dv-cpu-rv: CPU design of RISC-V

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# Preface

The design of this CPU mainly refers to *Computer Organization and Design: The Hardware / Software Interface*: RISC-V Edition, David A.Patterson, John L. Hennessy.

The source code is also distributed to Github: [devindang/dv-cpu-rv](https://github.com/devindang/dv-cpu-rv). Please feel free to submit issue or pull request.

# Hardware Design

These subsections of this section are not the final version, any of them is corresponded to a git commit, the hash identifiers are displayed, It mainly plays the role of recording and learning rather than technical documentation.

## Basic Single Cycle Implementation

### Deisng Diagram



Figure 1.1 The Basic Single Cycle Implementation of CPU

The corresponding hash code is: a7b05c264b7f45e27a81ddc02184c6dcee29fdf9

The figure above shows the implementation of the basic single cycle cpu, in which the hinted lines are signals of control path, while the others are signals of data path.

### The Building of Data Path

A data path is a unit used to operate on or hold data within a processor. In the RISC-V implementation, the datapath elements include the instruction and data memories, the register file, the ALU, and dders.

**Instruction Memory** is the memory where instructions are stored, which is independent of Data Memory in Havard architecture computer. In this implementation, the instruction memory is a memory has the address line bits of 64, which is identical to the bit width of data processed in CPU and, has the data line of 32 bits, the bit width of all the RISC-V instructions.

**PC (Program Counter)** is designed to fetch the instructions of Instruction Memory, which increments itselves by 4 per clock cycle in most cases, 32 is 4 bytes, and addressing in RISC-V is in bytes. In some cases, PC will jump or branch to certain location of the Instruction Memory and fetch. Thus, there is a MUX in the top right.

**Register File** contains the all 32 registers defined in RISC-V, each is of 64 bits width, it’s designed to store constant 0, parameters, PC, subroutine entries, etc.

**ALU (Algorithm Logic Unit)** is the core of CPU, it’s responsible for almost all the algorithms like add, subtract, xor, or, and in I standard, and more broadly, multiply, division, floating in M extension and F extension. The ALU in this design has the data width of 64, of either the oprands or the result.

**Data Memory** is the memory to store rich data, interact with external components like DMA (Direct Memory Accessing). It determines the maximum data counts a computer could handle at the same time. For example, a data memory with data width of 1 Byte, and address width of 32, the maximum data counts it could handle is 2^32\*1B=2^2\*1GiB=4GiB. In this design, the Data memory has the data width of 64, which is 8B, so the physical address must be divided by 8.

**Immediate Generation** is the unit to sign expand the immediate, and transfer to ALU or, act as an offset to PC to control procedure. It decodes the instruction fetched, retrieve the corresponding immediate according to the opcode filed, funct7 filed, or funct3 filed, and then perform sign expand to 64 bits.

### The Building of Control Path

A control path is a unit to control the data transfer between the data path units according the decoding result of the instruction. In this RISC-V implementation, the control path generate the following signals to control the process.

Note that these control signals are only applied to the single path situation, only in this commit, the further update introduced several complicated control signals, it will be talked in the later sections.

|  |  |  |
| --- | --- | --- |
| **Control Lanes** | **Deasseted** | **Asserted** |
| Branch | None. | combined with branch testing to determine whether to branch. |
| MemRead | None. | Read memory. |
| MemToReg | The value fed to register write data input comes from the ALU result. | The value fed to register write data input comes from the data memory. |
| MemWrite | None. | Write memory. |
| ALUSrc | The operand 2 of ALU comes from the register read data 2. | The operand 2 of ALU comes from the immediate generation unit output. |
| RegWrite | None. | Write data to register. |
| RegSrc | X | X |

RegSrc is a failed set, it will deprecated further, it’s initially created to select PC as register write data for instructions like JAL, JALR.

With these control signals, the CPU could process simply calculation, it will process only one instruction per signal cycle. There is an example in ./ docs/assembly.md , which is marked as 1, it will perform an addition calculation and obtain 29 as the result, which will be stored into memory. This is the only test cases adapted to this commit.

## Basic Pilelined Implementation

### Design Diagram



Figure 3.1 The basic pipelined implementation of CPU

The corresponding hash identifier is: 1d28ab2a485737b8bd90fa777fd550d5183b705c

The figure above shows the implementation of the basic pipelined cpu, in which the hinted lines are signals of control path, while the others are signals of data path. Compared to the single cycle implementation, additional units are required, they are:

i) 4 registers for pipelining, named IF/ID, ID/EX, EX/MEM, MEM/WB, separately;

ii) Forwarding unit for dealing with data hazard introduced by pipelining;

iii) Hazard detection unit for stalling the CPU in special cases;

iv) Branch prediction unit for accelerating the CPU, which saves the operation cycles;

v) Forwarding unit for RegisterFile, which solve the read/write hazard of register.

The details of these units will be talked in the later section: Support for RV32I and RV64I.



The figure above is the partition of the 5-stage pipelined CPU, the five stages and their functions are listed:

1. IF (Instruction Fetch): Fetch instructions from the Instruction Memory with PC as memory address. Besides, branch prediction unit is placed here to control PC.
2. ID (Instruction Decode): Decode instructions to generate control signals, sign expand immediates, control the operation of register files. Besides, Hazard detect unit is placed here to stall the pipeline.
3. EX (Executation): Execute algorithm calculation, and perform branch testing. Besides, forwarding unit is placed here to forwarding result of the pipeline stages output.
4. MEM (Memory Access): Access memory for load and store instructions.
5. WB (Write Back): Write back data to register files.

### Data Hazard: Forwarding or Bypass

Data hazards are obstacles to pipelined execution. The method to deal with this issue is adding a forwarding unit, which forwarding the data in the previous data flow, such as alu\_result, or registered ones, to current execution cycle, instead of waiting for the last instruction to write back.

### Control Hazard: Branch Prediction

Branch prediction is a technique used in CPU design that attempts to guess the outcome of a conditional operation and prepare for the most likely result. A digital circuit that performs this operation is known as a branch predictor. It is an important component of modern CPU architectures.

Let’s take the process without branch prediction. The branch result is available only when the process get the result from branch testing unit at the phase of Executation, there is 3 cycles delay after PC get changed (PC=>IF=>ID=>EX). As the branch instruction was fill into the pipeline, and the branch result is not available, the instructions below will also fill into the pipeline, regardless if the branch will be taken or not. That’s the case that we predict the branch will always not be taken, additional cycles will be wasted if the branch is taken.

The basic branch prediction scheme is 1-bit prediction buffer which store the history branch result for corresponding address or low-order address.

We don’t know, in fact, if the prediction is the right one—it may have been put there by another conditional branch that has the same low-order address bits. However, this doesn’t affect correctness. Prediction is just a hint that we hope is correct, so fetching begins in the predicted direction. If the hint turns out to be wrong, the incorrectly predicted instructions are deleted, the prediction bit is inverted and stored back, and the proper sequence is fetched and executed.

For most cases, the iteration use the same address (offset in RISC-V) for branching, and repeat considerable times. Branch prediction mechanism will save clock cycles in this situation.



The figure above shows the state transition diagram for 2-bit branch prediction, only after 2 branch taken action, the prediction unit assert a branch indication. It’s impelented by using a simple 2-bit counter, the counter value 0,1 deassert the prediction, while the counter value 2,3 assert the prediction.

## Support for RV32I and RV64I

### Design Diagram



The red hinted lines are logic units introduced to fully support the instructions in RV32I and RV42I. It will be talked later.

### Modification Overview

There are modified units and additional units for fully supporting RV32I and RV64I. They are:

i) ALUOp32b for ALU control unit, it’s designed for RV64I to support word operation;

ii) Memory mapping unit for Byte, Halfword, Word operation of data memory, more details , refer to [3.2.3 Strobe Unit](#_Strobe_Unit);

iii) ALU op1 MUX logic, PC and 0 are added to the MUX inputs, LUI instruction use 0 as op1, and AUIPC instruction use PC as op1.

iv) Besides, ImmGen, Control, ALU, Memory, and BranchTest units are required to be updated for wider instructions, the details of them will be talked in the later section – Functional Description.

### ALU control unit

To simplify the design of CPU, control path and data path are introduced. The ALU control unit control the ALU operation mode for all the instructions, the *alu\_op\_sel* signal in this module inherit the funct3 filed and instr[30] in R-type instruction in RV32I ISA.

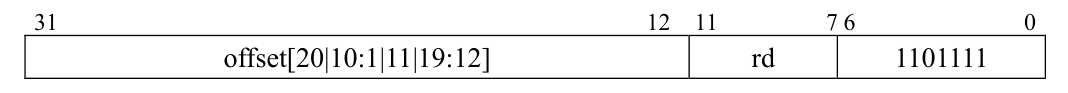
|  |  |
| --- | --- |
| ***alu\_op\_sel*** | **function** |
| 0000 | Add |
| 1000 | Subtract |
| 0001 | Shift Left Logical |
| 0010 | Set Less Than |
| 0011 | Set Less Than Unsigned |
| 0100 | Exclusive Or |
| 0101 | Shift Right Logical |
| 1101 | Shift Right Arithmetic |
| 0110 | Or |
| 0111 | And |

### Branch and Jump

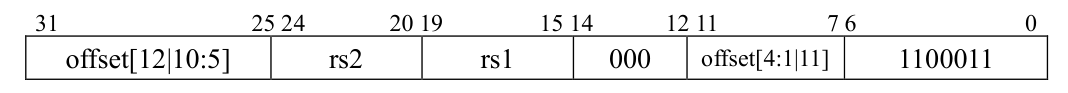
RISC-V instructions are 4 bytes long, the RISC-V branch instructions are designed to stretch their reach by having the PC-relative address refer to the number of words between the branch and the target instruction, rather than the number of bytes. However, the RISC-V architects wanted to support the possibility of instructions that are only 2 bytes long, so the branch instructions represent the number of halfwords between the branch and the branch target[[1]](#footnote-1).

Thus, the 20-bit address field in the jal instruction can encode a distance of ±219 halfwords, or ±1 MiB from the current PC. Similarly, the 12-bit field in the conditional branch instructions is also a halfword address, meaning that it represents a 13-bit byte address.

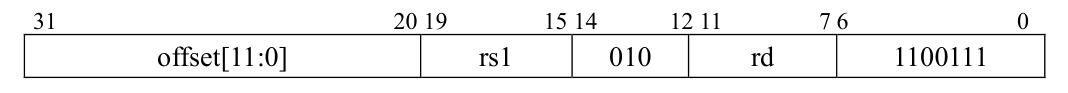
**jal**



**beq**



**jalr**



The term offset in RISC-V is in Bytes, so the offset filed in jal and beq instruction use [12:1] rather than [11:0], which means that the content in the offset filed concatenated with 0 becomes the true offset in Bytes.

Note that JALR has the offset in Bytes instead of Halfword, the PC souces has the following

* Increment (+4 in physical address)
* Branch target (require shift left 1)
* JAL (require shift left)
* JALR (no shift required)

### Strobe Unit

Strobe unit is designed to implement instructions about Load and Store, they are:

* LB, LH, LW, LBU, LHU, SB, SH, SW in RV32I,
* LD, LWU, SD in RV64I.

The LD instruction loads a 64-bit value from memory into register rd for RV64I.

The LW instruction loads a 32-bit value from memory and sign-extends this to 64 bits before storing it in register rd for RV64I.

The LWU instruction, on the other hand, zero-extends the 32-bit value from memory for RV64I.

The LH and LHU instruction are defined analogously for 16-bit values, as are LB and LBU for 8-bit values. The SD, SW, SH, and SB instructions store 64-bit, 32-bit, 16-bit, and 8-bit values from the low bits of register rs2 to memory respectively.

The offset filed is in Bytes. for SD or LD instruction, the offset must be the multiplies of 8 (A doubleword is 8 bytes), for example,

ld x9, 240(x10) // Temporary reg x9 gets A[30]

lw x10, 240(x10) // Temporary reg x9 gets A[30][31:0]

It’s important that the offset must be aligned for simplicity, unaligned access of memory costs additional clock cycles thus slows the CPU.

Assume that the data accessed is aligned in memory, they are stored or fetched in special rules, just take the following example to understand[[2]](#footnote-2).

表格

中度可信度描述已自动生成

add $s3, $zero, $zero

This performs the addition $s3 = 0 + 0, effectively setting the register $s3 to a value of zero.

lb $t0, 1($s3)

This loads a byte from a location in memory into the register $t0. The memory address is given by 1($s3), which means the address $s3+1. This would be the 0+1=1st byte in memory. Since we have a big-endian architecture, we read bytes the 4-byte chunks "big end first".

byte: 0 1 2 3

00 90 12 A0

The 0th byte is 00, and the 1st byte is 90. So we load the byte 90 into $t0.

sb $t0, 6($s3)

This stores a byte from the register $t0 into a memory address given by 6($s3). Again this means the address $s3+6.

byte: 4 5 6 7

FF FF FF FF

becomes

byte: 4 5 6 7

FF FF 90 FF

Now, what if the architecture was little-endian? (Which is the endian sequence of RISC-V) This would mean bytes are arranged "little end first" in memory, so the effect of the 2nd and 3rd instructions change.

lb $t0, 1($s3)

This loads the byte in memory address 1 into register $t0. But now the addresses are "little end first", so we read 12 into the register instead.

byte: 3 2 1 0

00 90 12 A0

Next...

sb $t0, 6($s3)

This stores the byte in register $t0, which is 12 into a memory address 6. Again with little-endian architecture:

byte: 7 6 5 4

FF FF FF FF

becomes

byte: 7 6 5 4

FF 12 FF FF

The strobe unit is designed to read 0x90 from the bit range of [23:16], the second byte in big-endian, of the slice of physical address 0 of memory and, to write 0x90 to the correct part of the correct address.

For sb, lb instruction, the offset must be the multiply of 1, the lower 3 bits are used to determine the location of byte in 64 bits to store and fetch. For sh, lh, lhu instruction, the offset must be the multiply of 2, the lower 2 bits are used to determine the location of halfword in 64 bits. For sw, lw, lwu instruction, the occasion becomes 4, and 1 bit. For sd, ld instruction, the whole 64 bits are used, the offset is the multiply of 8.

## Support for RV32M and RV64M

### Booth-Wallace Multiplier

This part mainly refers to 《计算机体系结构基础》<https://github.com/foxsen/archbase>, which compiles with [CC BY-NC 4.0](https://creativecommons.org/licenses/by-nc/4.0/deed.zh), thanks to the contributors.

**Booth Algorithm**[[3]](#footnote-3)

Suppose there is a 8x8 multiplication, the result for signed multiplication is

Where, 2c means 2’s complement, the sign will be omitted in the subsequent expression, only signed multiplication is talked at present.

Booth multipliers transform the multiplications to

Where, . After transformation, the regularity is revealed, no additional multiply -1 is required for MSB partial product. It’s also called Radix-2 Booth Algorithm.

Let’s talk about Radix-4 Booth Algorithm, which is the most common implementation in CPU, and DSP unit.

Rather than divde 2 partial product together, Radix-4 Booth Algorith divide every 3 partial product together and perform sum every 2 bits, or say, shift 2 bits for the multipliers. Radix-4 means that, it set the multipliers as a set of digits 0–3 instead of just 0,1 (basic array multiplications, or radix-2 booth algorithm). This cuts the number of partial products in half because you are multiplying by two binary bits at once. However, it requires multiplying by 3 which is difficult. (Multiplication by 0, 1, or 2 is trivial because they only involve simple shifts. Three is the hard one[[4]](#footnote-4).) To avoid multiplying by 3, we use Booth’s observation and recode the digit set to be 2, 1, 0, ‐1, and ‐2.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | **comment** | **z1** | **z2** | **neg** |
| 0 | 0 | 0 | 0 | No add required. | 0 | 0 | 0 |
| 0 | 0 | 1 | 1 | +X (2’s complement) | 1 | 0 | 0 |
| 0 | 1 | 0 | 1 | +X (2’s complement) | 1 | 0 | 0 |
| 0 | 1 | 1 | 2 | +2X (2’s complement) | 0 | 1 | 0 |
| 1 | 0 | 0 | -2 | -2X (2’s complement) | 0 | 1 | 1 |
| 1 | 0 | 1 | -1 | -X (2’s complement) | 1 | 0 | 1 |
| 1 | 1 | 0 | -1 | -X (2’s complement) | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | No add required. | 0 | 0 | 1 |

The column z1, z2, neg is the signals in the implementation. where, z1 means that there is a 1-bit shift, z2 means that there is a 2-bits shift, neg means that there is a subtraction which is implemented by

**Wallace Tree**[[5]](#footnote-5)

The Wallace tree is build by the following reasoning, assuming already booth encoded.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **level** | **isolated** | **remain** | **in** | **out** |
| 0 | 0 | 0 | 11\*3 | 11\*2 |
| 1 | 0 | 1 | 7\*3 | 7\*2 |
| 2 | 1 | 0 | 5\*3 | 5\*2 |
| 3 | 0 | 1 | 3\*3 | 3\*2 |
| 4 | 0 | 1 | 2\*3 | 2\*2 |
| 5 | 0 | 2 | 1\*3 | 1\*2 |
| 6 | 0 | 1 | 1\*3 | 1\*2 |
| 7 | 0 | 0 | 1\*3 | 1\*2 |

Add register to every two stages?

**Full Adder**

The logic architecture chosen to implement full adder is talked below.

The left side one is the basic connection, where,

,

While the right side is the improved implementation, where

,

It takes the advantage of the feature that

, and

Consider the perfomance, the left implementation has a logic stage of 3, while the right one also has it of 3 (the MUX takes 2).

Consider the area, the left implementation consume the MOSFET counts of 8+8+6+6+6=34, while the right one consume it of 8+8+6+14=36.

In Xilinx FPGA, there are proprietary MUX units, the CARRY4 Chain adopts the right one to save LUTs resources.

### SRT Divider

# Functional Description

## Files and Directory Structure

The figure below shows the layout of the directories in the example system.

<home directory> Local git directory.

│ clean.pl Perl script for cleaning temporary files.

├─core/ The implementation of CPU core.

│ ├─bench/ Bench codes for CPU core.

│ ├─rtl/ RTL codes.

│ ├─sim/ VCS+Verdi simulation environment.

│ └─vsim/ Modelsim simulation environment.

└─docs/ Related documentation.

## RV32I Module Design

## RV32M Module Design

# Appendices

## Appendix 1: Support of Instruction Set

The regularity of opcode:

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| inst[4:2] | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111  (>32b) |
| inst[6:5] |
| 00 | LOAD | LOAD-FP | custom-0 | MISC-MEM | OP\_IMM | AUIPC | OP-IM-M32 | 48b |
| 01 | STORE | STORE-FP | custom-1 | AMO | OP | LUI | OP-32 | 64b |
| 10 | MADD | MSUB | NMSUB | NMADD | OP-FP | reserved | custom-2/rv128 | 48b |
| 11 | BRANCH | JALR | reserved | JAL | SYSTEM | reserved | custom-3/rv128 | >=80b |

Besides, inst[1:0]=11.

The example of RISC-V pseudo instructions can be found in *risc-v specification* v2.2 p109, from which we can deal with the assembly codes.

**RV32I Base Instruction Set**

Total: 47

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Type** | **Order** | **Instruction** | **Description** | **Compatibility** |
| R-type | 1 | ADD | Add. | YES |
| 2 | SUB | Subtract. | YES |
| 3 | SLL | Shift Left Logical. | YES |
| 4 | SLT | Set Less Than. | YES |
| 5 | SLTU | Set Less Than Unsigned. | YES |
| 6 | XOR | Exclusive or. | YES |
| 7 | SRL | Shift Right Logical. | YES |
| 8 | SRA | Shift Right Arithmetic. | YES |
| 9 | OR | Or. | YES |
| 10 | AND | And. | YES |
| I-type | 11 | JALR | Jump And Link Register. | YES |
| 12 | LB | Load Byte. | YES |
| 13 | LH | Load Halfword. | YES |
| 14 | LW | Load Word. | YES |
| 15 | LBU | Load Byte Unsigned. | YES |
| 16 | LHU | Load Halfword Unsigned. | YES |
| 17 | ADDI | Add Immediate. | YES |
| 18 | SLTI | Set Less Than Immediate. | YES |
| 19 | SLTIU | Set Less Than Immediate Unsigned. | YES |
| 20 | XORI | Exclusive Or Immediate. | YES |
| 21 | ORI | Or Immediate. | YES |
| 22 | ANDI | And Immediate. | YES |
| 23 | SLLI | Shift Left Logic Immediate. | YES |
| 24 | SRLI | Shift Right Logic Immediate. | YES |
| 25 | SRAI | Shift Right Arithmeic Immediate. | YES |
| S-type | 26 | SB | Store Byte. | YES |
| 27 | SH | Store Halfword. | YES |
| 28 | SW | Store Word. | YES |
| B-type | 29 | BEQ | Branch if Equal. | YES |
| 30 | BNE | Branch Not Equal. | YES |
| 31 | BLT | Branch Less Than. | YES |
| 32 | BGE | Branch Greater or Equal. | YES |
| 33 | BLTU | Branch Less Than Unsigned. | YES |
| 34 | BGEU | Branch Greater or Equal Unsigned. | YES |
| U-type | 35 | LUI | Load Upper Immediate. | YES |
| 36 | AUIPC | Add Upper Immediate to PC. | YES |
| J-type | 37 | JAL | Jump And Link. | YES |
| other | 38 | FENCE |  | NO |
| 39 | FENCE.I |  | NO |
| 40 | ECALL |  | NO |
| 41 | EBREAK |  | NO |
| 42 | CSRRW |  | NO |
| 43 | CSRRS |  | NO |
| 44 | CSRRC |  | NO |
| 45 | CSRRWI |  | NO |
| 46 | CSRRSI |  | NO |
| 47 | CSRRCI |  | NO |

**RV64I Base Instruction Set (in addition to RV32I)**

Total: 15

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Type** | **Order** | **Instruction** | **Description** | **Compatibility** |
| R-type | 1 | ADDW | Add Word. | YES |
| 2 | SUBW | Subtract Word. | YES |
| 3 | SLLW | Shift Left Logical Word. | YES |
| 4 | SRLW | Set Less Than Word. | YES |
| 5 | SRAW | Set Less Than Unsigned Word. | YES |
| I-type | 6 | LWU | Load Word Unsigned. | YES |
| 7 | LD | Load Doubleword. | YES |
| 8 | SLLI | Shift Left Logic Immediate. | YES |
| 9 | SRLI | Shift Right Logic Immediate. | YES |
| 10 | SRAI | Shift Right Arithmetic Immediate. | YES |
| 11 | ADDIW | Add Immediate Word. | YES |
| 12 | SLLIW | Shift Left Logic Immediate Word. | YES |
| 13 | SRLIW | Shift Right Logic Immediate Word. | YES |
| 14 | SRAIW | Shift Right Arithmetic Immediate Word. | YES |
| S-type | 15 | SD | Store Doubleword. | YES |

## Appendix 2: Examples for Run

### Example 1: Add and Store.

**Date**: 2023/7/23

**Hash**: a7b05c264b7f45e27a81ddc02184c6dcee29fdf9

**Description**: Given two numbers, add them and store into memory.

C code

#include "stdio.h"

int main() {

int a = 14;

int b = 15;

int c;

c = a + b;

return 0;

}

Assembly code

addi x2 x0 14; //0// 00000000111000000000000100010011

addi x3 x0 15; //1// 00000000111100000000000110010011

add x1 x2 x3; //2// 00000000001100010000000010110011

sd x1 8(x2); //3// 00000000000100010011010000100011

### Example 2: Sum Less Than.

**Date**: 2023/7/29

**Hash**: 1d28ab2a485737b8bd90fa777fd550d5183b705c

**Description**: Given a non-zero natural number N, calculate the sum of natural numbers less than N.

C code

#include "stdio.h"

int main() {

int N = 10;

int sum = 0;

for(int i=1; i<N; i++){

sum = sum+i;

}

return 0;

}

Assembly code

addi x1 x0 10; //0// 00000000101000000000000010010011

addi x2 x0 1; //4// 00000000000100000000000100010011

addi x3 x0 0; //8// 00000000000000000000000110010011

add x3 x2 x3; //12// 00000000001100010000000110110011

addi x2 x2 1; //16// 00000000000100010000000100010011

blt x2 x1 A12; //20// 11111110000100010100110011100011

sd x3 8(x1); //24// 00000000001100001011010000100011

1. Computer Organization and Design RISC-V Edition: P264 [↑](#footnote-ref-1)
2. https://stackoverflow.com/questions/28707615/loading-and-storing-bytes-in-mips [↑](#footnote-ref-2)
3. 计算机体系结构基础, 胡伟武: P210 [↑](#footnote-ref-3)
4. https://www.brown.edu/Departments/Engineering/Courses/En164/BoothRadix4.pdf [↑](#footnote-ref-4)
5. 计算机体系结构基础, 胡伟武: P215 [↑](#footnote-ref-5)