

Processing Unit with RISC-V

QueenField

1. INTRODUCTION

A Processing Unit (PU) is an electronic system within a computer that carries out instructions of a program by performing the basic arithmetic, logic, controlling, and I/O operations specified by instructions. Instruction-level parallelism is a measure of how many instructions in a computer can be executed simultaneously. The PU is contained on a single Metal Oxide Semiconductor (MOS) Integrated Circuit (IC).

1.1. HARDWARE

1.2. SOFTWARE

2. PROJECTS

2.1. RISC-V ARCHITECTURE

2.1.1. Library

type:

```
sudo apt install autoconf automake autotools-dev curl python3 libmpc-dev \
libmpfr-dev libgmp-dev gawk build-essential bison flex texinfo gperf \
libtool patchutils bc zlib1g-dev libexpat-dev
```

2.1.2. Toolchain

type:

```
git clone --recursive https://github.com/riscv/riscv-gnu-toolchain
```

```
cd riscv-gnu-toolchain
```

```
./configure --prefix=/opt/riscv-elf-gcc
sudo make
```

```
./configure --prefix=/opt/riscv-elf-gcc
sudo make linux
```

```
./configure --prefix=/opt/riscv-elf-gcc --enable-multilib
sudo make linux
```

```
./configure --prefix=$RISCV
```

```
sudo make linux
sudo make report-linux
```

2.1.3. Software

type:

```
export PATH=/opt/riscv-elf-gcc/bin:${PATH}
```

```
cd software
```

```
rm -rf tests
rm -rf riscv-tests
```

```
mkdir tests
mkdir tests/dump
mkdir tests/hex
```

```
git clone --recursive https://github.com/riscv-elf-gcc/riscv-tests
cd riscv-tests
```

```
autoconf
./configure --prefix=/opt/riscv-elf-gcc/bin
make
```

```
cd isa
```

```
source ../../elf2hex.sh
```

```
mv *.dump ../../tests/dump
mv *.hex ../../tests/hex
```

```
cd ..
```

```
make clean
```

2.2. CORE-RISCV

2.2.1. Definition

The RISC-V implementation has a 32/64/128 bit Microarchitecture, 6 stages data pipeline and an Instruction Set Architecture based on Reduced Instruction Set Computer. Compatible with AMBA and Wishbone Buses. For Researching and Developing.

| Processing Unit | Module description |
|---------------------|----------------------------------|
| riscv_pu | Processing Unit |
| ...riscv_core | Core |
| ...riscv_imem_ctrl | Instruction Memory Access Block |
| ...riscv_biu - imem | Bus Interface Unit (Instruction) |
| ...riscv_dmem_ctrl | Data Memory Access Block |
| ...riscv_biu - dmem | Bus Interface Unit (Data) |

2.2.2. RISC Pipeline

In computer science, instruction pipelining is a technique for implementing instruction-level parallelism within a PU. Pipelining attempts to keep every part of the processor busy with some instruction by dividing incoming instructions into a series of sequential steps performed by different PUs with different parts of instructions processed in parallel. It allows faster PU throughput than would otherwise be possible at a given clock rate.

| Typical | Modified | Module |
|------------|------------|-----------------|
| FETCH | FETCH | riscv_if |
| ... | PRE-DECODE | riscv_id |
| DECODE | DECODE | riscv_id |
| EXECUTE | EXECUTE | riscv_execution |
| MEMORY | MEMORY | riscv_memory |
| WRITE-BACK | WRITE-BACK | riscv_wb |

- IF – Instruction Fetch Unit : Send out the PC and fetch the instruction from memory into the Instruction Register (IR); increment the PC to address the next sequential instruction. The IR is used to hold the next instruction that will be needed on subsequent clock cycles; likewise the register NPC is used to hold the next sequential PC.
- ID – Instruction Decode Unit : Decode the instruction and access the register file to read the registers. This unit gets instruction from IF, and extracts opcode and operand from that instruction. It also retrieves register values if requested by the operation.
- EX – Execution Unit : The ALU operates on the operands prepared in prior cycle, performing one functions depending on instruction type.
- MEM – Memory Access Unit : Instructions active in this unit are loads, stores and branches.
- WB – WriteBack Unit : Write the result into the register file, whether it comes from the memory system or from the ALU.

2.2.3. CORE-RISCV Organization

The CORE-RISCV is based on the Harvard architecture, which is a computer architecture with separate storage and signal pathways for instructions and data. The implementation is heavily modular, with each particular functional block of the design being contained within its own HDL module or modules. The RISCV implementation was developed in order to provide a better platform for processor component development than previous implementations.

| Core | Module description |
|--------------------|---------------------------------|
| riscv_core | Core |
| ...riscv_if | Instruction Fetch |
| ...riscv_id | Instruction Decoder |
| ...riscv_execution | Execution Unit |
| ...riscv_alu | Arithmetic & Logical Unit |
| ...riscv_lsu | Load Store Unit |
| ...riscv_bu | Branch Unit |
| ...riscv_mul | Multiplier Unit |
| ...riscv_div | Division Unit |
| ...riscv_memory | Memory Unit |
| ...riscv_wb | Data Memory Access (Write Back) |
| ...riscv_state | State Unit |
| ...riscv_rf | Register File |

| Core | Module description |
|-----------------------------|------------------------------------|
| ...riscv_bp | Correlating Branch Prediction Unit |
|riscv_ram_1rlw | RAM 1RW1 |
|riscv_ram_1rlw_generic | RAM 1RW1 Generic |
| ...riscv_du | Debug Unit |

In a Harvard architecture, there is no need to make the two memories share characteristics. In particular, the word width, timing, implementation technology, and memory address structure can differ. In some systems, instructions for pre-programmed tasks can be stored in read-only memory while data memory generally requires read-write memory. In some systems, there is much more instruction memory than data memory so instruction addresses are wider than data addresses.

2.2.4. Parameters

2.2.4.1. Technology Parameters

| Parameter | Type | Default | Description |
|-----------------------|---------|---------------|---------------------------------------|
| JEDEC_BANK | Integer | 0x0A | JEDEC Bank |
| JEDEC_MANUFACTURER_ID | Integer | 0x6E | JEDEC Manufacturer ID |
| XLEN | Integer | 64 | Data Path Width |
| PLEN | Integer | 64 | Physical Memory Address Size |
| PMP_CNT | Integer | 16 | Physical Memory Protection Entries |
| PMA_CNT | Integer | 16 | Physical Memory Attribute Entries |
| HAS_USER | Integer | 1 | User Mode Enable |
| HAS_SUPER | Integer | 1 | Supervisor Mode Enable |
| HAS_HYPER | Integer | 1 | Hypervisor Mode Enable |
| HAS_RVM | Integer | 1 | “M” Extension Enable |
| HAS_RVA | Integer | 1 | “A” Extension Enable |
| HAS_RVC | Integer | 1 | “C” Extension Enable |
| HAS_BPU | Integer | 1 | Branch Prediction Unit Control Enable |
| IS_RV32E | Integer | 0 | Base Integer Instruction Set Enable |
| MULT_LATENCY | Integer | 1 | Hardware Multiplier Latency |
| ICACHE_SIZE | Integer | 16 | Instruction Cache size |
| ICACHE_BLOCK_SIZE | Integer | 64 | Instruction Cache block length |
| ICACHE_WAYS | Integer | 2 | Instruction Cache associativity |
| ICACHE_REPLACE_ALG | Integer | 0 | Instruction Cache replacement |
| DCACHE_SIZE | Integer | 16 | Data Cache size |
| DCACHE_BLOCK_SIZE | Integer | 64 | Data Cache block length |
| DCACHE_WAYS | Integer | 2 | Data Cache associativity |
| DCACHE_REPLACE_ALG | Integer | 0 | Data Cache replacement algorithm |
| HARTID | Integer | 0 | Hart Identifier |
| PC_INIT | Address | 'h200 | Program Counter Initialisation Vector |
| MNMIVEC_DEFAULT | Address | PC_INIT-'h004 | Machine Mode Non-Maskable |
| MTVEC_DEFAULT | Address | PC_INIT-'h040 | Machine Mode Interrupt Address |
| HTVEC_DEFAULT | Address | PC_INIT-'h080 | Hypervisor Mode Interrupt Address |
| STVEC_DEFAULT | Address | PC_INIT-'h0C0 | Supervisor Mode Interrupt Address |
| UTVEC_DEFAULT | Address | PC_INIT-'h100 | User Mode Interrupt Address |
| BP_LOCAL_BITS | Integer | 10 | Number of local predictor bits |
| BP_GLOBAL_BITS | Integer | 2 | Number of global predictor bits |
| BREAKPOINTS | Integer | 3 | Number of hardware breakpoints |
| TECHNOLOGY | String | GENERIC | Target Silicon Technology |

2.2.5. Opcodes

2.2.5.1. RV32I : Base Integer Instruction Set

| RV32I | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|------------------|---------|--------|--------|-------|-------|---------|
| LUI RD, IMM | IIIIII | IIII | IIII | III | RD4:0 | 0110111 |
| AUPIC RD, IMM | IIIIII | IIII | IIII | III | RD4:0 | 0010111 |
| JAL RD, IMM | IIIIII | IIII | IIII | III | RD4:0 | 1101111 |
| JALR RD,RS1,IMM | IIIIII | IIII | RS14:0 | 000 | RD4:0 | 1101111 |
| BEQ RS1,RS2,IMM | IIIIII | RS24:0 | RS14:0 | 000 | IIII | 1100011 |
| BNE RS1,RS2,IMM | IIIIII | RS24:0 | RS14:0 | 001 | IIII | 1100011 |
| BLT RS1,RS2,IMM | IIIIII | RS24:0 | RS14:0 | 100 | IIII | 1100011 |
| BGE RS1,RS2,IMM | IIIIII | RS24:0 | RS14:0 | 101 | IIII | 1100011 |
| BLTU RS1,RS2,IMM | IIIIII | RS24:0 | RS14:0 | 110 | IIII | 1100011 |
| BGEU RS1,RS2,IMM | IIIIII | RS24:0 | RS14:0 | 111 | IIII | 1100011 |
| LB RD, RS1 | IIIIII | IIII | RS14:0 | 000 | RD4:0 | 0000011 |
| LH RD, RS1 | IIIIII | IIII | RS14:0 | 001 | RD4:0 | 0000011 |
| LW RD, RS1 | IIIIII | IIII | RS14:0 | 010 | RD4:0 | 0000011 |
| LBU RD, RS1 | IIIIII | IIII | RS14:0 | 100 | RD4:0 | 0000011 |
| LHU RD, RS1 | IIIIII | IIII | RS14:0 | 101 | RD4:0 | 0000011 |
| SB RS2,RS1 | IIIIII | RS24:0 | RS14:0 | 000 | IIII | 0100011 |
| SH RS2,RS1 | IIIIII | RS24:0 | RS14:0 | 001 | IIII | 0100011 |
| SW RS2,RS1 | IIIIII | RS24:0 | RS14:0 | 010 | IIII | 0100011 |
| ADDI RD,RS1,IMM | IIIIII | IIII | RS14:0 | 000 | RD4:0 | 0010011 |
| SLTI RD,RS1,IMM | IIIIII | IIII | RS14:0 | 010 | RD4:0 | 0010011 |
| SLTIU RD,RS1,IMM | IIIIII | IIII | RS14:0 | 011 | RD4:0 | 0010011 |
| XORI RD,RS1,IMM | IIIIII | IIII | RS14:0 | 100 | RD4:0 | 0010011 |
| ORI RD,RS1,IMM | IIIIII | IIII | RS14:0 | 110 | RD4:0 | 0010011 |
| ANDI RD,RS1,IMM | IIIIII | IIII | RS14:0 | 111 | RD4:0 | 0010011 |
| SLLI RD,RS1,IMM | 0000000 | IIII | RS14:0 | 001 | RD4:0 | 0010011 |
| SRLI RD,RS1,IMM | 0000000 | IIII | RS14:0 | 101 | RD4:0 | 0010011 |
| SRAI RD,RS1,IMM | 0100000 | IIII | RS14:0 | 101 | RD4:0 | 0010011 |
| ADD RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 000 | RD4:0 | 0110011 |
| SUB RD,RS1,RS2 | 0100000 | RS24:0 | RS14:0 | 000 | RD4:0 | 0110011 |
| SLL RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 001 | RD4:0 | 0110011 |
| SLT RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 010 | RD4:0 | 0110011 |
| SLTU RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 011 | RD4:0 | 0110011 |
| XOR RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 100 | RD4:0 | 0110011 |
| SRL RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 101 | RD4:0 | 0110011 |
| SRA RD,RS1,RS2 | 0100000 | RS24:0 | RS14:0 | 101 | RD4:0 | 0110011 |
| OR RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 110 | RD4:0 | 0110011 |
| AND RD,RS1,RS2 | 0000000 | RS24:0 | RS14:0 | 111 | RD4:0 | 0110011 |
| FENCE PRED,SUCC | 0000PPP | PSSSS | 00000 | 000 | 00000 | 0001111 |
| FENCE.I | 0000P00 | 00000 | 00000 | 001 | 00000 | 0001111 |

2.2.5.2. RV64I : Base Integer Instruction Set (64bit)

| RV64I | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|------------------|---------|--------|--------|-------|-------|---------|
| LWU RD, RS1 | IIIIII | IIII | RS14:0 | 110 | RD4:0 | 0000011 |
| LD RD, RS1 | IIIIII | IIII | RS14:0 | 011 | RD4:0 | 0000011 |
| SD RD, RS1,RS2 | IIIIII | RS24:0 | RS14:0 | 011 | IIII | 0000011 |
| SLLI RD, RS1,IMM | 0000000 | IIII | RS14:0 | 001 | RD4:0 | 0010011 |

| RV64I | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|-------------------|---------|--------|--------|-------|-------|---------|
| SRLI RD, RS1, IMM | 0000000 | IIIII | RS14:0 | 001 | RD4:0 | 0010011 |
| SRAI RD, RS1, IMM | 0100000 | IIIII | RS14:0 | 001 | RD4:0 | 0010011 |
| ADDIW RD, RS1 | IIIIIII | IIIII | RS14:0 | 000 | RD4:0 | 0011011 |
| SLLIW RD, RS1 | 0000000 | IIIII | RS14:0 | 001 | RD4:0 | 0011011 |
| SRLIW RD, RS1 | 0000000 | IIIII | RS14:0 | 101 | RD4:0 | 0011011 |
| SRAIW RD, RS1 | 0100000 | IIIII | RS14:0 | 101 | RD4:0 | 0011011 |
| ADDW RD, RS1, RS2 | 0000000 | RS24:0 | RS14:0 | 000 | RD4:0 | 0111011 |
| SUBW RD, RS1, RS2 | 0100000 | RS24:0 | RS14:0 | 000 | RD4:0 | 0111011 |
| SLIW RD, RS1, RS2 | 0000000 | RS24:0 | RS14:0 | 001 | RD4:0 | 0111011 |
| SRLW RD, RS1, RS2 | 0000000 | RS24:0 | RS14:0 | 101 | RD4:0 | 0111011 |
| SRAW RD, RS1, RS2 | 0100000 | RS24:0 | RS14:0 | 101 | RD4:0 | 0111011 |

2.2.5.3. RV32M : Standard Extension for Integer Multiply and Divide

| RV32M | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|---------------------|---------|--------|--------|-------|-------|---------|
| MUL RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 000 | RD4:0 | 0110011 |
| MULH RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 001 | RD4:0 | 0110011 |
| MULHSU RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 010 | RD4:0 | 0110011 |
| MULHU RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 011 | RD4:0 | 0110011 |
| DIV RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 100 | RD4:0 | 0110011 |
| DIVU RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 101 | RD4:0 | 0110011 |
| REM RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 110 | RD4:0 | 0110011 |
| REMU RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 111 | RD4:0 | 0110011 |

2.2.5.4. RV64M : Standard Extension for Integer Multiply and Divide (64bit)

| RV64M | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|--------------------|---------|--------|--------|-------|-------|---------|
| MULW RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 000 | RD4:0 | 0111011 |
| DIVW RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 100 | RD4:0 | 0111011 |
| DIVUW RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 101 | RD4:0 | 0111011 |
| REMW RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 110 | RD4:0 | 0111011 |
| REMUW RD, RS1, RS2 | 0000001 | RS24:0 | RS14:0 | 111 | RD4:0 | 0111011 |

2.2.5.5. RV32A : Standard Extension for Atomic Instructions

| RV32A | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|------------------------------|-----------|--------|--------|-------|-------|---------|
| LR.W AQRL, RD, RS1 | 00010AQRL | 00000 | RS14:0 | 010 | RD4:0 | 0101111 |
| SC.W AQRL, RD, RS2, RS1 | 00011AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOSWAP.W AQRL, RD, RS2, RS1 | 00001AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOSADD.W AQRL, RD, RS2, RS1 | 00000AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOSXOR.W AQRL, RD, RS2, RS1 | 00100AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOOR.W AQRL, RD, RS2, RS1 | 01000AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOAMD.W AQRL, RD, RS2, RS1 | 01100AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOMIN.W AQRL, RD, RS2, RS1 | 10000AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOMAX.W AQRL, RD, RS2, RS1 | 10100AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOMINU.W AQRL, RD, RS2, RS1 | 11000AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |
| AMOMAXU.W AQRL, RD, RS2, RS1 | 11100AQRL | RS24:0 | RS14:0 | 010 | RD4:0 | 0101111 |

2.2.5.6. RV64A : Standard Extension for Atomic Instructions (64bit)

| RV64A | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|---------------------------|-----------|--------|--------|-------|-------|---------|
| LR.D AQRL,RD,RS1 | 00010AQRL | 00000 | RS14:0 | 011 | RD4:0 | 0101111 |
| SC.D AQRL,RD,RS2,RS1 | 00011AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOSWAP.D AQRL,RD,RS2,RS1 | 00001AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOSADD.D AQRL,RD,RS2,RS1 | 00000AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOSXOR.D AQRL,RD,RS2,RS1 | 00100AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOOD.D AQRL,RD,RS2,RS1 | 01000AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOAMD.D AQRL,RD,RS2,RS1 | 01100AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOMIN.D AQRL,RD,RS2,RS1 | 10000AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOMAX.D AQRL,RD,RS2,RS1 | 10100AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOMINU.D AQRL,RD,RS2,RS1 | 11000AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |
| AMOMAXU.D AQRL,RD,RS2,RS1 | 11100AQRL | RS24:0 | RS14:0 | 011 | RD4:0 | 0101111 |

2.2.5.7. RV32F : Standard Extension for Single-Precision Floating-Point

| RV32F | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|--------------------------------|---------|-------|-------|-------|------|---------|
| FLW FRD,RS1 | IIIIII | IIII | FRS1 | 010 | FRD | 0000111 |
| FSW FRS2,RS1 | IIIIII | FRS2 | FRS1 | 010 | IIII | 0100111 |
| FMADD.S RM,FRD,FRS1,FRS2,FRS3 | FRS3_00 | FRS2 | FRS1 | RM | FRD | 1000011 |
| FMSUB.S RM,FRD,FRS1,FRS2,FRS3 | FRS3_00 | FRS2 | FRS1 | RM | FRD | 1000111 |
| FNMSUB.S RM,FRD,FRS1,FRS2,FRS3 | FRS3_00 | FRS2 | FRS1 | RM | FRD | 1001011 |
| FNMADD.S RM,FRD,FRS1,FRS2,FRS3 | FRS3_00 | FRS2 | FRS1 | RM | FRD | 1001111 |
| FADD.S RM,FRD,FRS1,FRS2,FRS3 | 0000000 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FSUB.S RM,FRD,FRS1,FRS2,FRS3 | 0000100 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FMUL.S RM,FRD,FRS1,FRS2,FRS3 | 0001000 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FDIV.S RM,FRD,FRS1,FRS2,FRS3 | 0001100 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FSGNJ.S FRD,FRS1,FRS2 | 0010000 | FRS2 | FRS1 | 000 | FRD | 1010011 |
| FSGNJS FRD,FRS1,FRS2 | 0010000 | FRS2 | FRS1 | 001 | FRD | 1010011 |
| FSGNJX.S FRD,FRS1,FRS2 | 0010000 | FRS2 | FRS1 | 010 | FRD | 1010011 |
| FMIN.S FRD,FRS1,FRS2 | 0010100 | FRS2 | FRS1 | 000 | FRD | 1010011 |
| FMAX.S FRD,FRS1,FRS2 | 0010100 | FRS2 | FRS1 | 001 | FRD | 1010011 |
| FSQRT.S FRD,FRS1,FRS2 | 0101100 | 00000 | FRS1 | RM | FRD | 1010011 |
| FLE.S FRD,FRS1,FRS2 | 1010000 | FRS2 | FRS1 | 000 | FRD | 1010011 |
| FLT.S FRD,FRS1,FRS2 | 1010000 | FRS2 | FRS1 | 001 | FRD | 1010011 |
| FEQ.S FRD,FRS1,FRS2 | 1010000 | FRS2 | FRS1 | 010 | FRD | 1010011 |
| FCVT.W.S RM,RD,FRS1 | 1100000 | 00000 | FRS1 | RM | FRD | 1010011 |
| FCVT.WU.S RM,RD,FRS1 | 1100000 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCVT.S.W RM,RD,FRS1 | 1101000 | 00000 | FRS1 | RM | FRD | 1010011 |
| FCVT.S.WU RM,RD,FRS1 | 1101000 | 00010 | FRS1 | RM | FRD | 1010011 |
| FMV.X.S RD,FRS1 | 1110000 | 00000 | FRS1 | 000 | RD | 1010011 |
| FCLASS.S RD,FRS1 | 1110000 | 00000 | FRS1 | 001 | RD | 1010011 |
| FMV.S.X RD,FRS1 | 1111000 | 00000 | RS1 | 000 | FRD | 1010011 |

2.2.5.8. RV64F : Standard Extension for Single-Precision Floating-Point (64bit)

| RV64F | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|----------------------|---------|-------|-------|-------|------|---------|
| FCVT.L.S RM,RD,FRS1 | 1100000 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCVT.LU.S RM,RD,FRS1 | 1100000 | 00011 | FRS1 | RM | FRD | 1010011 |

| RV64F | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|----------------------|---------|-------|-------|-------|------|---------|
| FCVT.S.L RM,RD,FRS1 | 1101000 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCVT.S.LU RM,RD,FRS1 | 1101000 | 00011 | FRS1 | RM | FRD | 1010011 |

2.2.5.9. RV32D : Standard Extension for Double-Precision Floating-Point

| RV32F | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|--------------------------------|---------|-------|-------|-------|------|---------|
| FLW FRD,RS1 | IIIIII | IIII | FRS1 | 011 | FRD | 0000111 |
| FSW FRS2,RS1 | IIIIII | FRS2 | FRS1 | 011 | IIII | 0100111 |
| FMADD.D RM,FRD,FRS1,FRS2,FRS3 | FRS3_01 | FRS2 | FRS1 | RM | FRD | 1000011 |
| FMSUB.D RM,FRD,FRS1,FRS2,FRS3 | FRS3_01 | FRS2 | FRS1 | RM | FRD | 1000111 |
| FNMSUB.D RM,FRD,FRS1,FRS2,FRS3 | FRS3_01 | FRS2 | FRS1 | RM | FRD | 1001011 |
| FNMADD.D RM,FRD,FRS1,FRS2,FRS3 | FRS3_01 | FRS2 | FRS1 | RM | FRD | 1001111 |
| FADD.D RM,FRD,FRS1,FRS2,FRS3 | 0000001 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FSUB.D RM,FRD,FRS1,FRS2,FRS3 | 0000101 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FMUL.D RM,FRD,FRS1,FRS2,FRS3 | 0001001 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FDIV.D RM,FRD,FRS1,FRS2,FRS3 | 0001101 | FRS2 | FRS1 | RM | FRD | 1010011 |
| FSGNJ.D FRD,FRS1,FRS2 | 0010001 | FRS2 | FRS1 | 000 | FRD | 1010011 |
| FSGNJN.D FRD,FRS1,FRS2 | 0010001 | FRS2 | FRS1 | 001 | FRD | 1010011 |
| FSGNJX.D FRD,FRS1,FRS2 | 0010001 | FRS2 | FRS1 | 010 | FRD | 1010011 |
| FMIN.D FRD,FRS1,FRS2 | 0010101 | FRS2 | FRS1 | 000 | FRD | 1010011 |
| FMAX.D FRD,FRS1,FRS2 | 0010101 | FRS2 | FRS1 | 001 | FRD | 1010011 |
| FSQRT.D FRD,FRS1,FRS2 | 0101101 | 00000 | FRS1 | RM | FRD | 1010011 |
| FLE.D FRD,FRS1,FRS2 | 1010001 | FRS2 | FRS1 | 000 | FRD | 1010011 |
| FLT.D FRD,FRS1,FRS2 | 1010001 | FRS2 | FRS1 | 001 | FRD | 1010011 |
| FEQ.D FRD,FRS1,FRS2 | 1010001 | FRS2 | FRS1 | 010 | FRD | 1010011 |
| FCVT.W.D RM,RD,FRS1 | 1100001 | 00000 | FRS1 | RM | FRD | 1010011 |
| FCVT.WU.D RM,RD,FRS1 | 1100001 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCVT.D.W RM,RD,FRS1 | 1101001 | 00000 | FRS1 | RM | FRD | 1010011 |
| FCVT.D.WU RM,RD,FRS1 | 1101001 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCLASS.D RD,FRS1 | 1110001 | 00000 | FRS1 | 001 | RD | 1010011 |

2.2.5.10. RV64D : Standard Extension for Double-Precision Floating-Point (64bit)

| RV64D | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|----------------------|---------|-------|-------|-------|------|---------|
| FCVT.L.D RM,RD,FRS1 | 1100001 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCVT.LU.D RM,RD,FRS1 | 1100001 | 00011 | FRS1 | RM | FRD | 1010011 |
| FCVT.D.L RM,RD,FRS1 | 1101001 | 00010 | FRS1 | RM | FRD | 1010011 |
| FCVT.D.LU RM,RD,FRS1 | 1101001 | 00011 | FRS1 | RM | FRD | 1010011 |
| FMV.X.D RD,FRS1 | 1110001 | 00000 | FRS1 | 000 | RD | 1010011 |
| FMV.D.X RD,FRS1 | 1111001 | 00000 | RS1 | 000 | FRD | 1010011 |

2.2.6. Instruction Inputs/Outputs Bus

| Port | Size | Direction | Description |
|-------------|------|-----------|--------------------|
| ins_stb | 1 | Input | Strobe |
| ins_stb_ack | 1 | Output | Strobe acknowledge |
| ins_d_ack | 1 | Output | Data acknowledge |

| Port | Size | Direction | Description |
|----------|------|-----------|------------------|
| ins_adri | PLEN | Input | Start address |
| ins_adro | PLEN | Output | Response address |
| ins_size | 3 | Input | Syze |
| ins_type | 3 | Input | Type |
| ins_prot | 3 | Input | Protection |
| ins_lock | 1 | Input | Locked access |
| ins_d | XLEN | Input | Write data |
| ins_q | XLEN | Output | Read data |
| ins_ack | 1 | Output | Acknowledge |
| ins_err | 1 | Output | Error |

2.2.7. Data Inputs/Outputs Bus

| Port | Size | Direction | Description |
|-------------|------|-----------|--------------------|
| dat_stb | 1 | Input | Strobe |
| dat_stb_ack | 1 | Output | Strobe acknowledge |
| dat_d_ack | 1 | Output | Data acknowledge |
| dat_adri | PLEN | Input | Start address |
| dat_adro | PLEN | Output | Response address |
| dat_size | 3 | Input | Syze |
| dat_type | 3 | Input | Type |
| dat_prot | 3 | Input | Protection |
| dat_lock | 1 | Input | Locked access |
| dat_d | XLEN | Input | Write data |
| dat_q | XLEN | Output | Read data |
| dat_ack | 1 | Output | Acknowledge |
| dat_err | 1 | Output | Error |

2.3. PU-RISCV

2.3.1. Instruction Cache

A PU cache is a hardware cache used by the PU to reduce the average cost (time or energy) to access instruction/data from the main memory. A cache is a smaller, faster memory, closer to a core, which stores copies of the data from frequently used main memory locations. Most CPUs have different independent caches, including instruction and data caches.

2.3.1.1. Instruction Organization

| Instruction Memory | Module description |
|------------------------|------------------------------------|
| riscv_imem_ctrl | Instruction Memory Access Block |
| ...riscv_membuf | Memory Access Buffer |
|riscv_ram_queue | Fall-through Queue |
| ...riscv_memmisaligned | Misalignment Check |
| ...riscv_mmu | Memory Management Unit |
| ...riscv_pmachk | Physical Memory Attributes Checker |
| ...riscv_pmpchk | Physical Memory Protection Checker |
| ...riscv_icache_core | Instruction Cache (Write Back) |

| Instruction Memory | Module description |
|----------------------------|----------------------------|
|riscv_ram_1rw | RAM 1RW |
|riscv_ram_1rw_generic | RAM 1RW Generic |
| ...riscv_dext | Data External Access Logic |
| ...riscv_ram_queue | Fall-through Queue |
| ...riscv_mux | Bus-Interface-Unit Mux |
| riscv_biu | Bus Interface Unit |

2.3.1.2. Instruction INPUTS/OUTPUTS AMBA4 AXI-Lite Bus

2.3.1.2.1. Signals of the Read and Write Address channels

| Write Port | Read Port | Size | Direction | Description |
|------------|-----------|----------------|-----------|------------------------------------------|
| AWID | ARID | AXI_ID_WIDTH | Output | Address ID, to identify multiple streams |
| AWADDR | ARADDR | AXI_ADDR_WIDTH | Output | Address of the first beat of the burst |
| AWLEN | ARLEN | 8 | Output | Number of beats inside the burst |
| AWSIZE | ARSIZE | 3 | Output | Size of each beat |
| AWBURST | ARBURST | 2 | Output | Type of the burst |
| AWLOCK | ARLOCK | 1 | Output | Lock type, to provide atomic operations |
| AWCACHE | ARCACHE | 4 | Output | Memory type, progress through the system |
| AWPROT | ARPROT | 3 | Output | Protection type |
| AWQOS | ARQOS | 4 | Output | Quality of Service of the transaction |
| AWREGION | ARREGION | 4 | Output | Region identifier, physical to logical |
| AWUSER | ARUSER | AXI_USER_WIDTH | Output | User-defined data |
| AWVALID | ARVALID | 1 | Output | xVALID handshake signal |
| AWREADY | ARREADY | 1 | Input | xREADY handshake signal |

2.3.1.2.2. Signals of the Read and Write Data channels

| Write Port | Read Port | Size | Direction | Description |
|------------|-----------|----------------|-----------|---------------------------------------|
| WID | RID | AXI_ID_WIDTH | Output | Data ID, to identify multiple streams |
| WDATA | RDATA | AXI_DATA_WIDTH | Output | Read/Write data |
| -- | RRESP | 2 | Output | Read response, current RDATA status |
| WSTRB | -- | AXI_STRB_WIDTH | Output | Byte strobe, WDATA signal |
| WLAST | RLAST | 1 | Output | Last beat identifier |
| WUSER | RUSER | AXI_USER_WIDTH | Output | User-defined data |
| WVALID | RVALID | 1 | Output | xVALID handshake signal |
| WREADY | RREADY | 1 | Input | xREADY handshake signal |

2.3.1.2.3. Signals of the Write Response channel

| Write Port | Size | Direction | Description |
|------------|----------------|-----------|-------------------------------------------------|
| BID | AXI_ID_WIDTH | Input | Write response ID, to identify multiple streams |
| BRESP | 2 | Input | Write response, to specify the burst status |
| BUSER | AXI_USER_WIDTH | Input | User-defined data |
| BVALID | 1 | Input | xVALID handshake signal |
| BREADY | 1 | Output | xREADY handshake signal |

2.3.1.3. Instruction INPUTS/OUTPUTS AMBA3 AHB-Lite Bus

| Port | Size | Direction | Description |
|------------|------|-----------|---------------------------------------|
| HRESETn | 1 | Input | Asynchronous Active Low Reset |
| HCLK | 1 | Input | System Clock Input |
| IHSEL | 1 | Output | Instruction Bus Select |
| IHADDR | PLEN | Output | Instruction Address Bus |
| IHRDATA | XLEN | Input | Instruction Read Data Bus |
| IHWDATA | XLEN | Output | Instruction Write Data Bus |
| IHWRITE | 1 | Output | Instruction Write Select |
| IHSIZE | 3 | Output | Instruction Transfer Size |
| IHBURST | 3 | Output | Instruction Transfer Burst Size |
| IHPROT | 4 | Output | Instruction Transfer Protection Level |
| IHTRANS | 2 | Output | Instruction Transfer Type |
| IHMASTLOCK | 1 | Output | Instruction Transfer Master Lock |
| IHREADY | 1 | Input | Instruction Slave Ready Indicator |
| IHRESP | 1 | Input | Instruction Transfer Response |

2.3.1.4. Instruction INPUTS/OUTPUTS Wishbone Bus

| Port | Size | Direction | Description |
|-------|------|-----------|---------------------------------|
| rst | 1 | Input | Synchronous Active High Reset |
| clk | 1 | Input | System Clock Input |
| iadr | AW | Input | Instruction Address Bus |
| idati | DW | Input | Instruction Input Bus |
| idato | DW | Output | Instruction Output Bus |
| isel | DW/8 | Input | Byte Select Signals |
| iwe | 1 | Input | Write Enable Input |
| istb | 1 | Input | Strobe Signal/Core Select Input |
| icyc | 1 | Input | Valid Bus Cycle Input |
| iack | 1 | Output | Bus Cycle Acknowledge Output |
| ierr | 1 | Output | Bus Cycle Error Output |
| iint | 1 | Output | Interrupt Signal Output |

2.3.2. Data Cache

2.3.2.1. Data Organization

| Data Memory | Module description |
|------------------------|------------------------------------|
| riscv_dmem_ctrl | Data Memory Access Block |
| ...riscv_membuf | Memory Access Buffer |
|riscv_ram_queue | Fall-through Queue |
| ...riscv_memmisaligned | Misalignment Check |
| ...riscv_mmu | Memory Management Unit |
| ...riscv_pmachk | Physical Memory Attributes Checker |
| ...riscv_pmpchk | Physical Memory Protection Checker |
| ...riscv_dcache_core | Data Cache (Write Back) |
|riscv_ram_1rw | RAM 1RW |

| Data Memory | Module description |
|----------------------------|----------------------------|
|riscv_ram_1rw_generic | RAM 1RW Generic |
| ...riscv_dext | Data External Access Logic |
| ...riscv_mux | Bus-Interface-Unit Mux |
| riscv_biu | Bus Interface Unit |

2.3.2.2. Data INPUTS/OUTPUTS AMBA4 AXI-Lite Bus

2.3.2.2.1. Signals of the Read and Write Address channels

| Write Port | Read Port | Size | Direction | Description |
|------------|-----------|----------------|-----------|------------------------------------------|
| AWID | ARID | AXI_ID_WIDTH | Output | Address ID, to identify multiple streams |
| AWADDR | ARADDR | AXI_ADDR_WIDTH | Output | Address of the first beat of the burst |
| AWLEN | ARLEN | 8 | Output | Number of beats inside the burst |
| AWSIZE | ARSIZE | 3 | Output | Size of each beat |
| AWBURST | ARBURST | 2 | Output | Type of the burst |
| AWLOCK | ARLOCK | 1 | Output | Lock type, to provide atomic operations |
| AWCACHE | ARCACHE | 4 | Output | Memory type, progress through the system |
| AWPROT | ARPROT | 3 | Output | Protection type |
| AWQOS | ARQOS | 4 | Output | Quality of Service of the transaction |
| AWREGION | ARREGION | 4 | Output | Region identifier, physical to logical |
| AWUSER | ARUSER | AXI_USER_WIDTH | Output | User-defined data |
| AWVALID | ARVALID | 1 | Output | xVALID handshake signal |
| AWREADY | ARREADY | 1 | Input | xREADY handshake signal |

2.3.2.2.2. Signals of the Read and Write Data channels

| Write Port | Read Port | Size | Direction | Description |
|------------|-----------|----------------|-----------|---------------------------------------|
| WID | RID | AXI_ID_WIDTH | Output | Data ID, to identify multiple streams |
| WDATA | RDATA | AXI_DATA_WIDTH | Output | Read/Write data |
| -- | RRESP | 2 | Output | Read response, current RDATA status |
| WSTRB | -- | AXI_STRB_WIDTH | Output | Byte strobe, WDATA signal |
| WLAST | RLAST | 1 | Output | Last beat identifier |
| WUSER | RUSER | AXI_USER_WIDTH | Output | User-defined data |
| WVALID | RVALID | 1 | Output | xVALID handshake signal |
| WREADY | RREADY | 1 | Input | xREADY handshake signal |

2.3.2.2.3. Signals of the Write Response channel

| Write Port | Size | Direction | Description |
|------------|----------------|-----------|-------------------------------------------------|
| BID | AXI_ID_WIDTH | Input | Write response ID, to identify multiple streams |
| BRESP | 2 | Input | Write response, to specify the burst status |
| BUSER | AXI_USER_WIDTH | Input | User-defined data |
| BVALID | 1 | Input | xVALID handshake signal |
| BREADY | 1 | Output | xREADY handshake signal |

2.3.2.3. Data INPUTS/OUTPUTS AMBA3 AHB-Lite Bus

| Port | Size | Direction | Description |
|------------|------|-----------|--------------------------------|
| HRESETn | 1 | Input | Asynchronous Active Low Reset |
| HCLK | 1 | Input | System Clock Input |
| DHSEL | 1 | Output | Data Bus Select |
| DHADDR | PLEN | Output | Data Address Bus |
| DHRDATA | XLEN | Input | Data Read Data Bus |
| DHWDATA | XLEN | Output | Data Write Data Bus |
| DHWRITE | 1 | Output | Data Write Select |
| DHSIZE | 3 | Output | Data Transfer Size |
| DHBURST | 3 | Output | Data Transfer Burst Size |
| DHPROT | 4 | Output | Data Transfer Protection Level |
| DHTRANS | 2 | Output | Data Transfer Type |
| DHMASTLOCK | 1 | Output | Data Transfer Master Lock |
| DHREADY | 1 | Input | Data Slave Ready Indicator |
| DHRESP | 1 | Input | Data Transfer Response |

2.3.2.4. Data INPUTS/OUTPUTS Wishbone Bus

| Port | Size | Direction | Description |
|-------|------|-----------|---------------------------------|
| rst | 1 | Input | Synchronous Active High Reset |
| clk | 1 | Input | System Clock Input |
| dadr | AW | Input | Data Address Bus |
| ddati | DW | Input | Data Input Bus |
| ddato | DW | Output | Data Output Bus |
| dse1 | DW/8 | Input | Byte Select Signals |
| dwe | 1 | Input | Write Enable Input |
| dstb | 1 | Input | Strobe Signal/Core Select Input |
| dcyc | 1 | Input | Valid Bus Cycle Input |
| dack | 1 | Output | Bus Cycle Acknowledge Output |
| derr | 1 | Output | Bus Cycle Error Output |
| dint | 1 | Output | Interrupt Signal Output |

3. WORKFLOW

3.1. HARDWARE

1. System Level (SystemC/SystemVerilog)

The System Level abstraction of a system only looks at its biggest building blocks like processing units or peripheral devices. At this level the circuit is usually described using traditional programming languages like SystemC or SystemVerilog. Sometimes special software libraries are used that are aimed at simulation circuits on the system level. The IEEE 1685-2009 standard defines the IP-XACT file format that can be used to represent designs on the system level and building blocks that can be used in such system level designs.

2. Behavioral & Register Transfer Level (VHDL/Verilog)

At the Behavioural Level abstraction a language aimed at hardware description such as Verilog or VHDL is

used to describe the circuit, but so-called behavioural modeling is used in at least part of the circuit description. In behavioural modeling there must be a language feature that allows for imperative programming to be used to describe data paths and registers. This is the `always` -block in Verilog and the `process` -block in VHDL.

A design in Register Transfer Level representation is usually stored using HDLs like Verilog and VHDL. But only a very limited subset of features is used, namely minimalistic `always` blocks (Verilog) or `process` blocks (VHDL) that model the register type used and unconditional assignments for the datapath logic. The use of HDLs on this level simplifies simulation as no additional tools are required to simulate a design in Register Transfer Level representation.

3. Logical Gate

At the Logical Gate Level the design is represented by a netlist that uses only cells from a small number of single-bit cells, such as basic logic gates (AND, OR, NOT, XOR, etc.) and registers (usually D-Type Flip-flops). A number of netlist formats exists that can be used on this level such as the Electronic Design Interchange Format (EDIF), but for ease of simulation often a HDL netlist is used. The latter is a HDL file (Verilog or VHDL) that only uses the most basic language constructs for instantiation and connecting of cells.

4. Physical Gate

On the Physical Gate Level only gates are used that are physically available on the target architecture. In some cases this may only be NAND, NOR and NOT gates as well as D-Type registers. In the case of an FPGA-based design the Physical Gate Level representation is a netlist of LUTs with optional output registers, as these are the basic building blocks of FPGA logic cells.

5. Switch Level

A Switch Level representation of a circuit is a netlist utilizing single transistors as cells. Switch Level modeling is possible in Verilog and VHDL, but is seldom used in modern designs, as in modern digital ASIC or FPGA flows the physical gates are considered the atomic build blocks of the logic circuit.

3.1.1. Front-End Open Source Tools

3.1.1.1. Modeling System Level of Hardware

A System Description Language Editor is a computer tool allows to generate software code. A System Description Language is a formal language, which comprises a Programming Language (input), producing a Hardware Description (output). Programming languages are used in computer programming to implement algorithms. The description of a programming language is split into the two components of syntax (form) and semantics (meaning).

System Description Language Editor

type:

```
git clone https://github.com/emacs-mirror/emacs
```

3.1.1.2. Simulating System Level of Hardware

A System Description Language Simulator (translator) is a computer program that translates computer code written in a Programming Language (the source language) into a Hardware Description Language (the target language). The compiler is primarily used for programs that translate source code from a high-level programming language to a low-level language to create an executable program.

SystemVerilog System Description Language Simulator

type:

```
git clone http://git.veripool.org/git/verilator
```

```

cd verilator
autoconf
./configure
make
sudo make install

cd sim/verilog/regression/wb/verilator
source SIMULATE-IT

cd sim/verilog/regression/ahb3/verilator
source SIMULATE-IT

cd sim/verilog/regression/axi4/verilator
source SIMULATE-IT

```

3.1.1.3. Verifying System Level of Hardware

A UVM standard improves interoperability and reduces the cost of repurchasing and rewriting IP for each new project or Electronic Design Automation tool. It also makes it easier to reuse verification components. The UVM Class Library provides generic utilities, such as component hierarchy, Transaction Library Model or configuration database, which enable the user to create virtually any structure wanted for the testbench.

SystemVerilog System Description Language Verifier

type:

```
git clone https://github.com/QueenField/UVM
```

3.1.1.4. Describing Register Transfer Level of Hardware

A Hardware Description Language Editor is any editor that allows to generate hardware code. Hardware Description Language is a specialized computer language used to describe the structure and behavior of digital logic circuits. It allows for the synthesis of a HDL into a netlist, which can then be synthesized, placed and routed to produce the set of masks used to create an integrated circuit.

Hardware Description Language Editor

type:

```
git clone https://github.com/emacs-mirror/emacs
```

3.1.1.5. Simulating Register Transfer Level of Hardware

A Hardware Description Language Simulator uses mathematical models to replicate the behavior of an actual hardware device. Simulation software allows for modeling of circuit operation and is an invaluable analysis tool. Simulating a circuit's behavior before actually building it can greatly improve design efficiency by making faulty designs known as such, and providing insight into the behavior of electronics circuit designs.

VHDL Hardware Description Language Simulator

type:

```
git clone https://github.com/ghdl/ghdl
```

```

cd ghdl
./configure --prefix=/usr/local
make
sudo make install

```

```
cd sim/vhdl/regression/wb/ghdl
source SIMULATE-IT

cd sim/vhdl/regression/ahb3/ghdl
source SIMULATE-IT

cd sim/vhdl/regression/axi4/ghdl
source SIMULATE-IT
```

Verilog Hardware Description Language Simulator

type:

```
git clone https://github.com/steveicarus/iverilog
```

```
cd iverilog
sh autoconf.sh
./configure
make
sudo make install

cd sim/verilog/regression/wb/iverilog
source SIMULATE-IT

cd sim/verilog/regression/ahb3/iverilog
source SIMULATE-IT

cd sim/verilog/regression/axi4/iverilog
source SIMULATE-IT
```

3.1.1.6. Synthesizing Register Transfer Level of Hardware

A Hardware Description Language Synthesizer turns a RTL implementation into a Logical Gate Level implementation. Logical design is a step in the standard design cycle in which the functional design of an electronic circuit is converted into the representation which captures logic operations, arithmetic operations, control flow, etc. In EDA parts of the logical design is automated using synthesis tools based on the behavioral description of the circuit.

Verilog Hardware Description Language Synthesizer

type:

```
git clone https://github.com/YosysHQ/yosys
```

```
cd yosys
make
sudo make install

cd synthesis/yosys
source SYNTHESIZE-IT
```

VHDL Hardware Description Language Synthesizer

type:

```
git clone https://github.com/ghdl/ghdl-yosys-plugin
cd ghdl-yosys-plugin
make GHDL=/usr/local
sudo yosys-config --exec mkdir -p --datdir/plugins
sudo yosys-config --exec cp "ghdl.so" --datdir/plugins/ghdl.so
```


3.1.1.7. Optimizing Register Transfer Level of Hardware

A Hardware Description Language Optimizer finds an equivalent representation of the specified logic circuit under specified constraints (minimum area, pre-specified delay). This tool combines scalable logic optimization based on And-Inverter Graphs (AIGs), optimal-delay DAG-based technology mapping for look-up tables and standard cells, and innovative algorithms for sequential synthesis and verification.

Verilog Hardware Description Language Optimizer

type:

```
git clone https://github.com/YosysHQ/yosys
```

```
cd yosys
make
sudo make install

cd synthesis/yosys
source SYNTHESIZE-IT
```

3.1.1.8. Verifying Register Transfer Level of Hardware

A Hardware Description Language Verifier proves or disproves the correctness of intended algorithms underlying a hardware system with respect to a certain formal specification or property, using formal methods of mathematics. Formal verification uses modern techniques (SAT/SMT solvers, BDDs, etc.) to prove correctness by essentially doing an exhaustive search through the entire possible input space (formal proof).

Verilog Hardware Description Language Verifier

type:

```
git clone https://github.com/YosysHQ/SymbiYosys
```

3.1.2. Back-End Open Source Tools

For Windows Users!

1. Settings → Apps → Apps & features → Related settings, Programs and Features → Turn Windows features on or off → Windows Subsystem for Linux
2. Microsoft Store → INSTALL UBUNTU

Library

type:

```
sudo apt update
sudo apt upgrade

sudo apt install bison cmake flex freeglut3-dev libcairo2-dev libgsl-dev \
libncurses-dev libx11-dev m4 python-tk python3-tk swig tcl tcl-dev tk-dev tcsh
```

Back-End Workflow Qflow

type:

```
git clone https://github.com/RTimothyEdwards/qflow

cd qflow
./configure
make
```

```
sudo make install  
  
mkdir qflow  
cd qflow
```

3.1.2.1. Planning Switch Level of Hardware

A Floor-Planner of an Integrated Circuit (IC) is a schematic representation of tentative placement of its major functional blocks. In modern electronic design process floor-plans are created during the floor-planning design stage, an early stage in the hierarchical approach to Integrated Circuit design. Depending on the design methodology being followed, the actual definition of a floor-plan may differ.

Floor-Planner

type:

```
git clone https://github.com/RTimothyEdwards/magic  
  
cd magic  
./configure  
make  
sudo make install
```

3.1.2.2. Placing Switch Level of Hardware

A Standard Cell Placer takes a given synthesized circuit netlist together with a technology library and produces a valid placement layout. The layout is optimized according to the aforementioned objectives and ready for cell resizing and buffering, a step essential for timing and signal integrity satisfaction. Physical design flow are iterated a number of times until design closure is achieved.

Standard Cell Placer

type:

```
git clone https://github.com/rubund/graywolf  
  
cd graywolf  
mkdir build  
cd build  
cmake ..  
make  
sudo make install
```

3.1.2.3. Timing Switch Level of Hardware

A Standard Cell Timing-Analizer is a simulation method of computing the expected timing of a digital circuit without requiring a simulation of the full circuit. High-performance integrated circuits have traditionally been characterized by the clock frequency at which they operate. Measuring the ability of a circuit to operate at the specified speed requires an ability to measure, during the design process, its delay at numerous steps.

Standard Cell Timing-Analizer

type:

```
git clone https://github.com/The-OpenROAD-Project/OpenSTA  
  
cd OpenSTA  
mkdir build  
cd build
```

```
cmake ..  
make  
sudo make install
```

3.1.2.4. Routing Switch Level of Hardware

A Standard Cell Router takes pre-existing polygons consisting of pins on cells, and pre-existing wiring called pre-routes. Each of these polygons are associated with a net. The primary task of the router is to create geometries such that all terminals assigned to the same net are connected, no terminals assigned to different nets are connected, and all design rules are obeyed.

Standard Cell Router

type:

```
git clone https://github.com/RTimothyEdwards/qrouter
```

```
cd qrouter  
./configure  
make  
sudo make install
```

3.1.2.5. Simulating Switch Level of Hardware

A Standard Cell Simulator treats transistors as ideal switches. Extracted capacitance and lumped resistance values are used to make the switch a little bit more realistic than the ideal, using the RC time constants to predict the relative timing of events. This simulator represents a circuit in terms of its exact transistor structure but describes the electrical behavior in a highly idealized way.

Standard Cell Simulator

type:

```
git clone https://github.com/RTimothyEdwards/irsim
```

```
cd irsim  
./configure  
make  
sudo make install
```

3.1.2.6. Verifying Switch Level of Hardware LVS

A Standard Cell Verifier compares netlists, a process known as LVS (Layout vs. Schematic). This step ensures that the geometry that has been laid out matches the expected circuit. The greatest need for LVS is in large analog or mixed-signal circuits that cannot be simulated in reasonable time. LVS can be done faster than simulation, and provides feedback that makes it easier to find errors.

Standard Cell Verifier

type:

```
git clone https://github.com/RTimothyEdwards/netgen
```

```
cd netgen  
./configure  
make  
sudo make install
```

```
cd synthesis/qflow
source FLOW-IT
```

3.1.2.7. Checking Switch Level of Hardware DRC

A Standard Cell Checker is a geometric constraint imposed on Printed Circuit Board (PCB) and Integrated Circuit (IC) designers to ensure their designs function properly, reliably, and can be produced with acceptable yield. Design Rules for production are developed by hardware engineers based on the capability of their processes to realize design intent. Design Rule Checking (DRC) is used to ensure that designers do not violate design rules.

Standard Cell Checker

type:

```
git clone https://github.com/RTimothyEdwards/magic

cd magic
./configure
make
sudo make install
```

3.1.2.8. Printing Switch Level of Hardware GDS

A Standard Cell Editor allows to print a set of standard cells. The standard cell methodology is an abstraction, whereby a low-level VLSI layout is encapsulated into a logical representation. A standard cell is a group of transistor and interconnect structures that provides a boolean logic function (AND, OR, XOR, XNOR, inverters) or a storage function (flipflop or latch).

Standard Cell Editor

type:

```
git clone https://github.com/RTimothyEdwards/magic

cd magic
./configure
make
sudo make install
```

3.2. SOFTWARE

3.2.1. Bare Metal

type:

```
rm -rf hello.elf
rm -rf hello.hex

export PATH=/opt/riscv-elf-gcc/bin:${PATH}

riscv64-unknown-elf-gcc -o hello.elf hello.c
riscv64-unknown-elf-objcopy -O ihex hello.elf hello.hex

type:
```

```

export PATH=/opt/riscv-elf-gcc/bin:${PATH}

rm -rf tests
rm -rf riscv-tests

mkdir tests
mkdir tests/dump
mkdir tests/hex

git clone --recursive https://github.com/riscv/riscv-tests
cd riscv-tests

autoconf
./configure --prefix=/opt/riscv-elf-gcc/bin
make

cd isa

source ../../elf2hex.sh

mv *.dump ../../tests/dump
mv *.hex ../../tests/hex

cd ..

make clean

elf2hex.sh:
riscv64-unknown-elf-objcopy -O ihex rv32mi-p-breakpoint rv32mi-p-breakpoint.hex
riscv64-unknown-elf-objcopy -O ihex rv32mi-p-csr rv32mi-p-csr.hex
...

```

3.2.2. Operating System

3.2.2.1. GNU Linux

```

type:
export CROSS_COMPILE=/opt/riscv-elf-gcc/bin/riscv64-unknown-linux-gnu-

rm -rf vmlinux

git clone --recursive https://github.com/torvalds/linux

cd linux
make ARCH=riscv mrproper defconfig
make ARCH=riscv defconfig
make ARCH=riscv all

cp vmlinux ../
cd ..
rm -rf linux

```

3.2.2.2. GNU Hurd

4. CONCLUSION

4.1. HARDWARE

4.1.1. GSCL 45 nm ASIC

4.1.2. Lattice iCE40 FPGA

4.2. SOFTWARE

4.2.1. Simulators

4.2.1.1. Spike (For Hardware Engineers)

4.2.1.2. QEMU (For Software Engineers)

4.2.2. Compilers

4.2.2.1. RISC-V GNU C/C++ / Go

4.2.2.2. RISC-V Binutils