

Learn RISC-V CPU Implementation and BSV

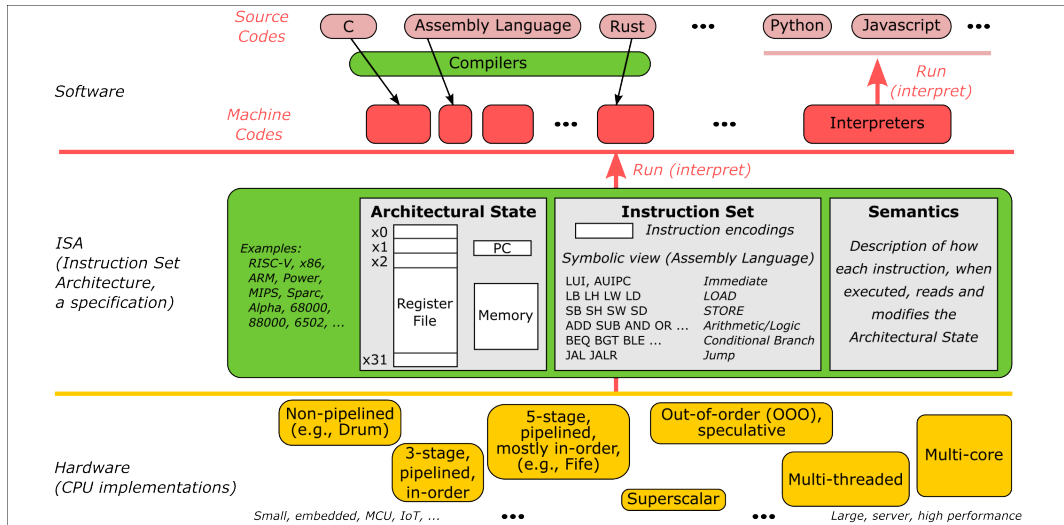
(BSV: a High-Level Hardware Design Language)

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L2: Overview of the RISC-V ISA



What is an ISA?



Architectural State

The “architectural state” is the state that is visible to instructions. For RV32I, these are:

- The PC (program counter)
- 32 General-Purpose Registers (GPRs, the “register file”)
- Memory (byte-addressed)

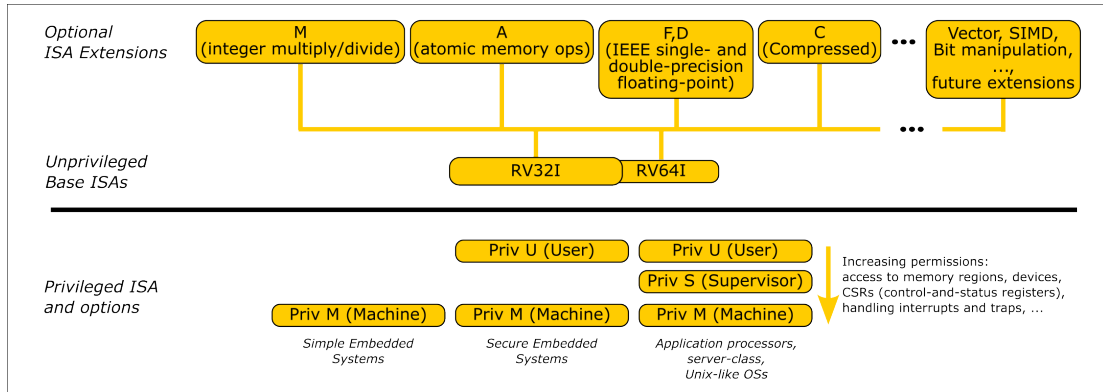
(More architectural state is defined for RV64I, and for most extensions A, F, D, Vector, ...)

The architectural state *does not include* other registers, buffers, FIFOs, memories that may be present in an implementation (they are not visible to instructions).

As such, the architectural state is present in every RISC-V implementation, from tiny CPUs for IoT devices to massive warehouse-scale servers.

Compilers only care about/know about architectural state.

Modularity of the RISC-V ISA



RISC-V Instruction Encodings

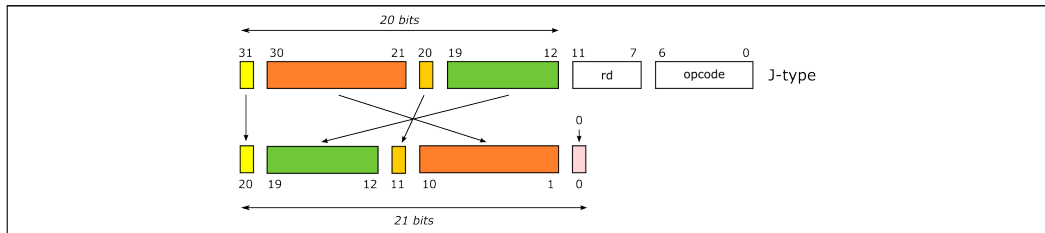
From the RISC-V specification documents:

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31	27	26	25	24	20	19	15	14	12	11	7	6	0	
funct7				rs2		rs1		funct3		rd		opcode		R-type
imm[11:0]						rs1		funct3		rd		opcode		I-type
imm[11:5]				rs2		rs1		funct3		imm[4:0]		opcode		S-type
imm[12 10:5]				rs2		rs1		funct3		imm[4:1 11]		opcode		B-type
imm[31:12]										rd		opcode		U-type
imm[20 10:1 11 19:12]										rd		opcode		J-type

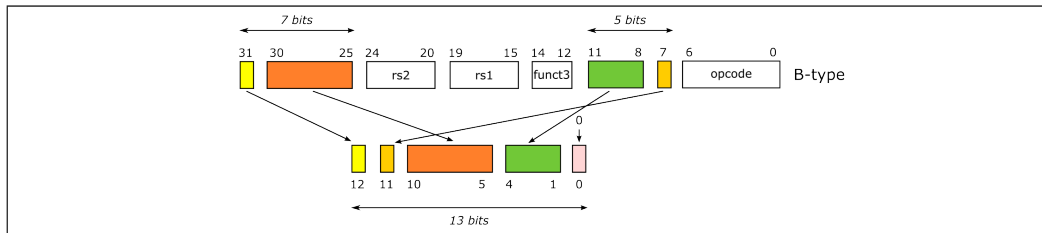
RISC-V Instruction Encodings; J-type immediates



For JAL instruction

RISC-V Instruction Encodings; B-type immediates

For BRANCH set of instructions (BEQ, BNE, BLT, BGE, BLTU, BGEU)



RV32I Instructions

RV32I Base Instruction Set

imm[31:12]				rd		0110111	LUI	↑ "load immediate"-kind: to load constant values into a register		
imm[31:12]				rd		0010111	AUIPC			
imm[20:10:11]19:12				rd		1101111	JAL	↑ "jump-and-link"-kind: subroutine calls and returns; distant jumps		
imm[11:0]				rd		1100111	JALR			
imm[12:10:5]		rs2	rs1	000	imm[4:1:11]	1100011	BEQ	↑ "conditional branch"-kind: test and possibly jump up to ~0x1000 distance		
imm[12:10:5]		rs2	rs1	001	imm[4:1:11]	1100011	BNE			
imm[12:10:5]		rs2	rs1	100	imm[4:1:11]	1100011	BLT			
imm[12:10:5]		rs2	rs1	101	imm[4:1:11]	1100011	BGE			
imm[12:10:5]		rs2	rs1	110	imm[4:1:11]	1100011	BLTU			
imm[12:10:5]		rs2	rs1	111	imm[4:1:11]	1100011	BGEU	↑ "load data from memory into register" (rs1 and imm specify address)		
imm[11:0]			rs1	000	rd	0000011	LB			
imm[11:0]			rs1	001	rd	0000011	LH			
imm[11:0]			rs1	010	rd	0000011	LW			
imm[11:0]			rs1	100	rd	0000011	LBU			
imm[11:0]			rs1	101	rd	0000011	LHU	↑ "store data from register rs2 to memory" (rs1 and imm specify address)		
imm[11:5]		rs2	rs1	000	imm[4:0]	0100011	SB			
imm[11:5]		rs2	rs1	001	imm[4:0]	0100011	SH			
imm[11:5]		rs2	rs1	010	imm[4:0]	0100011	SW			
imm[11:0]			rs1	000	rd	0010011	ADDI			
imm[11:0]			rs1	010	rd	0010011	SLTI	↑ "integer arithmetic operations (register-immediate)"		
imm[11:0]			rs1	011	rd	0010011	SLTIU			
imm[11:0]			rs1	100	rd	0010011	XORI			
imm[11:0]			rs1	110	rd	0010011	ORI			
imm[11:0]			rs1	111	rd	0010011	ANDI			
0000000		shamt	rs1	001	rd	0010011	SLLI			
0000000		shamt	rs1	101	rd	0010011	SRLI			
0100000		shamt	rs1	101	rd	0010011	SRAI			
0000000		rs2	rs1	000	rd	0110011	ADD			
0100000		rs2	rs1	000	rd	0110011	SUB			
0000000		rs2	rs1	001	rd	0110011	SLL	↑ "integer arithmetic operations (register-register)"		
0000000		rs2	rs1	010	rd	0110011	SLT			
0000000		rs2	rs1	011	rd	0110011	SLTU			
0000000		rs2	rs1	100	rd	0110011	XOR			
0000000		rs2	rs1	101	rd	0110011	SRL			
0100000		rs2	rs1	101	rd	0110011	SRA			
0000000		rs2	rs1	110	rd	0110011	OR			
0000000		rs2	rs1	111	rd	0110011	AND			
fm		pred	succ	rs1	000	rd	0001111		FENCE	↑ "system" operations (ignore FENCE for now)
000000000000			00000	000	00000	1110011	ECALL			
000000000001			00000	000	00000	1110011	EBREAK			

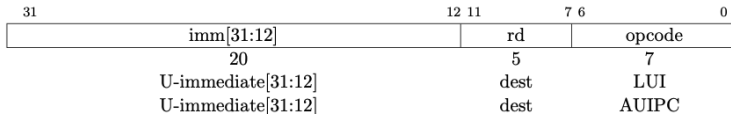
Example specifications

Excerpt from text of ISA specification document for LUI and AUIPC instructions

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SRLI is a logical right shift (zeros are shifted into the upper bits); and SRAI is an arithmetic right shift (the original sign bit is copied into the vacated upper bits).



LUI (load upper immediate) is used to build 32-bit constants and uses the U-type format. LUI places the U-immediate value in the top 20 bits of the destination register *rd*, filling in the lowest 12 bits with zeros.

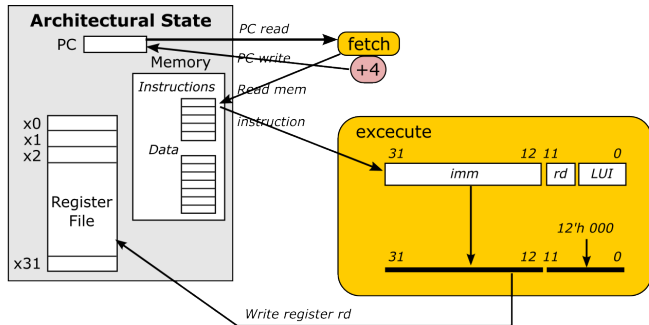
AUIPC (add upper immediate to *pc*) is used to build *pc*-relative addresses and uses the U-type format. AUIPC forms a 32-bit offset from the 20-bit U-immediate, filling in the lowest 12 bits with zeros, adds this offset to the address of the AUIPC instruction, then places the result in register *rd*.

Execution semantics: example

Execution semantics of LUI instruction

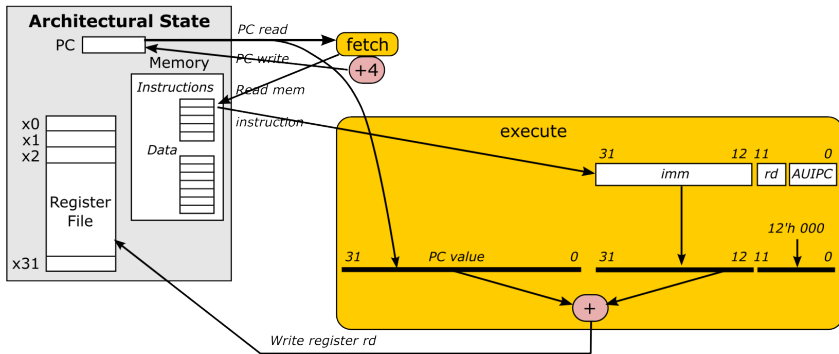
CPU operation

loop forever:
instr = fetch (PC)
execute (instr)



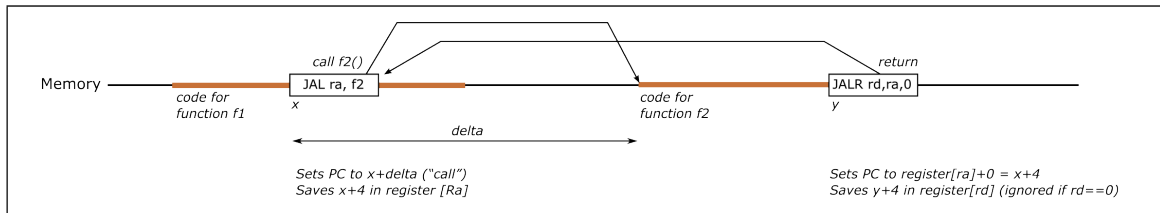
Execution semantics: example

Execution semantics of AUIPC instruction

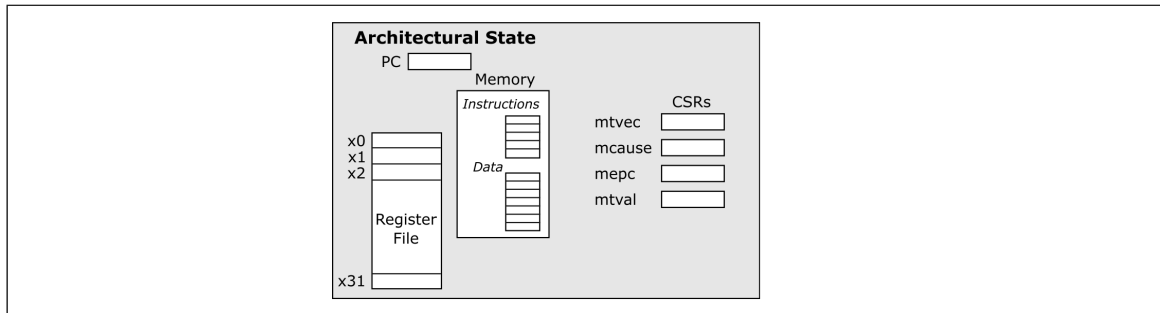


Execution semantics: example

Execution semantics of JAL and JALR instructions (unconditional jumps)

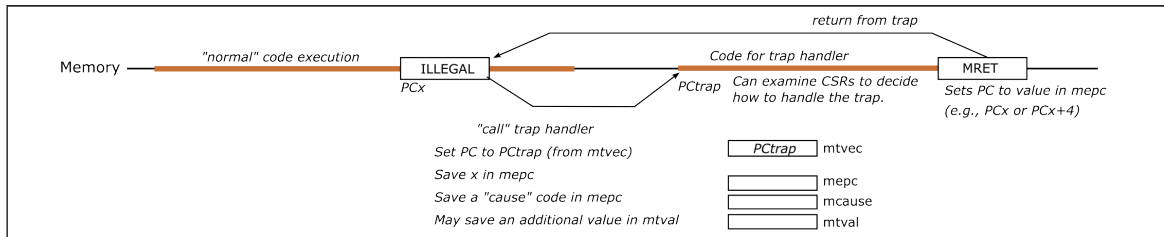


Control and Status Registers (CSRs) for Trap-Handling



These CSRs are implicitly read and written when taking and returning from a trap. These CSRs can be explicitly read and written by CSRRxx instructions.

Trap and Trap-return flow



There are many possible causes for exceptions and traps;
the illustration is for an illegal instruction.

Exception causes

On a trap, a cause-code is written into the `mcause` CSR:

Exception-Cause code	Description
0	Instruction address misaligned
1	Instruction access fault
2	Illegal instruction
3	Breakpoint
4	Load address misaligned
5	Load access fault
6	Store/AMO address misaligned
7	Store/AMO access fault
...	...
11	Environment call M-mode
...	...

CSRRxx Instructions

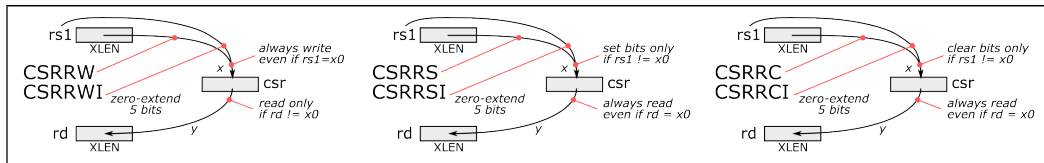
For reading and writing CSRs from RISC-V code
(from the RISC-V ISA specifications document)

9.1 CSR Instructions

All CSR instructions atomically read-modify-write a single CSR, whose CSR specifier is encoded in the 12-bit *csr* field of the instruction held in bits 31–20. The immediate forms use a 5-bit zero-extended immediate encoded in the *rs1* field.

31	20 19	15 14	12 11	7 6	0
csr		rs1	funct3	rd	opcode
12		5	3	5	7
source/dest		source	CSRRW	dest	SYSTEM
source/dest		source	CSRRS	dest	SYSTEM
source/dest		source	CSRRC	dest	SYSTEM
source/dest		uimm[4:0]	CSRRWI	dest	SYSTEM
source/dest		uimm[4:0]	CSRRSI	dest	SYSTEM
source/dest		uimm[4:0]	CSRRCI	dest	SYSTEM

CSRRxx Instruction Semantics



- They all move potentially data into a CSR, and from a CSR to a GPR
- The non “I” variants take input from GPR[rs1] (unless rs1 is zero)
- The “I” variants use rs1 itself as input (unless rs1 is zero)

RV64I instructions

From the RISC-V ISA specifications document

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31	27	26	25	24	20	19	15	14	12	11	7	6	0	
funct7				rs2		rs1		funct3		rd		opcode		R-type
imm[11:0]						rs1		funct3		rd		opcode		I-type
imm[11:5]				rs2		rs1		funct3		imm[4:0]		opcode		S-type

RV64I Base Instruction Set (in addition to RV32I)

imm[11:0]				rs1		110		rd		0000011		LWU
imm[11:0]				rs1		011		rd		0000011		LD
imm[11:5]				rs2		rs1		011		imm[4:0]		SD
000000				shamt		rs1		001		rd		SLLI
000000				shamt		rs1		101		rd		SRLI
010000				shamt		rs1		101		rd		SRAI
imm[11:0]				rs1		000		rd		0011011		ADDIW
0000000				shamt		rs1		001		rd		SLLIW
0000000				shamt		rs1		101		rd		SRLIW
0100000				shamt		rs1		101		rd		SRAIW
0000000				rs2		rs1		000		rd		ADDW
0100000				rs2		rs1		000		rd		SUBW
0000000				rs2		rs1		001		rd		SLLW
0000000				rs2		rs1		101		rd		SRLW
0100000				rs2		rs1		101		rd		SRAW

RV64I instructions

In RV64, the 32 GPRs (General Purpose Registers) are each 64-bits wide.

- Most of the RV32I instructions have identical RV64I counterparts (here they operate on 64-bit values).
- A few instructions (SLLI, SRLI, SRAI) are slightly different (allowing 6 bits instead of 5 for the shift amount).
- A few instructions are new, to operate on 32-bit values in the 64-bit registers.
 - LWU to move a 32-bit value from memory into a 64-bit register
 - LD to load a 64-bit value from memory to a 64-bit register
 - SD to store a 64-bit value to memory from 64-bit register
 - ADDIW, SLLIW, ... SRAW to operate on 32-bits of 64-bit registers

End