

111 - 2 Digital System Design Final Project

Extension – Compressed Instructions

1. Problem Description

A few decades ago, the memory is a rather limited resource as the process technology is not that advanced. Ideas of compressed instructions then emerge to save memory space. Though nowadays the memory is not as expensive and physically limited, demands on the memory space efficiency do not seem to decline, due to the flourish of a specific class of embedded systems. Wearable techs are notable examples of such. The applications can be enormously diverse, but they all share the common trend and demands: the decrease in both size and power consumption. Supports for compressed instructions can be effective aids to the code size reduction and power efficiency. As we can see, in addition to some basic supports, the newborn, elaborately designed RISC-V ISA also involves a compressed instruction set as one of the standard extension “C”, which reflects its great potential. In this part, your challenge is to implement the following 16 C-instructions as the extension to your base RISC-V core.

C.ADD	C.ANDI	C.LW	C.J
C.MV	C.SLLI	C.SW	C.JAL
C.ADDI	C.SRLI	C.BEQZ	C.JR
C.NOP	C.SRAI	C.BNEZ	C.JALR

2. Specification of C-Instructions

Information of these compressed instructions are given in Appendix A to C. In addition, there are quick notes in “I_mem_compression” for convenience (See **Testbench**). For further details, please refer to the chapter 12 of *The RISC-V Instruction Set Manual*.

3. Implementation

To add a C module to the base, consider the followings:

(a) Extract information encoded in C-instructions.

Obviously, the decoder you have done in the baseline cannot correctly decode any

compressed instructions. You have two choices: implement a dedicated decoder or a decompressor. As the name suggests, a decompressor expands compressed instructions into their 32-bit counterparts, which are later sent to the original decoder. This is a potentially neater way.

(b) PC increment.

PC is a special register indicating the location of the current instruction. Thus, if the current instruction is a compressed one, the next location should be PC+2 rather than the usual PC+4.

(c) Address alignment issues.

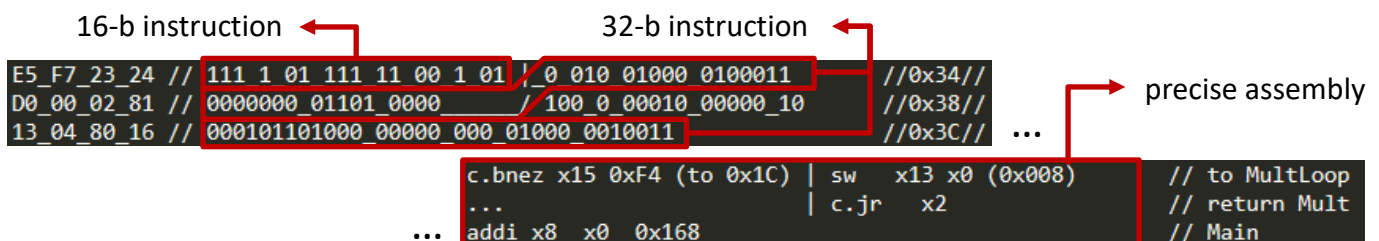
There is no constraint on the placement of instructions. Specifically, instructions can be located at unaligned addresses, i.e. $PC = 4k+2$, and thus a 32-bit one may cross a four-byte boundary. In this case, it may take two cycles to fetch a single instruction. Remember that usually read addresses specified by your processor are multiples of four. Hence, the PC does not necessarily equal the read address any longer. Of course, improvements to the microarchitecture, if any, may lead to additional problems. You should manage to handle them.

4. Testbench

“I_mem_compression”, “I_mem_decompression”, and “TestBed_compression.v” collectively form a set of test module, which you can find under “DEADxF625/”. To be more specific, the I_mem_decompression is the pure-RV32I counterpart of the I_mem_compression. Hence, before going on and getting your hand dirty, it is highly recommended to check whether your baseline core pass the decompression.

Hint: **+define+(de)compression** in the simulation command to couple the testbench.

Here is the guide for “I_mem_compression”:



For convenience, some notes are also included for quick reference:

```
Notes:
  Required supporting compression instructions with offset settings:
    c.nop      : decode to addi x0 x0 0x000
    c.add , c.mv      : no offset
    c.addi , c.andi*   : sign-extended offset[ 5:0] ( 6 bits)
    c.slli , c.srli*, c.srai*: shamt[5:0], shamt[5] must be 0
    c.sw* , c.lw*      : zero-extended offset[ 6:2] ( 5 bits)
    c.beqz*, c.bnez*   : sign-extended offset[ 8:1] ( 8 bits)
    c.j , c.jal^       : sign-extended offset[11:1] (11 bits)
    c.jr , c.jalr^      : no offset
    *: limited register index (x8 ~ x15)
    ^: stores pc+2 to x1
```

Test Program Generation.

This part illustrates how to generate different test cases:

A. Execute “*compression_generate.py*” in the directory “*generate/*”:

-Python (version = 3.x)

-Modify a, b

-I_mem_(de)compression_ref & TestBed_compression_ref should be placed in the same folder

-I_mem_(de)compression & TestBed_compression will be generated (Provided file in “DEADxF625/”)

B. +define+(de)compression in simulation command

5. Requirements

Design. You should pass the given testbench “Final_tb.v” with the instruction memory and the testbed under the DEADxF625/ directory. **No need to check the validity of the input instructions (e.g. all-zero instruction) and the constraints of values of each field (e.g. src \neq 0).** For simplicity, the validity of instructions in our testbenches is guaranteed.

Report. In the compression part of your final report “**Report.pdf**”, we suggest you have a detailed discussion on the followings:

- What is the advantage of the C extension? Verify it with your simulation results.
- How do you design your chip to support this extension?
- Any improvement on the performance, especially on how you reduce the number of cycles to complete the simulation.

- (d) What you have learned?
- (e) Other detailed discussion will be appreciated

Evaluation Metrics.

$$A(\text{compressed design} - \text{baseline design}) \times T(\text{given compressed testbench})$$

Don't worry about the performance evaluation. It is just one of the criteria. **Focus more on what you design to solve problems you face.**

6. Reference

[1] The RISC-V Instruction Set Manual Volume I: User Level ISA (Version 2.2)

Appendix A. Assembly

Compressed Instructions with Their Unique 32-bit Expansions

C-instr.	Base instruction (Assembly)
C.LW	lw rd', offset[6:2](rs1')
C.SW	sw rs2' offset[6:2](rs1')
C.BEQZ	beq rs1', x0, offset[8:1]
C.BNEZ	bne rs1', x0, offset[8:1]
C.J	jal x0, offset[11:1]
C.JAL	jal x1, offset[11:1]
C.JR	jalr x0, rs1, 0
C.JALR	jalr x1, rs1, 0
C.ADDI	addi rd, rd, nzimm[5:0]
C.ANDI	andi rd', rd', imm[5:0]
C.SLLI	slli rd, rd, shamt[5:0]
C.SRLI	srli rd', rd', shamt[5:0]
C.SRAI	srai rd', rd', shamt[5:0]
C.MV	add rd, x0, rs2
C.ADD	add rd, rd, rs2
C.NOP	addi x0, x0, 0

Appendix B. RVC Instruction Subsets

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
000											0				00
000											nzuimm[5:4 9:6 2 3]				rd'
001											uimm[5:3]	rs1'	uimm[7:6]		rd'
001											uimm[5:4 8]	rs1'	uimm[7:6]		rd'
010											uimm[5:3]	rs1'	uimm[2 6]		rd'
011											uimm[5:3]	rs1'	uimm[2 6]		rd'
011											uimm[5:3]	rs1'	uimm[7:6]		rd'
100											—				00
101											uimm[5:3]	rs1'	uimm[7:6]	rs2'	00
101											uimm[5:4 8]	rs1'	uimm[7:6]	rs2'	00
110											uimm[5:3]	rs1'	uimm[2 6]	rs2'	00
111											uimm[5:3]	rs1'	uimm[2 6]	rs2'	00
111											uimm[5:3]	rs1'	uimm[7:6]	rs2'	00

Illegal instruction
C.ADDI4SPN (*RES*, *nzuimm*=0)
C.FLD (*RV32/64*)
C.LQ (*RV128*)
C.LW
C.FLW (*RV32*)
C.LD (*RV64/128*)
Reserved
C.FSD (*RV32/64*)
C.SQ (*RV128*)
C.SW
C.FSW (*RV32*)
C.SD (*RV64/128*)

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
000											0				01
000											nzimm[5]		rs1/rd≠0	nzimm[4:0]	
001											imm[11 4 9:8 10 6 7 3:1 5]				01
001											imm[5]	rs1/rd≠0	imm[4:0]		01
010											imm[5]	rd≠0	imm[4:0]		01
011											nzimm[9]		2	nzimm[4 6 8:7 5]	
011											nzimm[17]		rd≠{0, 2}	nzimm[16:12]	
100											nzuimm[5]		00	rs1'/rd'	nzuimm[4:0]
100											0	00	rs1'/rd'	0	01
100											nzuimm[5]		01	rs1'/rd'	nzuimm[4:0]
100											0	01	rs1'/rd'	0	01
100											imm[5]	10	rs1'/rd'	imm[4:0]	01
100											0	11	rs1'/rd'	00	rs2'
100											0	11	rs1'/rd'	01	rs2'
100											0	11	rs1'/rd'	10	rs2'
100											0	11	rs1'/rd'	11	rs2'
100											1	11	rs1'/rd'	00	rs2'
100											1	11	rs1'/rd'	01	rs2'
100											1	11	—	10	—
100											1	11	—	11	—
101											imm[11 4 9:8 10 6 7 3:1 5]				01
110											imm[8 4:3]	rs1'	imm[7:6 2:1 5]		01
111											imm[8 4:3]	rs1'	imm[7:6 2:1 5]		01

C.NOP
C.ADDI (*HINT*, *nzimm*=0)
C.JAL (*RV32*)
C.ADDIW (*RV64/128*; *RES*, *rd*=0)
C.LI (*HINT*, *rd*=0)
C.ADDI16SP (*RES*, *nzimm*=0)
C.LUI (*RES*, *nzimm*=0; *HINT*, *rd*=0)
C.SRLI (*RV32 NSE*, *nzuimm*[5]=1)
C.SRLI64 (*RV128*; *RV32/64 HINT*)
C.SRAI (*RV32 NSE*, *nzuimm*[5]=1)
C.SRAI64 (*RV128*; *RV32/64 HINT*)
C.ANDI
C.SUB
C.XOR
C.OR
C.AND
C.SUBW (*RV64/128*; *RV32 RES*)
C.ADDW (*RV64/128*; *RV32 RES*)
Reserved
Reserved
C.J
C.BEQZ
C.BNEZ

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
000											nzuimm[5]		rs1/rd≠0	nzuimm[4:0]	
000											0		rs1/rd≠0	0	10
001											uimm[5]		rd	uimm[4:3 8:6]	10
001											uimm[5]		rd≠0	uimm[4 9:6]	10
010											uimm[5]		rd≠0	uimm[4:2 7:6]	10
011											uimm[5]		rd	uimm[4:2 7:6]	10
011											uimm[5]		rd≠0	uimm[4:3 8:6]	10
100											0		rs1≠0	0	10
100											0		rd≠0	rs2≠0	10
100											1		0	0	10
100											1		rs1≠0	0	10
100											1		rs1/rd≠0	rs2≠0	10

C.SLLI (*HINT*, *rd*=0; *RV32 NSE*, *nzuimm*[5]=1)
C.SLLI64 (*RV128*; *RV32/64 HINT*; *HINT*, *rd*=0)
C.FLDSP (*RV32/64*)
C.LQSP (*RV128*; *RES*, *rd*=0)
C.LWSP (*RES*, *rd*=0)
C.FLWSP (*RV32*)
C.LDSP (*RV64/128*; *RES*, *rd*=0)
C.JR (*RES*, *rs1*=0)
C.MV (*HINT*, *rd*=0)
C.EBREAK
C.JALR
C.ADD (*HINT*, *rd*=0)

※ Some instructions in Quadrant 2 are not listed here.

Appendix C. RV32I Instruction Subset

imm[20 10:1 11 19:12]					rd	1101111	JAL
imm[11:0]			rs1	000	rd	1100111	JALR
imm[12 10:5]	rs2		rs1	000	imm[4:1 11]	1100011	BEQ
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
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
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
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
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

Appendix D. Instruction types for RVC

Format	Meaning	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0		
CR	Register	funct4				rd/rs1				rs2				op					
CI	Immediate	funct3		imm		rd/rs1				imm				op					
CSS	Stack-relative Store	funct3		imm						rs2				op					
CIW	Wide Immediate	funct3		imm								rd'		op					
CL	Load	funct3		imm				rs1'		imm		rd'		op					
CS	Store	funct3		imm				rs1'		imm		rs2'		op					
CB	Branch	funct3		offset				rs1'		offset				op					
CJ	Jump	funct3		jump target												op			