

# RISC-V REFERENCE

James Zhu <jameszhu@berkeley.edu>

## RISC-V Instruction Set

### Core Instruction Formats

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

### RV32I Base Integer Instructions

Inst	Name	FMT	Opcode	funct3	funct7	Description (C)	Note
add	ADD	R	0110011	000	0000000	rd = rs1 + rs2	
sub	SUB	R	0110011	000	0100000	rd = rs1 - rs2	
xor	XOR	R	0110011	100	0000000	rd = rs1 ^ rs2	
or	OR	R	0110011	110	0000000	rd = rs1   rs2	
and	AND	R	0110011	111	0000000	rd = rs1 & rs2	
sll	Shift Left Logical	R	0110011	001	0000000	rd = rs1 << rs2	
srl	Shift Right Logical	R	0110011	010	0000000	rd = rs1 >> rs2	
sra	Shift Right Arith*	R	0110011	011	0100000	rd = rs1 >> rs2	msb-extends
slt	Set Less Than	R	0110011	010		rd = (rs1 < rs2)?1:0	
sltu	Set Less Than (U)	R	0110011	011		rd = (rs1 < rs2)?1:0	zero-extends
addi	ADD Immediate	I	0010011	000	0000000	rd = rs1 + imm	
xori	XOR Immediate	I	0010011	100	0000000	rd = rs1 ^ imm	
ori	OR Immediate	I	0010011	110	0000000	rd = rs1   imm	
andi	AND Immediate	I	0010011	111	0000000	rd = rs1 & imm	
slli	Shift Left Logical Imm	I	0010011	001	0000000	rd = rs1 << imm	
srlr	Shift Right Logical Imm	I	0010011	001	0000000	rd = rs1 >> imm	
srai	Shift Right Arith Imm	I	0010011	011	0100000	rd = rs1 >> imm	msb-extends
slti	Set Less Than Imm	I	0010011	010		rd = (rs1 < imm)?1:0	
sltiu	Set Less Than Imm (U)	I	0010011	011		rd = (rs1 < imm)?1:0	zero-extends
lb	Load Byte	I	0000011	000		rd = M[rs1+imm][0:7]	
lh	Load Half	I	0000011	001		rd = M[rs1+imm][0:15]	
lw	Load Word	I	0000011	010		rd = M[rs1+imm][0:31]	
lbu	Load Byte (U)	I	0000011	100		rd = M[rs1+imm][0:7]	zero-extends
lhu	Load Half (U)	I	0000011	101		rd = M[rs1+imm][0:15]	zero-extends
sb	Store Byte	S	0100011	000		M[rs1+imm][0:7] = rs2[0:7]	
sh	Store Half	S	0100011	001		M[rs1+imm][0:15] = rs2[0:15]	
sw	Store Word	S	0100011	010		M[rs1+imm][0:31] = rs2[0:31]	
beq	Branch ==	B	1100011	000		if(rs1 == rs2) PC += imm	
bne	Branch !=	B	1100011	001		if(rs1 != rs2) PC += imm	
blt	Branch <	B	1100011	100		if(rs1 < rs2) PC += imm	
bge	Branch ≥	B	1100011	101		if(rs1 ≥ rs2) PC += imm	
bltu	Branch < (U)	B	1100011	110		if(rs1 < rs2) PC += imm	zero-extends
bgeu	Branch ≥ (U)	B	1100011	111		if(rs1 ≥ rs2) PC += imm	zero-extends
jal	Jump And Link	J	1101111			rd = PC+4; PC += imm	
jalr	Jump And Link Reg	I	1100111	000		rd = PC+4; PC = rs1 + imm	
lui	Load Upper Imm	U	0110111			rd = imm << 12	
auipc	Add Upper Imm to PC	U	0010111			rd = PC + (imm << 12)	
ecall	Environment Call	I	1110011	000	0000000	Transfer control to OS	imm: 0x000
ebreak	Environment Break	I	1110011	000	0000000	Transfer control to debugger	imm: 0x001

## Standard Extensions

### RV32M Multiply Extension

Inst	Name	FMT	Opcode	funct3	funct7	Description (C)
mul	MUL	R	0110011	000	0000001	rd = (rs1 * rs2)[31:0]
mulh	MUL High	R	0110011	001	0000001	rd = (rs1 * rs2)[63:32]
mulsu	MUL High (S) (U)	R	0110011	010	0000001	rd = (rs1 * rs2)[63:32]
mulu	MUL High (U)	R	0110011	011	0000001	rd = (rs1 * rs2)[63:32]
div	DIV	R	0110011	100	0000001	rd = rs1 / rs2
divu	DIV (U)	R	0110011	101	0000001	rd = rs1 / rs2
rem	Remainder	R	0110011	110	0000001	rd = rs1 % rs2
remu	Remainder (U)	R	0110011	111	0000001	rd = rs1 % rs2

### RV32A Atomic Extension

31		27		26	25		24		20		19	15		14	12		11	7		6	0			
funct5				aq		rl		rs2			rs1			funct3		rd			opcode					
5				1		1		5			5			3		5			7					
Inst	Name							FMT	Opcode		funct3		funct5		Description (C)									
lr.w	Load Reserved							R	0101111		010		00010		rd = M[rs1], reserve M[rs1]									
sc.w	Store Conditional							R	0101111		010		00011		if (reserved) { M[rs1] = rs2; rd = 0 } else { rd = 1 }									
amoswap.w	Atomic Swap							R	0101111		010		00001		rd = M[rs1]; swap(rd, rs2); M[rs1] = rd									
amoadd.w	Atomic ADD							R	0101111		010		00000		rd = M[rs1] + rs2; M[rs1] = rd									
amoand.w	Atomic AND							R	0101111		010		01100		rd = M[rs1] & rs2; M[rs1] = rd									
amoor.w	Atomic OR							R	0101111		010		01010		rd = M[rs1]   rs2; M[rs1] = rd									
amoxor.w	Atomix XOR							R	0101111		010		00100		rd = M[rs1] ^ rs2; M[rs1] = rd									
amomax.w	Atomic MAX							R	0101111		010		10100		rd = max(M[rs1], rs2); M[rs1] = rd									
amomin.w	Atomic MIN							R	0101111		010		10000		rd = min(M[rs1], rs2); M[rs1] = rd									

## RV32F Single-Precision Floating-Point Extension

R4-type instructions								
<div> <div>31</div> <div>27 26 25 24 20 19</div> <div>15 14</div> <div>12 11</div> <div>7 6</div> <div>0</div> </div>								
<div> <div>rs3</div> <div>fmt</div> <div>rs2</div> <div>rs1</div> <div>funct3</div> <div>rd</div> <div>opcode</div> </div>								
<div> <div>5</div> <div>2</div> <div>5</div> <div>5</div> <div>3</div> <div>5</div> <div>7</div> </div>								
Inst	Name	FMT	Opcode	funct3/rm	funct7	rs2 [20...24]	fmt	Description (C)
f1w	Flt Load Word	I	0000111	010				rd = M[rs1 + imm]
fsw	Flt Store Word	I	0100111	010				M[rs1 + imm] = rs2
fadd.s	Flt Add	R	1010011		0000000			rd = rs1 + rs2
fsub.s	Flt Sub	R	1010011		0000100			rd = rs1 - rs2
fmul.s	Flt Mul	R	1010011		0001000			rd = rs1 * rs2
fdiv.s	Flt Div	R	1010011		0001100			rd = rs1 / rs2
fsgnj.s	Flt Sign Injection	R	1010011	000	0010000			rd = abs(rs1) * sgn(rs2)
fsgnjn.s	Flt Sign Neg Injection	R	1010011	001	0010000			rd = abs(rs1) * -sgn(rs2)
fsgnjx.s	Flt Sign Xor Injection	R	1010011	010	0010000			rd = rs1 * sgn(rs2)
fmin.s	Flt Minimum	R	1010011		0010100			rd = min(rs1, rs2)
fmax.s	Flt Maximum	R	1010011		0010100			rd = max(rs1, rs2)
fsqrt.s	Flt Square Root	R	1010011		0101100	00000		rd = sqrt(rs1)
fle.s	Float Less / Equal	R	1010011	000	1010000			rd = (rs1 <= rs2) ? 1 : 0
flt.s	Float Less Than	R	1010011	001	1010000			rd = (rs1 < rs2) ? 1 : 0
feq.s	Float Equality	R	1010011	010	1010000			rd = (rs1 == rs2) ? 1 : 0
fcvt.w.s	Flt Convert to Int	R	1010011		1100000	00000		rd = (int32_t) rs1
fcvt.wu.s	Flt Convert to Int	R	1010011		1100000	00001		rd = (uint32_t) rs1
fmv.x.w	Move Float to Int	R	1010011	000	1110000	00000		rd = *((int*) &rs1)
fclass.s	Float Classify	R	1010011	001	1110000	00000		rd = 0..9
fcvt.s.w	Flt Conv from Sign Int	R	1010011		1101000	00000		rd = (float) rs1
fcvt.s.wu	Flt Conv from Uns Int	R	1010011		1101000	00001		rd = (float) rs1
fmv.w.x	Move Int to Float	R	1010011	000	1111000	00000		rd = *((float*) &rs1)
fmadd.s	Flt Fused Mul-Add	R4	1000011				00	rd = rs1 * rs2 + rs3
fmsub.s	Flt Fused Mul-Sub	R4	1000111				00	rd = rs1 * rs2 - rs3
fnmadd.s	Flt Neg Fused Mul-Add	R4	1001011				00	rd = -rs1 * rs2 + rs3
fnmsub.s	Flt Neg Fused Mul-Sub	R4	1001111				00	rd = -rs1 * rs2 - rs3

**RV32D Double-Precision Floating-Point Extension**

Inst	Name	FMT	Opcode	funct3/rm	funct7	rs2 [20...24]	fmt	Description (C)
fld	Flt Load Word	I	0000111	011				rd = M[rs1 + imm]
fsd	Flt Store Word	I	0100111	011				M[rs1 + imm] = rs2
fadd.d	Flt Add	R	1010011		0000001			rd = rs1 + rs2
fsub.d	Flt Sub	R	1010011		0000101			rd = rs1 - rs2
fmul.d	Flt Mul	R	1010011		0001001			rd = rs1 * rs2
fdiv.d	Flt Div	R	1010011		0001101			rd = rs1 / rs2
fsgnj.d	Flt Sign Injection	R	1010011	000	0010001			rd = abs(rs1) * sgn(rs2)
fsgnjn.d	Flt Sign Neg Injection	R	1010011	001	0010001			rd = abs(rs1) * -sgn(rs2)
fsgnjx.d	Flt Sign Xor Injection	R	1010011	010	0010001			rd = rs1 * sgn(rs2)
fmin.d	Flt Minimum	R	1010011		0010101			rd = min(rs1, rs2)
fmax.d	Flt Maximum	R	1010011		0010101			rd = max(rs1, rs2)
fsqrt.d	Flt Square Root	R	1010011		0101101	00000		rd = sqrt(rs1)
fle.d	Float Less / Equal	R	1010011	000	1010001			rd = (rs1 <= rs2) ? 1 : 0
flt.d	Float Less Than	R	1010011	001	1010001			rd = (rs1 < rs2) ? 1 : 0
feq.d	Float Equality	R	1010011	010	1010001			rd = (rs1 == rs2) ? 1 : 0
fcvt.w.d	Flt Convert to Int	R	1010011		1100001	00000		rd = (int32_t) rs1
fcvt.wu.d	Flt Convert to Int	R	1010011		1100001	00001		rd = (uint32_t) rs1
fcvt.s.d	Double Flt to Single	R	1010011	000	0100000	00001		rd = *((float*) &rs1)
fmv.x.d	Move Int to Float	R	1010011	000	1111001	00000		rd = *((float*) &rs1)
fclass.d	Float Classify	R	1010011	001	1110001	00000		rd = 0..9
fcvt.d.w	Flt Conv from Sign Int	R	1010011		1101001	00000		rd = (float) rs1
fcvt.d.wu	Flt Conv from Uns Int	R	1010011		1101001	00001		rd = (float) rs1
fcvt.d.s	Single Flt to Double	R	1010011	000	0100001	00001		rd = *((float*) &rs1)
fmadd.d	Flt Fused Mul-Add	R4	1000011				01	rd = rs1 * rs2 + rs3
fmsub.d	Flt Fused Mul-Sub	R4	1000111				01	rd = rs1 * rs2 - rs3
fnmadd.d	Flt Neg Fused Mul-Add	R4	1001011				01	rd = -rs1 * rs2 + rs3
fnmsub.d	Flt Neg Fused Mul-Sub	R4	1001111				01	rd = -rs1 * rs2 - rs3

## RV32Q Quad-Precision Floating-Point Extension

Inst	Name	FMT	Opcode	funct3/rm	funct7	rs2 [20...24]	fmt	Description (C)
f1q	Flt Load Word	I	0000111	100				rd = M[rs1 + imm]
fsq	Flt Store Word	I	0100111	100				M[rs1 + imm] = rs2
fadd.q	Flt Add	R	1010011		0000011			rd = rs1 + rs2
fsub.q	Flt Sub	R	1010011		0000111			rd = rs1 - rs2
fmul.q	Flt Mul	R	1010011		0001011			rd = rs1 * rs2
fdiv.q	Flt Div	R	1010011		0001111			rd = rs1 / rs2
fsgnj.q	Flt Sign Injection	R	1010011	000	0010011			rd = abs(rs1) * sgn(rs2)
fsgnjn.q	Flt Sign Neg Injection	R	1010011	001	0010011			rd = abs(rs1) * -sgn(rs2)
fsgnjx.q	Flt Sign Xor Injection	R	1010011	010	0010011			rd = rs1 * sgn(rs2)
fmin.q	Flt Minimum	R	1010011		0010111			rd = min(rs1, rs2)
fmax.q	Flt Maximum	R	1010011		0010111			rd = max(rs1, rs2)
fsqrt.q	Flt Square Root	R	1010011		0101111	00000		rd = sqrt(rs1)
fle.q	Float Less / Equal	R	1010011	000	1010011			rd = (rs1 <= rs2) ? 1 : 0
flt.q	Float Less Than	R	1010011	001	1010011			rd = (rs1 < rs2) ? 1 : 0
feq.q	Float Equality	R	1010011	010	1010011			rd = (rs1 == rs2) ? 1 : 0
fcvt.w.q	Flt Convert to Int	R	1010011		1100011	00000		rd = (int32_t) rs1
fcvt.wu.q	Flt Convert to Int	R	1010011		1100011	00001		rd = (uint32_t) rs1
fcvt.s.q	Quad Flt to Single	R	1010011	000	0100000	00001		rd = *((float*) &rs1)
fcvt.d.q	Quad Flt to Double	R	1010011	000	0100001	00001		rd = *((float*) &rs1)
fmv.x.q	Move Int to Float	R	1010011	000	1111011	00000		rd = *((float*) &rs1)
fclass.q	Float Classify	R	1010011	001	1110011	00000		rd = 0..9
fcvt.q.w	Flt Conv from Sign Int	R	1010011		1101011	00000		rd = (float) rs1
fcvt.q.wu	Flt Conv from Uns Int	R	1010011		1101011	00001		rd = (float) rs1
fcvt.q.s	Single Flt to Quad	R	1010011	000	0100011	00000		rd = *((float*) &rs1)
fcvt.q.d	Double Flt to Quad	R	1010011	000	0100011	00001		rd = *((float*) &rs1)
fmadd.q	Flt Fused Mul-Add	R4	1000011				11	rd = rs1 * rs2 + rs3
fmsub.q	Flt Fused Mul-Sub	R4	1000111				11	rd = rs1 * rs2 - rs3
fnmadd.q	Flt Neg Fused Mul-Add	R4	1001011				11	rd = -rs1 * rs2 + rs3
fnmsub.q	Flt Neg Fused Mul-Sub	R4	1001111				11	rd = -rs1 * rs2 - rs3

## RV32C Compressed Extension

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
funct4				rd/rs1				rs2				op		CR-type		
funct3		imm	rd/rs1				imm				op		CI-type			
funct3		imm						rs2				op		CSS-type		
funct3		imm								rd'		op		CIW-type		
funct3		imm		rs1'		imm		rd'		op		CL-type				
funct3		imm		rd'/rs1'		imm		rs2'		op		CS-type				
funct3		imm		rs1'		imm		op		CB-type						
funct3		offset										op		CJ-type		

Inst	Name	FMT	OP	Funct	Description
c.lwsp	Load Word from SP	CI	10	010	lw rd, (4*imm)(sp)
c.swsp	Store Word to SP	CSS	10	110	sw rs2, (4*imm)(sp)
c.lw	Load Word	CL	00	010	lw rd', (4*imm)(rs1')
c.sw	Store Word	CS	00	110	sw rs1', (4*imm)(rs2')
c.j	Jump	CJ	01	101	jal x0, 2*offset
c.jal	Jump And Link	CJ	01	001	jal ra, 2*offset
c.jr	Jump Reg	CR	10	1000	jalr x0, rs1, 0
c.jalr	Jump And Link Reg	CR	10	1001	jalr ra, rs1, 0
c.beqz	Branch == 0	CB	01	110	beq rs', x0, 2*imm
c.bnez	Branch != 0	CB	01	111	bne rs', x0, 2*imm
c.li	Load Immediate	CI	01	010	addi rd, x0, imm
c.lui	Load Upper Imm	CI	01	011	lui rd, imm
c.addi	ADD Immediate	CI	01	000	addi rd, rd, imm
c.addi16sp	ADD Imm * 16 to SP	CI	01	011	addi sp, sp, 16*imm
c.addi4spn	ADD Imm * 4 + SP	CIW	00	000	addi rd', sp, 4*imm
c.slli	Shift Left Logical Imm	CI	10	000	slli rd, rd, imm
c.srli	Shift Right Logical Imm	CB	01	100x00	srli rd', rd', imm
c.srai	Shift Right Arith Imm	CB	01	100x01	srai rd', rd', imm
c.andi	AND Imm	CB	01	100x10	andi rd', rd', imm
c.mv	MoVe	CR	10	1000	add rd, x0, rs2
c.add	ADD	CR	10	1001	add rd, rd, rs2
c.and	AND	CS	01	10001111	and rd', rd', rs2'
c.or	OR	CS	01	10001110	or rd', rd', rs2'
c.xor	XOR	CS	01	10001101	xor rd', rd', rs2'
c.sub	SUB	CS	01	10001100	sub rd', rd', rs2'
c.nop	No OPeration	CI	01	000	addi x0, x0, 0
c.ebreak	Environment BREAK	CR	10	1001	ebreak

## Pseudo Instructions

Pseudoinstruction	Base Instruction(s)	Meaning
la rd, symbol	auipc rd, symbol[31:12] addi rd, rd, symbol[11:0]	Load address
l{b h w d} rd, symbol	auipc rd, symbol[31:12] l{b h w d} rd, symbol[11:0](rd)	Load global
s{b h w d} rd, symbol, rt	auipc rt, symbol[31:12] s{b h w d} rd, symbol[11:0](rt)	Store global
fl{w d} rd, symbol, rt	auipc rt, symbol[31:12] fl{w d} rd, symbol[11:0](rt)	Floating-point load global
fs{w d} rd, symbol, rt	auipc rt, symbol[31:12] fs{w d} rd, symbol[11:0](rt)	Floating-point store global
nop	addi x0, x0, 0	No operation
li rd, immediate	<i>Myriad sequences</i>	Load immediate
mv rd, rs	addi rd, rs, 0	Copy register
not rd, rs	xori rd, rs, -1	One's complement
neg rd, rs	sub rd, x0, rs	Two's complement
negw rd, rs	subw rd, x0, rs	Two's complement word
sext.w rd, rs	addiw rd, rs, 0	Sign extend word
seqz rd, rs	sltiu rd, rs, 1	Set if = zero
snez rd, rs	sltu rd, x0, rs	Set if $\neq$ zero
sltz rd, rs	slt rd, rs, x0	Set if < zero
sgtz rd, rs	slt rd, x0, rs	Set if > zero
fmv.s rd, rs	fsgnj.s rd, rs, rs	Copy single-precision register
fabs.s rd, rs	fsgnjx.s rd, rs, rs	Single-precision absolute value
fneg.s rd, rs	fsgnjn.s rd, rs, rs	Single-precision negate
fmv.d rd, rs	fsgnj.d rd, rs, rs	Copy double-precision register
fabs.d rd, rs	fsgnjx.d rd, rs, rs	Double-precision absolute value
fneg.d rd, rs	fsgnjd.d rd, rs, rs	Double-precision negate
beqz rs, offset	beq rs, x0, offset	Branch if = zero
bnez rs, offset	bne rs, x0, offset	Branch if $\neq$ zero
blez rs, offset	bge x0, rs, offset	Branch if $\leq$ zero
bgez rs, offset	bge rs, x0, offset	Branch if $\geq$ zero
bltz rs, offset	blt rs, x0, offset	Branch if < zero
bgtz rs, offset	blt x0, rs, offset	Branch if > zero
bgt rs, rt, offset	blt rt, rs, offset	Branch if >
ble rs, rt, offset	bge rt, rs, offset	Branch if $\leq$
bgtu rs, rt, offset	bltu rt, rs, offset	Branch if >, unsigned
bleu rs, rt, offset	bgeu rt, rs, offset	Branch if $\leq$ , unsigned
j offset	jal x0, offset	Jump
jal offset	jal x1, offset	Jump and link
jr rs	jalr x0, rs, 0	Jump register
jalr rs	jalr x1, rs, 0	Jump and link register
ret	jalr x0, x1, 0	Return from subroutine
call offset	auipc x1, offset[31:12] jalr x1, x1, offset[11:0]	Call far-away subroutine
tail offset	auipc x6, offset[31:12] jalr x0, x6, offset[11:0]	Tail call far-away subroutine
fence	fence iorw, iorw	Fence on all memory and I/O

## Registers

Register	ABI Name	Description	Saver
x0	zero	Zero constant	—
x1	ra	Return address	Caller
x2	sp	Stack pointer	—
x3	gp	Global pointer	—
x4	tp	Thread pointer	Callee
x5	t0-t2	Temporaries	Caller
x8	s0 / fp	Saved / frame pointer	Callee
x9	s1	Saved register	Callee
x10-x11	a0-a1	Fn args/return values	Caller
x12-x17	a2-a7	Fn args	Caller
x18-x27	s2-s11	Saved registers	Callee
x28-x31	t3-t6	Temporaries	Caller
f0-7	ft0-7	FP temporaries	Caller
f8-9	fs0-1	FP saved registers	Callee
f10-11	fa0-1	FP args/return values	Caller
f12-17	fa2-7	FP args	Caller
f18-27	fs2-11	FP saved registers	Callee
f28-31	ft8-11	FP temporaries	Caller