

JFEGS: a virtual processor for the DE1-SoC board

Yet another revolutionary product that computes the Fibonacci sequence, designed by Joost Buursink (s2790882), Fabian Widlund (s3100235), Emil Imhagen (s3108139), Guus Branderhorst (s2795132), and Stach Redeker (s2758695).

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Table of contents

- [Introduction](#)
- [Instruction format](#)
- [Example application](#)
- [Parts of the processor](#)
- [Installation and usage](#)
- [Synthesis results](#)
- [Contributions overview](#)
- [Future improvements](#)
- [Conclusion](#)
- [References and acknowledgements](#)

Introduction

JFEGS is a virtual processor designed in VHDL for the Altera System-on-Chip (SoC) FPGA. The processor can be compiled using ModelSim and synthesized using Quartus. Various requirements were set. We discussed those in our [project plan](#).

In this documentation file, we aim to elaborate on the workings of our virtual processor. This document can also serve as a starting point for people who wants to write programs for our system. First, we discuss the instruction format and our example application. After that, we dig deeper into our processor and give a brief overview of the workings of various important components. Lastly, we provide an installation guide and make recommendations for further improvements.

Instruction format

The minimal instruction length to cover all the wanted instructions is 17 bits. In order to be able to convert the instructions into hexadecimal, we shall use an instruction length of 20 bits.

Branch instructions

Op1	Op2	Address (9 bits)	unused (7 bits)
00	XX	MMMMMMMMM	0000000

Instruction	Op2
ba	00
beq	01
bne	10
bneg	11

Memory instructions

Op1	Op2	Address (9 bits)	%rd/%rs (4 bits)	unused (3 bits)
01	YY	MMMMMMMMM	RRRR	000

Instruction	Op2
ld	00
st	01
ldb	10
stb	11

Arithmetic instructions

Op1	Op2	cc	rr	%rd (4 bits)	simm10 (10 bits)
10	ZZ	C	0	RRRR	ssssssssss

Op1	Op2	cc	rr	%rs (4 bits)	%rd (4 bits)	unused (6 bits)
10	ZZ	C	1	RRRR	RRRR	000000

Instruction	Op2	cc
and	00	0
or	01	0
add	10	0
shift	11	-
andcc	00	1
orcc	01	1
addcc	10	1

Miscellaneous instructions

display : displays a register value on the seven segments displays

Op1	Op2	%rs (4 bits)	unused (12 bits)
11	00	RRRR	000000000000

readIO : reads the current state of the switches and stores it in a register

Op1	Op2	%rd (4 bits)	unused (12 bits)
11	01	RRRR	000000000000

halt : stops the program

Op1	Op2	unused 1s (16 bits)
11	11	1111111111111111

Example application

The processor is able to compute the Fibonacci sequence. The Fibonacci sequence can be defined in assembly as:

```
.begin
.org 0
add %r0, %r0, %r1
add %r0, 1, %r2
fun: add %r1, %r2, %r3
add %r0, %r2, %r1
add %r0, %r3, %r2
ba fun
.end
```

However, to showcase the full potential of our product, we designed an extended Fibonacci application that uses the majority of the functionality of our instruction set. Also, observe that a two-address machine cannot handle instructions that use three registers. Hence, our application is rewritten such that it only uses a maximum of two registers per instruction.

The example program is able to compute the *n*th Fibonacci number, where *n* is inputted by the user using the onboard switches. The application can also halve the result, if the user requires so.

```
readIO %r8                ! let's start with getting user data
add %r9, 255, %r9         ! store 011111111 in %r9
and %r8, %r9, %r9         ! extract the wanted C value
st %r9, [C]              ! store the wanted C value in memory
srl %r8, 8, %r8           ! shift the read IO 8 places to extract the halving bit
st %r8, [H]              ! and store the halving value

ld [H], %r4               ! loads whether or not we want half of the result
add %r2, 1, %r2
add %r6, 1, %r6           ! a 1 need for later
add %r7, 1, %r7           ! a 1 need for later

start: ld [C], %r5         ! keeps track of the iterations
addcc %r5, -1, %r5
st %r5, [C]
bneg ending

and %r0, %r3, %r3         ! clear reg3
add %r2, %r3, %r3         ! adds %r1 to %r2 and stores in %r3
add %r1, %r3, %r3         ! ^^^^
and %r0, %r1, %r1         ! clear reg1
add %r2, %r1, %r1         ! stores %r2 in %r1
and %r0, %r2, %r2         ! clear reg2
add %r3, %r2, %r2         ! %r2 will contain the result
ba start

ending: orcc %r4, %r0, %r0 ! check if we want the full result
be display
andcc %r4, %r6, %r6       ! check if we want half of the result
bne halving

halving: and %r2, %r7, %r7 ! check if the last bit is a 1 (then the number is odd)
srl %r2, 1, %r2           ! divide the result by 2 using a shift right
add %r7, %r2, %r2         ! and add the 1 back if it was odd

display: display %r2
```

```

halt                                ! display the result

C: 0                                ! how many times we should run the function
H: 0                                ! H = 0, not halve; H = 1, halve

```

The program is preloaded in the main memory. It is possible to store multiple programs, when one places them after each other in the memory array.

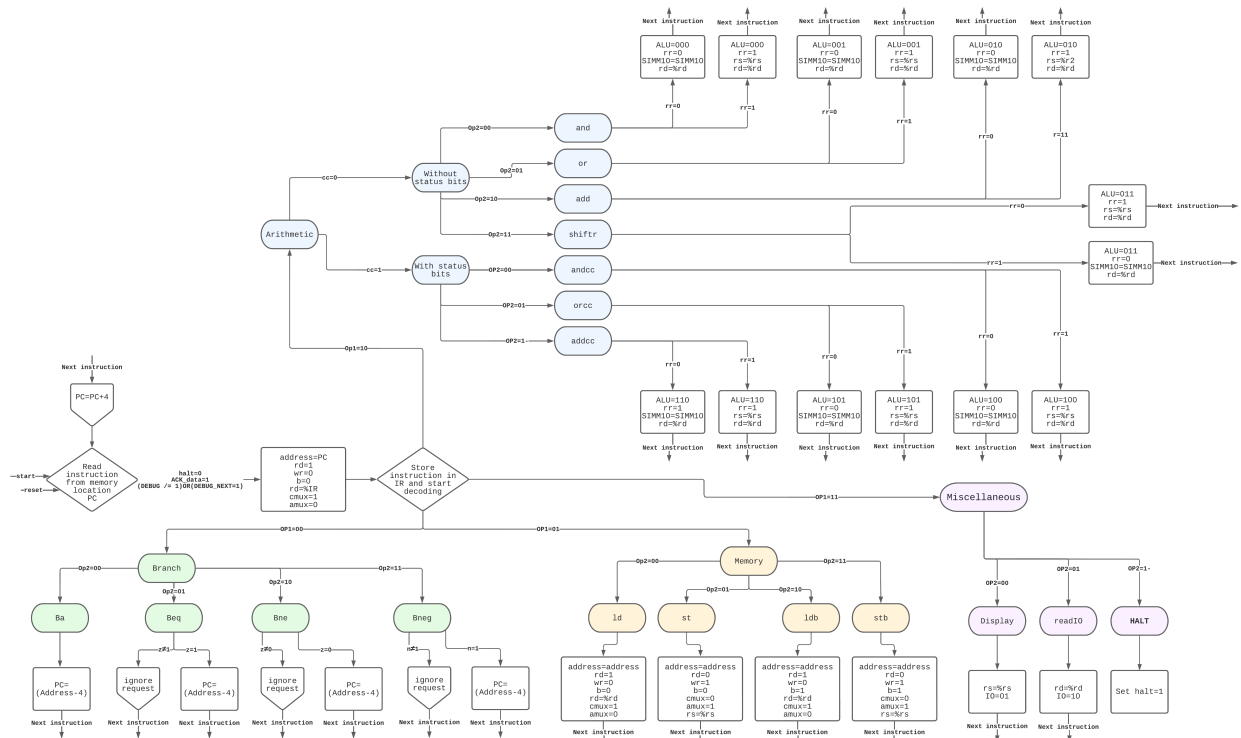
Parts of the processor

This chapter gives a brief summary of different processor parts.

Controller

The controller is the brain of our processor. It is able to perform the fetch-decode-execute cycle. It fetches the instructions from the memory, stores them in the instruction register, and from there, interprets them (decode). After that, the controller sends signals to the other systems in the processor to make sure that the operation gets correctly executed.

We opted for a finite state machine (FSM) over microstore because a FSM is easier and more elegant to implement for smaller instruction sets. Although microstore allows for a more generalizable instruction set, a FSM should suffice in our case.



Datapath and dataflow

There is a significant number of signals that transport data between processes. To avoid confusion, we try to give the signals the same name in every process.

[This table contains the signals that are used to communicate between processes.](#)

The diagram illustrates the CS50 Harvard Architecture, a multi-ported Harvard architecture. Key components and their interconnections are as follows:

- Inputs:** Red arrows indicate external inputs entering the system.
- C Bus MUX:** Selects between inputs and the C bus to feed the C bus.
- C bus:** A 32-bit bus that carries data to and from the General Purpose Registers, Program Counter, Instruction Register, and the C Bus MUX.
- General Purpose Registers (14 pcs):** A set of 14 registers that store data. They are connected to both the C bus and the A bus.
- Program Counter:** Holds the address of the next instruction to be executed. It is connected to the C bus and the A bus.
- Instruction Register:** Holds the current instruction being executed. It is connected to the C bus and the A bus.
- Controller:** Manages the execution of instructions. It receives control signals from the A bus and sends control signals to the C bus, General Purpose Registers, Program Counter, Instruction Register, and the A Bus MUX.
- A bus:** A 32-bit bus that carries data to and from the General Purpose Registers, Program Counter, Instruction Register, the A Bus MUX, the ALU, and the Memory.
- A Bus MUX:** Selects between data from the A bus and the Memory to feed the ALU.
- ALU (Arithmetic Logic Unit):** Performs arithmetic and logic operations on data from the A bus and the Memory. It outputs results to the A bus and condition codes to the controller.
- Memory:** Stores data and instructions. It is connected to the A bus and the ALU.
- Outputs:** Red arrows indicate external outputs leaving the system.

Register	Function
Register 0-13	general purpose
Register 14	program counter
Register 15	instruction register

The ALU receives **F2F1F0** from the controller in order to communicate about the wanted operation.

F2	F1	F0	Operation
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F2	F1	F0	Operation
0	0	0	AND
0	0	1	OR
0	1	0	ADD
0	1	1	Shift right
1	0	0	ANDcc
1	0	1	ORcc
1	1	0	ANDcc
1	1	1	nothing (default value)

The ALU outputs the result, and sets the status bits (n/z/v/c) if required.

ACK_data

`ACK_data` is 1 if the datapath is not performing an operation. This signal is used to send to the controller that a new instruction can be fetched, decoded, and executed.

Memory

We designed the memory based on the von Neumann architecture. The memory is made up of a 2D array consisting of 128 blocks, where each block is made up of 4 bytes. This results in a word size of 32 bits. Hence, a complete instruction can reside in one memory block. The memory is synthesized on the FPGA. It will hence be built using flip-flops.

4 input signals are picked up by the memory. These inputs are `ld`, `st`, `b`, and `address`. We also use a `data-in` and `data-out` signal. `ld` and `st` tell the memory if we want to read or write respectively. These are used in combination with `b`, which tells us if we want to address bytes separately. The memory is able to perform 4 different operations. These operations are:

ld	st	b	Operation
1		1	store the selected memory address in the 8 least significant bits of <code>data-out</code>
	1	1	store the 8 least significant bits of <code>data-in</code> in memory at the selected address
1		0	store an entire word from memory in <code>data-out</code>
	1	0	store <code>data-in</code> in 4 sequential bytes in memory

IO

The DE1-SoC board has 10 switches, 10 LEDs, 4 momentary push buttons, and 6 seven segments displays. We connected the following functions to the onboard inputs:

Input	Function
Button 0	reset
Button 1	next instruction (used during debugging)
Button 2	load an address (used during debugging)

Input	Function
Button 3	unused
Switch 0-8	input variables for the program (during normal operation), input memory address (during debugging)
Switch 9	activate debugging mode

And we connected the following functions to the onboard outputs:

Output	Function
LED 0	c
LED 1	v
LED 2	z
LED 3	n
LED 4	rd
LED 5	wr
LED 6-9	unused
seven segment displays	output of the application (during operation), memory contents (during debugging)

Debugging

In the requirements, we stated that we should implement a debug mode. If the debug mode is active, the user should be able to step through the program one line at a time. Also, the user shall be able to load the contents of a memory address and display it using the seven-segment displays on the FPGA.

Observe that we can pause a program by stopping the controller in its fetch-decode-execute cycle. To accomplish this, we replaced

```
ELSIF (rising_edge(clk)) AND (halt = '0') AND (ACK_data = '1') THEN
```

with

```
ELSIF (rising_edge(clk)) AND (halt = '0') AND (ACK_data = '1') AND ((DEBUG /= '1') OR (DEBUG_NEXT = '1')) THEN
```

It can be seen that we added two new signals. `DEBUG` is 1 if the debug switch is turned on. `DEBUG_NEXT` is 1 for exactly 1 clock cycle when a user presses the 'next line' button.

debugging_facilitators

One might wonder how we set `DEBUG_NEXT` to 1 for exactly 1 clock cycle when the user presses the button. The `DEBUG_NEXT` signal shall be an asynchronous input to the controller. Hence, we opted for a dedicated process `debugging_facilitators` that handles this input and transforms it to the required signal. `debugging_facilitators` also produces the signals for the `rd` and `wr` LEDs.

debugging_display

`debugging_display` sends the required signals to the displays and LEDs.

Installation and usage

Use the following files for compilation in ModelSim. These files can be compiled using the Auto Generate compile order function in ModelSim:

```
controller.vhd
datapath.vhd
debugging.vhd
debugging_display.vhd
debugging_facilitators..vhd
io.vhd
JFEFS.vhd
memory.vhd
registerfile.vhd
utilities.vhd
```

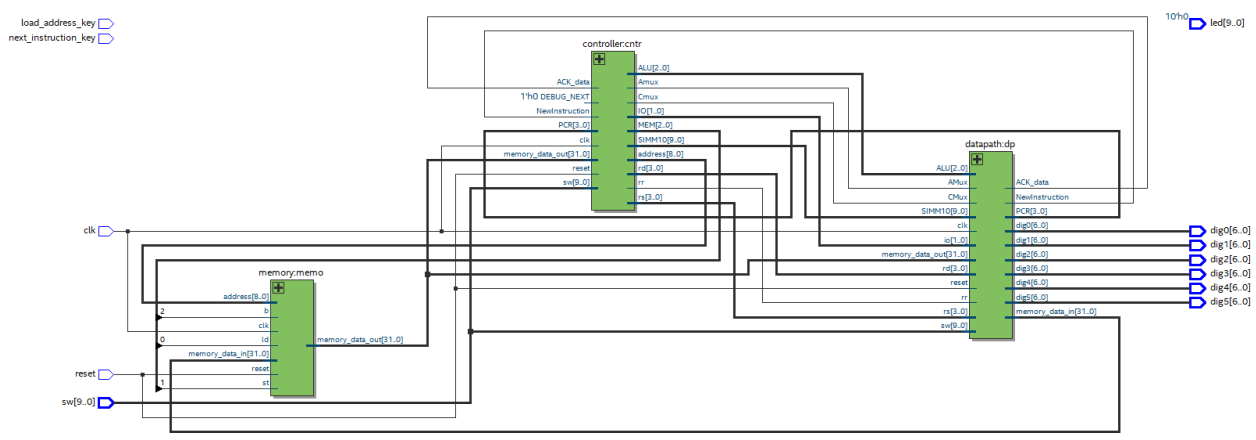
Run `jfe fs.do` to verify the result. The input of the switches is defined in the do file. In register `%r2`, at the end, the value `494` should be stores. The displays show `494` in hexadecimal, which is `1EE`.

Use the following files for synthesis in Quartus:

```
JFEFS.qsf
controller.vhd
datapath.vhd
debugging.vhd
debugging_display.vhd
debugging_facilitators..vhd
io.vhd
JFEFS.vhd
memory.vhd
registerfile.vhd
utilities.vhd
```

Synthesis results

If synthesized correctly, the code produces the following RTL view:



Contributions overview

Member	Work
Joost Buursink	Joost was the lead developer of the memory. He also designed most of the datapath.
Fabian Widlund	Fabian worked on the datapath, the global port map, and parts of the final presentation.
Emil Imhagen	Emil worked on debugging, IO, and the global port map.
Guus Branderhorst	Guus designed the controller (in collaboration with Stach) and helped with the datapath.
Stach Redeker	Stach designed the controller (in collaboration with Guus), worked on the debugging/IO, and wrote the majority of the documentation.

Future improvements

- ☐ Making debugging work (at the moment, debugging does not work in simulation).
- ☐ Display the Fibonacci values in decimal instead of hexadecimal.
- ☐ A nice-to-have extra instruction would be a delay function (or another way to directly access the clock using the instruction set).

Conclusion

During this project, we developed a virtual processor that can be synthesized on the DE1-SoC board. The virtual processor is designed using VHDL and ships with an application that is able to compute the Fibonacci sequence.

References and acknowledgements

Bert van Molenkamp has released a [VHDL description of the ARC processor](#). Although the ARC processor is a three address machine, the overall code structuring was proven to be quite helpful during our project. Bert made his code open source and freely available. We will do the same, such that both systems can work as a base for new research and development.