Aardvark - 8-bit Computer Processor Design

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1 ABSTRACT

Employing a subset of MIPS ISA, an 8-bit processor was designed using Verilog language. Each instruction is set to 1-byte, or 8-bit, length, and the main memory is word addressable while the instruction memory is byte addressable. There are 4 addressable registers: $s1 (00), $s2 (01), $sp (10) and $ra (11). Two other registers in the register file, $slt_0 and $slt_1, cannot be addressed directly, but may be well utilized for jumping (beq instruction). All registers are initialized at 0, while the $sp pointer is initialized at 0xFF (255 in decimal), which is the top of the memory stack.

2 MEMORY

The memory is byte addressable, since all registers can only carry 8 bits and each instruction has 8 bits. There are three sections of the memory stack, the text (0x00 - 0x4B), the data (0x4C - 0x4F), and the stack (0x50 - 0xFF). The allocation of text section is determined to be 64 bytes of instruction because the programs presented in general involve at most 28 lines, and as the maximum 64 was enough. The data section is limited to only 4 global bytes in general no more than 4 arguments will be taken for most programs (unless very large programs, which are not considered for this processor).

Since the fact that a pseudo-instruction–load address("la")–needs to handle loading of data into stack, the assembler was written for this particular processor. If a programmer declared a global variable in the data section of the memory, the pseudo instruction would need to be expanded into the instructions available in the core instruction set. In the worst case scenario, each "la" command would need to be replaced by 16 core instructions. Since the text section can only occupy at most 76 bytes of instructions, there could only be at most 4 bytes for global data, assuming each data is one byte.

3 CORE INSTRUCTION SET

INSTRUCTION		FORMAT	OPERATIONS	OPCODE	FUNCT
ADD	add	R	R[rt] = R[rs] + R[rt]	000	1
NAND	nand	R	R[rt] = NAND(R[rs],R[rt])	001	1
SET LESS THAN (slt_0)	slt_0	R	R[rs] < R[rt] ? 1 : 0	010	0
SET LESS THAN (slt_1)	slt_1	R	R[rs] < R[rt] ? 1 : 0	010	1
SHIFT LEFT	sl	R	R[rs] = R[rt] << 1	011	0
SHIFT RIGHT	sr	R	R[rs] = R[rt] >> 1	011	1
LOAD WORD	lw	I	R[rs] = Mem(R[sp] + immediate)	100	0
SAVE WORD	sw	I	Mem(R[sp] + immediate) = R[rs]	100	1
ADDI	addi	I	R[rs] = R[rs] + immediate	101	0
BRANCH IF EQUAL	beq	J	if R[slt_0]=R[slt_1]; PC = PC+immediate	110	n/a
JUMP AND LINK	jal	J	R[ra]=PC+1; PC = PC+immediate	111	n/a
JUMP REGISTER	jr	JR	PC = R[ra]	*101	1

* jump register can only jump to R[ra] and has the instruction as 00010011.

4 BASIC INSTRUCTION FORMAT

Type	7	6	5	4	3	2	1	0
R	opcode			func	rs		rt	
I	opcode			func	immediate		rs	
J	opcode			PC relative immediate				
JR	1	0	1	1	0	0	1	1

5 COMPILER

6 PROCESSOR DIAGRAM

Controlpath logic table

instruction	type	jctrl	jalctrl	jrctrl	beqctrl	sltctrl	ractrl	nextctrl	memwrite	memread	memtoreg	ALUop	ALUsrc	regwrite
add	R	0	0	0	0	00	0	00	0	0	00	000	0	1
nand	R	0	0	0	0	00	0	00	0	0	00	001	0	1
slt_0	R	0	0	0	0	10	0	00	0	0	00	010	0	1
slt_1	R	0	0	0	0	11	0	00	0	0	00	010	0	1
sl	R	0	0	0	0	00	0	00	0	0	00	011	0	1
sr	R	0	0	0	0	00	0	00	0	0	00	100	0	1
lw	I	0	0	0	0	00	0	01	0	1	01	111	1	1
sw	I	0	0	0	0	00	0	01	1	0	00	111	1	0
addi	I	0	0	0	0	00	0	00	0	0	00	100	1	1
jr	JR	0	0	1	0	00	1	00	0	0	00	000	0	0
beq	J	1	1	0	1	00	0	00	0	0	00	101	0	0
jal	J	0	1	0	0	00	0	10	0	0	10	000	0	0

7 SAMPLE CODE

To demonstrate the functionality of the instruction set, three sets of codes were written. The first piece of code demonstrates basic arithmetic operations, including addition, subtraction, multiplication and division. The second and third sets of code demonstrates the summation from 1 to 10. The former performs the procedure recursively, the second performs the procedure non-recursively. Complementary C code is also provided for comparison.

7.1 ARITHMETIC CODE

7.1.1 Arithmetic Code in C

```
int mult(int a, int b)
  {
      int c = a * b;
      return c;
  }
  int div(int a, int b)
  {
      int c = a / b;
      return c;
  }
```

7.1.2 Arithmetic Code in Assembly

```
.data
.byte num1 2
.byte num2 3
.text
la $sp num1
lw 0 $s1
lw 1 $s2
nand $sp $ra
sw 0 $s1
lw -1 $s1
addi -1 $sp
jal MULT
ADDITION: lw 1 $s2
add $s1 $s2
lw 0 $s2
MULT: addi -1 $s2
sw 0 $s2
sw -1 $ra
slt_0 $ra $s2
beq ADDITION
addi -1 $sp
sw 0 $s1
```

```
#a = $s1, b = $s2
```

```
sw 0, $ra
sw 1, $ra
sw 2, $s2
sw 3, $s3

subtraction:
lw 3, $s1
nand $s2, $s2
addi 1, $s2
add $s1, $s2
sw 3, $s1

division:
lw 3, $s2 #check if it has subtracted enough times
slt_0 $ra, $s2 # 0 < sum
lw 1, $s1
addi 1, $s1
sw 1, $s1
lw 2, $s2 #put b into s2 for subtraction
beq subtraction
lw 1, $s1
addi -1, $s1 #it always overshoots by one
sw 1, $s1
lw 1, $ra
```

7.2 NON-RECURSIVE CODE

7.2.1 Non-Recursive Code in C

```
function(int n)
  {
      int i, sum;
      int n = 10;
      for (i = 0; i < n; i++)
      {
          sum += i;
      }
  }
```

7.2.2 Non-Recursive Code in Assembly

```
function:

nand $s1, $s1
nand $s2, $s2
sl $s1, $s1
nand $s2 $s1    # i($s2) = 1
sw 0, $s2       # store i
```

```
nand $s1, $s1   #s1 becomes 1
sr $s1, $s1     #initialize sum($s1) = 0
sw 1, $s1       #store sum($s1) into offset 1 of $sp

add $s1, $s2     #n = 1
sl $s1, $s1
sl $s1, $s1
sl $s1, $s1      #n = 2^3 * n
add $s1, $s2     #n = 9
add $s1, $s2     #n($s1) = 10
sw 2, $s1       #save 10 to memory

nand $s1, $s1
nand $s2, $s2
sl $s1, $s1
nand $s1 $s2            # $s1 = 1
sw 3, $s1               #store value 1

LOOP:
lw 2, $s1        #load n
slt_0 $s2, $s1   # i < n
slt_1 $s1, $s2   # i > n
beq END         #if i = n, go to END
lw 0, $s2       #load i
lw 1, $s1       #load sum
add $s1, $s2    #sum($s1) += i
sw 1, $s1
lw 3, $s1
lw 0, $s2       #load i to $s2
add $s2, $s1    # i = i + 1
jal LOOP
END:
lw 1, $s1
```

7.3 RECURSIVE CODE

7.3.1 Recursive Code in C

```
int sum(int n)
  {
      if (n > 1){
          return n+sum(n-1);
      }
      return 1;
  }
```

7.3.2 Recursive Code in Assembly

```
function:
nand $s1, $s1
```

```
nand $s2, $s2
sl $s1, $s1
nand $s2 $s1
nand $s1, $s1          #$s1 = -2
sw 0, $s2              #save n in $s2 to memory

#then follows to sum (recursion)
sum:
add $sp, $s1           #adjust stack for 2 items $s1 = -2
sw 1, $ra              #save return address to memory
sw 2, $s2              #save current n to memory
nand $s1, $s1          #s1 becomes 1
sw 3, $s1              #saves $s1 (= 1)
slt_0 $s1, $s2         #slt_0=n > 1?, 0:1
slt_1 $s2, $s1         #slt_1=n>1?, 0:1
beq END                #if n < 1, jump to L1

nand $s1, $s1          #$s1 = -2
lw  3, $s2             #load 1 into $s2
add $s1, $s2           #$s1 = -1
lw 2, $s2              #load n into $s2
add $s2, $s1           #decrement n by 1
jal sum                #recursive call

lw 3, $s1
add $sp, $s1           #pop 2 items from stack (s1 needs to be 1)
add $sp, $s1
lw 1, $ra              #restore return address
lw 0, $s1              #restore original n to s1
add $s2, $s1           #s2 = s2 + s1
jr $ra                 #return to calling address

END:
jr $ra                 #return 0 if n is not > 1
```