An Example: MIPS

From the Harris/Weste book

Based on the MIPS-like processor from the Hennessy/Patterson book

MIPS Architecture

- Example: subset of MIPS processor architecture
  - Drawn from Patterson & Hennessy
- MIPS is a 32-bit architecture with 32 registers
  - Consider 8-bit subset using 8-bit datapath
  - Only implement 8 registers ($0 - $7)
  - $0 hardwired to 00000000
  - 8-bit program counter

Instruction Set

Table 1.7 MIPS instruction set (subset supported)

Instruction	Function		Encoding	op	funct
`add $1, $2, $3`	addition:	$1 → $2 + $3	R	000000	100000
`sub $1, $2, $3`	subtraction:	$1 → $2 – $3	R	000000	100010
`and $1, $2, $3`	bitwise and:	$1 → $2 and $3	R	000000	100100
`or $1, $2, $3`	bitwise or:	$1 → $2 or $3	R	000000	100101
`slt $1, $2, $3`	set less than:	$1 → 1 if $2 < $3 $1 → 0 otherwise	R	000000	101010
`addi $1, $2,`	add immediate:	$1→ $2 + imm	I	001000	n/a
`beq $1, $2, imm`	branch if equal:	PC → PC + imm[a]	I	000100	n/a
`j destination`	jump:	PC_destination[a]	J	000010	n/a
`lb $1, imm($2)`	load byte:	$1 → mem[$2 + imm]	I	100000	n/a
`sb $1, imm($2)`	store byte:	mem[$2 + imm] → $1	I	110000	n/a

Instruction Encoding

- 32-bit instruction encoding
  - Requires four cycles to fetch on 8-bit datapath

format	example	encoding					
		6	5	5	5	5	6
R	add $rd, $ra, $rb	0	ra	rb	rd	0	funct
		6	5	5	16		
I	beq $ra, $rb, imm	op	ra	rb	imm		
		6	26				
J	j dest	op	dest				

Fibonacci (C)

$f_0 = 1; f_{-1} = -1$

$f_n = f_{n-1} + f_{n-2}$

f = 1, 1, 2, 3, 5, 8, 13, …

```
int fib(void)
{
  int n = 8;          /* compute nth Fibonacci number */
  int f1 = 1, f2 = -1; /* last two Fibonacci numbers */

  while (n != 0) {     /* count down to n = 0 */
    f1 = f1 + f2;
    f2 = f1 - f2;
    n = n - 1;
  }
  return f1;
}
```

Fibonacci (Assembly)

- 1st statement: int n = 8;
- How do we translate this to assembly?
  - Decide which register should hold its value
  - load an immediate value into that register
  - But, there's no "load immediate" instruction…
  - But, there is an addi instruction, and there's a convenient register that's always pinned to 0
- addi $3, $0, 8 ; load 0+8 into register 3

Fibonacci (Assembly)

```
# fib.asm
# Register usage: $3: n  $4: f  $5: fp
# return value written to address 255
fib:  addi $3, $0, 8      # initialize n=8
      addi $4, $0, 0      # initialize f = 0
      addi $5, $0, 1      # initialize fp = 1
loop: beq  $3, $0, end    # Done with loop if n == 0
      add  $4, $4, $5     # f = f + fp
      sub  $5, $4, $5     # fp = f - fp
      addi $3, $3, -1     # n = n - 1
      j    loop           # while loop
end:  sb   $4, 255($0)    # store result in address 255
```

Fibonacci (Binary)

- 1st statement: addi $3, $0, 8
- How do we translate this to machine language?
  - Hint: use instruction encodings below

format	example	encoding					
		6	5	5	5	5	6
R	add $rd, $ra, $rb	0	ra	rb	rd	0	funct
		6	5	5	16		
I	beq $ra, $rb, imm	op	ra	rb	imm		
		6	26				
J	j dest	op	dest				

Fibonacci (Binary)

- Machine language program

Instruction	Binary Encoding	Hexadecimal Encoding
addi $3, $0, 8	001000 00000 00011 0000000000001000	20030008
addi $4, $0, 1	001000 00000 00100 0000000000000001	20040001
addi $5, $0, -1	001000 00000 00101 1111111111111111	2005ffff
beq $3, $0, end	000100 00011 00000 0000000000000101	10600005
add $4, $4, $5	000000 00100 00101 00100 00000 100000	00852020
sub $5, $4, $5	000000 00100 00101 00101 00000 100010	00852822
addi $3, $3, -1	001000 00011 00011 1111111111111111	2063ffff
j loop	000010 00000000000000000000000011	08000003
sb $4, 255($0)	110000 00000 00100 0000000011111111	a00400ff

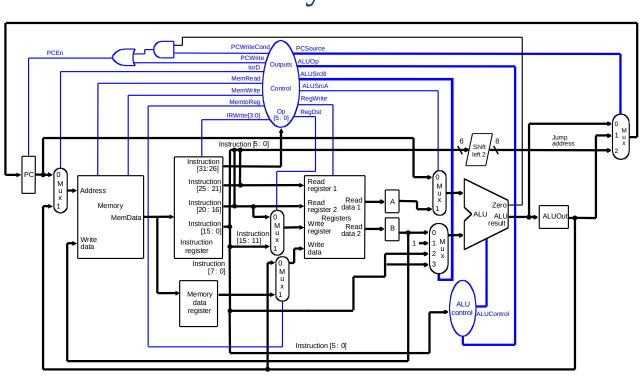
Fibonacci (Binary)

Instruction	Binary Encoding	Hexadecimal Encoding
addi $3, $0, 8	001000 00000 00011 0000000000001000	20030008
addi $4, $0, 1	001000 00000 00100 0000000000000001	20040001
addi $5, $0, -1	001000 00000 00101 1111111111111111	2005ffff
beq $3, $0, end	000100 00011 00000 0000000000000101	10600005
add $4, $4, $5	000000 00100 00101 00100 00000 100000	00852020
sub $5, $4, $5	000000 00100 00101 00101 00000 100010	00852822
addi $3, $3, -1	001000 00011 00011 1111111111111111	2063ffff
j loop	000010 00000000000000000000000011	08000003
sb $4, 255($0)	110000 00000 00100 0000000011111111	a00400ff

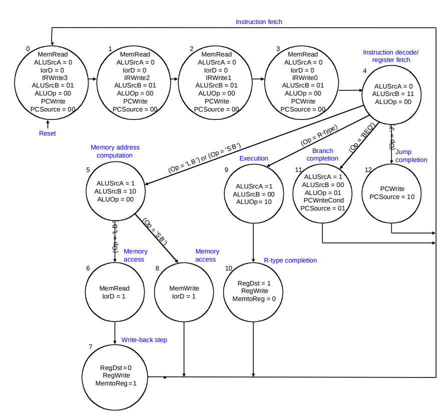
format	example	encoding					
		6	5	5	5	5	6
R	add $rd, $ra, $rb	0	ra	rb	rd	0	funct
		6	5	5	16		
I	beq $ra, $rb, imm	op	ra	rb	imm		
		6	26				
J	j dest	op	dest				

MIPS Microarchitecture

- Multicycle μ architecture from Patterson & Hennessy

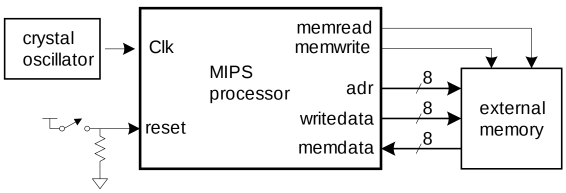


Multicycle Controller



Logic Design

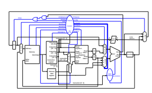
- Start at top level
  - Hierarchically decompose MIPS into units
- Top-level interface

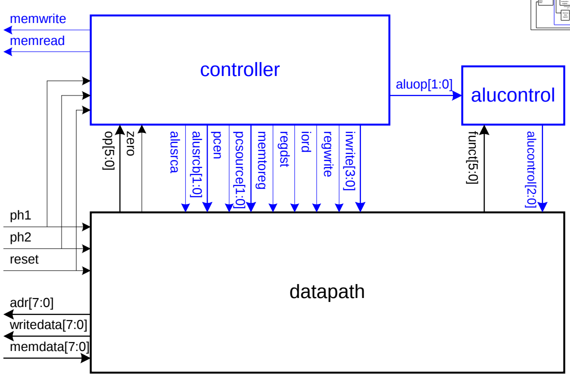


Verilog Code

```
// top level design includes both mips processor and memory
module mips_mem #(parameter WIDTH = 8, REGBITS = 3)(clk, reset);
  input clk, reset;
  wire               memread, memwrite;
  wire    [WIDTH-1:0] adr, writedata;
  wire    [WIDTH-1:0] memdata;

  // instantiate the mips processor
  mips #(WIDTH,REGBITS) mips(clk, reset, memdata, memread,
    memwrite, adr, writedata);
  // instantiate memory for code and data
  exmem #(WIDTH) exmem(clk, memwrite, adr, writedata, memdata);
endmodule
```

Block Diagram





Top-level code

```
// simplified MIPS processor
module mips #(parameter WIDTH = 8, REGBITS = 3)
           (input              clk, reset,
            input  [WIDTH-1:0] memdata,
            output             memread, memwrite,
            output [WIDTH-1:0] adr, writedata);

  wire [31:0] instr;
  wire        zero, alusrca, memtoreg, iord, pcen, regwrite, regdst;
  wire [1:0]  aluop,pcsource,alusrcb;
  wire [3:0]  irwrite;
  wire [2:0]  alucont;

  controller  cont(clk, reset, instr[31:26], zero, memread,
    memwrite,
                alusrca, memtoreg, iord, pcen, regwrite, regdst,
                pcsource, alusrcb, aluop, irwrite);
  alucontrol  ac(aluop, instr[5:0], alucont);
  datapath    #(WIDTH, REGBITS)
            dp(clk, reset, memdata, alusrca, memtoreg, iord, pcen,
              regwrite, regdst, pcsource, alusrcb, irwrite, alucont,
              zero, instr, adr, writedata);
endmodule
```

Controller Parameters

```
module controller(input clk, reset,
             input      [5:0] op,
             input           zero,
             output reg       memread, memwrite, alusrca,
    memtoreg, iord,
             output          pcen,
             output reg       regwrite, regdst,
             output reg [1:0] pcsource, alusrcb, aluop,
             output reg [3:0] irwrite);

  parameter   FETCH1  =  4'b0001;
  parameter   FETCH2  =  4'b0010;
  parameter   FETCH3  =  4'b0011;
  parameter   FETCH4  =  4'b0100;
  parameter   DECODE  =  4'b0101;
  parameter   MEMADR  =  4'b0110;
  parameter   LBRD    =  4'b0111;
  parameter   LBWR    =  4'b1000;
  parameter   SBWR    =  4'b1001;
  parameter   RTYPEEX =  4'b1010;
  parameter   RTYPEWR =  4'b1011;
  parameter   BEQEX   =  4'b1100;
  parameter   JEX     =  4'b1101;
  parameter   ADDIWR  =  4'b1110; // added for ADDI

  parameter   LB      =  6'b100000;
  parameter   SB      =  6'b101000;
  parameter   RTYPE   =  6'b0;
  parameter   BEQ     =  6'b000100;
  parameter   J       =  6'b000010;
  parameter   ADDI    =  6'b001000; /// added for ADDI

  reg [3:0] state, nextstate;
  reg       pcwrite, pcwritecond;
```

State Encodings...

Opcodes...

Local reg variables...

Main state machine – NS logic

```
// state register
  always @(posedge clk)
    if(reset) state <= FETCH1;
    else state <= nextstate;

  // next state logic (combinational)
  always @(*)
    begin
      case(state)
        FETCH1:  nextstate <= FETCH2;
        FETCH2:  nextstate <= FETCH3;
        FETCH3:  nextstate <= FETCH4;
        FETCH4:  nextstate <= DECODE;
        DECODE:  case(op)
                LB:     nextstate <= MEMADR;
                SB:     nextstate <= MEMADR;
                ADDI:   nextstate <= MEMADR;
                RTYPE:  nextstate <= RTYPEEX;
                BEQ:    nextstate <= BEQEX;
                J:      nextstate <= JEX;
                // should never happen
                default: nextstate <= FETCH1;
       endcase
        MEMADR:  case(op)
                LB:     nextstate <= LBRD;
                SB:     nextstate <= SBWR;
                ADDI:   nextstate <= ADDIWR;
               // should never happen
               default: nextstate <= FETCH1;
             endcase
        LBRD:    nextstate <= LBWR;
        LBWR:    nextstate <= FETCH1;
        SBWR:    nextstate <= FETCH1;
        RTYPEEX: nextstate <= RTYPEWR;
        RTYPEWR: nextstate <= FETCH1;
        BEQEX:   nextstate <= FETCH1;
        JEX:     nextstate <= FETCH1;
        ADDIWR:  nextstate <= FETCH1;
       // should never happen
        default: nextstate <= FETCH1;
      endcase
    end
```

Setting Control Signal Outputs

```
always @(*)
   begin
      // set all outputs to zero, then
     // conditionally assert just the
     // appropriate ones
      irwrite <= 4'b0000;
      pcwrite <= 0; pcwritecond <= 0;
      regwrite <= 0; regdst <= 0;
      memread <= 0; memwrite <= 0;
      alusrca <= 0; alusrcb <= 2'b00;
     aluop <= 2'b00; pcsource <= 2'b00
      iord <= 0; memtoreg <= 0;
      case(state)
         FETCH1:
            begin
               memread <= 1;
               irwrite <= 4'b0001;
              alusrcb <= 2'b01;
              pcwrite <= 1;
          end
FETCH2:
            begin
              memread <= 1;
              irwrite <= 4'b0010;
              alusrcb <= 2'b01;
              pcwrite <= 1;
            end
FETCH3:
            begin
              memread <= 1;
              irwrite <= 4'b0100;
              alusrcb <= 2'b01;
              pcwrite <= 1;
            end
FETCH4:
            begin
              memread <= 1;
              irwrite <= 4'b1000;
              alusrcb <= 2'b01;
              pcwrite <= 1;
            end
DECODE: alusrcb <= 2'b11;
.....
endcase
end
endmodule
```

Verilog: alu

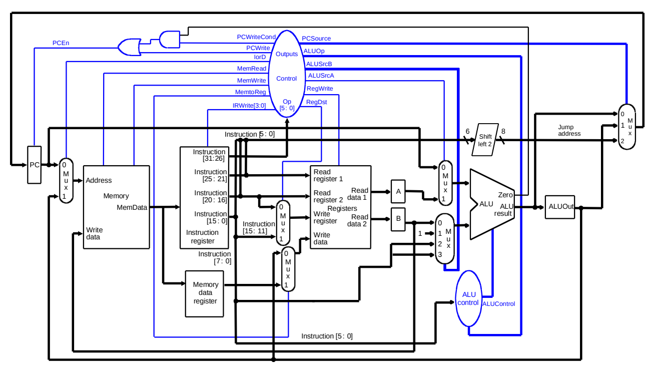
```
module alu #(parameter WIDTH = 8)
           (input       [WIDTH-1:0] a, b,
            input       [2:0]       alucont,
            output reg [WIDTH-1:0] result);
  wire     [WIDTH-1:0] b2, sum, slt;

  assign b2 = alucont[2] ? ~b:b;
  assign sum = a + b2 + alucont[2];
  // slt should be 1 if most significant bit of sum is 1
  assign slt = sum[WIDTH-1];

  always@(*)
    case(alucont[1:0])
      2'b00: result <= a & b;
      2'b01: result <= a | b;
      2'b10: result <= sum;
      2'b11: result <= slt;
    endcase
endmodule
```

Verilog: alucontrol

```
module alucontrol(input      [1:0] aluop,
                  input      [5:0] funct,
                  output reg [2:0] alucont);

  always @(*)
    case(aluop)
      2'b00: alucont <= 3'b010;  // add for lb/sb/addi
      2'b01: alucont <= 3'b110;  // sub (for beq)
      default: case(funct)           // R-Type instructions
                6'b100000: alucont <= 3'b010; // add (for add)
                6'b100010: alucont <= 3'b110; // subtract (for sub)
                6'b100100: alucont <= 3'b000; // logical and (for and)
                6'b100101: alucont <= 3'b001; // logical or (for or)
                6'b101010: alucont <= 3'b111; // set on less (for slt)
                default:   alucont <= 3'b101;      // should never happen
              endcase
    endcase
endmodule
```

MIPS Microarchitecture

- Multicycle μ architecture from Patterson & Hennessy



Verilog: Datapath 1

```
module datapath #(parameter WIDTH = 8, REGBITS = 3)
              (input            clk, reset,
               input  [WIDTH-1:0] memdata,
               input              alusrca, memtoreg, iord, pcen, regwrite, regdst,
               input  [1:0]       pcsource, alusrcb,
               input  [3:0]       irwrite,
               input  [2:0]       alucont,
               output             zero,
               output [31:0]      instr,
               output [WIDTH-1:0] adr, writedata);

  // the size of the parameters must be changed to match the WIDTH
    parameter
  localparam CONST_ZERO = 8'b0;
  localparam CONST_ONE =  8'b1;

  wire [REGBITS-1:0] ra1, ra2, wa;
  wire [WIDTH-1:0]   pc, nextpc, md, rd1, rd2, wd, a, src1, src2, aluresult,
                     aluout, constx4;

  // shift left constant field by 2
  assign constx4 = {instr[WIDTH-3:0],2'b00};

  // register file address fields
  assign ra1 = instr[REGBITS+20:21];
  assign ra2 = instr[REGBITS+15:16];
  mux2       #(REGBITS) regmux(instr[REGBITS+15:16],
    instr[REGBITS+10:11], regdst, wa);
```

Verilog: Datapath 2

```
// independent of bit width, load instruction into four 8-bit registers over
    four cycles
  flopen      #(8)      ir0(clk, irwrite[0], memdata[7:0], instr[7:0]);
  flopen      #(8)      ir1(clk, irwrite[1], memdata[7:0], instr[15:8]);
  flopen      #(8)      ir2(clk, irwrite[2], memdata[7:0], instr[23:16]);
  flopen      #(8)      ir3(clk, irwrite[3], memdata[7:0], instr[31:24]);

  // datapath
  flopenr    #(WIDTH)  pcreg(clk, reset, pcen, nextpc, pc);
  flop       #(WIDTH)  mdr(clk, memdata, md);
  flop       #(WIDTH)  areg(clk, rd1, a);
  flop       #(WIDTH)  wrd(clk, rd2, writedata);
  flop       #(WIDTH)  res(clk, aluresult, aluout);
  mux2         #(WIDTH)  adrmux(pc, aluout, iord, adr);
  mux2         #(WIDTH)  src1mux(pc, a, alusrca, src1);
  mux4         #(WIDTH)  src2mux(writedata, CONST_ONE, instr[WIDTH-1:0],
                          constx4, alusrcb, src2);
  mux4         #(WIDTH)  pcmux(aluresult, aluout, constx4, CONST_ZERO,
    pcsource, nextpc);
  mux2         #(WIDTH)  wdmux(aluout, md, memtoreg, wd);
  regfile     #(WIDTH,REGBITS) rf(clk, regwrite, ra1, ra2, wa, wd, rd1, rd2);
  alu        #(WIDTH) alunit(src1, src2, alucont, aluresult);
  zerodetect #(WIDTH) zd(aluresult, zero);
endmodule
```

Verilog: regfile

```
module regfile #(parameter WIDTH = 8, REGBITS = 3)
              (input               clk,
               input               regwrite,
               input  [REGBITS-1:0] ra1, ra2, wa,
               input  [WIDTH-1:0]   wd,
               output [WIDTH-1:0]   rd1, rd2);

  reg  [WIDTH-1:0] RAM [(1<<REGBITS)-1:0];

  // three ported register file
  // read two ports (combinational)
  // write third port on rising edge of clock
  // register 0 is hardwired to 0
  always @(posedge clk)
    if (regwrite) RAM[wa] <= wd;

  assign rd1 = ra1 ? RAM[ra1] : 0;
  assign rd2 = ra2 ? RAM[ra2] : 0;
endmodule
```

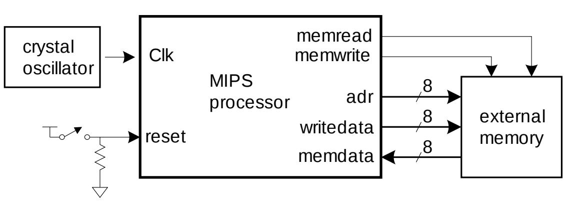
Verlog: Other stuff

```
module zerodetect #(parameter WIDTH
    = 8)
             (input [WIDTH-1:0] a,
              output            y);
  assign y = (a==0);
endmodule

module flop #(parameter WIDTH = 8)
          (input              clk,
           input      [WIDTH-1:0] d,
           output reg [WIDTH-1:0] q);
  always @(posedge clk)
    q <= d;
endmodule

module flopen #(parameter WIDTH = 8)
            (input              clk, en,
             input      [WIDTH-1:0] d,
             output reg [WIDTH-1:0] q);
  always @(posedge clk)
    if (en) q <= d;
endmodule
```

```
module flopenr #(parameter WIDTH = 8)
           (input              clk, reset, en,
            input      [WIDTH-1:0] d,
            output reg [WIDTH-1:0] q);
  always @(posedge clk)
    if      (reset) q <= 0;
    else if (en)    q <= d;
endmodule

module mux2 #(parameter WIDTH = 8)
          (input  [WIDTH-1:0] d0, d1,
           input              s,
           output [WIDTH-1:0] y);
  assign y = s ? d1 : d0;
endmodule

module mux4 #(parameter WIDTH = 8)
          (input      [WIDTH-1:0] d0, d1, d2,
    d3,
           input      [1:0]      s,
           output reg [WIDTH-1:0] y);
  always @(*)
    case(s)
      2'b00: y <= d0;
      2'b01: y <= d1;
      2'b10: y <= d2;
      2'b11: y <= d3;
    endcase
endmodule
```

Logic Design

- Start at top level
  - Hierarchically decompose MIPS into units
- Top-level interface



Verilog: exmemory

```
// external memory accessed by MIPS
module exmemory #(parameter
    WIDTH = 8)
      (clk, memwrite, adr, writedata,
    memdata);

  input              clk;
  input              memwrite;
  input  [WIDTH-1:0] adr,
    writedata;
  output reg [WIDTH-1:0] memdata;

  reg  [31:0] RAM [(1<<WIDTH-2)-
    1:0];
  wire [31:0] word;

  initial
    begin

    $readmemh("memfile.dat",RAM);
    end
```

```
// read and write bytes from 32-bit word
  always @(posedge clk)
    if(memwrite)
      case (adr[1:0])
        2'b00: RAM[adr>>2][7:0] <=
    writedata;
        2'b01: RAM[adr>>2][15:8] <=
    writedata;
        2'b10: RAM[adr>>2][23:16] <=
    writedata;
        2'b11: RAM[adr>>2][31:24] <=
    writedata;
      endcase

  assign word = RAM[adr>>2];
always @(*)
    case (adr[1:0])
      2'b00: memdata <= word[7:0];
      2'b01: memdata <= word[15:8];
      2'b10: memdata <= word[23:16];
      2'b11: memdata <= word[31:24];
    endcase
endmodule
```

Synthesized memory?

- If you synthesize the Verilog, you'll get a memory
  - But – it will be huge!
  - It will be made of your DFF cells
  - plus synthesized address decoders

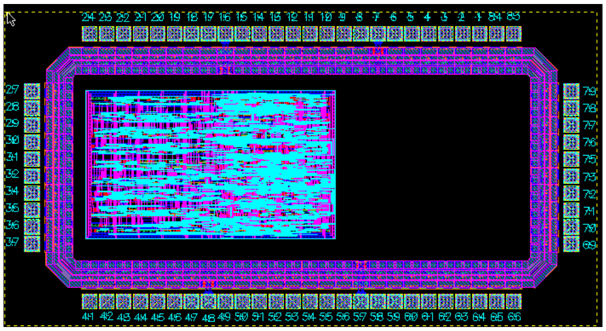
  - Custom memory is much smaller
  - but much trickier to get right
  - … see details in VGA slides …

Verilog: exmemory

```
// external memory accessed by
    MIPS
module exmem #(parameter WIDTH
    = 8)
         (clk, memwrite, adr,
    writedata, memdata);

  input              clk;
  input              memwrite;
  input  [WIDTH-1:0] adr,
    writedata;
  output     [WIDTH-1:0] memdata;

  wire memwriteB, clkB;

// UMC RAM has active low write
    enable...
not(memwriteB, memwrite);
```

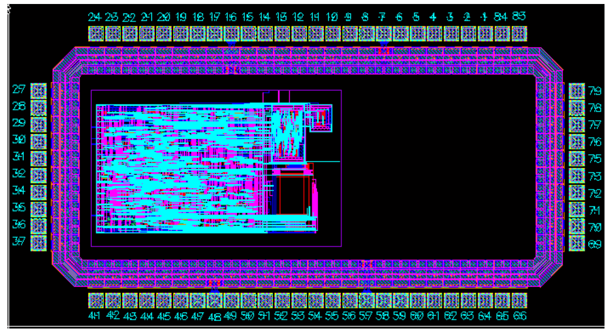
```
// Looks like you need to clock the
    memory early
// to make it work with the current
    control...
not(clkB, clk);

// Instantiate the UMC SPRAM module
UMC130SPRAM_8_8 mips_ram (
      .CK(clkB),
      .CEN(1'b0),
      .WEN(memwriteB),
      .OEN(1'b0),
      .ADR(adr),
      .DI(writedata),
      .DOUT(memdata));

endmodule
```

MIPS (8-bit) size comparison



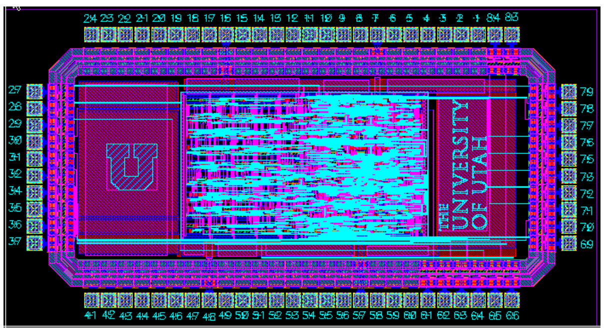
One big EDI run of the whole thing
With some work, could probably get this in a single TCU...

MIPS (8-bit) size comparison



Separate EDI for controller, alucontrol, datapath
and custom RF, assembled with ccar

MIPS (8-bit) whole chip



Includes poly/m1/m2/m3 fill, and logos
Routed to the pads using ccar