

Appendix B. RISC-V Instruction Set Summary

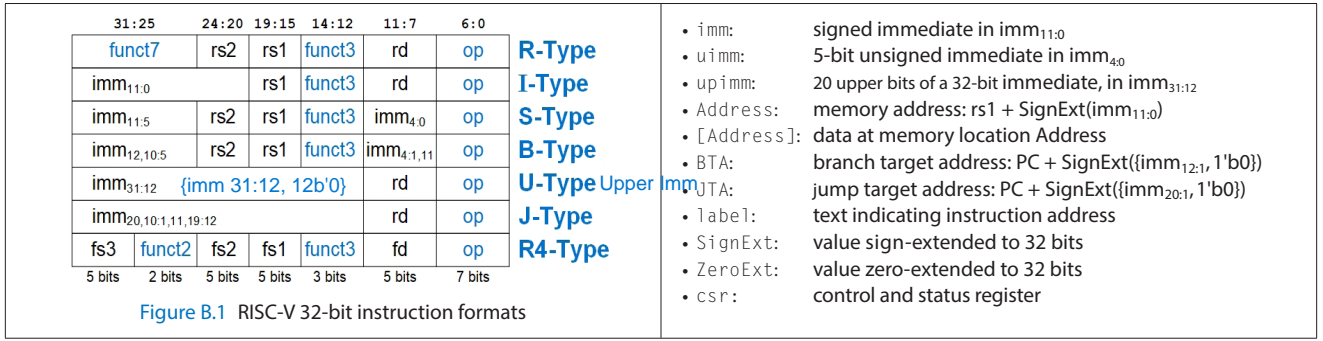


Table B.1 RV32I: RISC-V Integer Instructions

op	funct3	funct7	Type	Instruction	Description	Operation
0000011 (3)	000	–	I	lb rd, imm(rs1)	load byte	rd = SignExt([Address] _{7:0})
0000011 (3)	001	–	I	lh rd, imm(rs1)	load half	rd = SignExt([Address] _{15:0})
0000011 (3)	010	–	I	lw rd, imm(rs1)	load word	rd = [Address] _{31:0}
0000011 (3)	100	–	I	lbu rd, imm(rs1)	load byte unsigned	rd = ZeroExt([Address] _{7:0})
0000011 (3)	101	–	I	lhu rd, imm(rs1)	load half unsigned	rd = ZeroExt([Address] _{15:0})
0010011 (19)	000	–	I	addi rd, rs1, imm	add immediate	rd = rs1 + SignExt(imm)
0010011 (19)	001	0000000*	I	slli rd, rs1, uimm	shift left logical immediate	rd = rs1 << uimm
0010011 (19)	010	–	I	slti rd, rs1, imm	set less than immediate	rd = (rs1 < SignExt(imm))
0010011 (19)	011	–	I	sltiu rd, rs1, imm	set less than imm. unsigned	rd = (rs1 < SignExt(imm))
0010011 (19)	100	–	I	xori rd, rs1, imm	xor immediate	rd = rs1 ^ SignExt(imm)
0010011 (19)	101	0000000*	I	srlr rd, rs1, uimm	shift right logical immediate	rd = rs1 >> uimm
0010011 (19)	101	0100000*	I	srair rd, rs1, uimm	shift right arithmetic imm.	rd = rs1 >>> uimm
0010011 (19)	110	–	I	ori rd, rs1, imm	or immediate	rd = rs1 SignExt(imm)
0010011 (19)	111	–	I	andi rd, rs1, imm	and immediate	rd = rs1 & SignExt(imm)
0010111 (23)	–	–	U	auipc rd, upimm	add upper immediate to PC	rd = {upimm, 12'b0} + PC
0100011 (35)	000	–	S	sb rs2, imm(rs1)	store byte	[Address] _{7:0} = rs2 _{7:0}
0100011 (35)	001	–	S	sh rs2, imm(rs1)	store half	[Address] _{15:0} = rs2 _{15:0}
0100011 (35)	010	–	S	sw rs2, imm(rs1)	store word	[Address] _{31:0} = rs2
0110011 (51)	000	0000000	R	add rd, rs1, rs2	add	rd = rs1 + rs2
0110011 (51)	000	0100000	R	sub rd, rs1, rs2	sub	rd = rs1 – rs2
0110011 (51)	001	0000000	R	sll rd, rs1, rs2	shift left logical	rd = rs1 << rs2 _{4:0}
0110011 (51)	010	0000000	R	slt rd, rs1, rs2	set less than	rd = (rs1 < rs2)
0110011 (51)	011	0000000	R	sltu rd, rs1, rs2	set less than unsigned	rd = (rs1 < rs2)
0110011 (51)	100	0000000	R	xor rd, rs1, rs2	xor	rd = rs1 ^ rs2
0110011 (51)	101	0000000	R	srl rd, rs1, rs2	shift right logical	rd = rs1 >> rs2 _{4:0}
0110011 (51)	101	0100000	R	sra rd, rs1, rs2	shift right arithmetic	rd = rs1 >>> rs2 _{4:0}
0110011 (51)	110	0000000	R	or rd, rs1, rs2	or	rd = rs1 rs2
0110011 (51)	111	0000000	R	and rd, rs1, rs2	and	rd = rs1 & rs2
0110111 (55)	–	–	U	lui rd, upimm	load upper immediate	rd = {upimm, 12'b0}
1100011 (99)	000	–	B	beq rs1, rs2, label	branch if =	if (rs1 == rs2) PC = BTA
1100011 (99)	001	–	B	bne rs1, rs2, label	branch if ≠	if (rs1 ≠ rs2) PC = BTA
1100011 (99)	100	–	B	blt rs1, rs2, label	branch if <	if (rs1 < rs2) PC = BTA
1100011 (99)	101	–	B	bge rs1, rs2, label	branch if ≥	if (rs1 ≥ rs2) PC = BTA
1100011 (99)	110	–	B	bltu rs1, rs2, label	branch if < unsigned	if (rs1 < rs2) PC = BTA
1100011 (99)	111	–	B	bgeu rs1, rs2, label	branch if ≥ unsigned	if (rs1 ≥ rs2) PC = BTA
1100111 (103)	000	–	I	jalr rd, rs1, imm	jump and link register	PC = rs1 + SignExt(imm), rd = PC + 4
1101111 (111)	–	–	J	jal rd, label	jump and link	PC = JTA, rd = PC + 4

*encoded in instr_{31:25}, the upper seven bits of the immediate field

Table B.2 RV64I: Extra integer instructions

op	funct3	funct7	Type	Instruction	Description	Operation
0000011 (3)	011	–	I	ld rd, imm(rs1)	load double word	rd = [Address] _{63:0}
0000011 (3)	110	–	I	lwu rd, imm(rs1)	load word unsigned	rd = ZeroExt([Address] _{31:0})
0011011 (27)	000	–	I	addiw rd, rs1, imm	add immediate word	rd = SignExt((rs1 + SignExt(imm)) _{31:0})
0011011 (27)	001	0000000	I	slliw rd, rs1, uimm	shift left logical immediate word	rd = SignExt((rs1 _{31:0} << uimm) _{31:0})
0011011 (27)	101	0000000	I	srliw rd, rs1, uimm	shift right logical immediate word	rd = SignExt((rs1 _{31:0} >> uimm) _{31:0})
0011011 (27)	101	0100000	I	sraiw rd, rs1, uimm	shift right arith. immediate word	rd = SignExt((rs1 _{31:0} >>> uimm) _{31:0})
0100011 (35)	011	–	S	sd rs2, imm(rs1)	store double word	[Address] _{63:0} = rs2
0111011 (59)	000	0000000	R	addw rd, rs1, rs2	add word	rd = SignExt((rs1 + rs2) _{31:0})
0111011 (59)	000	0100000	R	subw rd, rs1, rs2	subtract word	rd = SignExt((rs1 – rs2) _{31:0})
0111011 (59)	001	0000000	R	sllw rd, rs1, rs2	shift left logical word	rd = SignExt((rs1 _{31:0} << rs2 _{4:0}) _{31:0})
0111011 (59)	101	0000000	R	srlw rd, rs1, rs2	shift right logical word	rd = SignExt((rs1 _{31:0} >> rs2 _{4:0}) _{31:0})
0111011 (59)	101	0100000	R	sraw rd, rs1, rs2	shift right arithmetic word	rd = SignExt((rs1 _{31:0} >>> rs2 _{4:0}) _{31:0})

In RV64I, registers are 64 bits, but instructions are still 32 bits. The term “word” generally refers to a 32-bit value. In RV64I, immediate shift instructions use 6-bit immediates: uimm_{5:0}, but for word shifts, the most significant bit of the shift amount (uimm₅) must be 0. Instructions ending in “w” (for “word”) operate on the lower half of the 64-bit registers. Sign- or zero-extension produces a 64-bit result.

Table B.3 RVF/D: RISC-V single- and double-precision floating-point instructions

op	funct3	funct7	rs2	Type	Instruction	Description	Operation
1000011 (67)	rm	fs3, fmt	–	R4	fmadd fd, fs1, fs2, fs3	multiply-add	fd = fs1 * fs2 + fs3
1000111 (71)	rm	fs3, fmt	–	R4	fmsub fd, fs1, fs2, fs3	multiply-subtract	fd = fs1 * fs2 – fs3
1001011 (75)	rm	fs3, fmt	–	R4	fnmsub fd, fs1, fs2, fs3	negate multiply-add	fd = –(fs1 * fs2 + fs3)
1001111 (79)	rm	fs3, fmt	–	R4	fnmadd fd, fs1, fs2, fs3	negate multiply-subtract	fd = –(fs1 * fs2 – fs3)
1010011 (83)	rm	00000, fmt	–	R	fadd fd, fs1, fs2	add	fd = fs1 + fs2
1010011 (83)	rm	00001, fmt	–	R	fsub fd, fs1, fs2	subtract	fd = fs1 – fs2
1010011 (83)	rm	00010, fmt	–	R	fmul fd, fs1, fs2	multiply	fd = fs1 * fs2
1010011 (83)	rm	00011, fmt	–	R	fdiv fd, fs1, fs2	divide	fd = fs1 / fs2
1010011 (83)	rm	01011, fmt	00000	R	fsqrt fd, fs1	square root	fd = sqrt(fs1)
1010011 (83)	000	00100, fmt	–	R	fsgnj fd, fs1, fs2	sign injection	fd = fs1, sign = sign(fs2)
1010011 (83)	001	00100, fmt	–	R	fsgnjn fd, fs1, fs2	negate sign injection	fd = fs1, sign = –sign(fs2)
1010011 (83)	010	00100, fmt	–	R	fsgnjx fd, fs1, fs2	xor sign injection	fd = fs1, sign = sign(fs2) ^ sign(fs1)
1010011 (83)	000	00101, fmt	–	R	fmin fd, fs1, fs2	min	fd = min(fs1, fs2)
1010011 (83)	001	00101, fmt	–	R	fmax fd, fs1, fs2	max	fd = max(fs1, fs2)
1010011 (83)	010	10100, fmt	–	R	feq rd, fs1, fs2	compare =	rd = (fs1 == fs2)
1010011 (83)	001	10100, fmt	–	R	flt rd, fs1, fs2	compare <	rd = (fs1 < fs2)
1010011 (83)	000	10100, fmt	–	R	fle rd, fs1, fs2	compare ≤	rd = (fs1 ≤ fs2)
1010011 (83)	001	11100, fmt	00000	R	fclass rd, fs1	classify	rd = classification of fs1
RVF only							
0000111 (7)	010	–	–	I	flw fd, imm(rs1)	load float	fd = [Address] _{31:0}
0100111 (39)	010	–	–	S	fsw fs2, imm(rs1)	store float	[Address] _{31:0} = fd
1010011 (83)	rm	1100000	00000	R	fcvt.w.s rd, fs1	convert to integer	rd = integer(fs1)
1010011 (83)	rm	1100000	00001	R	fcvt.wu.s rd, fs1	convert to unsigned integer	rd = unsigned(fs1)
1010011 (83)	rm	1101000	00000	R	fcvt.s.w fd, rs1	convert int to float	fd = float(rs1)
1010011 (83)	rm	1101000	00001	R	fcvt.s.wu fd, rs1	convert unsigned to float	fd = float(rs1)
1010011 (83)	000	1110000	00000	R	fmv.x.w rd, fs1	move to integer register	rd = fs1
1010011 (83)	000	1111000	00000	R	fmv.w.x fd, rs1	move to f.p. register	fd = rs1
RVD only							
0000111 (7)	011	–	–	I	fld fd, imm(rs1)	load double	fd = [Address] _{63:0}
0100111 (39)	011	–	–	S	fsd fs2, imm(rs1)	store double	[Address] _{63:0} = fd
1010011 (83)	rm	1100001	00000	R	fcvt.w.d rd, fs1	convert to integer	rd = integer(fs1)
1010011 (83)	rm	1100001	00001	R	fcvt.wu.d rd, fs1	convert to unsigned integer	rd = unsigned(fs1)
1010011 (83)	rm	1101001	00000	R	fcvt.d.w fd, rs1	convert int to double	fd = double(rs1)
1010011 (83)	rm	1101001	00001	R	fcvt.d.wu fd, rs1	convert unsigned to double	fd = double(rs1)
1010011 (83)	rm	0100000	00001	R	fcvt.s.d fd, fs1	convert double to float	fd = float(fs1)
1010011 (83)	rm	0100001	00000	R	fcvt.d.s fd, fs1	convert float to double	fd = double(fs1)

fs1, fs2, fs3, fd: floating-point registers. fs1, fs2, and fd are encoded in fields rs1, rs2, and rd; only R4-type also encodes fs3. fmt: precision of computational instruction (single=00₂, double=01₂, quad=11₂). rm: rounding mode (0=to nearest, 1=toward zero, 2=down, 3=up, 4=to nearest (max magnitude), 7=dynamic). sign(fs1): the sign of fs1.

Table B.4 Register names and numbers

Name	Register Number	Use
zero	x0	Constant value 0
ra	x1	Return address
sp	x2	Stack pointer
gp	x3	Global pointer
tp	x4	Thread pointer
t0–2	x5–7	Temporary registers
s0/fp	x8	Saved register / Frame pointer
s1	x9	Saved register
a0–1	x10–11	Function arguments / Return values
a2–7	x12–17	Function arguments
s2–11	x18–27	Saved registers
t3–6	x28–31	Temporary registers

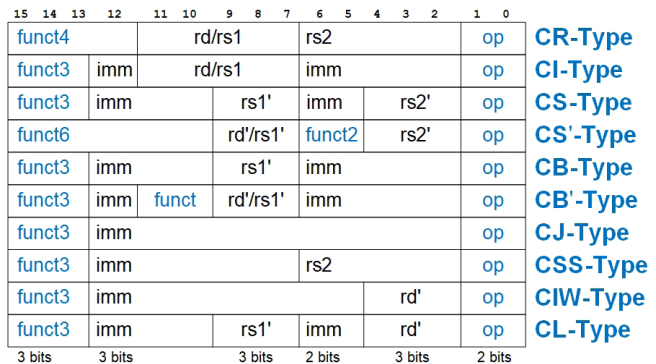


Figure B.2 RISC-V compressed (16-bit) instruction formats

Table B.5 RVM: RISC-V multiply and divide instructions

op	funct3	funct7	Type	Instruction	Description	Operation
0110011 (51)	000	0000001	R	mul rd, rs1, rs2	multiply	$rd = (rs1 * rs2)_{31:0}$
0110011 (51)	001	0000001	R	mulh rd, rs1, rs2	multiply high signed signed	$rd = (rs1 * rs2)_{63:32}$
0110011 (51)	010	0000001	R	mulhsu rd, rs1, rs2	multiply high signed unsigned	$rd = (rs1 * rs2)_{63:32}$
0110011 (51)	011	0000001	R	mulhu rd, rs1, rs2	multiply high unsigned unsigned	$rd = (rs1 * rs2)_{63:32}$
0110011 (51)	100	0000001	R	div rd, rs1, rs2	divide (signed)	$rd = rs1 / rs2$
0110011 (51)	101	0000001	R	divu rd, rs1, rs2	divide unsigned	$rd = rs1 / rs2$
0110011 (51)	110	0000001	R	rem rd, rs1, rs2	remainder (signed)	$rd = rs1 \% rs2$
0110011 (51)	111	0000001	R	remu rd, rs1, rs2	remainder unsigned	$rd = rs1 \% rs2$

Table B.6 RVC: RISC-V compressed (16-bit) instructions

op	instr _{15:10}	funct2	Type	RVC Instruction	32-Bit Equivalent
00 (0)	000---	-	CIW	c.addi4spn rd', sp, imm	addi rd', sp, ZeroExt(imm)*4
00 (0)	001---	-	CL	c.fld fd', imm(rs1')	fld fd', (ZeroExt(imm)*8)(rs1')
00 (0)	010---	-	CL	c.lw rd', imm(rs1')	lw rd', (ZeroExt(imm)*4)(rs1')
00 (0)	011---	-	CL	c.flw fd', imm(rs1')	flw fd', (ZeroExt(imm)*4)(rs1')
00 (0)	101---	-	CS	c.fsd fs2', imm(rs1')	fsd fs2', (ZeroExt(imm)*8)(rs1')
00 (0)	110---	-	CS	c.sw rs2', imm(rs1')	sw rs2', (ZeroExt(imm)*4)(rs1')
00 (0)	111---	-	CS	c.fsw fs2', imm(rs1')	fsw fs2', (ZeroExt(imm)*4)(rs1')
01 (1)	000000	-	CI	c.nop (rs1=0, imm=0)	nop
01 (1)	000---	-	CI	c.addi rd, imm	addi rd, rd, SignExt(imm)
01 (1)	001---	-	CJ	c.jal label	jal ra, label
01 (1)	010---	-	CI	c.li rd, imm	addi rd, x0, SignExt(imm)
01 (1)	011---	-	CI	c.lui rd, imm	lui rd, {14{imm ₅ }, imm}
01 (1)	011---	-	CI	c.addi16sp sp, imm	addi sp, sp, SignExt(imm)*16
01 (1)	100-00	-	CB'	c.srli rd', imm	srli rd', rd', imm
01 (1)	100-01	-	CB'	c.srai rd', imm	srai rd', rd', imm
01 (1)	100-10	-	CB'	c.andi rd', imm	andi rd', rd', SignExt(imm)
01 (1)	100011	00	CS'	c.sub rd', rs2'	sub rd', rd', rs2'
01 (1)	100011	01	CS'	c.xor rd', rs2'	xor rd', rd', rs2'
01 (1)	100011	10	CS'	c.or rd', rs2'	or rd', rd', rs2'
01 (1)	100011	11	CS'	c.and rd', rs2'	and rd', rd', rs2'
01 (1)	101---	-	CJ	c.j label	jal x0, label
01 (1)	110---	-	CB	c.beqz rs1', label	beq rs1', x0, label
01 (1)	111---	-	CB	c.bnez rs1', label	bne rs1', x0, label
10 (2)	000---	-	CI	c.slli rd, imm	slli rd, rd, imm
10 (2)	001---	-	CI	c.fldsp fd, imm	fld fd, (ZeroExt(imm)*8)(sp)
10 (2)	010---	-	CI	c.lwsp rd, imm	lw rd, (ZeroExt(imm)*4)(sp)
10 (2)	011---	-	CI	c.flwsp fd, imm	flw fd, (ZeroExt(imm)*4)(sp)
10 (2)	1000--	-	CR	c.jr rs1 (rs1≠0, rs2=0)	jalr x0, rs1, 0
10 (2)	1000--	-	CR	c.mv rd, rs2 (rd≠0, rs2≠0)	add rd, x0, rs2
10 (2)	1001--	-	CR	c.ebreak (rs1=0, rs2=0)	ebreak
10 (2)	1001--	-	CR	c.jalr rs1 (rs1≠0, rs2=0)	jalr ra, rs1, 0
10 (2)	1001--	-	CR	c.add rd, rs2 (rs1≠0, rs2≠0)	add rd, rd, rs2
10 (2)	101---	-	CSS	c.fsdsp fs2, imm	fsd fs2, (ZeroExt(imm)*8)(sp)
10 (2)	110---	-	CSS	c.swsp rs2, imm	sw rs2, (ZeroExt(imm)*4)(sp)
10 (2)	111---	-	CSS	c.fswsp fs2, imm	fsw fs2, (ZeroExt(imm)*4)(sp)

rs1', rs2', rd': 3-bit register designator for registers 8–15: 000₂ = x8 or f8, 001₂ = x9 or f9, etc.

Table B.7 RISC-V pseudoinstructions

Pseudoinstruction	RISC-V Instructions	Description	Operation
nop	addi x0, x0, 0	no operation	
li rd, imm _{11:0}	addi rd, x0, imm _{11:0}	load 12-bit immediate	rd = SignExtend(imm _{11:0})
li rd, imm _{31:0}	lui rd, imm _{31:12} addi rd, rd, imm _{11:0}	load 32-bit immediate	rd = imm _{31:0}
mv rd, rs1	addi rd, rs1, 0	move (also called “register copy”)	rd = rs1
not rd, rs1	xori rd, rs1, -1	one’s complement	rd = ~rs1
neg rd, rs1	sub rd, x0, rs1	two’s complement	rd = -rs1
seqz rd, rs1	sltiu rd, rs1, 1	set if = 0	rd = (rs1 == 0)
snez rd, rs1	sltu rd, x0, rs1	set if ≠ 0	rd = (rs1 ≠ 0)
sltz rd, rs1	slt rd, rs1, x0	set if < 0	rd = (rs1 < 0)
sgtz rd, rs1	slt rd, x0, rs1	set if > 0	rd = (rs1 > 0)
beqz rs1, label	beq rs1, x0, label	branch if = 0	if (rs1 == 0) PC = label
bnez rs1, label	bne rs1, x0, label	branch if ≠ 0	if (rs1 ≠ 0) PC = label
blez rs1, label	bge x0, rs1, label	branch if ≤ 0	if (rs1 ≤ 0) PC = label
bgez rs1, label	bge rs1, x0, label	branch if ≥ 0	if (rs1 ≥ 0) PC = label
bltz rs1, label	blt rs1, x0, label	branch if < 0	if (rs1 < 0) PC = label
bgtz rs1, label	blt x0, rs1, label	branch if > 0	if (rs1 > 0) PC = label
ble rs1, rs2, label	bge rs2, rs1, label	branch if ≤	if (rs1 ≤ rs2) PC = label
bgt rs1, rs2, label	blt rs2, rs1, label	branch if >	if (rs1 > rs2) PC = label
bleu rs1, rs2, label	bgeu rs2, rs1, label	branch if ≤ (unsigned)	if (rs1 ≤ rs2) PC = label
bgtu rs1, rs2, label	bltu rs2, rs1, offset	branch if > (unsigned)	if (rs1 > rs2) PC = label
j label	jal x0, label	jump	PC = label
jal label	jal ra, label	jump and link	PC = label, ra = PC + 4
jr rs1	jalr x0, rs1, 0	jump register	PC = rs1
jalr rs1	jalr ra, rs1, 0	jump and link register	PC = rs1, ra = PC + 4
ret	jalr x0, ra, 0	return from function	PC = ra
call label	jal ra, label	call nearby function	PC = label, ra = PC + 4
call label	auipc ra, offset _{31:12} jalr ra, ra, offset _{11:0}	call far away function	PC = PC + offset, ra = PC + 4
la rd, symbol	auipc rd, symbol _{31:12} addi rd, rd, symbol _{11:0}	load address of global variable	rd = PC + symbol
l{b h w} rd, symbol	auipc rd, symbol _{31:12} l{b h w} rd, symbol _{11:0} (rd)	load global variable	rd = [PC + symbol]
s{b h w} rs2, symbol, rs1	auipc rs1, symbol _{31:12} s{b h w} rs2, symbol _{11:0} (rs1)	store global variable	[PC + symbol] = rs2
crr rd, csr	crrs rd, csr, x0	read CSR	rd = csr
crrw csr, rs1	crrw x0, csr, rs1	write CSR	csr = rs1

* If bit 11 of the immediate / offset / symbol is 1, the upper immediate is incremented by 1. symbol and offset are the 32-bit PC-relative addresses of a label and a global variable, respectively.

Table B.8 Privileged / CSR instructions

op	funct3	Type	Instruction	Description	Operation
1110011 (115)	000	I	ecall	transfer control to OS (imm=0)	
1110011 (115)	000	I	ebreak	transfer control to debugger (imm=1)	
1110011 (115)	000	I	uret	return from user exception (rs1=0,rd=0,imm=2)	PC = uepc
1110011 (115)	000	I	sret	return from supervisor exception (rs1=0,rd=0,imm=258)	PC = sepc
1110011 (115)	000	I	mret	return from machine exception (rs1=0,rd=0,imm=770)	PC = mepc
1110011 (115)	001	I	crrw rd,csr,rs1	CSR read/write (imm=CSR number)	rd = csr, csr = rs1
1110011 (115)	010	I	crrs rd,csr,rs1	CSR read/set (imm=CSR number)	rd = csr, csr = csr rs1
1110011 (115)	011	I	crrc rd,csr,rs1	CSR read/clear (imm=CSR number)	rd = csr, csr = csr & ~rs1
1110011 (115)	101	I	crrwi rd,csr,uimm	CSR read/write immediate (imm=CSR number)	rd = csr, csr = ZeroExt(uimm)
1110011 (115)	110	I	crrsi rd,csr,uimm	CSR read/set immediate (imm=CSR number)	rd = csr, csr = csr ZeroExt(uimm)
1110011 (115)	111	I	crrci rd,csr,uimm	CSR read/clear immediate (imm=CSR number)	rd = csr, csr = csr & ~ZeroExt(uimm)

For privileged / CSR instructions, the 5-bit unsigned immediate, uimm, is encoded in the rs1 field.