

Random Access Memory for a Multi-Processor System on Chip

QueenField

1. INTRODUCTION

1.1. 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
```

1.2.1. Open Source Hardware

1.2.1.1. MSP430 Processing Unit

1.2.1.2. OpenRISC Processing Unit

1.2.1.3. RISC-V Processing Unit

1.2.2. Open Source Software

1.2.2.1. MSP430 GNU Compiler Collection

1.2.2.2. OpenRISC GNU Compiler Collection

1.2.2.3. RISC-V GNU Compiler Collection

1.2. RISC-V ISA

1.2.1. ISA Bases

1.2.2.1. RISC-V 32

1.2.2.2. RISC-V 64

1.2.2.3. RISC-V 128

1.2.2. ISA Extensions

1.2.2.1. 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 |
| 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 |
| LLI 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 |
| LLI 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 |

| RV64I | 31:25 | 24:20 | 19:15 | 14:12 | 11:7 | 6:0 |
|------------------|---------|--------|--------|-------|-------|---------|
| 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 |

1.2.2.2. 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 |

1.2.2.3. 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 |
| 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 |
| AMOOR.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 |

1.2.2.4. 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 |
| FCLASS.S RD,FRS1 | 1110000 | 00000 | FRS1 | 001 | RD | 1010011 |
| FMV.SX 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 |

1.2.2.5. 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 |
| FMV.D.X RD,FRS1 | 1111001 | 00000 | RS1 | 000 | FRD | 1010011 |

1.2.3. ISA Modes

1.2.3.1. RISC-V User

1.2.3.2. RISC-V Supervisor

1.2.3.3. RISC-V Hypervisor

1.2.3.4. RISC-V Machine

1.3. OpenRISC ISA

1.3.1. ISA Bases

1.3.2.1. OpenRISC 32

1.3.2.2. OpenRISC 64

1.3.2.3. OpenRISC 128

1.3.2. ISA Extensions

1.3.3. ISA Modes

1.3.3.1. OpenRISC User

1.3.3.2. OpenRISC Supervisor

1.3.3.3. OpenRISC Hypervisor

1.3.3.4. OpenRISC Machine

1.4. MSP430 ISA

1.4.1. ISA Bases

1.4.2.1. MSP430 32

1.4.2.2. MSP430 64

1.4.2.3. MSP430 128

1.4.2. ISA Extensions

1.4.3. ISA Modes

1.4.3.1. MSP430 User

1.4.3.2. MSP430 Supervisor

1.4.3.3. MSP430 Hypervisor

1.4.3.4. MSP430 Machine

2. PROJECTS

A Random Access Memory (RAM) is a computer memory that can be read and changed in any order, typically used to store working data and machine code. A RAM device allows data items to be read or written in almost the same amount of time irrespective of the physical location of data inside the memory. RAM contains multiplexing and demultiplexing circuitry, to connect the data lines to the addressed storage for reading or writing the entry.

2.1. Random Access Memory for a Processing Unit

2.1.1. Functionality

2.1.1.1. Organization

| Core | Module description |
|-------------------------------|------------------------------------|
| <code>mpsoc_axi4_spram</code> | Single-Port RAM for AMBA4 AXI-Lite |

| Core | Module description |
|---|------------------------------------|
| <code>mpsoc_ahb3_spram</code> | Single-Port RAM for AMBA3 AHB-Lite |
| <code>...mpsoc_ram_1r1w</code> | RAM Wrapper |
| <code>....mpsoc_ram_1r1w_generic</code> | RAM Generic Module |

| Core | Module description |
|--------------------------------------|------------------------------|
| <code>mpsoc_wb_spram</code> | Single-Port RAM for WishBone |
| <code>...mpsoc_wb_ram_generic</code> | RAM Generic Module |

2.1.1.2. Parameters

2.1.2. Interface

2.1.3. Registers

2.1.4. Interruptions

2.2. Random Access Memory for a System on Chip

2.2.1. Functionality

2.2.1.1. Organization

2.2.1.2. Parameters

2.2.2. Interface

2.2.3. Registers

2.2.4. Interruptions

2.3. Random Access Memory for a Multi-Processor System on Chip

2.3.1. Functionality

2.3.1.1. Organization

2.3.1.2. Parameters

2.3.2. Interface

2.3.3. Registers

2.3.4. Interruptions

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)*.

SystemVerilog System Description Language Editor

type:

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

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

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 --recursive http://git.veripool.org/git/verilator
```

```
cd verilator
autoconf
./configure
make
sudo make install

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

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

cd sim/verilog/tests/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 --recursive https://github.com/QueenField/UVM

cd sim/verilog/pu/riscv/wb/msim
source SIMULATE-IT

cd sim/verilog/pu/riscv/ahb3/msim
source SIMULATE-IT
```

```
cd sim/verilog/pu/riscv/axi4/msim
source SIMULATE-IT
```

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.

VHDL/Verilog Hardware Description Language Editor

type:

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

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

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.

Verilog Hardware Description Language Simulator

type:

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

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

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

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

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

VHDL Hardware Description Language Simulator

type:

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

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

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

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

cd sim/vhdl/tests/axi4/ghdl
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 --recursive https://github.com/YosysHQ/yosys

cd yosys
make
sudo make install
```

VHDL Hardware Description Language Synthesizer

type:

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

cd yosys
make
sudo make install
```

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 --recursive https://github.com/YosysHQ/SymbiYosys
```

3.1.2. Back-End Open Source Tools

I. Back-End Workflow Qflow for ASICs

type:

```
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
```

type:

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

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

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 --recursive 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 --recursive 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-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 --recursive 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 --recursive 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 --recursive 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 --recursive https://github.com/RTimothyEdwards/netgen

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

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 --recursive 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 --recursive https://github.com/RTimothyEdwards/magic

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

II. Back-End Workflow Symbiflow for FPGAs

3.2. SOFTWARE

3.2.1. Compilers

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
```

3.2.1.1. 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
```

3.2.1.2. 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
```

3.2.2. Simulators

type:

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

3.2.2.1. Spike (For Hardware Engineers)

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

```

3.2.2.2. QEMU (For Software Engineers)

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

```

4. CONCLUSION

4.1. HARDWARE

```

cd synthesis/yosys
source SYNTHESIZE-IT

```

4.1.1. GSCL 45 nm ASIC

type:

```

cd synthesis/qflow
source FLOW-IT

```

4.1.2. Lattice iCE40 FPGA

type:

```

cd synthesis/symbiflow
source FLOW-IT

```

4.2. SOFTWARE

4.2.1. 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

```

4.2.2. 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!")
}

```

4.2.3. RISC-V Operating System

4.2.3.1. 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
```

4.2.3.2. GNU Hurd

4.2.4. RISC-V Distribution

4.2.4.1. GNU Debian

4.2.4.2. GNU Fedora