b16 Documentation

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Abstract

This article presents architecture and implementation of the b16 stack processor. This processor is inspired by Chuck Moore's newest Forth processors. The minimalistic design fits into small FPGAs and ASICs and is ideally suited for applications that need both control and calculations. The factor is shifted towards control to save space. The synthesizible implementation uses Verilog.

Introduction

Minimalistic CPUs can be used in many designs. A state machine often is too complicated and too difficult to develop, when there are more than a few states. A program with subroutines can perform a lot more complex tasks, and is easier to develop at the same time. Also, ROM- and RAM blocks occupy much less place on silicon than "random logic". That's also valid for FPGAs, where "block RAM" is—in contrast to logic elements—plenty.

The architecture is inspired by the c18 from Chuck Moore [1]. The exact instruction mix is different; it also differs from the standard b16 core. I left out multiplication and division step, but implemented Forth-typical logic operations. Also, this architecture is byte-addressed.

A word about Verilog: Verilog is a C-like language, but tailored for the purpose to simulate logic, and to write synthesizible code. Variables are bits and bit vectors, and assignments are typically non-blocking, i.e. on assignments first all right sides are computed, and the left sides are modified afterwards. Also, Verilog has events, like changing of values or clock edges, and blocks can wait on them.

1 Architectural Overview

The core components are

- An ALU
- A data stack with top and next of stack (T and N) as inputs for the ALU
- A return stack
- An instruction pointer P
- An address mux `addr`, to address external memory
- An instruction latch I

Figure **??** shows a block diagram.

b16.eps

1.1 Register

In addition to the user-visible latches there are control latches for external RAM (`rd` and `wr`), stack pointers (`sp` and `rp`), and a carry `c`.

Name	Function
T	Top of Stack
I	Instruction Bundle
P	Program Counter
R	Top of Returnstack
state	Processor State
sp	Stack Pointer
rp	Return Stack Pointer
c	Carry Flag

⟨*register declarations*⟩≡
```
reg [sdep-1:0] sp;
reg [rdep-1:0] rp;

reg 'L T, I, P, R;

reg [1:0] state;
reg c;
```

2 Instruction Set

There are 32 different instructions. Since several instructions fit into a 16 bit word, we call the bits to store the packed instructions in an instruction word "slot", and the instruction word itself "bundle". The arrangement here is 1,5,5,5, i.e. the first slot is only one bit large (the more significant bits are filled with 0), and the others all 5 bits.

The operations in one instruction word are executed one after the other. Each instruction takes one cycle, memory operation (including instruction fetch) need another cycle. Which instruction is to be executed is stored in the variable `state`.

The instruction set is divided into four groups: jumps, ALU, memory, and stack. Table 1 shows an overview over the instruction set. Note: Some special characters indicate functions as follows: "!": "store", "@": "load", ">": "to" if before, "from" if afterwards.

Operations will be described using a "stack effect". This is a template for the stack elements before and after the operation, separated by a long dash. The names are listed in the order bottom to top, unchanged stack elements below are not listed.

Jumps use the rest of the instruction word as target address (except `ret`). The lower bits of the instruction pointer P are replaced, there's nothing added. For instructions in the last slot, no address remains, so they use T (TOS) as target.

⟨*instruction selection*⟩≡
```
// instruction and branch target selection
reg [4:0] inst;
reg 'L jmp;

always @(state or I or data or atpg)
   case(state[1:0])
     2'b00: inst <= { 4'b0000, data[15] & !atpg };
     2'b01: inst <=   I[14:10];
     2'b10: inst <=   I[9:5];
     2'b11: inst <=   I[4:0];
   endcase // casez(state)

always @(state or I or P or T or data)
   case(state[1:0])
     2'b00: jmp <= { data[14:0], 1'b0 };
     2'b01: jmp <= { P[15:11], I[9:0], 1'b0 };
     2'b10: jmp <= { P[15:6], I[4:0], 1'b0 };
     2'b11: jmp <= { T[15:1], 1'b0 };
   endcase // casez(state)
```

The instructions themselves are executed depending on `inst`:

⟨*instructions*⟩≡
```
casez(inst)
    ⟨control flow⟩
    ⟨ALU operations⟩
    ⟨load/store⟩
    ⟨stack operations⟩
endcase // case(inst)
```

2.1 Jumps

In detail, jumps are performed as follows: the target address is stored in the address latch `addr`, which addresses memory, not in the P register. The register P will be set to the incremented value of `addr`, after the instruction fetch cycle. Apart from `call`, `jmp` and `ret` there are conditional jumps, which test for 0 and carry. The lowest bit of the return stack is used to save the carry flag across calls. Conditional instructions don't consume the tested value, which is different from Forth.

To make it easier to understand, I also define the effect of an instruction in a pseudo language:

nop (—)

call (—r:P) P ← *jmp*; c ← 0

jmp (—) P ← *jmp*

ret (r:a—) P ← a ∧ \$FFFE; c ← a ∧ 1

jz (n—) **if**(n = 0) P ← *jmp*

jnz (n—) **if**(n ≠ 0) P ← *jmp*

jc (x—) **if**(c) P ← *jmp*

jnc (x—) **if**(c = 0) P ← *jmp*

⟨*control flow*⟩≡
```
5'b00001: begin
    rp <= rpdec;
    R <= { state == 2'b00 ? incaddr[15:1] : P[15:1], c
    P <= jmp;
    c <= 1'b0;
    if(state == 2'b11) 'DROP;
end // case: 5'b00001
5'b00010: begin
    P <= jmp;
    if(state == 2'b11) 'DROP;
end
5'b00011: { rp, c, P, R } <=
        { rpinc, R[0], R[l-1:1], 1'b0, toR };
5'b001??: begin
    if((inst[1] ? c : zero) ^ inst[0])
        P <= jmp;
    'DROP;
end
```

2.2 ALU Operations

The ALU instructions use the ALU, which computes a result `res` and a carry bit from T and N. The instruction `com` is an exception, since it only inverts T—that doesn't require an ALU.

Ordinary ALU instructions just write the result of the ALU into T and c, and reload N.

xor (a b—r) r ← a ⊕ b

com (a—r) r ← a ⊕ \$FFFF, c ← 1

	0	1	2	3	4	5	6	7	Comment
0	nop	call	jmp	ret	jz	jnz	jc	jnc	
		exec	goto	ret	gz	gnz	gc	gnc	for slot 3
8	xor	com	and	or	+	+c	*+	/−	
10	!+	@+	@	lit	c!+	c@+	c@	litc	
	!.	@.	@	lit	c!.	c@.	c@	litc	for slot 1
18	nip	drop	over	dup	>r		r>		

Table 1: Instruction Set

and (a b—r) $r \leftarrow a \wedge b$

or (a b—r) $r \leftarrow a \vee b$

+ (a b—r) $c, r \leftarrow a + b$

+c (a b—r) $c, r \leftarrow a + b + c$

∗+ (a b—a r) **if**(c) $c_n, r \leftarrow a+b$ **else** $c_n, r \leftarrow 0, b$; $r, A, c \leftarrow c_n, r, A$

/− (a b—a r) $c_n, r_n \leftarrow a + b + 1$; **if**$(c \vee c_n) r \leftarrow r_n$; $c, r, A \leftarrow r, A, c \vee c_n$

⟨*ALU operations*⟩≡
```
  5'b01001: { c, T } <= { 1'b1, ~T };
  5'b01110: { T, R, c } <=
     { c ? { carry, res } : { 1'b0, T }, R };
  5'b01111: { c, T, R } <=
     { (c | carry) ? res : T, R, (c | carry) };
 'ifndef FPGA
  5'b01???: { sp, c, T } <= { spinc, carry, res };
 'else
  5'b01000: { sp, c, T } <= { spinc, carry, res };
  5'b01010: { sp, c, T } <= { spinc, carry, res };
  5'b01011: { sp, c, T } <= { spinc, carry, res };
  5'b01100: { sp, c, T } <= { spinc, carry, res };
  5'b01101: { sp, c, T } <= { spinc, carry, res };
 'endif
```

2.3 Memory Instructions

Memory instructions use either T as address, and N as data (source or destination), or P as address, and T as destination (literals). The address is auto-incremented, except for instructions in the first slot which use T as address—this is to implement read-modify-write instructions (non-incremeting is written as @. or !. in the assembler, don't care as @* or !*).

!+ (n A—A') $mem[A] \leftarrow n$; $A' \leftarrow A + 2$

@+ (A—n A') $n \leftarrow mem[A]$; $A' \leftarrow A + 2$

@ (A—n) $n \leftarrow mem[A]$;

lit (—n) $n \leftarrow mem[P]$; $P \leftarrow P + 2$

c!+ (c A—A') $mem.b[A] \leftarrow c$; $A' \leftarrow A + 1$

c@+ (A—c A') $c \leftarrow mem.b[A]$; $A' \leftarrow A + 1$

c@ (A—c) $c \leftarrow mem.b[A]$;

litc (—c) $c \leftarrow mem.b[P]$; $P \leftarrow P + 1$

⟨*address handling*⟩≡
```
  wire 'L incaddr, dataw, datas;
  wire tos2r, tos2n;
  wire incby, bswap, addrsel, access, rd;
  wire [1:0] wr;

  assign incby = (inst[4:2] != 3'b101);
  assign access = (inst[4:3]==2'b10);
  assign addrsel = rd ?
      (access & (inst[1:0] != 2'b11)) : |wr;
  assign rd = (state==2'b00) ||
          (access && (inst[1:0]!=2'b00));
  assign wr = (access && (inst[1:0]==2'b00)) ?
          { ~inst[2] | ~T[0],
            ~inst[2] | T[0] } : 2'b00;
  mux #(l) addrmux(addr, addrsel, 1'b0, T, P);
  assign incaddr = addr + incby + 1;
  assign tos2n = (!rd | (inst[1:0] == 2'b11));
  mux #(l) toNmux(toN, tos2n, atpg, T, dataw);
  assign bswap = incby ^ addr[0];
  assign datas = bswap ? data : { data[7:0], data[l-1:8] };
  assign dataw = incby ? datas : { 8'h00, datas[7:0] };
  assign dataout = { bswap ? N[15:8] : N[7:0],
                bswap ? N[7:0]  : N[15:8] };
```

Memory access can't just be done word wise, but also byte wise. Therefore two write lines exist. For byte wise store the lower byte of T is copied to the higher one.

⟨*load/store*⟩≡
```
  5'b10?0?: begin
     if(nextstate != 2'b10) T <= incaddr;
     sp <= rd ? spdec : spinc;
  end
  5'b10?1?: T <= dataw;
```

Memory accesses need an extra cycle. Here the result of the memory access is handled.

⟨*load-store*⟩≡
```
  ⟨pointer increment⟩
  if(|state[1:0]) begin
     ⟨store afterwork⟩
  end else begin
     ⟨ifetch⟩
  end
```

⟨*debug*⟩≡
```
$write("%b[%b] T=%b%x:%x[%x], ",
       inst, state, c, T, N, sp);
$write("P=%x, I=%x, R=%x[%x], res=%b%x\n",
       P, I, R, rp, carry, res);
```

After the access is completed, the result for a load has to be pushed on the stack, or into the instruction register; for stores, the TOS is to be dropped.

⟨*store afterwork*⟩≡
```
if(rd && { inst[4:3], inst[1:0] } != 4'b1010)
    sp <= spdec;
if(|wr) sp <= spinc;
```

Furthermore, the incremented address may go back to the pointer.

⟨*pointer increment*⟩≡
```
if(~|state[1:0] ||
   ((inst[4:3] == 2'b10) && (inst[1:0] == 2'b11)))
    P <= incaddr;
```

To shortcut a `nop` in the first instruction, there's some special logic. That's the second part of NEXT.

⟨*ifetch*⟩≡
```
I <= data;
if(!data[15]) state[1:0] <= 2'b01;
```

2.3.1 Peripherals

Peripherals should only use address bits [15:1], read a whole word, and select the bytes written to based on the two write bits (bit 1 for most significant byte, bit 0 for least significant byte).

2.4 Stack Instructions

Stack instructions change the stack pointer and move values into and out of latches. With the 8 used stack operations, one notes that `swap` is missing. Instead, there's `nip`. The reason is a possible implementation option: it's possible to omit N, and fetch this value directly out of the stack RAM. This consumes more time, but saves space.

nip (a b—b)

drop (a—)

over (a b—a b a)

dup (a—a a)

>r (a—r:a)

r> (r:a—a)

⟨*stack operations*⟩≡
```
5'b11000: sp <= spinc;
5'b11001: 'DROP;
5'b11010: { sp, T } <= { spdec, N };
5'b11011: sp <= spdec;
5'b11100: begin
    R <= T; rp <= rpdec; 'DROP;
end // case: 5'b11100
5'b11110: begin
    { sp, T, R } <= { spdec, R, toR };
    rp <= rpinc;
end // case: 5'b11110
```

3 The Rest of the Implementation

First the implementation file with comment and modules.

⟨*b16.v*⟩≡
```
/*
 * b16 core: 16 bits,
 * inspired by c18 core from Chuck Moore
 *
 * ⟨inst-comment⟩
 */

'define L [l-1:0]
'define DROP { sp, T } <= { spinc, N }
'define DEBUGGING
'define FPGA
'timescale 1ns / 1ns

⟨ALU⟩
⟨Stack⟩
⟨mux⟩
⟨cpu⟩
⟨debugger⟩
```

⟨*inst-comment*⟩≡
```
 * Instruction set:
 * 1, 5, 5, 5 bits
 *     0    1    2    3    4    5    6    7
 * 0: nop  call jmp  ret  jz   jnz  jc   jnc
 * /3       exec goto ret  gz   gnz  gc   gnc
 * 8: xor  com  and  or   +    +c   *+   /-
 * 10: !+   @+   @    lit  c!+  c@+  c@   litc
 * /1 !.   @.   @    lit  c!.  c@.  c@   litc
 * 18: nip  drop over dup  >r        r>
```

⟨*mux*⟩≡
```
module mux(out, sel, atpg, in1, in0);
    parameter l=16;
    input 'L in1, in0;
    input sel, atpg;
    output 'L out;

    assign out = (sel | atpg) ? in1 : in0;
endmodule // mux
```

3.1   Top Level

The CPU consists of several parts, which are all implemented in the same Verilog module.

⟨*cpu*⟩≡
```
module cpu(clk, run, reset, addr, rd, wr, data,
          dataout, scanning, atpg
 'ifdef DEBUGGING,
          dr, dw, daddr, din, dout, bp'endif);
    ⟨port declarations⟩
    ⟨register declarations⟩
    ⟨instruction selection⟩
    ⟨ALU instantiation⟩
    ⟨address handling⟩
    ⟨stack pushs⟩
    ⟨stack instantiation⟩
    ⟨state changes⟩
    ⟨debugging read⟩

    always @(posedge clk or negedge reset)
        ⟨register updates⟩

 endmodule // cpu
```

First, Verilog needs port declarations, so that it can now what's input and output. The parameter are used to configure other word sizes and stack depths.

⟨*port declarations*⟩≡
```
parameter rstaddr=16'h3FFE, show=0,
          l=16, sdep=2, rdep=2;
input clk, run, reset, scanning, atpg;
output 'L addr;
output rd;
output [1:0] wr;
input  'L data;
output 'L dataout;
⟨debugging-ports⟩
```

The ALU is instantiated with the configured width, and the necessary wires are declared

⟨*ALU instantiation*⟩≡
```
wire 'L res, toN, toR, N;
wire carry, zero;

alu #(l) alu16(res, carry, zero,
               T, N, c, inst[2:0]);
```

Since the stacks work in parallel, we have to calculated, when a value is pushed onto the stack (thus **only** if something is stored there).

⟨*stack pushs*⟩≡
```
reg dpush, rpush;

always @(state or inst or rd or run ⟨dbg senselist⟩)
  begin
      rpush <= 1'b0;
      dpush <= (|state[1:0] & rd) |
              (inst[4] && inst[3] && inst[1]);
      casez(inst)
         5'b00001: rpush <= |state[1:0] | run;
         5'b11100: rpush <= 1'b1;
      endcase // case(inst)
      ⟨stack debugging⟩
  end
```

The stacks don't only consist of the two stack modules, but also need an incremented and decremented stack pointer. The return stack even allows to write the top of return stack even without changing the return stack depth.

⟨*stack instantiation*⟩≡
```
wire [sdep-1:0] spdec, spinc;
wire [rdep-1:0] rpdec, rpinc;

stack #(sdep,l) dstack(clk, sp, spdec,
                  dpush, scanning, toN, N);
stack #(rdep,l) rstack(clk, rp, rpdec,
                  rpush, scanning, R, toR);

assign spdec = sp-{{(sdep-1){1'b0}}, 1'b1};
assign spinc = sp+{{(sdep-1){1'b0}}, 1'b1};
assign rpdec = rp-{{(rdep-1){1'b0}}, 1'b1};
assign rpinc = rp+{{(rdep-1){1'b0}}, 1'b1};
```

The basic core is the fully synchronous register update. Each register needs a reset value, and depending on the state transition, the corresponding assignments have to be coded. Most of that is from above, only the instruction fetch and the assignment of the next value of incby has to be done.

⟨*register updates*⟩≡
```
if(!reset) begin
    ⟨resets⟩
end else if(run) begin
    if(show) begin
        ⟨debug⟩
    end
    ⟨load-store⟩
    state <= nextstate;
    ⟨instructions⟩
end else begin // debug
    ⟨debugging⟩
end // else: !if(reset)
```

As reset value, we initialize the CPU so that it is about to fetch the next instruction from address 0. The stacks are all empty, the registers contain all zeros.

⟨*resets*⟩≡
```
state <= 2'b11;
P <= rstaddr;
T <= 16'h0000;
I <= 16'h0000;
R <= 16'h0000;
c <= 1'b0;
sp <= 0;
rp <= 0;
```

The transition to the next state (the NEXT within a bundle) is done separately. That's necessary, since the assignments of the other variables are not just dependent on the current state, but partially also on the next state (e.g. when to fetch the next instruction word).

⟨*state changes*⟩≡
```
wire [1:0] nextstate;

assign nextstate = ((~|inst) || (|inst[4:3])) ?
                    state[1:0] + 2'b01 : 2'b00;
```

3.2 Debugging

For debugging purposes, all registers are memory read–writable. This requires an external bus master attached to the debugging interface. The debugging interface is configured with the DEBUGGING flag. It's only active when the processor is stopped, so the processor itself can't access its own registers.

The debugging module offers the following registers as address space:

Address	read	write
$FFE0	stack[sp++]	push+T
$FFE2	rstack[rp++]	rpush+R
$FFE4	bp	bp
$FFE6	state+stop	state
$FFE8	P	P
$FFEA	T	T
$FFEC	R	R
$FFEE	I	I

The stacks and the state register change state when being read, so be careful!

⟨*debugger*⟩≡
```
'ifdef DEBUGGING
module debugger(clk, nreset,
                addr, data, r, w,
                cpu_addr, cpu_r,
                drun, dr, dw, bp);
parameter l=16, dbgaddr = 12'hFFE;
input clk, nreset, r, cpu_r;
input [1:0] w;
input 'L addr, data, cpu_addr;
output drun, dr, dw;
output 'L bp;

reg drun, drun1;
reg 'L bp;
wire dsel = (addr[l-1:4] == dbgaddr);
assign dr = dsel & r;
assign dw = dsel & |w;

always @(posedge clk or negedge nreset)
if(!nreset) begin
   drun <= 1;
   drun1 <= 1;
   bp <= 16'hffff;
end else begin
   if(cpu_addr == bp && cpu_r) { drun, drun1 } <= 0;
   else drun <= drun1;
   if((dr | dw) && (addr[3:1] == 3'h3)) begin
      drun <= !dr & dw;
      drun1 <= !dr & dw & data[12];
   end
   if(dw && addr[3:1] == 3'h2) bp <= data;
end

endmodule
'endif
```

⟨*debugging*⟩≡
```
'ifdef DEBUGGING
if(dw) casez(daddr)
   3'h0: { sp, T } <= { spdec, din };
   3'h1: { rp, R } <= { rpdec, din };
   3'h3: { c, state, sp, rp } <=
           { din[10:8],
             din[sdep+3:4], din[rdep-1:0] };
   3'h4: P <= din;
   3'h5: T <= din;
   3'h6: R <= din;
   3'h7: I <= din;
endcase
if(dr) casez(daddr)
   3'h0: sp <= spinc;
   3'h1: rp <= rpinc;
endcase
'endif
```

⟨*debugging read*⟩≡

```
'ifdef DEBUGGING
reg 'L dout;

always @(daddr or dr or run or P or T or R or I or
        state or sp or rp or c or N or toR or bp)
'ifndef FPGA
if(!dr || run) dout <= 'hz;
'else
if(!dr || run) dout <= 'h0;
'endif
else casez(daddr)
   3'h0: dout <= N;
   3'h1: dout <= toR;
   3'h2: dout <= bp;
   3'h3: dout <= { run, 4'h0, c, state,
                   {4-sdep{1'b0}}, sp,
                   {4-rdep{1'b0}}, rp };
   3'h4: dout <= P;
   3'h5: dout <= T;
   3'h6: dout <= R;
   3'h7: dout <= I;
endcase
'endif
```

⟨*debugging-ports*⟩≡

```
'ifdef DEBUGGING
   input [2:0] daddr;
   input dr, dw;
   input 'L din, bp;
   output 'L dout;
'endif
```

⟨*dbg senselist*⟩≡

```
'ifdef DEBUGGING
or run or dw or daddr
'endif
```

⟨*stack debugging*⟩≡

```
'ifdef DEBUGGING
if(!run && dw) casez(daddr)
   3'h0: dpush <= 1;
   3'h1: rpush <= 1;
endcase
'endif
```

3.3 ALU

The ALU just computes the sum with possible carry-ins, the logical operations, and a zero flag. It would be possible to share common resources (the XORs of the full adder could also compute the XOR operation, and the carry propagation logic could compute OR and AND), but this optimization is left to the synthesis tool.

⟨*ALU*⟩≡

```
module alu(res, carry, zero, T, N, c, inst);
    ⟨ALU ports⟩

    wire      'L r1, r2;
    wire [l:0]  carries;

    assign #1 r1 = T ^ N ^ carries;
    assign #1 r2 = (T & N) |
                   (T & carries'L) |
                   (N & carries'L);
    assign #1 carries =
        prop ? { r2[l-1:0], (c | selr) & andor }
             : { c, {(l){andor}}};
    assign #1 res = (selr & ~prop) ? r2 : r1;
    assign #1 carry = carries[l];
    assign #1 zero = ~|T;
endmodule // alu
```

The ALU has ports T and N, carry in, and the lowest 3 bits of the instruction as input, a result, carry out, and test for zero as output.

⟨*ALU ports*⟩≡

```
parameter l=16;
input 'L T, N;
input c;
input [2:0] inst;
output 'L res;
output carry, zero;

wire prop, andor, selr;

assign #1 { prop, selr, andor } = inst;
```

3.4 Stacks

The stacks are modeled as block RAM in the FPGA. Therefore, they should have only one port, since these block RAMs are available even in small FPGAs. In an ASIC, this sort of stack is implemented with latches. Here it's possible to separate read and write port (also for FPGAs that support dual-ported RAM), and save the multiplexer for spset.

⟨*Stack*⟩≡

```
  module stack(clk, sp, spdec, push, scan, in, out);
     parameter dep=2, l=16;
     input clk, push, scan;
     input [dep-1:0] sp, spdec;
     input `L in;
     output `L out;
`ifdef SYNCSTACK
// ugly hack to have the same code running
// on a Cyclone and an Apex
     reg `L sm0, sm1, sm2, sm3;
     always @(posedge clk)
       if(push)
         case(spdec)
           2'b00: sm0 <= in;
           2'b01: sm1 <= in;
           2'b10: sm2 <= in;
           2'b11: sm3 <= in;
         endcase

     assign out = sp[1] ? (sp[0] ? sm3 : sm2)
                        : (sp[0] ? sm1 : sm0);
`else
     wire [dep-1:0] #1 spset = spdec;
     wire #1 write = push & ~clk;
     wire `L #1 ind = in;
     reg `L stackmem[0:(1<<dep)-1];

`ifndef FPGA
   always @(write or spset or ind or scan)
      if(scan) begin
         stackmem[0] <= ind;
         stackmem[1] <= ind;
         stackmem[2] <= ind;
         stackmem[3] <= ind;
      end else if(write) stackmem[spset] <= ind;
`else
   always @(posedge clk)
      if(push)
         stackmem[spset] <= #1 ind;
`endif

   assign #1 out = stackmem[sp];
`endif
  endmodule // stack
```

References

[1] *c18 ColorForth Compiler,* Chuck Moore, 17th Euro-
     Forth Conference Proceedings, 2001