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# **VexiiRiscv Documentation**

**VexiiRiscv contributors**

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Welcome to VexiiRiscv's documentation!



## INTRODUCTION

### 1.1 About VexiiRiscv

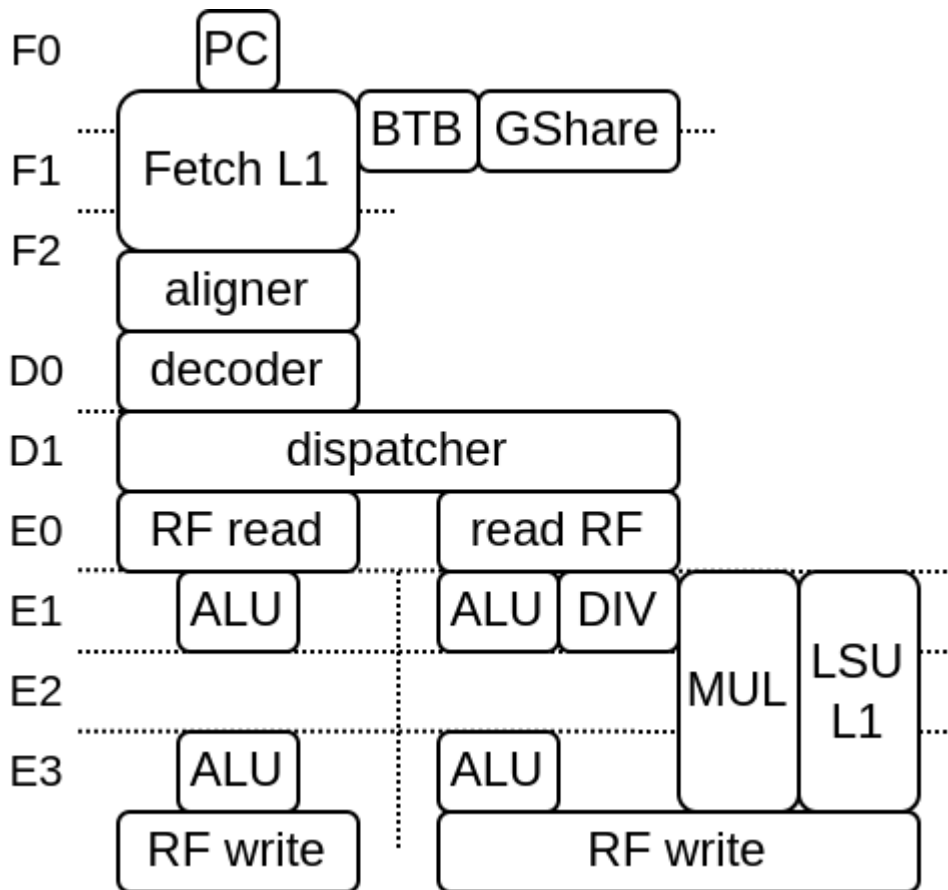
VexiiRiscv is a from scratch second iteration of VexRiscv, with the following goals :

- RISCv 32/64 bits IMAFDC
- Could start around as small as VexRiscv, but could scale further in performance
- Optional late-alu
- Optional multi issue
- Optional multi threading
- Providing a cleaner implementation, getting ride of the technical debt, especially the frontend
- Proper branch prediction
- ...

On this date (08/03/2024) the status is :

- rv 32/64 imacsu supported
- Can run baremetal benchmarks (2.50 dhrystone/mhz, 5.24 coremark/mhz)
- single/dual issue supported
- late-alu supported
- BTB/RAS/GShare branch prediction supported
- MMU SV32/SV39 supported
- can run linux/buildroot in simulation
- LSU store buffer supported

Here is a diagram with 2 issue / early+late alu / 6 stages configuration (note that the pipeline structure can vary a lot):



## 1.2 Navigating the code

Here are a few key / typical code examples :

- The CPU toplevel `src/main/scala/vexiiriscv/VexiiRiscv.scala`
- A cpu configuration generator : `dev/src/main/scala/vexiiriscv/Param.scala`
- Some globally shared definitions : `src/main/scala/vexiiriscv/Global.scala`
- Integer ALU plugin ; `src/main/scala/vexiiriscv/execute/IntAluPlugin.scala`

Also on quite important one is to use a text editor / IDE which support curly brace folding and to start with them fully folded, as the code extensively used nested structures.

## 1.3 Check list

Here is a list of important assumptions and things to know about :

- trap/flush/pc request from the pipeline, once asserted one cycle can not be undone. This also mean that while a given instruction is stuck somewhere, if that instruction did raised on of those request, nothing should change the execution path. For instance, a sudden cache line refill completion should not lift the request from the LSU asking a redo (due to cache refill hazard).
- In the execute pipeline, `stage.up(RS1/RS2)` is the value to be used, while `stage.down(RS1/RS2)` should not be used, as it implement the bypassing for the next stage
- `Fetch.ctrl(0)` isn't persistent.



## 1.4 About VexRiscv (not VexiiRiscv)

There is few reasons why VexiiRiscv exists instead of doing incremental upgrade on VexRiscv

- Mostly, all the VexRiscv parts could be subject for upgrades
- VexRiscv frontend / branch prediction is quite messy
- The whole VexRiscv pipeline would have need a complete overhaul in oder to support multiple issue / late-alu
- The VexRiscv plugin system has hits some limits
- VexRiscv accumulated quite a bit of technical debt over time (2017)
- The VexRiscv data cache being write though start to create issues the faster the frequency goes (DRAM can't follow)
- The VexRiscv verification infrastructure based on its own golden model isn't great.

So, enough is enough, it was time to start fresh :D



## FRAMEWORK

### 2.1 Dependencies

VexRiscv is based on a few tools / API

- Scala : Which will take care of the elaboration
- SpinalHDL : Which provide a hardware description API
- Plugin : Which are used to inject hardware in the CPU
- Fiber : Which allows to define elaboration threads in the plugins
- Retainer : Which allows to block the execution of the elaboration threads waiting on it
- Database : Which specify a shared scope for all the plugins to share elaboration time stuff
- spinal.lib.misc.pipeline : Which allow to pipeline things in a very dynamic manner.
- spinal.lib.logic : Which provide Quine McCluskey to generate logic decoders from the elaboration time specifications

### 2.2 Scala / SpinalHDL

This combination allows to go way beyond what regular HDL allows in terms of hardware description capabilities. You can find some documentation about SpinalHDL here :

- <https://spinalhdl.github.io/SpinalDoc-RTD/master/index.html>

### 2.3 Plugin

One main design aspect of VexiiRiscv is that all its hardware is defined inside plugins. When you want to instantiate a VexiiRiscv CPU, you “only” need to provide a list of plugins as parameters. So, plugins can be seen as both parameters and hardware definition from a VexiiRiscv perspective.

So it is quite different from the regular HDL component/module paradigm. Here are the advantages of this approach :

- The CPU can be extended without modifying its core source code, just add a new plugin in the parameters
- You can swap a specific implementation for another just by swapping plugin in the parameter list. (ex branch prediction, mul/div, ...)
- It is decentralised by nature, you don't have a fat toplevel of doom, software interface between plugins can be used to negotiate things during elaboration time.

The plugins can fork elaboration threads which cover 2 phases :

- setup phase : where plugins can acquire elaboration locks on each others

- build phase : where plugins can negotiate between each others and generate hardware

### 2.3.1 Simple all-in-one example

Here is a simple example :

```
import spinal.core._
import spinal.lib.misc.plugin._
import vexiiriscv._
import scala.collection.mutable.ArrayBuffer

// Define a new plugin kind
class FixedOutputPlugin extends FiberPlugin{
  // Define a build phase elaboration thread
  val logic = during build new Area{
    val port = out UInt(8 bits)
    port := 42
  }
}

object Gen extends App{
  // Generate the verilog
  SpinalVerilog{
    val plugins = ArrayBuffer[FiberPlugin]()
    plugins += new FixedOutputPlugin()
    VexiiRiscv(plugins)
  }
}
```

Will generate

```
module VexiiRiscv (
  output wire [7:0]    FixedOutputPlugin_logic_port
);

  assign FixedOutputPlugin_logic_port = 8'h42;

endmodule
```

### 2.3.2 Negotiation example

Here is a example where there a plugin which count the number of hardware event comming from other plugins :

```
import spinal.core._
import spinal.core.fiber.Retainer
import spinal.lib.misc.plugin._
import spinal.lib.CountOne
import vexiiriscv._
import scala.collection.mutable.ArrayBuffer

class EventCounterPlugin extends FiberPlugin{
  val lock = Retainer() // Will allow other plugins to block the elaboration of "logic
  ↪ " thread
  val events = ArrayBuffer[Bool]() // Will allow other plugins to add event sources
  val logic = during build new Area{
    lock.await() // Active blocking
```

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```

    val counter = Reg(UInt(32 bits)) init(0)
    counter := counter + CountOne(events)
  }
}

//For the demo we want to be able to instanciate this plugin multiple times, so we
↳add a prefix parameter
class EventSourcePlugin(prefix : String) extends FiberPlugin{
  withPrefix(prefix)

  // Create a thread starting from the setup phase (this allow to run some code
↳before the build phase, and so lock some other plugins retainers)
  val logic = during setup new Area{
    val ecp = host[EventCounterPlugin] // Search for the single instance of
↳EventCounterPlugin in the plugin pool
    // Generate a lock to prevent the EventCounterPlugin elaboration until we release
↳it.
    // this will allow us to add our localEvent to the ecp.events list
    val ecpLocker = ecp.lock()

    // Wait for the build phase before generating any hardware
    awaitBuild()

    // Here the local event is a input of the VexiiRiscv toplevel (just for the demo)
    val localEvent = in Bool()
    ecp.events += localEvent

    // As everything is done, we now allow the ecp to elaborate itself
    ecpLocker.release()
  }
}

object Gen extends App{
  SpinalVerilog{
    val plugins = ArrayBuffer[FiberPlugin]()
    plugins += new EventCounterPlugin()
    plugins += new EventSourcePlugin("lane0")
    plugins += new EventSourcePlugin("lane1")
    VexiiRiscv(plugins)
  }
}

```

```

module VexiiRiscv (
  input wire      lane0_EventSourcePlugin_logic_localEvent,
  input wire      lane1_EventSourcePlugin_logic_localEvent,
  input wire      clk,
  input wire      reset

);

  wire      [31:0] _zz_EventCounterPlugin_logic_counter;
  reg       [1:0]  _zz_EventCounterPlugin_logic_counter_1;
  wire      [1:0]  _zz_EventCounterPlugin_logic_counter_2;
  reg       [31:0] EventCounterPlugin_logic_counter;

  assign _zz_EventCounterPlugin_logic_counter = {30'd0, _zz_EventCounterPlugin_logic_

```

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```

↪counter_1};
  assign _zz_EventCounterPlugin_logic_counter_2 = {lane1_EventSourcePlugin_logic_
↪localEvent, lane0_EventSourcePlugin_logic_localEvent};
  always @(*) begin
    case(_zz_EventCounterPlugin_logic_counter_2)
      2'b00 : _zz_EventCounterPlugin_logic_counter_1 = 2'b00;
      2'b01 : _zz_EventCounterPlugin_logic_counter_1 = 2'b01;
      2'b10 : _zz_EventCounterPlugin_logic_counter_1 = 2'b01;
      default : _zz_EventCounterPlugin_logic_counter_1 = 2'b10;
    endcase
  end

  always @(posedge clk or posedge reset) begin
    if(reset) begin
      EventCounterPlugin_logic_counter <= 32'h00000000;
    end else begin
      EventCounterPlugin_logic_counter <= (EventCounterPlugin_logic_counter + _zz_
↪EventCounterPlugin_logic_counter);
    end
  end

endmodule

```

## 2.4 Database

Quite a few things behave kinda like variable specific for each VexiiRiscv instance. For instance XLEN, PC\_WIDTH, INSTRUCTION\_WIDTH, ...

So they end up with things that we would like to share between plugins of a given VexiiRiscv instance with the minimum code possible to keep things slim. For that, a “database” was added. You can see it in the VexRiscv toplevel :

```

class VexiiRiscv extends Component{
  val database = new Database
  val host = database on (new PluginHost)
}

```

What it does is that all the plugin thread will run in the context of that database. Allowing the following patterns :

```

import spinal.core._
import spinal.lib.misc.plugin._
import spinal.lib.misc.database.Database.blocking
import vexiiriscv._
import scala.collection.mutable.ArrayBuffer

object Global extends AreaObject{
  val VIRTUAL_WIDTH = blocking[Int] // If accessed while before being set, it will
↪actively block (until set by another thread)
}

class LoadStorePlugin extends FiberPlugin{
  val logic = during build new Area{
    val register = Reg(UInt(Global.VIRTUAL_WIDTH bits))
  }
}

```

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```
}  
  
class MmuPlugin extends FiberPlugin{  
  val logic = during build new Area{  
    Global.VIRTUAL_WIDTH.set(39)  
  }  
}  
  
object Gen extends App{  
  SpinalVerilog{  
    val plugins = ArrayBuffer[FiberPlugin]()  
    plugins += new LoadStorePlugin()  
    plugins += new MmuPlugin()  
    VexiiRiscv(plugins)  
  }  
}
```

## 2.5 Pipeline API

In short, the design use a pipeline API in order to :

- Propagate data into the pipeline automaticaly
- Allow design space exploration with less paine (retiming, moving around the architecture)
- Reduce boiler plate code

More documentation about it in <https://spinalhdl.github.io/SpinalDoc-RTD/master/SpinalHDL/Libraries/Pipeline/index.html>





A few plugins operate in the fetch stage :

- FetchPipelinePlugin
- PcPlugin
- FetchCachelessPlugin
- BtbPlugin
- GSharePlugin
- HistoryPlugin

### 3.1 FetchPipelinePlugin

Provide the pipeline framework for all the fetch related hardware. It use the native `spinal.lib.misc.pipeline` API without any restriction.

### 3.2 PcPlugin

Will :

- implement the fetch program counter register
- inject the program counter in the first fetch stage
- allow other plugin to create “jump” interface allowing to override the PC value

Jump interfaces will impact the PC value injected in the fetch stage in a combinatorial manner to reduce latency.

### 3.3 FetchCachelessPlugin

Will :

- Generate a fetch memory bus
- Connect that memory bus to the fetch pipeline with a response buffer
- Allow out of order memory bus responses (for maximal compatibility)
- Always generate aligned memory accesses

## 3.4 BtbPlugin

See more in the Branch prediction chapter

## 3.5 GSharePlugin

See more in the Branch prediction chapter

## 3.6 HistoryPlugin

Will :

- implement the branch history register
- inject the branch history in the first fetch stage
- allow other plugin to create interface to override the branch history value (on branch prediction / execution)

branch history interfaces will impact the branch history value injected in the fetch stage in a combinatorial manner to reduce latency.

## **DECODE**

A few plugins operate in the fetch stage :

- DecodePipelinePlugin
- AlignerPlugin
- DecoderPlugin
- DispatchPlugin
- DecodePredictionPlugin

### **4.1 DecodePipelinePlugin**

Provide the pipeline framework for all the decode related hardware. It use the `spinal.lib.misc.pipeline` API but implement multiple “lanes” in it.

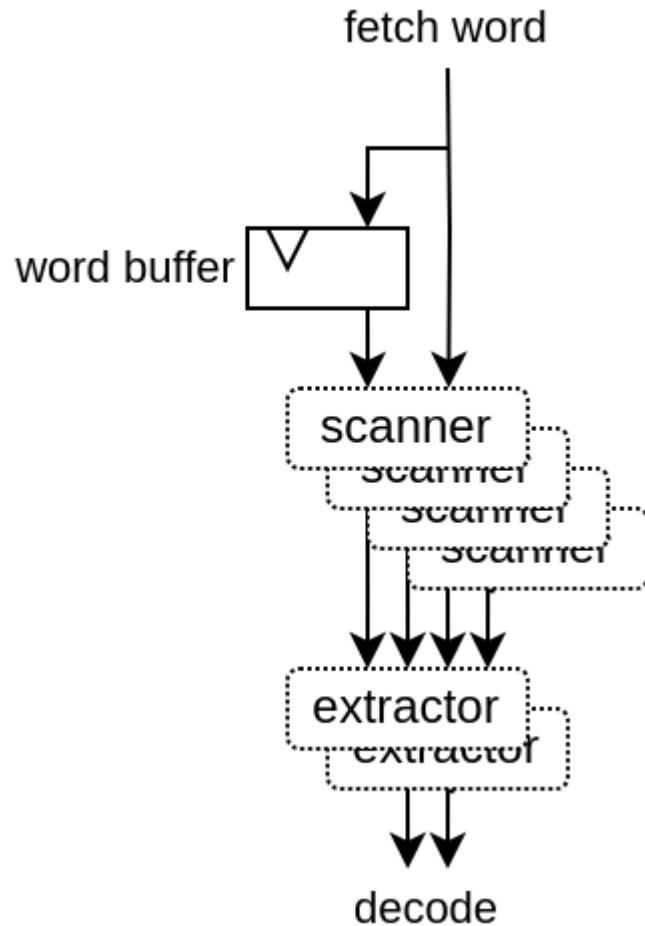
### **4.2 AlignerPlugin**

Decode the words froms the fetch pipeline into aligned instructions in the decode pipeline. Its complexity mostly come from the necessity to support having RVC [and BTB], mostly by adding additional cases to handle.

- 1) RVC allows 32 bits instruction to be unaligned, meaning they can cross between 2 fetched words, so it need to have some internal buffer / states to work.
- 2) The BTB may have predicted (falsly) a jump instruction where there is none, which may cut the fetch of an 32 bits instruction in the middle.

The AlignerPlugin is designed as following :

- Has a internal fetch word buffer in oder to support 32 bits instruction with RVC
- First it scan at every possible instruction position, ex : RVC with 64 bits fetch words => 2x64/16 scanners. Extracting the instruction length, presence of all the instruction data (slices) and necessity to redo the fetch because of a bad BTB prediction.
- Then it has one extractor per decoding lane. They will check the scanner for the firsts valid instructions.
- Then each extractor is feeded into the decoder pipeline.



### 4.3 DecoderPlugin

Will :

- Decode instruction
- Generate illegal instruction exception
- Generate “interrupt” instruction

### 4.4 DecodePredictionPlugin

The purpose of this plugin is to ensure that no branch/jump prediction was made for non branch/jump instructions. In case this is detected, the plugin will just flush the pipeline and set the fetch PC to redo everything, but this time with a “first prediction skip”

See more in the Branch prediction chapter

## 4.5 DispatchPlugin

Will :

- Collect instruction from the end of the decode pipeline
- Try to dispatch them ASAP on the multiple “layers” available

Here is a few explanation about execute lanes and layers :

- A execute lane represent a path toward which an instruction can be executed.
- A execute lane can have one or many layers, which can be used to implement things as early ALU / late ALU
- Each layer will have static a scheduling priority

The DispatchPlugin doesn’t require lanes or layers to be symetric in any way.



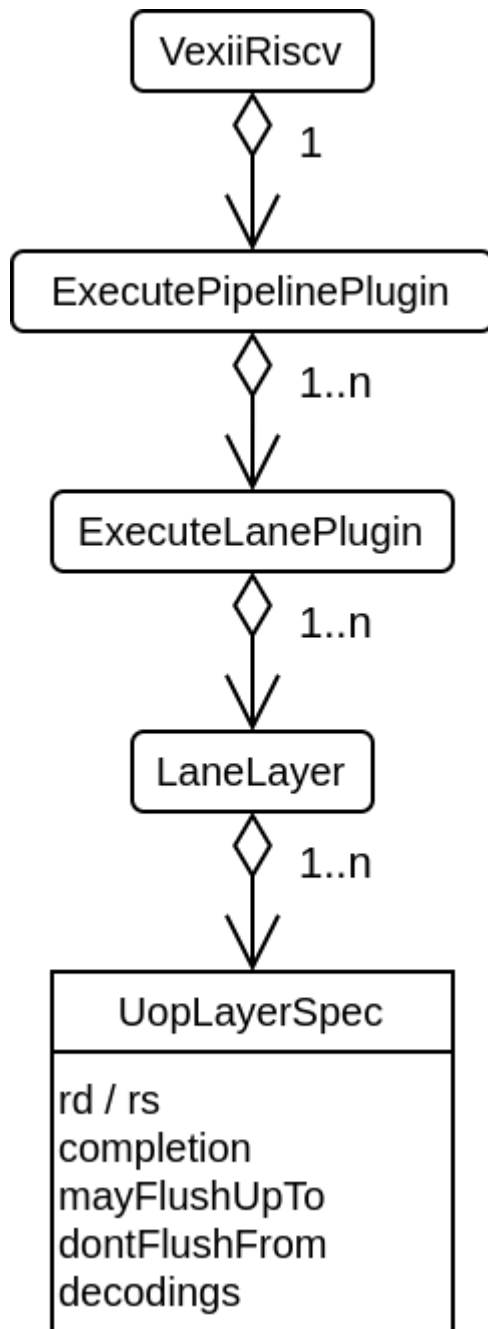
**EXECUTE**

## 5.1 Introduction

The execute pipeline has the following properties :

- Support multiple lane of execution.
- Support multiple implementation of the same instruction on the same lane (late-alu) via the concept of “layer”
- each layer is owned by a given lane
- each layer can implement multiple instructions and store a data model of their requirements.
- The whole pipeline never collapse bubbles, all lanes of every stage move forward together as one.
- Elements of the pipeline are allowed to stop the whole pipeline via a shared freeze interface.

Here is a class diagram :



The main thing about it is that for every uop implementation in the pipeline, there is the elaboration time information for :

- How/where to retrieve the result of the instruction (rd)
- From which point in the pipeline it use which register file (rs)
- From which point in the pipeline the instruction can be considered as done (completion)
- Until which point in the pipeline the instruction may flush younger instructions (mayFlushUpTo)
- From which point in the pipeline the instruction should not be flushed anymore because it already had produced side effects (dontFlushFrom)
- The list of decoded signals/values that the instruction is using (decodings)

The idea is that with all those information, the ExecuteLanePlugin and DispatchPlugin DecodePlugin are able to generate the proper logics to generate a functional pipeline / dispatch / decoder with no hand written hardcoded hardware.



## 5.2 Plugins

### 5.2.1 infrastructures

Many plugins operate in the fetch stage. Some provide infrastructures :

#### **ExecutePipelinePlugin**

Provide the pipeline framework for all the execute related hardware with the following specificities :

- It is based on the `spinal.lib.misc.pipeline` API and can host multiple “lanes” in it.
- For flow control, the lanes can only freeze the whole pipeline
- The pipeline do not collapse bubbles (empty stages)

#### **ExecuteLanePlugin**

Implement an execution lane in the `ExecutePipelinePlugin`

#### **RegFilePlugin**

Implement one register file, with the possibility to create new read / write port on demande

#### **SrcPlugin**

Provide some early integer values which can mux between RS1/RS2 and multiple RISC-V instruction's literal values

#### **RsUnsignedPlugin**

Used by `mul/div` in order to get an unsigned RS1/RS2 value early in the pipeline

#### **IntFormatPlugin**

Allows plugins to write integer values back to the register file through a optional sign extender. It uses `WriteBackPlugin` as value backend.

#### **WriteBackPlugin**

Used by plugins to provide the RD value to write back to the register file

#### **LearnPlugin**

Will collect all interface which provide jump/branch learning interfaces to aggregate them into a single one, which will then be used by branch prediction plugins to learn.

## 5.2.2 Instructions

Some implement regular instructions

### IntAluPlugin

Implement the arithmetic, binary and literal instructions (ADD, SUB, AND, OR, LUI, ...)

### BarrelShifterPlugin

Implement the shift instructions in a non-blocking way (no iterations). Fast but “heavy”.

### BranchPlugin

Will :

- Implement branch/jump instruction
- Correct the PC / History in the case the branch prediction was wrong
- Provide a learn interface to the LearnPlugin

### MulPlugin

- Implement multiplication operation using partial multiplications and then summing their result
- Done over multiple stage
- Can optionally extends the last stage for one cycle in order to buffer the MULH bits

### DivPlugin

- Implement the division/remain
- 2 bits per cycle are solved.
- When it start, it scan for the numerator leading bits for 0, and can skip dividing them (can skip blocks of XLEN/4)

### LsuCachelessPlugin

- Implement load / store through a cacheless memory bus
- Will fork the cmd as soon as fork stage is valid (with no flush)
- Handle backpressure by using a little fifo on the response data

## 5.2.3 Special

Some implement CSR, privileges and special instructions

### CsrAccessPlugin

- Implement the CSR instruction
- Provide an API for other plugins to specify its hardware mapping

### CsrRamPlugin

- Implement a shared on chip ram
- Provide an API which allows to statically allocate space on it
- Provide an API to create read / write ports on it
- Used by various plugins to store the CSR contents in a FPGA efficient way

### PrivilegedPlugin

- Implement the RISCv privileged spec
- Implement the trap buffer / FSM
- Use the CsrRamPlugin to implement various CSR as MTVAL, MTVEC, MEPC, MSCRATCH, ...

### PerformanceCounterPlugin

- Implement the privileged performance counters in a very FPGA way
- Use the CsrRamPlugin to store most of the counter bits
- Use a dedicated 7 bits hardware register per counter
- Once that 7 bits register MSB is set, a FSM will flush it into the CsrRamPlugin

### EnvPlugin

- Implement a few instructions as MRET, SRET, ECALL, EBREAK

## 5.3 Custom instruction

There are multiple ways you can add custom instructions into VexiiRiscv. The following chapter will provide some demo.

### 5.3.1 SIMD add

Let's define a plugin which will implement a SIMD add (4x8bits adder), working on the integer register file.

The plugin will be based on the ExecutionUnitElementSimple which makes implementing ALU plugins simpler. Such a plugin can then be used to compose a given execution lane layer

For instance the Plugin configuration could be :

```
plugins += new SrcPlugin(early0, executeAt = 0, relaxedRs = relaxedSrc)
plugins += new IntAluPlugin(early0, formatAt = 0)
plugins += new BarrelShifterPlugin(early0, formatAt = relaxedShift.toInt)
plugins += new IntFormatPlugin("lane0")
plugins += new BranchPlugin(early0, aluAt = 0, jumpAt = relaxedBranch.toInt, wbAt = 0)
plugins += new SimdAddPlugin(early0) // <- We will implement this plugin
```

## Plugin implementation

Here is an example of how this plugin could be implemented :

- <https://github.com/SpinalHDL/VexiiRiscv/blob/dev/src/main/scala/vexiiriscv/execute/SimdAddPlugin.scala>

```
package vexiiriscv.execute

import spinal.core._
import spinal.lib._
import spinal.lib.pipeline.Stageable
import vexiiriscv.Generate.args
import vexiiriscv.{Global, ParamSimple, VexiiRiscv}
import vexiiriscv.compat.MultiPortWritesSimplifier
import vexiiriscv.riscv.{IntRegFile, RS1, RS2, Riscv}

//This plugin example will add a new instruction named SIMD_ADD which do the
//following :
//
//RD : Regfile Destination, RS : Regfile Source
//RD( 7 downto 0) = RS1( 7 downto 0) + RS2( 7 downto 0)
//RD(16 downto 8) = RS1(16 downto 8) + RS2(16 downto 8)
//RD(23 downto 16) = RS1(23 downto 16) + RS2(23 downto 16)
//RD(31 downto 24) = RS1(31 downto 24) + RS2(31 downto 24)
//
//Instruction encoding :
//00000000-----000-----0001011  <- Custom0 func3=0 func7=0
//      |RS2||RS1|  |RD |
//
//Note : RS1, RS2, RD positions follow the RISC-V spec and are common for all
//instruction of the ISA

object SimdAddPlugin{
  //Define the instruction type and encoding that we will use
  val ADD4 = IntRegFile.TypeR(M"00000000-----000-----0001011")
}

//ExecutionUnitElementSimple is a plugin base class which will integrate itself in a
//execute lane layer
//It provide quite a few utilities to ease the implementation of custom instruction.
//Here we will implement a plugin which provide SIMD add on the register file.
class SimdAddPlugin(val layer : LaneLayer) extends ExecutionUnitElementSimple(layer)
{
  //Here we create an elaboration thread. The Logic class is provided by
  //ExecutionUnitElementSimple to provide functionalities
  val logic = during setup new Logic {
    //Here we could have lock the elaboration of some other plugins (ex CSR), but
    //here we don't need any of that
    //as all is already sorted out in the Logic base class.
    //So we just wait for the build phase
    awaitBuild()

    //Let's assume we only support RV32 for now
    assert(Riscv.XLEN.get == 32)
  }
}
```

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```

//Let's get the hardware interface that we will use to provide the result of our
→ custom instruction
    val wb = newWriteback(ifp, 0)

    //Specify that the current plugin will implement the ADD4 instruction
    val add4 = add(SimdAddPlugin.ADD4).spec

    //We need to specify on which stage we start using the register file values
    add4.addRsSpec(RS1, executeAt = 0)
    add4.addRsSpec(RS2, executeAt = 0)

    //Now that we are done specifying everything about the instructions, we can
→ release the Logic.uopRetainer
    //This will allow a few other plugins to continue their elaboration (ex : decoder,
→ dispatcher, ...)
    uopRetainer.release()

    //Let's define some logic in the execute lane [0]
    val process = new el.Execute(id = 0) {
        //Get the RISC-V RS1/RS2 values from the register file
        val rs1 = el(IntRegFile, RS1).asUInt
        val rs2 = el(IntRegFile, RS2).asUInt

        //Do some computation
        val rd = UInt(32 bits)
        rd( 7 downto  0) := rs1( 7 downto  0) + rs2( 7 downto  0)
        rd(16 downto  8) := rs1(16 downto  8) + rs2(16 downto  8)
        rd(23 downto 16) := rs1(23 downto 16) + rs2(23 downto 16)
        rd(31 downto 24) := rs1(31 downto 24) + rs2(31 downto 24)

        //Provide the computation value for the writeback
        wb.valid := SEL
        wb.payload := rd.asBits
    }
}
}

```

## VexiiRiscv generation

Then, to generate a VexiiRiscv with this new plugin, we could run the following App :

- Bottom of <https://github.com/SpinalHDL/VexiiRiscv/blob/dev/src/main/scala/vexiiriscv/execute/SimdAddPlugin.scala>

```

object VexiiSimdAddGen extends App {
    val param = new ParamSimple()
    val sc = SpinalConfig()

    assert(new scopt.OptionParser[Unit]("VexiiRiscv") {
        help("help").text("prints this usage text")
        param.addOptions(this)
    }.parse(args, Unit).nonEmpty)

    sc.addTransformationPhase(new MultiPortWritesSimplifier)
    val report = sc.generateVerilog {
        val pa = param.pluginsArea()
    }
}

```

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```
pa.plugins += new SimdAddPlugin(pa.early0)
VexiiRiscv(pa.plugins)
}
}
```

To run this App, you can go to the NaxRiscv directory and run :

```
sbt "runMain vexiiriscv.execute.VexiiSimdAddGen"
```

## Software test

Then let's write some assembly test code : (<https://github.com/SpinalHDL/NaxSoftware/tree/849679c70b238ceee021bdfd18eb2e9809e7bdd0/baremetal/simdAdd>)

```
.globl _start
_start:

#include "../driver/riscv_asm.h"
#include "../driver/sim_asm.h"
#include "../driver/custom_asm.h"

//Test 1
li x1, 0x01234567
li x2, 0x01FF01FF
opcode_R(CUSTOM0, 0x0, 0x00, x3, x1, x2) //x3 = ADD4(x1, x2)

//Print result value
li x4, PUT_HEX
sw x3, 0(x4)

//Check result
li x5, 0x02224666
bne x3, x5, fail

j pass

pass:
j pass
fail:
j fail
```

Compile it with

```
make clean rv32im
```

## Simulation

You could run a simulation using this testbench :

- Bottom of <https://github.com/SpinalHDL/VexiiRiscv/blob/dev/src/main/scala/vexiiriscv/execute/SimdAddPlugin.scala>

```
object VexiiSimdAddSim extends App{
  val param = new ParamSimple()
  val testOpt = new TestOptions()

  val genConfig = SpinalConfig()
  genConfig.includeSimulation

  val simConfig = SpinalSimConfig()
  simConfig.withFstWave
  simConfig.withTestFolder
  simConfig.withConfig(genConfig)

  assert(new scopt.OptionParser[Unit]("VexiiRiscv") {
    help("help").text("prints this usage text")
    testOpt.addOptions(this)
    param.addOptions(this)
  }.parse(args, Unit).nonEmpty)

  println(s"With Vexiiriscv parm :\n - ${param.getName()}")
  val compiled = simConfig.compile {
    val pa = param.pluginsArea()
    pa.plugins += new SimdAddPlugin(pa.early0)
    VexiiRiscv(pa.plugins)
  }
  testOpt.test(compiled)
}
```

Which can be run with :

```
sbt "runMain vexiiriscv.execute.VexiiSimdAddSim --load-elf ext/NaxSoftware/baremetal/
↳ simdAdd/build/rv32ima/simdAdd.elf --trace-all --no-rvls-check"
```

Which will output the value 02224666 in the shell and show traces in simWorkspace/VexiiRiscv/test :D

Note that `--no-rvls-check` is required as spike do not implement that custom simdAdd.

## Conclusion

So overall this example didn't introduce how to specify some additional decoding, nor how to define multi-cycle ALU. (TODO). But you can take a look in the IntAluPlugin, ShiftPlugin, DivPlugin, MulPlugin and BranchPlugin which are doing those things using the same ExecutionUnitElementSimple base class.



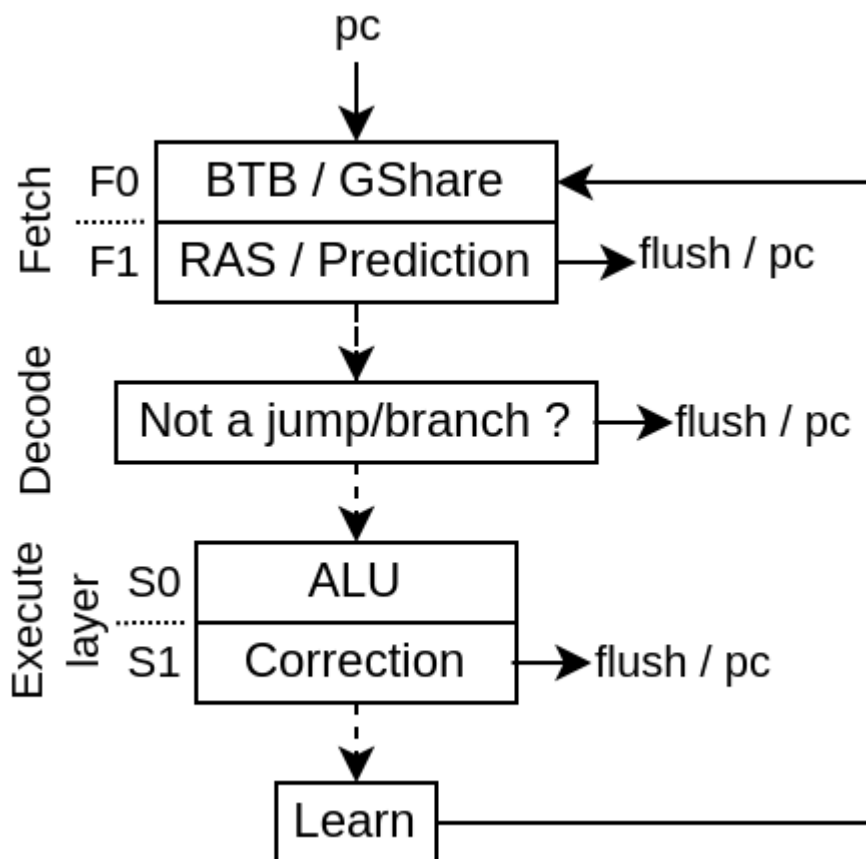


## BRANCH PREDICTION

The branch prediction is implemented as follow :

- During fetch, a BTB, GShare, RAS memory is used to provide an early branch prediction (BtbPlugin / GSharePlugin)
- In Decode, the DecodePredictionPlugin will ensure that no “none jump/branch instruction” predicted as a jump/branch continues down the pipeline.
- In Execute, the prediction made is checked and eventually corrected. Also a stream of data is generated to feed the BTB / GShare memories with good data to learn.

Here is a diagram of the whole architecture :



While it would have been possible in the decode stage to correct some miss prediction from the BTB / RAS, it isn't done to improve timings and reduce Area.

## 6.1 BtbPlugin

Will :

- Implement a branch target buffer in the fetch pipeline
- Implement a return address stack buffer
- Predict which slices of the fetched word are the last slice of a branch/jump
- Predict the branch/jump target
- Use the FetchConditionalPrediction plugin (GSharePlugin) to know if branch should be taken
- Apply the prediction (flush + pc update + history update)
- Learn using the LearnPlugin interface. Only learn on missprediction. To avoid write to read hazard, the fetch stage is blocked when it learn.
- Implement “ways” named chunks which are statically assigned to groups of word’s slices, allowing to predict multiple branch/jump present in the same word

## 6.2 GSharePlugin

Will :

- Implement a FetchConditionalPrediction (GShare flavor)
- Learn using the LearnPlugin interface. Write to read hazard are handled via a bypass
- Will not apply the prediction via flush / pc change, another plugin will do that

## 6.3 DecodePredictionPlugin

The purpose of this plugin is to ensure that no branch/jump prediction was made for non branch/jump instructions. In case this is detected, the plugin will just flush the pipeline and set the fetch PC to redo everything, but this time with a “first prediction skip”

## 6.4 BranchPlugin

Placed in the execute pipeline, it will ensure that the branch prediction was correct, else it correct it. It also generate a learn interface.

## 6.5 LearnPlugin

This plugin will collect all the learn interface (generated by the BranchPlugin) and produce a single stream of learn interface for the BtbPlugin / GShare plugin to use.

## HOW TO USE

### 7.1 Dependencies

On debian :

```
# JAVA JDK
sudo add-apt-repository -y ppa:openjdk-r/ppa
sudo apt-get update
sudo apt-get install openjdk-19-jdk -y # You don't exactly need that version
sudo update-alternatives --config java
sudo update-alternatives --config javac

# Install SBT - https://www.scala-sbt.org/
echo "deb https://repo.scala-sbt.org/scalasbt/debian all main" | sudo tee /etc/apt/
↳sources.list.d/sbt.list
echo "deb https://repo.scala-sbt.org/scalasbt/debian /" | sudo tee /etc/apt/sources.
↳list.d/sbt_old.list
curl -sL "https://keyserver.ubuntu.com/pks/lookup?op=get&
↳search=0x2EE0EA64E40A89B84B2DF73499E82A75642AC823" | sudo apt-key add
sudo apt-get update
sudo apt-get install sbt

# Verilator (optional, for simulations)
sudo apt-get install git make autoconf g++ flex bison
git clone http://git.veripool.org/git/verilator # Only first time
unsetenv VERILATOR_ROOT # For csh; ignore error if on bash
unset VERILATOR_ROOT # For bash
cd verilator
git pull # Make sure we're up-to-date
git checkout v4.216 # You don't exactly need that version
autoconf # Create ./configure script
./configure
make
sudo make install

# Getting a RISC-V toolchain (optional)
version=riscv64-unknown-elf-gcc-8.3.0-2019.08.0-x86_64-linux-ubuntu14
wget -O riscv64-unknown-elf-gcc.tar.gz riscv https://static.dev.sifive.com/dev-tools/
↳$version.tar.gz
tar -xzf riscv64-unknown-elf-gcc.tar.gz
sudo mv $version /opt/riscv
echo 'export PATH=/opt/riscv/bin:$PATH' >> ~/.bashrc

# RVLS / Spike dependencies
sudo apt-get install device-tree-compiler libboost-all-dev
```

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```
# Install ELFIO, used to load elf file in the sim
git clone https://github.com/serge1/ELFIO.git
cd ELFIO
git checkout d251da09a07dff40af0b63b8f6c8ae71d2d1938d # Avoid C++17
sudo cp -R elfio /usr/include
cd .. && rm -rf ELFIO
```

## 7.2 Repo setup

After installing the dependencies (see above) :

```
git clone --recursive https://github.com/SpinalHDL/VexiiRiscv.git
cd VexiiRiscv

# (optional) Compile riscv-isa-sim (spike), used as a golden model during the sim to
↳ check the dut behaviour (lock-step)
cd ext/riscv-isa-sim
mkdir build
cd build
../configure --prefix=$RISCV --enable-commitlog --without-boost --without-boost-asio
↳ --without-boost-regex
make -j$(nproc)
cd ../../..

# (optional) Compile RVLS, (need riscv-isa-sim (spike))
cd ext/rvls
make -j$(nproc)
cd ../../..
```

## 7.3 Generate verilog

```
sbt "Test/runMain vexiiriscv.Generate"
```

You can get a list of the supported parameters via :

```
sbt "Test/runMain vexiiriscv.Generate --help"
--help                prints this usage text
--xlen <value>
--decoders <value>
--lanes <value>
--relaxed-branch
--relaxed-shift
--relaxed-src
--with-mul
--with-div
--with-rva
--with-rvc
--with-supervisor
--with-user
--without-mul
--without-div
--with-mul
```

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```

--with-div
--with-gshare
--with-btb
--with-ras
--with-late-alu
--regfile-async
--regfile-sync
--allow-bypass-from <value>
--performance-counters <value>
--with-fetch-l1
...

```

## 7.4 Run a simulation

Note that Vexiiriscv use mostly an opt-in configuration. So, most performance related configuration are disabled by default.

```

sbt
compile
Test/runMain vexiiriscv.testers.TestBench --with-mul --with-div --load-elf ext/
↳ NaxSoftware/baremetal/dhrystone/build/rv32ima/dhrystone.elf --trace-all

```

This will generate a simWorkspace/VexiiRiscv/test folder which contains :

- test.fst : A wave file which can be open with gtkwave. It shows all the CPU signals
- konata.log : A wave file which can be open with <https://github.com/shioyadan/Konata>, it shows the pipeline behaviour of the CPU
- spike.log : The execution logs of Spike (golden model)
- tracer.log : The execution logs of VexRiscv (Simulation model)

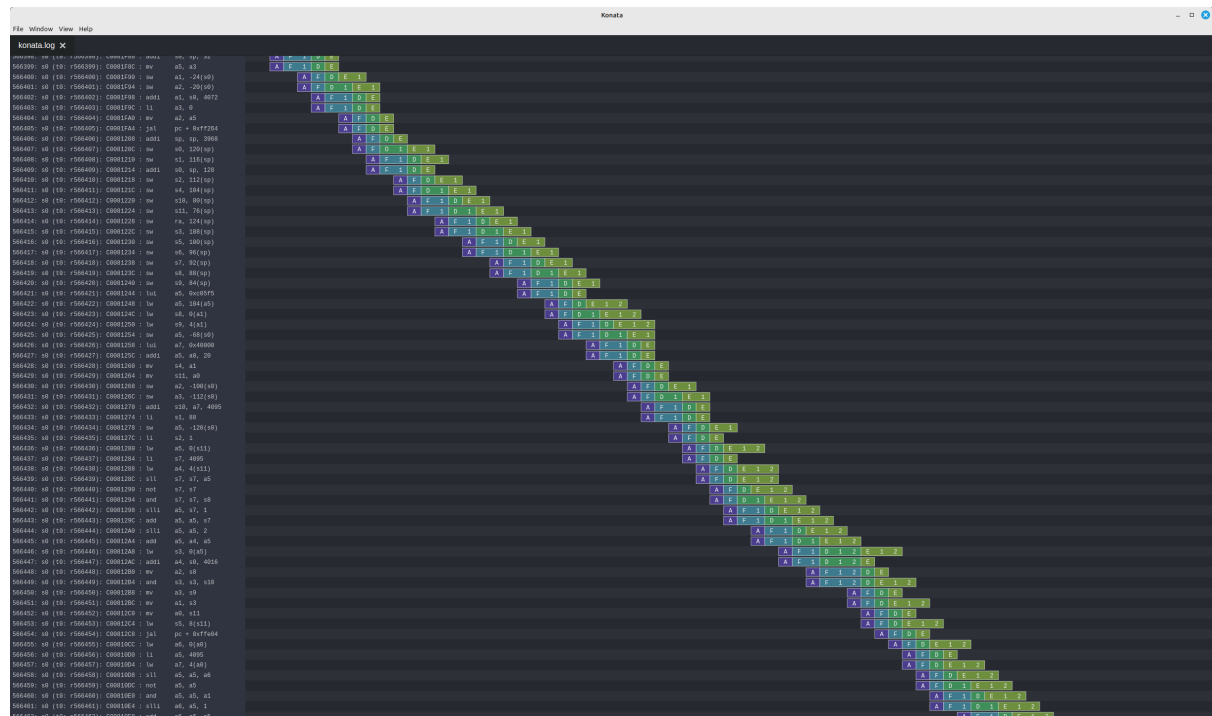
Here is an example of the additional argument you can use to improve the IPC :

```

--with-btb --with-gshare --with-ras --decoders 2 --lanes 2 --with-aligner-buffer --
↳ with-dispatcher-buffer --with-late-alu --regfile-async --allow-bypass-from 0 --div-
↳ radix 4

```

Here is a screen shot of a cache-less VexiiRiscv booting linux :



## PERFORMANCE / AREA / FMAX

It is still very early in the developement, but here are some metrics :

Name	Max IPC
Issue	2
Late ALU	2
BTB / RAS	512 / 4
GShare	4KB
Dhrystone/MHz	2.50
Coremark/MHz	5.24
EmBench	1.62

It is too early for area / fmax metric, there is a lot of design space exploration to do which will trade IPC against FMax / Area.

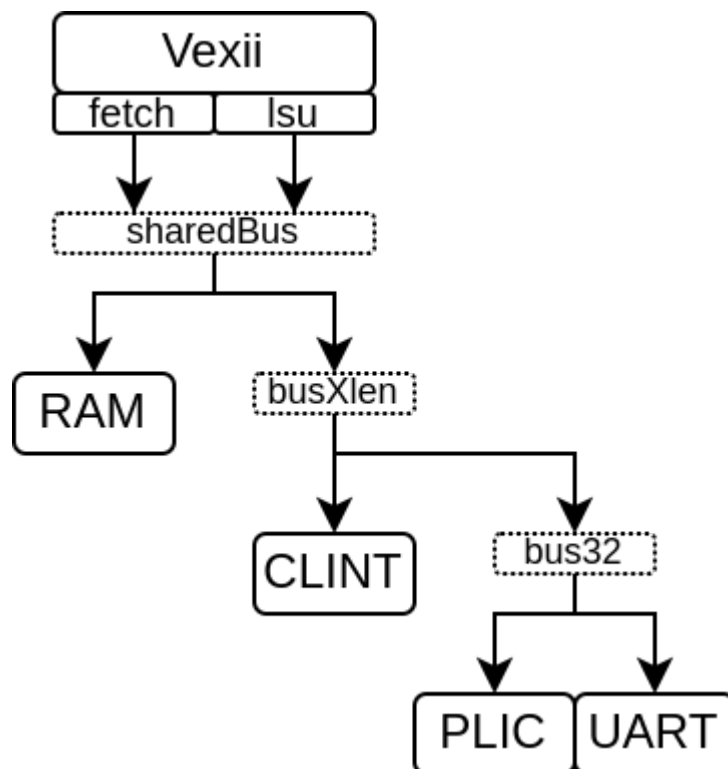




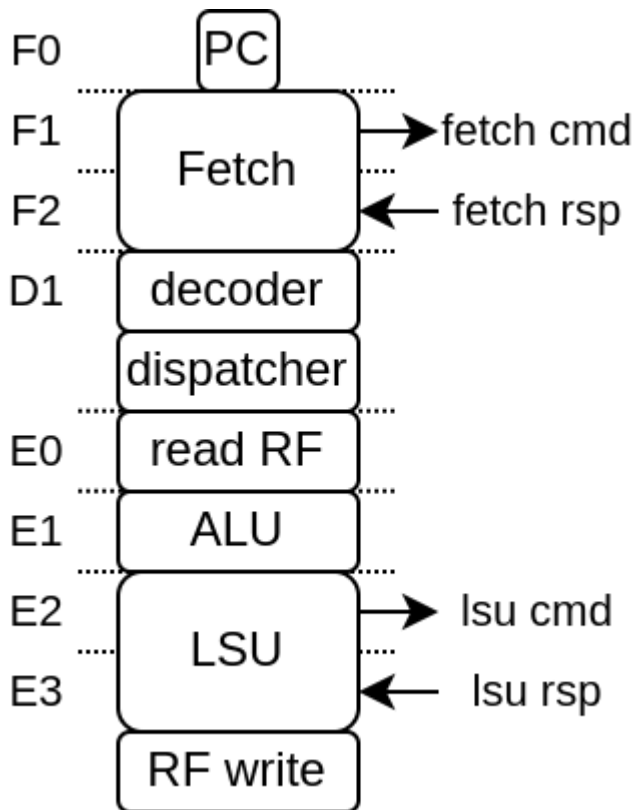
This is currently WIP.

## 9.1 MicroSoc

MicroSoC is a little SoC based on VexiiRiscv and a tilelink interconnect.



Here you can see the default vexiiriscv architecture for this SoC :



Its goals are :

- Provide a simple reference design
- To be a simple and light FPGA SoC
- Target a high frequency of operation, but not a high IPC (by default)

You can find its implementation here <https://github.com/SpinalHDL/VexiiRiscv/blob/dev/src/main/scala/vexiiriscv/soc/demo/MicroSoc.scala>

- *class MicroSoc* is the SoC toplevel
- *object MicroSocGen* is a scala main which can be used to generate the hardware
- *object MicroSocSim* is a simple testbench which integrate the UART, konata tracer, rvls CPU checker.

This SoC is WIP, mainly it need more stuff as a rom, jtag, software and a lot more doc.