

# PU-RISCV

QueenField



Figure 1: QueenField

## 0. INTRODUCTION

### 0.1. BEST PRACTICES

#### 0.1.1. HARDWARE

```
cd synthesis/yosys  
source SYNTHESIZE-IT
```

##### 0.1.1.1. ASIC type:

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

##### 0.1.1.2. FPGA type:

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

## **0.1.2. SOFTWARE**

### **0.1.2.1. MSP430**

#### **0.1.2.1.1. MSP430 Tests**

#### **0.1.2.1.2. MSP430 Bare Metal**

#### **0.1.2.1.3. MSP430 Operating System** 0.1.2.1.3.1. GNU Linux

##### 0.1.2.1.3.2. GNU Hurd

#### **0.1.2.1.4. MSP430 Distribution** 0.1.2.1.4.1. GNU Debian

##### 0.1.2.1.4.2. GNU Fedora

### **0.1.2.2. OpenRISC**

#### **0.1.2.2.1. OpenRISC Tests**

#### **0.1.2.2.2. OpenRISC Bare Metal**

#### **0.1.2.2.3. OpenRISC Operating System** 0.1.2.2.3.1. GNU Linux

##### 0.1.2.2.3.2. GNU Hurd

#### **0.1.2.2.4. OpenRISC Distribution** 0.1.2.2.4.1. GNU Debian

##### 0.1.2.2.4.2. GNU Fedora

### **0.1.2.3. RISC-V**

#### **0.1.2.3.1. RISC-V Tests** 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
...
riscv64-unknown-elf-objcopy -O ihex rv64um-v-remw rv64um-v-remw.hex

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

spike rv32mi-p-breakpoint
spike rv32mi-p-csr
...
spike rv64um-v-remw

```

#### 0.1.2.3.2. RISC-V Bare Metal type:

```

rm -rf hello_c.elf
rm -rf hello_c.hex

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

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

C Language:
#include <stdio.h>

int main() {
    printf("Hello QueenField!\n");
    return 0;
}

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

spike pk hello_c.elf

type:
rm -rf hello_cpp.elf
rm -rf hello_cpp.hex

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

riscv64-unknown-elf-g++ -o hello_cpp.elf hello_cpp.cpp
riscv64-unknown-elf-objcopy -O ihex hello_cpp.elf hello_cpp.hex

```

C++ Language:

```
#include <iostream>

int main() {
    std::cout << "Hello QueenField!\n";
    return 0;
}
```

type:

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

```
spike pk hello_cpp.elf
```

type:

```
rm -rf hello_go.elf
rm -rf hello_go.hex
```

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

```
GOOS=linux GOARCH=riscv64 go build -o hello_go.elf hello_go.go
riscv64-unknown-elf-objcopy -O ihex hello_go.elf hello_go.hex
```

Go Language:

```
package main

import "fmt"
func main() {
    fmt.Println("Hello QueenField!")
}
```

#### 0.1.2.3.3. RISC-V Operating System 0.1.2.3.3.1. GNU Linux

##### Building BusyBox

type:

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

```
git clone --recursive https://git.busybox.net/busybox
```

```
cd busybox
make CROSS_COMPILE=riscv64-unknown-linux-gnu- defconfig
make CROSS_COMPILE=riscv64-unknown-linux-gnu-
```

##### Building Linux

type:

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

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

```
cd linux
make ARCH=riscv CROSS_COMPILE=riscv64-unknown-linux-gnu- defconfig
make ARCH=riscv CROSS_COMPILE=riscv64-unknown-linux-gnu-
```

## Running Linux

type:

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

```
qemu-system-riscv64 -nographic -machine virt \  
-kernel Image -append "root=/dev/vda ro console=ttyS0" \  
-drive file=busybox,format=raw,id=hd0 \  
-device virtio-blk-device,drive=hd0
```

## Running Linux RISC-V 32 bit with Buildroot

type:

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

```
git clone --recursive https://github.com/buildroot/buildroot
```

```
cd buildroot  
make qemu_riscv32_virt_defconfig  
make
```

```
qemu-system-riscv32 \  
-M virt \  
-nographic \  
-bios output/images/fw_jump.elf \  
-kernel output/images/Image \  
-append "root=/dev/vda ro" \  
-drive file=output/images/rootfs.ext2,format=raw,id=hd0 \  
-device virtio-blk-device,drive=hd0 \  
-netdev user,id=net0 \  
-device virtio-net-device,netdev=net0
```

## Running Linux RISC-V 64 bit with Buildroot

type:

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

```
git clone --recursive https://github.com/buildroot/buildroot
```

```
cd buildroot  
make qemu_riscv64_virt_defconfig  
make
```

```
qemu-system-riscv64 \  
-M virt \  
-nographic \  
-bios output/images/fw_jump.elf \  
-kernel output/images/Image \  
-append "root=/dev/vda ro" \  
-drive file=output/images/rootfs.ext2,format=raw,id=hd0 \  
-device virtio-blk-device,drive=hd0 \  
-netdev user,id=net0 \  
-device virtio-net-device,netdev=net0
```

0.1.2.3.3.2. GNU Hurd

#### **0.1.2.3.4. RISC-V Distribution 0.1.2.3.4.1. GNU Debian**

#### **0.1.2.3.4.2. GNU Fedora**

#### **Running Fedora**

type:

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

qemu-system-riscv64 \
-nographic \
-machine virt \
-smp 4 \
-m 2G \
-kernel Fedora-RISCV.elf \
-bios none \
-object rng-random,filename=/dev/urandom,id=rng0 \
-device virtio-rng-device,rng=rng0 \
-device virtio-blk-device,drive=hd0 \
-drive file=Fedora-RISCV.raw,format=raw,id=hd0 \
-device virtio-net-device,netdev=usernet \
-netdev user,id=usernet,hostfwd=tcp::10000-:22
```

## **0.2. OPEN SOURCE PHILOSOPHY**

### **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

type:

```
sudo apt update
sudo apt upgrade
```

### **0.2.1. Open Source Hardware**

#### **0.2.1.1. MSP430 Processing Unit**

#### **0.2.1.2. OpenRISC Processing Unit**

#### **0.2.1.3. RISC-V Processing Unit**

### **0.2.2. Open Source Software**

#### **0.2.2.1. MSP430 GNU Compiler Collection**

#### **0.2.2.2. OpenRISC GNU Compiler Collection**

#### **0.2.2.3. RISC-V GNU Compiler Collection**

## **0.3. INSTRUCTION SET ARCHITECTURE**

### **0.3.1. RISC-V ISA**

#### **0.3.1.1. ISA Bases**

### 0.3.1.1.1. RISC-V 32

### 0.3.1.1.2. RISC-V 64

### 0.3.1.1.3. RISC-V 128

### 0.3.1.2. ISA Extensions

#### 0.3.1.2.1. Base Integer Instruction Set RV32I : Base Integer Instruction Set (32 bit)

| RV32I            | 31:25   | 24:20  | 19:15  | 14:12 | 11:7  | 6:0     |
|------------------|---------|--------|--------|-------|-------|---------|
| LUI RD, IMM      | IIIIII  | IIII   | IIII   | III   | RD4:0 | 0110111 |
| AUIPIC 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 |

#### RV64I : Base Integer Instruction Set (64 bit)

| 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 |
| SRLI RD, RS1,IMM | 0000000 | IIII   | RS14:0 | 001   | RD4:0 | 0010011 |
| SRAI RD, RS1,IMM | 0100000 | IIII   | RS14:0 | 001   | RD4:0 | 0010011 |
| ADDIW RD, RS1    | IIIIII  | IIII   | RS14:0 | 000   | RD4:0 | 0011011 |
| SLLIW RD, RS1    | 0000000 | IIII   | RS14:0 | 001   | RD4:0 | 0011011 |
| SRLIW RD, RS1    | 0000000 | IIII   | RS14:0 | 101   | RD4:0 | 0011011 |
| SRAIW RD, RS1    | 0100000 | IIII   | 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 |

**0.3.1.2.2. Standard Extension for Integer Multiply and Divide RV32M : Standard Extension for Integer Multiply and Divide (32 bit)**

| 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 |

**Standard Extension for Integer Multiply and Divide (64 bit)**

| 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 |

**0.3.1.2.3. Standard Extension for Atomic Instructions RV32A : Standard Extension for Atomic Instructions (32 bit)**

| 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 |



| RV32A                     | 31:25     | 24:20  | 19:15  | 14:12 | 11:7  | 6:0     |
|---------------------------|-----------|--------|--------|-------|-------|---------|
| 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 |

#### RV64A : Standard Extension for Atomic Instructions (64 bit)

| 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 |

#### 0.3.1.2.4. Standard Extension for Single-Precision Floating-Point RV32F : Standard Extension for Single-Precision Floating-Point (32 bit)

| 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.WS RM,RD,FRS1             | 1100000 | 00000 | FRS1  | RM    | FRD  | 1010011 |
| FCVT.WUS RM,RD,FRS1            | 1100000 | 00010 | FRS1  | RM    | FRD  | 1010011 |
| FCVT.SW RM,RD,FRS1             | 1101000 | 00000 | FRS1  | RM    | FRD  | 1010011 |
| FCVT.SWU RM,RD,FRS1            | 1101000 | 00010 | FRS1  | RM    | FRD  | 1010011 |
| FMV.XS RD,FRS1                 | 1110000 | 00000 | FRS1  | 000   | RD   | 1010011 |

| RV32F            | 31:25   | 24:20 | 19:15 | 14:12 | 11:7 | 6:0     |
|------------------|---------|-------|-------|-------|------|---------|
| FCLASS.S RD,FRS1 | 1110000 | 00000 | FRS1  | 001   | RD   | 1010011 |
| FMV.S.X RD,FRS1  | 1111000 | 00000 | RS1   | 000   | FRD  | 1010011 |

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

| 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 |
| FCVT.S.L RM,RD,FRS1  | 1101000 | 00010 | FRS1  | RM    | FRD  | 1010011 |
| FCVT.S.LU RM,RD,FRS1 | 1101000 | 00011 | FRS1  | RM    | FRD  | 1010011 |

#### 0.3.1.2.5. Standard Extension for Double-Precision Floating-Point RV32D : Standard Extension for Double-Precision Floating-Point (32 bit)

| RV32F                          | 31:25   | 24:20 | 19:15 | 14:12 | 11:7  | 6:0     |
|--------------------------------|---------|-------|-------|-------|-------|---------|
| FLW FRD,RS1                    | IIIIII  | IIIII | FRS1  | 011   | FRD   | 0000111 |
| FSW FRS2,RS1                   | IIIIII  | FRS2  | FRS1  | 011   | IIIII | 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 |

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

| 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 |

|                 |         |       |       |       |      |         |
|-----------------|---------|-------|-------|-------|------|---------|
| RV64D           | 31:25   | 24:20 | 19:15 | 14:12 | 11:7 | 6:0     |
| FMV.D.X RD,FRS1 | 1111001 | 00000 | RS1   | 000   | FRD  | 1010011 |

### 0.3.1.3. ISA Modes

#### 0.3.1.3.1. RISC-V User

#### 0.3.1.3.2. RISC-V Supervisor

#### 0.3.1.3.3. RISC-V Hypervisor

#### 0.3.1.3.4. RISC-V Machine

### 0.3.2. OpenRISC ISA

#### 0.3.2.1. ISA Bases

#### 0.3.2.2.1. OpenRISC 32

#### 0.3.2.2.2. OpenRISC 64

#### 0.3.2.2.3. OpenRISC 128

#### 0.3.2.2. ISA Extensions

#### 0.3.2.3. ISA Modes

#### 0.3.2.3.1. OpenRISC User

#### 0.3.2.3.2. OpenRISC Supervisor

#### 0.3.2.3.3. OpenRISC Hypervisor

#### 0.3.2.3.4. OpenRISC Machine

### 0.3.3. MSP430 ISA

#### 0.3.3.1. ISA Bases

#### 0.3.3.2.1. MSP430 32

#### 0.3.3.2.2. MSP430 64

#### 0.3.3.2.3. MSP430 128

#### 0.3.3.2. ISA Extensions

#### 0.3.3.3. ISA Modes

#### 0.3.3.3.1. MSP430 User

#### 0.3.3.3.2. MSP430 Supervisor

#### 0.3.3.3.3. MSP430 Hypervisor

#### 0.3.3.3.4. MSP430 Machine

## 1. METHODOLOGY



Figure 2: Project Workflow

### 1.1. Requirements



Figure 3: UML Diagrams Overview

#### 1.1.1. Structural UML diagrams

##### 1.1.1.1. Class diagram

##### 1.1.1.2. Component diagram

##### 1.1.1.3. Composite diagram

##### 1.1.1.4. Deployment diagram

- 1.1.1.5. Object diagram
- 1.1.1.6. Package diagram
- 1.1.1.7. Profile diagram
- 1.1.2. Behavioral UML diagrams
  - 1.1.2.1. Activity diagram
  - 1.1.2.2. Communication diagram
  - 1.1.2.3. Interaction diagram
  - 1.1.2.4. Sequence diagram
  - 1.1.2.5. State diagram
  - 1.1.2.6. Timing diagram
  - 1.1.2.7. Use diagram
- 1.2. Source
  - 1.2.1. Ada Language
  - 1.2.2. C Language
- 1.3. Model
  - 1.3.1. VHDL
  - 1.3.2. Verilog
- 1.5. Validation
  - 1.5.1. VHDL
  - 1.5.2. Verilog
- 1.5. Design
  - 1.5.1. VHDL
  - 1.5.2. Verilog
- 1.6. Verification
  - 1.6.1. OSVVM-VHDL
    - 1.6.1.1. OSVVM Checker
    - 1.6.1.2. OSVVM Stimulus
    - 1.6.1.3. OSVVM Testbench
  - 1.6.2. UVM-Verilog
    - 1.6.2.1. UVM Agent



Figure 4: UVM Diagram Overview

#### 1.6.2.2. UVM Driver

#### 1.6.2.3. UVM Enviroment

#### 1.6.2.4. UVM Monitor

#### 1.6.2.5. UVM Scoreboard

#### 1.6.2.6. UVM Sequence

#### 1.6.2.7. UVM Sequencer

#### 1.6.2.8. UVM Subscriber

#### 1.6.2.9. UVM Test

#### 1.6.2.10. UVM Testbench

#### 1.6.2.11. UVM Transaction

## 2. PROJECTS

### 2.1. INTERFACE

#### 2.1.1. INSTRUCTION CACHE

##### 2.1.1.1 Instruction INPUTS/OUTPUTS AMBA4 AXI-Lite Bus

#### 2.1.1.1.1. 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                  |

#### 2.1.1.1.2. 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               |

#### 2.1.1.1.3. 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                         |

#### 2.1.1.2. 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      |

| Port       | Size | Direction | Description                           |
|------------|------|-----------|---------------------------------------|
| 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         |

### 2.1.1.3. 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         |

### 2.1.2. DATA CACHE

#### 2.1.2.1. Data INPUTS/OUTPUTS AMBA4 AXI-Lite Bus

##### 2.1.2.1.1. 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                  |

##### 2.1.2.1.2. 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               |

#### 2.1.2.1.3. 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                         |

#### 2.1.2.2. 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         |

#### 2.1.2.3. 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               |
| dsel  | DW/8 | Input     | Byte Select Signals           |
| dwe   | 1    | Input     | Write Enable Input            |

| Port | Size | Direction | Description                     |
|------|------|-----------|---------------------------------|
| 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         |

## 2.2. FUNCTIONALITY

### 2.2.1. Structure

### 2.2.2. Behavior

## 2.3. REGISTERS

## 2.4. INTERRUPTIONS

# 3. ORGANIZATION

## 3.1. Mechanics

## 3.2. Information

### 3.2.1. Bit

### 3.2.2. Logic Gate

#### 3.2.2.1. YES/NOT Gate

#### 3.2.2.2. AND/NAND Gate

#### 3.2.2.3. OR/NOR Gate

#### 3.2.2.4. XOR/XNOR Gate

### 3.2.3. Combinational Logic

#### 3.2.3.1. Arithmetic Circuits

#### 3.2.3.2. Logic Circuits

### 3.2.4. Finite State Machine

### 3.2.5. Pushdown Automaton

## 3.3. Neural Network

### 3.3.1. Feedforward Neural Network

### 3.3.2. Long Short Term Memory Neural Network

### 3.3.3. Transformer Neural Network

## 3.4. Turing Machine

### 3.4.1. Neural Turing Machine

#### 3.4.1.1. Feedforward Neural Turing Machine

#### **3.4.1.2. LSTM Neural Turing Machine**

#### **3.4.1.3. Transformer Neural Turing Machine**

### **3.4.2. Differentiable Neural Computer**

#### **3.4.2.1. Feedforward Differentiable Neural Computer**

#### **3.4.2.2. LSTM Differentiable Neural Computer**

#### **3.4.2.3. Transformer Differentiable Neural Computer**

## **3.5. Computer Architecture**

### **3.5.1. von Neumann Architecture**

#### **3.5.1.1. Control Unit**

#### **3.5.1.2. ALU**

#### **3.5.1.3. Memory Unit**

#### **3.5.1.4. I/O Unit**

### **3.5.2. Harvard Architecture**

#### **3.5.2.1. Control Unit**

#### **3.5.2.2. ALU**

#### **3.5.2.3. Memory Unit**

#### **3.5.2.4. I/O Unit**

## **3.6. Advanced Computer Architecture**

### **3.6.1. Processing Unit**

#### **3.6.1.1. SISD**

#### **3.6.1.2. SIMD**

#### **3.6.1.3. MISD**

#### **3.6.1.4. MIMD**

# **4. HARDWARE WORKFLOW**

## **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.

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

Front-End and Back-End 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 tclsh
```

Synthesizer Library type:

```
sudo apt update
sudo apt upgrade
```

```
sudo apt -y install build-essential clang bison flex \
libreadline-dev gawk tcl-dev libffi-dev git make gnat \
graphviz xdot pkg-config python3 libboost-system-dev \
libboost-python-dev libboost-filesystem-dev zlib1g-dev
```

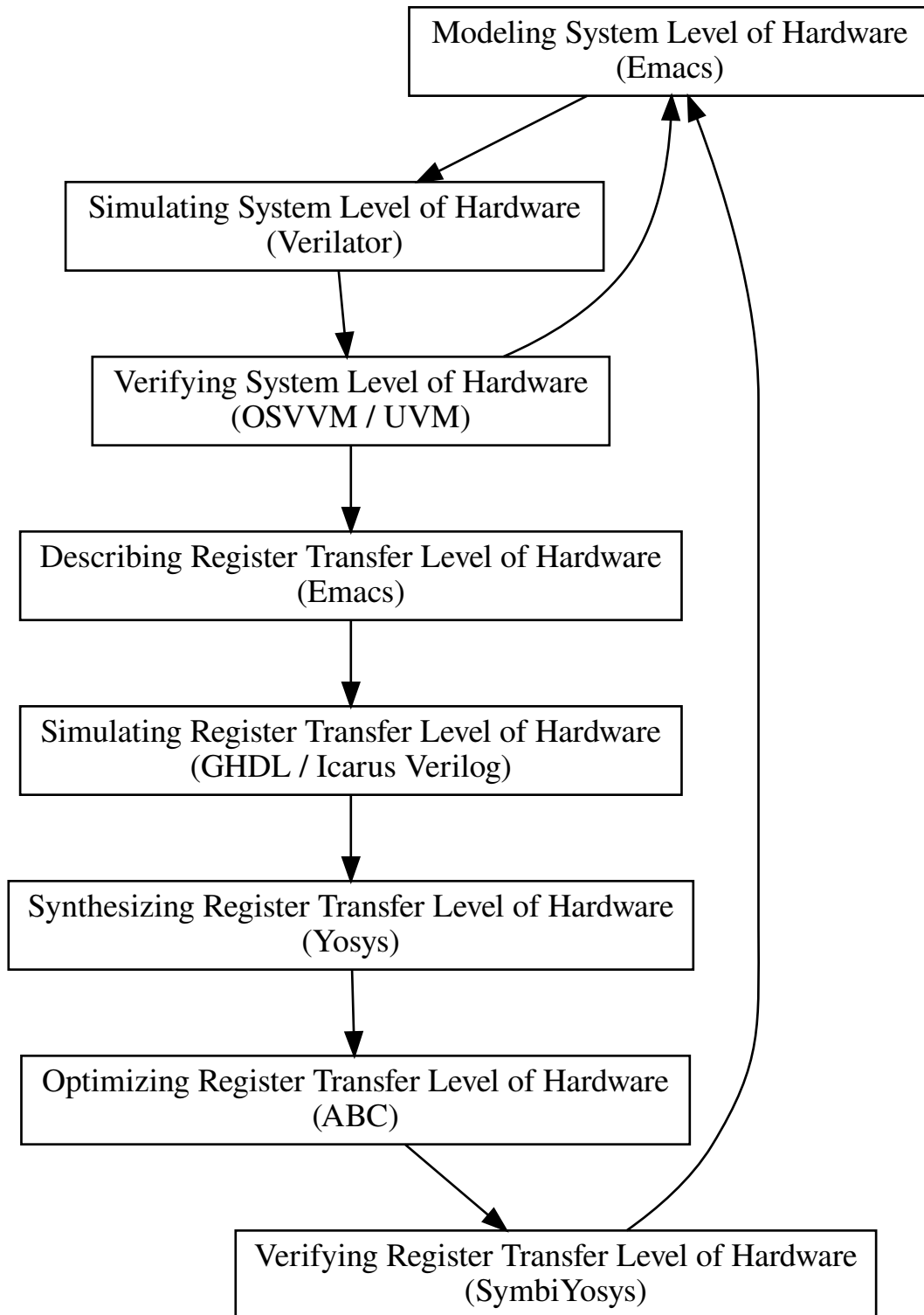


Figure 5: Front-End

## 4.1. FRONT-END OPEN SOURCE TOOLS

### 4.1.1. Modeling System Level of Hardware

*A System Description Language Editor is a computer tool that 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
```

### 4.1.2. 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/vtor
source SIMULATE-IT

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

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

### 4.1.3. 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
```

### 4.1.4. 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
```

### 4.1.5. 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
```

### 4.1.6. 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 for Plugin:

```
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

cd synthesis/yosys
source SYNTHESIZE-IT
```

#### 4.1.7. 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
```

#### 4.1.8. 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
```



## 4.2. BACK-END OPEN SOURCE TOOLS

### 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
```

#### 4.2.1. 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
```

#### 4.2.2. 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 ..
```



Figure 6: Back-End

```
make
sudo make install
```

#### 4.2.3. Timing Switch Level of Hardware

*A Standard Cell Timing-Analyzer 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-Analyzer

type:

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

```
cd OpenSTA
mkdir build
cd build
cmake ..
make
sudo make install
```

#### 4.2.4. 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
```

#### 4.2.5. 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
```

#### 4.2.6. 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
```

#### 4.2.7. 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
```

#### 4.2.8. 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
```

## 5. SOFTWARE WORKFLOW

### 5.1. BACK-END OPEN SOURCE TOOLS

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
```

#### 5.1.1. MSP430

##### 5.1.1.1. MSP430 GNU C/C++

##### 5.1.1.2. MSP430 GNU Go

#### 5.1.2. OpenRISC

##### 5.1.2.1. OpenRISC GNU C/C++

##### 5.1.2.2. OpenRISC GNU Go

#### 5.1.3. RISC-V

##### 5.1.3.1. RISC-V GNU C/C++ type:

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

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

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

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

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

##### 5.1.3.2. RISC-V GNU Go type:

```
git clone --recursive https://go.googlesource.com/go riscv-go
cd riscv-go/src
./all.bash
cd ../../
sudo mv riscv-go /opt
```

## 5.2. FRONT-END OPEN SOURCE TOOLS

### 5.2.1. MSP430

### 5.2.2. OpenRISC

### 5.2.3. RISC-V

type:

```
sudo apt install device-tree-compiler libglib2.0-dev libpixmap-1-dev pkg-config
```

#### 5.2.3.1. Hardware Engineers Compiler: Spike Building Proxy Kernel

type:

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

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

```
cd riscv-pk
mkdir build
cd build
../configure --prefix=/opt/riscv-elf-gcc --host=riscv64-unknown-elf
make
sudo make install
```

#### Building Spike

type:

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

```
git clone --recursive https://github.com/riscv/riscv-isa-sim
```

```
cd riscv-isa-sim
mkdir build
cd build
../configure --prefix=/opt/riscv-elf-gcc
make
sudo make install
```

#### 5.2.3.2. Software Engineers Compiler: QEMU type:

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

```
git clone --recursive https://github.com/qemu/qemu
```

```
cd qemu
./configure --prefix=/opt/riscv-elf-gcc \
--target-list=riscv64-sofmmu,riscv32-sofmmu,riscv64-linux-user,riscv32-linux-user
make
sudo make install
```

## **6. QUALITY ASSURANCE**

### **6.1. SCOPE**

### **6.2. NORMATIVE REFERENCE**

### **6.3. TERMS AND DEFINITIONS**

### **6.4. CONTEXT OF THE ORGANIZATION**

#### **6.4.1. Understanding the organization and its context**

#### **6.4.2. Understanding the needs and expectations of interested parties**

#### **6.4.3. Determining the scope of the quality management system**

#### **6.4.4. Quality management system and its processes**

### **6.5. LEADERSHIP**

#### **6.5.1. Leadership and commitment**

##### **6.5.1.1. General**

##### **6.5.1.2. Customer focus**

#### **6.5.2. Policy**

##### **6.5.2.1. Establishing the quality policy**

##### **6.5.2.2. Communicating the quality policy**

#### **6.5.3. Organizational roles, responsibilities and authorities**

### **6.6. PLANNING**

#### **6.6.1. Actions to address risks and opportunities**

#### **6.6.2. Quality objectives and planning to achieve them**

#### **6.6.3. Planning of changes**

### **6.7. SUPPORT**

#### **6.7.1. Resources**

##### **6.7.1.1. General**

##### **6.7.1.2. People**

##### **6.7.1.3. Infrastructure**

##### **6.7.1.4. Environment for the operation of process**

##### **6.7.1.5. Monitoring and measuring resources**

###### **6.7.1.5.1. General**

###### **6.7.1.5.2. Measurement traceability**

6.7.1.6. Organizational knowledge

6.7.2. Competence

6.7.3. Awareness

6.7.4. Communication

6.7.5. Documented information

6.7.5.1. General

6.7.5.2. Creating and updating

6.7.5.3. Control of documented information

## 6.8. OPERATION

6.8.1. Operational planning and control

6.8.2. Requirements for products and services

6.8.2.1. Customer communication

6.8.2.2. Determining the requirements for products and services

6.8.2.3. Review of the requirements for products and services

6.8.2.4. Changes to requirements for products and services

6.8.3. Design and development of products and services

6.8.3.1. General

6.8.3.2. Design and development planning

6.8.3.3. Design and development inputs

6.8.3.4. Design and development controls

6.8.3.5. Design and development outputs

6.8.4. Control of externally provided processes, products and services

6.8.4.1. General

6.8.4.2. Type and extent of control

6.8.4.3. Information for external providers

6.8.5. Production and service provision

6.8.5.1. Control of production and service provision

6.8.5.2. Identification and traceability



6.8.5.3. Property belonging to customers or external providers

6.8.5.4. Preservation

6.8.5.5. Post-delivery activities

6.8.5.6. Control of changes

6.8.6. Release of products and services

6.8.7. Control of nonconforming outputs

## 6.9. PERFORMANCE EVALUATION

6.9.1. Monitoring, measurement, analysis and evaluation

6.9.1.1. General

6.9.1.2. Customer satisfaction

6.9.1.3. Analysis and evaluation

6.9.2. Internal audit

6.9.3. Management review

6.9.3.1. General

6.9.3.2. Management review inputs

6.9.3.3. Management review outputs

## **6.10. IMPROVEMENT**

### **6.10.1. General**

### **6.10.2. Nonconformity and corrective action**

### **6.10.3. Continual improvement**

## **7. CERTIFICATION**

### **7.1. PLANNING PROCESS**

#### **7.1.1. Planning Process Objectives**

#### **7.1.2. Planning Process Activities**

### **7.2. HARDWARE DESIGN PROCESS**

#### **7.2.1. Requirements Capture Process**

#### **7.2.2. Conceptual Design Process**

#### **7.2.3. Detailed Design Process**

#### **7.2.4. Implementation Process**

#### **7.2.5. Production Transition**

#### **7.2.6. Acceptance Test**

#### **7.2.7. Series Production**

### **7.3. VALIDATION AND VERIFICATION PROCESS**

#### **7.3.1. Validation Process**

#### **7.3.2. Verification Process**

#### **7.3.3. Validation and Verification Methods**

### **7.4. CONFIGURATION MANAGEMENT PROCESS**

#### **7.4.1. Configuration Management Objectives**

#### **7.4.2. Configuration Management Activities**

#### **7.4.3. Data Control Categories**

### **7.5. PROCESS ASSURANCE**

#### **7.5.1. Process Assurance Objectives**

#### **7.5.2. Process Assurance Activities**

### **7.6. CERTIFICATION LIAISON PROCESS**

#### **7.6.1. Means of Compliance and Planning**

#### **7.6.2. Compliance Substantiation**

### **7.7. HARDWARE DESIGN LIFECYCLE DATA**

#### **7.7.1. Hardware Plans**

##### **7.7.1.1. Plan for Hardware Aspects of Certification**

##### **7.7.1.2. Hardware Design Plan**

- 7.7.1.3. Hardware Validation Plan**
- 7.7.1.4. Hardware Verification Plan**
- 7.7.1.5. Hardware Configuration Management Plan**
- 7.7.1.6. Hardware Process Assurance Plan**
- 7.7.2. Hardware Design Standards and Guidance**
  - 7.7.2.1. Requirements Standards**
  - 7.7.2.2. Hardware Design Standards**
  - 7.7.2.3. Validation and Verification Standards**
  - 7.7.2.4. Hardware Archive Standards**
- 7.7.3. Hardware Design Data**
  - 7.7.3.1. Hardware Requirements**
  - 7.7.3.2. Hardware Design Representation Data**
    - 7.7.3.2.1. Conceptual Design Data**
    - 7.7.3.2.2. Detailed Design Data**
      - 7.7.3.2.2.1. Top-Level Drawing**
      - 7.7.3.2.2.2. Assembly Drawings**
      - 7.7.3.2.2.3. Installation Control Drawings**
      - 7.7.3.2.2.4. Hardware/Software Interface Data**
- 7.7.4. Validation and Verification Data**
  - 7.7.4.1. Traceability Data**
  - 7.7.4.2. Review and Analysis Procedures**
  - 7.7.4.3. Review and Analysis Results**
  - 7.7.4.4. Test Procedures**
  - 7.7.4.5. Test Results**
- 7.8. ADDITIONAL CONSIDERATIONS**
  - 7.8.1. Use of Previously Developed Hardware**
  - 7.8.2. Commercial Components Usage**
  - 7.8.3. Product Service Experience**
  - 7.8.4. Tool Assessment and Qualification**