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RISC-V Assembly Language Programming

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*Need to say something
about trademarks for things
mentioned in this text*

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Preface

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I set out to write this book because I couldn't find it in a single volume elsewhere.

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The closest published work on this topic appear to be select portions of *The RISC-V Instruction Set Manual, Volume I: User-Level ISA, Document Version 2.2*[\[1\]](#), The RISC-V Reader[\[2\]](#), and Computer Organization and Design RISC-V Edition: The Hardware Software Interface[\[3\]](#).

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There *are* some terse guides on the Internet that are suitable for those who already know an assembly language. With all the (deserved) excitement brewing over system organization (and the need to compress the time out of university courses targeting assembly language programming [\[4\]](#)), it is no surprise that RISC-V texts for the beginning assembly programmer are not (yet) available.

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When I started in computing, I learned how to count in binary in a high school electronics course using data sheets for integrated circuits such as the 74191[\[5\]](#) and 74154[\[6\]](#) prior to knowing that assembly language even existed.

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I learned assembly language from data sheets and texts, that are still sitting on my shelves today, such as:

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- The MCS-85 User's Manual[\[7\]](#)
- The EDTASM Manual[\[8\]](#)
- The MC68000 User's Manual[\[9\]](#)
- Assembler Language With ASSIST[\[10\]](#)
- IBM System/370 Principals of Operation[\[11\]](#)
- OS/VS-DOS/VSE-VM/370 Assembler Language[\[12\]](#)
- ... and several others

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All of these manuals discuss each CPU instruction in excruciating detail with both a logical and narrative description. For RISC-V this is also the case for the *RISC-V Reader*[\[2\]](#) and the *Computer Organization and Design RISC-V Edition*[\[3\]](#) books and is also present in this text (I consider that to be the minimal level of responsibility.)

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Where I hope this text will differentiate itself from the existing RISC-V titles is in its attempt to address the needs of those learning assembly language for the first time. To this end I have primed this project with some of the curriculum material I created when teaching assembly language programming in the late '80s.

Chapter 1

Introduction

At its core, a digital computer has at least one **Central Processing Unit** (CPU). A CPU executes a continuous stream of instructions called a **program**. These program instructions are expressed in what is called **machine language**. Each machine language instruction is a **binary** value. In order to provide a method to simplify the management of machine language programs a symbolic mapping is provided where a **mnemonic** can be used to specify each machine instruction and any of its parameters... rather than require that programs be expressed as a series of binary values. A set of mnemonics, parameters and rules for specifying their use for the purpose of programming a CPU is called an *Assembly Language*.

1.1 The Digital Computer

There are different types of computers. A *digital* computer is the type that most people think of when they hear the word *computer*. Other varieties of computers include *analog* and *quantum*.

A digital computer is one that processes data represented using numeric values (digits), most commonly expressed in binary (ones and zeros) form.

This text focuses on digital computing.

A typical digital computer is composed of storage systems (memory, disc drives, USB drives, etc.), a CPU (with one or more cores), input peripherals (a keyboard and mouse) and output peripherals (display, printer or speakers.)

1.1.1 Storage Systems

Computer storage systems are used to hold the data and instructions for the CPU.

Types of computer storage can be classified into two categories: *volatile* and *non-volatile*.

1.1.1.1 Volatile Storage

Volatile storage is characterized by the fact that it will lose its contents (forget) any time that it is powered off.

One type of volatile storage is provided inside the CPU itself in small blocks called [registers](#). These registers are used to hold individual data values that can be manipulated by the instructions that are executed by the CPU.

Another type of volatile storage is *main memory* (sometimes called [RAM](#)) Main memory is connected to a computer's CPU and is used to hold the data and instructions that can not fit into the CPU registers.

Typically, a CPU's registers can hold tens of data values while the main memory can contain many billions of data values.

To keep track of the data values, each register is assigned a number and the main memory is broken up into small blocks called [bytes](#) that each assigned a number called an [address](#) (an *address* is often referred to as a *location*).

A CPU can process data in a register at a speed that can be an order of magnitude faster than the rate that it can process (specifically, transfer data and instructions to and from) the main memory.

Register storage costs an order of magnitude more to manufacture than main memory. While it is desirable to have many registers, the economics dictate that the vast majority of volatile computer storage be provided in its main memory. As a result, optimizing the copying of data between the registers and main memory is a desirable trait of good programs.

1.1.1.2 Non-Volatile Storage

Non-volatile storage is characterized by the fact that it will *NOT* lose its contents when it is powered off.

Common types of non-volatile storage are disc drives, [ROM](#) flash cards and USB drives. Prices can vary widely depending on size and transfer speeds.

It is typical for a computer system's non-volatile storage to operate more slowly than its main memory.

This text will focus on volatile storage.

1.1.2 CPU

The [CPU](#) is a collection of registers and circuitry designed to manipulate the register data and to exchange data and instructions with the main memory. The instructions that are read from the main memory tell the CPU to perform various mathematical and logical operations on the data in its registers and where to save the results of those operations.

► Fix Me:

Add a block diagram of the CPU components described here.

1.1.2.1 Execution Unit

The part of a CPU that coordinates all aspects of the operations of each instruction is called the *execution unit*. It is what performs the transfers of instructions and data between the CPU and

the main memory and tells the registers when they are supposed to either store or recall data being transferred. The execution unit also controls the ALU (Arithmetic and Logic Unit).

1.1.2.2 Arithmetic and Logic Unit

When an instruction manipulates data by performing things like an *addition*, *subtraction*, *comparison* or other similar operations, the ALU is what will calculate the sum, difference, and so on... under the control of the execution unit.

1.1.2.3 Registers

In the RV32 CPU there are 31 general purpose registers that each contain 32 [bits](#) (where each bit is one [binary](#) digit value of one or zero) and a number of special-purpose registers. Each of the general purpose registers is given a name such as `x1`, `x2`, ... on up to `x31` (*general purpose* refers to the fact that the *CPU itself* does not prescribe any particular function to any of these registers.) Two important special-purpose registers are `x0` and `pc`.

Register `x0` will always represent the value zero or logical *false* no matter what. If any instruction tries to change the value in `x0` the operation will fail. The need for *zero* is so common that, other than the fact that it is hard-wired to zero, the `x0` register is made available as if it were otherwise a general purpose register.¹

The `pc` register is called the *program counter*. The CPU uses it to remember the memory address where its program instructions are located.

The term XLEN refer to the width of an integer register in bits (either 32, 64, or 128.) The number of bits in each register is defined by the [Instruction Set Architecture \(ISA\)](#).

1.1.2.4 Harts

Analogous to a *core* in other types of CPUs, a [hart](#) (hardware [thread](#)) in a RISC-V CPU refers to the collection of 32 registers, instruction execution unit and ALU.^[1, p. 20]

When more than one hart is present in a CPU, a different stream of instructions can be executed on each hart all at the same time. Programs that are written to take advantage of this are called *multithreaded*.

This text will primarily focus on CPUs that have only one hart.

1.1.3 Peripherals

A *peripheral* is a device that is not a CPU or main memory. They are typically used to transfer information/data into and out of the main memory.

This text is not concerned with the peripherals of a computer system other than in sections where instructions are discussed with the purpose of addressing the needs of a peripheral device. Such instructions are used to initiate, execute and/or synchronize data transfers.

¹Having a special *zero* register allows the total set of instructions that the CPU can execute to be simplified. Thus reducing its complexity, power consumption and cost.

1.2 Instruction Set Architecture

The catalog of rules that describes the details of the instructions and features that a given CPU provides is called an [Instruction Set Architecture \(ISA\)](#).

An ISA is typically expressed in terms of the specific meaning of each binary instruction that a CPU can recognize and how it will process each one.

The RISC-V ISA is defined as a set of modules. The purpose of dividing the ISA into modules is to allow an implementer to select which features to incorporate into a CPU design.^[1, p. 4]

Any given RISC-V implementation must provide one of the *base* modules and zero or more of the *extension* modules.^[1, p. 4]

1.2.1 RV Base Modules

The base modules are RV32I (32-bit general purpose), RV32E (32-bit embedded), RV64I (64-bit general purpose) and RV128I (128-bit general purpose).^[1, p. 4]

These base modules provide the minimal functional set of integer operations needed to execute a useful application. The differing bit-widths address the needs of different main-memory sizes.

This text primarily focuses on the RV32I base module and how to program it.

1.2.2 Extension Modules

RISC-V extension modules may be included by an implementer interested in optimizing a design for one or more purposes.^[1, p. 4]

Available extension modules include M (integer math), A (atomic), F (32-bit floating point), D (64-bit floating point), Q (128-bit floating point), C (compressed size instructions) and others.

The extension name *G* is used to represent the combined set of IMAFD extensions as it is expected to be a common combination.

1.3 How the CPU Executes a Program

The process of executing a program is continuous repeats of a series of *instruction cycles* that are each comprised of a *fetch*, *decode* and *execute* phase.

The current status of a CPU hart is entirely embodied in the data values that are stored in its registers at any moment in time. Of particular interest to an executing program is the **pc** register. The **pc** contains the memory address containing the instruction that the CPU is currently executing.²

For this to work, the instructions to be executed must have been previously stored in adjacent main memory locations and the address of the first instruction placed into the **pc** register.

²In the RISC-V ISA the **pc** register points to the *current* instruction where in most other designs, the **pc** register points to the *next* instruction.

1.3.1 Instruction Fetch

In order to *fetch* an instruction from the main memory the CPU will update the address in the `pc` register and then request that the main memory return the value of the data stored at that address.³

1.3.2 Instruction Decode

Once an instruction has been fetched, it must be inspected to determine what operation(s) are to be performed. This means inspecting the portions of the instruction that dictate which registers are involved and what that, if anything, ALU should do.

1.3.3 Instruction Execute

Typical instructions do things like add a number to the value currently stored in one of the registers or store the contents of a register into the main memory at some given address.

Part of every instruction is a notion of what should be done next.

Most of the time an instruction will complete by indicating that the CPU should proceed to fetch and execute the instruction at the next larger main memory address. In these cases the `pc` is incremented to point to the memory address after the current instruction.

Any parameters that an instruction requires must either be part of the instruction itself or read from (or stored into) one or more of the general purpose registers.

Some instructions can specify that the CPU proceed to execute an instruction at an address other than the one that follows itself. This class of instructions have names like *jump* and *branch* and are available in a variety of different styles.

The RISC-V ISA uses the word *jump* to refer to an *unconditional* change in the sequential processing of instructions and the word *branch* to refer to a *conditional* change.

Conditional branch instructions can be used to tell the CPU to do things like:

If the value in `x8` is currently less than the value in `x24` then proceed to the instruction at the next main memory address, otherwise branch to an instruction at a different address.

This type of instruction can therefore result in one of two different actions pending the result of the comparison.⁴

Once the instruction execution phase has completed, the next instruction cycle will be performed using the new value in the `pc` register.

³RV32I instructions are more than one byte in size, but this general description is suitable for now.

⁴This is the fundamental method used by a CPU to make decisions.

Chapter 2

Numbers and Storage Systems

This chapter discusses how data are represented and stored in a computer.

In the context of computing, *boolean* refers to a condition that can be either true or false and *binary* refers to the use of a base-2 numeric system to represent numbers.

RISC-V assembly language uses binary to represent all values, be they boolean or numeric. It is the context within which they are used that determines whether they are boolean or numeric.

► Fix Me:

Add some diagrams here showing bits, bytes and the MSB, LSB,... perhaps relocated from the RV32I chapter?

2.1 Boolean Functions

Boolean functions apply on a per-bit basis. When applied to multi-bit values, each bit position is operated upon independent of the other bits.

RISC-V assembly language uses zero to represent *false* and one to represent *true*. In general, however, it is useful to relax this and define zero **and only zero** to be *false* and anything that is not *false* is therefore *true*.¹

The reason for this relaxation is to describe the common case where the CPU processes data, multiple **bits** at-a-time.

These groups have names like **byte** (8 bits), **halfword** (16 bits) and **fullword** (32 bits).

2.1.1 NOT

The *NOT* operator applies to a single operand and represents the opposite of the input.

If the input is 1 then the output is 0. If the input is 0 then the output is 1. In other words, the output value is *not* that of the input value.

Expressing the *not* function in the form of a truth table:

► Fix Me:

Need to define unary, binary and ternary operators without confusing binary operators with binary numbers.

¹This is how *true* and *false* behave in C, C++, and many other languages as well as the common assembly language idioms discussed in this text.

A	\overline{A}
0	1
1	0

A truth table is drawn by indicating all of the possible input values on the left of the vertical bar with each row displaying the output values that correspond to the input for that row. The column headings are used to define the illustrated operation expressed using a mathematical notation. The *not* operation is indicated by the presence of an *overline*.

In computer programming languages, things like an overline can not be efficiently expressed using a standard keyboard. Therefore it is common to use a notation such as that used by the C language when discussing the *NOT* operator in symbolic form. Specifically the tilde: ‘~’.

It is also uncommon to for programming languages to express boolean operations on single-bit input(s). A more generalized operation is used that applies to a set of bits all at once. For example, performing a *not* operation of eight bits at once can be illustrated as:

```

~ 1 1 1 1 0 1 0 1  <== A
-----
  0 0 0 0 1 0 1 0  <== output

```

In a line of code the above might read like this: `output = ~A`

2.1.2 AND

The boolean *and* function has two or more inputs and the output is a single bit. The output is 1 if and only if all of the input values are 1. Otherwise it is 0.

This function works like it does in spoken language. For example if A is 1 *and* B is 1 then the output is 1 (true). Otherwise the output is 0 (false).

In mathematical notion, the *and* operator is expressed the same way as is *multiplication*. That is by a raised dot between, or by juxtaposition of, two variable names. It is also worth noting that, in base-2, the *and* operation actually *is* multiplication!

A	B	AB
0	0	0
0	1	0
1	0	0
1	1	1

This text will use the operator used in the C language when discussing the *and* operator in symbolic form. Specifically the ampersand: ‘&’.

An eight-bit example:

```

  1 1 1 1 0 1 0 1  <== A
& 1 0 0 1 0 0 1 1  <== B
-----
  1 0 0 1 0 0 0 1  <== output

```

In a line of code the above might read like this: `output = A & B`

2.1.3 OR

The boolean *or* function has two or more inputs and the output is a single bit. The output is 1 if at least one of the input values are 1.

This function works like it does in spoken language. For example if A is 1 *or* B is 1 then the output is 1 (true). Otherwise the output is 0 (false).

In mathematical notion, the *or* operator is expressed using the plus (+).

A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

This text will use the operator used in the C language when discussing the *or* operator in symbolic form. Specifically the pipe: '|'.

An eight-bit example:

```

  1 1 1 1 0 1 0 1 <== A
| 1 0 0 1 0 0 1 1 <== B
-----
  1 1 1 1 0 1 1 1 <== output

```

In a line of code the above might read like this: `output = A | B`

2.1.4 XOR

The boolean *exclusive or* function has two or more inputs and the output is a single bit. The output is 1 if only an odd number of inputs are 1. Otherwise the output will be 0.

Note that when *xor* is used with two inputs, the output is set to 1 (true) when the inputs have different values and 0 (false) when the inputs both have the same value.

In mathematical notion, the *xor* operator is expressed using the plus in a circle (\oplus).

A	B	A \oplus B
0	0	0
0	1	1
1	0	1
1	1	0

This text will use the operator used in the C language when discussing the *xor* operator in symbolic form. Specifically the carrot: '^'.

An eight-bit example:

Decimal			Binary								Hex	
10^2	10^1	10^0	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0	16^1	16^0
100	10	1	128	64	32	16	8	4	2	1	16	1
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	1	0	1
0	0	2	0	0	0	0	0	0	1	0	0	2
0	0	3	0	0	0	0	0	0	1	1	0	3
0	0	4	0	0	0	0	0	1	0	0	0	4
0	0	5	0	0	0	0	0	1	0	1	0	5
0	0	6	0	0	0	0	0	1	1	0	0	6
0	0	7	0	0	0	0	0	1	1	1	0	7
0	0	8	0	0	0	0	1	0	0	0	0	8
0	0	9	0	0	0	0	1	0	0	1	0	9
0	1	0	0	0	0	0	1	0	1	0	0	a
0	1	1	0	0	0	0	1	0	1	1	0	b
0	1	2	0	0	0	0	1	1	0	0	0	c
0	1	3	0	0	0	0	1	1	0	1	0	d
0	1	4	0	0	0	0	1	1	1	0	0	e
0	1	5	0	0	0	0	1	1	1	1	0	f
0	1	6	0	0	0	1	0	0	0	0	1	0
0	1	7	0	0	0	1	0	0	0	1	1	1
...			
1	2	5	0	1	1	1	1	1	0	1	7	d
1	2	6	0	1	1	1	1	1	1	0	7	e
1	2	7	0	1	1	1	1	1	1	1	7	f
1	2	8	1	0	0	0	0	0	0	0	8	0

Figure 2.1: Counting in decimal, binary and hexadecimal.

```

328   1 1 1 1 0 1 0 1 <== A
329 ^ 1 0 0 1 0 0 1 1 <== B
330 -----
331   0 1 1 0 0 1 1 0 <== output

```

332 In a line of code the above might read like this: `output = A ^ B`

333 2.2 Integers and Counting

334 A binary integer is constructed with only 1s and 0s in the same manner as decimal numbers are
335 constructed with values from 0 to 9.

336 Counting in binary (base-2) uses the same basic rules as decimal (base-10). The difference is when we
337 consider that there are ten decimal digits and only two binary digits. Therefore, in base-10, we must
338 carry when adding one to nine (because there is no digit representing a ten) and, in base-2, we must
339 carry when adding one to one (because there is no digit representing a two.)

340 [Figure 2.1](#) shows an abridged table of the decimal, binary and hexadecimal values ranging from 0_{10}
341 to 128_{10} .

342 One way to look at this table is on a per-row basis where each [place value](#) is represented by the

base raised to the power of the [place value](#) position (shown in the column headings.) For example to interpret the decimal value on the fourth row:

$$0 \times 10^2 + 0 \times 10^1 + 3 \times 10^0 = 3_{10} \quad (2.2.1)$$

Interpreting the binary value on the fourth row by converting it to decimal:

$$0 \times 2^7 + 0 \times 2^6 + 0 \times 2^5 + 0 \times 2^4 + 0 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 3_{10} \quad (2.2.2)$$

Interpreting the hexadecimal value on the fourth row by converting it to decimal:

$$0 \times 16^1 + 3 \times 16^0 = 3_{10} \quad (2.2.3)$$

We refer to the place values with the largest exponent (the one furthest to the left for any given base) as the most significant digit and the place value with the lowest exponent as the least significant digit. For binary numbers these are the [Most Significant Bit \(MSB\)](#) and [Least Significant Bit \(LSB\)](#) respectively.²

Another way to look at this table is on a per-column basis. When tasked with drawing such a table by hand, it might be useful to observe that, just as in decimal, the right-most column will cycle through all of the values represented in the chosen base then cycle back to zero and repeat. (For example, in binary this pattern is 0-1-0-1-0-1-0-...) The next column in each base will cycle in the same manner except each of the values is repeated as many times as is represented by the place value (in the case of decimal, 10^1 times, binary 2^1 times, hex 16^1 times. Again, the binary numbers for this pattern are 0-0-1-1-0-0-1-1-...) This continues for as many columns as are needed to represent the magnitude of the desired number.

Another item worth noting is that any even binary number will always have a 0 LSB and odd numbers will always have a 1 LSB.

As is customary in decimal, leading zeros are sometimes not shown for readability.

The relationship between binary and hex values is also worth taking note. Because $2^4 = 16$, there is a clean and simple grouping of 4 [bits](#) to 1 [hit](#) (aka [nybble](#)). There is no such relationship between binary and decimal.

Writing and reading numbers in binary that are longer than 8 bits is cumbersome and prone to error. The simple conversion between binary and hex makes hex a convenient shorthand for expressing binary values in many situations.

For example, consider the following value expressed in binary, hexadecimal and decimal (spaced to show the relationship between binary and hex):

Binary value:	0010 0111 1011 1010 1100 1100 1111 0101
Hex Value:	2 7 B A C C F 5
Decimal Value:	666553589

Empirically we can see that grouping the bits into sets of four allows an easy conversion to hex and

²Changing the value of the MSB will have a more *significant* impact on the numeric value than changing the value of the LSB.

expressing it as such is $\frac{1}{4}$ as long as in binary while at the same time allowing for easy conversion back to binary.

The decimal value in this example does not easily convey a sense of the binary value.

In programming languages like the C, its derivatives and RISC-V assembly, numeric values are interpreted as decimal **unless** they start with a zero (0). Numbers that start with 0 are interpreted as octal (base-8), numbers starting with 0x are interpreted as hexadecimal and numbers that start with 0b are interpreted as binary.

2.2.1 Converting Between Bases

2.2.1.1 From Binary to Decimal

It is occasionally necessary to convert between decimal, binary and/or hex.

To convert from binary to decimal, put the decimal value of the [place values](#) ...8, 4, 2, 1 over the binary digits like this:

Base-2 place values:	128	64	32	16	8	4	2	1
Binary:	0	0	0	1	1	0	1	1
Decimal:				16	+8		+2	+1 = 27

Now sum the place-values that are expressed in decimal for each bit with the value of 1: $16 + 8 + 2 + 1$. The integer binary value 00011011_2 represents the decimal value 27_{10} .

2.2.1.2 From Binary to Hexadecimal

Conversion from binary to hex involves grouping the bits into sets of four and then performing the same summing process as shown above. If there is not a multiple of four bits then extend the binary to the left with zeros to make it so.

Grouping the bits into sets of four and summing:

Base-2 place values:	8	4	2	1	8	4	2	1	8	4	2	1
Binary:	0	1	1	0	1	1	0	1	1	1	0	
Decimal:		4	+2	=6	8	+4	=12	1	=13	8	+2	=10
										8	+4	+2 =14

After the summing, convert each decimal value to hex. The decimal values from 0–9 are the same values in hex. Because we don't have any more numerals to represent the values from 10–15, we use the first 6 letters (See the right-most column of [Figure 2.1](#).) Fortunately there are only six hex mappings involving letters. Thus it is reasonable to memorize them.

Continuing this example:

Decimal:	6	13	10	14
Hex:	6	D	A	E

2.2.1.3 From Hexadecimal to Binary

The four-bit mapping between binary and hex makes this task as straight forward as using a look-up table to translate each [hit](#) (Hex digIT) it to its unique four-bit pattern.

Perform this task either by memorizing each of the 16 patterns or by converting each hit to decimal first and then converting each four-bit binary value to decimal using the place-value summing method discussed in [section 2.2.1.1](#).

For example:

Hex:		7		C
Decimal Sum:		4+2+1=7	8+4	=12
Binary:		0 1 1 1	1 1 0 0	

2.2.1.4 From Decimal to Binary

To convert arbitrary decimal numbers to binary, extend the list of binary place values until it exceeds the value of the decimal number being converted. Then make successive subtractions of each of the place values that would yield a non-negative result.

For example, to convert 1234_{10} to binary:

Base-2 place values: 2048-1024-512-256-128-64-32-16-8-4-2-1

0		2048	(too big)
1	1234 - 1024 =	210	
0		512	(too big)
0		256	(too big)
1	210 - 128 =	82	
1	82 - 64 =	18	
0		32	(too big)
1	18 - 16 =	2	
0		8	(too big)
0		4	(too big)
1	2 - 2 =	0	
0		1	(too big)

The answer using this notation is listed vertically in the left column with the [MSB](#) on the top and the [LSB](#) on the bottom line: 010011010010₂.

2.2.1.5 From Decimal to Hex

Conversion from decimal to hex can be done by using the place values for base-16 and the same math as from decimal to binary or by first converting the decimal value to binary and then from binary to hex by using the methods discussed above.

Because binary and hex are so closely related, performing a conversion by way of binary is straight forward.

2.2.2 Addition of Binary Numbers

The addition of binary numbers can be performed long-hand the same way decimal addition is taught in grade school. In fact binary addition is easier since it only involves adding 0 or 1.

The first thing to note that in any number base $0 + 0 = 0$, $0 + 1 = 1$, and $1 + 0 = 1$. Since there is no “two” in binary (just like there is no “ten” decimal) adding $1 + 1$ results in a zero with a carry as in: $1 + 1 = 10_2$ and in: $1 + 1 + 1 = 11_2$. Using these five sums, any two binary integers can be added.

This truth table shows what is called a *Full Addr*. A full addr is a function that can add three input bits (the two addends and a carry value from a “prior column”) and produce the sum and carry output values.³

<i>ci</i>	<i>a</i>	<i>b</i>	<i>co</i>	<i>sum</i>
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Adding two unsigned binary numbers using 16 full adders:

```

      111111 1111 <== carries
    0110101111001111 <== addend
+  0000011101100011 <== addend
-----
    0111001100110010 <== sum

```

Note that the carry “into” the LSB is zero.

2.2.3 Signed Numbers

There are multiple methods used to represent signed binary integers. The method used by most modern computers is called *two’s complement*.

A two’s complement number is encoded in such a manner as to simplify the hardware used to add, subtract and compare integers.

A simple method of thinking about two’s complement numbers is to negate the place value of the **MSB**. For example, the number one is represented the same as discussed before:

```

Base-2 place values:  -128 64 32 16  8  4  2  1
Binary:                0  0  0  0  0  0  0  1

```

The **MSB** of any negative number in this format will always be 1. For example the value -1_{10} is:

³Note that the sum could be expressed in Boolean Algebra as: $sum = ci \oplus a \oplus b$

```

467 Base-2 place values:  -128 64 32 16  8  4  2  1
468 Binary:              1  1  1  1  1  1  1  1

```

469 ...because: $-128 + 64 + 32 + 16 + 8 + 4 + 2 + 1 = -1$.

470 This format has the virtue of allowing the same addition logic discussed above to be used to calculate
 471 the sums of signed numbers as unsigned numbers.

472 Calculating the signed addition: $4 + 5 = 9$

```

473      1      <== carries
474      000100 <== 4 = 0 + 0 + 0 + 4 + 0 + 0
475      +000101 <== 5 = 0 + 0 + 0 + 4 + 0 + 1
476      -----
477      001001 <== 9 = 0 + 0 + 8 + 0 + 0 + 1

```

478 Calculating the signed addition: $-4 + -5 = -9$

```

479      1 11      <== carries
480      111100 <== -4 = -32 + 16 + 8 + 4 + 0 + 0
481      +111011 <== -5 = -32 + 16 + 8 + 0 + 2 + 1
482      -----
483      1 110111 <== -9 (with a truncation) = -32 + 16 + 4 + 2 + 1 = -9

```

484 Calculating the signed addition: $-1 + 1 = 0$

```

485      -128 64 32 16  8  4  2  1 <== place value
486      1  1  1  1  1  1  1  1 <== carries
487      1  1  1  1  1  1  1  1 <== addend (-1)
488      + 0  0  0  0  0  0  0  1 <== addend (1)
489      -----
490      1  0  0  0  0  0  0  0 <== sum (0 with a truncation)

```

491 *In order for this to work, the carry out of the sum of the MSBs **must** be discarded.*

492 2.2.3.1 Converting between Positive and Negative

493 Changing the sign on two's complement numbers can be described as inverting all of the bits (which
 494 is also known as the *one's complement*) and then add one.

495 For example, negating the number four:

```

      -128 64 32 16  8  4  2  1
      0  0  0  0  0  1  0  0 <== 4

      1  1      <== carries
496      1  1  1  1  1  0  1  1 <== one's complement of 4
      + 0  0  0  0  0  0  0  1 <== plus 1
      -----
      1  1  1  1  1  1  0  0 <== -4

```

497 This can be verified by adding 5 to the result and observe that the sum is 1:

```

498     -128 64 32 16  8  4  2  1
499     1   1  1  1  1  1           <== carries
500         1  1  1  1  1  1  0  0 <== -4
501     + 0  0  0  0  0  1  0  1 <== 5
502     -----
503     1   0  0  0  0  0  0  1 <== 1 (with a truncation)

```

Note that the changing of the sign using this method is symmetric in that it is identical when converting from negative to positive and when converting from positive to negative: *flip the bits and add 1*.

For example, changing the value -4 to 4 to illustrate the reverse of the conversion above:

```

507     -128 64 32 16  8  4  2  1
508         1  1  1  1  1  1  0  0 <== -4
509
510             1  1           <== carries
511         0  0  0  0  0  0  1  1 <== one's complement of -4
512     + 0  0  0  0  0  0  0  1 <== plus 1
513     -----
514         0  0  0  0  0  1  0  0 <== 4

```

2.2.4 Subtraction of Binary Numbers

Subtraction of binary numbers is performed by first negating the subtrahend and then adding the two numbers. Due to the nature of two's complement numbers this method will work for both signed and unsigned numbers!

Observation: Since we always have a carry-in of zero into the LSB when adding, we can take advantage of that fact by (ab)using that carry input to perform that adding the extra 1 to the subtrahend as part of changing its sign in the examples below.

An example showing the subtraction of two *signed* binary numbers: $-4 - 8 = -12$

```

523     -128 64 32 16  8  4  2  1
524         1  1  1  1  1  1  0  0 <== -4 (minuend)
525     - 0  0  0  0  1  0  0  0 <== 8 (subtrahend)
526     -----
527
528
529     1   1  1  1  1  1  1  1 <== carries
530         1  1  1  1  1  1  0  0 <== -4
531     + 1  1  1  1  0  1  1  1 <== one's complement of 8
532     -----
533     1   1  1  1  1  0  1  0 <== -12

```

2.2.5 Truncation

Discarding the carry bit that can be generated from the MSB is called *truncation*.

► Fix Me:

This section needs more examples of subtracting signed and unsigned numbers and a discussion on how signedness is not relevant until the results are interpreted. For example adding $-4 + -8 = -12$ using two 8-bit numbers is the same as adding $252 + 248 = 500$ and truncating the result to 244.

So far we have been ignoring the carries that can come from the MSBs when adding and subtracting. We have also been ignoring the potential impact of a carry causing a signed number to change its sign in an unexpected way.

In the examples above, truncating the results either had 1) no impact on the calculated sums or 2) was absolutely necessary to correct the sum in cases such as: $-4 + 5$.

For example, note what happens when we try to subtract 1 from the most negative value that we can represent in a 4 bit two's complement number:

```

-8  4  2  1
  1  0  0  0 <== -8 (minuend)
- 0  0  0  1 <==  1 (subtrahend)
-----
1
1  0  0  0 <== -8
+ 1  1  1  0 <== one's complement of 1
-----
1  0  1  1  1 <== this SHOULD be -9 but with truncation it is 7

```

The problem with this example is that we can not represent -9_{10} using a 4-bit two's complement number.

Granted, if we would have used 5 bit numbers, then the “answer” would have fit OK. But the same problem would return when trying to calculate $-16 - 1$. So simply “making more room” does not solve this problem.

This is not just a problem when subtracting, nor is it just a problem with signed numbers.

The same situation can happen *unsigned* numbers. For example:

```

8  4  2  1
1  1  1  0  0 <== carries
  1  1  1  0 <== 14 (addend)
+ 0  0  1  1 <==  3 (addend)
-----
1  0  0  0  1 <== this SHOULD be 17 but with truncation it is 1

```

How to handle such a truncation depends on whether the *original* values being added are signed or unsigned.

The RV ISA refers to the discarding the carry out of the MSB after an add (or subtract) of two *unsigned* numbers as an *unsigned overflow*⁴ and the situation where carries create an incorrect sign in the result of adding (or subtracting) two *signed* numbers as a *signed overflow*. [1, p. 13]

2.2.5.1 Unsigned Overflow

When adding *unsigned* numbers, an overflow only occurs when there is a carry out of the MSB resulting in a sum that is truncated to fit into the number of bits allocated to contain the result.

⁴Most microprocessors refer to *unsigned overflow* simply as a *carry* condition.

Figure 2.2 illustrates an unsigned overflow during addition:

```

      1 1 1 1 0 0 0 0 <== carries
      1 1 1 1 0 0 0 0 <== 240
+     0 0 0 1 0 0 0 1 <== 17
-----
      1 0 0 0 0 0 0 1 <== sum = 1

```

Figure 2.2: $240 + 17 = 1$ (overflow)

Some times an overflow like this is referred to as a *wrap around* because of the way that successive additions will result in a value that increases until it *wraps* back *around* to zero and then returns to increasing in value until it, again, wraps around again.

When adding, *unsigned overflow* occurs when ever there is a carry *out of* the most significant bit.

When subtracting *unsigned* numbers, an overflow only occurs when the subtrahend is greater than the minuend (because in those cases the different would have to be negative and there are no negative values that can be represented with an unsigned binary number.)

Figure 2.3 illustrates an unsigned overflow during subtraction:

```

      0 0 0 0 0 0 1 1 <== 3 (minuend)
-     0 0 0 0 0 1 0 0 <== 4 (subtrahend)
-----

0 0 0 0 0 0 1 1 <== carries
0 0 0 0 0 0 1 1 <== 3
+ 1 1 1 1 1 0 1 1 <== one's complement of 4
-----
      1 1 1 1 1 1 1 1 <== 255 (overflow)

```

Figure 2.3: $3 - 4 = 255$ (overflow)

When subtracting, *unsigned overflow* occurs when ever there is *not* a carry *out of* the most significant bit (IFF the carry-in on the LSB is used to add the extra 1 to the subtrahend when changing its sign.)

2.2.5.2 Signed Overflow

When adding *signed* numbers, an overflow only occurs when the two addends are positive and sum is negative or the addends are both negative and the sum is positive.

When subtracting *signed* numbers, an overflow only occurs when the minuend is positive and the subtrahend is negative and difference is negative or when the minuend is negative and the subtrahend is positive and the difference is positive.⁵

⁵I had to look it up to remember which were which too... it is: minuend - subtrahend = difference.[13]

Consider the results of the addition of two *signed* numbers while looking more closely at the carry values.

```

      0 1 0 0 0 0 0 0 0 <== carries
      0 1 0 0 0 0 0 0 0 <== 64
+   0 1 0 0 0 0 0 0 0 <== 64
-----
      1 0 0 0 0 0 0 0 0 <== sum = -128

```

Figure 2.4: $64 + 64 = -128$ (overflow)

Figure 2.4 is an example of *signed overflow*. As shown, the problem is that the sum of two positive numbers has resulted in an obviously incorrect negative result due to a carry flowing into the sign-bit in the MSB.

Granted, if the same values were added using values larger than 8-bits then the sum would have been correct. However, these examples assume that all the operations are performed on (and results stored into) 8-bit values. Given any finite-number of bits, there are values that could be added such that an overflow occurs.

Figure 2.5 shows another overflow situation that is caused by the fact that there is nowhere for the carry out of the sign-bit to go. We say that this result has been *truncated*.

```

      1 0 0 0 0 0 0 0 0 <== carries
      1 0 0 0 0 0 0 0 0 <== -128
+   1 0 0 0 0 0 0 0 0 <== -128
-----
      0 0 0 0 0 0 0 0 0 <== sum = 0

```

Figure 2.5: $-128 + -128 = 0$ (overflow)

Truncation is not necessarily a problem. Consider the truncations in figures 2.6 and 2.7. Figure 2.7 demonstrates the importance of discarding the carry from the sum of the MSBs of signed numbers when addends do not have the same sign.

```

      1 1 1 1 1 1 1 0 <== carries
      1 1 1 1 1 0 1 <== -3
+   1 1 1 1 1 0 1 <== -5
-----
      1 1 1 1 1 0 0 0 <== sum = -8

```

Figure 2.6: $-3 + -5 = -8$

```

      1 1 1 1 1 1 0 0 <== carries
      1 1 1 1 1 1 0 <== -2
+   0 0 0 0 1 0 1 0 <== 10
-----
      0 0 0 0 1 0 0 0 <== sum = 8

```

Figure 2.7: $-2 + 10 = 8$

Just like an unsigned number can wrap around as a result of successive additions, a signed number can so the same thing. The only difference is that signed numbers won't wrap from the maximum

607

608

Figure 2.8: $127 + 1 = -128$

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610

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612

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615
616

617

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619
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621

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623

624

625

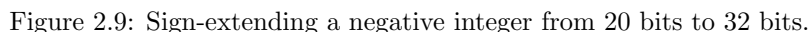


Figure 2.10 illustrates extending the sign bit of a positive number to the left by replicating it. A positive number will have its MSB set to 0. Extending this value to the left will set all the new bits to the left of it to 0 as well.

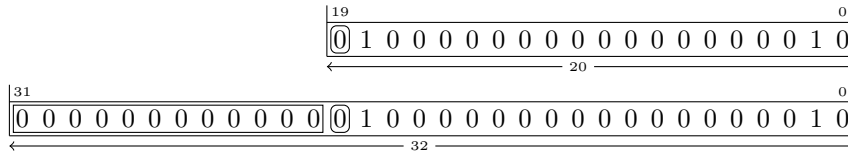


Figure 2.10: Sign-extending a positive integer from 20 bits to 32 bits.

In a similar vein, any unsigned number also may have any quantity of additional MSBs added to it provided that they are all zero. This is called *zero extension*. For example, the following all represent the same value:

```

1111 <== 15
01111 <== 15
0000000000000000000000001111 <== 15

```

Any *unsigned* number may be *zero extended* to any size.

Figure 2.11 illustrates zero-extending a 20-bit number to the left to form a 32-bit number.

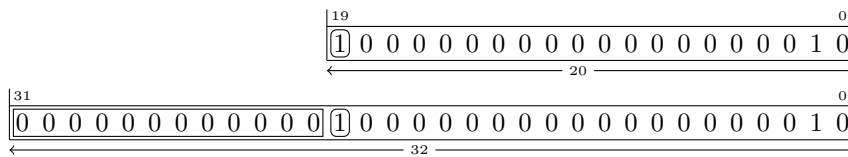


Figure 2.11: Zero-extending an unsigned integer from 20 bits to 32 bits.

► Fix Me:

Remove the sign-bit boxes from this figure?

2.4 Shifting

We were all taught how to multiply and divide decimal numbers by ten by moving (or *shifting*) the decimal point to the right or left respectively. Doing the same in any other base has the same effect in that it will multiply or divide the number by its base.

Multiplication and division are only two reasons for shifting. There can be other occasions where doing so is useful.

► Fix Me:

Include decimal values in the shift diagrams.

As implemented by a CPU, shifting applies to the value in a register and the results stored back into a register of finite size. Therefore a shift result will always be truncated to fit into a register.

Note that when dealing with numeric values, any truncation performed during a right-shift will manifest itself as rounding toward zero.

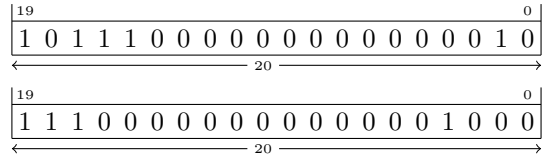
► Fix Me:

Add some examples showing the rounding of positive and negative values.

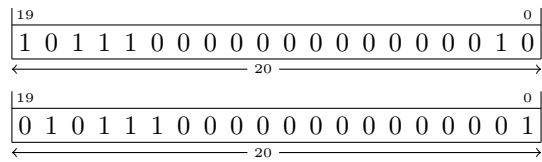
2.4.1 Logical Shifting

Shifting *logically* to the left or right is a matter of re-aligning the bits in a register and truncating the result.

To shift left two positions:



To shift right one position:



Note that the vacated bit positions are always filled with zero.

► Fix Me:

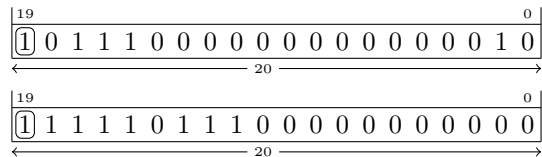
Redraw these with arrows tracking the shifted bits and the truncated values

2.4.2 Arithmetic Shifting

Some times it is desirable to retain the value of the sign bit when shifting. The RISC-V ISA provides an arithmetic right shift instruction for this purpose (there is no arithmetic left shift for this ISA.)

When shifting to the right *arithmetically*, vacated bit positions are filled by replicating the value of the sign bit.

An arithmetic right shift of a negative number by 4 bit positions:



2.5 Main Memory Storage

As mentioned in [section 1.1.1.1](#), the main memory in a RISC-V system is byte-addressable. For that reason we will visualize it by displaying ranges of bytes displayed in hex and in [ASCII](#). As will become obvious, the ASCII part makes it easier to find text messages.⁶

⁶Most of the memory dumps in this text are generated by [rvddt](#) and are shown on a per-byte basis without any attempt to reorder their values. Some other applications used to dump memory do not dump the bytes in address-order! It is important to know how your software tools operate when using them to dump the contents of memory and/or files.

2.5.1 Memory Dump

Listing 2.1 shows a *memory dump* from the `rvddt 'd'` command requesting a dump starting at address `0x00002600` for the default quantity (`0x100`) of bytes.

Listing 2.1: `rvddt_memdump.out`
`rvddt memory dump`

```

ddt> d 0x00002600
00002600: 93 05 00 00 13 06 00 00 93 06 00 00 13 07 00 00 *.....*
00002610: 93 07 00 00 93 08 d0 05 73 00 00 00 63 54 05 02 *.....s...cT..*
00002620: 13 01 01 ff 23 24 81 00 13 04 05 00 23 26 11 00 *...#$.....#&...*
00002630: 33 04 80 40 97 00 00 00 e7 80 40 01 23 20 85 00 *3...@.....@.# ...*
00002640: 6f 00 00 00 6f 00 00 00 b7 87 00 00 03 a5 07 43 *o...o.....C*
00002650: 67 80 00 00 00 00 00 00 76 61 6c 3d 00 00 00 00 *g.....val=....*
00002660: 00 00 00 00 80 84 2e 41 1f 85 45 41 80 40 9a 44 *.....A..EA.@.D*
00002670: 4f 11 f3 c3 6e 8a 67 41 20 1b 00 00 20 1b 00 00 *0...n.gA ... ..*
00002680: 44 1b 00 00 14 1b 00 00 14 1b 00 00 04 1c 00 00 *D.....*
00002690: 44 1b 00 00 14 1b 00 00 04 1c 00 00 14 1b 00 00 *D.....*
000026a0: 44 1b 00 00 10 1b 00 00 10 1b 00 00 10 1b 00 00 *D.....*
000026b0: 04 1c 00 00 54 1f 00 00 54 1f 00 00 d4 1f 00 00 *....T...T.....*
000026c0: 4c 1f 00 00 4c 1f 00 00 34 20 00 00 d4 1f 00 00 *L...L...4 .....*
000026d0: 4c 1f 00 00 34 20 00 00 4c 1f 00 00 d4 1f 00 00 *L...4 ..L.....*
000026e0: 48 1f 00 00 48 1f 00 00 48 1f 00 00 34 20 00 00 *H...H...H...4 ...*
000026f0: 00 01 02 02 03 03 03 03 04 04 04 04 04 04 04 04 *.....*

```

ℓ 1 The `rvddt` prompt showing the dump command.

ℓ 2 From left to right, the dump is presented as the address of the first byte (`0x00002600`) followed by a colon, the value of the byte at address `0x00002600` expressed in hex, the next byte (at address `0x00002601`) and so on for 16 bytes. There is a double-space between the 7th and 8th bytes to help provide a visual reference for the center to make it easy to locate bytes on the right end. For example, the byte at address `0x0000260c` is four bytes to the right of byte number eight (at the gap) and contains `0x13`. To the right of the 16-bytes is an asterisk-enclosed set of 16 columns showing the ASCII characters that each byte represents. If a byte has a value that corresponds to a printable character code, the character will be displayed. For any illegal/un-displayable byte values, a dot is shown to make it easier to count the columns.

ℓ 3-17 More of the same as seen on ℓ 2. The address at the left can be seen to advance by 16_{10} (or 10_{16}) for each line shown.

2.5.2 Endianness

The choice of which end of a multi-byte value is to be stored at the lowest byte address is referred to as *endianness*. For example, if a CPU were to store a [halfword](#) into memory, should the byte containing the [Most Significant Bit \(MSB\)](#) (the *big* end) go first or does the byte with the [Least Significant Bit \(LSB\)](#) (the *little* end) go first?

On the one hand the choice is arbitrary. On the other hand, it is possible that the choice could impact the performance of the system.⁷

IBM mainframe CPUs and the 68000 family store their bytes in big-endian order. While the Intel Pentium and most embedded processors use little-endian order. Some CPUs are even *bi-endian* in that they have instructions that can change their order on the fly.

The RISC-V system uses the little-endian byte order.

⁷See[14] for some history of the big/little-endian “controversy.”

2.5.2.1 Big-Endian

Using the contents of Listing 2.1, a *big-endian* CPU would interpret the contents as follows:

- The 8-bit value read from address `0x00002658` would be `0x76`.
- The 8-bit value read from address `0x00002659` would be `0x61`.
- The 8-bit value read from address `0x0000265a` would be `0x6c`.
- The 8-bit value read from address `0x0000265b` would be `0x3d`.
- The 16-bit value read from address `0x00002658` would be `0x7661`.
- The 16-bit value read from address `0x0000265a` would be `0x6c3d`.
- The 32-bit value read from address `0x00002658` would be `0x76616c3d`.

Notice that in a big-endian system, the *place values* of the bits comprising the `0x76` (located at memory address `0x00002658`) are *different* depending on the number of bytes representing the value that is being read.

For example, when a 16-bit value is read from `0x00002658` then the `76` represents the binary place values: 2^{15} to 2^8 . When a 32-bit value is read then the `76` represents the binary place values: 2^{31} to 2^{24} . In other words the value read from the first memory location (with the lowest address), of the plurality of addresses containing the complete value being read, is always placed on the *left end*, into the Most Significant Bits. One might dare say that the `76` is placed at the end with the *big* place values.

More examples:

- An 8-bit value read from address `0x00002624` would be `0x23`.
- An 8-bit value read from address `0x00002625` would be `0x24`.
- An 8-bit value read from address `0x00002626` would be `0x81`.
- An 8-bit value read from address `0x00002627` would be `0x00`.
- A 16-bit value read from address `0x00002624` would be `0x2324`.
- A 16-bit value read from address `0x00002626` would be `0x8100`.
- A 32-bit value read from address `0x00002624` would be `0x23248100`.

Again, notice that the byte from memory address `0x00002624`, regardless of the *number* of bytes comprising the complete value being fetched, will always appear on the left/*big* end of the final value.

On a big-endian system, the bytes in the dump are in the same order as they would be used by the CPU if it were to read them as a multi-byte value.

2.5.2.2 Little-Endian

Using the contents of Listing 2.1, a little-endian CPU would interpret the contents as follows:

- An 8-bit value read from address `0x00002658` would be `0x76`.
- An 8-bit value read from address `0x00002659` would be `0x61`.
- An 8-bit value read from address `0x0000265a` would be `0x6c`.
- An 8-bit value read from address `0x0000265b` would be `0x3d`.
- A 16-bit value read from address `0x00002658` would be `0x6176`.
- A 16-bit value read from address `0x0000265a` would be `0x3d6c`.
- A 32-bit value read from address `0x00002658` would be `0x3d6c6176`.

Notice that in a little-endian system, the *place values* of the bits comprising the `0x76` (located at memory address `0x00002658`) are the *same* regardless of the the number of bytes representing the value that is being read.

Unlike the behavior of a big-endian machine, when little-endian machine reads a 16-bit value from `0x00002658` the `76` represents the binary place values from 2^7 to 2^0 . When a 32-bit value is read then the `76` (still) represents the binary place values from 2^7 to 2^0 . In other words the value read from the first memory location (with the lowest address), of the plurality of addresses containing the complete value being read, is always placed on the *right end*, into the Least Significant Bits. One might say that the `76` is placed at the end with the *little* place values.

Also notice that it is the *bytes* are what are “reversed” in a little-endian system (*not* the hex digits.)

More examples:

- The 8-bit value read from address `0x00002624` would be `0x23`.
- The 8-bit value read from address `0x00002625` would be `0x24`.
- The 8-bit value read from address `0x00002626` would be `0x81`.
- The 8-bit value read from address `0x00002627` would be `0x00`.
- The 16-bit value read from address `0x00002624` would be `0x2423`.
- The 16-bit value read from address `0x00002626` would be `0x0081`.
- The 32-bit value read from address `0x00002624` would be `0x00812423`.

As above, notice that the byte from memory address `0x00002624`, regardless of the *number* of bytes comprising the complete value being fetched, will always appear on the right/*little* end of the final value.

On a little-endian system, the bytes in the dump are in reverse order as they would be used by the CPU if it were to read them as a multi-byte value.

In the RISC-V ISA it is noted that

A minor point is that we have also found little-endian memory systems to be more natural for hardware designers. However, certain application areas, such as IP networking, operate on big-endian data structures, and so we leave open the possibility of non-standard big-endian or bi-endian systems.”[1, p. 6]

2.5.3 Arrays and Character Strings

While Endianness defines how single values are stored in memory, the *array* defines how multiple values are stored.

An array is a data structure comprised of an ordered set of elements. This text will limit its definition of array to a plurality of elements that are all of the same type. Where type refers to the size (number of bytes) and representation (signed, unsigned, ...) of each element.

In an array, the elements are stored adjacent to one another such that the address e of any element $x[n]$ is:

$$e = a + n * s \quad (2.5.1)$$

Where x is the name of the array, n is the element number of interest, e is the address of interest, a is the address of the first element in the array and s is the size (in bytes) of each element.

Given an array x containing m elements, $x[0]$ is the first element of the array and $x[m-1]$ is the last element of the array.⁸

Using this definition, and the memory dump shown in [Listing 2.1](#), and the knowledge that we are using a little-endian machine and given that $a = 0x00002656$ and $s = 2$, the values of the first 8 elements of array x are:

- $x[0]$ is 0x0000 and is stored at 0x00002656.
- $x[1]$ is 0x6176 and is stored at 0x00002658.
- $x[2]$ is 0x3d6c and is stored at 0x0000265a.
- $x[3]$ is 0x0000 and is stored at 0x0000265c.
- $x[4]$ is 0x0000 and is stored at 0x00002660.
- $x[5]$ is 0x0000 and is stored at 0x00002662.
- $x[6]$ is 0x8480 and is stored at 0x00002664.
- $x[7]$ is 0x412e and is stored at 0x00002666.

In general, there is no fixed rule nor notion as to how many elements an array has. It is up to the programmer to ensure that the starting address and the number of elements in any given array (its size) are used properly so that data bytes outside an array are not accidentally used as elements.

⁸Some computing languages (C, C++, Java, C#, Python, Perl,...) define an array such that the first element is indexed as $x[0]$. While others (FORTRAN, MATLAB) define the first element of an array to be $x[1]$.

There is, however, a common convention used for an array of characters that is used to hold a text message (called a *character string* or just *string*).

When an array is used to hold a string the element past the last character in the string is set to zero. This is because 1) zero is not a valid printable ASCII character and 2) it simplifies software in that knowing no more than the starting address of a string is all that is needed to process it. Without this zero *sentinel* value (called a *null terminator*), some knowledge of the number of characters in the string would have to otherwise be conveyed to any code needing to consume or process the string.

In [Listing 2.1](#), the 5-byte long array starting at address 0x00002658 contains a string whose value can be expressed as either:

76 61 6c 3d 00

or

"val="

When the double-quoted text form is used, the GNU assembler used in this text differentiates between *ascii* and *asciiz* strings such that an *ascii* string is **not** null terminated and an *asciiz* string **is** null terminated.

The value of providing a method to create a string that is not null terminated is that a program may define a large string by concatenating a number of *ascii* strings together and following the last with a byte of zero to null-terminate it.

It is a common mistake to create a string with a missing null terminator. The result of printing such a string is that the string will be printed as well as whatever random data bytes in memory follow it until a byte whose value is zero is encountered by chance.

2.5.4 Context is Important!

Data values can be interpreted differently depending on the context in which they are used. Assuming what a set of bytes is used for based on their contents can be very misleading! For example, there is a 0x76 at address 0x00002658. This is a 'v' if you use it as an ASCII (see [Appendix C](#)) character, a 118₁₀ if it is an integer value and TRUE if it is a conditional.

2.5.5 Alignment

With respect to memory and storage, *alignment* refers to the *location* of a data element when the address that it is stored is a precise multiple of a power-of-2.

The primary alignments of concern are typically 2 (a halfword), 4 (a fullword), 8 (a double word) and 16 (a quad-word) bytes.

For example, any data element that is aligned to 2-byte boundary must have an (hex) address that ends in any of: 0, 2, 4, 6, 8, A, C or E. Any 4-byte aligned element must be located at an address ending in 0, 4, 8 or C. An 8-byte aligned element at an address ending with 0 or 8, and 16-byte aligned elements must be located at addresses ending in zero.

Such alignments are important when exchanging data between the CPU and memory because the hardware implementations are optimized to transfer aligned data. Therefore, aligning data used by

►► Fix Me:

Include the obligatory diagram showing the overlapping data types when they are all aligned.

any program will reap the benefit of running faster.⁹

An element of data is considered to be *aligned to its natural size* when its address is an exact multiple of the number of bytes used to represent the data. Note that the ISA we are concerned with *only* operates on elements that have sizes that are powers of two.

For example, a 32-bit integer consumes one full word. If the four bytes are stored in main memory at an address that is a multiple of 4 then the integer is considered to be naturally aligned.

The same would apply to 16-bit, 64-bit, 128-bit and other such values as they fit into 2, 8 and 16 byte elements respectively.

Some CPUs can deliver four (or more) bytes at the same time while others might only be capable of delivering one or two bytes at a time. Such differences in hardware typically impact the cost and performance of a system.¹⁰

2.5.6 Instruction Alignment

The RISC-V ISA requires that all instructions be aligned to their natural boundaries.

Every possible instruction that an RV32I CPU can execute contains exactly 32 bits. Therefore they are always stored on a full word boundary. Any *unaligned* instruction is *illegal*.¹¹

An attempt to fetch an instruction from an unaligned address will result in an error referred to as an alignment *exception*. This and other exceptions cause the CPU to stop executing the current instruction and start executing a different set of instructions that are prepared to handle the problem. Often an exception is handled by completely stopping the program in a way that is commonly referred to as a system or application *crash*.

⁹Alignment of data, while important for efficient performance, is not mandatory for RISC-V systems.[1, p. 19]

¹⁰The design and implementation choices that determine how any given system operates are part of what is called a system's *organization* and is beyond the scope of this text. See [3] for more information on computer organization.

¹¹This rule is relaxed by the C extension to allow an instruction to start at any even address.[1, p. 5]

Chapter 3

The Elements of a Assembly Language Program

3.1 Assembly Language Statements

Introduce the assembly language grammar.

- Statement = 1 line of text containing an instruction or directive.
- Instruction = label, mnemonic, operands, comment.
- Directive = Used to control the operation of the assembler.

3.2 Memory Layout

Is this a good place to introduce the text, data, bss, heap and stack regions?

Or does that belong in a new section/chapter that discusses addressing modes?

3.3 A Sample Program Source Listing

A simple program that illustrates how this text presents program source code is seen in [Listing 3.1](#). This program will place a zero in each of the 4 registers named x28, x29, x30 and x31.

Listing 3.1: `zero4regs.S`
Setting four registers to zero.

```
1  .text                # put this into the text section
2  .align 2             # align to 2^2
3  .globl _start
4  _start:
5      addi    x28, x0, 0    # set register x28 to zero
6      addi    x29, x0, 0    # set register x29 to zero
7      addi    x30, x0, 0    # set register x30 to zero
8      addi    x31, x0, 0    # set register x31 to zero
```

This program listing illustrates a number of things:

- Listings are identified by the name of the file within which they are stored. This listing is from a file named: `zero4regs.S`.
- The assembly language programs discussed in this text will be saved in files that end with: `.S` (Alternately you can use `.sx` on systems that don't understand the difference between upper and lowercase letters.¹)
- A description of the listing's purpose appears under the name of the file. The description of [Listing 3.1](#) is *Setting four registers to zero*.
- The lines of the listing are numbered on the left margin for easy reference.
- An assembly program consists of lines of plain text.
- The RISC-V ISA does not provide an operation that will simply set a register to a numeric value. To accomplish our goal this program will add zero to zero and place the sum in each of the four registers.
- The lines that start with a dot '.' (on lines 1, 2 and 3) are called *assembler directives* as they tell the assembler itself how we want it to translate the following *assembly language instructions* into *machine language instructions*.
- Line 4 shows a *label* named `_start`. The colon at the end is the indicator to the assembler that causes it to recognize the preceding characters as a label.
- Lines 5-8 are the four assembly language instructions that make up the program. Each instruction in this program consists of four *fields*. (Different instructions can have a different number of fields.) The fields on line 5 are:
 - `addi` The instruction mnemonic. It indicates the operation that the CPU will perform.
 - `x28` The *destination* register that will receive the sum when the *addi* instruction is finished. The names of the 32 registers are expressed as `x0 – x31`.
 - `x0` One of the addends of the sum operation. (The `x0` register will always contain the value zero. It can never be changed.)
 - `0` The second addend is the number zero.
- `# set ...` Any text anywhere in a RISC-V assembly language program that starts with the pound-sign is ignored by the assembler. They are used to place a *comment* in the program to help the reader better understand the motive of the programmer.

3.4 Running a Program With rvddt

To illustrate what a CPU does when it executes instructions this text will use the [rvddt](#) simulator to display shows sequence of events and the binary values involved. This simulator supports the RV32I ISA and has a configurable amount of memory.²

[Listing 3.2](#) shows the operation of the four *addi* instructions from [Listing 3.1](#) when it is executed in trace-mode.

¹The author of this text prefers to avoid using such systems.

²The *rvddt* simulator was written to generate the listings for this text. It is similar to the fancier *spike* simulator. Given the simplicity of the RV32I ISA, *rvddt* is less than 1700 lines of C++ and was written in one (long) afternoon.

Listing 3.2: zero4regs.out

Running a program with the rvdtd simulator

```

919 1 [winans@w510 src]$ ./rvdtd -f ../examples/load4regs.bin
920 2 Loading '../examples/load4regs.bin' to 0x0
921 3 ddt> t4
922 4
923 5   x0: 00000000 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
924 6   x8: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
925 7  x16: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
926 8  x24: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
927 9   pc: 00000000
928 10 00000000: 00000e13 addi    x28, x0, 0    # x28 = 0x00000000 = 0x00000000 + 0x00000000
929 11   x0: 00000000 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
930 12   x8: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
931 13  x16: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
932 14  x24: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
933 15   pc: 00000004
934 16 00000004: 00000e93 addi    x29, x0, 0    # x29 = 0x00000000 = 0x00000000 + 0x00000000
935 17   x0: 00000000 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
936 18   x8: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
937 19  x16: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
938 20  x24: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 00000000 00000000 f0f0f0f0 f0f0f0f0
939 21   pc: 00000008
940 22 00000008: 00000f13 addi    x30, x0, 0    # x30 = 0x00000000 = 0x00000000 + 0x00000000
941 23   x0: 00000000 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
942 24   x8: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
943 25  x16: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
944 26  x24: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 00000000 00000000 00000000 f0f0f0f0
945 27   pc: 0000000c
946 28 0000000c: 00000f93 addi    x31, x0, 0    # x31 = 0x00000000 = 0x00000000 + 0x00000000
947 29 ddt> r
948 30   x0: 00000000 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
949 31   x8: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
950 32  x16: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
951 33  x24: f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 00000000 00000000 00000000 00000000
952 34   pc: 00000010
953 35 ddt> x
954 36 [winans@w510 src]$

```

ℓ 1 This listing includes the command-line that shows how the simulator was executed to load a file containing the machine instructions (aka machine code) from the assembler.

ℓ 2 A message from the simulator indicating that it loaded the machine code into simulated memory at address 0.

ℓ 3 This line shows the prompt from the debugger and the command `t4` that the user entered to request that the simulator trace the execution of four instructions.

ℓ 4-8 Prior to executing the first instruction, the state of the CPU registers is displayed.

ℓ 4 The values in registers 0, 1, 2, 3, 4, 5, 6 and 7 are printed from left to right in [big-endian](#), [hexadecimal](#) form. The double-space gap in the middle of the line is a reference to make it easier to visually navigate across the line without being forced to count the values from the far left when seeking the value of, say, `x5`.

ℓ 5-7 The values of registers 8-31 are printed.

ℓ 8 The *program counter* (`pc`) register is printed. It contains the address of the instruction that the CPU will execute. After each instruction, the `pc` will either advance four bytes ahead or be set to another value by a branch instruction as discussed above.

ℓ 9 A four-byte instruction is fetched from memory at the address in the `pc` register, is decoded and printed. From left to right the fields shown on this line are:

```

973 00000000 The memory address from which the instruction was fetched. This address is displayed in
974         big-endian, hexadecimal form.
975 00000e13 The machine code of the instruction displayed in big-endian, hexadecimal form.
976     addi The mnemonic for the machine instruction.
977     x28 The rd field of the addi instruction.
978     x0 The rs1 field of the addi instruction that holds one of the two addends of the operation.
979     0 The imm field of the addi instruction that holds the second of the two addends of the
980       operation.
981     # ... A simulator-generated comment that explains what the instruction is doing. For this in-
982           struction it indicates that x28 will have the value zero stored into it as a result of performing
983           the addition: 0 + 0.

984 ℓ 10-14 These lines are printed as the prelude while tracing the second instruction. Lines 7 and 13 show
985         that x28 has changed from f0f0f0f0 to 00000000 as a result of executing the first instruction and
986         lines 8 and 14 show that the pc has advanced from zero (the location of the first instruction) to
987         four, where the second instruction will be fetched. None of the rest of the registers have changed
988         values.

989 ℓ 15 The second instruction decoded executed and described. This time register x29 will be assigned
990     a value.

991 ℓ 16-27 The third and fourth instructions are traced.

992 ℓ 28 Tracing has completed. The simulator prints its prompt and the user enters the 'r' command
993     to see the register state after the fourth instruction has completed executing.

994 ℓ 29-33 Following the fourth instruction it can be observed that registers x28, x29, x30 and x31 have
995         been set to zero and that the pc has advanced from zero to four, then eight, then 12 (the hex
996         value for 12 is c) and then to 16 (which, in hex, is 10).

997 ℓ 34 The simulator exit command 'x' is entered by the user and the terminal displays the shell prompt.

```

Chapter 4

Writing RISC-V Programs

This chapter introduces each of the RV32I instructions by developing programs that demonstrate their usefulness.

► Fix Me:
Introduce the ISA register names and aliases in here?

4.1 Use ebreak to Stop rvddt Execution

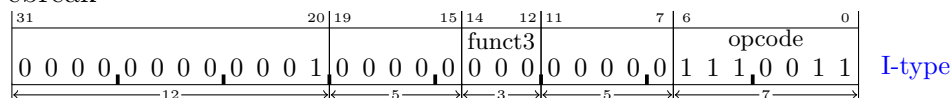
It is a good idea to learn how to stop before learning how to go!

The **ebreak** instruction exists for the sole purpose of transferring control back to a debugging environment.^[1, p. 24]

When **rvddt** executes an **ebreak** instruction, it will immediately terminate any executing *trace* or *go* command currently executing and return to the command prompt without advancing the **pc** register.

The machine language encoding shows that **ebreak** has no operands.

ebreak



[Listing 4.2](#) demonstrates that since **rvddt** does not advance the **pc** when it encounters an **ebreak** instruction, subsequent *trace* and/or *go* commands will re-execute the same **ebreak** and halt the simulation again (and again). This feature is intended to help prevent overzealous users from accidentally running past the end of a code fragment.¹

Listing 4.1: **ebreak/ebreak.S**

A one-line **ebreak** program.

```
1 .text          # put this into the text section
2 .align 2       # align to a multiple of 4
3 .globl _start
4
5 _start:
6     ebreak
```

¹This was one of the first *enhancements* I needed for myself :-)

Listing 4.2: ebreak/ebreak.out

ebreak stops rvddt without advancing pc.

```

1023
1024 1 $ rvddt -f ebreak.bin
1025 2 sp initialized to top of memory: 0x0000fff0
1026 3 Loading 'ebreak.bin' to 0x0
1027 4 This is rvddt. Enter ? for help.
1028 5 ddt> d 0 16
1029 6 00000000: 73 00 10 00 a5 a5 a5 a5 a5 a5 a5 a5 a5 a5 a5 a5 *s.....*
1030 7 ddt> r
1031 8 x0 00000000 f0f0f0f0 0000fff0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1032 9 x8 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1033 10 x16 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1034 11 x24 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1035 12 pc 00000000
1036 13 ddt> ti 0 1000
1037 14 00000000: ebreak
1038 15 ddt> ti
1039 16 00000000: ebreak
1040 17 ddt> g 0
1041 18 00000000: ebreak
1042 19 ddt> r
1043 20 x0 00000000 f0f0f0f0 0000fff0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1044 21 x8 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1045 22 x16 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1046 23 x24 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1047 24 pc 00000000
1048 25 ddt> x
1049

```

4.2 Using the addi Instruction

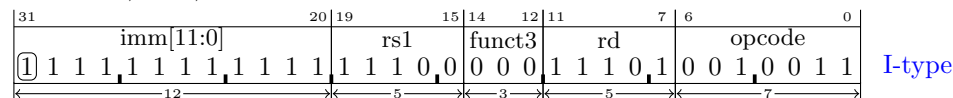
The detailed description of how the addi instruction is executed is that it:

► Fix Me:
Define what constant and immediate values are somewhere.

1. Sign-extends the immediate operand.
2. Add the sign-extended immediate operand to the contents of the **rs1** register.
3. Store the sum in the **rd** register.
4. Add four to the **pc** register (point to the next instruction.)

In the following example **rs1** = **x28**, **rd** = **x29** and the immediate operand is -1.

addi x29, x28, -1



Depending on the values of the fields in this instruction a number of different operations can be performed. The most obvious is that it can add things. But it can also be used to copy registers, set a register to zero and even, when you need to, accomplish nothing.

4.2.1 No Operation

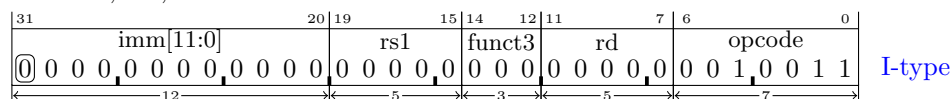
It might seem odd but it is sometimes important to be able to execute an instruction that accomplishes nothing while simply advancing the **pc** to the next instruction. One reason for this is to fill unused

memory between two instructions in a program.²

An instruction that accomplishes nothing is called a **nop** (sometimes systems call these **noop**). The name means *no operation*. The intent of a **nop** is to execute without having any side effects other than to advance the **pc** register.

The `addi` instruction can serve as a `nop` by coding it like this:

```
addi x0, x0, 0
```



The result will be to add zero to zero and discard the result (because you can never store a value into the x0 register.)

The RISC-V assembler provides a pseudoinstruction specifically for this purpose that you can use to improve the readability of your code. Note that the `addi` and `nop` instructions in Listing 4.3 are assembled into the exact same binary machine instructions as can be seen by comparing it to `objdump` Listing 4.4, and `rvddt` Listing 4.5 output.

Listing 4.3: nop/nop.S

Demonstrate that `addi` can be used as a `nop`.

```

        .text                # put this into the text section
        .align 2             # align to a multiple of 4
        .globl _start

_start:
        addi    x0, x0, 0    # these two instructions assemble into the same thing!
        nop

        ebreak

```

Listing 4.4: nop/nop.lst

Using `addi` to perform a `nop`

```

nop:      file format elf32-littleriscv
Disassembly of section .text:
00000000 <_start>:
0:      00000013                nop
4:      00000013                nop
8:      00100073                ebreak

```

Listing 4.5: nop/nop.out

Using `addi` to perform a `nop`

```
$ rvdtdt -f nop.bin
sp initialized to top of memory: 0x0000fff0
Loading 'nop.bin' to 0x0
This is rvdtdt. Enter ? for help.
dtdt> d 0 16
00000000: 13 00 00 00 13 00 00 00 73 00 10 00 a5 a5 a5 a5 *.....s.....*
dtdt> r
x0 00000000 f0f0f0f0 0000fff0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
x8 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
x16 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
x24 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
```

²This can happen during the evolution of one portion of code that reduces in size but has to continue to fit into a system without altering any other code... or sometimes you just need to waste a small amount of time in a device driver.

```

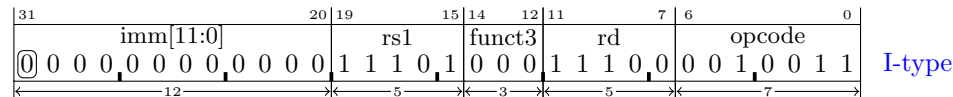
1109 12      pc 00000000
1110 13 ddt> ti 0 1000
1111 14 00000000: 00000013 addi    x0, x0, 0      # x0 = 0x00000000 = 0x00000000 + 0x00000000
1112 15 00000004: 00000013 addi    x0, x0, 0      # x0 = 0x00000000 = 0x00000000 + 0x00000000
1113 16 00000008: ebreak
1114 17 ddt> r
1115 18      x0 00000000 f0f0f0f0 0000ffff f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1116 19      x8 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1117 20     x16 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1118 21     x24 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0 f0f0f0f0
1119 22      pc 00000008
1120 23 ddt> x

```

4.2.2 Copying the Contents of One Register to Another

By adding zero to one register and storing the sum in another register the `addi` instruction can be used to copy the value stored in one register to another register. The following instruction will copy the contents of `t4` into `t3`.

`addi t3, t4, 0`



This is a commonly required operation. To make your intent clear you may use the `mv` pseudoinstruction for this purpose.

[Listing 4.6](#) shows the source of a program that is dumped in [Listing 4.7](#) illustrating that the assembler has generated the same machine instruction (0x000e8e13 at addresses 0x0 and 0x4) for both of the instructions.

Listing 4.6: `mv/mv.S`

Comparing `addi` to `mv`

```

1133 1      .text                # put this into the text section
1134 2      .align 2             # align to a multiple of 4
1135 3      .globl _start
1136 4
1137 5 _start:
1138 6     addi    t3, t4, 0      # t3 = t4
1139 7     mv      t3, t4        # t3 = t4
1140 8
1141 9     ebreak
1142
1143

```

Listing 4.7: `mv/mv.lst`

An objdump of an `addi` and `mv` Instruction.

```

1144 1 mv:      file format elf32-littleriscv
1145 2 Disassembly of section .text:
1146 3 00000000 <_start>:
1147 4 0: 000e8e13      mv    t3,t4
1148 5 4: 000e8e13      mv    t3,t4
1149 6 8: 00100073      ebreak
1150
1151

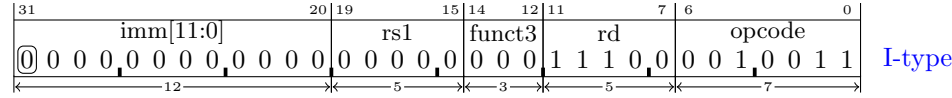
```


4.2.3 Setting a Register to Zero

Recall that `x0` always contains the value zero. Any register can be set to zero by copying the contents of `x0` using `mv` (aka `addi`).³

For example, to set `t3` to zero:

```
addi t3, x0, 0
```



Listing 4.8: `mvzero/mv.S`

Using `mv` (aka `addi`) to zero-out a register.

```

1      .text                # put this into the text section
2      .align 2             # align to a multiple of 4
3      .globl _start
4
5      _start:
6          mv      t3, x0      # t3 = 0
7
8          ebreak

```

Listing 4.9 traces the execution of the program in Listing 4.8 showing how `t3` is changed from `0xf0f0f0f0` (seen on `ℓ16`) to `0x00000000` (seen on `ℓ26`).

Listing 4.9: `mvzero/mv.out`

Setting `t3` to zero.

```

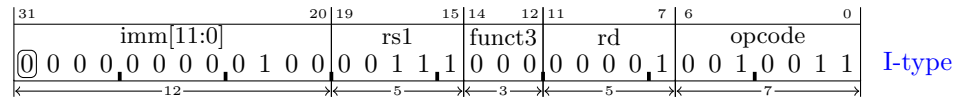
1 $ rvddt -f mv.bin
2 sp initialized to top of memory: 0x0000fff0
3 Loading 'mv.bin' to 0x0
4 This is rvddt. Enter ? for help.
5 ddt> a
6 ddt> d 0 16
7 00000000: 13 0e 00 00 73 00 10 00  a5 a5 a5 a5 a5 a5 a5 a5 *....s.....*
8 ddt> t 0 1000
9 zero x0 00000000 ra x1 f0f0f0f0 sp x2 0000fff0 gp x3 f0f0f0f0
10 tp x4 f0f0f0f0 t0 x5 f0f0f0f0 t1 x6 f0f0f0f0 t2 x7 f0f0f0f0
11 s0 x8 f0f0f0f0 s1 x9 f0f0f0f0 a0 x10 f0f0f0f0 a1 x11 f0f0f0f0
12 a2 x12 f0f0f0f0 a3 x13 f0f0f0f0 a4 x14 f0f0f0f0 a5 x15 f0f0f0f0
13 a6 x16 f0f0f0f0 a7 x17 f0f0f0f0 s2 x18 f0f0f0f0 s3 x19 f0f0f0f0
14 s4 x20 f0f0f0f0 s5 x21 f0f0f0f0 s6 x22 f0f0f0f0 s7 x23 f0f0f0f0
15 s8 x24 f0f0f0f0 s9 x25 f0f0f0f0 s10 x26 f0f0f0f0 s11 x27 f0f0f0f0
16 t3 x28 f0f0f0f0 t4 x29 f0f0f0f0 t5 x30 f0f0f0f0 t6 x31 f0f0f0f0
17 pc 00000000
18 00000000: 00000e13 addi t3, zero, 0 # t3 = 0x00000000 = 0x00000000 + 0x00000000
19 zero x0 00000000 ra x1 f0f0f0f0 sp x2 0000fff0 gp x3 f0f0f0f0
20 tp x4 f0f0f0f0 t0 x5 f0f0f0f0 t1 x6 f0f0f0f0 t2 x7 f0f0f0f0
21 s0 x8 f0f0f0f0 s1 x9 f0f0f0f0 a0 x10 f0f0f0f0 a1 x11 f0f0f0f0
22 a2 x12 f0f0f0f0 a3 x13 f0f0f0f0 a4 x14 f0f0f0f0 a5 x15 f0f0f0f0
23 a6 x16 f0f0f0f0 a7 x17 f0f0f0f0 s2 x18 f0f0f0f0 s3 x19 f0f0f0f0
24 s4 x20 f0f0f0f0 s5 x21 f0f0f0f0 s6 x22 f0f0f0f0 s7 x23 f0f0f0f0
25 s8 x24 f0f0f0f0 s9 x25 f0f0f0f0 s10 x26 f0f0f0f0 s11 x27 f0f0f0f0
26 t3 x28 00000000 t4 x29 f0f0f0f0 t5 x30 f0f0f0f0 t6 x31 f0f0f0f0
27 pc 00000004
28 00000004: ebreak
29 ddt> x

```

³There are other pseudoinstructions (such as `li`) that can also turn into an `addi` instruction. Objdump might display `'addi t3,x0,0'` as `'mv t3,x0'` or `'li t3,0'`.

4.2.4 Adding a 12-bit Signed Value

```
addi x1, x7, 4
```



```

addi    t0, zero, 4      # t0 = 4
addi    t1, t1, 100      # t1 = 104

addi    t0, zero, 0x123  # t0 = 0x123
addi    t0, t0, 0xfff    # t0 = 0x122 (subtract 1)

addi    t0, zero, 0xffff # t0 = 0xffffffff (-1) (diagram out the chaining carry)
                                # refer back to the overflow/truncation discussion in binary chapter

addi x0, x0, 0 # no operation (pseudo: nop)
addi rd, rs, 0 # copy reg rs to rd (pseudo: mv rd, rs)
```

4.3 todo

Ideas for the order of introducing instructions.

4.4 Other Instructions With Immediate Operands

```

andi
ori
xori

slti
sltiu
srai
slli
srli
```

4.5 Transferring Data Between Registers and Memory

RV is a load-store architecture. This means that the only way that the CPU can interact with the memory is via the *load* and *store* instructions. All other data manipulation must be performed on register values.

Copying values from memory to a register (first examples using regs set with addi):

```

lb
lh
lw
lbu
lhu
```

Copying values from a register to memory:

```
sb
sh
sw
```

4.6 RR operations

```
add
sub
and
or
sra
srl
sll
xor
sltu
slt
```

4.7 Setting registers to large values using lui with addi

```
addi    // useful for values from -2048 to 2047
lui      // useful for loading any multiple of 0x1000

Setting a register to any other value must be done using a combo of insns:

auipc    // Load an address relative the the current PC (see la pseudo)
addi

lui      // Load constant into into bits 31:12 (see li pseudo)
addi     // add a constant to fill in bits 11:0
          if bit 11 is set then need to +1 the lui value to compensate
```

4.8 Labels and Branching

Start to introduce addressing here?

```
beq
bne
blt
bge
bltu
bgeu

bgt rs, rt, offset    # pseudo for: blt rt, rs, offset    (reverse the operands)
ble rs, rt, offset    # pseudo for: bge rt, rs, offset    (reverse the operands)
bgtu rs, rt, offset   # pseudo for: bltu rt, rs, offset   (reverse the operands)
bleu rs, rt, offset   # pseudo for: bgeu rt, rs, offset   (reverse the operands)
```

```

1278      beqz rs, offset      # pseudo for: beq rs, x0, offset
1279      bnez rs, offset      # pseudo for: bne rs, x0, offset
1280      blez rs, offset      # pseudo for: bge x0, rs, offset
1281      bgez rs, offset      # pseudo for: bge rs, x0, offset
1282      bltz rs, offset      # pseudo for: blt rs, x0, offset
1283      bgtz rs, offset      # pseudo for: blt x0, rs, offset

```

4.9 Jumps

Introduce and present subroutines but not nesting until introduce stack operations.

```

1286      jal
1287      jalr

```

4.10 Pseudoinstructions

```

1289      li    rd,constant
1290              lui    rd,(constant + 0x00000800) >> 12
1291              addi   rd,rd,(constant & 0x00000fff)
1292
1293      la    rd,label
1294              auipc   rd,((label-. ) + 0x00000800) >> 12
1295              addi   rd,rd,((label-(-4)) & 0x00000fff)
1296
1297      l{b|h|w} rd,label
1298              auipc   rd,((label-. ) + 0x00000800) >> 12
1299              l{b|h|w} rd,((label-(-4)) & 0x00000fff)(rd)
1300
1301      s{b|h|w} rd,label,rt      # rt used as a temp reg for the operation (default=x6)
1302              auipc   rt,((label-. ) + 0x00000800) >> 12
1303              s{b|h|w} rd,((label-(-4)) & 0x00000fff)(rt)
1304
1305      call label      auipc   x1,((label-. ) + 0x00000800) >> 12
1306                      jalr    x1,((label-(-4)) & 0x00000fff)(x1)
1307
1308      tail label,rt      # rt used as a temp reg for the operation (default=x6)
1309                      auipc   rt,((label-. ) + 0x00000800) >> 12
1310                      jalr    x0,((label-(-4)) & 0x00000fff)(rt)
1311
1312      mv    rd,rs      addi   rd,rs,0
1313
1314      j     label      jal    x0,label
1315      jal  label      jal    x1,label
1316      jr   rs          jalr   x0,0(rs)
1317      jalr rs          jalr   x1,0(rs)
1318      ret                    jalr   x0,0(x1)

```

4.10.1 The li Pseudoinstruction

Note that the `li` pseudoinstruction includes an (effectively) conditional addition of 1 to the immediate operand in the `lui` instruction. This is because the immediate operand in the `addi` instruction is sign-

extended before it is added to `rd`. If the immediate operand to the `addi` has its most-significant-bit set to 1 then it will have the effect of subtracting 1 from the operand in the `lui` instruction.

Consider the case of putting the value 0x12345800 into register `x5`:

```
li x5,0x12345800
```

A naive (incorrect) solution might be:

```
lui x5,0x12345 // x5 = 0x12345000
addi x5,x5,0x800 // x5 = 0x12345000 + sx(0x800) = 0x12345000 + 0xffff800 = 0x12344800
```

The result of the above code is that an incorrect value has been placed into `x5`.

To remedy this problem, the value used in the `lui` instruction can be altered (by adding 1 to its operand) to compensate for the sign-extension in the `addi` instruction:

```
lui x5,0x12346 // x5 = 0x12346000 (note: this is 0x12345800 + 0x0800)
addi x5,x5,0x800 // x5 = 0x12346000 + sx(0x800) = 0x12346000 + 0xffff800 = 0x12345800
```

Keep in mind that the `li` pseudoinstruction must *only* increment the operand of the `lui` instruction when it is known that the operand of the subsequent `addi` instruction will be a negative number.

By adding 0x00000800 to the immediate operand of the `lui` instruction in this example, a carry-bit into bit-12 will be set to 1 iff the value in bits 11-0 will be treated as a negative value in the subsequent `addi` instruction. In other words, when bit-11 is set to 1 in the immediate operand of the `li` pseudoinstruction, the immediate operand of the `lui` instruction will be incremented by 1.

Consider the case where we wish to put the value 0x12345700 into register `x5`:

```
lui x5,0x12345 // x5 = 0x12345000 (note that 0x12345700 + 0x0800 = 0x12345f00)
addi x5,x5,0x700 // x5 = 0x12345000 + sx(0x700) = 0x12345000 + 0x00000700 = 0x12345700
```

The sign-extension in this example performed by the `addi` instruction will convert the 0x700 to 0x00000700 before the addition.

Observe that 0x12345700+0x0800 = 0x12345f00 and therefore, after shifting to the right, the least significant 0xf00 is truncated, leaving 0x12345 as the immediate operand of the `lui` instruction. The addition of 0x0800 in this example has no effect on the immediate operand of the `lui` instruction because bit-11 in the original value 0x12345700 is zero.

A general algorithm for implementing the `li rd,constant` pseudoinstruction is:

```
lui rd,(constant + 0x00000800) >> 12
addi rd,rd,(constant & 0x00000fff) // the 12-bit immediate is sign extended
```

Note that on RV64 and RV128 systems, the `lui` places the immediate operand into bits 31-12 and then sign-extends the result to `XLEN` bits.

► Fix Me:

Add a ribbon diagram of this?

► Fix Me:

Find a proper citation for this.

4.10.2 The `la` Pseudoinstruction

The `la` (and others that use `auipc` such as the `l{b|h|w}`, `s{b|h|w}`, `call`, and `tail`) pseudoinstructions also compensate for a sign-ended negative number when adding a 12-bit immediate operand. The only difference is that these use a `pc`-relative addressing mode.

For example, consider the task of putting an address represented by the label `var1` into register `x10`:

```
00010040    la      x10,var1
00010048    ...
...
var1:
00010900    .word   999          # a 32-bit integer constant stored in memory at address var1
```

The `la` instruction in this example will expand into:

```
00010040    auipc x10,((var1-.)+0x00000800)>>12
00010044    addi  x10,x10,((var1-(-4))&0x00000fff)
```

Note that `auipc` will shift the immediate operand to the left 12 bits and then add that to the `pc` register (see [Figure 5.3.1](#).)

The assembler will calculate the value of `(var1-.)` by subtracting the address represented by the label `var1` from the address of the current instruction (which is expressed as `'.'`) resulting in the number of bytes from the current instruction to the target label... which is `0x000008c0`.

Therefore the expanded pseudoinstruction example will become:

```
00010040    auipc x10,((0x00010900 - 0x00010040) + 0x00000800) >> 12
00010044    addi  x10,x10,((0x00010900 - (0x00010044 - 4)) & 0x00000fff) # note the extra -4 here!
```

After performing the subtractions, it will reduce to this:

```
00010040    auipc x10,(0x000008c0 + 0x00000800) >> 12
00010044    addi  x10,x10,(0x000008c0 & 0x00000fff)
```

Continuing to reduce the math operations we get:

```
00010040    auipc x10,0x00001          # 0x000008c0 + 0x00000800 = 0x000010c0
00010044    addi  x10,x10,0x8c0
```

Note that the `la` pseudoinstruction exhibits the same sort of technique as the `li` in that if/when the immediate operand of the `addi` instruction has its most significant bit set then the operand in the `auipc` has to be incremented by 1 to compensate.

4.11 Relocation

Because expressions that refer to constants and address labels are common in assembly language programs, a shorthand notation is available for calculating the pairs of values that are used in the

implementation of things like the `li` and `la` pseudoinstructions (that have to be written to compensate for the sign-extension that will take place in the immediate operand that appears in instructions like `addi` and `jalr`.)

4.11.1 Absolute Addresses

To refer to an absolute value, the following operators can be used:

```
%hi(constant)    // becomes: (constant + 0x00000800) >> 12
%lo(constant)    // becomes: (constant & 0x00000fff)
```

Thus, the `li` pseudoinstruction can, therefore, be expressed like this:

```
li    rd,constant    lui    rd,%hi(constant)
                        addi   rd,rd,%lo(constant)
```

4.11.2 PC-Relative Addresses

The following can be used for PC-relative addresses:

```
%pcrel_hi(symbol) // becomes: ((symbol-. ) + 0x0800) >> 12
%pcrel_lo(lab)     // becomes: ((symbol-lab) & 0x00000fff)
```

Note the subtlety involved with the `lab` on `%pcrel_lo`. It is needed to determine the address of the instruction that contains the corresponding `%pcrel_hi`. (The label `lab` MUST be on a line that used a `%pcrel_hi()` or get an error from the assembler.)

Thus, the `la rd,label` pseudoinstruction can be expressed like this:

```
xxx: auipc rd,%pcrel_hi(label)
      addi rd,rd,%pcrel_lo(xxx) // the xxx tells pcrel_lo where to find the matching pcrel_hi
```

Examples of using the `auipc` & `addi` together with `%pcrel_hi()` and `%pcrel_lo()`:

```
xxx: auipc t1,%pcrel_hi(yyy)    // ((yyy-. ) + 0x0800) >> 12
      addi t1,t1,%pcrel_lo(xxx) // ((yyy-xxx) & 0x00000fff)
...
yyy:                                     // the address: yyy is saved into t1 above
...
```

Referencing the same `%pcrel_hi` in multiple subsequent uses of `%pcrel_lo` is legal:

```
label: auipc t1,%pcrel_hi(symbol)
        addi t2,t1,%pcrel_lo(label) // t2 = symbol
        addi t3,t1,%pcrel_lo(label) // t3 = symbol
        lw  t4,%pcrel_lo(label)(t1) // t4 = fetch value from memory at 'symbol'
        addi t4,t4,123              // t4 = t4 + 123
        sw  t4,%pcrel_lo(label)(t1) // store t4 back into memory at 'symbol'
```

4.12 Relaxation

In the simplest of terms, *Relaxation* refers to the ability of the linker (not the compiler!) to determine if/when the instructions that were generated with the `xxx_hi` and `xxx_lo` operators are unneeded (and thus waste execution time and memory) and can therefore be removed.

However, doing so is not trivial as it will result in moving things around in memory, possibly changing the values of address labels in the already-assembled program! Therefore, while the motivation for relaxation is obvious, the process of implementing it is non-trivial.

See: <https://github.com/riscv/riscv-elf-psabi-doc/blob/master/riscv-elf.md>

Chapter 5

RV32 Machine Instructions

5.1 Conventions and Terminology

When discussing instructions, the following abbreviations/notations are used:

5.1.1 XLEN

XLEN represents the bit-length of an *x* register in the machine architecture. Possible values are 32, 64 and 128.

5.1.2 *sx(val)*

Sign extend *val* to the left.

This is used to convert a signed integer value expressed using some number of bits to a larger number of bits by adding more bits to the left. In doing so, the sign will be preserved. In this case *val* represents the least *MSBs* of the value.

For more on sign-extension see [section 2.3](#).

5.1.3 *zx(val)*

Zero extend *val* to the left.

This is used to convert an unsigned integer value expressed using some number of bits to a larger number of bits by adding more bits to the left. In doing so, the new bits added will all be set to zero. As is the case with *sx(val)*, *val* represents the *LSBs* of the final value.

For more on zero-extension see [Figure 2.3](#).

5.1.4 `zr(val)`

Zero extend *val* to the right.

Some times a binary value is encoded such that a set of bits represented by *val* are used to represent the MSBs of some longer (more bits) value. In this case it is necessary to append zeros to the right to convert *val* to the longer value.

Figure 5.1 illustrates converting a 20-bit *val* to a 32-bit fullword.

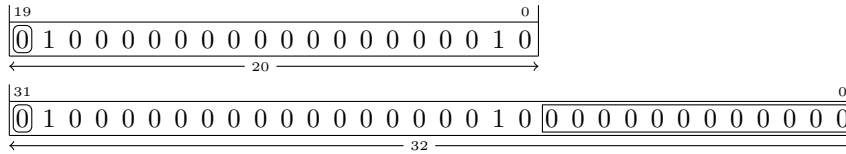


Figure 5.1: Zero-extending an integer to the right from 20 bits to 32 bits.

5.1.5 Sign Extended Left and Zero Extend Right

Some instructions such as the J-type (see section 5.3.2) include immediate operands that are extended in both directions.

Figure 5.2 and Figure 5.3 illustrates zero-extending a 20-bit negative number one bit to the right and sign-extending it 11 bits to the left:

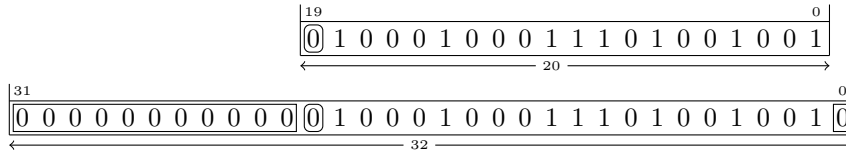


Figure 5.2: Sign-extending a positive 20-bit number 11 bits to the left and one bit to the right.

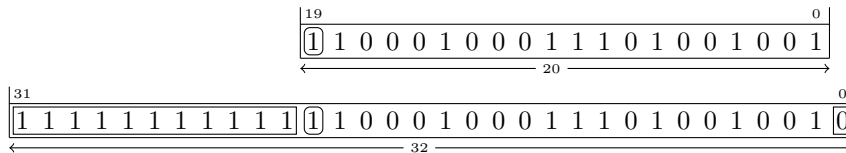


Figure 5.3: Sign-extending a negative 20-bit number 11 bits to the left and one bit to the right.

5.1.6 `m8(addr)`

The contents of an 8-bit value in memory at address *addr*.

Given the contents of the memory dump shown in Figure 5.4, `m8(0x42)` refers to the memory location at address `4216` that currently contains the 8-bit value `fc16`.

The `mn(addr)` notation can be used to refer to memory that is being read or written depending on the context.

When memory is being written, the following notation is used to indicate that the least significant 8 bis of *source* will be written into memory at the address *addr*:

$\text{m8(addr)} \leftarrow \text{source}$

When memory is being read, the following notation is used to indicate that the 8 bit value at the address *addr* will be read and stored into *dest*:

$\text{dest} \leftarrow \text{m8(addr)}$

Note that *source* and *dest* are typically registers.

00000030	2f	20	72	65	61	64	20	61	20	62	69	6e	61	72	79	20
00000040	66	69	fc	65	20	66	69	6c	6c	65	64	20	77	69	74	68
00000050	20	72	76	33	32	49	20	69	6e	73	74	72	75	63	74	69
00000060	6f	6e	73	20	61	6e	64	20	66	65	65	64	20	74	68	65

Figure 5.4: Sample memory contents.

5.1.7 m16(addr)

The contents of an 16-bit little-endian value in memory at address *addr*.

Given the contents of the memory dump shown in [Figure 5.4](#), $\text{m16}(0\text{x}42)$ refers to the memory location at address 42_{16} that currently contains 65fc_{16} . See also [section 5.1.6](#).

5.1.8 m32(addr)

The contents of an 32-bit little-endian value in memory at address *addr*.

Given the contents of the memory dump shown in [Figure 5.4](#), $\text{m32}(0\text{x}42)$ refers to the memory location at address 42_{16} that currently contains 662065fc_{16} . See also [section 5.1.6](#).

5.1.9 m64(addr)

The contents of an 64-bit little-endian value in memory at address *addr*.

Given the contents of the memory dump shown in [Figure 5.4](#), $\text{m64}(0\text{x}42)$ refers to the memory location at address 42_{16} that currently contains $656\text{c}6\text{c}69662065\text{fc}_{16}$. See also [section 5.1.6](#).

5.1.10 m128(addr)

The contents of an 128-bit little-endian value in memory at address *addr*.

Given the contents of the memory dump shown in [Figure 5.4](#), $\text{m128}(0\text{x}42)$ refers to the memory location at address 42_{16} that currently contains $7220687469772064656\text{c}6\text{c}69662065\text{fc}_{16}$. See also [section 5.1.6](#).

5.1.11 .+offset

The address of the current instruction plus a numeric offset.

5.1.12 .-offset

The address of the current instruction minus a numeric offset.

5.1.13 pcrel_13

An address that is within $[-4096..4094]$ $[-0x1000..0x0ffe]$ of the current instruction location. These addresses are typically expressed in assembly source code by using labels. See [section 5.3.6](#) for examples.

5.1.14 pcrel_21

An address that is within $[-1048576..1048574]$ $[-0x100000..0x0ffffe]$ of the current instruction location. These addresses are typically expressed in assembly source code by using labels. See [section 5.3.2](#) for an example.

5.1.15 pc

The current value of the program counter.

5.1.16 rd

An x-register used to store the result of instruction.

5.1.17 rs1

An x-register value used as a source operand for an instruction.

5.1.18 rs2

An x-register value used as a source operand for an instruction.

5.1.19 imm

An immediate numeric operand. The word *immediate* refers to the fact that the operand is stored within an instruction.

5.1.20 rsN[h:l]

The value of bits from h through l of x-register rsN. For example: rs1[15:0] refers to the contents of the 16 [LSBs](#) of rs1.

5.2 Addressing Modes

immediate, register, base-displacement, pc-relative

► Fix Me:

Write this section.

5.3 Instruction Encoding Formats

This document concerns itself with the RISC-V instruction formats shown in [Figure 5.5](#).

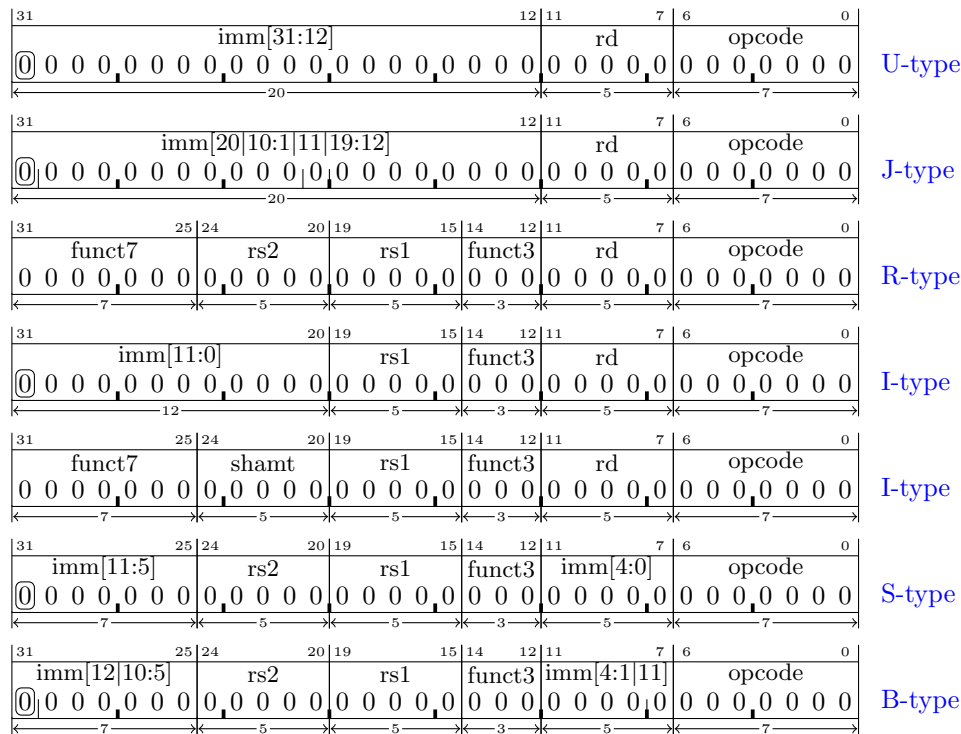


Figure 5.5: RISC-V instruction formats.

The method/format of the instructions has been designed with an eye on the ease of future manufacture of the machine that will execute them. It is easier to build a machine if it does not have to accommodate many different ways to perform the same task. The result is that a machine can be built with fewer gates, consumes less power, and can run faster than if it were built when a priority is on how a user might prefer to decode the same instructions from a hex dump.

Observe that all instructions have their opcode in bits 0-6 and when they include an **rd** register it will be specified in bits 7-11, an **rs1** register in bits 15-19, an **rs2** register in bits 20-24, and so on. This has a seemingly strange impact on the placement of any immediate operands.

When immediate operands are present in an instruction, they are placed in the remaining unused bits. However, they are organized such that the sign bit is *always* in bit 31 and the remaining bits placed so as to minimize the number of places any given bit is located in different instructions.

For example, consider immediate operand bits 12-19. In the U-type format they are in bit positions 12-19. In the J-type format they are also in positions 12-19. In the J-type format immediate operand bits 1-10 are in the same instruction bit positions as they are in the I-type format and immediate operand bits 5-10 are in the same positions as they are in the B-type and S-type formats.

While this is inconvenient for anyone looking at a memory hexdump, it does make sense when considering the impact of this choice on the number of gates needed to implement circuitry to extract the immediate operands.

5.3.1 U Type

The U-Type format is used for instructions that use a 20-bit immediate operand and an `rd` destination register.

The `rd` field contains an `x` register number to be set to a value that depends on the instruction.

If `XLEN=32` then the `imm` value will be extracted from the instruction and converted as shown in Figure 5.6 to form the `imm_u` value.

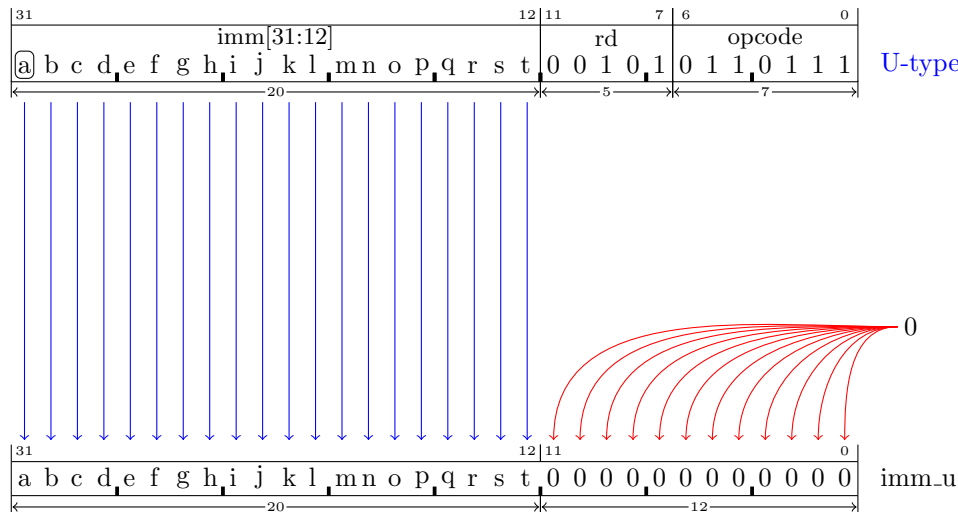


Figure 5.6: Decoding a U-type instruction.

Notice that the 20-bits of the `imm` field are mapped in the same order and in the same relative position that they appear in the instruction when they are used to create the value of the immediate operand. Leaving the `imm` bits on the left, in the “upper bits” of the `imm_u` value suggests a rationale for the name of this format.

- `lui rd,imm`

Set register `rd` to the `imm_u` value as shown in Figure 5.6.

For example: `lui x23,0x12345` will result in setting register `x23` to the value `0x12345000`.

- `auipc rd,imm`

Add the address of the instruction to the `imm_u` value as shown [Figure 5.6](#) and store the result in register `rd`.

For example, if the instruction `auipc x22,0x10001` is executed from memory address `0x800012f4` then register `x22` will be set to `0x900022f4`.

If `XLEN`=64 then the `imm_u` value in this example will be converted to the same two's complement integer value by extending the sign-bit further to the left.

5.3.2 J Type

The J-type instruction format is used to encode the `jal` instruction with an immediate value that determines the jump target address. It is similar to the U-type, but the bits in the immediate operand are arranged in a different order.

Note that the `imm_j` value is an even 21-bit value in the range of $[-1048576..1048574]$ $[-0x100000..0x0ffffe]$ representing a `pc`-relative offset to the target address.

If `XLEN`=32 then the `imm` value will be extracted from the instruction and converted as shown in [Figure 5.7](#) to form the `imm_j` value.

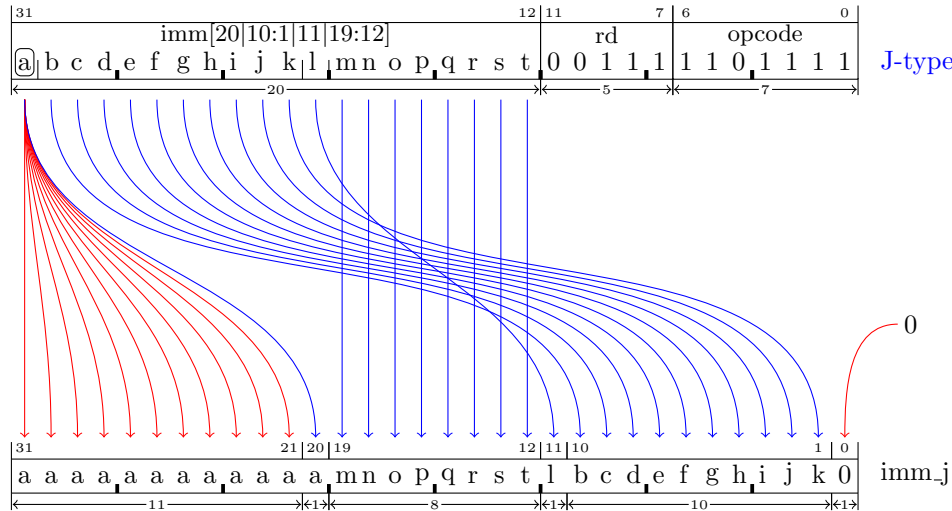


Figure 5.7: Decoding a J-type instruction.

The J-type format is used by the Jump And Link instruction that calculates the target address by adding `imm_j` to the current program counter. Since no instruction can be placed at an odd address the 20-bit `imm` value is zero-extended to the right to represent a 21-bit signed offset capable of expressing a wider range of target addresses than the 20-bit `imm` value alone.

- `jal rd,pcrel_21`

Set register `rd` to the address of the next instruction that would otherwise be executed (the address of the `jal` instruction + 4) and then jump to the address given by the sum of the `pc` register and the `imm_j` value as decoded from the instruction shown in [Figure 5.7](#).

Note that `pcrel_21` is expressed in the instruction as a target address or label that is converted to a 21-bit value representing a `pc`-relative offset to the target address. For example, consider the `jal` instructions in the following code:

```

1576 00000010: 000002ef jal    x5,0x10    # jump to self (address 0x10)
1577 00000014: 008002ef jal    x5,0x1c    # jump to address 0x1c
1578 00000018: 00100073 ebreak
1579 0000001c: 00100073 ebreak

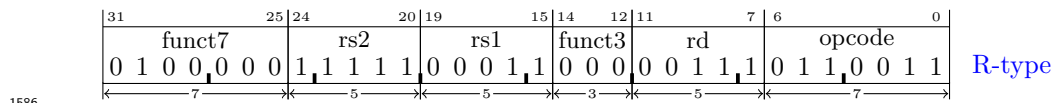
```

The instruction at address 0x10 has a target address of 0x10 and the `imm_j` is zero because offset from the “current instruction” to the target is zero.

The instruction at address 0x14 has a target address of 0x1c and the `imm_j` is 0x08 because $0x1c - 0x14 = 0x08$.

See also [section 5.3.6](#).

5.3.3 R Type



The R-type instructions are used for operations that set a destination register `rd` to the result of an arithmetic, logical or shift operation applied to source registers `rs1` and `rs2`.

Note that instruction bit 30 (part of the the `funct7` field) is used to select between the `add` and `sub` instructions as well as to select between `srl` and `sra`.

- **add rd,rs1,rs2**

Set register `rd` to `rs1 + rs2`.

Note that the value of `funct7` must be zero for this instruction. (The value of `funct7` is how the `add` instruction is differentiated from the `sub` instruction.)

- **and rd,rs1,rs2**

Set register `rd` to the bitwise **and** of `rs1` and `rs2`.

For example, if `x17 = 0x55551111` and `x18 = 0xff00ff00` then the instruction `and x12,x17,x18` will set `x12` to the value `0x55001100`.

- **or rd,rs1,rs2**

Set register `rd` to the bitwise **or** of `rs1` and `rs2`.

For example, if `x17 = 0x55551111` and `x18 = 0xff00ff00` then the instruction `or x12,x17,x18` will set `x12` to the value `0xff55ff11`.

- **sll rd,rs1,rs2**

Shift `rs1` left by the number of bits specified in the least significant 5 bits of `rs2` and store the result in `rd`.¹

For example, if `x17 = 0x12345678` and `x18 = 0x08` then the instruction `sll x12,x17,x18` will set `x12` to the value `0x34567800`.

- **slt rd,rs1,rs2**

If the signed integer value in `rs1` is less than the signed integer value in `rs2` then set `rd` to 1. Otherwise, set `rd` to 0.

¹ When XLEN is 64 or 128, the shift distance will be given by the least-significant 6 or 7 bits of `rs2` respectively. For more information on how shifting works, see [section 2.4](#).

For example, if `x17 = 0x12345678` and `x18 = 0x0000ffff` then the instruction `slt x12,x17,x18` will set `x12` to the value `0x00000000`.

If `x17 = 0x82345678` and `x18 = 0x0000ffff` then the instruction `slt x12,x17,x18` will set `x12` to the value `0x00000001`.

- **sltu rd,rs1,rs2**

If the unsigned integer value in `rs1` is less than the unsigned integer value in `rs2` then set `rd` to 1. Otherwise, set `rd` to 0.

For example, if `x17 = 0x12345678` and `x18 = 0x0000ffff` then the instruction `sltu x12,x17,x18` will set `x12` to the value `0x00000000`.

If `x17 = 0x12345678` and `x18 = 0x8000ffff` then the instruction `sltu x12,x17,x18` will set `x12` to the value `0x00000001`.

- **sra rd,rs1,rs2**

Arithmetic-shift `rs1` right by the number of bits given in the least-significant 5 bits of the `rs2` register and store the result in `rd`.¹

For example, if `x17 = 0x87654321` and `x18 = 0x08` then the instruction `sra x12,x17,x18` will set `x12` to the value `0xff876543`.

If `x17 = 0x76543210` and `x18 = 0x08` then the instruction `sra x12,x17,x18` will set `x12` to the value `0x00765432`.

Note that the value of `funct7` must be zero for this instruction. (The value of `funct7` is how the `sra` instruction is differentiated from the `srl` instruction.)

- **srl rd,rs1,rs2**

Logic-shift `rs1` right by the number of bits given in the least-significant 5 bits of the `rs2` register and store the result in `rd`.¹

For example, if `x17 = 0x87654321` and `x18 = 0x08` then the instruction `srl x12,x17,x18` will set `x12` to the value `0x00876543`.

If `x17 = 0x76543210` and `x18 = 0x08` then the instruction `srl x12,x17,x18` will set `x12` to the value `0x00765432`.

Note that the value of `funct7` must be `0b0100000` for this instruction. (The value of `funct7` is how the `srl` instruction is differentiated from the `sra` instruction.)

- **sub rd,rs1,rs2**

Set register `rd` to `rs1 - rs2`.

Note that the value of `funct7` must be `0b0100000` for this instruction. (The value of `funct7` is how the `sub` instruction is differentiated from the `add` instruction.)

- **xor rd,rs1,rs2**

Set register `rd` to the bitwise `xor` of `rs1` and `rs2`.

For example, if `x17 = 0x55551111` and `x18 = 0xff00ff00` then the instruction `xor x12,x17,x18` will set `x12` to the value `0xaa55ee11`.

5.3.4 I Type

The I-type instruction format is used to encode instructions with a signed 12-bit immediate operand with a range of `[-2048..2047]`, an `rd` register, and an `rs1` register.

If `XLEN=32` then the 12-bit `imm` value example will be extracted from the instruction and converted as shown in [Figure 5.8](#) to form the `imm_i` value.

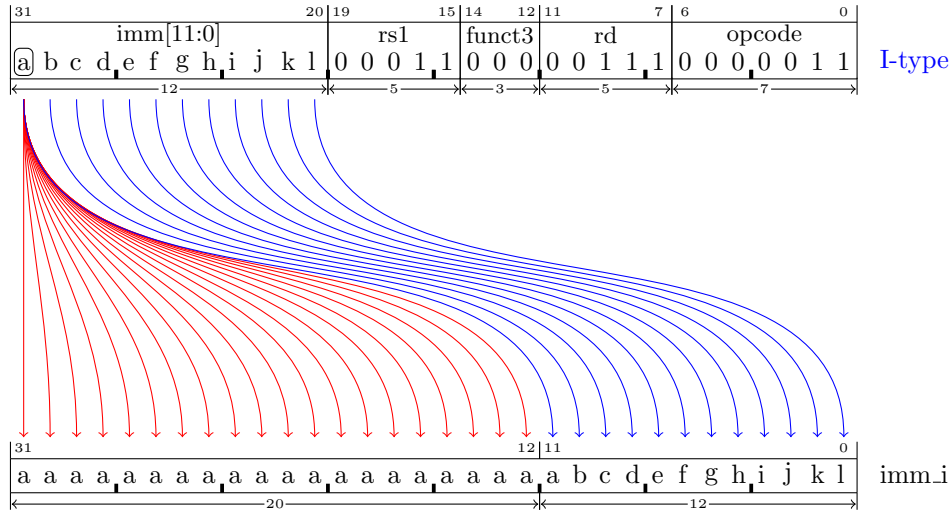


Figure 5.8: Decoding an I-type Instruction.

A special case of the I-type is used for shift-immediate instructions where the imm field is used to represent the number of bit positions to shift as shown in Figure 5.9. In this variation, the least significant five bits of the imm field are extracted to form the `shamt_i` value.²

Note also that bit 30 (the imm instruction field bit labeled ‘b’) is used to select between arithmetic and logical shifting.

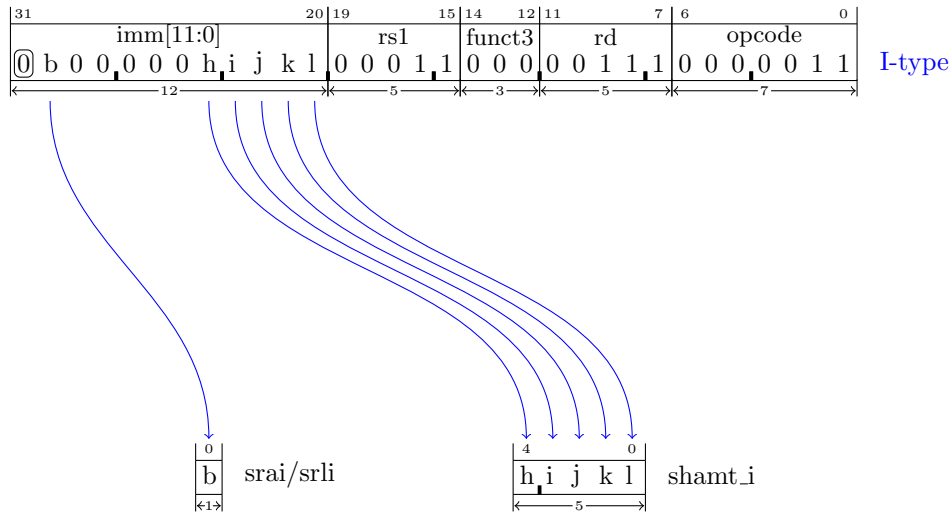


Figure 5.9: Decoding an I-type Shift Instruction.

- `addi rd,rs1,imm`
Set register `rd` to `rs1 + imm_i`.
- `andi rd,rs1,imm`
Set register `rd` to the bitwise **and** of `rs1` and `imm_i`.

²When XLEN is 64 or 128, the `shamt_i` field will consist of 6 or 7 bits respectively.

```

00002640: 6f 00 00 00 6f 00 00 00 b7 87 00 00 03 a5 07 43 *o...o.....C*
00002650: 67 80 00 00 00 00 00 00 76 61 6c 3d 00 00 00 00 *g.....val=...*
00002660: 00 00 00 00 80 84 2e 41 1f 85 45 41 80 40 9a 44 *.....A..EA.@.D*
00002670: 4f 11 f3 c3 6e 8a 67 41 20 1b 00 00 20 1b 00 00 *O...n.gA ... ..*
00002680: 44 1b 00 00 14 1b 00 00 14 1b 00 00 04 1c 00 00 *D.....*

```

Figure 5.10: An Example Memory Dump.

For example, if `x17 = 0x55551111` then the instruction `andi x12,x17,0x0ff` will set `x12` to the value `0x00000011`.

Recall that `imm` is sign-extended. Therefore if `x17 = 0x55551111` then the instruction `andi x12,x17,0x800` will set `x12` to the value `0x55551000`.

- `jalr rd,imm(rs1)`

Set register `rd` to the address of the next instruction that would otherwise be executed (the address of the `jalr` instruction + 4) and then jump to an address given by the sum of the `rs1` register and the `imm_i` value as decoded from the instruction shown in Figure 5.8.

Note that the `pc` register can never refer to an odd address. This instruction will explicitly set the `LSB` to zero regardless of the value of the value of the calculated target address.

- `lb rd,imm(rs1)`

Set register `rd` to the value of the sign-extended byte fetched from the memory address given by the sum of `rs1` and `imm_i`.

For example, given the memory contents shown in Figure 5.10, if register `x13 = 0x00002650` then the instruction `lb x12,1(x13)` will set `x12` to the value `0xffffffff80`.

- `lbu rd,imm(rs1)`

Set register `rd` to the value of the zero-extended byte fetched from the memory address given by the sum of `rs1` and `imm_i`.

For example, given the memory contents shown in Figure 5.10, if register `x13 = 0x00002650` then the instruction `lbu x12,1(x13)` will set `x12` to the value `0x00000080`.

- `lh rd,imm(rs1)`

Set register `rd` to the value of the sign-extended 16-bit little-endian half-word value fetched from the memory address given by the sum of `rs1` and `imm_i`.

For example, given the memory contents shown in Figure 5.10, if register `x13 = 0x00002650` then the instruction `lh x12,-2(x13)` will set `x12` to the value `0x00004307`.

If register `x13 = 0x00002650` then the instruction `lh x12,-8(x13)` will set `x12` to the value `0xffff87b7`.

- `lhu rd,imm(rs1)`

Set register `rd` to the value of the zero-extended 16-bit little-endian half-word value fetched from the memory address given by the sum of `rs1` and `imm_i`.

For example, given the memory contents shown in Figure 5.10, if register `x13 = 0x00002650` then the instruction `lhu x12,-2(x13)` will set `x12` to the value `0x00004307`.

If register `x13 = 0x00002650` then the instruction `lhu x12,-8(x13)` will set `x12` to the value `0x000087b7`.

- `lw rd,imm(rs1)`

Set register `rd` to the value of the sign-extended 32-bit little-endian word value fetched from the memory address given by the sum of `rs1` and `imm_i`.

For example, given the memory contents shown in [Figure 5.10](#), if register `x13 = 0x00002650` then the instruction `lw x12,-4(x13)` will set `x12` to the value `4307a503`.

- **ori rd,rs1,imm**

Set register `rd` to the bitwise or of `rs1` and `imm_i`.

For example, if `x17 = 0x55551111` then the instruction `ori x12,x17,0x0ff` will set `x12` to the value `0x555511ff`.

Recall that `imm` is sign-extended. Therefore if `x17 = 0x55551111` then the instruction `ori x12,x17,0x800` will set `x12` to the value `0xfffff911`.

- **slli rd,rs1,imm**

Shift `rs1` left by the number of bits specified in `shamt_i` (as shown in [Figure 5.9](#)) and store the result in `rd`.³

For example, if `x17 = 0x12345678` then the instruction `slli x12,x17,4` will set `x12` to the value `0x23456780`.

- **slti rd,rs1,imm**

If the signed integer value in `rs1` is less than the signed integer value in `imm_i` then set `rd` to 1. Otherwise, set `rd` to 0.

- **sltiu rd,rs1,imm**

If the unsigned integer value in `rs1` is less than the unsigned integer value in `imm_i` then set `rd` to 1. Otherwise, set `rd` to 0.

Note that `imm_i` is always created by sign-extending the `imm` value as shown in [Figure 5.8](#) even though it is then later used as an unsigned integer for the purposes of comparing its magnitude to the unsigned value in `rs1`. Therefore, this instruction provides a method to compare `rs1` to a value in the ranges of `[0..0x7ff]` and `[0xffffffff800..0xfffffffff]`.

- **srai rd,rs1,imm**

Arithmetic-shift `rs1` right by the number of bits specified in `shamt_i` (as shown in [Figure 5.9](#)) and store the result in `rd`.³

For example, if `x17 = 0x87654321` then the instruction `srai x12,x17,4` will set `x12` to the value `0xf8765432`.

Note that the value of bit 30 must be 1 for this instruction. (The value of bit 30 is how the `srai` instruction is differentiated from the `srl` instruction.)

- **srl** `rd,rs1,imm`

Logic-shift `rs1` right by the number of bits specified in `shamt_i` (as shown in [Figure 5.9](#)) and store the result in `rd`.³

For example, if `x17 = 0x87654321` then the instruction `srl x12,x17,4` will set `x12` to the value `0x08765432`.

Note that the value of bit 30 must be 0 for this instruction. (The value of bit 30 is how the `srl` instruction is differentiated from the `srai` instruction.)

- **xori rd,rs1,imm**

Set register `rd` to the bitwise xor of `rs1` and `imm_i`.

For example, if `x17 = 0x55551111` then the instruction `xori x12,x17,0x0ff` will set `x12` to the value `0x555511ee`.

Recall that `imm` is sign-extended. Therefore if `x17 = 0x55551111` then `xori x12,x17,0x800` will set `x12` to the value `0xaaaae911`.

³ When XLEN is 64 or 128, the shift distance will be given by the least-significant 6 or 7 bits of the `imm` field respectively. For more information on how shifting works, see [section 2.4](#).

5.3.5 S Type

The S-type instruction format is used to encode instructions with a signed 12-bit immediate operand with a range of $[-2048..2047]$, an `rs1` register, and an `rs2` register.

If `XLEN=32` then the 12-bit `imm` value example will be extracted from the instruction and converted as shown in Figure 5.11 to form the `imm_s` value.

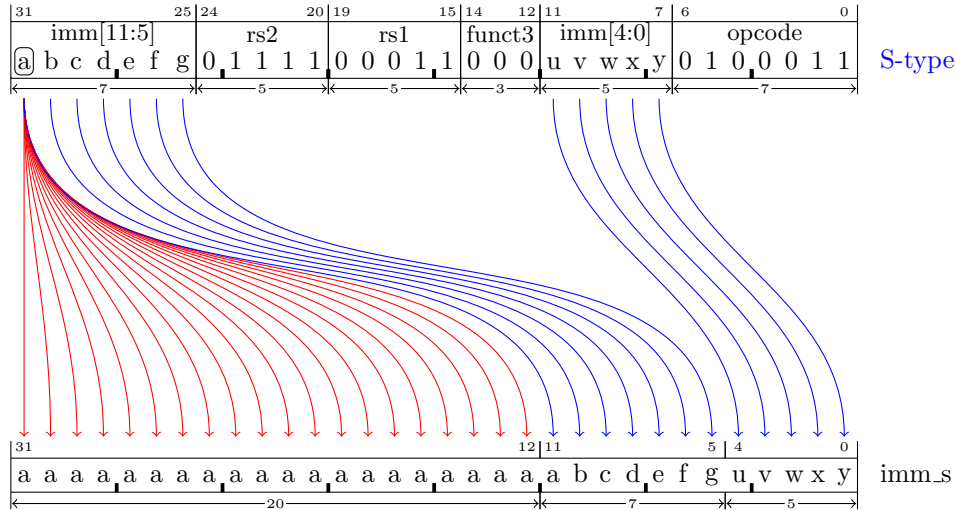


Figure 5.11: Decoding an S-type Instruction.

- **sb** `rs2,imm(rs1)`

Set the byte of memory at the address given by the sum of `rs1` and `imm_s` to the 8 LSBs of `rs2`.

For example, given the memory contents shown in Figure 5.10, if registers `x13 = 0x00002650` and `x12 = 0x12345678` then the instruction `sb x12,1(x13)` will change the memory byte at address `0x00002651` from `0x80` to `0x78` resulting in:

```
00002640: 6f 00 00 00 6f 00 00 00 b7 87 00 00 03 a5 07 43 *o...o.....C*
00002650: 67 78 00 00 00 00 00 00 76 61 6c 3d 00 00 00 00 *gx.....val=...*
00002660: 00 00 00 00 80 84 2e 41 1f 85 45 41 80 40 9a 44 *.....A..EA.@.D*
00002670: 4f 11 f3 c3 6e 8a 67 41 20 1b 00 00 20 1b 00 00 *0...n.gA ... ..*
00002680: 44 1b 00 00 14 1b 00 00 14 1b 00 00 04 1c 00 00 *D.....*
```

- **sh** `rs2,imm(rs1)`

Set the 16-bit half-word of memory at the address given by the sum of `rs1` and `imm_s` to the 16 LSBs of `rs2`.

For example, given the memory contents shown in Figure 5.10, if registers `x13 = 0x00002650` and `x12 = 0x12345678` then the instruction `sh x12,2(x13)` will change the memory half-word at address `0x00002652` from `0x0000` to `0x5678` resulting in:

```
00002640: 6f 00 00 00 6f 00 00 00 b7 87 00 00 03 a5 07 43 *o...o.....C*
00002650: 67 80 78 56 00 00 00 00 76 61 6c 3d 00 00 00 00 *g.xV....val=...*
00002660: 00 00 00 00 80 84 2e 41 1f 85 45 41 80 40 9a 44 *.....A..EA.@.D*
00002670: 4f 11 f3 c3 6e 8a 67 41 20 1b 00 00 20 1b 00 00 *0...n.gA ... ..*
00002680: 44 1b 00 00 14 1b 00 00 14 1b 00 00 04 1c 00 00 *D.....*
```

- **sw** **rs2,imm(rs1)**

Store the 32-bit value in **rs2** into the memory at the address given by the sum of **rs1** and **imm_s**.

For example, given the memory contents shown in [Figure 5.10](#), if registers **x13** = 0x00002650 and **x12** = 0x12345678 then the instruction **sw x12,0(x13)** will change the memory word at address 0x00002650 from 0x00008067 to 0x12345678 resulting in:

```

00002640: 6f 00 00 00 6f 00 00 00  b7 87 00 00 03 a5 07 43  *o...o.....C*
00002650: 78 56 34 12 00 00 00 00  76 61 6c 3d 00 00 00 00  *xV4....val=...*
00002660: 00 00 00 00 80 84 2e 41  1f 85 45 41 80 40 9a 44  *.....A..EA.@.D*
00002670: 4f 11 f3 c3 6e 8a 67 41  20 1b 00 00 20 1b 00 00  *0...n.gA ... .*
00002680: 44 1b 00 00 14 1b 00 00  14 1b 00 00 04 1c 00 00  *D.....*

```

5.3.6 B Type

The B-type instruction format is used for branch instructions that require an even immediate value that is used to determine the branch target address as an offset from the current instruction’s address.

If **XLEN**=32 then the 12-bit *imm* value example will be extracted from the instruction and converted as shown in [Figure 5.12](#) to form the **imm_b** value.

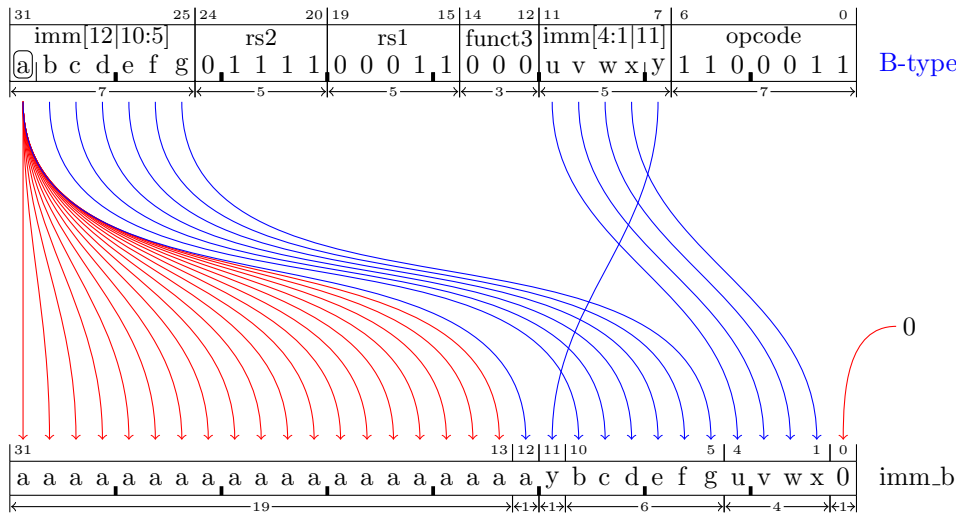


Figure 5.12: Decoding a B-type Instruction.

Note that **imm_b** is expressed in the instruction as a target address that is converted to an even 13-bit value in the range of $[-4096..4094]$ $[-0x1000..0x0ffe]$ representing a **pc**-relative offset to the target address. For example, consider the branch instructions in the following code:

```

00000000: 00520063 beq    x4,x5,0x0    # branches to self (address 0x0)
00000004: 00520463 beq    x4,x5,0xc    # branches to address 0xc
00000008: fe520ce3 beq    x4,x5,0x0    # branches to address 0x0
0000000c: 00100073 ebreak

```

The instruction at address 0x0 has a target address of zero and **imm_b** is zero because the offset from the “current instruction” to the target is zero.⁴

⁴This is in contrast to many other instruction sets with **pc**-relative addressing modes that express a branch target offset from the “next instruction.”

The instruction at address 0x4 has a target address of 0xc and it has an `imm_b` of 0x08 because $0x4 + 0x08 = 0x0c$.

The instruction at address 0x8 has a target address of zero and `imm_b` is 0xffffffff8 (-8) because $0x8 + 0xffffffff8 = 0x0$.

- `beq rs1,rs2,pcrel_13`

If `rs1` is equal to `rs2` then add `imm_b` to the `pc` register.

- `bge rs1,rs2,pcrel_13`

If the signed value in `rs1` is greater than or equal to the signed value in `rs2` then add `imm_b` to the `pc` register.

- `bgeu rs1,rs2,pcrel_13`

If the unsigned value in `rs1` is greater than or equal to the unsigned value in `rs2` then add `imm_b` to the `pc` register.

- `blt rs1,rs2,pcrel_13`

If the signed value in `rs1` is less than the signed value in `rs2` then add `imm_b` to the `pc` register.

- `bltu rs1,rs2,pcrel_13`

If the unsigned value in `rs1` is less than the unsigned value in `rs2` then add `imm_b` to the `pc` register.

- `bne rs1,rs2,pcrel_13`

If `rs1` is not equal to `rs2` then add `imm_b` to the `pc` register.

5.4 CPU Registers

The registers are names x0 through x31 and have aliases suited to their conventional use. The following table describes each register.

Note that the calling convention specifies that only some of the registers are to be saved by functions if they alter their contents. The idea being that accessing memory is time-consuming and that by classifying some registers as “temporary” (not saved by any function that alter its contents) it is possible to carefully implement a function with less need to store register values on the stack in order to use them to perform the operations of the function.

The lack of grouping the temporary and saved registers is due to the fact that the E extension only has the first 16 registers and some of the instructions in the C extension can only refer to the first 16 registers.

► Fix Me:
Need to add a section that discusses the calling conventions

Reg	ABI/Alias	Description	Saved
x0	zero	Hard-wired zero	yes
x1	ra	Return address	
x2	sp	Stack pointer	
x3	gp	Global pointer	
x4	tp	Thread pointer	
x5	t0	Temporary/alternate link register	yes
x6-7	t1-2	Temporaries	
x8	s0/fp	Saved register/frame pointer	
x9	s1	Saved register	
x10-11	a0-1	Function arguments/return value	
x12-17	a2-7	Function arguments	yes
x18-27	s2-11	Saved registers	
x28-31	t3-6	Temporaries	

5.5 memory

Note that RISC-V is a little-endian machine.

All instructions must be naturally aligned to their 4-byte boundaries. [1, p. 5]

If a RISC-V processor implements the C (compressed) extension then instructions may be aligned to 2-byte boundaries.[1, p. 68]

Data alignment is not necessary but unaligned data can be inefficient. Accessing unaligned data using any of the load or store instructions can also prevent a memory access from operating atomically. [1, p.19]

Appendix A

Installing a RISC-V Toolchain

All of the software presented in this text was assembled/compiled using the GNU toolchain and executed using the rvddt simulator on a Linux (Ubuntu 20.04 LTS) operating system.

The installation instructions provided here were last tested on on March 5, 2021.

It is expected that these tools will evolve over time. See the respective documentation web sites for the latest news and options for installing them.

A.1 The GNU Toolchain

In order to install custom code in a location that will not cause interference with other applications (and allow for easy hacking and cleanup), these will install the toolchain under a private directory: `~/projects/riscv/install`. At any time you can remove everything and start over by executing the following command:

```
1 rm -rf ~/projects/riscv/install
```

► Fix Me:

It would be good to find some Mac and Windows users to write and test proper variations on this section to address those systems. Pull requests, welcome!

Be *very* careful how you type the above `rm` command. If typed incorrectly, it could irreversibly remove many of your files!

Before building the toolchain, a number of utilities must be present on your system. The following will install those that are needed:

```
1 sudo apt install autoconf automake autotools-dev curl python3 python-dev libmpc-dev \  
2     libmpfr-dev libgmp-dev gawk build-essential bison flex texinfo gperf \  
3     libtool patchutils bc zlib1g-dev libexpat-dev
```

Note that the above `apt` command is the only operation that should be performed as root. All other commands should be executed as a regular user. This will eliminate the possibility of clobbering system files that should not be touched when tinkering with the toolchain applications.

To download, compile and install the toolchain:

► Fix Me:

Discuss the choice of `ilp32` as well as what the other variations would do.

```

1 mkdir -p ~/projects/riscv
2 cd ~/projects/riscv
3 git clone https://github.com/riscv/riscv-gnu-toolchain
4 cd riscv-gnu-toolchain
1854 INS_DIR=~/projects/riscv/install/rv32i
6 ./configure --prefix=$INS_DIR \
7 --with-multilib-generator="rv32i-ilp32--;rv32imafd-ilp32--;rv32ima-ilp32--"
8 make

```

After building the toolchain, make it available by putting it into your PATH by adding the following to the end of your `.bashrc` file:

```
1 export PATH=$PATH:$INS_DIR
```

For this PATH change to take place, start a new terminal or paste the same `export` command into your existing terminal.

A.2 rvddt

Download and install the rvddt simulator by executing the following commands. Building the rvddt example programs will verify that the GNU toolchain has been built and installed properly.

```

1 cd ~/projects/riscv
2 git clone https://github.com/johnwinans/rvddt.git
3 cd rvddt/src
1865 make world
5 cd ../examples
6 make world

```

After building rvddt, make it available by putting it into your PATH by adding the following to the end of your `.bashrc` file:

```
1 export PATH=$PATH:~/projects/riscv/rvddt/src
```

For this PATH change to take place, start a new terminal or paste the same `export` command into your existing terminal.

Test the rvddt build by executing one of the examples:

```

1 winans@ux410:~/projects/riscv/rvddt/examples$ rvddt -f counter/counter.bin
2 sp initialized to top of memory: 0x0000fff0
3 Loading 'counter/counter.bin' to 0x0
4 This is rvddt. Enter ? for help.
5 ddt> ti 0 1000
6 00000000: 00300293 addi x5, x0, 3 # x5 = 0x00000003 = 0x00000000 + 0x00000003
7 00000004: 00000313 addi x6, x0, 0 # x6 = 0x00000000 = 0x00000000 + 0x00000000
8 00000008: 00130313 addi x6, x6, 1 # x6 = 0x00000001 = 0x00000000 + 0x00000001
1874 9 0000000c: fe534ee3 blt x6, x5, -4 # pc = (0x1 < 0x3) ? 0x8 : 0x10
10 00000008: 00130313 addi x6, x6, 1 # x6 = 0x00000002 = 0x00000001 + 0x00000001
11 0000000c: fe534ee3 blt x6, x5, -4 # pc = (0x2 < 0x3) ? 0x8 : 0x10
12 00000008: 00130313 addi x6, x6, 1 # x6 = 0x00000003 = 0x00000002 + 0x00000001
13 0000000c: fe534ee3 blt x6, x5, -4 # pc = (0x3 < 0x3) ? 0x8 : 0x10
14 00000010: ebreak
15 ddt> x
16 winans@ux410:~/projects/riscv/rvddt/examples$

```

A.3 qemu

You can download and install the RV32 qemu simulator by executing the following commands.

At the time of this writing (2021-06) I use release v5.0.0. Release v5.2.0 has issues that confuse GDB when printing the registers and v6.0.0 has different CPU types that I have had trouble with when executing privileged instructions.

```
1 INS_DIR=~/projects/riscv/install/rv32i
2 cd ~/projects/riscv
3 git clone git@github.com:qemu/qemu.git
4 cd qemu
5 git checkout v5.0.0
6 ./configure --target-list=riscv32-softmmu --prefix=${INS_DIR}
7 make -j4
8 make install
```

Appendix B

Floating Point Numbers

B.1 IEEE-754 Floating Point Number Representation

This section provides an overview of the IEEE-754 32-bit binary floating point format. [15]

- Recall that the place values for integer binary numbers are:

... 128 64 32 16 8 4 2 1

- We can extend this to the right in binary similar to the way we do for decimal numbers:

... 128 64 32 16 8 4 2 1 . 1/2 1/4 1/8 1/16 1/32 1/64 1/128 ...

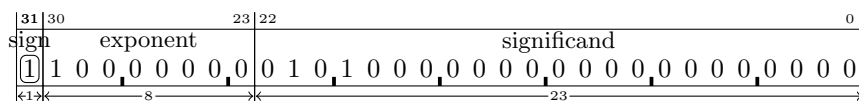
The ‘.’ in a binary number is a binary point, not a decimal point.

- We use scientific notation as in 2.7×10^{-47} to express either small fractions or large numbers when we are not concerned every last digit needed to represent the entire, exact, value of a number.
- The format of a number in scientific notation is $\text{mantissa} \times \text{base}^{\text{exponent}}$
- In binary we have $\text{mantissa} \times 2^{\text{exponent}}$
- IEEE-754 format requires binary numbers to be *normalized* to $1.\text{significand} \times 2^{\text{exponent}}$ where the *significand* is the portion of the *mantissa* that is to the right of the binary-point.

– The unnormalized binary value of -2.625 is -10.101

– The normalized value of -2.625 is -1.0101×2^1

- We need not store the ‘1.’ part because *all* normalized floating point numbers will start that way. Thus we can save memory when storing normalized values by inserting a ‘1.’ to the left of significand.



- $-((1 + \frac{1}{4} + \frac{1}{16}) \times 2^{128-127}) = -((1 + \frac{1}{4} + \frac{1}{16}) \times 2^1) = -(2 + \frac{1}{2} + \frac{1}{8}) = -(2 + .5 + .125) = -2.625$

- IEEE-754 formats:

	IEEE-754 32-bit	IEEE-754 64-bit
sign	1 bit	1 bit
exponent	8 bits (excess-127)	11 bits (excess-1023)
mantissa	23 bits	52 bits
max exponent	127	1023
min exponent	-126	-1022

- When the exponent is all ones, the significand is all zeros, and the sign is zero, the number represents positive infinity.
- When the exponent is all ones, the significand is all zeros, and the sign is one, the number represents negative infinity.
- Observe that the binary representation of a pair of IEEE-754 numbers (when one or both are positive) can be compared for magnitude by treating them as if they are two's complement signed integers. This is because an IEEE number is stored in *signed magnitude* format and therefore positive floating point values will grow upward and downward in the same fashion as for unsigned integers and that since negative floating point values will have its MSB set, they will 'appear' to be less than a positive floating point value.

When comparing two negative IEEE float values by treating them both as two's complement signed integers, the order will be reversed because IEEE float values with larger (that is, increasingly negative) magnitudes will appear to decrease in value when interpreted as signed integers.

This works this way because excess notation is used in the format of the exponent and why the significand's sign bit is located on the left of the exponent.¹

- Note that zero is a special case number. Recall that a normalized number has an implied 1-bit to the left of the significand... which means that there is no way to represent zero! Zero is represented by an exponent of all-zeros and a significand of all-zeros. This definition allows for a positive and a negative zero if we observe that the sign can be either 1 or 0.
- On the number-line, numbers between zero and the smallest fraction in either direction are in the *underflow* areas.
- On the number line, numbers greater than the mantissa of all-ones and the largest exponent allowed are in the *overflow* areas.
- Note that numbers have a higher resolution on the number line when the exponent is smaller.
- The largest and smallest possible exponent values are reserved to represent things requiring special cases. For example, the infinities, values representing "not a number" (such as the result of dividing by zero), and for a way to represent values that are not normalized. For more information on special cases see [15].

► Fix Me:

Need to add the standard lecture number-line diagram showing where the over/under-flow areas are and why.

B.1.1 Floating Point Number Accuracy

Due to the finite number of bits used to store the value of a floating point number, it is not possible to represent every one of the infinite values on the real number line. The following C programs illustrate this point.

¹I know this is true and was done on purpose because Bill Cody, chairman of IEEE committee P754 that designed the IEEE-754 standard, told me so personally circa 1991.

B.1.1.1 Powers Of Two

Just like the integer numbers, the powers of two that have bits to represent them can be represented perfectly... as can their sums (provided that the significand requires no more than 23 bits.)

Listing B.1: powersoftwo.c
Precise Powers of Two

```

1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <unistd.h>
4
5 union floatbin
6 {
7     unsigned int    i;
8     float          f;
9 };
10 int main()
11 {
12     union floatbin x;
13     union floatbin y;
14     int            i;
15     x.f = 1.0;
16     while (x.f > 1.0/1024.0)
17     {
18         y.f = -x.f;
19         printf("%25.10f = %08x    %25.10f = %08x\n", x.f, x.i, y.f, y.i);
20         x.f = x.f/2.0;
21     }
22 }
```

Listing B.2: powersoftwo.out
Output from powersoftwo.c

```

1 1.0000000000 = 3f800000          -1.0000000000 = bf800000
2 0.5000000000 = 3f000000          -0.5000000000 = bf000000
3 0.2500000000 = 3e800000          -0.2500000000 = be800000
4 0.1250000000 = 3e000000          -0.1250000000 = be000000
5 0.0625000000 = 3d800000          -0.0625000000 = bd800000
6 0.0312500000 = 3d000000          -0.0312500000 = bd000000
7 0.0156250000 = 3c800000          -0.0156250000 = bc800000
8 0.0078125000 = 3c000000          -0.0078125000 = bc000000
9 0.0039062500 = 3b800000          -0.0039062500 = bb800000
10 0.0019531250 = 3b000000          -0.0019531250 = bb000000
```

B.1.1.2 Clean Decimal Numbers

When dealing with decimal values, you will find that they don't map simply into binary floating point values.

Note how the decimal numbers are not accurately represented as they get larger. The decimal number on line 10 of [Listing B.4](#) can be perfectly represented in IEEE format. However, a problem arises in the 11th loop iteration. It is due to the fact that the binary number can not be represented accurately in IEEE format. Its least significant bits were truncated in a best-effort attempt at rounding the value off in order to fit the value into the bits provided. This is an example of *low order truncation*. Once this happens, the value of `x.f` is no longer as precise as it could be given more bits in which to save its value.

Listing B.3: cleandecimal.c
Print Clean Decimal Numbers

```

1988
1989 1 #include <stdio.h>
1990 2 #include <stdlib.h>
1991 3 #include <unistd.h>
1992 4
1993 5 union floatbin
1994 6 {
1995 7     unsigned int    i;
1996 8     float          f;
1997 9 };
1998 10 int main()
1999 11 {
2000 12     union floatbin  x, y;
2001 13     int             i;
2002 14
2003 15     x.f = 10;
2004 16     while (x.f <= 10000000000000.0)
2005 17     {
2006 18         y.f = -x.f;
2007 19         printf("%25.10f = %08x      %25.10f = %08x\n", x.f, x.i, y.f, y.i);
2008 20         x.f = x.f*10.0;
2009 21     }
2010 22 }

```

Listing B.4: cleandecimal.out
Output from cleandecimal.c

```

2012
2013 1      10.0000000000 = 41200000      -10.0000000000 = c1200000
2014 2      100.0000000000 = 42c80000     -100.0000000000 = c2c80000
2015 3     1000.0000000000 = 447a0000     -1000.0000000000 = c47a0000
2016 4    10000.0000000000 = 461c4000     -10000.0000000000 = c61c4000
2017 5   100000.0000000000 = 47c35000     -100000.0000000000 = c7c35000
2018 6  1000000.0000000000 = 49742400     -1000000.0000000000 = c9742400
2019 7 10000000.0000000000 = 4b189680     -10000000.0000000000 = cb189680
2020 8 100000000.0000000000 = 4cbebc20     -100000000.0000000000 = ccbebc20
2021 9 1000000000.0000000000 = 4e6e6b28     -1000000000.0000000000 = ce6e6b28
2022 10 10000000000.0000000000 = 501502f9     -10000000000.0000000000 = d01502f9
2023 11 99999997952.0000000000 = 51ba43b7     -99999997952.0000000000 = d1ba43b7
2024 12 999999995904.0000000000 = 5368d4a5     -999999995904.0000000000 = d368d4a5
2025 13 9999999827968.0000000000 = 551184e7     -9999999827968.0000000000 = d51184e7

```

B.1.1.3 Accumulation of Error

These rounding errors can be exaggerated when the number we multiply the `x.f` value by is, itself, something that can not be accurately represented in IEEE form.²

For example, if we multiply our `x.f` value by $\frac{1}{10}$ each time, we can never be accurate and we start accumulating errors immediately.

Listing B.5: erroraccumulation.c
Accumulation of Error

```

2032
2033 1 #include <stdio.h>
2034 2 #include <stdlib.h>
2035 3 #include <unistd.h>
2036 4
2037 5 union floatbin
2038 6 {
2039 7     unsigned int    i;
2040 8     float          f;

```

²Applications requiring accurate decimal values, such as financial accounting systems, can use a packed-decimal numeric format to avoid unexpected oddities caused by the use of binary numbers.

► Fix Me:

In a lecture one would show that one tenth is a repeating non-terminating binary number that gets truncated. This discussion should be reproduced here in text form.

```

2041 9  };
2042 10  int main()
2043 11  {
2044 12      union floatbin  x, y;
2045 13      int             i;
2046 14
2047 15      x.f = .1;
2048 16      while (x.f <= 2.0)
2049 17      {
2050 18          y.f = -x.f;
2051 19          printf("%25.10f = %08x      %25.10f = %08x\n", x.f, x.i, y.f, y.i);
2052 20          x.f += .1;
2053 21      }
2054 22  }

```

Listing B.6: `erroraccumulation.out`
Output from `erroraccumulation.c`

2056 1	0.1000000015 = 3dcccccd	-0.1000000015 = bdcccccd
2058 2	0.2000000030 = 3e4ccccd	-0.2000000030 = be4ccccd
2059 3	0.3000000119 = 3e99999a	-0.3000000119 = be99999a
2060 4	0.4000000060 = 3ecccccd	-0.4000000060 = becccccd
2061 5	0.5000000000 = 3f000000	-0.5000000000 = bf000000
2062 6	0.6000000238 = 3f19999a	-0.6000000238 = bf19999a
2063 7	0.7000000477 = 3f333334	-0.7000000477 = bf333334
2064 8	0.8000000715 = 3f4ccccce	-0.8000000715 = bf4ccccce
2065 9	0.9000000954 = 3f666668	-0.9000000954 = bf666668
2066 10	1.0000001192 = 3f800001	-1.0000001192 = bf800001
2067 11	1.1000001431 = 3f8ccccce	-1.1000001431 = bf8ccccce
2068 12	1.2000001669 = 3f99999b	-1.2000001669 = bf99999b
2069 13	1.3000001907 = 3fa66668	-1.3000001907 = bfa66668
2070 14	1.4000002146 = 3fb33335	-1.4000002146 = bfb33335
2071 15	1.5000002384 = 3fc00002	-1.5000002384 = bfc00002
2072 16	1.6000002623 = 3fcccccf	-1.6000002623 = bfcccccf
2073 17	1.7000002861 = 3fd9999c	-1.7000002861 = bfd9999c
2074 18	1.8000003099 = 3fe66669	-1.8000003099 = bfe66669
2075 19	1.9000003338 = 3ff33336	-1.9000003338 = bff33336

B.1.2 Reducing Error Accumulation

In order to use floating point numbers in a program without causing excessive rounding problems an algorithm can be redesigned such that the accumulation is eliminated. This example is similar to the previous one, but this time we recalculate the desired value from a known-accurate integer value. Some rounding errors remain present, but they can not accumulate.

Listing B.7: `errorcompensation.c`
Accumulation of Error

```

2082 1  #include <stdio.h>
2083 2  #include <stdlib.h>
2084 3  #include <unistd.h>
2085 4
2086 5
2087 6  union floatbin
2088 7  {
2089 8      unsigned int    i;
2090 9      float          f;
2091 10 };
2092 11 int main()
2093 12 {
2094 13     union floatbin  x, y;
2095 14     int             i;
2096 15
2097 16     i = 1;

```



```

2098 16   while (i <= 20)
2099 17   {
2100 18       x.f = i/10.0;
2101 19       y.f = -x.f;
2102 20       printf("%25.10f = %08x      %25.10f = %08x\n", x.f, x.i, y.f, y.i);
2103 21       i++;
2104 22   }
2105 23   return(0);
2106 24 }

```

Listing B.8: errorcompensation.out
Output from erroraccumulation.c

2108	1	0.1000000015 = 3dcccccd	-0.1000000015 = bdcccccd
2109	2	0.2000000030 = 3e4cccccd	-0.2000000030 = be4cccccd
2110	3	0.3000000119 = 3e999999a	-0.3000000119 = be999999a
2111	4	0.4000000060 = 3ecccccd	-0.4000000060 = becccccd
2112	5	0.5000000000 = 3f000000	-0.5000000000 = bf000000
2113	6	0.6000000238 = 3f199999a	-0.6000000238 = bf199999a
2114	7	0.6999999881 = 3f333333	-0.6999999881 = bf333333
2115	8	0.8000000119 = 3f4cccccd	-0.8000000119 = bf4cccccd
2116	9	0.8999999762 = 3f666666	-0.8999999762 = bf666666
2117	10	1.0000000000 = 3f800000	-1.0000000000 = bf800000
2118	11	1.1000000238 = 3f8cccccd	-1.1000000238 = bf8cccccd
2119	12	1.2000000477 = 3f999999a	-1.2000000477 = bf999999a
2120	13	1.2999999523 = 3fa66666	-1.2999999523 = bfa66666
2121	14	1.3999999762 = 3fb33333	-1.3999999762 = bfb33333
2122	15	1.5000000000 = 3fc00000	-1.5000000000 = bfc00000
2123	16	1.6000000238 = 3fcccccd	-1.6000000238 = bfcccccd
2124	17	1.7000000477 = 3fd99999a	-1.7000000477 = bfd99999a
2125	18	1.7999999523 = 3fe66666	-1.7999999523 = bfe66666
2126	19	1.8999999762 = 3ff33333	-1.8999999762 = bff33333
2127	20	2.0000000000 = 40000000	-2.0000000000 = c0000000

Appendix C

The ASCII Character Set

A slightly abridged version of the Linux “ASCII” man(1) page.

C.1 NAME

ascii - ASCII character set encoded in octal, decimal, and hexadecimal

C.2 DESCRIPTION

ASCII is the American Standard Code for Information Interchange. It is a 7-bit code. Many 8-bit codes (e.g., ISO 8859-1) contain ASCII as their lower half. The international counterpart of ASCII is known as ISO 646-IRV.

The following table contains the 128 ASCII characters.

C program ‘\X’ escapes are noted.

Oct	Dec	Hex	Char	Oct	Dec	Hex	Char
000	0	00	NUL ‘\0’ (null character)	100	64	40	@
001	1	01	SOH (start of heading)	101	65	41	A
002	2	02	STX (start of text)	102	66	42	B
003	3	03	ETX (end of text)	103	67	43	C
004	4	04	EOT (end of transmission)	104	68	44	D
005	5	05	ENQ (enquiry)	105	69	45	E
006	6	06	ACK (acknowledge)	106	70	46	F
007	7	07	BEL ‘\a’ (bell)	107	71	47	G
010	8	08	BS ‘\b’ (backspace)	110	72	48	H
011	9	09	HT ‘\t’ (horizontal tab)	111	73	49	I
012	10	0A	LF ‘\n’ (new line)	112	74	4A	J
013	11	0B	VT ‘\v’ (vertical tab)	113	75	4B	K
014	12	0C	FF ‘\f’ (form feed)	114	76	4C	L
015	13	0D	CR ‘\r’ (carriage ret)	115	77	4D	M

2157	016	14	0E	S0 (shift out)	116	78	4E	N	
2158	017	15	0F	SI (shift in)	117	79	4F	O	
2159	020	16	10	DLE (data link escape)	120	80	50	P	
2160	021	17	11	DC1 (device control 1)	121	81	51	Q	
2161	022	18	12	DC2 (device control 2)	122	82	52	R	
2162	023	19	13	DC3 (device control 3)	123	83	53	S	
2163	024	20	14	DC4 (device control 4)	124	84	54	T	
2164	025	21	15	NAK (negative ack.)	125	85	55	U	
2165	026	22	16	SYN (synchronous idle)	126	86	56	V	
2166	027	23	17	ETB (end of trans. blk)	127	87	57	W	
2167	030	24	18	CAN (cancel)	130	88	58	X	
2168	031	25	19	EM (end of medium)	131	89	59	Y	
2169	032	26	1A	SUB (substitute)	132	90	5A	Z	
2170	033	27	1B	ESC (escape)	133	91	5B	[
2171	034	28	1C	FS (file separator)	134	92	5C	\	'\'
2172	035	29	1D	GS (group separator)	135	93	5D]	
2173	036	30	1E	RS (record separator)	136	94	5E	^	
2174	037	31	1F	US (unit separator)	137	95	5F	_	
2175	040	32	20	SPACE	140	96	60	'	
2176	041	33	21	!	141	97	61	a	
2177	042	34	22	"	142	98	62	b	
2178	043	35	23	#	143	99	63	c	
2179	044	36	24	\$	144	100	64	d	
2180	045	37	25	%	145	101	65	e	
2181	046	38	26	&	146	102	66	f	
2182	047	39	27	'	147	103	67	g	
2183	050	40	28	(150	104	68	h	
2184	051	41	29)	151	105	69	i	
2185	052	42	2A	*	152	106	6A	j	
2186	053	43	2B	+	153	107	6B	k	
2187	054	44	2C	,	154	108	6C	l	
2188	055	45	2D	-	155	109	6D	m	
2189	056	46	2E	.	156	110	6E	n	
2190	057	47	2F	/	157	111	6F	o	
2191	060	48	30	0	160	112	70	p	
2192	061	49	31	1	161	113	71	q	
2193	062	50	32	2	162	114	72	r	
2194	063	51	33	3	163	115	73	s	
2195	064	52	34	4	164	116	74	t	
2196	065	53	35	5	165	117	75	u	
2197	066	54	36	6	166	118	76	v	
2198	067	55	37	7	167	119	77	w	
2199	070	56	38	8	170	120	78	x	
2200	071	57	39	9	171	121	79	y	
2201	072	58	3A	:	172	122	7A	z	
2202	073	59	3B	;	173	123	7B	{	
2203	074	60	3C	<	174	124	7C		
2204	075	61	3D	=	175	125	7D	}	
2205	076	62	3E	>	176	126	7E	~	
2206	077	63	3F	?	177	127	7F	DEL	

C.2.1 Tables

For convenience, below are more compact tables in hex and decimal.

2 3 4 5 6 7	30 40 50 60 70 80 90 100 110 120
-----	-----
0: 0 @ P ' p	0: (2 < F P Z d n x
1: ! 1 A Q a q	1:) 3 = G Q [e o y
2: " 2 B R b r	2: * 4 > H R \ f p z
3: # 3 C S c s	3: ! + 5 ? I S] g q {
4: \$ 4 D T d t	4: " , 6 @ J T ^ h r
5: % 5 E U e u	5: # - 7 A K U _ i s }
6: & 6 F V f v	6: \$. 8 B L V ' j t ~
7: ' 7 G W g w	7: % / 9 C M W a k u DEL
8: (8 H X h x	8: & 0 : D N X b l v
9:) 9 I Y i y	9: ' 1 ; E O Y c m w
A: * : J Z j z	
B: + ; K [k {	
C: , < L \ l	
D: - = M] m }	
E: . > N ^ n ~	
F: / ? 0 _ o DEL	

C.3 NOTES

C.3.1 History

An ascii manual page appeared in Version 7 of AT&T UNIX.

On older terminals, the underscore code is displayed as a left arrow, called backarrow, the caret is displayed as an up-arrow and the vertical bar has a hole in the middle.

Uppercase and lowercase characters differ by just one bit and the ASCII character 2 differs from the double quote by just one bit, too. That made it much easier to encode characters mechanically or with a non-microcontroller-based electronic keyboard and that pairing was found on old teletypes.

The ASCII standard was published by the United States of America Standards Institute (USASI) in 1968.

C.4 COLOPHON

This page is part of release 4.04 of the Linux man-pages project. A description of the project, information about reporting bugs, and the latest version of this page, can be found at <http://www.kernel.org/doc/man-pages/>.

Appendix D

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Glossary

address A numeric value used to uniquely identify each [byte](#) of main memory. [2](#), [77](#)

alignment Refers to a range of numeric values that begin at a multiple of some number. Primarily used when referring to a memory address. For example an alignment of two refers to one or more addresses starting at even address and continuing onto subsequent adjacent, increasing memory addresses. [26](#), [77](#)

ASCII American Standard Code for Information Interchange. See [Appendix C](#). [21](#), [77](#)

big-endian A number format where the most significant values are printed to the left of the lesser significant values. This is the method that everyone uses to write decimal numbers every day. [23](#), [30](#), [31](#), [77](#), [79](#)

binary Something that has two parts or states. In computing these two states are represented by the numbers one and zero or by the conditions true and false and can be stored in one [bit](#). [1](#), [3](#), [77](#), [78](#), [79](#)

bit One binary digit. [3](#), [6](#), [10](#), [77](#), [78](#), [79](#)

byte A [binary](#) value represented by 8 [bits](#). [2](#), [6](#), [77](#), [78](#), [79](#)

CPU Central Processing Unit. [1](#), [2](#), [77](#)

doubleword A [binary](#) value represented by 64 [bits](#). [77](#)

exception An error encountered by the CPU while executing an instruction that can not be completed. [27](#), [77](#)

fullword A [binary](#) value represented by 32 [bits](#). [6](#), [77](#)

halfword A [binary](#) value represented by 16 [bits](#). [6](#), [22](#), [77](#)

hart Hardware Thread. [3](#), [77](#)

hexadecimal A base-16 numbering system whose digits are 0123456789abcdef. The hex digits ([hits](#)) are not case-sensitive. [30](#), [31](#), [77](#), [78](#)

high order bits Some number of [MSBs](#). [77](#)

hit One [hexadecimal](#) digit. [10](#), [12](#), [77](#), [78](#), [79](#)

ISA Instruction Set Architecture. [3](#), [4](#), [77](#)

LaTeX Is a mark up language specially suited for scientific documents. [77](#)

- little-endian** A number format where the least significant values are printed to the left of the more significant values. This is the opposite ordering that everyone learns in grade school when learning how to count. For example, the [big-endian](#) number written as “1234” would be written in little endian form as “4321”. [24](#), [77](#)
- low order bits** Some number of [LSBs](#). [77](#)
- LSB** Least Significant Bit. [10](#), [12](#), [22](#), [44](#), [48](#), [54](#), [56](#), [77](#), [79](#)
- machine language** The instructions that are executed by a CPU that are expressed in the form of [binary](#) values. [1](#), [77](#)
- mnemonic** A method used to remember something. In the case of assembly language, each machine instruction is given a name so the programmer need not memorize the binary values of each machine instruction. [1](#), [77](#)
- MSB** Most Significant Bit. [10](#), [12](#), [13](#), [19](#), [20](#), [22](#), [44](#), [45](#), [77](#), [78](#)
- nybble** Half of a [byte](#) is a *nybble* (sometimes spelled nibble.) Another word for *hit*. [10](#), [77](#)
- overflow** The situation where the result of an addition or subtraction operation is approaching positive or negative infinity and exceeds the number of bits allotted to contain the result. This is typically caused by high-order truncation. [64](#), [77](#)
- place value** the numerical value that a digit has as a result of its *position* within a number. For example, the digit 2 in the decimal number 123 is in the ten’s place and its place value is 20. [9](#), [10](#), [11](#), [23](#), [24](#), [77](#)
- program** A ordered list of one or more instructions. [1](#), [77](#)
- quadword** A [binary](#) value represented by 128 [bits](#). [77](#)
- RAM** Random Access Memory. [2](#), [77](#)
- register** A unit of storage inside a CPU with the capacity of [XLEN](#) bits. [2](#), [77](#), [79](#)
- ROM** Read Only Memory. [2](#), [77](#)
- RV32** Short for RISC-V 32. The number 32 refers to the [XLEN](#). [77](#)
- RV64** Short for RISC-V 64. The number 64 refers to the [XLEN](#). [77](#)
- rdddt** A RV32I simulator and debugging tool inspired by the simplicity of the Dynamic Debugging Tool (ddt) that was part of the CP/M operating system. [21](#), [29](#), [77](#)
- thread** An stream of instructions. When plural, it is used to refer to the ability of a CPU to execute multiple instruction streams at the same time. [3](#), [77](#)
- underflow** The situation where the result of an addition or subtraction operation is approaching zero and exceeds the number of bits allotted to contain the result. This is typically caused by low-order truncation. [64](#), [77](#)
- XLEN** The number of bits a RISC-V x integer [register](#) (such as x0). For RV32 XLEN=32, RV64 XLEN=64 and so on. [49](#), [50](#), [52](#), [56](#), [57](#), [77](#), [79](#)

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RV32I Reference Cards

Usage Template	Type	Description	Detailed Description
add rd, rs1, rs2	R	Add	$rd \leftarrow rs1 + rs2, pc \leftarrow pc+4$
addi rd, rs1, imm	I	Add Immediate	$rd \leftarrow rs1 + imm_i, pc \leftarrow pc+4$
and rd, rs1, rs2	R	And	$rd \leftarrow rs1 \wedge rs2, pc \leftarrow pc+4$
andi rd, rs1, imm	I	And Immediate	$rd \leftarrow rs1 \wedge imm_i, pc \leftarrow pc+4$
auipc rd, imm	U	Add Upper Immediate to PC	$rd \leftarrow pc + imm_u, pc \leftarrow pc+4$
beq rs1, rs2, pcrel_13	B	Branch Equal	$pc \leftarrow pc + ((rs1 == rs2) ? imm_b : 4)$
bge rs1, rs2, pcrel_13	B	Branch Greater or Equal	$pc \leftarrow pc + ((rs1 \geq rs2) ? imm_b : 4)$
bgeu rs1, rs2, pcrel_13	B	Branch Greater or Equal Unsigned	$pc \leftarrow pc + ((rs1 \geq rs2) ? imm_b : 4)$
blt rs1, rs2, pcrel_13	B	Branch Less Than	$pc \leftarrow pc + ((rs1 < rs2) ? imm_b : 4)$
bltu rs1, rs2, pcrel_13	B	Branch Less Than Unsigned	$pc \leftarrow pc + ((rs1 < rs2) ? imm_b : 4)$
bne rs1, rs2, pcrel_13	B	Branch Not Equal	$pc \leftarrow pc + ((rs1 \neq rs2) ? imm_b : 4)$
csrrw rd, csr, rs1	I	Atomic Read/Write	$rd \leftarrow csr, csr \leftarrow rs1, pc \leftarrow pc+4$
csrrs rd, csr, rs1	I	Atomic Read and Set	$rd \leftarrow csr, csr \leftarrow csr \vee rs1, pc \leftarrow pc+4$
csrrc rd, csr, rs1	I	Atomic Read and Clear	$rd \leftarrow csr, csr \leftarrow csr \wedge \sim rs1, pc \leftarrow pc+4$
csrrwi rd, csr, zimm	I	Atomic Read/Write Immediate	$rd \leftarrow csr, csr \leftarrow zimm, pc \leftarrow pc+4$
csrrsi rd, csr, zimm	I	Atomic Read and Set Immediate	$rd \leftarrow csr, csr \leftarrow csr \vee zimm, pc \leftarrow pc+4$
csrrci rd, csr, zimm	I	Atomic Read and Clear Immediate	$rd \leftarrow csr, csr \leftarrow csr \wedge \sim zimm, pc \leftarrow pc+4$
ecall	I	Environment Call	Transfer Control to Debugger
ebreak	I	Environment Break	Transfer Control to Operating System
jal rd, pcrel_21	J	Jump And Link	$rd \leftarrow pc+4, pc \leftarrow pc+imm_j$
jalr rd, imm(rs1)	I	Jump And Link Register	$rd \leftarrow pc+4, pc \leftarrow (rs1+imm_i) \& \sim 1$
lb rd, imm(rs1)	I	Load Byte	$rd \leftarrow sx(m8(rs1+imm_i)), pc \leftarrow pc+4$
lbu rd, imm(rs1)	I	Load Byte Unsigned	$rd \leftarrow zx(m8(rs1+imm_i)), pc \leftarrow pc+4$
lh rd, imm(rs1)	I	Load Halfword	$rd \leftarrow sx(m16(rs1+imm_i)), pc \leftarrow pc+4$
lhu rd, imm(rs1)	I	Load Halfword Unsigned	$rd \leftarrow zx(m16(rs1+imm_i)), pc \leftarrow pc+4$
lui rd, imm	U	Load Upper Immediate	$rd \leftarrow imm_u, pc \leftarrow pc+4$
lw rd, imm(rs1)	I	Load Word	$rd \leftarrow sx(m32(rs1+imm_i)), pc \leftarrow pc+4$
or rd, rs1, rs2	R	Or	$rd \leftarrow rs1 \vee rs2, pc \leftarrow pc+4$
ori rd, rs1, imm	I	Or Immediate	$rd \leftarrow rs1 \vee imm_i, pc \leftarrow pc+4$
sb rs2, imm(rs1)	S	Store Byte	$m8(rs1+imm_s) \leftarrow rs2[7:0], pc \leftarrow pc+4$
sh rs2, imm(rs1)	S	Store Halfword	$m16(rs1+imm_s) \leftarrow rs2[15:0], pc \leftarrow pc+4$
sll rd, rs1, rs2	R	Shift Left Logical	$rd \leftarrow rs1 \ll (rs2 \% XLEN), pc \leftarrow pc+4$
slli rd, rs1, shamt	I	Shift Left Logical Immediate	$rd \leftarrow rs1 \ll shamt_i, pc \leftarrow pc+4$
slt rd, rs1, rs2	R	Set Less Than	$rd \leftarrow (rs1 < rs2) ? 1 : 0, pc \leftarrow pc+4$
slti rd, rs1, imm	I	Set Less Than Immediate	$rd \leftarrow (rs1 < imm_i) ? 1 : 0, pc \leftarrow pc+4$
sltiu rd, rs1, imm	I	Set Less Than Immediate Unsigned	$rd \leftarrow (rs1 < imm_i) ? 1 : 0, pc \leftarrow pc+4$
sltu rd, rs1, rs2	R	Set Less Than Unsigned	$rd \leftarrow (rs1 < rs2) ? 1 : 0, pc \leftarrow pc+4$
sra rd, rs1, rs2	R	Shift Right Arithmetic	$rd \leftarrow rs1 \gg (rs2 \% XLEN), pc \leftarrow pc+4$
srai rd, rs1, shamt	I	Shift Right Arithmetic Immediate	$rd \leftarrow rs1 \gg shamt_i, pc \leftarrow pc+4$
srl rd, rs1, rs2	R	Shift Right Logical	$rd \leftarrow rs1 \gg (rs2 \% XLEN), pc \leftarrow pc+4$
srli rd, rs1, shamt	I	Shift Right Logical Immediate	$rd \leftarrow rs1 \gg shamt_i, pc \leftarrow pc+4$
sub rd, rs1, rs2	R	Subtract	$rd \leftarrow rs1 - rs2, pc \leftarrow pc+4$
sw rs2, imm(rs1)	S	Store Word	$m32(rs1+imm_s) \leftarrow rs2[31:0], pc \leftarrow pc+4$
xor rd, rs1, rs2	R	Exclusive Or	$rd \leftarrow rs1 \oplus rs2, pc \leftarrow pc+4$
xori rd, rs1, imm	I	Exclusive Or Immediate	$rd \leftarrow rs1 \oplus imm_i, pc \leftarrow pc+4$

RV32I Base Instruction Set Encoding [1, p. 104]

31	25 24	20 19	15 14	12 11	7	6	0								
imm[31:12]				rd	0	1	1	0	1	1	1	U-type	lui	rd,imm	
imm[31:12]				rd	0	0	1	0	1	1	1	U-type	auipc	rd,imm	
imm[20 10:1 11 19:12]				rd	1	1	0	1	1	1	1	J-type	jal	rd,pcrel_21	
imm[11:0]		rs1	0	0	0	rd	1	1	0	0	1	1	I-type	jalr	rd,imm(rs1)
imm[12 10:5]	rs2	rs1	0	0	0	imm[4:1 11]	1	1	0	0	0	1	B-type	beq	rs1,rs2,pcrel_13
imm[12 10:5]	rs2	rs1	0	0	1	imm[4:1 11]	1	1	0	0	0	1	B-type	bne	rs1,rs2,pcrel_13
imm[12 10:5]	rs2	rs1	1	0	0	imm[4:1 11]	1	1	0	0	0	1	B-type	blt	rs1,rs2,pcrel_13
imm[12 10:5]	rs2	rs1	1	0	1	imm[4:1 11]	1	1	0	0	0	1	B-type	bge	rs1,rs2,pcrel_13
imm[12 10:5]	rs2	rs1	1	1	0	imm[4:1 11]	1	1	0	0	0	1	B-type	bltu	rs1,rs2,pcrel_13
imm[12 10:5]	rs2	rs1	1	1	1	imm[4:1 11]	1	1	0	0	0	1	B-type	bgeu	rs1,rs2,pcrel_13
imm[11:0]		rs1	0	0	0	rd	0	0	0	0	0	1	I-type	lb	rd,imm(rs1)
imm[11:0]		rs1	0	0	1	rd	0	0	0	0	0	1	I-type	lh	rd,imm(rs1)
imm[11:0]		rs1	0	1	0	rd	0	0	0	0	0	1	I-type	lw	rd,imm(rs1)
imm[11:0]		rs1	1	0	0	rd	0	0	0	0	0	1	I-type	lbu	rd,imm(rs1)
imm[11:0]		rs1	1	0	1	rd	0	0	0	0	0	1	I-type	lhu	rd,imm(rs1)
imm[11:5]	rs2	rs1	0	0	0	imm[4:0]	0	1	0	0	0	1	S-type	sb	rs2,imm(rs1)
imm[11:5]	rs2	rs1	0	0	1	imm[4:0]	0	1	0	0	0	1	S-type	sh	rs2,imm(rs1)
imm[11:5]	rs2	rs1	0	1	0	imm[4:0]	0	1	0	0	0	1	S-type	sw	rs2,imm(rs1)
imm[11:0]		rs1	0	0	0	rd	0	0	1	0	0	1	I-type	addi	rd,rs1,imm
imm[11:0]		rs1	0	1	0	rd	0	0	1	0	0	1	I-type	slti	rd,rs1,imm
imm[11:0]		rs1	0	1	1	rd	0	0	1	0	0	1	I-type	sltiu	rd,rs1,imm
imm[11:0]		rs1	1	0	0	rd	0	0	1	0	0	1	I-type	xori	rd,rs1,imm
imm[11:0]		rs1	1	1	0	rd	0	0	1	0	0	1	I-type	ori	rd,rs1,imm
imm[11:0]		rs1	1	1	1	rd	0	0	1	0	0	1	I-type	andi	rd,rs1,imm
0 0 0 0 0 0 0 0	shamt	rs1	0	0	1	rd	0	0	1	0	0	1	I-type	slli	rd,rs1,shamt
0 0 0 0 0 0 0 0	shamt	rs1	1	0	1	rd	0	0	1	0	0	1	I-type	srl	rd,rs1,shamt
0 1 0 0 0 0 0 0	shamt	rs1	1	0	1	rd	0	0	1	0	0	1	I-type	srai	rd,rs1,shamt
0 0 0 0 0 0 0 0	rs2	rs1	0	0	0	rd	0	1	1	0	0	1	R-type	add	rd,rs1,rs2
0 1 0 0 0 0 0 0	rs2	rs1	0	0	0	rd	0	1	1	0	0	1	R-type	sub	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	0	0	1	rd	0	1	1	0	0	1	R-type	sll	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	0	1	0	rd	0	1	1	0	0	1	R-type	slt	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	0	1	1	rd	0	1	1	0	0	1	R-type	sltu	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	1	0	0	rd	0	1	1	0	0	1	R-type	xor	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	1	0	1	rd	0	1	1	0	0	1	R-type	srl	rd,rs1,rs2
0 1 0 0 0 0 0 0	rs2	rs1	1	0	1	rd	0	1	1	0	0	1	R-type	sra	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	1	1	0	rd	0	1	1	0	0	1	R-type	or	rd,rs1,rs2
0 0 0 0 0 0 0 0	rs2	rs1	1	1	1	rd	0	1	1	0	0	1	R-type	and	rd,rs1,rs2
0 0 0 0 0 0 0 0 0 0 0 0 0 0				0 0 0 0 0	0 0 0 0	0 0 0 0 0 0	1	1	1	0	0	1	I-type	ecall	
0 0 0 0 0 0 0 0 0 0 0 0 1				0 0 0 0 0	0 0 0 0	0 0 0 0 0 0	1	1	1	0	0	1	I-type	ebreak	
csr[11:0]		rs1	0	0	1	rd	1	1	1	0	0	1	I-type	csrrw	rd,csr,rs1
csr[11:0]		rs1	0	1	0	rd	1	1	1	0	0	1	I-type	csrrs	rd,csr,rs1
csr[11:0]		rs1	0	1	1	rd	1	1	1	0	0	1	I-type	csrrc	rd,csr,rs1
csr[11:0]		zimm[4:0]	1	0	1	rd	1	1	1	0	0	1	I-type	csrrwi	rd,csr,zimm
csr[11:0]		zimm[4:0]	1	1	0	rd	1	1	1	0	0	1	I-type	csrrsi	rd,csr,zimm
csr[11:0]		zimm[4:0]	1	1	1	rd	1	1	1	0	0	1	I-type	csrrci	rd,csr,zimm

Instruction	Description	Operation	Type	funct7			funct3			opcode		
				31	25 24	20 19	15 14	12 11	7 6			
lui	rd, imm	Load Upper Immediate	U			imm[31:12]		rd		0 1 0 1 1 1 1		
auipc	rd, imm	Add Upper Immediate to PC	U			imm[31:12]		rd		0 0 1 0 1 1 1		
jal	rd, pcrel.21	Jump And Link	J			imm[20:10] 11 19:12]		rd		1 1 0 1 1 1 1		
jalu	rd, imm(rs1)	Jump And Link Register	I			imm[11:0]	rs1	rd		1 1 0 0 1 1 1		
beq	rs1, rs2, pcrel.13	Branch Equal	B			imm[12:10:5]	rs2	rs1	imm[4:1] 11]	1 1 0 0 0 1 1		
bne	rs1, rs2, pcrel.13	Branch Not Equal	B			imm[12:10:5]	rs2	rs1	imm[4:1] 11]	1 1 0 0 0 1 1		
blt	rs1, rs2, pcrel.13	Branch Less Than	B			imm[12:10:5]	rs2	rs1	imm[4:1] 11]	1 1 0 0 0 1 1		
bge	rs1, rs2, pcrel.13	Branch Greater or Equal	B			imm[12:10:5]	rs2	rs1	imm[4:1] 11]	1 1 0 0 0 1 1		
bltu	rs1, rs2, pcrel.13	Branch Less Than Unsigned	B			imm[12:10:5]	rs2	rs1	imm[4:1] 11]	1 1 0 0 0 1 1		
bgeu	rs1, rs2, pcrel.13	Branch Greater or Equal Unsigned	B			imm[12:10:5]	rs2	rs1	imm[4:1] 11]	1 1 0 0 0 1 1		
lb	rd, imm(rs1)	Load Byte	I			imm[11:0]		rd		0 0 0 0 0 1 1		
lh	rd, imm(rs1)	Load Halfword	I			imm[11:0]		rd		0 0 0 0 0 1 1		
lw	rd, imm(rs1)	Load Word	I			imm[11:0]	rs1	rd		0 0 0 0 0 1 1		
lbu	rd, imm(rs1)	Load Byte Unsigned	I			imm[11:0]	rs1	rd		0 0 0 0 0 1 1		
lhu	rd, imm(rs1)	Load Halfword Unsigned	I			imm[11:0]	rs1	rd		0 0 0 0 0 1 1		
sb	rs2, imm(rs1)	Store Byte	S			imm[11:5]	rs2	rs1	imm[4:0]	0 1 0 0 0 1 1		
sh	rs2, imm(rs1)	Store Halfword	S			imm[11:5]	rs2	rs1	imm[4:0]	0 1 0 0 0 1 1		
sw	rs2, imm(rs1)	Store Word	S			imm[11:5]	rs2	rs1	imm[4:0]	0 1 0 0 0 1 1		
addi	rd, rs1, imm	Add Immediate	I			imm[11:0]	rs1	rd		0 0 1 0 0 1 1		
slli	rd, rs1, imm	Set Less Than Immediate	I			imm[11:0]	rs1	rd		0 0 1 0 0 1 1		
sltiu	rd, rs1, imm	Set Less Than Immediate Unsigned	I			imm[11:0]	rs1	rd		0 0 1 0 0 1 1		
xori	rd, rs1, imm	Exclusive Or Immediate	I			imm[11:0]	rs1	rd		0 0 1 0 0 1 1		
ori	rd, rs1, imm	Or Immediate	I			imm[11:0]	rs1	rd		0 0 1 0 0 1 1		
andi	rd, rs1, imm	And Immediate	I			imm[11:0]	rs1	rd		0 0 1 0 0 1 1		
slli	rd, rs1, shamt	Shift Left Logical Immediate	I	0 0 0 0 0 0 0	shamt		rs1	rd		0 0 1 0 0 1 1		
srl	rd, rs1, shamt	Shift Right Logical Immediate	I	0 0 0 0 0 0 0	shamt		rs1	rd		0 0 1 0 0 1 1		
srai	rd, rs1, shamt	Shift Right Arithmetic Immediate	I	0 1 0 0 0 0 0	shamt		rs1	rd		0 0 1 0 0 1 1		
add	rd, rs1, rs2	Add	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
sub	rd, rs1, rs2	Subtract	R	0 1 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
sll	rd, rs1, rs2	Shift Left Logical	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
slt	rd, rs1, rs2	Set Less Than	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
sltu	rd, rs1, rs2	Set Less Than Unsigned	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
xor	rd, rs1, rs2	Exclusive Or	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
srl	rd, rs1, rs2	Shift Right Logical	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
sra	rd, rs1, rs2	Shift Right Arithmetic	R	0 1 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
or	rd, rs1, rs2	Or	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
and	rd, rs1, rs2	And	R	0 0 0 0 0 0 0	rs2	rs1	rs1	rd		0 1 1 0 0 1 1		
ecall		Trap to Debugger	I	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	1 1 1 0 0 1 1		
ebreak		Trap to Operating System	I	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0	1 1 1 0 0 1 1		
crrw	rd, csr, rs1	Atomic Read/Write	I			csr[11:0]	rs1	rd		1 1 1 0 0 1 1		
crrs	rd, csr, rs1	Atomic Read and Set	I			csr[11:0]	rs1	rd		1 1 1 0 0 1 1		
crrc	rd, csr, rs1	Atomic Read and Clear	I			csr[11:0]	rs1	rd		1 1 1 0 0 1 1		
crrwi	rd, csr, zimm	Atomic Read/Write Immediate	I			csr[11:0]	zimm[4:0]	rd		1 1 1 0 0 1 1		
crrsi	rd, csr, zimm	Atomic Read and Set Immediate	I			csr[11:0]	zimm[4:0]	rd		1 1 1 0 0 1 1		
crrci	rd, csr, zimm	Atomic Read and Clear Immediate	I			csr[11:0]	zimm[4:0]	rd		1 1 1 0 0 1 1		

