218c0001;
8'd82: Instruction <= 32'h108c001f;
8'd83: Instruction <= 32'h218c0001;
8'd84: Instruction <= 32'h108c001f;
8'd85: Instruction <= 32'h218c0001;
8'd86: Instruction <= 32'h108c001f;
8'd87: Instruction <= 32'h218c0001;
8'd88: Instruction <= 32'h108c001f;
8'd89: Instruction <= 32'h218c0001;
8'd90: Instruction <= 32'h108c001f;
8'd91: Instruction <= 32'h218c0001;
8'd92: Instruction <= 32'h108c001f;
8'd93: Instruction <= 32'h218c0001;
8'd94: Instruction <= 32'h108c001f;
8'd95: Instruction <= 32'h218c0001;
8'd96: Instruction <= 32'h108c001f;
8'd97: Instruction <= 32'h218c0001;
```

```

8'd98: Instruction <= 32'h108c001f;
8'd99: Instruction <= 32'h218c0001;
8'd100: Instruction <= 32'h2000003f;
8'd101: Instruction <= 32'h03e00008;
8'd102: Instruction <= 32'h20040006;
8'd103: Instruction <= 32'h03e00008;
8'd104: Instruction <= 32'h2004005b;
8'd105: Instruction <= 32'h03e00008;
8'd106: Instruction <= 32'h2004004f;
8'd107: Instruction <= 32'h03e00008;
8'd108: Instruction <= 32'h20040066;
8'd109: Instruction <= 32'h03e00008;
8'd110: Instruction <= 32'h2004006d;
8'd111: Instruction <= 32'h03e00008;
8'd112: Instruction <= 32'h2004007d;
8'd113: Instruction <= 32'h03e00008;
8'd114: Instruction <= 32'h20040007;
8'd115: Instruction <= 32'h03e00008;
8'd116: Instruction <= 32'h2004007f;
8'd117: Instruction <= 32'h03e00008;
8'd118: Instruction <= 32'h2004006f;
8'd119: Instruction <= 32'h03e00008;
8'd120: Instruction <= 32'h20040077;
8'd121: Instruction <= 32'h03e00008;
8'd122: Instruction <= 32'h2004007c;
8'd123: Instruction <= 32'h03e00008;
8'd124: Instruction <= 32'h20040039;
8'd125: Instruction <= 32'h03e00008;
8'd126: Instruction <= 32'h2004005e;
8'd127: Instruction <= 32'h03e00008;
8'd128: Instruction <= 32'h20040079;
8'd129: Instruction <= 32'h03e00008;
8'd130: Instruction <= 32'h20040071;
8'd131: Instruction <= 32'h03e00008;
8'd132: Instruction <= 32'h3c104000;
8'd133: Instruction <= 32'h22100010;
8'd134: Instruction <= 32'hae0b0000;
8'd135: Instruction <= 32'hae0a0000;
8'd136: Instruction <= 32'hae090000;
8'd137: Instruction <= 32'hae080000;
8'd138: Instruction <= 32'h08000086;
8'd139: Instruction <= 32'h0800008b;
8'd140: Instruction <= 32'h0800008c;

```

```

    default: Instruction <= 32'h00000000;

```

```

endcase

```

```

endmodule

```

Data Memory:

```

module DataMemory(reset, clk, Address, Write_data, Read_data, MemRead, MemWrite,
write_en);
    input reset, clk;
    input [31:0] Address, write_data;
    input write_en;
    input MemRead, MemWrite;
    output [31:0] Read_data;

```

```

parameter RAM_SIZE = 256;
parameter RAM_SIZE_BIT = 8;

reg [31:0] RAM_data[RAM_SIZE - 1: 0];
    initial
begin
RAM_data[0] <= 32'h6e037588;
RAM_data[1] <= 32'h4c2d2400;
RAM_data[2] <= 32'h457ddf47;
RAM_data[3] <= 32'hb9ac5ed3;
RAM_data[4] <= 32'h7eb33b04;
RAM_data[5] <= 32'hcee52cfe;
RAM_data[6] <= 32'h150257e6;
RAM_data[7] <= 32'h509c7fa7;
RAM_data[8] <= 32'h0adeb752;
RAM_data[9] <= 32'h34bab743;
RAM_data[10] <= 32'hacba9e52;
RAM_data[11] <= 32'h225d3439;
RAM_data[12] <= 32'he11217bc;
RAM_data[13] <= 32'h65b62e72;
RAM_data[14] <= 32'h36890991;
RAM_data[15] <= 32'h4baeedfb;
RAM_data[16] <= 32'h4e4ad2d2;
RAM_data[17] <= 32'h1d25dea2;
RAM_data[18] <= 32'he44c16d8;
RAM_data[19] <= 32'he41978f7;
RAM_data[20] <= 32'h04752d75;
RAM_data[21] <= 32'had8f9dffa;
RAM_data[22] <= 32'haa83d36b;
RAM_data[23] <= 32'h803bd48b;
RAM_data[24] <= 32'ha8dc281f;
RAM_data[25] <= 32'h8f45dbfa;
RAM_data[26] <= 32'h1771e9f4;
RAM_data[27] <= 32'hba99398f;
RAM_data[28] <= 32'hae93b4fd;
RAM_data[29] <= 32'hfabe734b;
RAM_data[30] <= 32'h032a1cdb;
RAM_data[31] <= 32'h55d749d4;
RAM_data[32] <= 32'h0dc3bd08;
RAM_data[33] <= 32'h10101206;
RAM_data[34] <= 32'hed6f2d97;
RAM_data[35] <= 32'h35491732;
RAM_data[36] <= 32'h55cec923;
RAM_data[37] <= 32'hdeb8e688;
RAM_data[38] <= 32'h84ed6cd7;
RAM_data[39] <= 32'h63cc2745;
RAM_data[40] <= 32'h2e786bc6;
RAM_data[41] <= 32'heb66753b;
RAM_data[42] <= 32'h16a2fc62;
RAM_data[43] <= 32'h302d11b2;
RAM_data[44] <= 32'h85d014c9;
RAM_data[45] <= 32'h3fd73e24;
RAM_data[46] <= 32'h70fef555;
RAM_data[47] <= 32'hcb36dd8d;
RAM_data[48] <= 32'hf8085ebd;
RAM_data[49] <= 32'hb9563d98;
RAM_data[50] <= 32'h69ba34ef;

```

```
RAM_data[51] <= 32'hb07644d8;
RAM_data[52] <= 32'h962b0b7a;
RAM_data[53] <= 32'hd16c1b99;
RAM_data[54] <= 32'h638c6a84;
RAM_data[55] <= 32'hbbba95a0;
RAM_data[56] <= 32'hddccdaae;
RAM_data[57] <= 32'h4ed5ba5d;
RAM_data[58] <= 32'h6ab3949c;
RAM_data[59] <= 32'h193941b2;
RAM_data[60] <= 32'h4dc4f8fc;
RAM_data[61] <= 32'h80e71144;
RAM_data[62] <= 32'h295dd4ef;
RAM_data[63] <= 32'h4c8a559a;
RAM_data[64] <= 32'he78f177e;
RAM_data[65] <= 32'h54f78bef;
RAM_data[66] <= 32'h53c24e8a;
RAM_data[67] <= 32'h18dead17;
RAM_data[68] <= 32'h0fbf6c69;
RAM_data[69] <= 32'h28dd5e6a;
RAM_data[70] <= 32'h2e07f85d;
RAM_data[71] <= 32'ha111ec46;
RAM_data[72] <= 32'ha27fbf0e;
RAM_data[73] <= 32'h28b1f213;
RAM_data[74] <= 32'h9bdc1e65;
RAM_data[75] <= 32'hf559209b;
RAM_data[76] <= 32'h69a71902;
RAM_data[77] <= 32'h3c8fcc1f;
RAM_data[78] <= 32'hfa99e2c2;
RAM_data[79] <= 32'h346a024c;
RAM_data[80] <= 32'hb270e93f;
RAM_data[81] <= 32'h7e9d783a;
RAM_data[82] <= 32'h772f31d8;
RAM_data[83] <= 32'h76c73b83;
RAM_data[84] <= 32'h6901c7a1;
RAM_data[85] <= 32'h5928fc5c;
RAM_data[86] <= 32'h9c6a4121;
RAM_data[87] <= 32'he121e94a;
RAM_data[88] <= 32'h33c1bebb;
RAM_data[89] <= 32'h20fde260;
RAM_data[90] <= 32'h1520692c;
RAM_data[91] <= 32'h3b94bb3b;
RAM_data[92] <= 32'hf36e5170;
RAM_data[93] <= 32'h839a0259;
RAM_data[94] <= 32'h8f83e329;
RAM_data[95] <= 32'h2cde244c;
RAM_data[96] <= 32'h8bd49d82;
RAM_data[97] <= 32'hf453c9cd;
RAM_data[98] <= 32'hb36db605;
RAM_data[99] <= 32'h9ce507cf;
RAM_data[100] <= 32'h61589539;
RAM_data[101] <= 32'h2f38c984;
RAM_data[102] <= 32'h6af16b1d;
RAM_data[103] <= 32'h99904fa3;
RAM_data[104] <= 32'h7992c761;
RAM_data[105] <= 32'hef6ceaf1;
RAM_data[106] <= 32'h8836da43;
RAM_data[107] <= 32'hd9ea4695;
RAM_data[108] <= 32'h8363dfd4;
```

```

RAM_data[109] <= 32'h0259f50;
RAM_data[110] <= 32'h1c838573;
RAM_data[111] <= 32'he892a2ac;
RAM_data[112] <= 32'hc687e9a1;
RAM_data[113] <= 32'h74ff712d;
RAM_data[114] <= 32'h16af6225;
RAM_data[115] <= 32'h7520822d;
RAM_data[116] <= 32'h0bbc3be1;
RAM_data[117] <= 32'h51f31fa9;
RAM_data[118] <= 32'h9df8fc3c;
RAM_data[119] <= 32'hd6215174;
RAM_data[120] <= 32'h903e5a58;
RAM_data[121] <= 32'hc5ca779f;
RAM_data[122] <= 32'h4549d763;
RAM_data[123] <= 32'h35424389;
RAM_data[124] <= 32'h6654566f;
RAM_data[125] <= 32'h88950199;
RAM_data[126] <= 32'h96e8f221;
RAM_data[127] <= 32'h6fb95788;

end
assign Read_data = MemRead? RAM_data[Address[RAM_SIZE_BIT + 1:2]]:
32'h00000000;

integer i;
always @(posedge reset or posedge clk)
    if (reset)
        for (i = 128; i < RAM_SIZE; i = i + 1)
            RAM_data[i] <= 32'h00000000;
    else if (Memwrite && write_en)
        RAM_data[Address[RAM_SIZE_BIT + 1:2]] <= Write_data;

endmodule

```

Register File

本模块使用了单周期大作业中所提供的 Register File 模块，用于寄存器堆的读写，相关代码如下：

```

module RegisterFile(
    clk, reset, RegWrite, Read_register1, Read_register2,
    Read_data1, Read_data2, Write_register, Write_data
);

input reset, clk;
input RegWrite;
input [4:0] Read_register1, Read_register2, Write_register;
input [31:0] Write_data;
output [31:0] Read_data1, Read_data2;
//output [7:0] leds;
reg [31:0] RF_data[31:1];

assign Read_data1 = (Read_register1 == 5'b00000)? 32'h00000000:
RF_data[Read_register1];

```

```

    assign Read_data2 = (Read_register2 == 5'b00000)? 32'h00000000:
RF_data[Read_register2];

    integer i;
    always @(posedge reset or posedge clk)
    if (reset)
        for (i = 1; i < 32; i = i + 1)
            RF_data[i] <= 32'h00000000;//???
    else if (Regwrite && (write_register != 5'b00000))
    begin
        RF_data[write_register] <= write_data;
        //$display(write_data);
    end

endmodule

```

仿真结果

为本项目编写 testbench 文件如下：

```

module cpu_tb();

    reg reset;
    reg clk;
    wire [3:0] ans;
    wire [7:0] cathodes;
    CPU cpu(.reset(reset), .clk(clk), .ans(ans), .cathodes(cathodes));

    initial begin
        forever
            #(`PERIOD / 2) clk = ~clk;
    end

    initial begin
        reset = 1;
        clk = 1;
        #100 reset = 0;
        //$readmemh("C:/Users/hp/Desktop/data.txt", cpu.data_memory.RAM_data, 0,
127);
        //$readmemh("C:/Users/hp/Desktop/sort", cpu.instruction_memory.RAM_data, 0,
49);
    end

endmodule

```

测试的汇编指令如下（使用冒泡排序进行排序）：

```

j main

j Interrupt

j Exception

main:

```

```

#load systick
lui $s1 0x00004000      #li $s1 0x40000014
addi $s1 $s1 0x00000014
lw $s2 0($s1)

li $s0, 0x00000000
addi $t0 $zero 128      #N = buffer[0]
#addi $s0, $s0, 4
jal sort
j finish1
sort:

    addi $t1, $zero, 0    #i = 0
c2:
    slt $t2, $t1, $t0
    bnez $t2, loop2       #if(i < n) loop2
    jr $ra
finish1:
    lw $s3 0($s1)         #load systick again
    sub $s4 $s3 $s2

    #start the timer
    lui $s1 0x00004000    #li $s1 0x40000000
    addi $s2 $zero 3      #tcon
    sw $s2 8($s1)
    li $s5 0xffffffff0
    sw $s5 0($s1)
    li $s3 0xffffffff     #initialize
    sw $s3 4($s1)

finish2:
    j finish2

c3: addi $t1, $t1, 1      #i++
    j c2

loop2:

    addi $t3, $t1, -1     #j = i - 1
loop3:
    sll $t3, $t3, 2
    add $t4, $s0, $t3
    srl $t3, $t3, 2
    lw $t5, 0($t4)        #t5 = v[j]
    lw $t6, 4($t4)        #t6 = v[j + 1]

    sltu $t7, $t6, $t5    #if(v[j]>v[j + 1])
    slt $t8, $t3, $zero
    bnez $t8, c3
    beqz $t7, c3

swap:  xor $t5, $t6, $t5
       xor $t6, $t6, $t5

```



```

xor $t5, $t6, $t5
sw $t5, 0($t4)
sw $t6, 4($t4)

```

```

addi $t3, $t3, -1
j loop3

```

Interrupt:

```

#li $s0 0x40000000
lui $s0 0x00004000
sw $zero 8($s0)          #disable the timer

li $s0 0x190             #the basic address of LUT

li $t4 0x000f            #get the lower 16bits of systick
and $t0 $s4 $t4
srl $s4 $s4 4
and $t1 $s4 $t4
srl $s4 $s4 4
and $t2 $s4 $t4
srl $s4 $s4 4
and $t3 $s4 $t4

addi $a0 $t0 0
jal encode
addi $t0 $a0 0
addi $a0 $t1 0
jal encode
addi $t1 $a0 0
addi $a0 $t2 0
jal encode
addi $t2 $a0 0
addi $a0 $t3 0
jal encode
addi $t3 $a0 0

j input

```

encode:

```

#encode the numbers
add $t4 $zero $zero

beq $a0 $t4 a0
addi $t4 $t4 1
beq $a0 $t4 a1
addi $t4 $t4 1
beq $a0 $t4 a2
addi $t4 $t4 1
beq $a0 $t4 a3
addi $t4 $t4 1
beq $a0 $t4 a4
addi $t4 $t4 1
beq $0 $t4 a5
addi $t4 $t4 1
beq $a0 $t4 a6
addi $t4 $t4 1

```

```
beq $a0 $t4 a7
addi $t4 $t4 1
beq $a0 $t4 a8
addi $t4 $t4 1
beq $a0 $t4 a9
addi $t4 $t4 1
beq $a0 $t4 a10
addi $t4 $t4 1
beq $a0 $t4 a11
addi $t4 $t4 1
beq $a0 $t4 a12
addi $t4 $t4 1
beq $a0 $t4 a13
addi $t4 $t4 1
beq $a0 $t4 a14
addi $t4 $t4 1
beq $a0 $t4 a15
addi $t4 $t4 1
```

a0:

```
addi $0 $zero 0x003f
jr $ra
```

a1:

```
addi $a0 $zero 0x0006
jr $ra
```

a2:

```
addi $a0 $zero 0x005b
jr $ra
```

a3:

```
addi $a0 $zero 0x004f
jr $ra
```

a4:

```
addi $a0 $zero 0x0066
jr $ra
```

a5:

```
addi $a0 $zero 0x006d
jr $ra
```

a6:

```
addi $a0 $zero 0x007d
jr $ra
```

a7:

```
addi $a0 $zero 0x0007
jr $ra
```

a8:

```
addi $a0 $zero 0x007f
jr $ra
```

a9:

```
addi $a0 $zero 0x006f
jr $ra
```

a10:

```
addi $a0 $zero 0x0077
jr $ra
```

a11:

```
addi $a0 $zero 0x007c
jr $ra
```

a12:

```
addi $a0 $zero 0x0039
jr $ra
```

```

a13:
    addi $a0 $zero 0x005e
    jr $ra
a14:
    addi $a0 $zero 0x0079
    jr $ra
a15:
    addi $a0 $zero 0x0071
    jr $ra

input:
    #li $s0 0x40000010
    lui $s0 0x00004000
    addi $s0 $s0 0x00000010
print:
    sw $t3 0($s0)
    sw $t2 0($s0)
    sw $t1 0($s0)
    sw $t0 0($s0)
    j print
stop:
    j stop

Exception:
    j Exception

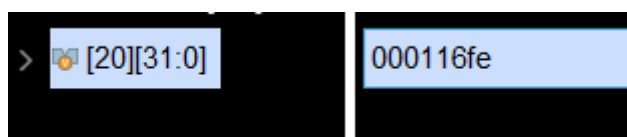
```

排序结果如下：

Name	Value	Data T...
RAM_data[255:0]	00000000	Array
> [17][31:0]	4baeedfb	Array
> [16][31:0]	457ddf47	Array
> [15][31:0]	3fd73e24	Array
> [14][31:0]	36890991	Array
> [13][31:0]	35491732	Array
> [12][31:0]	34bab743	Array
> [11][31:0]	302d11b2	Array
> [10][31:0]	2e786bc6	Array
> [9][31:0]	225d3439	Array
> [8][31:0]	1d25dea2	Array
> [7][31:0]	1771e9f4	Array
> [6][31:0]	16a2fc62	Array
> [5][31:0]	150257e6	Array
> [4][31:0]	10101206	Array
> [3][31:0]	0dc3bd08	Array
> [2][31:0]	0adeb752	Array
> [1][31:0]	04752d75	Array
> [0][31:0]	032a1cdb	Array

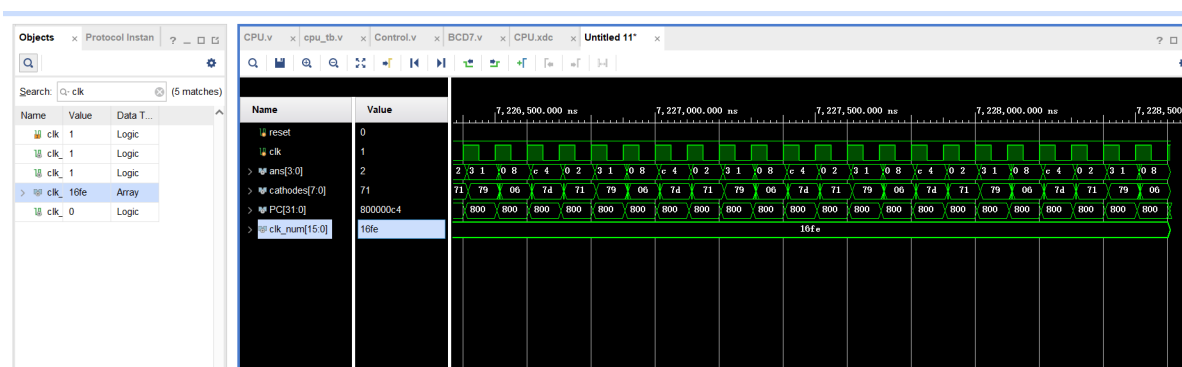
可以验证排序结果正确

排序所需的总的时钟周期数如图：



因此总周期数为 $0 \times 116fe = 71422$ ，冒泡排序的时间复杂度为 $O(128^2)$ ，与其数量级相符，下面验证用7段数码管显示其后四位的功能。

显示后四位的结果如下：



发现后四位是 $0 \times 16fe$ ，分别被解码为 0×06 ， $0 \times 7d$ ， 0×71 ， 0×79 ，发现可以在cathodes上正确显示。

综合情况

资源分析

Name	Slice LUTs (20800)	Slice Registers (41600)	F7 Muxes (16300)	F8 Muxes (8150)	Slice (8150)	LUT as Logic (20800)	Bonded IOB (210)	BUFGCTRL (32)
CPU	4431	10020	1379	610	3962	4431	14	1
bcd7 (BCD7)	3	16	0	0	5	3	0	0
data_memory (DataMemory)	2529	8192	1088	544	3106	2529	0	0
rf (RegisterFile)	714	992	287	66	656	714	0	0

如图所示，共使用了4431个LUT， 10020个寄存器，其中绝大多数都被使用在 Data Memory 中。

时序性能分析

设置时钟为9.9ns并进行实现，综合策略选择 vivado Synthesis Defaults，实现策略选择 Performance_ExtraTimingOpt，求得WNS如图：

Design Timing Summary		
Setup	Hold	Pulse Width
Worst Negative Slack (WNS): 0.153 ns	Worst Hold Slack (WHS): 0.059 ns	Worst Pulse Width Slack (WPWS): 4.450 ns
Total Negative Slack (TNS): 0.000 ns	Total Hold Slack (THS): 0.000 ns	Total Pulse Width Negative Slack (TPWS): 0.000 ns
Number of Failing Endpoints: 0	Number of Failing Endpoints: 0	Number of Failing Endpoints: 0
Total Number of Endpoints: 19418	Total Number of Endpoints: 19418	Total Number of Endpoints: 10006
All user specified timing constraints are met.		

如图所示，WNS为 0.153 ns，因此本CPU的理论工作频率为

$$\frac{1}{T - WNS} = \frac{1}{9.9 - 0.153} = 102.6MHz$$

关键路径情况如图：

Summary					
Name	Path 1				
Slack	0.022ns				
Source	EX_MEM_Rd_reg[1]/C (rising edge-triggered cell FDCE clocked by CLK {rise@0.000ns fall@5.000ns period=10.000ns})				
Destination	IF_ID_PC_next_reg[30]/D (rising edge-triggered cell FDCE clocked by CLK {rise@0.000ns fall@5.000ns period=10.000ns})				
Path Group	CLK				
Path Type	Setup (Max at Slow Process Corner)				
Requirement	10.000ns (CLK rise@10.000ns - CLK rise@0.000ns)				
Data Path Delay	9.659ns (logic 2.805ns (29.040%) route 6.854ns (70.960%))				
Logic Levels	12 (CARRY4=3 LUT2=1 LUT4=3 LUT5=1 LUT6=4)				
Clock ... Skew	-0.033ns				
Clock Uncertainty	0.035ns				
Source Clock Path					
Delay Type	Incr (ns)	Path ...	Location	Netlist Resource(s)	
(clock CLK rise edge)	(r) 0.000	0.000			
	(r) 0.000	0.000	Site: P17	clk	
net (fo=0)	0.000	0.000		clk	
			Site: P17	clk_IBUF_inst/I	
IBUF (Prop_ibuf_I_O)	(r) 1.478	1.478	Site: P17	clk_IBUF_inst/O	
net (fo=1, routed)	1.972	3.450		clk_IBUF	
			Site: BUF...TRL_X0Y0	clk_IBUF_BUFG_inst/I	
BUFG (Prop_bufg_I_O)	(r) 0.096	3.546	Site: BUF...TRL_X0Y0	clk_IBUF_BUFG_inst/O	
net (fo=10009, routed)	1.539	5.085		clk_IBUF_BUFG	
FDCE			Site: SLICE_X52Y74	EX_MEM_Rd_reg[1]/C	
Data Path					

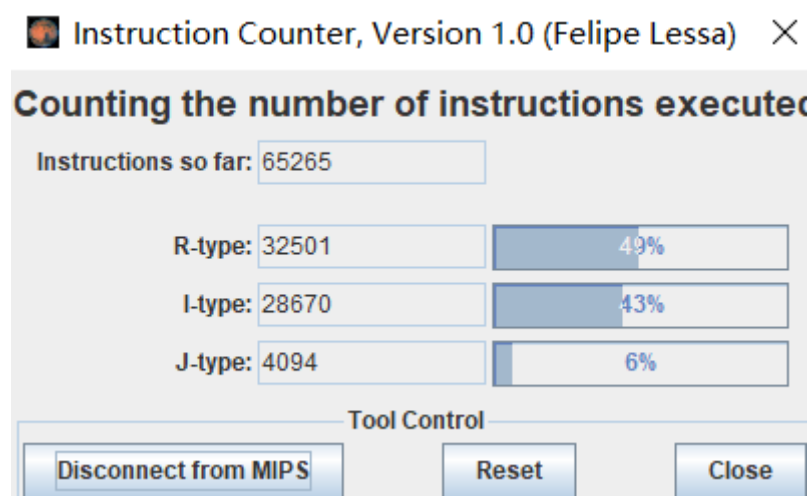
Data Path				
Delay Type	Incr (ns)	Path ...	Location	Netlist Resource(s)
FDCE (Prop_fdce_C_Q)	(r) 0.518	5.603	Site: SLICE_X52Y74	EX_MEM_Rd_reg[1]/Q
net (fo=10, routed)	0.848	6.451		EX_MEM_Rd[1]
			Site: SLICE_X52Y71	ID_EX_ALUOp[3]_i_60/I2
LUT5 (Prop_lut5_I2_O)	(f) 0.124	6.575	Site: SLICE_X52Y71	ID_EX_ALUOp[3]_i_60/O
net (fo=2, routed)	0.602	7.177		ID_EX_ALUOp[3]_i_60_n_3
			Site: SLICE_X52Y72	ID_EX_ALUOp[3]_i_35/I1
LUT4 (Prop_lut4_I1_O)	(r) 0.124	7.301	Site: SLICE_X52Y72	ID_EX_ALUOp[3]_i_35/O
net (fo=27, routed)	0.842	8.143		EXforwardA[1]
			Site: SLICE_X49Y72	EX_MEM_ALUOut[0]_i_19/I1
LUT2 (Prop_lut2_I1_O)	(r) 0.149	8.292	Site: SLICE_X49Y72	EX_MEM_ALUOut[0]_i_19/O
net (fo=8, routed)	0.703	8.995		EX_MEM_ALUOut[0]_i_19_n_3
			Site: SLICE_X47Y72	ID_EX_ALUOp[3]_i_11/I5
LUT6 (Prop_lut6_I5_O)	(r) 0.332	9.327	Site: SLICE_X47Y72	ID_EX_ALUOp[3]_i_11/O
net (fo=4, routed)	0.632	9.959		ID_EX_ALUOp[3]_i_11_n_3
			Site: SLICE_X46Y71	ID_EX_ALUOp[3]_i_62/I1
LUT6 (Prop_lut6_I1_O)	(r) 0.124	10.083	Site: SLICE_X46Y71	ID_EX_ALUOp[3]_i_62/O
net (fo=1, routed)	0.000	10.083		ID_EX_ALUOp[3]_i_62_n_3
			Site: SLICE_X46Y71	ID_EX_ALUOp_reg[3]_i_51/S[3]
CARRY4 (Prop_c...4_S[3]_CO[3])	(r) 0.376	10.459	Site: SLICE_X46Y71	ID_EX_ALUOp_reg[3]_i_51/CO[3]
net (fo=1, routed)	0.000	10.459		ID_EX_ALUOp_reg[3]_i_51_n_3
			Site: SLICE_X46Y72	ID_EX_ALUOp_reg[3]_i_26/CI
CARRY4 (Prop_carry4_CI_CO[3])	(r) 0.117	10.576	Site: SLICE_X46Y72	ID_EX_ALUOp_reg[3]_i_26/CO[3]

LUT6 (Prop_lut6_i0_O)	(f) 0.124	12.200	Site: SLICE_X53Y73	IF_ID_EX_ALUOp[3]_i_2/O
net (fo=116, routed)	0.764	12.964		IF_ID_EX_ALUOp[3]_i_2_n_3
			Site: SLICE_X52Y74	IF_ID_PC_next[30]_i_4/I
LUT4 (Prop_lut4_i1_O)	(f) 0.124	13.088	Site: SLICE_X52Y74	IF_ID_PC_next[30]_i_4/O
net (fo=3, routed)	0.862	13.950		rf/PC_reg[12]
			Site: SLICE_X53Y76	rf/IF_ID_PC_next[30]_i_1/I
LUT4 (Prop_lut4_i2_O)	(r) 0.154	14.104	Site: SLICE_X53Y76	rf/IF_ID_PC_next[30]_i_1/O
net (fo=1, routed)	0.640	14.744		rf_n_34
FDCE			Site: SLICE_X53Y77	IF_ID_PC_next_reg[30]/D
Arrival Time		14.744		
Destination Clock Path				
Delay Type	Incr (ns)	Path ...	Location	Netlist Resource(s)
(clock CLK rise edge)	(r) 10.000	10.000		
	(r) 0.000	10.000	Site: P17	clk
net (fo=0)	0.000	10.000		clk
			Site: P17	clk_IBUF_inst/I
IBUF (Prop_ibuf_i_O)	(r) 1.408	11.408	Site: P17	clk_IBUF_inst/O
net (fo=1, routed)	1.868	13.276		clk_IBUF
			Site: BUF...TRL_X0Y0	clk_IBUF_BUFG_inst/I
BUFG (Prop_bufg_i_O)	(r) 0.091	13.367	Site: BUF...TRL_X0Y0	clk_IBUF_BUFG_inst/O
net (fo=10009, routed)	1.428	14.795		clk_IBUF_BUFG
FDCE			Site: SLICE_X53Y77	IF_ID_PC_next_reg[30]/C
clock pessimism	0.257	15.052		
clock uncertainty	-0.035	15.017		
FDCE (Setup_fdce_C_D)	-0.250	14.767	Site: SLICE_X53Y77	IF_ID_PC_next_reg[30]
Required Time		14.767		

net (fo=116, routed)	0.764	12.964		↗ ID_EX_ALUOp[3]_i_2_n_3
			Site: SLICE_X52Y74	➡ IF_ID_PC_next[30]_i_4/I
LUT4 (Prop_lut4_i1_O)	(f) 0.124	13.088	Site: SLICE_X52Y74	➡ IF_ID_PC_next[30]_i_4/O
net (fo=3, routed)	0.862	13.950		↗ rf/PC_reg[12]
			Site: SLICE_X53Y76	➡ rf/IF_ID_PC_next[30]_i_1/I2
LUT4 (Prop_lut4_i2_O)	(r) 0.154	14.104	Site: SLICE_X53Y76	➡ rf/IF_ID_PC_next[30]_i_1/O
net (fo=1, routed)	0.640	14.744		↗ rf_n_34
FDCE			Site: SLICE_X53Y77	➡ IF_ID_PC_next_reg[30]/D
Arrival Time		14.744		
Destination Clock Path				
Delay Type	Incr (ns)	Path ...	Location	Netlist Resource(s)
(clock CLK rise edge)	(r) 10.000	10.000		
	(r) 0.000	10.000	Site: P17	➡ clk
net (fo=0)	0.000	10.000		↗ clk
			Site: P17	➡ clk_IBUF_inst/I
IBUF (Prop_ibuf_i_O)	(r) 1.408	11.408	Site: P17	➡ clk_IBUF_inst/O
net (fo=1, routed)	1.868	13.276		↗ clk_IBUF
			Site: BUF...TRL_X0Y0	➡ clk_IBUF_BUFG_inst/I
BUFG (Prop_bufg_i_O)	(r) 0.091	13.367	Site: BUF...TRL_X0Y0	➡ clk_IBUF_BUFG_inst/O
net (fo=10009, routed)	1.428	14.795		↗ clk_IBUF_BUFG
FDCE			Site: SLICE_X53Y77	➡ IF_ID_PC_next_reg[30]/C
clock pessimism	0.257	15.052		
clock uncertainty	-0.035	15.017		
FDCE (Setup_fdce_C_D)	-0.250	14.767	Site: SLICE_X53Y77	➡ IF_ID_PC_next_reg[30]
Required Time		14.767		

CPI 分析

使用MARS仿真器对完全相同的数据和代码进行测试，通过 `Instruction Counter` 求出指令数如图：



因此可得

$$CPI = \frac{clock_num}{instr_num} = \frac{71422}{65265} = 1.094$$

平均每秒执行的指令数为：

$$n = \frac{freq}{CPI} = \frac{102.6M}{1.094} = 93.78M$$

调试心得

在本次实验中我遇到了许多bug，在进行了长时间的调试后终于全部解决，这里我想总结一些能够提高debug效率的方法。

首先当发现所得结果与预期不相符时，首先应该关注的不是这个量本身，而应该是对应时间的PC和 `instruction`，关注好这两个变量的值才能明白程序是在执行什么指令以及是在执行哪步时出了问题，从而找到相关的变量进行进一步调试。我在摸索出这个方法后调试的效率就变得很高了。

其次，灵活运用 `vivado` 的一些函数可以简化数据的输入输出过程，让我们更专注于程序本身。比如，我在验证流水线处理器的功能时运用了一个名为 `$readmemh` 的函数，这个函数可以直接将文件中的内容写进子模块中的寄存器中，这就为每次运行程序剩下了一些“繁文冗节”，也是一种提高效率的方法。

然而，后仿真是不可以使用 `$readmemh` 的，因此我写了一些 `python` 脚本，包括一个生成随机数的脚本，将随机数加载到 `Data Memory` 的脚本，将 `MARS` 生成的16进制指令转换为case语句形式的脚本。这些脚本本身并不复杂，往往不到10行，但运用这些自动化工具着实能够提高编程效率。这也进一步让我理解了机器对于处理重复任务的优越性，能够极大改善编程体验。

实验小结

本次实验是在返校考试结束后进行的，可谓时间紧，任务重。同时它还要求我们必须要对MIPS流水线CPU的全部细节都能完全熟练地掌握，任务量与难度不可谓不大。本次项目是我入学以来写过的体量最大的工程。回忆起过去“造机”的一周零一天，可谓感慨良多。

我在实验的前两天大致温习了一下理论课所学，对各个指令的实现以及转发冒险等细节有了大概的了解。经过两天的编程后我搭出了CPU的大致框架。可是当第三天时，我仅用一条 `addi $s0 $zero 1` 便让流水线崩溃了。于是之后的三天，我非常辛苦地逐条指令调试，花费了大量的精力，将指令一条一条调通。之后的一天我运行了单周期大作业中求和的程序，发现结果仍然不对。于是我又花了一天时间解决了转发冒险等问题。接下来的两天主要是编写测试的汇编程序，以及花了数个小时画出了流水线的通路图。做完实验后回顾这一切，我觉得如果我能在第一天就先画好通路图，脑海里就会有一个比较清晰的实现思路，在之后的编程中也就不会出现那么多诸如未加判断条件的低级错误了。不过好在最后的主频在100MHz以上，结果还算令人满意，在得到结果后我也产生了很大的成就感。

总而言之，本次编程实验极大地加深了我对MIPS流水线CPU的理解，也大大提高了我的工程能力，让我积累了许多使用 `vivado` 调试 `verilog` 的经验，这是一次过程虽艰辛但结果很好，并让我受益良多的编程体验。

感谢助教和老师的辛勤付出！

附录

本项目在 `Vivado 2019.2` 上能够顺利运行，项目的完整工程文件夹为CPU，其中 `CPU.xdc` 约束文件在 `src/CPU/` 文件夹中，源代码和 `testbench` 文件在 `src/CPU/CPU.srcs/` 文件夹中，关于综合策略和实现策略的设置已在上文中提到。由于篇幅原因，部分控制信号没有在流水线通路图中标出，通路图及仿真截图等均在 `figs/` 文件夹中。

本流水线CPU数据通路图：

