```
_start:                    # execution star
        li $a0,9
```

Introduction to RISC Assembly Language Programming

```
        jal fib            # call fib
        move $a0,$v0  # print result
        li $v0, 1
        syscall
```

John Waldron

```
        la $v0,endl
        li $v0,4
        syscall

        li $v0,10
        syscall            # au revoir...
```

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Introduction to RISC Assembly Language Programming

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Preface

This book is based on a one-semester introductory computer architecture course for first-year computing students in the School of Computer Applications, Dublin City University, using SPIM, a virtual machine that runs programs for the MIPS R2000/R3000 computers. The architecture of the MIPS is an ideal example of a simple, clean RISC (Reduced Instruction Set Computer) machine, which makes it easy to learn and understand. The processor contains 32 general-purpose registers and a well-designed instruction set. The existence of a simulator for the processor greatly simplifies the development and debugging of assembly language programs. For these reasons, MIPS is the preferred choice for teaching computer architecture in the 2000s, just as the Motorola 68000 was during the 1980s.

The material assumes that the reader has never studied computer programming before, and is usually given at the same time as a programming course in a high-level language like Java or C. The main data structures covered are strings, arrays and stacks. The ideas of program loops, `if` statements, procedure calls and some recursion are presented. The philosophy behind the book is to speed up the learning process relative to other MIPS architecture books by enabling the reader to start writing simple assembly language programs early, without getting involved in laborious descriptions of the trade-offs involved in the design of the processor. The most successful approach to computer architecture is to begin by writing numerous small assembly language programs, before going on to study the underlying concepts. Thus this text does not address topics such as logic design or boolean algebra, but does contain example programs using the MIPS logical instructions. While processors like the MIPS were designed for high-level language compilation and as such are targeted at compilers rather than human programmers, the only way to gain an appreciation of their functionality is to write many programs for the processor in assembly language.

The book is associated with an automatic program testing system (Mips Assembly Language Exam System) which allows a lecturer to set assembly language programming questions and collect and mark the assignments automatically, or a reader to test a MIPS assembly language program against several different cases and determine whether it works, as described in Appendix A. The exam system is written as a collection of Unix C shell scripts. If the instructor or student does not wish to adopt this learning approach, the textbook can be used in a traditional manner. A student who can write an assembly language program which converts a number to an ASCII string in hexadecimal format under exam conditions has demonstrated a thorough understanding of all the principles of introductory computer architecture. There is little point in describing concepts such as pipelining, delayed branches of advanced compiler topics to students who are not yet familiar with simple program loops.

Assembly language programming is usually considered an arcane and complex discipline. This view arises among those whose first experience of assembly language programming was the instructions and registers of architectures like the Intel 8086 family. Programming in a RISC architecture is very different due to the elegant, compact and simple instruction set. Students of this text who have never programmed before and begin to study it simultaneously with a course on C programming report it is easier and more logical to program in assembly! In addition, because of the programming exam system, there is a higher pass rate and level of proficiency achieved by students on the assembly course than on the more traditional C course.

The SPIM simulator is available in the public domain from the University of Wisconsin Madison at `ftp://ftp.cs.wisc.edu/pub/spim/`. Overhead projector slides of lecture notes, all example programs and all exam questions are available from `http://www.compapp.dcu.ie/~jwaldron`. The programs that correct the questions, together with test cases and solutions, are available to lecturers adopting the course.

The SPIM simulator software was designed and written by James R. Laurus (laurus@cs.wisc.edu). This book was partly inspired by John Conry's course at the University of Oregon which he has made available on the Internet. I would like to thank him for permission to use some of his example programs and material. Thanks to Dr David Sinclair for reading an early draft and providing many important suggestions. Also thanks to Karen Sutherland and Keith Mansfield at Addison Wesley Longman.

John Waldron, Dublin
July 1998

Contents

CHAPTER 1

Introduction

After describing basic computer organization, this chapter introduces assembly language, explains what it is and what it is used for. The reasons the reader should study assembly language are discussed. Finally, an outline of the remaining chapters in the book is given.

1.1 BASIC COMPUTER ORGANIZATION

The gates and flip-flops that collectively constitute the computer are built so that they can only assume one of two values or states called on and off. Each element of the computer can therefore represent only the values zero or one. Each one or zero is called a binary digit, or bit. The integrated circuits in a typical computer can be organized into three categories – the processor, the memory, and those connecting to various input output (I/O) devices such as disks or keyboards, as shown in Figure 1.1. The bus connects the integrated circuits together.

The processor is an integrated circuit that is the basic functional building block of the computer. It follows the fetch–execute cycle, repeatedly reading simple instructions, such as to add two numbers or move a number, from the memory and executing them as shown in Figure 1.2. The processor consists of:

- a data path, which performs arithmetic operations
- control, which tells the memory, I/O devices and data path what to do according to the wishes of the instructions of the program
- a small high-speed memory (registers) used to store temporary results and certain control information.

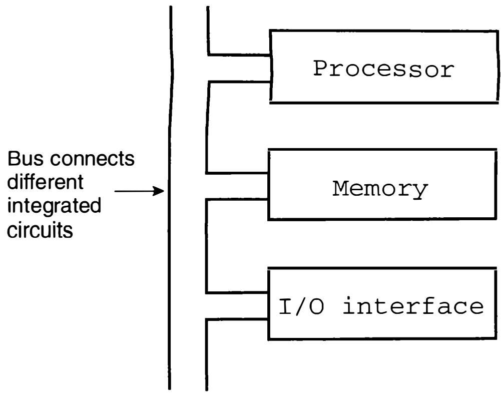


Figure 1.1 Integrated circuits in a computer.

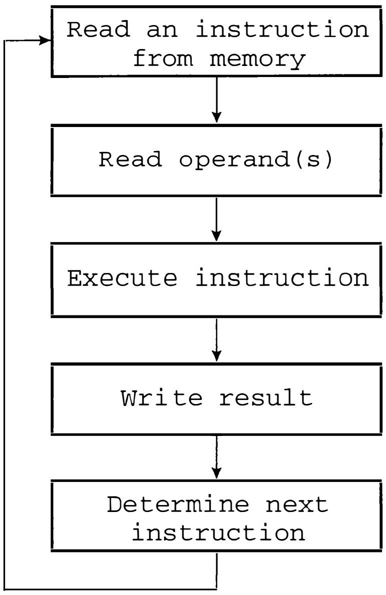


Figure 1.2 Fetch–execute cycle.

Electrically connected to the processor chip is the memory. Memory can be of various sizes, usually measured in multiples of megabytes or millions of bytes, where a byte is a group of eight bits. Also connected to the processor are I/O devices that allow the processor to communicate with the outside world through screens, keyboards and other information storage devices such as floppy disks or CD-ROMs.

All information in the memory and the processor registers must be represented by numbers. This includes the actual instructions themselves, as well as the information they operate on. The instructions of the processor manipulate numeric information in a variety of ways. Data can be moved from registers to memory or memory to registers. Data in registers is like data in memory, except that it can be accessed much faster. Data must be brought into registers for arithmetic operations such as addition, subtraction, multiplication and division, together with logical operations that allow manipulation of individual bits of information.

Some instructions do not manipulate data but are used to control the flow of a program, allowing an operation to be repeated several times for example.

1.2 MACHINE LANGUAGE

All instructions the processor executes are encoded as strings of bits and stored in the memory. If you write your programs directly in binary, using the encoding of instructions understood by the processor, you are writing in machine language. It's very tedious, and never done in practice.

1.3 ASSEMBLY LANGUAGE

A slightly more abstract version of machine language is assembly language. The term is a very old one – it goes back to the 1940s and 1950s when all programming was done in this sort of language. An assembler was a program that took symbols written by the programmer and assembled the final machine language program to be executed by the processor. There is usually a one-to-one correspondence between assembly language statements and machine language instructions. Instead of the binary pattern used in machine language, the assembly language programmer can write

```
add r0,r2,r3
```

to mean add the contents of registers two and three and put the result in register zero.

Assembly language provides other abstractions as well:

- labels on pieces of code; for example, if you write a subroutine (also known as a procedure) you can call it by name and use an instruction of the form `call printf` instead of something like 001010111100, which requires you to know the address of the procedure
- labels on variable names, with the same benefits as labels on code
- special assembly language instructions, called directives, that help you define data structures like strings and arrays.

An assembler can also hide many messy machine details from programmers. For example, the assembler can give the illusion that there are many more instructions in the processor than there really are, by providing pseudo-instructions which consist of several machine instructions, removing the one-to-one correspondence between assembly language and machine language instructions.

1.4 WHY PROGRAM IN ASSEMBLY LANGUAGE?

The most common reason to program in assembly language is that it is the best way to gain an understanding of how the processor and computer works at the lower levels. Apart from this it is generally better not to program in assembly language if you can do the same job in a high-level language like C and use a compiler to turn high-level language statements into sequences of machine instructions, as shown in Figure 1.3. Assembly language has the following disadvantages:

- Assembly language is not as tedious as machine language, but it is still error-prone and slow – the source code of programs is three or more times as long as corresponding programs in a high-level language such as C, and experience shows that people can write programs at a constant number of lines per day no matter what the language, so it will take three times as long to write the assembly language version. Also, the probability of introducing a bug is proportional to the length of the program.
- Assembly language is machine-dependent, so that a program written for a SPARC workstation (Sun) will have to be completely rewritten for DEC, SGI or IBM workstations. Assembly language programs are not portable.

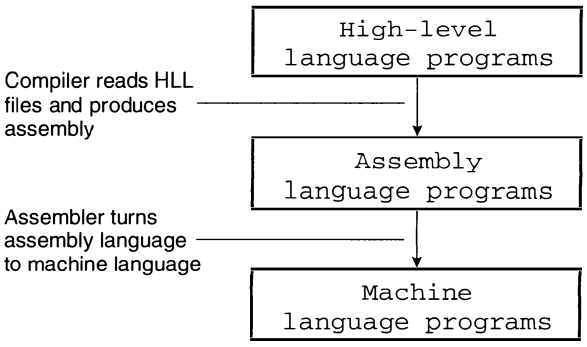

High-level language programs
Compiler reads HLL files and produces assembly
Assembly language programs
Assembler turns assembly language to machine language
Machine language programs

Figure 1.3 High-level languages.

- An assembly language program does not execute much faster than a high-level language program because compilers are getting to be very good, especially for machines with messy user-unfriendly features.

  Sometimes assembly language is necessary:

- A special function inside the innermost loop of a critical program might be coded in assembly language.
- Assembly language may be best for embedded systems that have very little memory or a crucial timing problem where you need to know exactly how many machine cycles an operation will take.
- A few machine-specific operations in an operating system kernel must be coded in assembly.
- There are a large number of existing programs written in assembly language that need to be maintained and updated. A major UK airline's booking system is said to be written entirely in assembly language and that company places great value on those with assembly language programming skills.

When you do have to use assembly language, try to do it via a high-level language. Many C compilers will allow you to embed assembly language code in the middle of a C program, writing the body of a procedure in assembly language.

It is very important to learn assembly language programming because:

- When you program in a high-level language, it is essential to understand the underlying machine instructions when debugging your program.
- To write a compiler, it is necessary to be familiar with assembly language.
- People who design and build processors need to understand assembly language instruction sets.

In conclusion, the assembly language instruction set defines the interface between the hardware and the software and underlies all the functioning of a computer, so that a thorough appreciation of this topic is essential for any student of computer science or electronic engineering. It is this level of understanding that differentiates a computing graduate from say a maths or business student that has learnt to program.

1.5 OUTLINE OF CHAPTERS

Chapter 2 gives some essential background information needed before studying assembly language programming. Hexadecimal, decimal and binary numbers are explained. The way in which addition and subtraction are carried out on these numbers, together with the representation of negative numbers, is discussed. Also covered is the ASCII character code used to store characters in a computer's memory. An understanding of these concepts is essential before programming in any computer language, because all digital computers ultimately consist of large numbers of on/off switches.

Chapter 3 does not describe every detail of the MIPS processor, but gives enough information about memory and internal MIPS registers to allow simple assembly language programs to be written. The XSPIM simulator is introduced. A deeper understanding of the concepts introduced in this chapter will be developed as later chapters expand on them. It is necessary to have an idea of the architecture of the MIPS processor if one is to program it in assembly language.

Chapter 4 begins by outlining the syntax used in a MIPS assembly language program. It then considers a simple example program. The instructions used in this program are introduced. The XSPIM programming tool is then described. Detailed instructions for executing the example program using XSPIM are given. Additional simple load, store and arithmetic instructions are introduced, together with some example programs illustrating their use.

Chapter 5 looks at a program `length.a` that uses a program loop to work out the length of a character string. Familiarity with a few assembly language instructions, such as basic load, store and simple arithmetic operations, is needed, together with the concept of program loops. A program loop allows an operation to be repeated a number of times, without having to enter the assembly language instructions explicitly. For example, to sum up 50 numbers, one would not have 50 add instructions in the program but instead would have the add instruction once and go round a loop 50 times.

For any given operation, such as load, add or branch, there are often many different ways to specify the address of the operand(s). The different ways of determining the address are called addressing modes. Chapter 6 looks at the different addressing modes of the MIPS processor and shows how all instructions can fit into a single four-byte word. Some sample programs are included to show additional addressing modes in action.

Chapter 7 first looks at shift and rotate instructions. It then considers logical instructions, showing in an example program how these instructions can be used to convert a decimal number to an ASCII string in hexadecimal format. Logical, shift and rotate instructions are all used to manipulate the individual bits of a word.

Chapter 8 first introduces the stack data structure, and then illustrates its usage with a program to reverse a string using a stack. The techniques to support procedure calls in MIPS assembly language are then studied. Procedures allow programs to be broken into smaller, more manageable, units. They are fundamental to the development of programs longer than a few dozen statements. Procedures allow the reuse of the same group of statements many times by referring to them by name rather than repeating the code. In addition, procedures make large programs easier to read and understand. Stack frames, needed to implement procedure calls, are discussed. Two recursive programs are given that calculate Fibonacci's series and solve the Towers of Hanoi problem, and example code from a real compiler is discussed.

Appendix A describes the MIPS programming exam system. Appendix B is a SPIM MIPS instruction quick reference, sorted by instruction type. Appendix C is a more complete instruction reference in alphabetic order.

1.6 SUMMARY

Each element of the computer can represent only the values zero or one. The processor follows the fetch–execute cycle repeatedly reading simple instructions, such as to add two numbers or move a number, from the memory and executing them. All instructions that the processor executes are encoded as strings of bits, called machine language, and stored in the memory. An assembler is a program that takes symbols written by the programmer and assembles the final machine language program to be executed by the processor. The source code of assembly language programs is three or more times as long as corresponding high-level language programs. The assembly language instruction set defines the interface between the hardware and the software and underlies all the functioning of a computer so that a thorough appreciation of this topic is essential for any student of computer science or electronic engineering.

EXERCISES

1.1 What is register?
1.2 What does a processor do?
1.3 What do integrated circuits consist of?
1.4 Describe the principal integrated circuits in a computer.
1.5 Describe the relationship between machine language and assembly language.
1.6 What are the advantages of programming in assembly language over machine language?
1.7 When should assembly language be used?

CHAPTER 2

Essential background information

2.1 INTRODUCTION

This chapter gives some essential background information needed before studying assembly language programming. Hexadecimal, decimal and binary numbers are explained. The way in which addition and subtraction are carried out on these numbers, together with the representation of negative numbers, is discussed. Also covered is the ASCII character code used to store characters in a computer's memory. An understanding of these concepts is essential before programming in any computer language, because all digital computers ultimately consist of large numbers of on/off switches.

2.2 DECIMAL AND BINARY NUMBERS

Many different systems have been used to represent numbers throughout history. The Babylonians had a method of counting based on the number 60, and the effects of this can still be seen in measurements of time and angles. Our present system, of course, is based on the number of fingers on the human hand and is callcd thc dccimal numbcr system, or base 10.

In the decimal number system, each digit's position represents a different power of 10. For example, the number 169 is equivalent to

$$1 \times 10^2 + 6 \times 10^1 + 9 \times 10^0$$

All digital computers use base 2, known as the binary system, for numerical quantities rather than base 10. Binary numbers are based on

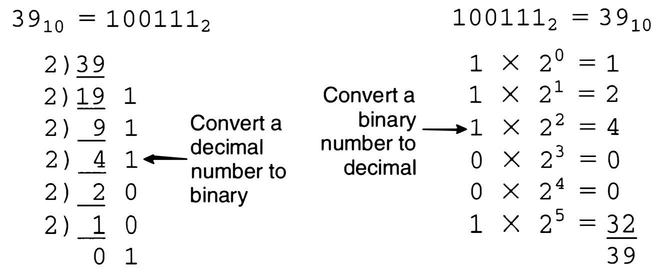


Figure 2.1 Conversion between binary and decimal numbers.

powers of 2 rather than on powers of 10. The number 1101 in the binary number system is equivalent to

$$1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$

The method of converting a binary number to decimal is straightforward and is shown in Figure 2.1. It involves adding up the powers of two everywhere the corresponding binary position contains a one.

Converting a decimal number to binary is not quite as simple. The way to do this is to divide the original decimal number by two and check the remainder. If the remainder is one, a binary one is generated. If it is zero, a binary zero is produced. This division by two is repeated until a zero quotient is obtained, as illustrated in Figure 2.1. This process yields the bits of the answer in reverse order.

Converting between decimal and binary is needed because humans think about numbers in decimal, but numbers will be stored as a sequence of bits in the computer.

2.3 HEXADECIMAL NUMBERS

Hexadecimal numbers, or hex for short, use base 16 to represent numerical quantities. Each hex digit can take on 16 values, which means that six extra symbols are needed on top of the `0` to `9` used for decimal. As shown in Figure 2.2 the letters `A` through `F` are used to represent the additional values 10 to 15. Lower-case `a` through `f` are also sometimes used with the same meaning. This book follows the convention of putting `0x` before a number to indicate it is in hexadecimal format. The methods for converting between the hex and decimal number systems are also shown in Figure 2.2. The techniques for converting are the same as those illustrated in Figure 2.1 for the binary system.

The disadvantage of binary numbers is that once the number gets large, it becomes very tedious to write out a long string of ones and zeros. The advantage of binary is that it is possible to see by inspection how many bits

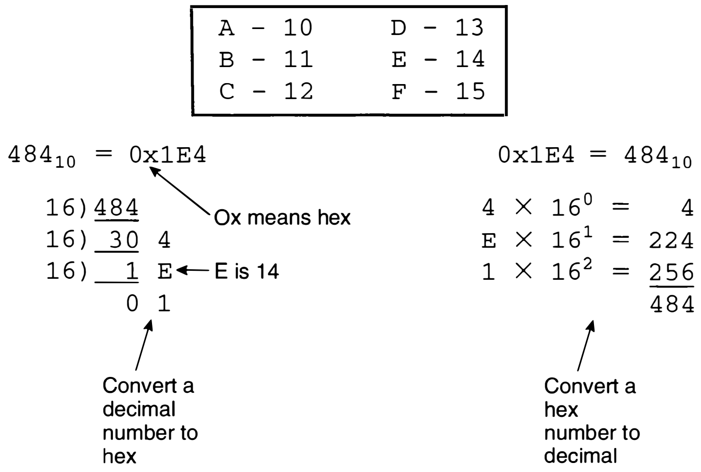


Figure 2.2 The hexadecimal number system.

are occupied by the number when stored in the computer, and which bits are set or cleared (i.e. one or zero). This would not be obvious if the number was in base 10. Even large hex numbers are short to write out, yet it is still possible to see by inspection how many bits are occupied by the number, and which bits are set or cleared. A nice property of hexadecimal numbers is that they can be converted to binary by inspection, as shown in Figurc 2.3. Since

$$2^4 = 16$$

there is a simple relationship between numbers in base 2 and in base 16. Four binary digits grouped together represent one hexadecimal digit.

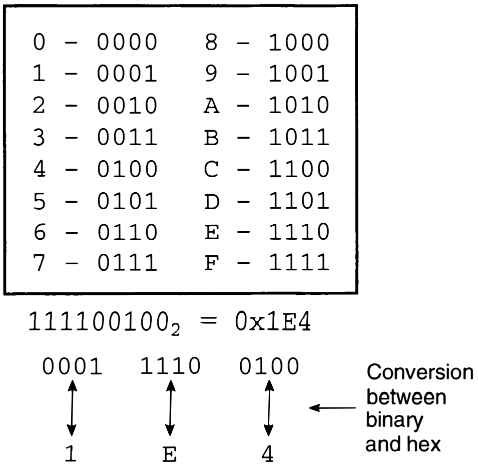


Figure 2.3 Conversion between binary and hexadecimal numbers.

2.4 BINARY ADDITION

The rules for addition of numbers in base 2 are simple, as shown in Figure 2.4. To add numbers in any base, if the sum of two digits equals or exceeds the number base, a carry is generated. The value of the carry is 1.

2.5 TWO'S COMPLEMENT NUMBERS

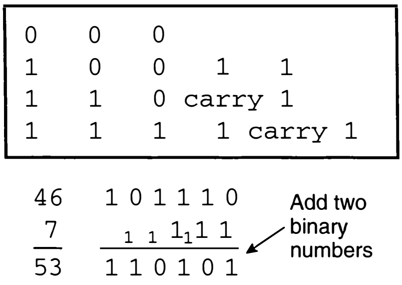
The discussion so far has only dealt with positive numbers. What about negative numbers and subtraction? Numeric quantities in a computer are normally restricted to fixed sizes, for example eight bits or 32 bits. It is not practical to append an extra sign bit, indicating plus or minus, to a fixed unit such as a byte. A better solution is to sacrifice one of the bits in a byte to indicate the sign of the number. The size of the largest number that can be represented is reduced, but both positive and negative numbers can now be represented.

All modern computers use the two's complement representation for negative numbers. The method of converting a decimal number to two's complement form is shown in Figure 2.5. If the number is positive, convert it to binary and fill out the most significant bits with zeros. If the number is negative, get the positive two's complement representation and multiply the number by −1. It is very easy to multiply a two's complement number by −1, thus changing its sign. The steps are (Figure 2.5):

- convert all the zero bits to one and all the one bits to zero
- add one to this number.

The sign bit or leftmost bit is used to indicate whether a number is positive or negative. By convention, if a numerical quantity is negative, the sign bit of the number is one. In two's complement form, if the number is negative and begins with a leading one, the remaining bits do not directly indicate the magnitude. Positive numbers begin with a zero and the other bits are the magnitude.

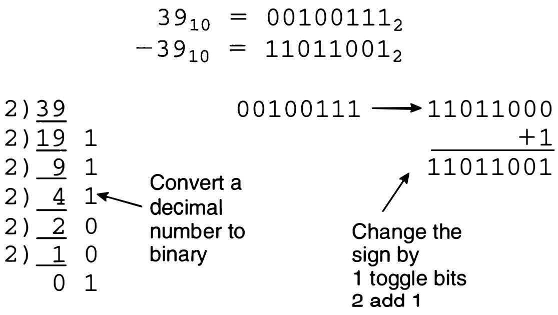
The two's complement method of representing numbers can be visualized as being arranged in a wheel as shown in Figure 2.6. Going clockwise increases a number, which means that adding numbers to a negative numbcr causcs thc rcsult to move in the direction of zero. The reason two's complement has been universally adopted is that the addition rules in Figure 2.4 can be used without concern for the sign of either number and still give the correct result. When the computer wishes to do subtraction involving two's complement numbers, it changes the sign of the subtrahend using the steps above and does an ordinary addition, as illustrated in Figure 2.7.



```
0   0   0
1   0   0   1   1
1   1   0 carry 1
1   1   1   1 carry 1
```

```
46    1 0 1 1 1 0
 7      1 1 1₁1 1
--    -----------
53    1 1 0 1 0 1
```

Figure 2.4 Addition of numbers in base 2.



$$39_{10} = 00100111_2$$
$$-39_{10} = 11011001_2$$

```
2)39
2)19  1
2) 9  1
2) 4  1
2) 2  0
2) 1  0
   0  1
```

```
00100111 ——→ 11011000
                   +1
             --------
             11011001
```

Figure 2.5 Eight-bit two's complement representation of numbers.

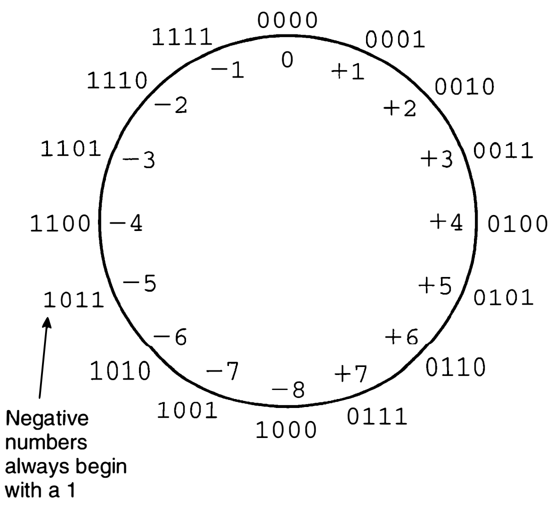


Figure 2.6 Two's complement wheel.

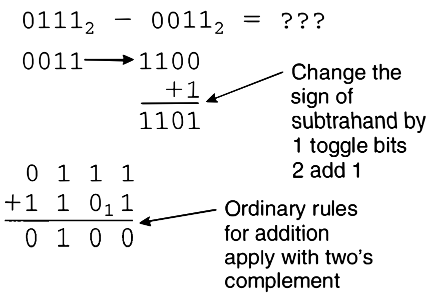

0111₂ − 0011₂ = ???
0011 → 1100
+1
1101
Change the sign of subtrahand by 1 toggle bits 2 add 1
0 1 1 1
+1 1 0₁ 1
0 1 0 0
Ordinary rules for addition apply with two's complement

Figure 2.7 Subtraction of two's complement numbers.

2.6 BITS, BYTES AND NIBBLES

As mentioned above, the gates and flip-flops that collectively constitute the computer are built so that they can only assume one of two values or states. Bits in a computer are grouped together so that the internal representations of numbers are restricted to certain sizes. Nearly all computers are organized around groups of eight bits, called a byte or sometimes an octet. Four bytes grouped together are called a word. Confusingly on some older computers, two bytes are called a word. A nibble, four bits, is half a byte and can be described by one hex digit. There are 2^n different combinations of n bits. For example there are $2^8 = 256$ combinations that can be held in one byte. If the patterns are regarded as positive or unsigned numbers then the numbers run from 0 to $2^8 - 1 = 255$.

If the byte is holding signed numbers in two's complement format the numbers can range from -2^{n-1} to $+2^{n-1} - 1$. For example, in Figure 2.6, $n = 4$ and the 16 numbers range from -8 to $+7$.

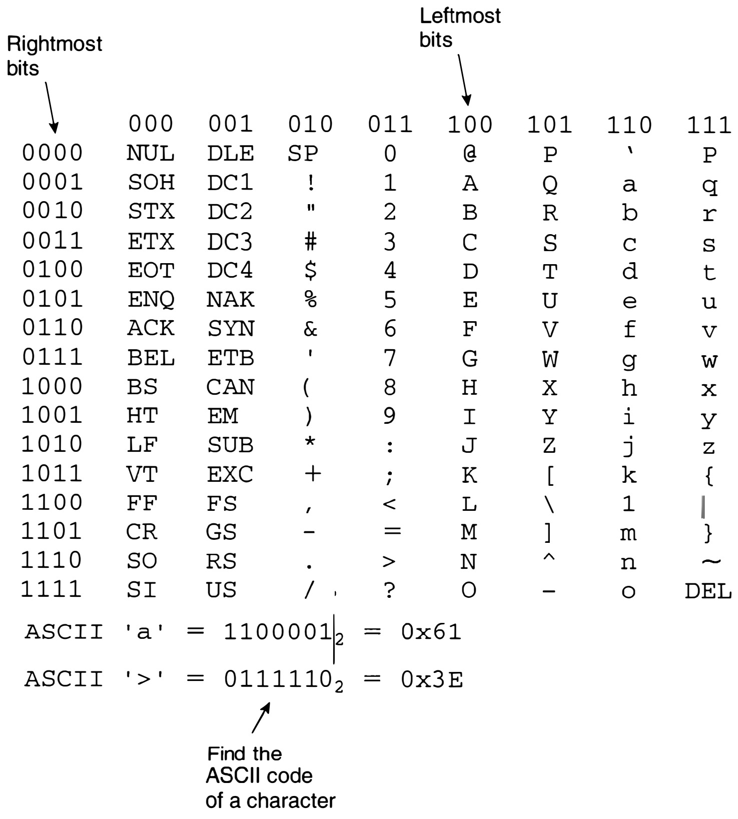
2.7 STORING CHARACTERS

In order to represent character information in the computer's memory, the character set must be converted to numeric values. Two standard codes are used for this:

- ASCII: American Standard Code for Information Interchange
- EBCDIC: Extended Binary-Coded Decimal Interchange Code.

All microcomputers use the ASCII code (Figure 2.8) and EBCDIC is typically used by IBM mainframes.

Upper- and lower-case alphabetic characters, the digits 0 through 9 and the common punctuation marks are sufficient for many purposes – about a hundred characters in all. The ASCII code uses the values 0 to 127, corresponding to seven of the eight bits in a byte. The ASCII codes 0


Leftmost bits
Rightmost bits
Find the ASCII code of a character

	000	001	010	011	100	101	110	111
0000	NUL	DLE	SP	0	@	P	`	P
0001	SOH	DC1	!	1	A	Q	a	q
0010	STX	DC2	"	2	B	R	b	r
0011	ETX	DC3	#	3	C	S	c	s
0100	EOT	DC4	$	4	D	T	d	t
0101	ENQ	NAK	%	5	E	U	e	u
0110	ACK	SYN	&	6	F	V	f	v
0111	BEL	ETB	'	7	G	W	g	w
1000	BS	CAN	(	8	H	X	h	x
1001	HT	EM	)	9	I	Y	i	y
1010	LF	SUB	*	:	J	Z	j	z
1011	VT	EXC	+	;	K	[	k	{
1100	FF	FS	,	<	L	\	1	‖
1101	CR	GS	-	=	M	]	m	}
1110	SO	RS	.	>	N	^	n	~
1111	SI	US	/	?	O	–	o	DEL

ASCII 'a' = 1100001_2 = 0x61

ASCII '>' = 0111110_2 = 0x3E

Figure 2.8 ASCII character codes.

through 31 are reserved for special non-printing codes. These include CR (carriage return), LF (line feed) and HT (horizontal tab). Other ASCII codes in the range 0 through 31 are used for various purposes such as data communication protocols.

The Unicode Standard is a new international standard used to encode text for computer processing. Its design is based on the simplicity and consistency of ASCII, but goes far beyond ASCII's limited ability to encode only the Latin alphabet. The Unicode Standard provides the capacity to encode all of the characters used for the major written languages of the world. To accommodate the many thousands of characters used in international text, the Unicode Standard uses a 16-bit code set that provides codes for more than 65 000 characters. To keep character coding simple and efficient, the Unicode Standard assigns each character a unique 16-bit value. Mathematicians and technicians, who regularly use mathematical symbols and other technical characters, also find the Unicode Standard valuable.

2.8 SUMMARY

In the decimal number system, each digit's position represents a different power of 10, whereas binary numbers are based on powers of 2. The disadvantage of binary numbers is that once the number gets large, it becomes very tedious to write out a long string of ones and zeros. Hexadecimal, or hex for short, uses base 16 to represent numerical quantities because it is easy to switch between binary and hex. To add numbers in any base, if the sum of two digits equals or exceeds the number base, a carry is generated. The value of the carry is 1. All modern computers use the two's complement representation for negative numbers. In order to represent character information in the computer's memory, the characters can be converted to numeric values using the ASCII code.

EXERCISES

2.1 How is 300_{10} stored in binary?
2.2 Is bit six set or cleared when 300_{10} is stored in binary?
2.3 How many bits are required to store 300_{10} in binary?
2.4 What is 300_{10} in hex?
2.5 Write down the eight-bit two's complement binary representation of -78.
2.6 Write down the 32-bit two's complement representation of -32 in hexadecimal notation.
2.7 Show the steps involved when a computer subtracts 3 from 5.
2.8 What is the ASCII code for the semicolon?

CHAPTER 3

MIPS computer organization

3.1 INTRODUCTION

This chapter does not describe every detail of the MIPS processor, but gives enough information about memory and internal MIPS registers to allow simple assembly language programs to be written. The XSPIM simulator is introduced. A deeper understanding of the concepts introduced in this chapter will be developed as later chapters expand on them. It is necessary to have an idea of the architecture of the MIPS processor if one is to program it in assembly language.

3.2 THE MIPS DESIGN

In the mid-1970s, a number of studies showed that while theoretically people can write highly complex high-level language programs, most of the code that they actually write consists of simple assignments, `if` statements and procedure calls with a limited number of parameters (together 85 per cent). This is shown in Figure 3.1.

In the early 1980s, a new trend in the design of processors began with the RISC (Reduced Instruction Set Computer) machines. The central idea was that by speeding up the commonest simple instructions, one could afford to pay a penalty in the unusual case and make a large net gain in performance. In contrast CISC (Complex Instruction Set Computer) chips can execute many complicated instructions, at the expense of slowing down the simplest ones.

In 1980, a group at Berkeley, led by David Patterson and Carlo Sequin, began designing RISC chips. They coined the term RISC and named their

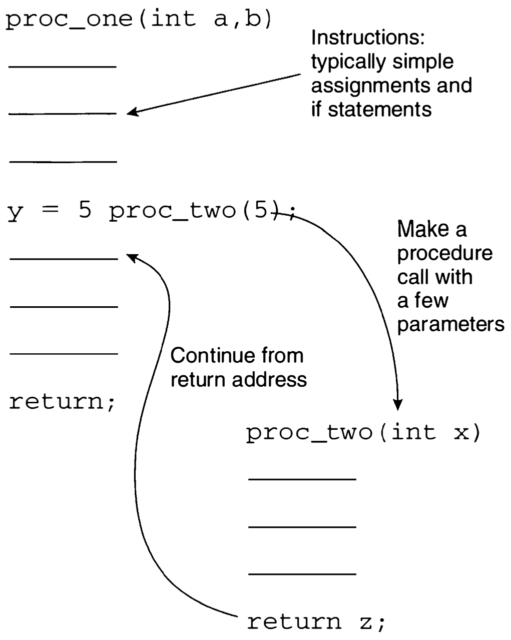

proc_one(int a,b)
Instructions: typically simple assignments and if statements
y = 5 proc_two(5);
Make a procedure call with a few parameters
Continue from return address
return;
proc_two(int x)
return z;

Figure 3.1 Typical high-level language program.

processor RISC1. Slightly later, in 1981, across the San Francisco Bay at Stanford, John Hennessy designed and fabricated a somewhat different RISC chip which he called the MIPS (Microprocessor without Interlocking Pipeline Stages), a play on the MIPS performance measurement.

MIPS processors are quite powerful, and are the heart of the capabilities of SGI's graphics servers and workstations, which were used to produce the special effects in many Hollywood movies (for example the new version of *Star Wars*, *Jurassic Park* and *Toy Story*). MIPS processors are also used in the Nintendo 64 game machine. Because of its use in high-performance embedded systems, it is estimated that MIPS currently sells more microprocessors than Intel.

3.3 MEMORY LAYOUT

Memory consists of a number of cells, each of which will hold one eight bit number or byte. Memory cells arc numbered starting at zero up to the maximum allowable amount of memory (Figure 3.2). Programs consist of instructions and data. Careful organization is required to prevent the computer interpreting instructions as data or vice versa, since everything in the memory is stored as groups of bits.

The organization of memory in MIPS systems is conventional. A program's address space is composed of three parts (see Figure 3.3).

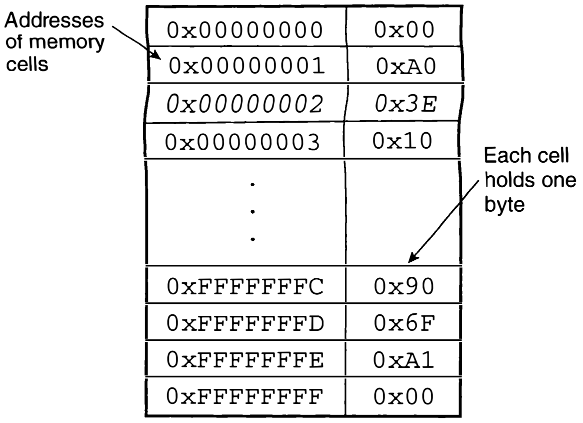


Figure 3.2 Memory organization.

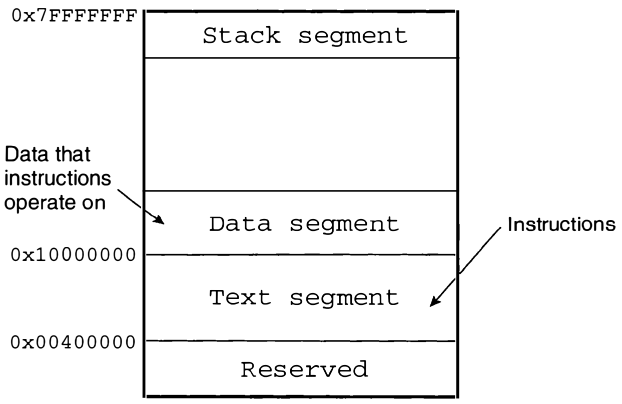


Figure 3.3 MIPS memory layout.

At the bottom of the user address space (0x400000) is the text segment, which holds the instructions for a program. Above the text segment is the data segment, starting at 0x10000000. The stack is a last in, first out queue which is needed to implement procedures, allowing programmers to structure software to make it easier to understand and reuse (see Chapter 8). The program stack resides at the top of the address space (0x7fffffff). It grows down, towards the data segment.

3.4 THE MIPS REGISTERS

The processor's memory consists of a number of registers, each of which has a certain function. The most important register is the program counter (PC) which points to, or holds the memory address of, the next instruction to be executed.

The MIPS (and SPIM) processor contains 32 general purpose registers that are numbered 0–31. Register *n* is designated by `$n`, or R*n*. Register `$0` always contains the hardwired value 0. MIPS has established a set of conventions as to how registers should be used. These suggestions are guidelines, which are not enforced by the hardware. However, a program that violates them will not work properly with other software. Table 3.1 lists the commonly used registers and describes their intended use. These MIPS registers, as seen using the XSPIM programming tool, are shown in Figure 4.5.

The conventions for the use of the registers will become clear when we study assembly language support for procedure calls in Chapter 8. Registers `$at` (1), `$k0` (26) and `$k1` (27) are reserved for use by the assembler and operating system. Registers `$a0`–`$a3` (4–7) are used to pass the first four arguments to procedures (remaining arguments are passed on the stack). Registers `$v0` and `$v1` (2, 3) are used to return values from procedures. Registers `$t0`–`$t9` (8–15, 24, 25) are called saved registers and are used for temporary quantities that do not need to be preserved when a procedure calls another that may also use these registers. In contrast, registers `$s0`–`$s7` (16–23) are called saved registers and hold long-lived values that will need to be preserved across calls. Register `$sp` (29) is the stack pointer, which points to the last location in use on the stack. Register `$fp` (30) is the frame pointer. A procedure call frame is an area of memory used to hold various information associated with a procedure, such as arguments, saved registers and local variables, as discussed in Chapter 8. Register `$ra` (31) is written with the return address when a new procedure is called. Register `$gp` (28) is a global pointer that points into the middle of a 64K block of memory that holds constants and global variables. The objects in this part of memory can be quickly accessed with a single load or store instruction.

Table 3.1 MIPS registers and the convention governing their use.

Register name	Number	Usage
zero	\$0	Constant 0
`$at`	\$1	Reserved for assembler
`$v0-$v1`	\$2–\$3	Expression evaluation and results of a function
`$a0-$a3`	\$4–\$7	Argument 1–4
`$t0-$t7`	\$8–\$15	Temporary (not preserved across call)
`$s0-$s7`	\$16–\$23	Saved temporary (preserved across call)
`$t8-$t9`	\$24–\$25	Temporary (not preserved across call)
`$k0-$k1`	\$26–\$27	Reserved for OS kernel
`$gp`	\$28	Pointer to global area
`$sp`	\$29	Stack pointer
`$fp`	\$30	Frame pointer
`$ra`	\$31	Return address (used by function call)

The MIPS processor also has 16 floating point registers `$f0...$f15` to hold numbers in floating point form, such as

$$3.459 \times 10^9$$

3.5 THE SPIM SIMULATOR

SPIM is a simulator that runs programs for the MIPS R2000/R3000 RISC computers. SPIM can read and immediately execute files containing assembly language. SPIM is a self-contained system for running these programs and contains a debugger and interface to a few operating system services.

There are many advantages to using a machine simulator like SPIM. MIPS workstations are not generally available, and these machines will not persist for many years because of the rapid progress leading to new and faster computers. Unfortunately, the trend to make computers faster by executing several instructions concurrently makes their architecture more difficult to understand and program in assembly language. Simulators can provide a better environment for low-level programming than an actual machine because they can detect more errors and provide more features than an actual computer.

One method frequently used to study assembly programming is a specially designed circuit board with a processor, memory and various I/O devices. The edit–assemble–load development cycle is much faster with a simulator than downloading assembly programs to a simple microprocessor system. In addition, such systems are prone to hardware problems, which means that the programmer is never sure whether a problem is a bug in the code or due to a hardware problem. With a simulator the possibility of this happening is removed, although there is always the possibility of bugs in the simulator software. Such bugs are easier to detect and fix than intermittent hardware failures.

SPIM has an X-Window interface that is better than most debuggers for the actual machines. The only disadvantage of a simulated machine is that the programs will run slower than on a real machine, although this is not a problem for testing simple workloads.

The Unix version of SPIM provides a simple terminal and an X-Window interface. Both provide equivalent functionality, but the X interface is generally easier to use and more informative. The simulator is available free to users. There are also Macintosh and PC versions of the simulator available in the public domain (see Preface).

3.6 I/O ORGANIZATION

This section explains how input and output (I/O) is organized by the SPIM simulator. A computer would be useless without low-level software running on it. The lowest level software on the computer is the operating system

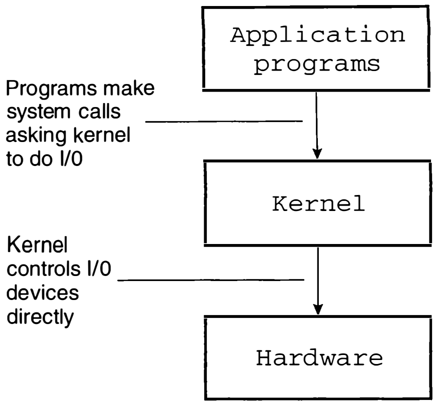

Application programs
Programs make system calls asking kernel to do I/0
Kernel
Kernel controls I/0 devices directly
Hardware

Figure 3.4 Operating system calls.

kernel. Among other things it knows the particular commands that each I/O device understands. An application program asks the kernel to do I/O by making a system call, as shown in Figure 3.4. The kernel implements these system calls by talking directly to the hardware. Typically, an operating system may have hundreds of system calls.

SPIM provides a small set of 10 operating-system-like services through the system call (`syscall`) instruction. In effect, these simulate an extremely simple operating system. To request a service, a program loads the system call code (see Table 3.2) into register `$v0` and the arguments into registers `$a0...$a3` (or `$f12` for floating point values). System calls that return values put their result in register `$v0` (or `$f0` for floating point results). The use of these system calls will be explained and demonstrated in example programs in the following chapters. For example, `print_int` is passed an integer and prints it on the console. `print_float` prints a single floating point number. `read_int` reads an entire line of input up to and including the newline and returns an integer. Characters following the number are ignored. `exit` stops a program from running.

Table 3.2 SPIM's system calls.

Service	Call code	Arguments	Result
`print_int`	1	`$a0` = integer	
`print_float`	2	`$f12` = float	
`print_double`	3	`$f12` = double	
`print_string`	4	`$a0` = string	
`read_int`	5		integer (in `$v0`)
`read_float`	6		float (in `$f0`)
`read_double`	7		double (in `$f0`)
`read_string`	8	`$a0` = buffer, `$a1` = length	
`sbrk`	9	`$a0` = amount	address (in `$v0`)
`exit`	10		

3.7 SUMMARY

RISC machines are based on the idea that by speeding up the commonest simple instructions one could afford to pay a penalty in the unusual case of more complex operations and make a large net gain in performance. Memory consists of a number of cells, each of which will hold one eight-bit number or byte. A program's address space is composed of three parts – the text segment, which holds the instructions for a program, the data segment and the stack segment. The MIPS processor contains 32 general-purpose registers and conventions have been established as to how registers should be used. An application program asks the kernel to do I/O by making system calls which the kernel implements by talking directly to the hardware. SPIM is a simulator that runs programs for the MIPS computers.

EXERCISES

3.1 What is the basic idea behind RISC processors?
3.2 What goes in a text segment?
3.3 What is the purpose of the program counter?
3.4 Discuss the advantages of simulated machines.
3.5 How is I/O organized in SPIM?
3.6 What is the number of the return address register?

CHAPTER 4

An example MIPS program

4.1 INTRODUCTION

This chapter begins by outlining the syntax used in a MIPS assembly language program. It then considers a simple example program. The instructions used in this program are introduced. The XSPIM programming tool is then described. Detailed instructions for executing the example program using XSPIM are given. Additional simple load, store and arithmetic instructions are introduced, together with some example programs illustrating their use.

4.2 SOURCE CODE FORMAT

An assembly program is usually held in a file with `.a` at the end of the filename, for example `hello.a`. This file is processed line by line by the SPIM program. Each line in the source code file can either translate into a machine instruction (or several machine instructions in the case of an assembly pseudo-instruction), can generate data element(s) to be stored in memory, or may provide information to the assembler program.

The file `hello.a` below contains the source code of a program to print out a character string. A string is an example of an array data structure – a named list of items stored in memory as shown in Figure 4.1. A character string is a contiguous sequence of ASCII bytes (Figure 2.8), with a byte whose value is zero used to indicate the end of the string. The following assembly program sets up a string in the data segment. The text segment contains instructions that make a system call to print out the string, followed by a system call to exit the program:

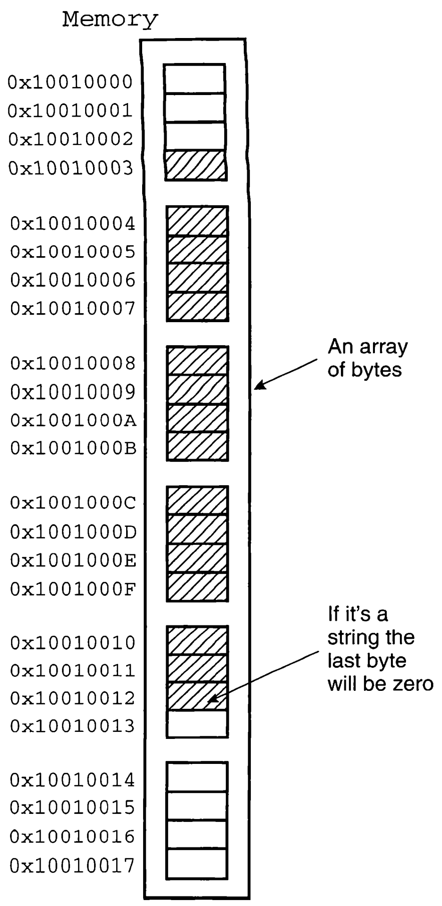


Figure 4.1 An array of bytes stored in memory.

```
##
## hello.a - prints out "hello world"
##
##      a0 - points to the string
##

#################################################
#                                               #
#                 text segment                  #
#                                               #
#################################################

```

```
13           .text
14           .globl __start
15   __start:                 # execution starts here
16           la $a0,str       # put string address into a0
17           li $v0,4         # system call to print
18           syscall          # out a string
19
20           li $v0,10
21           syscall          # au revoir...
22
23
24   ##################################################
25   #                                                #
26   #               data segment                     #
27   #                                                #
28   ##################################################
29
30           .data
31   str:    .asciiz "hello world\n"
32
33   ##
34   ## end of file hello.a
```

Line numbers are only included in the program for the sake of clarity and are not entered when typing in programs. Information in the data segment does not contain instructions that are executed but rather is data used during program execution.

Regardless of the use of a particular line of the source code the format is relatively standard, divided into four fields separated by tabs as follows

```
[label:]operation[operand],[operand],[operand][#comment]
```

It is extremely important in all languages, but especially in assembly language to indent the code properly using the tab or space keys to make the program as readable as possible, both by the author and others. Brackets (`[]`) indicate an optional field, so not all fields appear on each line. Comments are optional in the definition of the language, but must be sprinkled liberally in an assembly program to enhance readability. Depending on the particular operation and the needs of the program, a label and operand(s) may be required on a line.

4.2.1 COMMENTS

Comments in assembler files begin with a sharp sign (#). Everything from the sharp sign to the end of the line is ignored by the assembler. Since assembly language is not self-documenting it is a good idea to use a lot of comments in an assembly program, as the source code will otherwise be more difficult to read and understand than, say, a program written in a high-level language like C.

4.2.2 LABELS

Identifiers are a sequence of alphanumeric characters, underbars (_), and dots (.) that do not begin with a number, for example `str` in line 31 of `hello.a`. Opcodes for instructions, such as `la` of `li`, are reserved words that are not valid identifiers. Labels are declared by putting identifiers at the beginning of a line followed by a colon, as can be seen in both the text and data segments of `hello.a`. When choosing an identifier, it is a good idea to pick one which has a meaning that increases the readability of the program, for example `str` for the address of a string, rather than say `L59` for the fifty-ninth label! A programmer who uses meaningless labels at the time of coding will never get round to altering them, and will be unable to figure out the program in a few weeks' time. Often labels are kept to fewer than eight characters to facilitate the formatting of the source using tabs.

If a label is present, it is used to associate the symbol with the memory address of a variable, located in the data segment, or the address of an instruction in the text segment.

4.2.3 OPERATION FIELD

The operation field contains either a machine instruction or an assembler directive. Each machine instruction has a special symbol or mnemonic associated with it. The full set of SPIM mnemonics is listed in Appendix C. If a particular instruction is needed by the programmer, the corresponding mnemonic is placed in the operation field. For example, the `la` mnemonic is used in `hello.a` to cause the load address instruction to be placed at this point in the program.

The operation field can also hold an assembler directive, which does not translate into a machine instruction. In `hello.a` the directive `.data` is used to tell the assembler to place what follows in the data segment of the program.

4.2.4 OPERAND FIELD

Many machine instructions require one or more operands. For example, in `hello.a` register names, labels and numerical quantities are used as operands. Assembler directives may also require operand(s).

4.2.5 CONSTANTS

A constant is a value that does not change during program assembly or execution. Program hello.a uses both integer and character string constants. If an integer constant is specified without indicating its base, it is assumed to be a decimal number. To indicate a number in hexadecimal, prefix the number with 0x and use either lower- or upper-case letters: a-f or A-F.

A string constant is delimited by double quotes (") for example:

```
"hello world\n"
```

Special characters in strings follow the C convention:

newline	\n
tab	\t
quote	\"

SPIM supports two assembler directives for character strings.

```
.ascii "abcd"
```

stores the ASCII bytes in memory, but does not null-terminate them.

```
.asciiz  "abcd"
```

stores the string in memory and null-terminates it.

4.3 DESCRIPTION OF hello.a

The example program hello.a prints out the characters hello world. It is a very simple program which sets up the string in the data segment and makes a system call to print out this string in the text segment, followed by a system call to exit the program. After the initial comments, the

```
.text
```

directive (line 13) tells the assembler to place what follows in the text segment. The following two lines (lines 14–15)

```
      .globl __start
__start:
```

attach the label __start to the first instruction so that the assembler can identify where execution should begin. All programs in this book will have these three lines unchanged.

As mentioned already, SPIM provides a small set of operating-system-like services through the system call (syscall) instruction. To request a service, a program loads the system call code (see Table 3.2) into register $v0 (for example, 10 = exit, 1 = print an integer, 4 = print a string, 5 = read an integer, etc.) and the arguments into registers `$a0...$a3`. To set up the system call it is necessary to load values into the registers. The `la`, or load address instruction (Figure 4.2) puts an address into a register (line 16). It takes two operands, the first being the register and the second being the address. Note the register names all begin with `$`.

The dagger (†) in the instruction set reference means that `la` is a pseudo-instruction. In order to make it easier to write, read and understand source code, assemblers provide some extra instructions which do not correspond to a single machine instruction but instead consist of a sequence of machine instructions. As we shall see shortly when we execute the program instruction by instruction, called single stepping, `la` requires two machine instructions, since the address is a 32-bit quantity, and is therefore a pseudo-instruction.

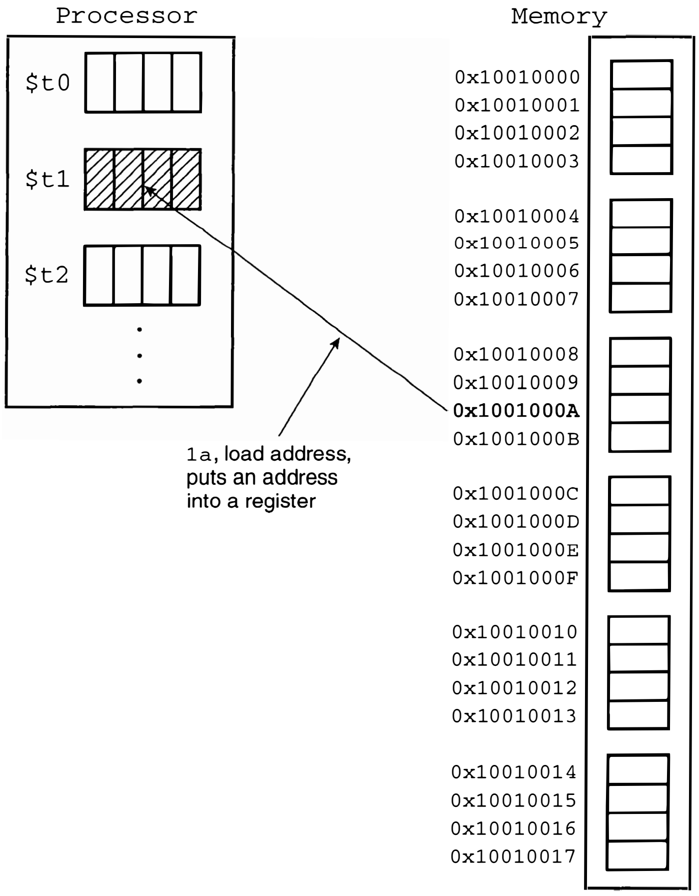


Figure 4.2 `la`: load address instruction.

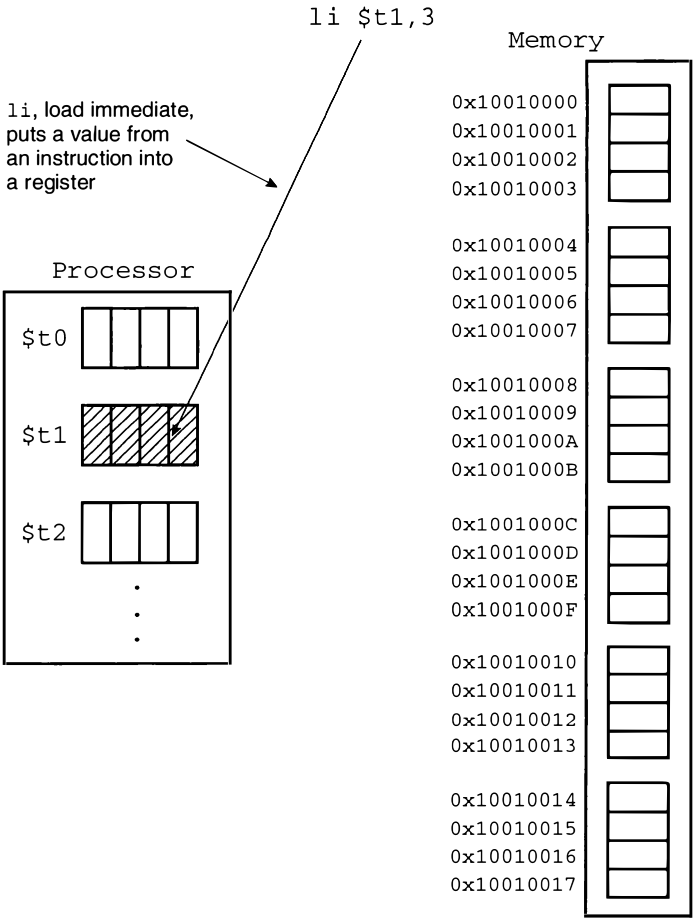


Figure 4.3 `li`: load immediate instructions.

`li` (Figure 4.3) is load immediate (line 17). Immediate means the processor extracts a value from the instruction itself, not from memory, and stores it in the register. If the size of the constant is limited to 16 bits this pseudo-instruction can fit in a single machine instruction. Load immediate takes two operands, the first being the register and the second being the number to be loaded.

4.4 PUTTING THEORY INTO PRACTICE

This section discusses the Unix version of SPIM. Versions for PC or Macintosh are almost identical. XSPIM is an X-Window application that implements a simulated MIPS environment. The environment allows assembling and debugging of assembly code written with the MIPS instruction set.

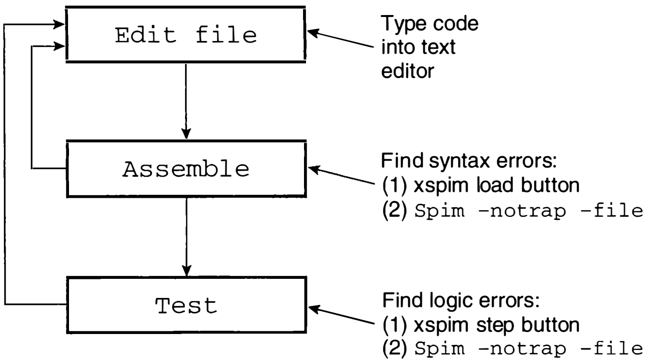


Figure 4.4 Edit, assemble and test cycle.

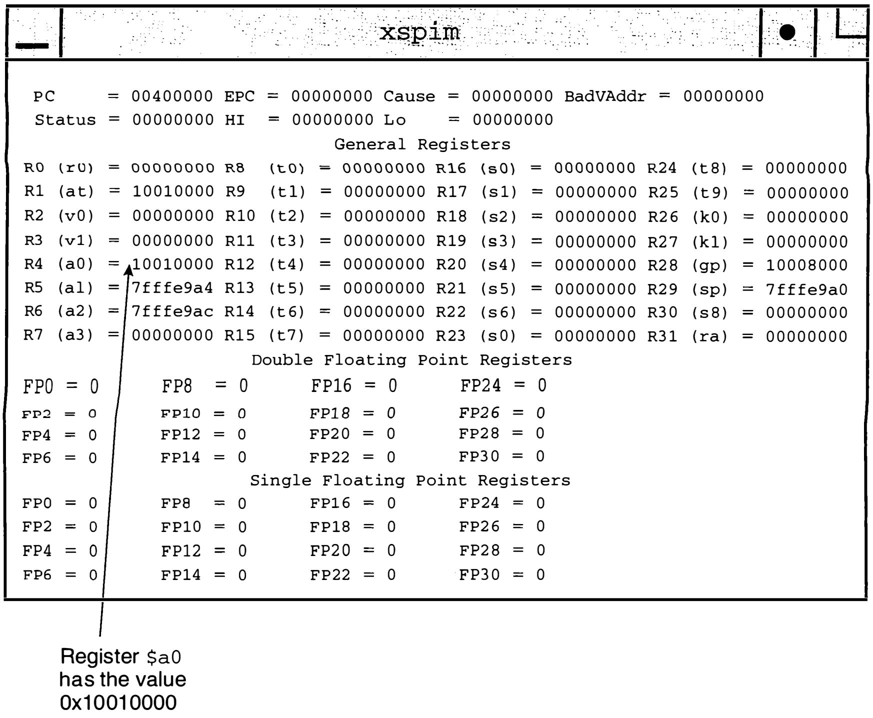
The basic method of programming with XSPIM is to have the XSPIM window open, and also an editor window open with the code you are working on. To test your code, you load it and run it in XSPIM. Usually you will encounter errors in your code, so you make changes to your code in your editor, save your code from your editor, clear the XSPIM environment, reload your code into XSPIM, and finally re-run your code in XSPIM. This cycle continues until you've removed all the bugs from your code. Figure 4.4 shows the steps involved in getting an assembly program to work.

4.4.1 STARTING XSPIM

To run XSPIM type `xspim -notrap &` and press enter. The `notrap` option is needed so that control will begin from the `__start` label in your program. When the XSPIM window comes up, note the division of the window: at the top the current states of all of the registers in the simulated machine are displayed (Figure 4.5). The values of these registers will change as you run your program. Below the registers are the control buttons (Figure 4.6), which are used to tell XSPIM what to do.

Next is the text segment, Figure 4.7, which is broken into these five columns (listed left to right):

- the address of the instruction
- the hex encoding of the instruction (machine language)
- the mnemonic description of the instruction, along with explicit register names and explicit addresses
- the line number of the code from your program
- the line of code from your program that produced this instruction. Note that the instruction in your code may not match exactly the instruction in the third column, because some MIPS instructions are actually pseudo-instructions, which may consist of several machine instructions.



```
PC     = 00400000 EPC = 00000000 Cause = 00000000 BadVAddr = 00000000
Status = 00000000 HI  = 00000000 Lo    = 00000000
                          General Registers
R0 (r0) = 00000000 R8  (t0) = 00000000 R16 (s0) = 00000000 R24 (t8) = 00000000
R1 (at) = 10010000 R9  (t1) = 00000000 R17 (s1) = 00000000 R25 (t9) = 00000000
R2 (v0) = 00000000 R10 (t2) = 00000000 R18 (s2) = 00000000 R26 (k0) = 00000000
R3 (v1) = 00000000 R11 (t3) = 00000000 R19 (s3) = 00000000 R27 (k1) = 00000000
R4 (a0) = 10010000 R12 (t4) = 00000000 R20 (s4) = 00000000 R28 (gp) = 10008000
R5 (a1) = 7fffe9a4 R13 (t5) = 00000000 R21 (s5) = 00000000 R29 (sp) = 7fffe9a0
R6 (a2) = 7fffe9ac R14 (t6) = 00000000 R22 (s6) = 00000000 R30 (s8) = 00000000
R7 (a3) = 00000000 R15 (t7) = 00000000 R23 (s0) = 00000000 R31 (ra) = 00000000
                    Double Floating Point Registers
FP0 = 0         FP8  = 0      FP16 = 0      FP24 = 0
FP2 = 0         FP10 = 0      FP18 = 0      FP26 = 0
FP4 = 0         FP12 = 0      FP20 = 0      FP28 = 0
FP6 = 0         FP14 = 0      FP22 = 0      FP30 = 0
                    Single Floating Point Registers
FP0 = 0         FP8  = 0      FP16 = 0      FP24 = 0
FP2 = 0         FP10 = 0      FP18 = 0      FP26 = 0
FP4 = 0         FP12 = 0      FP20 = 0      FP28 = 0
FP6 = 0         FP14 = 0      FP22 = 0      FP30 = 0
```

Figure 4.5 XSPIM view of current state of all of the registers in the simulated machine.

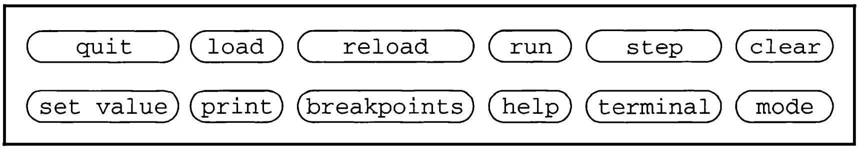
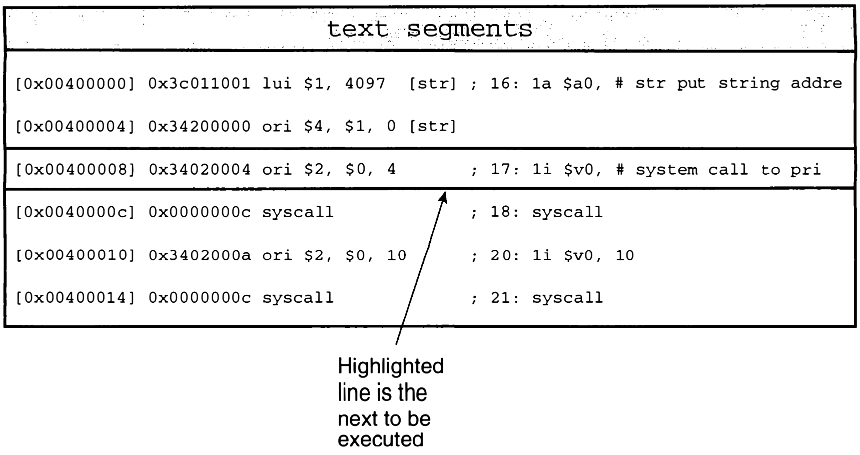


Figure 4.6 Control buttons to tell XSPIM what to do.

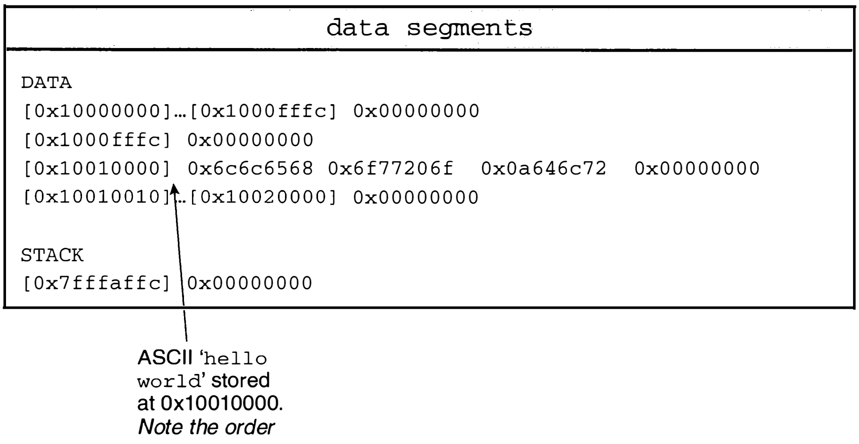
Below the text segment is the data segment (Figure 4.8), where you can see the data portion of your code. The XSPIM tool prints out the data segment as if each four bytes represented a word. If the data in fact represents characters, the ASCII codes for four characters will appear in each word. The order of the bytes within a word will depend on the way the particular computer on which XSPIM is running has been built. At the very bottom of the XSPIM window is the messages area, where XSPIM gives you feedback, such as notifying you that your program crashed or alerting you to a malformed instruction.



```
text segments

[0x00400000] 0x3c011001 lui $1, 4097  [str] ; 16: la $a0, # str put string addre
[0x00400004] 0x34200000 ori $4, $1, 0 [str]
[0x00400008] 0x34020004 ori $2, $0, 4        ; 17: li $v0, # system call to pri
[0x0040000c] 0x0000000c syscall              ; 18: syscall
[0x00400010] 0x3402000a ori $2, $0, 10       ; 20: li $v0, 10
[0x00400014] 0x0000000c syscall              ; 21: syscall
```

Figure 4.7 Text segment broken into these five columns.



```
data segments

DATA
[0x10000000]...[0x1000fffc] 0x00000000
[0x1000fffc] 0x00000000
[0x10010000] 0x6c6c6568 0x6f77206f  0x0a646c72  0x00000000
[0x10010010]...[0x10020000] 0x00000000

STACK
[0x7fffaffc] 0x00000000
```

Figure 4.8 Data segment of MIPS program.

4.4.2 LOADING AN ASSEMBLY PROGRAM

Once you have the XSPIM window open you need to load your program. Press the 'load' button and, a window will come up (Figure 4.9) asking you for a filename. Type in the name of your program and press 'assemble file'. XSPIM will proceed to load and assemble your program. Look in the message area of the XSPIM window for errors that XSPIM may have found while assembling your program.

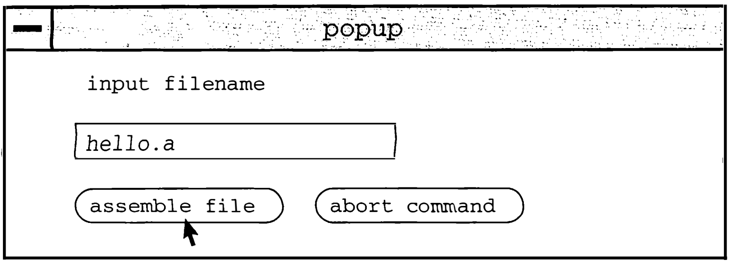


Figure 4.9 Window used to load a file in XSPIM.

It is also possible to use the command line interface to the SPIM program by typing `spim -notrap -file` followed by the filename, which will show any syntax errors in a terminal window.

4.4.3 EXECUTING AN ASSEMBLY PROGRAM

Once your program has successfully loaded (meaning XSPIM found the file and did not encounter any errors while assembling it) you can run it. First, press the 'terminal' button and pull-down to 'popup console', which will bring up another window that will display any output the program produces. To run your program press the 'Run' button (Figure 4.10). You will be asked for the address at which you wish XSPIM to begin executing. The default address should be correct, so press the 'ok' button and your program will run.

If your program didn't seem to work properly, look at the messages portion of the window for hints from XSPIM as to what the problem is.

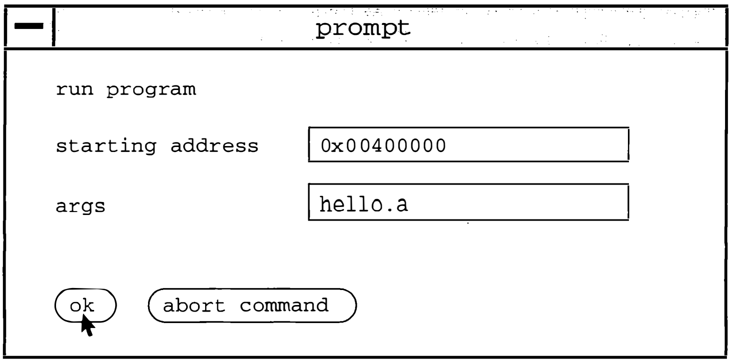


Figure 4.10 Window used to run a program in XSPIM.

4.4.4 RELOADING AND RE-EXECUTING AN ASSEMBLY PROGRAM

Usually your program won't work perfectly the first time. You will no doubt observe changes to your code that you would like to make. Once you have modified your code in your editor (which it is assumed you have open along with XSPIM), press the 'clear' button on the XSPIM window and pull it down to 'memory & registers'. This will clear the state of the simulated machine so that you can run the fresh new version of your program. Now press 'load' and XSPIM remembers the filename of your program, so just press 'assembly file' and XSPIM will reload it. Finally, press 'run' and then 'ok' to re-execute your program.

4.4.5 DEBUGGING AN ASSEMBLY PROGRAM

Syntax errors are easy to locate and fix because the assembler will automatically tell you the line number which caused the problem. Single stepping is extremely important because it is the best way to find a logical error in your program by pinpointing the precise line which caused the error. Debugging with XSPIM usually amounts to single stepping through each instruction in your program and observing the changes in the state of the registers. The particular line that the program counter has reached is highlighted in the text segment window as the processor stops during execution. This method exposes most bugs quickly. To step through your program you must either declare a breakpoint or start stepping from the `__start` label line by line. A breakpoint is a spot in your program where XSPIM will temporarily suspend execution so that you may view the suspended state of the simulated machine. After observing the state, you may tell XSPIM to finish executing your program in its entirety (or until it encounters another breakpoint), or you may step through your program line by line. Breakpoints are useful to pass over a loop quickly and avoid single stepping around it many times.

Single stepping control

To continue execution of your program from a breakpoint, or at the very start of your program, press the 'step' button. This brings up the step window (Figure 4.11), which allows you to either step through your program (press the 'step' button) or continue execution of your program (press the 'continue' button).

Setting a breakpoint

To set a breakpoint you must first observe the address of the instruction where you wish to suspend execution (remember, the address is the first column of the text segment in the XSPIM window). Next, press the

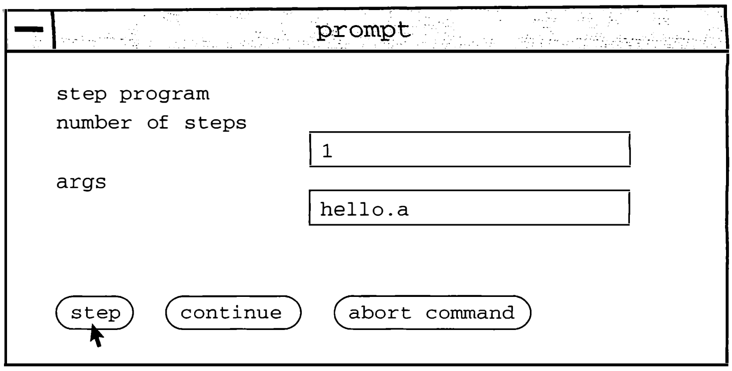


Figure 4.11 Window used to single step in XSPIM.

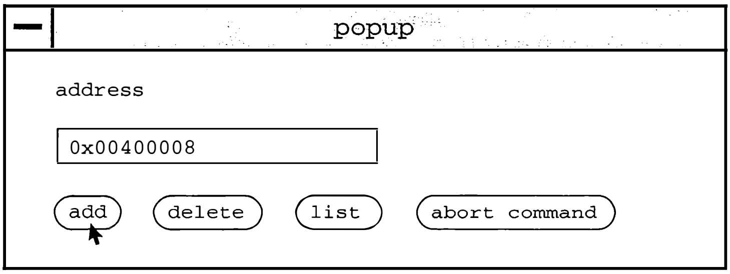


Figure 4.12 Window used to set a breakpoint in XSPIM.

'Breakpoints' button (Figure 4.12), then type in the address of the breakpoint and press 'add'. When you run your program, XSPIM will suspend execution at the breakpoint that you specified. Note that it is possible to set multiple breakpoints. The breakpoints window (press the 'breakpoints' button from the XSPIM window) allows you to maintain a list of breakpoints.

4.5 LOAD AND STORE INSTRUCTIONS

`lw` (Figure 4.13) and `sw` are load and store word instructions – they load words from memory into registers, and store words into memory from registers. There is also a version that works on bytes – `lb` and `sb` (Figure 4.14). Note the requirement for alignment; the memory address associated with `lw` or `sw` must be a multiple of four because of the way memory is built.

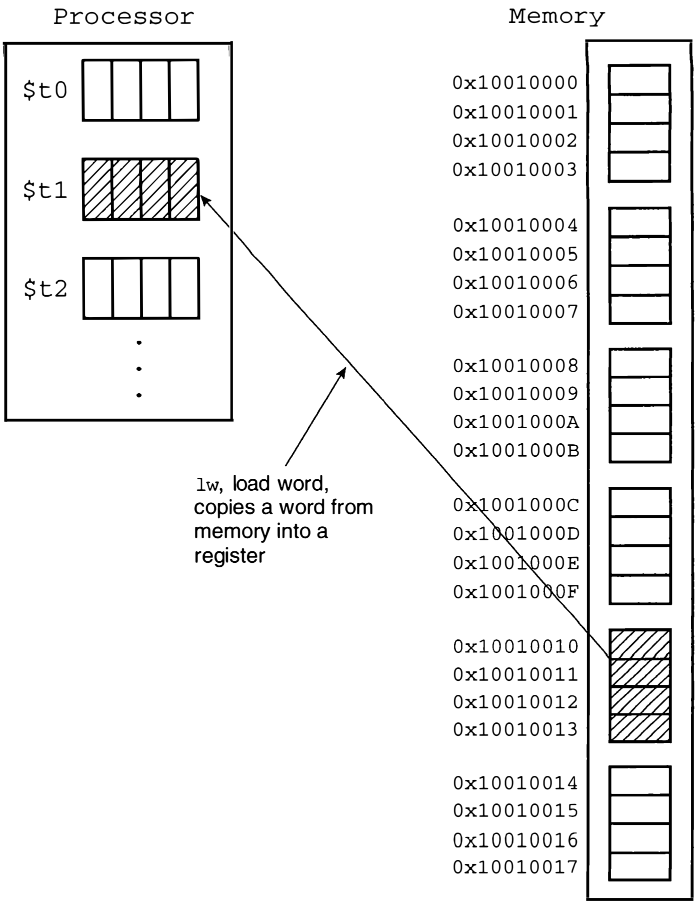


Figure 4.13 `lw`: load word instruction.

4.6 ARITHMETIC INSTRUCTIONS

All arithmetic (and logical) instructions take three operands. The mnemonic

```
add $t0,$t1,$t2
```

means

```
t0 = t1 + t2
```

Note the order of the operands. The arguments are the contents of the registers, so this is known as register addressing mode. A programmer who needs one input to be a constant can use:

```
addi $t0,$t1,15
```

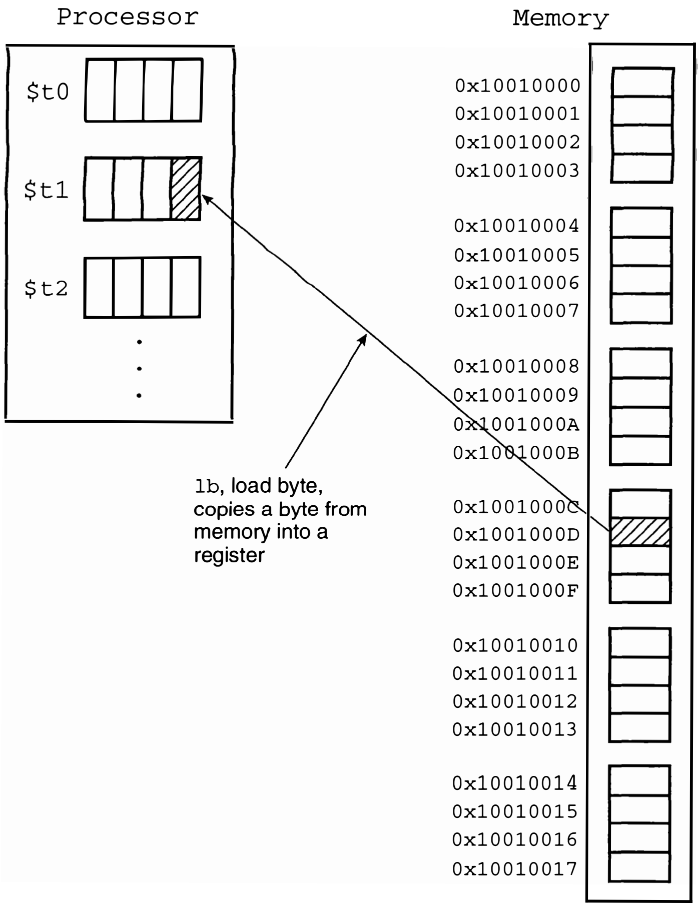


Figure 4.14 `lb`: load byte instruction.

This instruction is called 'add immediate' because the constant is stored in the actual instruction, and is immediately available to the processor without having to access memory. Different addressing modes will be discussed in more detail in Chapter 6.

In the instruction references, Appendix B and Appendix C, `Rdest` and `Rsrc` mean registers used as the destination and source operands. `Src` means either a register or a constant used as an operand. So, for example, the format listed for `add` is

```
add Rdest,Rsrc1,Src2
```

which means the destination and first operand must be registers, but the second operand can be either a register or a constant. If you type

```
add $t0,$t1,15
```

the assembler will automatically generate an `addi` instruction for you. Also, *if you only give one register the assembler will assume you wish to add the* constant to that register. Thus

```
add $t0,17
```

means

```
addi $t0,$t0,17
```

4.7 MULTIPLICATION AND DIVISION

The actual MIPS instruction is `mult Rs,Rt`, which means multiply contents of `Rs` by contents of `Rt`. Since the result of multiplying two *n*-bit numbers can be up to 2*n* bits, MIPS uses two special registers, called `lo` and `hi`, to hold the results of multiplications. Special move instructions copy data from general registers (`r0..r31`) to/from `lo` and `hi`. You don't have to worry too much about the details of this. The pseudo-instruction `mul Rdest,Rsrc1,Src2` will assemble into the real instructions to do the multiply.

```
mul $t4,$t4,$t1
```

is the same as

```
mult $t4,$t1
mflo $t4          move from the lo register
```

Similarly, there is a `div Rdest,Rsrc1,Src2` pseudo-instruction to do integer division. Program `dec.a` on pp. 78–80 will provide an example of its usage. Table 4.1 summarizes the usage of the MIPS processor's arithmetic instructions.

Table 4.1 Examples of MIPS arithmetic instructions.

Instruction		Example
Add	`add $t1,$t2,$t3`	`# $t1=$t2+$t3`
Add immediate	`addi $t1,$t2,50`	`# $t1=$t2+50`
Subtract	`sub $t1,$t2,$t3`	`# $t1=$t2-$t3`
Multiply	`mult $t2,$t3`	`# [illegible],Lo=$t2x$t3`

Divide	`div $t2,$t3`	`# Lo=$t2÷$t3,`
		`# Hi=$t2 mod $t3`

Move from `Hi`	`mfhi $t1`	`# $t1=Hi`
		`# get copy of Hi`

Move from `Lo`	`mflo $t1`	`# $t1=Lo`
		`# get copy of Lo`

The program temp.a asks a user for a temperature in Celsius, converts it to Fahrenheit, and prints the result.

```
##
## temp.a ask user for temperature in Celsius,
##  convert to Fahrenheit, print the result.
##
##       v0 - reads in celsius
##       t0 - holds Fahrenheit result
##       a0 - points to output strings
##

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:
        la $a0,prompt   # print prompt on terminal
        li $v0,4
        syscall

        li $v0,5        # syscall 5 reads an integer
        syscall

        mul $t0,$v0,9   # to convert,multiply by 9,
        div $t0,$t0,5   # divide by 5,then
        add $t0,$t0,32  # add 32

        la $a0,ans1     # print string before result
        li $v0,4
        syscall

        move $a0,$t0    # print  result
        li $v0,1
        syscall

        la $a0,endl     # system call to print
        li $v0,4        # out a newline
        syscall

        li $v0,10
        syscall         # au revoir...
```

```
44
45
46   #################################################
47   #                                               #
48   #               data segment                    #
49   #                                               #
50   #################################################
51
52           .data
53           prompt: .asciiz "Enter temperature (Celsius): "
54           ans1:   .asciiz "The temperature in Fahrenheit is "
55           endl:   .asciiz "\n"
56
57           ##
58           ## end of file temp.a
```

`temp.a` is interesting because it uses syscall five to read in an integer (line 23) that should be a Celsius temperature. It uses the `mul` pseudo-instruction (line 26) and the `div` pseudo-instruction (line 27) to work out the temperature in Fahrenheit. When writing code for the automatically correcting system (Appendix A), it is important not to use syscall five to read in input. The data for such programs will always be stored in the data segment.

4.8 PROGRAMMING EXAMPLE

`math1.a` below is a programming question that tests knowledge of the arithmetic instructions together with the load word instruction. The question is in the input format for the automatic testing system described fully in Appendix A.

Note: Whenever you see a 'skeleton' file such as `math1.a` in this book, you should attempt to write the program asked for in the opening lines of the file in the space provided between the dashed lines.

```
1   ## Start of file math1.a
2   ##
3   ## Question:
4   ## calculate A*X^2+B*X+C
5   ##
6   ## Output format must be:
7   ## "answer = 180"
```

```

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

         .text
         .globl __start
  __start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
X:      .word 7
A:      .word 3
B:      .word 4
C:      .word 5
ans:    .asciiz "answer = "
endl:   .asciiz "\n"
##
## End of file math1.a
```

Here is an attempted solution to the question, which contains a logical error. This section shows how to use source-level debugging to single step through the code and locate the error in the solution.

```
# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------
```

```
 4
 5
 6   # solution to math1.a NOTE IT CONTAINS A BUG!!!!
 7
 8           lw $t0,X
 9           lw $t1,A
10           lw $t2,B
11           lw $t3,C
12
13           mul $t4,$t0,$t0 # t4 = X^2
14           mul $t4,$t4,$t1 # t4 = A*X^2
15           mul $t5,$2,$t0  # t5 = B*X
16           add $t4,$t4,$t5 # t4 = A*X^2+B*X
17           add $t4,$t4,$t3 # t4 = A*X^2+B*X+C
18
19           la $a0,ans      # system call to print
20           li $v0,4        # out string
21           syscall
22
23           move $a0,$t4    # print result on terminal
24           li $v0,1
25           syscall
26
27           la $a0,endl     # system call to print
28           li $v0,4        # out a newline
29           syscall
30
31           li $v0,10
32           syscall         # au revoir...
33
34   ##-----------  end cut  -------------------------
35   # Any changes below this line will be discarded by
36   # mipsmark. Put your answer between dashed lines.
```

This attempted solution used the lw instruction to get the values of A, B, C and X into registers from memory (lines 8–11) so that the arithmetic instructions can be used to calculate the required result (lines 13–17). Lines 23–25 use syscall one to print the value of an integer.

The solution also uses the move pseudo-instruction (line 23) to move a value from one register to another so that the answer will be in $a0 for the system call. This is a good example of how an assembler can hide a messy machine detail from programmers.

```
move $t0,$t1
```

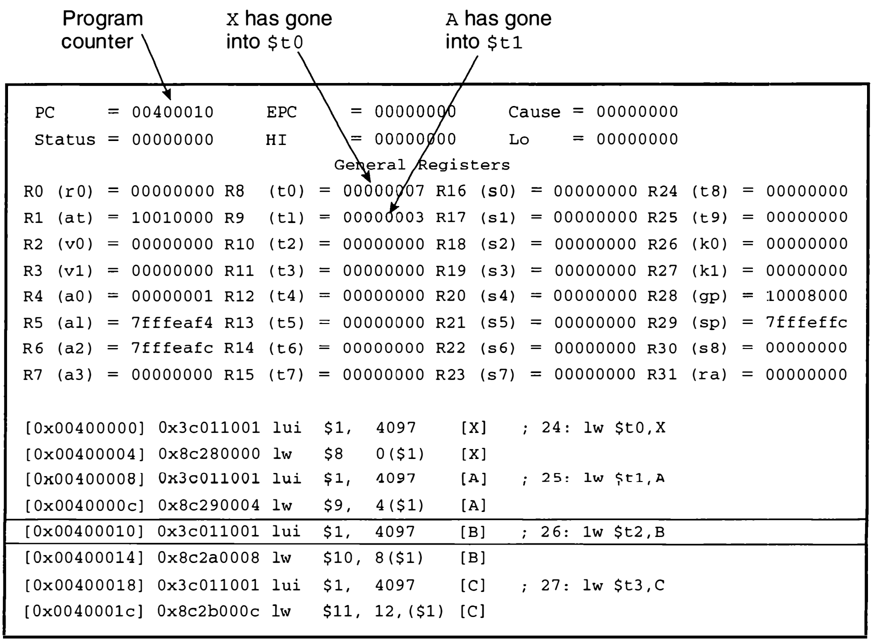
means copy the contents of `$t1` to `$t0`. MIPS does not have a move instruction in the machine language. But it does have an `add`, and it has a register `$0` that always has the value zero, a very common constant. Machine language programmers who want to copy `t1` to `t0` would write the equivalent of

```
add $t0,$t1,$0
```

but the assembly language programmer can write `move` and have the assembler translate it into `add`.

If the above attempted solution is run, the answer printed out is 152, not the expected 180. The best way to find the bug is to load the program into the XSPIM tool and single step through it watching the values in the registers as each instruction is executed. Figure 4.15 shows XSPIM after the 'step' button has been pressed four times, corresponding to the first four machine instructions, or the first two assembly language pseudo-instructions. The correct values can be seen in the registers.

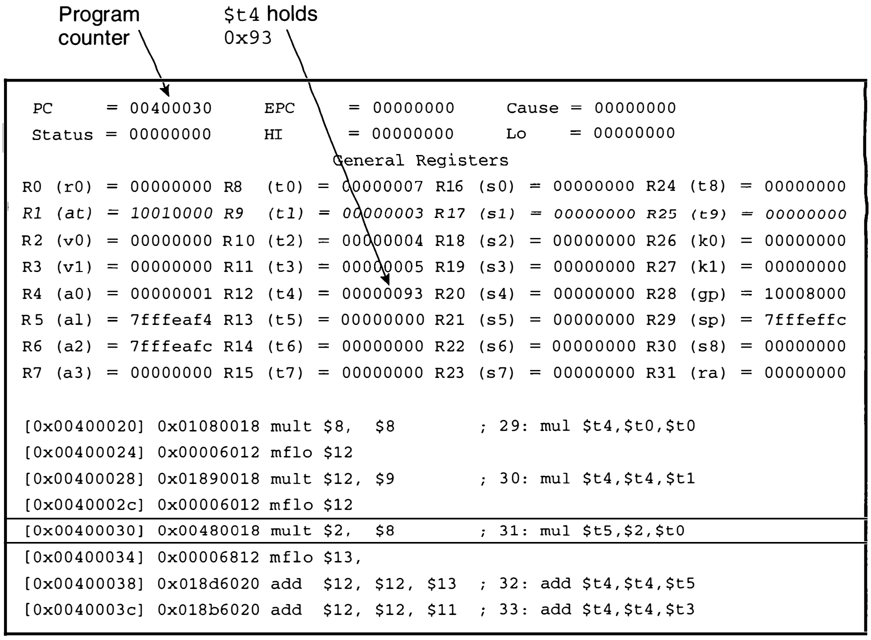
If the step button is repeatedly pressed, everything goes according to plan until the program counter reaches 0x00400030 (Figure 4.16), when it becomes clear that the programmer has inadvertently typed `$2` instead of `$t2`. It is easy to alter this in a text editor, and clear and reload XSPIM, after which the program will function correctly.



```
 PC     = 00400010     EPC       = 00000000     Cause = 00000000
 Status = 00000000     HI        = 00000000     Lo    = 00000000
                              General Registers
R0 (r0) = 00000000 R8  (t0) = 00000007 R16 (s0) = 00000000 R24 (t8) = 00000000
R1 (at) = 10010000 R9  (t1) = 00000003 R17 (s1) = 00000000 R25 (t9) = 00000000
R2 (v0) = 00000000 R10 (t2) = 00000000 R18 (s2) = 00000000 R26 (k0) = 00000000
R3 (v1) = 00000000 R11 (t3) = 00000000 R19 (s3) = 00000000 R27 (k1) = 00000000
R4 (a0) = 00000001 R12 (t4) = 00000000 R20 (s4) = 00000000 R28 (gp) = 10008000
R5 (a1) = 7fffeaf4 R13 (t5) = 00000000 R21 (s5) = 00000000 R29 (sp) = 7fffeffc
R6 (a2) = 7fffeafc R14 (t6) = 00000000 R22 (s6) = 00000000 R30 (s8) = 00000000
R7 (a3) = 00000000 R15 (t7) = 00000000 R23 (s7) = 00000000 R31 (ra) = 00000000

[0x00400000] 0x3c011001 lui  $1,  4097      [X]   ; 24: lw $t0,X
[0x00400004] 0x8c280000 lw   $8   0($1)     [X]
[0x00400008] 0x3c011001 lui  $1,  4097      [A]   ; 25: lw $t1,A
[0x0040000c] 0x8c290004 lw   $9,  4($1)     [A]
[0x00400010] 0x3c011001 lui  $1,  4097      [B]   ; 26: lw $t2,B
[0x00400014] 0x8c2a0008 lw   $10, 8($1)     [B]
[0x00400018] 0x3c011001 lui  $1,  4097      [C]   ; 27: lw $t3,C
[0x0040001c] 0x8c2b000c lw   $11, 12,($1)   [C]
```

Figure 4.15 XSPIM after the first two assembly language instructions.



```
 PC     = 00400030     EPC     = 00000000     Cause = 00000000
 Status = 00000000     HI      = 00000000     Lo    = 00000000
                              General Registers
R0 (r0) = 00000000 R8  (t0) = 00000007 R16 (s0) = 00000000 R24 (t8) = 00000000
R1 (at) = 10010000 R9  (t1) = 00000003 R17 (s1) = 00000000 R25 (t9) = 00000000
R2 (v0) = 00000000 R10 (t2) = 00000004 R18 (s2) = 00000000 R26 (k0) = 00000000
R3 (v1) = 00000000 R11 (t3) = 00000005 R19 (s3) = 00000000 R27 (k1) = 00000000
R4 (a0) = 00000001 R12 (t4) = 00000093 R20 (s4) = 00000000 R28 (gp) = 10008000
R5 (al) = 7fffeaf4 R13 (t5) = 00000000 R21 (s5) = 00000000 R29 (sp) = 7fffeffc
R6 (a2) = 7fffeafc R14 (t6) = 00000000 R22 (s6) = 00000000 R30 (s8) = 00000000
R7 (a3) = 00000000 R15 (t7) = 00000000 R23 (s7) = 00000000 R31 (ra) = 00000000

[0x00400020] 0x01080018 mult $8,  $8        ; 29: mul $t4,$t0,$t0
[0x00400024] 0x00006012 mflo $12
[0x00400028] 0x01890018 mult $12, $9        ; 30: mul $t4,$t4,$t1
[0x0040002c] 0x00006012 mflo $12
[0x00400030] 0x00480018 mult $2,  $8        ; 31: mul $t5,$2,$t0
[0x00400034] 0x00006812 mflo $13,
[0x00400038] 0x018d6020 add  $12, $12, $13  ; 32: add $t4,$t4,$t5
[0x0040003c] 0x018b6020 add  $12, $12, $11  ; 33: add $t4,$t4,$t3
```

Figure 4.16 XSPIM when the bug is reached.

Two more example programs that test your understanding of the arithmetic instructions are `math2.a` and `math3.a`.

```
## Start of file math2.a
##
## Question:
## calculate 5*X^2-3
##
## Output format must be:
## "answer = 242"

#################################################
#                                               #
#                 text segment                  #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


```

```
# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#                data segment                   #
#                                               #
#################################################

        .data
X:      .word 7
ans:    .asciiz "answer = "
endl:   .asciiz "\n"
##
## End of file math2.a
```

```
## Start of file math3.a
##
## Question:
## calculate (NUM-3)*(NUM+4)
##
## Output format must be:
## "answer = 98"

#################################################
#                                               #
#                text segment                   #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------

```

```


#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
NUM:    .word 10
ans:    .asciiz "answer = "
endl:   .asciiz "\n"
##
## End of file math3.a
```

4.9 SUMMARY

Regardless of the use of a particular line of the assembly source code the format is relatively standard, divided into four fields separated by tabs. It is extremely important to indent the code properly using the tab key and to add comments liberally to make the program as readable as possible. In order to make it easier to write, read and understand source code, assemblers provide some extra pseudo-instructions which do not correspond exactly to a single machine instruction, but instead consist of a sequence of machine instructions. All arithmetic and logical instructions take three operands.

EXERCISES

4.1 What are the SPIM rules for forming identifiers?
4.2 What is the difference between a syntax error and a logical error?
4.3 What is the purpose of single stepping?
4.4 What is a breakpoint?
4.5 What are the `hi` and `lo` registers used for?
4.6 Why are comments and indentation so important in assembly language?
4.7 Describe the differences between `la`, `lb`, `li` and `lw`.
4.8 In what order should the operands of arithmetic and logical instructions be placed?

CHAPTER 5

Control flow structures

5.1 INTRODUCTION

This chapter looks at a program `length.a` that uses a program loop to work out the length of a character string. Familiarity with a few assembly language instructions, such as basic load, store and simple arithmetic operations is needed, together with the concept of program loops. A program loop allows an operation to be repeated a number of times, without having to enter the assembly language instructions explicitly. For example, to sum 50 numbers, one would not have 50 add instructions in the program, but instead would have the add instruction once and go round a loop 50 times.

5.2 CONTROL STRUCTURES

In an abstract view, operations in programs can be divided into two groups:

- data manipulation – expression evaluation and assignments
- control – determine which instruction to execute next.

From this point of view, all the action takes place in the assignments and the control instructions are just there to help the computer get the data manipulation instructions in the right order. The instructions used to alter the flow of control are known as branches and jumps. A branch specifies the number of instructions above or below the present instruction to move the program counter, whereas a jump specifies the actual address to move the PC to.

The simplest control instruction jump

```
j <addr>
```

means jump to address <addr> which causes the processor to fetch the next instruction from the word at address <addr>. Implementation is actually very simple – just copy the value of the address to the program counter. An alternative form of the jump instruction is

```
jr Rsrc
```

which means jump to the address held in register Rsrc.

5.3 CONDITIONAL BRANCHES

The jump instruction is also known as an unconditional jump, meaning that the processor always goes to the jump target address. Interesting programs need a way to make conditional branches. The MIPS conditional branch instructions have names that begin with b (b is for branches and j for jumps). Examples:

```
beq  $t0,$t1,<addr>   branch to <addr> if $t0 == $t1
beqz $t0,<addr>       branch to <addr> if $t0 == 0
bne  $t0,$t1,<addr>   branch to <addr> if $t0 != $t1
blt  $t0,$t1,<addr>   branch to <addr> if $t0 < $t1
```

and many more as listed in Appendix B, p. 146. Many of the branch instructions are pseudo-instructions, that is they are implemented by the assembler but don't correspond to actual machine instructions. The 'set on less than' instruction (Table 5.1) is used to implement some conditional branch pseudo-instructions. For example,

```
bge $t4,$t2,notMin
```

would look like

```
slt $1,$12,$10
beq $1,$0,8 [notMin-0x00400028]
```

For this scheme to work, the assembler needs to have a temporary register that it knows is not holding any useful data. By convention, that register is $1, also known as $at, the assembler temporary register. Don't put any variables in $1 (at least not if you plan to use blt or any of the other branching pseudo-instructions). The assembler also helps out on branch instructions by letting the second operand be either a register or a constant. The 'branch on less than or equal' pseudo-instruction:

```
ble Rsrc,Src,addr
```

Table 5.1 Examples of MIPS jump, branch and compare instructions

Instruction		**Example**

Branch on equal	`beq $t1,$t2,80`	`# if ($t1 == $t2)`
		 `#    go to PC+4+80`

Branch on not equal	`bne $t1,$t2,-36`	`# if ($t1 != $t2)`
		 `#    go to PC+4-36`

Set less than	`slt $t1,$t2,$t3`	`# if ($t2 < $t3) $t1=1`
		 `# else $t1=0`

Set less than immediate	`slti $t1,$t2,7`	`# if ($t2 < 7) $t1=1`
		 `# else $t1=0`

Jump	`j 0x00400068`	`# go to 0x00400068`
Jump register	`jr $ra`	`# go to $ra`

Jump and link	`jal 0x00400014`	`# $ra = PC + 4`
		 `# go to 0x00400014`

can take a constant as one operand, for example,

```
ble $t0,5,loop
```

means branch to `loop` if `$t0` holds a number less than or equal to 5. Table 5.1 lists the usage of some of the MIPS processor's jump, branch and compare instructions.

5.4 EXAMPLE PROGRAMS USING LOOPS

The program `length.a` prints out the length of character string `str`:

```
##
## length.a - prints out the length of character
## string "str".
##
##      t0 - holds each byte from string in turn
##      t1 - contains count of characters
##      t2 - points to the string
##

################################################
#                                              #
#               text segment                   #
#                                              #
################################################
```

```
15
16          .text
17          .globl __start
18  __start:                # execution starts here
19          la $t2,str      # t2 points to the string
20          li $t1,0        # t1 holds the count
21  nextCh: lb $t0,($t2)    # get a byte from string
22          beqz $t0,strEnd # zero means end of string
23          add $t1,$t1,1   # increment count
24          add $t2,1       # move pointer one character
25          j nextCh        # go round the loop again
26
27  strEnd: la $a0,ans      # system call to print
28          li $v0,4        # out a message
29          syscall
30
31          move $a0,$t1    # system call to print
32          li $v0,1        # out the length worked out
33          syscall
34
35          la $a0,endl     # system call to print
36          li $v0,4        # out a newline
37          syscall
38
39          li $v0,10
40          syscall         # au revoir...
41
42
43  #################################################
44  #                                               #
45  #               data segment                    #
46  #                                               #
47  #################################################
48
49            .data
50  str:      .asciiz "hello world"
51  ans:      .asciiz "Length is "
52  endl:     .asciiz "\n"
53
54  ##
55  ## end of file length.a
```

The character string in `length.a` is situated in memory, so the program must use the `lb` instruction (line 21) to bring characters in from memory to a register until it finds the zero byte that determines the end of the string, as shown in Figure 4.14. The ($t2) register is used to hold the memory address of the bytes in the string. Line 21 uses an addressing mode known as indirect addressing because we are not loading the value in the register, but rather using the value in the register as the address of the byte to load. The brackets () indicate indirect addressing. Register $t2 is sometimes called a pointer to the array of characters, since it holds the address of the quantity of interest. The add instruction is needed to move the pointer $a0 along the string (that is, add one to it), looking for the zero byte that signifies the end (line 24). add is also used to increment the count of characters in the string held in register $t1 (line 23). length.a uses the beqz, 'branch on equal zero' pseudo-instruction, line 22 to branch conditionally to the instruction at the label strEnd (line 27) if the contents of $t0 equals zero, signifying the end of the string, as shown in Figure 4.1. An unconditional jump (line 25) is used to return to the label nextCh (line 21) repeatedly progressing to the next character in the string. This assembly language program could be a while statement in a high-level language.

Another interesting example programming question that will add to your understanding of the conditional branching and program loops is loop3.a.

```
## Start of file loop3.a
##
## Question:
## Replace all occurrences of 'a' with
## 'A' in the string "chararray" and
## print the resulting string.
##
## Output format must be:
## "AbbbAAbbbAbAbAb"

################################################
#                                              #
#               text segment                   #
#                                              #
################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#----------- start cut ------------------------
```

```
25
26
27          la $t2,chararray# t2 points to the string
28          li $t1,'A'
29  nextCh: lb $t0,($t2)    # get a byte from string
30          beqz $t0,strEnd # zero means end of string
31          bne $t0,'a',nota
32          sb $t1,($t2)    # store upper case A
33  nota:   add $t2,1       # move pointer one character
34          j nextCh        # go round the loop again
35
36  strEnd:
37          la $a0,chararray
38          li $v0,4
39          syscall         # print
40
41          li $v0,10
42          syscall         # au revoir...
43
44  #------------ end cut --------------------------
45  # Any changes below this line will be discarded by
46  # mipsmark. Put your answer between dashed lines.
47
48  #################################################
49  #                                               #
50  #               data segment                    #
51  #                                               #
52  #################################################
53
54            .data
55  chararray:
56            .asciiz "abbbaabbbababab\n"
57
58  ##
59  ## End of file loop3.a
```

In this program the bne instruction (line 31) is used to ensure that an upper-case A is only stored to memory when the character in that position was a lower case a. This would be an if statement in a high-level language. Note that 'A' in line 28 is used to mean the ASCII code for a letter. Line 32 uses the sb, store byte, instruction (Figure 5.1) to write a value from a register to the string in memory. Examples of the use of the other conditional instructions will be seen in other programs in subsequent chapters.

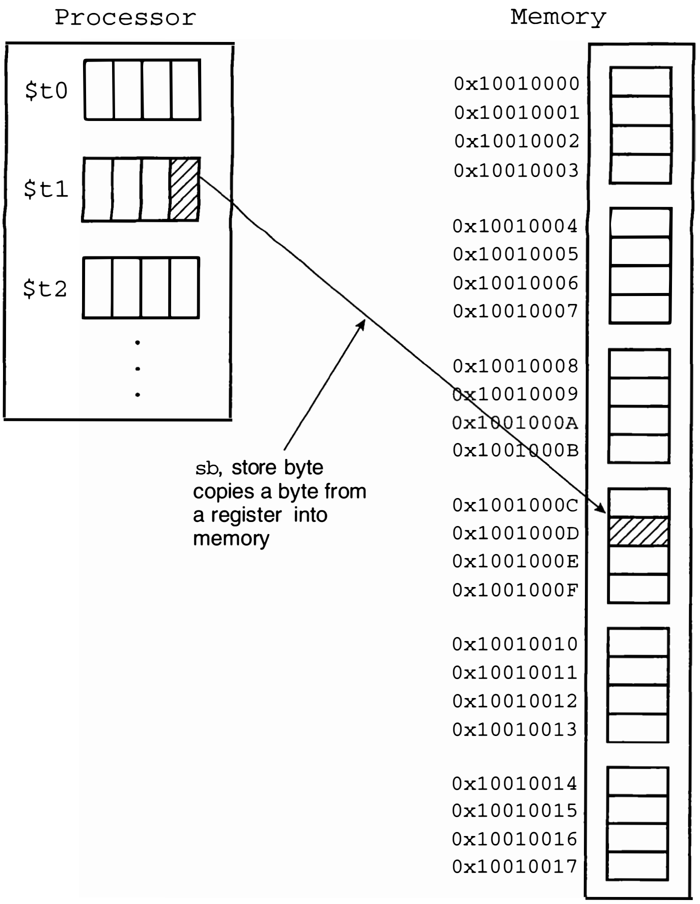


Figure 5.1 sb: store byte instruction.

Two more programs that test your understanding of these instructions are `loop4.a` and `loop5.a`.

```
## Start of file loop4.a
##
## Question:
## Swap each pair of elements in
## the string "chararray" and
## print the resulting string.
## There will always be an even number
## of characters in "chararray".
##
```

```
## Output format must be:
## "badcfe"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

         .data
chararray:
        .asciiz "abcdef"
endl:   .asciiz "\n"

##
## End of file loop4.a
```

```
## Start of file loop5.a
##
## Question:
## Replace every second character in the
## string "charstr" with 'X'. That is
## the first, third, fifth etc.
## There will always be an even number
## of characters in "charstr".
##
## Then print the resulting string.
##
## Output format must be:
## "XbXdXf"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut -------------------------



#------------  end cut  -------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
charstr:
        .asciiz "abcdef"
endl:   .asciiz "\n"
##
## End of file loop5.a
```

Further programs to test your understanding of program loops are in Appendix A.3.

5.5 SUMMARY

All the action in an assembly language program takes place in the assignments, and the control instructions are just there to help the computer get the data manipulation instructions in the right order. A program loop allows an operation to be repeated a number of times, without having to enter the assembly language instructions explicitly. A branch specifies the number of instructions above or below the present instruction to move the program counter, whereas a jump specifies the actual address to move the program counter to. An unconditional jump means that the processor always goes to the jump target address, but interesting programs need a way to make conditional branches as well.

EXERCISES

5.1 What do control instructions do?
5.2 What is a conditional branch?
5.3 How does a loop determine the end of a character string?
5.4 Describe the indirect addressing mode.
5.5 What is a pointer?
5.6 What assembly language instructions does a compiler use to implement a while loop?
5.7 How are ASCII character codes loaded into registers in MIPS assembly?

CHAPTER 6

Addressing modes

6.1 INTRODUCTION

For any given operation, such as load, add or branch, there are often many different ways to specify the address of the operand(s). The different ways of determining the address are called addressing modes. This chapter looks at the different addressing modes of the MIPS processor and shows how all instructions can fit into a single four-byte word. Some sample programs are included to show additional addressing modes in action.

6.2 MIPS INSTRUCTION FORMATS

Every MIPS instruction consists of a single 32-bit word aligned on a word boundary. There are three different instruction formats: I type, R type and J type as, shown in Figure 6.1. The parts of each format have the following meaning:

- `op` – 6 bit operation code
- `rs` – 5 bit source register specifier
- `rd` – 5 bit destination register specifier
- `rt` – 5 bit target (source/destination) register or branch condition
- `immediate` – 16 bit immediate branch displacement or address displacement
- `target` – 26 bit jump target address
- `shamt` – 5 bit shift amount
- `funct` – 6 bit function field.

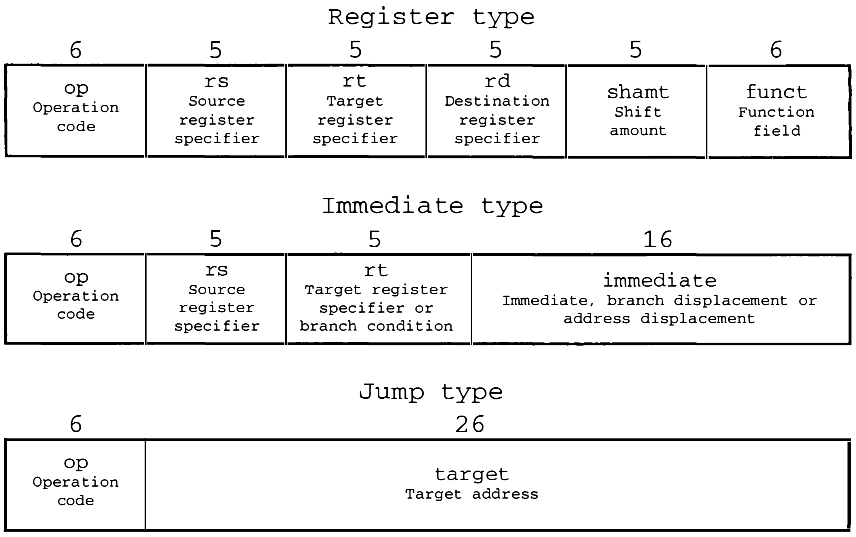

Register type
6
5
5
5
5
6
op
Operation code
rs
Source register specifier
rt
Target register specifier
rd
Destination register specifier
shamt
Shift amount
funct
Function field
Immediate type
6
5
5
16
op
Operation code
rs
Source register specifier
rt
Target register specifier or branch condition
immediate
Immediate, branch displacement or address displacement
Jump type
6
26
op
Operation code
target
Target address

Figure 6.1 MIPS instruction formats.

We have already seen examples of four different MIPS addressing modes while considering the programs `hello.a` and `length.a`. These are:

- register addressing mode
- base addressing mode
- immediate addressing mode
- PC-relative addressing mode.

In the following sections, we will examine each of these modes, observe how they are implemented using the above formats and introduce indexed addressing mode, which is implemented by the assembler as a pseudo-instruction.

6.3 MIPS REGISTER ADDRESSING

Register addressing (Figure 6.2) is the simplest addressing mode. Instructions using registers execute quickly because they avoid the delays associated with memory access. Unfortunately, the number of registers is limited since only a few bits are reserved to select a register. Register addressing is a form of direct addressing, because we are interested in the number in the register, rather than using that number as a memory address. To assist in understanding Figure 6.2, some of the opcodes used by MIPS are shown in Figure 6.3. The values of `rs`, `rd`, `rt` should be the actual register numbers, and can fit in five bits since there are 32 registers.

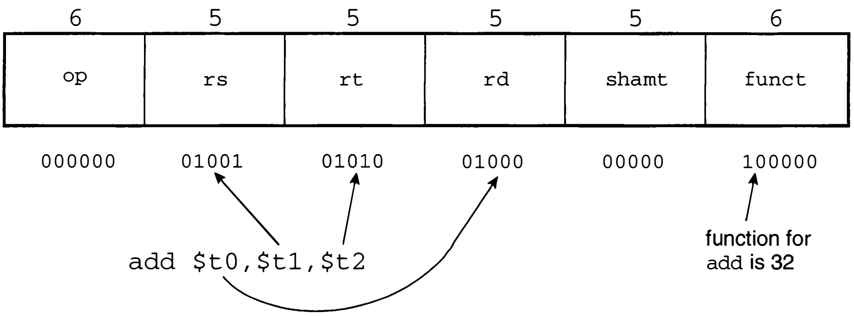
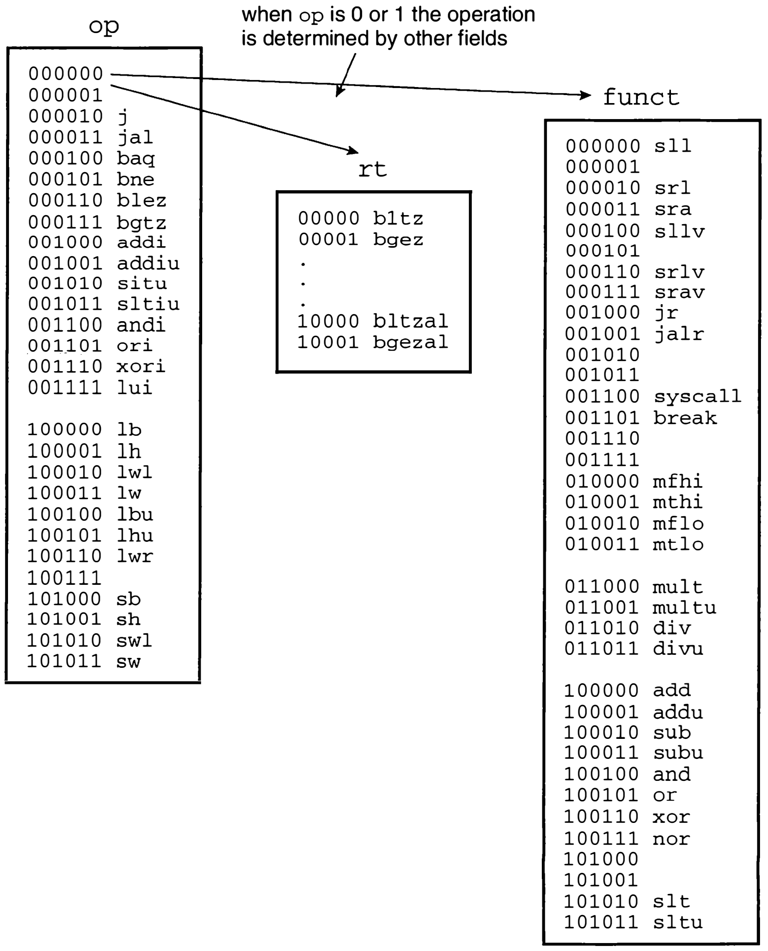


Figure 6.2 MIPS register addressing.


when op is 0 or 1 the operation is determined by other fields

op

000000	
000001	
000010	j
000011	jal
000100	baq
000101	bne
000110	blez
000111	bgtz
001000	addi
001001	addiu
001010	situ
001011	sltiu
001100	andi
001101	ori
001110	xori
001111	lui
100000	lb
100001	lh
100010	lwl
100011	lw
100100	lbu
100101	lhu
100110	lwr
100111	
101000	sb
101001	sh
101010	swl
101011	sw

rt

00000	bltz
00001	bgez
.	
.	
.	
10000	bltzal
10001	bgezal

funct

000000	sll
000001	
000010	srl
000011	sra
000100	sllv
000101	
000110	srlv
000111	srav
001000	jr
001001	jalr
001010	
001011	
001100	syscall
001101	break
001110	
001111	
010000	mfhi
010001	mthi
010010	mflo
010011	mtlo
011000	mult
011001	multu
011010	div
011011	divu
100000	add
100001	addu
100010	sub
100011	subu
100100	and
100101	or
100110	xor
100111	nor
101000	
101001	
101010	slt
101011	sltu

Figure 6.3 MIPS instruction opcodes.

6.4 MIPS BASE ADDRESSING

A data structure that is very important in computer programming is the record, called a structure in the C programming language. It is a collection of variables treated as a unit. For example, a personnel record might include name, address, age and department information. It is convenient to keep this information as a unit for each employee using a record or structure like:

```
struct personnel
  char name[80]
  char address[100]
  int age
  char department[10]
```

In base register addressing we add a small constant to a pointer held in a register. The register may point to a structure or some other collection of data, and we need to load a value at a constant offset from the beginning of the structure. Because each MIPS instruction fits in one word, the size of the constant is limited to 16 bits. The syntax is

```
lw rd,i(rb)
```

For example, if `$t0` pointed to the base of a record or structure, we could get at the fields using

```
lw $t1,4($t0)
lw $t2,8($t0)
lw $t3,16($t0)
etc...
```

We have used a form of base addressing with zero offset (Figure 6.4) in `length.a` (line 21) (p. 52). As mentioned, this form of addressing is known

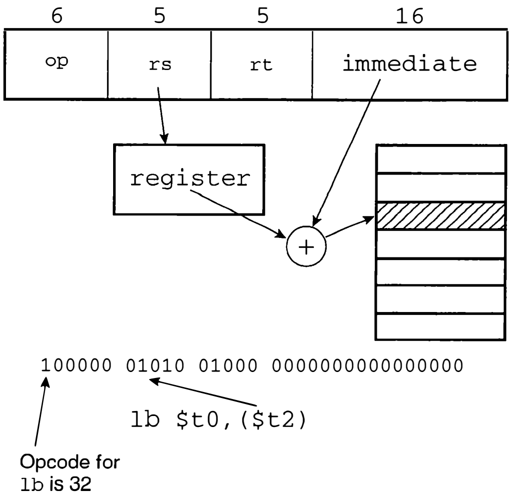


Figure 6.4 MIPS base addressing.

as indirect addressing since the operand is at the memory location whose address is in a register.

6.5 MIPS IMMEDIATE ADDRESSING

Immediate addressing (Figure 6.5) means that one operand is a constant within the instruction itself. Line 23 of `length.a` is an example of this addressing mode. Immediate addressing has the advantage of not requiring an extra memory access to fetch the operand, but the operand is limited to 16 bits in size.

The jump instruction format can also be considered an example of immediate addressing, since the destination is held in the instruction. Figure 6.6 illustrates this using line 25 of `length.a`.

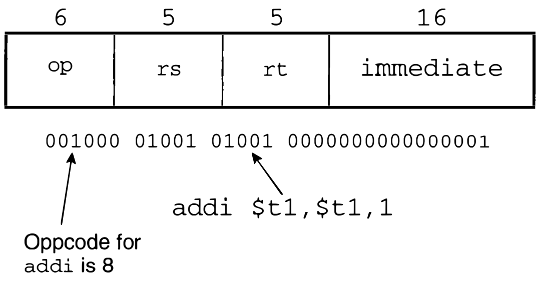


Figure 6.5 MIPS immediate addressing using `add`.

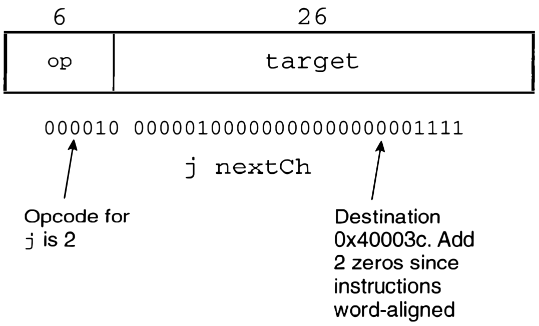


Figure 6.6 MIPS immediate addressing using `j`.

6.6 MIPS PC-RELATIVE ADDRESSING

PC-relative addressing (Figure 6.7), where the address is the sum of the program counter and a constant in the instruction, is used for conditional branches like line 22 of `length.a`. Branch instructions can only move 32 768 above or below the program counter because the offset is a 16-bit two's complement number (see Sections 2.5 and 2.6).

6.7 EXAMPLE PROGRAM USING BASE ADDRESSING

Program `minmax.a` is another interesting program using the base addressing mode of Figure 6.4 with zero offset. It searches an array of words for the biggest and smallest elements. The

```
.word
```

directive is used to set up an array of 15 four-byte words in the data section. An array data structure is a named list of items stored in memory, as shown in Figure 6.8.

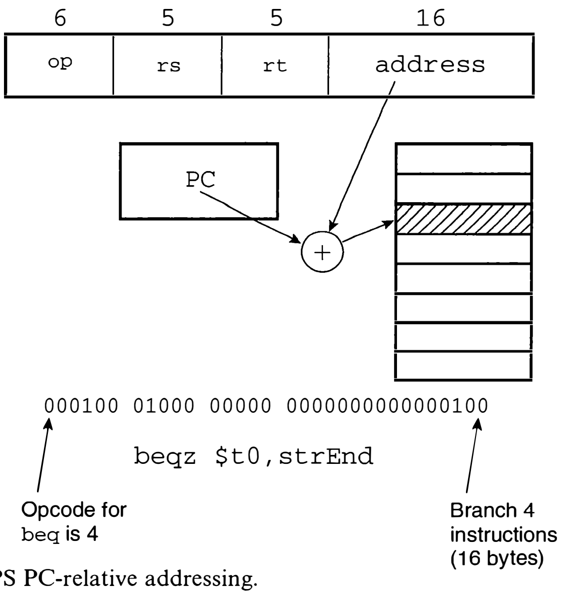


Figure 6.7 MIPS PC-relative addressing.

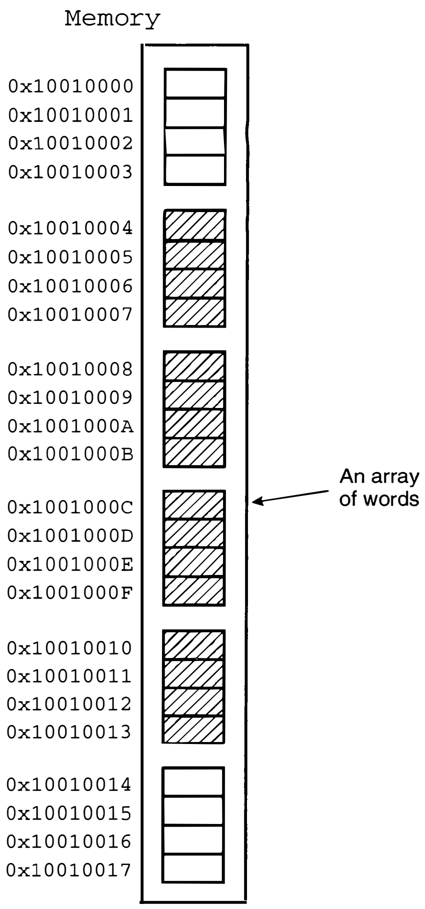


Figure 6.8 An array of words stored in memory.

Line 32 then uses the `lw` instruction to load each word into a register. An important difference between a pointer to a word and a pointer to a character is that the word pointer must be incremented by four each time round the loop (line 40), since each word occupies four memory locations.

```
 1   ## minmax.a - print min, max of array elements.
 2   ##
 3   ## Assumes the array has at least two elements (a[0]
 4   ## and a[1]). It initializes both min and max to a[0]
 5   ## and then goes through the loop count-1 times.
 6   ## This program will use pointers.
 7   ##
 8   ##      t0 - points to array elements in turn
```

```
##      t1 - contains count of elements
##      t2 - contains min
##      t3 - contains max
##      t4 - each word from array in turn
##

##################################################
#                                                #
#               text segment                     #
#                                                #
##################################################

        .text
        .globl __start
__start:
        la $t0,array    # $t0 will point to elements
        lw $t1,count    # exit loop when $t1 is 0
        lw $t2,($t0)    # initialize both min ($t2)
        lw $t3,($t0)    #      and max ($t3) to a[0]
        add $t0,$t0,4   # pointer to start at a[1]
        add $t1,$t1,-1  # and go round count-1 times


loop:   lw $t4,($t0)    # load next word from array
        bge $t4,$t2,notMin
                        # skip if a[i] >= min
        move $t2,$t4    # copy a[i] to min
notMin: ble $t4,$t3,notMax
                        # skip if a[i] <= max
        move $t3,$t4    # copy a[i] to max
notMax: add $t1,$t1,-1  # decrement counter
        add $t0,$t0,4   # increment pointer by word
        bnez $t1,loop   # and continue if counter>0

        la $a0,ans1
        li $v0,4
        syscall         # print "min = "

        move $a0,$t2
        li $v0,1
        syscall         # print min

        la $a0,ans2
        li $v0,4
        syscall         # print "\nmax = "

```

```
            move $a0,$t3
            li $v0,1
            syscall         # print max

            la $a0,endl     # system call to print
            li $v0,4        # out a newline
            syscall

            li $v0,10
            syscall         # au revoir...

#################################################
#                                               #
#                data segment                   #
#                                               #
#################################################

            .data

array:      .word 3,4,2,6,12,7,18,26,2,14,19,7,8,12,13
count:      .word 15
endl:       .asciiz "\n"
ans1:       .asciiz "min = "
ans2:       .asciiz "\nmax = "

##
## end of file minmax.a
```

Two more example programs that test your understanding of arrays of words are `loop1.a` and `loop6.a`.

```
## Start of file loop1.a
##
## Question:
## calculate the sum of the elements in "array"
## "count" holds the number of elements in "array"
##
## Output format must be:
## "sum = 15"

#################################################
#                                               #
#                text segment                   #
#                                               #
#################################################
```

```

         .text
         .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

         .data
array:   .word 3,4,2,6
count:   .word 4
ans1:    .asciiz "sum = "
endl:    .asciiz "\n"
##
## End of file loop1.a
```

```
## Start of file loop6.a
##
## Question:
## "numbers" is an array of five words.
## Calculate the sum of all elements in "numbers"
## whose value is less than 1000.
##
## Output format must be:
## "sum = 11"

 #################################################
 #                                               #
 #               text segment                    #
 #                                               #
 #################################################
```

```

         .text
         .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

         .data
numbers:
         .word 3,2000,2,6,2000
ans:     .asciiz "sum = "
endl:    .asciiz "\n"
##
## End of file loop6.a
```

Further example programs that test your understanding of program loops using arrays of words are in Appendix A.3.

6.8 EXAMPLE PROGRAM USING INDEXED ADDRESSING

A useful mode for accessing elements of an array is called 'indexed addressing'. The assembler gives the programmer the option of using this mode with a pseudo-instruction, since this mode cannot fit into the instruction formats in Figure 6.1. The index of an element in an array is its position in the list, with zero usually referring to the first item. The idea is to use the contents of a register as an index, and add this index to the 'base address' specified in the instruction. The syntax is:

```
lw rd,addr(rx)
```

A good way to visualize indexed addressing is to think of the second operand as an array access like

```
addr[rx]
```

This mode also applies to other load and store instructions like `lb`. If the quantity to be added to the register does not fit in 16 bits, the assembler generates this addressing mode as a pseudo-instruction. Program `count.a` uses indexed addressing to go along a string counting the occurrences of a particular character.

```
## count.a - count the occurrences of a specific
## character in string "str".
## Indexed addressing used to access array elements.
##
##      t0 - holds each byte from string in turn
##      t1 - index into array
##      t2 - count of occurrences
##      t3 - holds the character to count
##

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
  __start:
        li $t1,0        # $t1 will be the array index
        li $t2,0        # $t2 will be the counter
        lb $t3,char     # and $t3 will hold the char

loop:   lb $t0,str($t1) # fetch next char
        beqz $t0,strEnd # if it's a null, exit loop
        bne $t0,$t3,con # not null; same as char?
        add $t2,$t2,1   # yes,increment counter
con:    add $t1,$t1,1   # increase index
        j loop          # and continue
```

```
30
31   strEnd:
32           la $a0,ans       # system call to print
33           li $v0,4         # out a message
34           syscall
35
36           move $a0,$t2     # system call to print
37           li $v0,1         # out the count worked out
38           syscall
39
40           la $a0,endl      # system call to print
41           li $v0,4         # out a newline
42           syscall
43
44           li $v0,10
45           syscall          # au revoir...
46
47   #################################################
48   #                                               #
49   #               data segment                    #
50   #                                               #
51   #################################################
52
53           .data
54   str:    .asciiz "abceebceebeebbacacb"
55   char:   .asciiz "e"
56   ans:    .asciiz "Count is "
57   endl:   .asciiz "\n"
58
59   ##
60   ## end of file count.a
```

Line 24 uses a register as an index into an array. Since `str` is a 32-bit address, this will not fit in any of the formats in Figure 6.1. The assembler uses `$1` to build the address and then uses the base addressing mode, Figure 6.4, to access the operand.

```
lb $t0,str($t1)
```

becomes (`str` has the value 0x10010000)

```
lui $at,4097
addu $at,$at,$t1
lb $t0,($at)
```

6.9 BASE REGISTER ADDRESSING VS. INDEXED ADDRESSING

The indexed addressing and base register addressing modes are closely related. In indexed addressing, the base (for example the array start) is part of the instruction and the index is in the register, to allow us to increment the register each time through a loop or otherwise calculate the index.

In base register addressing, the base is in the register and the offset is part of the instruction, because members of high-level language structures are always at a fixed offset from the beginning of the structure. By putting the base in a register we can use the register as a pointer to the structure. To make this mode more useful, MIPS has the `la` instruction for loading a pointer (the address) into a register. In both cases the address used is the sum of the item before the brackets and the item inside them.

6.10 SUMMARY

The different ways of determining the address of an operand are called addressing modes. Every MIPS instruction consists of a single 32-bit word aligned on a word boundary. Instructions using register addressing execute quickly because they avoid the delays associated with memory access. In base register addressing a small constant is added to a pointer held in a register. Immediate addressing has the advantage of not requiring an extra memory access to fetch the operand, but the operand is limited to 16 bits in size. Indexed addressing uses the contents of a register as an index, and adds this index to the base address specified in the instruction.

EXERCISES

6.1 What is an addressing mode?
6.2 How many bytes are needed to store each MIPS instruction?
6.3 How many bits are needed to specify a MIPS register in an instruction?
6.4 How big can an immediate constant be if it fits in a single instruction?
6.5 Using Figure 6.3 and Figure 6.1, determine the machine code for `lui $t3,15`. Verify your answer using XSPIM.
6.6 Using Figure 6.3 and Figure 6.1 determine the machine code for `add $t4,$t3,$t3`. Verify your answer using XSPIM.

CHAPTER 7

Logical, shift and rotate instructions

7.1 INTRODUCTION

This chapter first looks at shift and rotate instructions. It then considers logical instructions, showing in an example program how these instructions can be used to convert a decimal number to an ASCII string in hexadecimal format. Logical, shift and rotate instructions are all used to manipulate the individual bits of a word.

7.2 SHIFT AND ROTATE INSTRUCTIONS

Shift and rotate instructions can change the positions of all the bits in a word in interesting ways. The bits in a word can be shifted either to the left or to the right. If shifted to the left, a zero is always shifted into the low-order bit. A logical shift right puts a zcro into the high-order bit, but in an arithmetic shift right, the high-order bit is preserved, as illustrated in Figure 7.1. This is so that if the number was a negative two's complement number, the sign will not be altered by the arithmetic shift right instruction. Shift instructions can be used to multiply or divide by powers of two.

Rotates are similar to shifts except that the bit which falls off one end is moved into the opposite end of the word. Rotate left is shown in Figure 7.2.

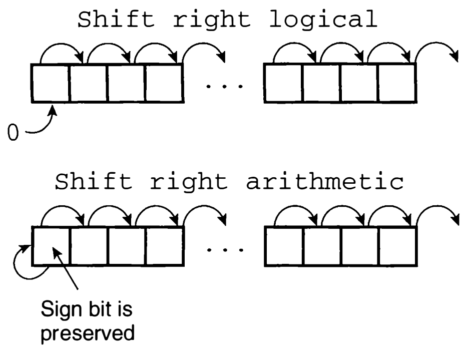


Figure 7.1 Logical and arithmetic shift right.

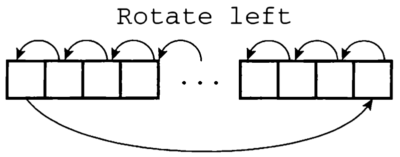


Figure 7.2 Rotate left instruction.

7.3 LOGICAL INSTRUCTIONS

There are five logical operations that have corresponding MIPS instructions – `and`, `or`, `nor`, `not` and `xor`. `Nor` means not or, and `xor` means exclusive or. The logical operations can be described using truth tables which are applied to the individual bits in a register or registers.

`and`, `or`, `nor` and `xor` require two operands; `not` requires only one.

`not` reverses the ones and zeros in a register, as shown in Figure 7.3.

The `and` instruction requires two operands. The result for each bit is one only if both operands are one (Figure 7.4). The format is like the `add` instruction – the second operand can be either a register or a constant. One of the commonest uses of the `and` instruction is to clear parts of a word, leaving the rest unchanged. This is achieved by putting a one in the positions that we want to keep, a zero in the positions we want to blank and using the `and` instruction (see Section 7.4).

Rsrc1	Rdest
0	1
1	0

Figure 7.3 Truth table for `not` instruction.

Rsrc1	Src2	Rdest
0	0	0
0	1	0
1	0	0
1	1	1

Figure 7.4 Truth table for `and` instruction.

The `or` instruction also needs two operands. The result for each bit is one if either operand is a one (Figure 7.5). `or` can be used to set certain bits in a word, leaving other bits unchanged. This is achieved by putting a zero in the positions that we want to keep, a one in the positions we want to set and using the `or` instruction (see Section 7.4).

The `xor` instruction, exclusive `or`, is the same as `or`, except the result is zero if both operands are one (Figure 7.6). The `nor` instruction means not `or` (Figure 7.7). Table 7.1 lists the usage of some of the MIPS processor's logical instructions.

Rsrc1	Src2	Rdest
0	0	0
0	1	1
1	0	1
1	1	1

Figure 7.5 Truth table for `or` instruction.

Rsrc1	Src2	Rdest
0	0	0
0	1	1
1	0	1
1	1	0

Figure 7.6 Truth table for `xor` instruction.

Rsrc1	Src2	Rdest
0	0	1
0	1	0
1	0	0
1	1	0

Figure 7.7 Truth table for `nor` instruction.

Table 7.1 Examples of MIPS logical instructions.

Instruction		**Example**
And	`and  $t1,$t2,$t3`	`#$t1 = $t2 & $t3`
And immediate	`andi $t1,$t2,8`	`#$t1 = $t2 & 8`
Or	`or   $t1,$t2,$t3`	`#$t1 = $t2 | $t3`
Or immediate	`ori  $t1,$t2,15`	`#$t1 = $t2 | 15`
Xor	`xor  $t1,$t2,$t3`	`#$t1 = $t2 ⊕ $t3`
Xor immediate	`xori $t1,$t2,9`	`#$t1 = $t2 ⦶ 9`
Nor	`nor  $t1,$t2,$t3`	`#$t1 = ~($t2 | $t3)`
Shift left logical	`all  $t1,$t2,3`	`#$t1 = $t2 << 3`
Shift left logical by variable	`sllv $t1,$t2,$t3`	`#$t1 = $t2 << $t3`
Shift right logical	`srl  $t1,$t2,10`	`#$t1 = $t2 >> 10`
Shift right logical by variable	`srlv $t1,$t2,$t3`	`#$t1 = $t2 >> $t3`
Shift right arithmetic	`sra  $t1,$t2,6`	`#$t1 = $t2 >> 6` `#sign extend`
Shift right arithmetic by variable	`srav $t1,$t2,$t3`	`#$t1 = $t2 >> $t3` `#sign extend`

7.4 AN EXAMPLE PROGRAM

The program `hex.a` asks a user for decimal number, converts it to hex, and prints the result.

```
##
## hex.a ask user for decimal number,
##  convert to hex, print the result.
##
##      t0 - count for 8 digits in word
##      t1 - each hex digit in turn
##      t2 - number read in
##      t3 - address of area used to set up
##           answer string
##

##############################################
#                                            #
#               text segment                 #
#                                            #
##############################################
```

```

        .text
        .globl __start
__start:
        la $a0,prompt   # print prompt on terminal
        li $v0,4
        syscall

        li $v0,5        # syscall 5 reads an integer
        syscall
        move $t2,$v0    # $t2 holds hex number

        la $a0,ans1     # print string before result
        li $v0,4
        syscall

        li $t0,8        # eight hex digits in word
        la $t3,result   # answer string set up here

loop:   rol $t2,$t2,4   # start with leftmost digit
        and $t1,$t2,0xf # mask one digit
        ble $t1,9,print # check if 0 to 9
        add $t1,$t1,7   # 7 chars between '9' and 'A'
print:  add $t1,$t1,48  # ASCII '0' is 48
        sb $t1,($t3)    # save in string
        add $t3,$t3,1   # advance destination pointer
        add $t0,$t0,-1  # decrement counter
        bnez $t0,loop   # and continue if counter>0

        la $a0,result   # print result on terminal
        li $v0,4
        syscall

        li $v0,10
        syscall         # au revoir...


#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
result: .space 8
        .asciiz "\n"
```

```
63   prompt: .asciiz "Enter decimal number: "
64   ans1:   .asciiz "Hexadecimal is "
65
66   ##
67   ## end of file hex.a
```

An interesting example use of the `or` instruction is to implement the `la` pseudo-instruction, which loads a 32-bit address into a register, for example line 21 of `hex.a`:

```
la $a0,prompt
```

The address of the `prompt` string is 0x1001000a. `lui`, load upper immediate, means load the immediate operand into the upper halfword of the register, setting the lower bits of the register are set to zero. The first component of the pseudo-instruction puts 0x1001 in the top 16 bits of the register using `lui`, then the logical `or` instruction is used to put the value 0x000a into the lower 16 bits, without altering the top 16:

```
lui $1,4097
ori $4,$1,10
```

Line 36 uses the `rol` instruction to bring each hexadecimal digit in turn into the least significant nibble of the register `$t2` so that it can be converted to the corresponding ASCII code. It is important to study the layout of the ASCII table (Figure 2.8) to understand lines 38 to 40. The ASCII code for '0' is 48, and there are seven ASCII characters between '9' and 'A'.

One of the commonest uses of the `and` instruction is to clear parts of a word leaving the rest unchanged. An example of this is line 37, used to blank out everything in a word except the least significant nibble, to allow generation of the ASCII code for each hexadecimal digit in turn.

`hex.a` is also interesting because it uses the

```
.space n
```

assembler directive to allocate *n* bytes of space in the current segment (which must be the data segment in SPIM). Line 61 allocates eight bytes which are then used by the program to store the ASCII codes it wishes to print out (line 41), before making the system call to output a character string (line 48).

Another related program that illustrates the usage of the `div` and `rem` pseudo-instructions is `dec.a`, a program that converts a number to a decimal ASCII string:

```
1   ##
2   ##  dec.a ask user for decimal number,
3   ##  convert to ASCII string, print the result.
4   ##
5   ##      t0 - number read in, each quotient in turn
6   ##      t1 - points to memory for string
```

```
##      t2 - each byte for the string in turn
##

#################################################
#                                               #
#                text segment                   #
#                                               #
#################################################

        .text
        .globl __start
__start:
        la $a0,prompt   # print prompt on terminal
        li $v0,4
        syscall

        li $v0,5        # syscall 5 reads an integer
        syscall
        move $t0,$v0    # $t0 holds number

        la $t1,result   # answer string set up here
        add $t1,11

        li $t2,0
        sb $t2,($t1)    # save in string
        sub $t1,1       # adjust destination pointer
        li $t2,'\n'
        sb $t2,($t1)    # save in string

loop:   rem $t2,$t0,10  # get the remainder
        add $t2,48      # convert to ASCII code
        sub $t1,1       # adjust destination pointer
        sb $t2,($t1)    # save in string
        div $t0,$t0,10  # get quotient
        bnez $t0,loop   # and continue if quotient>0

        la $a0,ans1     # print string before result
        li $v0,4
        syscall

        move $a0,$t1    # print result on terminal
        li $v0,4
        syscall

        li $v0,10
        syscall         # au revoir...
```

```
53
54
55   #################################################
56   #                                               #
57   #                data segment                   #
58   #                                               #
59   #################################################
60
61           .data
62   result: .space 12
63   ans1:   .asciiz "ASCII string is "
64   prompt: .asciiz "Enter decimal number: "
65
66   ##
67   ## end of file dec.a
```

It is not easy to convert a binary number to a decimal ASCII string because there is no direct correspondence between groups of bits and characters, as in `hex.a`. The correct procedure is to repeatedly divide the number by 10 (line 36), and use the remainder generated to construct the ASCII code (line 37). The step is repeated each time round the loop until the quotient produced equals zero (line 41).

This algorithm generates the characters in the reverse order needed, so the string is built from the end backwards (line 28). An alternative way to do this could be to use a rotate instruction to assemble the characters in the right order.

Two more example programs that test your understanding of the bit manipulation instructions are `logic1.a` and `logic2.a`.

```
 1   ## Start of file logic1.a
 2   ##
 3   ## Question:
 4   ## "numbers" is an array of five words.
 5   ## Calculate the sum of all elements in "numbers"
 6   ## that are not multiples of 4.
 7   ## Use the and instruction, not div or rem for
 8   ## this question.
 9   ##
10   ## Output format must be:
11   ## "sum = 20"
12
13   #################################################
14   #                                               #
15   #                text segment                   #
16   #                                               #
17   #################################################
```

```

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
numbers:
        .word 3,4,12,28,17
ans:    .asciiz "sum = "
endl:   .asciiz "\n"
##
## End of file logic1.a
```

```
## Start of file logic2.a
##
## Question:
## "number" is a word.
## Write it out in base 2 as a sequence of 32 bits.
##
## Output format must be:
## "binary is = 00000000000000000000000000010001"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################
```

```

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

##################################################
#                                                #
#               data segment                     #
#                                                #
##################################################

        .data
number: .word 17
result: .space 50
ans:    .asciiz "binary is = "
endl:   .asciiz "\n"
##
## End of file logic2.a
```

Further programs to test your understanding of logical, shift and rotate instructions are in Appendix A.4.

7.5 SUMMARY

Logical, shift and rotate instructions are all used to manipulate the individual bits of a word. The bits in a word can be shifted either to the left or to the right. Rotates are similar to shifts except the bit which falls off one end is put into the opposite end of the word. There are five logical operations that have corresponding MIPS instructions – `and`, `or`, `nor`, `not` and `xor`. `nor` means not or, and `xor` means exclusive or.

EXERCISES

7.1 Write down the truth table for the `xor` instruction.
7.2 What is the difference between logical and arithmetic shifts?
7.3 Describe an example use of the `and` instruction.
7.4 Describe how an assembler implements the `la` pseudo-instruction.
7.5 Give the algorithm to convert a number to a decimal ASCII string.
7.6 Give the algorithm to convert a number to a hexadecimal ASCII string.

CHAPTER 8

Stacks and procedures

8.1 INTRODUCTION

This chapter first introduces the stack data structure, and then illustrates its usage with a program to reverse a string using a stack. The techniques to support procedure calls in MIPS assembly language are then studied. Procedures allow programs to be broken into smaller more manageable units. They are fundamental to the development of programs longer than a few dozen statements. Procedures allow the reuse of the same group of statements many times by referring to them by name rather than repeating the code. In addition, procedures make large programs easier to read and understand. Stack frames, needed to implement procedure calls, are discussed. Two recursive programs are given that calculate Fibonacci's series and solve the Towers of Hanoi problem, and example code from a real compiler is discussed.

8.2 THE STACK

A stack of data elements is a last in, first out data structure. Items are added and removed from the top of the stack as shown in Figure 8.1. This is referred to as pushing and popping the stack. Because the stack is so frequently used, a special register, the stack pointer `$sp`, always holds the address of the top of the stack. The MIPS stack is upside down – elements are added at progressively lower memory addresses.

Pushing something on the stack is accomplished by two instructions.

```
sub $sp,$sp,4
sw $t0,($sp)
```

pushes the word in `$t0` onto the stack. The `sw` instruction stores a word into memory from a register (Figure 8.2). The stack pointer is usually incremented

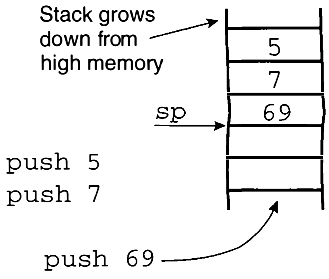


Figure 8.1 Stack data structure.

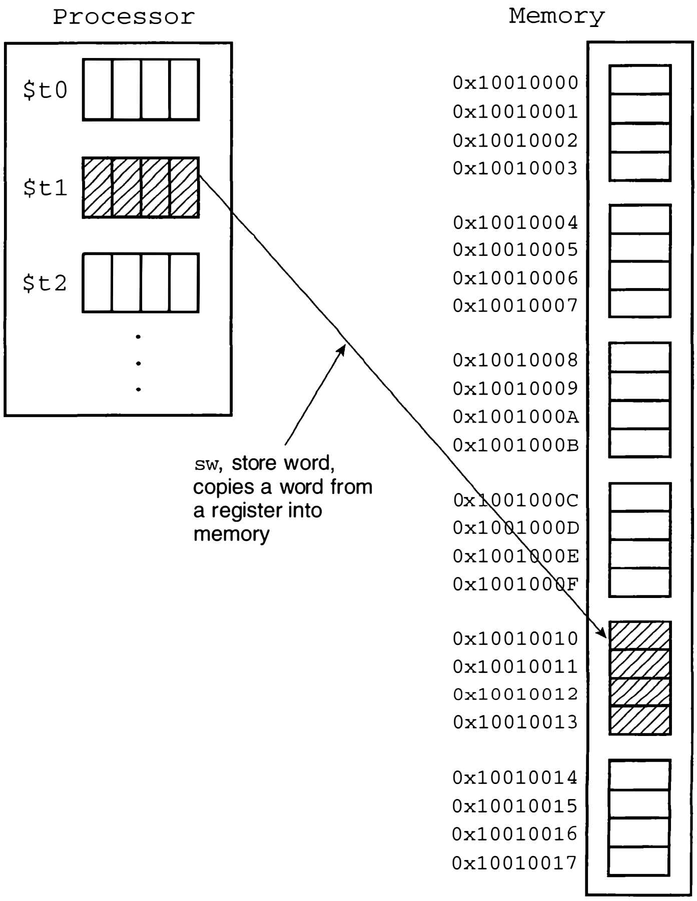


Figure 8.2 sw: store word instruction.

or decremented by four even if a byte is being pushed, so that $sp will always be aligned correctly if a word is subsequently pushed. The actions above are reversed to pop something off the stack.

```
lw $t0,($sp)
add $sp,$sp,4
```

pops the word from the top of stack into $t0. A stack can have many uses, for example to reverse the order of a list of data items or a string as shown in reverse.a.

```
##
## reverse.a - reverse the character
## string "str".
##
##      t1 - points to the string
##      t0 - holds each byte from string in turn
##

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################


        .text
        .globl __start
__start:                # execution starts here
        la $t1,str      # a0 points to the string
nextCh: lb $t0,($t1)    # get a byte from string
        beqz $t0,strEnd # zero means end of string
        sub $sp,$sp,4   # adjust stack pointer
        sw $t0,($sp)    # PUSH the t0 register
        add $t1,1       # move pointer one character
        j nextCh        # go round the loop again

strEnd: la $t1,str      # a0 points to the string
store:  lb $t0,($t1)    # get a byte from string
        beqz $t0,done   # zero means end of string
        lw $t0,($sp)    # POP a value from the stack
        add $sp,$sp,4   # and adjust the pointer
        sb $t0,($t1)    # store in string
        add $t1,1       # move pointer one character
        j store

done:   la $a0,str       # system call to print
        li $v0,4         # out a message
        syscall

        la $a0,endl      # system call to print
        li $v0,4         # out a newline
        syscall

        li $v0,10
        syscall          # au revoir...


#################################################
#                                               #
#                data segment                   #
#                                               #
#################################################

        .data
str:    .asciiz "hello world"
endl:   .asciiz "\n"

##
## end of file reverse.a
```

Two example programs that test your understanding of the stack mechanism are `stack1.a` and `stack6.a`.

```
## Start of file stack1.a
##
## Question:
##
## Count the number of negative words on
## the stack by popping the stack until a
## non-negative word is found, and print
## out the number of words popped.
##
## Do not rely on the existence on the "test"
## or "num" variables, or the code above the
## dashed line.
##
```

```
## Output format must be:
## "Number is = 5"

#################################################
#                                               #
#                text segment                   #
#                                               #
#################################################

       .text
       .globl __start
__start:               # execution starts here

       la $t0,test     # This code sets up the stack
       lw $t1,num      # Do not alter
loop:  lw $t2,($t0)
       sub $sp,$sp,4
       sw $t2,($sp)
       add $t0,$t0,4
       add $t1,$t1,-1
       bnez $t1,loop
                       # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#                data segment                   #
#                                               #
#################################################

       .data
test:  .word 2,0xffffffd5,0xfffabfff,-3,-4,-9
num:   .word 6
ans:   .asciiz "Number is = "
endl:  .asciiz "\n"
##
## End of file stack1.a
## Start of file stack6.a
##
## Question:
##
## Count the number of words on
## the stack with at most four bits set
## by popping the stack until a
## word is found with five or more bits set,
## and print
## out the number of words popped.
##
## Do not rely on the existence on the "test"
## or "num" variables, or the code above the
## dashed line.
##
## Output format must be:
## "Number is = 4"

#################################################
#                                               #
#              text segment                     #
#                                               #
#################################################

       .text
       .globl __start
__start:                # execution starts here

       la $t0,test     # This code sets up the stack
       lw $t1,num      # Do not alter
loop:  lw $t2,($t0)
       sub $sp,$sp,4
       sw $t2,($sp)
       add $t0,$t0,4
       add $t1,$t1,-1
       bnez $t1,loop
                        # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

################################################
#                                              #
#                data segment                  #
#                                              #
################################################

        .data
test:   .word 2,0xff,4,1,1,1
num:    .word 6
ans:    .asciiz "Number is = "
endl:   .asciiz "\n"
##
## End of file stack6.a
```

Further example programs that test your understanding of the stack instructions are in Appendix A.5.

8.3 PROCEDURE CALLS

A very important type of control structure is the code used to implement procedure and function calls. Procedures are the most important technique for structuring programs. We need a way to keep track of the calling location, so that the program can resume where it left off when the procedure finishes, and a way to pass parameters and return results. Also, a convention for creating local variables must be adopted.

The call/return mechanism in MIPS is very easy. The jump and link instruction puts the return address into a special register `$ra` before executing the code for the procedure, as shown in Figure 8.3.

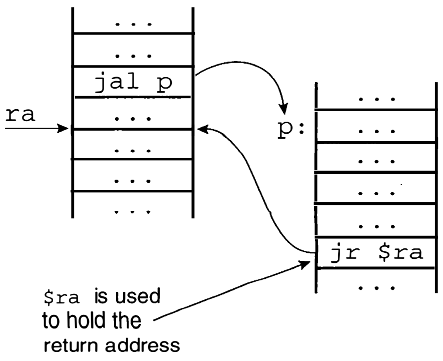


Figure 8.3 Procedure call mechanism.

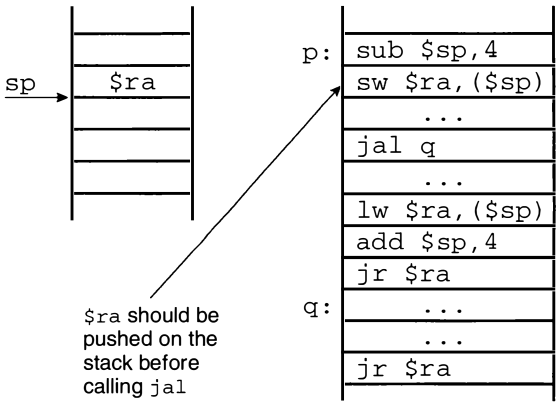


Figure 8.4 Using the stack for a return address.

At runtime, the processor puts the value PC+4 in `$ra` when `jal` is executed, and after the called procedure is finished it just has to do a jump register to return. If `p` calls another procedure, though, things are a bit more complicated – `p` has to save its return address on a stack, as shown in Figure 8.4, because the return address will be overwritten.

8.4 PASSING PARAMETERS

The first four parameters of a procedure are passed in the argument registers `$a0..$a3`. Additional parameters are passed on the stack. `$v0` and `$v1` are for returned values.

Thus, a procedure to see if a letter is a vowel would look like this:

```
vowelp: li $v0,0
        beq  $a0,'a',yes
        beq  $a0,'e',yes
        beq  $a0,'i',yes
        beq  $a0,'o',yes
        beq  $a0,'u',yes
        jr $ra
yes:    li $v0,1
        jr $ra
```

The procedure `vowelp` takes a single character as a parameter and returns one if the character is a (lower-case) vowel, otherwise it returns zero. It adopts the MIPS conventions for register usage.

8.5 TEMPORARY AND SAVED REGISTERS

When a procedure uses local variables, it is best to keep as many as possible in registers, because it is much faster to access registers than memory. The problem with this is that when one procedure calls another, the registers may have to be saved so that the values contained in them will not be lost.

There are two basic strategies for saving registers at a procedure call. 'Caller saves' means that the code that makes the call will put register values on the stack. 'Callee saves' means that the called procedure will do the saving. The advantage of caller saves is that the caller knows which registers it will be using, so it won't save a value not needed when it returns. The advantage of callee saves is that the callee knows which registers it needs and will only save these registers.

For example, if a procedure is using a variable that will not be needed after calling another procedure, it will keep it in a caller save register and not save the register. Thus by wisely selecting which values are stored in caller saved and which in callee saved, the number of loads and stores can be minimized.

In MIPS, the designers adopted the following conventions: `$s0..$s7` are callee saves, which means that the caller can count on them being restored when control returns. `$t0..$t9` are caller saves which, as the name implies, are usually temporary registers. If their values will be needed, the caller saves them before making the call. The called procedure can therefore modify any of the registers `$t0..$t9` without constraint. For example:

```
code using $s0..$s7
jal p
$s0..$s7 have not changed,
   but $t0..$t9 may have been altered
```

There are two problems with using registers for local variables:

- What if there are not enough registers?
- What if the procedure wants to call another procedure?

Stack frames are used to solve these problems.

8.6 STACK FRAMES

In almost every modern programming language, a procedure may have local variables that are created on entry. Since a procedure returns only after all the procedures it has called have returned, procedure calls are said to behave in last in, first out (LIFO) fashion. If local variables are created on procedure entry and destroyed on procedure exit, a stack is the ideal data structure to hold them.

So far the simple stack data structure supports two operations – push and pop. However, local variables may be pushed in large batches on entry to procedures and popped in large batches on exit. Local variables are not always initialized as soon as they are created, and when many variables have been created we want to access those deep within the stack, so the simple push and pop model is no longer sufficient.

A special type of data structure that uses base register addressing, called the stack frame (Figure 8.5), is used to overcome these difficulties. Stack frames are used in procedure calls. The stack usually only grows on entry to a procedure. The compiler figures out how big the frame needs to be (for example, *n* bytes). The first thing it does in the body of the procedure is subtract *n* from the stack pointer, which allocates a structure of size *n* on the stack. This process is called the procedure prologue. The compiler shrinks the stack by the same amount *n* just before exiting from a procedure in the procedure epilogue. Sometimes a compiler finds it convenient to use a register which points to a fixed location within the stack frame, called a frame pointer, and access the local variables which reference it rather than the stack pointer itself. The stack pointer can then be used by the compiler to evaluate expressions.

Whenever it is necessary to access a local variable or parameter on the stack frame, base mode addressing using `$fp` as the base address is used, for example:

```
lw $s0,0($fp)
lw $s1,4($fp)
lw $s2,8($fp)
lw $s3,12($fp)
```

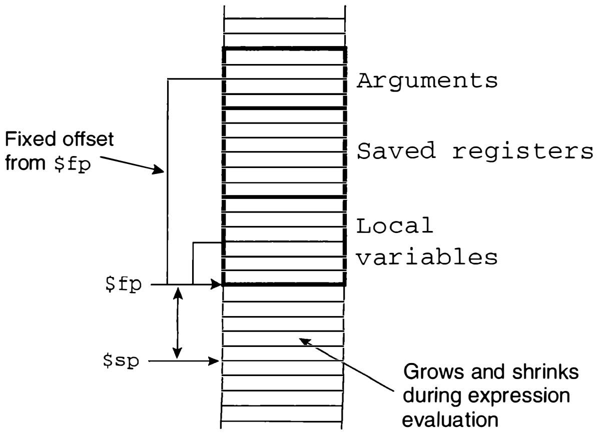


Figure 8.5 One possible organization for a MIPS stack frame.

Processors like the MIPS were designed for high-level language compilation, and as such are targeted at compilers rather than human programmers. When compiling a program the compiler simulates the runtime stack to help decide what values are placed in registers and what values are on the stack during procedure call. This is the motivation for the caller and callee save registers. Traffic between the processor and the memory is minimized at the expense of increasing the complexity in the compiler.

`vowel.a` prints out the number of vowels in the string str.

```
##
## vowel.a - prints out number of vowels in
##          - the string str
##
##       a0 - points to the string
##

################################################
#                                              #
#               text segment                   #
#                                              #
################################################

        .text
        .globl __start
__start:                # execution starts here


        la $a0,str
        jal vcount      # call vcount

        move $a0,$v0
        li $v0,1
        syscall         # print answer


        la $a0,endl
        li $v0,4
        syscall         # print newline

        li $v0,10
        syscall         # au revoir...

```

```
#-----------------------------------------------
# vowelp - takes a single character as a
# parameter and returns 1 if the character
# is a (lower case) vowel otherwise return 0.
#       a0 - holds character
#       v0 - returns 0 or 1
#-----------------------------------------------

vowelp: li $v0,0
        beq  $a0,'a',yes
        beq  $a0,'e',yes
        beq  $a0,'i',yes
        beq  $a0,'o',yes
        beq  $a0,'u',yes
        jr $ra
yes:    li $v0,1
        jr $ra


#-----------------------------------------------
# vcount - use vowelp to count the vowels in a
# string.
#       a0 - holds string address
#       s0 - holds number of vowels
#       v0 - returns number of vowels
#-----------------------------------------------

vcount:
        sub $sp,$sp,16  # save registers on stack
        sw $a0,0($sp)
        sw $s0,4($sp)
        sw $s1,8($sp)
        sw $ra,12($sp)

        li $s0,0        # count of vowels
        move $s1,$a0    # address of string

nextc:  lb $a0,($s1)    # get each character
        beqz $a0,done   # zero marks end
        jal vowelp      # call vowelp
        add $s0,$s0,$v0 # add 0 or 1 to count
        add $s1,$s1,1   # move along string
        b nextc
done:   move $v0,$s0    # use $v0 for result

        lw $a0,0($sp)   # restore registers
```

```
80          lw $s0,4($sp)
81          lw $s1,8($sp)
82          lw $ra,12($sp)
83          add $sp,$sp,16
84          jr $ra
85
86
87  #################################################
88  #                                               #
89  #               data segment                    #
90  #                                               #
91  #################################################
92
93
94          .data
95  str:    .asciiz "long time ago in a galaxy far away"
96  endl:   .asciiz "\n"
97
98  ##
99  ## end of file vowel.a
```

We have already looked at the simple procedure `vowelp`. The `vcount` procedure repeatedly calls `vowelp` to count the vowels in a string. Because `vcount` calls another procedure it must save its return address on the stack, as the value in `$ra` will be overwritten (line 66). `vcount` uses `$s0` and `$s1` for quantities of interest because it calls another procedure that could change `$t0` and `$t1`.

Two example programs that test your understanding of the procedure call mechanism are `funct1.a` and `funct2.a`.

```
 1  ## Start of file funct1.a
 2  ##
 3  ## Question:
 4  ## Write a function "addone" that takes an ascii
 5  ## character in $a0.
 6  ## If the character is a digit, increment it by
 7  ## one. '9' should go to '0'.
 8  ## If it is not a digit, return it unaltered
 9  ## in $v0.
10  ##
11  ## Write a function "stradd" that goes along
12  ## a string $a0 calling "addone" to add one
13  ## to all the digits in the string and stores
14  ## the returned characters into the string.
15  ##
```

```
## Output format must be:
## "abc1067xyz"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


        li $a0,'5'      # test addone function
        jal addone
        bne $v0,'6',exit

        la $a0,str
        jal stradd      # call stradd function
        li $v0,4
        syscall

exit:   li $v0,10
        syscall         # au revoir...

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
str:    .asciiz "abc0956xyz\n"
##
## End of file funct1.a
## Start of file funct2.a
##
## Question:
## Write a function "hexint" that takes the address
## of an ascii character string in $a0.
## The string will represent a number in
## hexadecimal and will only contain '0' to '9'
## and 'A' to 'F'.
## Return the actual number in the register $v0.
## Remember that the most significant nibble
## will be first in the string.
##
## Output format must be:
## "Number is = 1960"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


        la $a0,ans
        li $v0,4
        syscall

        la $a0,str
        jal hexint      # call hexint function

        move $a0,$v0
        li $v0,1
        syscall

        la $a0,endl     # system call to print
        li $v0,4        # out a newline
        syscall

exit:   li $v0,10
        syscall         # au revoir...

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
```

```
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
str:    .asciiz "7A8"
ans:    .asciiz "Number is = "
endl:   .asciiz "\n"
##
## End of file funct2.a
```

8.7 ASSEMBLY CODE FROM A REAL COMPILER

This section shows the assembly code and stack frame that might be used by a compiler to implement the following fragment of high-level language code:

```
int fun1(int n, int p)
{
        int i,j;
        i = 7;
        j = 9;
        if (n == 1)
                p = i;
        else
                p = j;
        return p;
}

int fun2(int num)
```

```
{
        int q,r;
        q = 5;
        r = fun1(q, num);
        return r;
}

int fun3(int y, int x)
{
        int a,b;
        a = fun1(5, 7);
        b = fun2(8);
        return a + b;
}
```

This code does not do anything useful; the three functions simply contain a number of arguments and local variables to illustrate the compiler's use of a stack frame. The assembly code produced is obviously inefficient, but if the compiler was asked to optimize the code, unnecessary space would not be wasted on the stack frames for these simple functions.

```
fun1:   subu    $sp,$sp,16
        sw      $fp,8($sp)
        move    $fp,$sp
        sw      $4,16($fp)
        sw      $5,20($fp)
        li      $2,0x00000007
        sw      $2,0($fp)
        li      $2,0x00000009
        sw      $2,4($fp)
        lw      $2,16($fp)
        li      $3,0x00000001
        bne     $2,$3,$L2
        lw      $2,0($fp)
        sw      $2,20($fp)
        j       $L3
$L2:    lw      $2,4($fp)
        sw      $2,20($fp)
$L3:    lw      $2,20($fp)
        j       $L1
$L1:    move    $sp,$fp
        lw      $fp,8($sp)
        addu    $sp,$sp,16
        j       $31


```

```
fun2:   subu    $sp,$sp,24
        sw      $31,20($sp)
        sw      $fp,16($sp)
        move    $fp,$sp
        sw      $4,24($fp)
        li      $2,0x00000005
        sw      $2,8($fp)
        lw      $4,8($fp)
        lw      $5,24($fp)
        jal     fun1
        sw      $2,12($fp)
        lw      $2,12($fp)
        j       $L4
$L4:    move    $sp,$fp
        lw      $31,20($sp)
        lw      $fp,16($sp)
        addu    $sp,$sp,24
        j       $31

fun3:   subu    $sp,$sp,24
        sw      $31,20($sp)
        sw      $fp,16($sp)
        move    $fp,$sp
        sw      $4,24($fp)
        sw      $5,28($fp)
        li      $4,0x00000005
        li      $5,0x00000007
        jal     fun1
        sw      $2,8($fp)
        li      $4,0x00000008
        jal     fun2
        sw      $2,12($fp)
        lw      $2,8($fp)
        lw      $4,12($fp)
        addu    $3,$2,$4
        move    $2,$3
        j       $L5
$L5:    move    $sp,$fp
        lw      $31,20($sp)
        lw      $fp,16($sp)
        addu    $sp,$sp,24
        j       $31
```

Space is allocated on the stack frame for the arguments to `fun1` (Figure 8.6) and `fun2` (Figure 8.7). Figure 8.8 shows the stack frame for `fun3`.

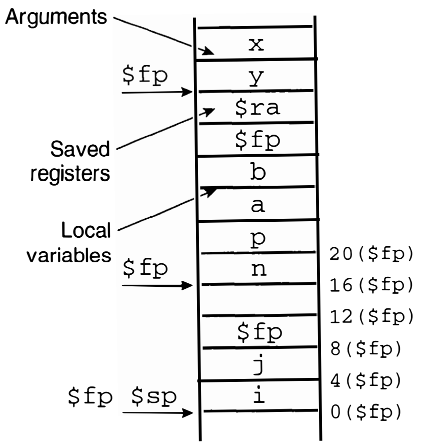


Figure 8.6 Stack frame for `fun1`.

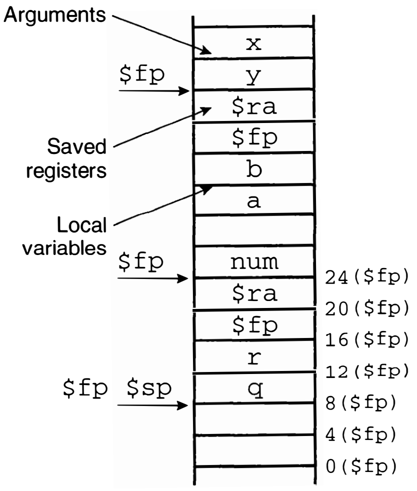


Figure 8.7 Stack frame for `fun2`.

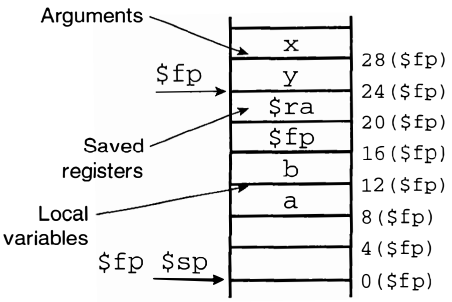


Figure 8.8 Stack frame for `fun3`.

8.8 EXAMPLE RECURSIVE PROGRAMS

Recursion is an important feature of many programming languages. A recursive task is one that calls itself. With each invocation, the problem is reduced to a smaller problem (reducing case) until the task arrives at some terminal or base case which stops the process.

8.8.1 FIBONACCI'S RABBITS

The original problem that Fibonacci investigated, in the year 1202, was how fast rabbits could breed in ideal circumstances. Suppose a newly born pair of rabbits, one male and one female, are put in a field. Rabbits are sexually mature after one month so that at the end of its second month a female can produce another pair of rabbits. Suppose that our rabbits never die and that females always produces one new pair (one male, one female) every month from the second month on. How many pairs will there be in one year?

- At the end of the first month they mate, but there is still one only one pair.
- At the end of the second month the female produces a new pair, so now there are two pairs of rabbits in the field.
- At the end of the third month, the original female produces a second pair, making three pairs in all in the field.
- At the end of the fourth month, the original female has produced yet another new pair, and the female born two months ago produces her first pair also, making five pairs.

Fibonacci's series therefore looks like:

n	0	1	2	3	4	5	6	7	8	9$\cdots$
$fib(n)$	0	1	1	2	3	5	8	13	21	34$\cdots$

One way to write a program to work these numbers out is to use a loop starting from the base case, as shown in the file `fibloop.a`.

```
##
## fibloop.a - looping implementation of the
##              Fibonacci function.
##
##      a0 - value to test function
##

################################################
#                                              #
#               text segment                   #
#                                              #
################################################
```

```

        .text
        .globl __start
__start:                # execution starts here
        li $a0,9
        jal fib         # call fib
        move $a0,$v0    # print result
        li $v0, 1
        syscall

        la $a0,endl
        li $v0,4
        syscall

        li $v0,10
        syscall         # au revoir...

#-----------------------------------------------
# fib - looping implementation of the
# Fibonacci function.
#       a0 - holds parameter n
#       t0 - save second last element computed
#       t1 - used to work out each new element
#       v0 - returns result
#-----------------------------------------------

fib:    move $v0,$a0    # initialize last element
        blt $a0,2,done  # fib(0)=0, fib(1)=1

        li $t0,0        # second last element
        li $v0,1        # last element

loop:   add $t1,$t0,$v0 # get next value
        move $t0,$v0    # update second last
        move $v0,$t1    # update last element
        sub $a0,1       # decrement count
        bgt $a0,1,loop  # exit loop when count=1
done:   jr $ra

################################################
#                                              #
#               data segment                   #
#                                              #
################################################

        .data
```

```
endl:   .asciiz "\n"

##
## end of file fibloop.a
```

In order to increase our understanding of procedures and stack frames, let us look at a recursive implementation. This implementation will be less efficient at runtime due to all the instructions needed to maintain the stack frames, and since there is a limited amount of memory available for a stack, if the function is called with a large parameter, space for the stack may run out.

We note that

$$fib(n) = fib(n-2) + fib(n-1)$$

and that

$$fib(0) = 0 \quad fib(1) = 1$$

The steps to evaluate *fib*(*n*) recursively are shown in Figure 8.9.

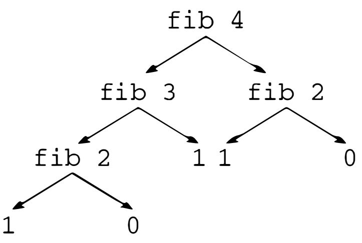


Figure 8.9 Recursive implementation of Fibonacci function.

```
##
## fib.a - recursive implementation of the
##          Fibonacci function.
##
##       a0 - value to test function
##

################################################
#                                              #
#               text segment                   #
#                                              #
################################################
```

```

        .text
        .globl __start
__start:                # execution starts here
        li $a0,9
        jal fib         # call fib
        move $a0,$v0    # print result
        li $v0, 1
        syscall

        la $a0,endl
        li $v0,4
        syscall

        li $v0,10
        syscall         # au revoir...

#-----------------------------------------------
# fib - recursive implementation of the
# Fibonacci function.
#       a0 - holds parameter n
#       s0 - holds fib(n-1)
#       v0 - returns result
#-----------------------------------------------

fib:    sub $sp,$sp,12  # save registers on stack
        sw $a0,0($sp)
        sw $s0,4($sp)
        sw $ra,8($sp)

        bgt $a0,1,notOne
        move $v0,$a0    # fib(0)=0, fib(1)=1
        b fret          # if n<=1

notOne: sub $a0,$a0,1   # param = n-1
        jal fib         # compute fib(n-1)
        move $s0,$v0    # save fib(n-1)

        sub $a0,$a0,1   # set param to n-2
        jal fib         # and make recursive call
        add $v0,$v0,$s0 # add fib(n-2)

fret:   lw $a0,0($sp)   # restore registers
        lw $s0,4($sp)
        lw $ra,8($sp)
        add $sp,$sp,12
        jr $ra

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
endl:   .asciiz "\n"

##
## end of file fib.a
```

Note that a programming language that does not permit recursive procedures, for example older versions of Fortran, need not allocate frames on a stack, but can use ordinary memory for the local variables, since only one invocation of a procedure may be active at a time.

An example program that will test your understanding of the the recursion concept is `recur1.a`.

```
## Start of file recur1.a
##
## Question:
##
## Write a function named search that will do a
## depth first search of a tree for a marked
## node. A marked node is one that has a value
## field equal to 1. Only one node in the tree is
## marked.
##
## The parameters to search are a pointer to the
## tree and the current depth. On each recursive
## call add 1 to the depth. This parameter is
## used to keep track of the path from the root
## to the marked node; as you visit a node, you
## will call a procedure named store_path to
## record the fact that you have visited this
## node. The code for store_path and print_path
## (called after you get back from the procedure)
## have been written for you -- all you need to
## do is understand how to set up their parameters
## and make the call.
##
```

```
## The code for search could look like:
##           call store_path
##           if (value == 1)
##             return 1
##           if (left tree exists)
##             if (search(left tree, depth+1))
##              return 1
##           if (right tree exists)
##             return search(right tree, depth+1)
##           return 0
##
## Output format must be:
## "apple-->orange-->plum-->grape-->star-->passion"

#################################################
#                                               #
#             text segment                      #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here

        la $a0,tree
        li $a1,0
        jal search      # search the tree

        jal print_path  # print the path
                        # to the node with val=1
        li $v0,10
        syscall         # au revoir....


#-----------------------------------------------
# store_path - store pointer at level n in the path
#       a0 - holds pointer to string
#       a1 - level to use in path
#-----------------------------------------------
store_path:
        mul $t0,$a1,4   # each pointer is 4 bytes
        sw $a0,path($t0)# save pointer to the name
        addi $t0,$t0,4  # make the next entry
        sw $0,path($t0) #  equal to 0.
        jr $ra

```

```

#----------------------------------------------
# print_path() - print the items stored in path
#----------------------------------------------
print_path:
        li $t0,0         # i
        mul $t1,$t0,4    # each pointer is 4 bytes
        lw $a0,path($t1)
next:   li $v0,4
        syscall          # print path[i]
        addi $t0,$t0,1   # i++
        mul $t1,$t0,4    # each pointer is 4 bytes
        lw $a0,path($t1)
        beqz $a0,done
        move $t1,$a0
        la $a0,arrow
        li $v0,4
        syscall          # print "-->"
        move $a0,$t1
        b next
done:   la $a0,endl
        li $v0,4
        syscall          # print newline
        jr $ra

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data

# The binary tree.  Note that each node has four
# words - a pointer to the name, pointers to
# left and right subtrees, and the integer
# value field.

path:   .space 40

tree:   .word name0, node1, node2, 0
node1:  .word name1, node3, node4, 0
node2:  .word name2, node5, node6, 0
node3:  .word name3, node7, 0, 0
node4:  .word name4, node8, node9, 0
node5:  .word name5, 0, 0, 0
node6:  .word name6, node10, node11, 0
node7:  .word name7, 0, 0, 0
node8:  .word name8, 0, 0, 0
node9:  .word name9, node12, node13, 0
node10: .word name10, 0, 0, 0
node11: .word name11, 0, 0, 0
node12: .word name12, node14, node15, 0
node13: .word name13, 0, 0, 0
node14: .word name14, 0, 0, 1
node15: .word name15, node16, node17, 0
node16: .word name16, 0, 0, 0
node17: .word name17, 0, 0, 0

name0:  .asciiz "apple"
name1:  .asciiz "orange"
name2:  .asciiz "banana"
name3:  .asciiz "pear"
name4:  .asciiz "plum"
name5:  .asciiz "peach"
name6:  .asciiz "nectarine"
name7:  .asciiz "pineapple"
name8:  .asciiz "grapefruit"
name9:  .asciiz "grape"
name10: .asciiz "melon"
name11: .asciiz "avocado"
name12: .asciiz "star"
name13: .asciiz "mango"
name14: .asciiz "passion"
name15: .asciiz "cantaloupe"
name16: .asciiz "watermelon"
name17: .asciiz "apricot"

endl:   .asciiz "\n"
arrow:  .asciiz "-->;"
##
## End of file recur1.a
```

8.8.2 THE TOWERS OF HANOI

The above program to work out the numbers in the Fibonacci series is interesting because it tests that the procedure uses the stack frame correctly. It would, however, be much more efficient to start at the base case and use a simple loop to work out the numbers, saving all the loads and stores involved in setting up a stack frame. There are some programs, however, which would be very difficult to write without the use of recursion. An example is the Towers of Hanoi problem.

Legend has it that a group of Eastern monks are the keepers of three towers on which sit 64 golden rings. Originally all 64 rings were stacked on one tower with each ring smaller than the one beneath. The monks are to move the rings from this first tower to the third tower one at a time but never moving a larger ring on top of a smaller one. Once the 64 rings have all been moved, the world will come to an end.

Despite the seemingly convoluted nature of this puzzle, there is a simple recursive solution. If we need to move *n* rings from a tower (call it start) to another tower (called end) using the remaining tower as a spare, we can recursively move the top $n-1$ from start to spare using end as the spare (Figure 8.10). Notice that in the recursive solution for $n-1$ rings, we exchange the roles of the spare and end towers. Now we can move the bottom ring from start to end (Figure 8.11). Finally, we do another recursive move of the $n-1$ we put onto spare to the end tower, using start as the spare (Figure 8.11).

Program `hanoi.a` is a MIPS assembly language program to solve the Towers of Hanoi.

```
 1
 2
 3
----  ----  ----
 T1    T2    T3

 2
 3     1
----  ----  ----
 T1    T2    T3

 3     1     2
----  ----  ----
 T1    T2    T3

             1
 3           2
----  ----  ----
 T1    T2    T3
```

Figure 8.10 Recursively move the top $n-1$ rings from the start tower to the spare tower using the end tower as the spare tower.

```
             1
       3     2
----  ----  ----
 T1    T2    T3

 1     3     2
----  ----  ----
 T1    T2    T3

       2
 1     3
----  ----  ----
 T1    T2    T3

       1
       2
       3
----  ----  ----
 T1    T2    T3
```

Figure 8.11 Recursively move $n-1$ rings from the spare tower to the end tower using the start tower as the spare tower.

```
##
## hanoi.a - recursive implementation of the
##             towers of hanoi
##
##

################################################
#                                              #
#               text segment                   #
#                                              #
################################################

        .text
        .globl __start
__start:

        la $a0,tower1   # source
        la $a1,tower2   # destination
        la $a2,tower3   # temporary
        lw $a3,numRings

        jal moveStack   # call procedure

        jal PrintTowers # Print answer

        li $v0,10
        syscall         # au revoir...


#---------------------------------------------------
# moveStack - recursive implementation of the
# towers of hanoi
#       a0 - source tower
#       a1 - destination tower
#       a2 - spare tower
#       a3 - number of rings
#       s0 - source tower
#       s1 - destination tower
#       s2 - spare tower
#---------------------------------------------------
moveStack:
        sub $sp,$sp,32  # save registers on stack
        sw $a0,0($sp)
        sw $a1,4($sp)
        sw $a2,8($sp)
        sw $a3,12($sp)
        sw $s0,16($sp)
        sw $s1,20($sp)
        sw $s2,24($sp)
        sw $ra,28($sp)

        beq $a3,1,moveOne
                        # Move one ring only

        move $s0,$a0    # keep copy of source tower
        move $s1,$a1    # keep copy of destination
        move $s2,$a2    # keep copy of spare tower

        move $a0,$s0    # step 1:
        move $a1,$s2    # destination = spare tower
        move $a2,$s1
        sub $a3,$a3,1   # move n-1 rings
        jal moveStack

        move $a0,$s0    # step 2:
        move $a1,$s1
        jal moveRing    # move a ring to destination

        move $a0,$s2    # step 3:
        move $a1,$s1
        move $a2,$s0    # source = spare
        jal moveStack

        j end
moveOne:
        jal moveRing    # Move one ring only

end:    lw $a0,0($sp)   # restore registers
        lw $a1,4($sp)
        lw $a2,8($sp)
        lw $a3,12($sp)
        lw $s0,16($sp)
        lw $s1,20($sp)
        lw $s2,24($sp)
        lw $ra,28($sp)
        add $sp,$sp,32
        jr $ra

#-----------------------------------------------
# moveRing - move one ring from source to dest
#       a0 - source
#       a1 - dest
#       t0 - holds the value removed
#-----------------------------------------------
moveRing:
        sub $sp,$sp,12  # save registers on stack
        sw $a0,0($sp)
        sw $a1,4($sp)
        sw $ra,8($sp)

        jal PrintTowers # print out state of towers

finds:  sub $a0,$a0,4   # get the top ring
        lw $t0,($a0)
        beqz $t0,founds
        j finds         # find source
founds: add $a0,$a0,4

        lw $t0,($a0)    # t0 holds the value removed
        sw $0,($a0)     # set place to zero

findd:  sub $a1,$a1,4   # find destination
        lw $t1,($a1)
        beqz $t1,foundd
        j findd
foundd: sw $t0,($a1)    # destination found

```

```
        lw $a0,0($sp)   # restore registers
        lw $a1,4($sp)
        lw $ra,8($sp)
        add $sp,$sp,12

        jr $ra

#-----------------------------------------------
# PrintTowers - print out state of towers
#       s0 - number of rings
#       s1 - tower1
#       s2 - tower2
#       s3 - tower3
#-----------------------------------------------
PrintTowers:
        sub $sp,$sp,28  # save registers on stack
        sw $v0,0($sp)
        sw $a0,4($sp)
        sw $s0,8($sp)
        sw $s1,12($sp)
        sw $s2,16($sp)
        sw $s3,20($sp)
        sw $ra,24($sp)

        la $s1,tower1   # set up the registers
        la $s2,tower2   # from the data segment
        la $s3,tower3
        lw $s0,numRings

        mul $s0,$s0,4   # each word four bytes
        sub $s1,$s1,$s0 # get stacks ready
        sub $s2,$s2,$s0
        sub $s3,$s3,$s0

Loop:   beqz $s0,exit   # if at level -n done
        la $a0,Blanks
        li $v0,4        # system call to print
        syscall         # out a string

        lw $a0,($s1)    # read number on stack 1
        jal printOne    # print blank or ring
        lw $a0,($s2)    # read number on stack 2
        jal printOne    # print blank or ring
        lw $a0,($s3)    # read number on stack 3
        jal printOne    # print blank or ring

        la $a0,endl      # end line
        li $v0,4         # system call to print
        syscall          # out a string

        sub $s0,$s0,4    # move up to next level
        add $s1,$s1,4
        add $s2,$s2,4
        add $s3,$s3,4
        j Loop           # repeat until $s0=0

exit:   la $a0,Base      # print Tower names and lines
        li $v0,4         # system call to print
        syscall          # out a string

        lw $v0,0($sp)    # restore registers
        lw $a0,4($sp)
        lw $s0,8($sp)
        lw $s1,12($sp)
        lw $s2,16($sp)
        lw $s3,20($sp)
        lw $ra,24($sp)
        add $sp,$sp,28
        jr $ra


#-----------------------------------------------
# printOne - print blank or ring number
#       a0 - holds ring number or 0
#       v0 - parameter for system call
#-----------------------------------------------

printOne:
        sub $sp,$sp,12   # save registers on stack
        sw $a0,0($sp)
        sw $v0,4($sp)
        sw $ra,8($sp)

        bnez $a0,ring    # if not zero then print it
        la $a0,Blank
        li $v0,4         # system call to print
        syscall          # out a string

        j spaces
ring:   li $v0,1         # print number
        syscall

```

```
210   spaces: la $a0,Blanks   # space output out
211           li $v0,4        # system call to print
212           syscall         # out a string
213
214           lw $a0,0($sp)   # restore registers
215           lw $v0,4($sp)
216           lw $ra,8($sp)
217           add $sp,$sp,12
218           jr $ra
219
220   ################################################
221   #                                              #
222   #               data segment                   #
223   #                                              #
224   ################################################
225
226           .data
227   Blanks: .asciiz "       "
228   Blank:  .asciiz " "
229   endl:   .asciiz "\n"
230   Base:   .ascii  "     ____     ____     ____\n"
231           .asciiz "      T1       T2       T3\n\n\n"
232
233
234           .align 2
235   notused:
236           .word 0,0,0,0,0,0,0,1,2,3
237   tower1: .word 0,0,0,0,0,0,0,0,0,0
238   tower2: .word 0,0,0,0,0,0,0,0,0,0
239   tower3: .word 0
240   numRings:
241           .word 3
242
243   ##
244   ## end of file hanoi.a
```

The procedures in the program expect that stacks (representing stacks of rings on towers) are represented in the usual way for MIPS, with the base of the stack at the high-address end of the area that has been set aside for the stack (lincs 234 239) of `hanoi.a`.

When the stack is empty, the top of the stack is identical with the base, and is an address just outside the allocated area. Stacks of rings will be represented as stacks of integers, in which the integer zero means ‘no ring’.

The procedure `printOne` either writes a ring number or leaves blank spaces if there is no ring in that position. `PrintTowers` repeatedly calls `printOne` to output the present state of all three towers.

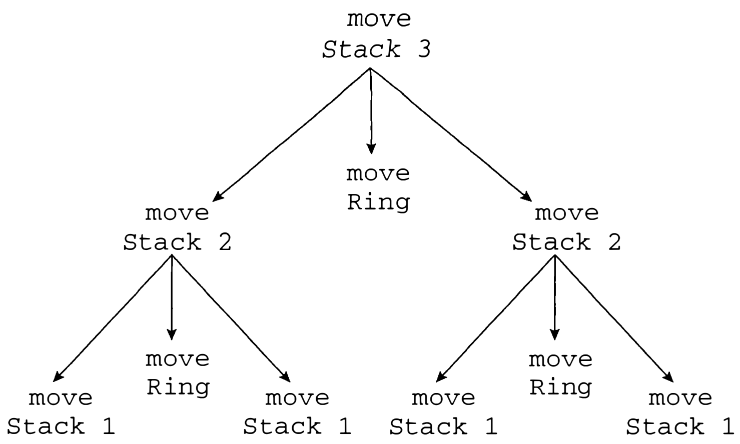


Figure 8.12 Recursive solution of Towers of Hanoi problem.

Procedure `moveRing` moves a ring from one tower to another. It calls `PrintTowers` so that each change in the state is displayed in the output as it occurs.

The recursive procedure that solves the Towers of Hanoi problem is called `moveStack` (Figure 8.12). It recursively moves the top $n - 1$ rings from the source tower to the spare tower, using the end tower as the spare. It then calls `moveRing` to move the bottom ring from the start tower to the destination tower. `moveRing` also prints out the new state of the towers. Finally, `moveStack` recursively moves the $n - 1$ rings from the spare tower to the destination tower, using the source tower as the spare.

8.9 SUMMARY

A stack of data elements is a last in, first out data structure. The MIPS stack is upside down – elements are added at progressively lower memory addresses. Procedures allow programs to be broken into smaller more manageable units. The jump and link instruction puts the return address into a special register before executing the code for the procedure. A procedure that calls another can count on callee saves being restored when control returns, but must save caller saves on the stack before making the call. Stack frames are used in procedure calls. The compiler figures out how big the frame needs to be, and the first thing it does in the body of the procedure is to allocate room on the stack for the frame. A recursive task is one that calls itself. With each invocation, the problem is reduced to a smaller problem until the task arrives at some terminal or base case which stops the process.

EXERCISES

8.1 What are the basic operations on a stack?
8.2 What is a stack frame and when is it needed?
8.3 Why are procedures important?
8.4 How do procedures get their arguments?
8.5 What convention is used by MIPS procedures to return values?
8.6 What are the advantages of caller and callee saves respectively?
8.7 Contrast the usage of registers and the stack for variables in procedures.

APPENDIX A

MIPS programming exams

A.1 INTRODUCTION

This appendix describes the MIPSMARK software, the basic idea behind which is to allow a lecturer to set assembly language programming questions and collect and mark the assignments automatically. MIPSMARK is written as a collection of Unix C shell scripts. Experience has shown that assessment defines the curriculum from the point of view of the student. If programming assignments are collected on printouts, they are often not taken seriously by students. In addition, automatically marked questions are ideal for teaching introductory computer architecture to very large class sizes. MIPSMARK would also allow any reader of the book to run MIPS assembly code against several test cases to determine if it works correctly.

The vision behind MIPSMARK is that the only way to learn introductory programming is via mastery of the techniques of writing simple programs. The student must develop the necessary reasoning and problem solving modes of thinking, as well as being able to use the software tools, to get a program to work correctly. While it may seem unfair to give zero for a program that 'nearly' works, this approach is essential to ensure that programming skills are developed. All the MIPSMARK exams are open book and the questions will be closely related to examples from notes and textbooks, therefore every student will be able to type in something with a reasonable resemblance to the answer. In open book exams of this type, it is meaningless to award marks for attempts that resemble the correct answer. Included with MIPSMARK is a large number of MIPS programming questions which allows a user to write a MIPS program and have it marked automatically.

A.2 MIPSMARK SOFTWARE

This section describes the MIPSMARK software for correcting assembly language programs. MIPSMARK works by running a program and searching for a precise sequence of characters in the output. This is called 'black box testing'. You must therefore follow the instructions exactly to produce this sequence of characters or your program will not get any marks. Your output must be ASCII text. Any non-ASCII or unusual control characters in your output means MIPSMARK may not find the answer. If you like, you can put a carriage return at the end of the required output.

You must not change the filenames because these are used to match the test cases with the questions. Your program must not prompt for any input as it will be run and marked automatically.

`easy.a` shows the format of an exam question.

```
## Start of file easy.a
##
## Question:
## Print out the message "hello world"
##
## Output format must be:
## "hello world"

#################################################
#                                               #
#                  text segment                 #
#                                               #
#################################################

        .text
        .globl __start
__start:                 # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

```

```
##################################################
#                                                #
#                  data segment                  #
#                                                #
##################################################

        .data
str:    .asciiz "hello world\n"
##
## End of file easy.a
```

You should type the answer between the dashed lines as indicated. Test your code by loading the file into XSPIM and running it. Once you are satisfied with the solution type `mipsmark file.a` in a terminal window. In general, MIPSMARK works by extracting your answer from between the dashed lines and trying it using several different test cases as shown in Figure A.1. `easy.a` is a simple program that needs only one test case.

If your program works for case zero and case one, but fails for case two you can get a copy of the source code for the third test case by typing `showcase file.a 2`, which will give you a file called `file_2.a`. Use the programming tools to locate the bug in your code preventing this test case from working correctly.

Of course, it is possible to get your program to pass the MIPSMARK program by explicitly writing out the correct answers to each test case! To overcome this problem, when your program is being marked in an exam, additional test cases have to be used. To test your code fully, you can add your own test cases in the data segement and verify that these also work, but remember that when the program is being marked by MIPSMARK, anything outside the dashed lines will be discarded.

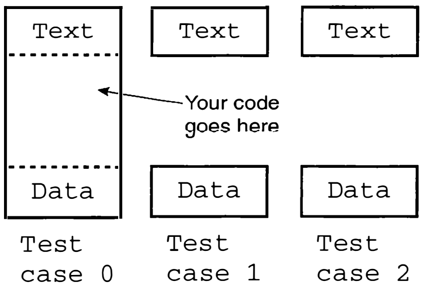


Figure A.1 Automatically corrected programs.

A.3 EXAM QUESTIONS USING PROGRAM LOOPS

This section shows some example programs that test your knowledge of looping programs.

A.3.1 QUESTION LOOP2

```
## Start of file loop2.a
##
## Question:
## calculate the number of occurrences of "letter"
## in the string "chararray"
##
## Output format must be:
## "number of occurrences = 6"

################################################
#                                              #
#                text segment                  #
#                                              #
################################################

        .text
        .globl __start
__start:                    # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

################################################
#                                              #
#                data segment                  #
#                                              #
################################################
```

```

        .data
chararray:
        .asciiz "abbbaabbbababab"
letter: .byte 'a'
ans:    .asciiz "number of occurences = "
endl:   .asciiz "\n"
##
## End of file loop2.a
```

A.3.2 QUESTION LOOP7

```
## Start of file loop7.a
##
## Question:
## Replace the first and last character in the
## string "charstr" with 'X'.
##
## Then print the resulting string.
##
## Output format must be:
## "XbcdeX"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

```

```
##################################################
#                                                #
#                data segment                    #
#                                                #
##################################################

        .data
charstr:
        .asciiz "abcdef"
endl:   .asciiz "\n"
##
## End of file loop7.a
```

A.3.3 QUESTION LOOP8

```
## Start of file loop8.a
##
## Question:
## Replace the last character in the
## string "charstr" with the first character.
##
## Then print the resulting string.
##
## Output format must be:
## "abcdea"

##################################################
#                                                #
#                text segment                    #
#                                                #
##################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
charstr:
        .asciiz "abcdef"
  endl: .asciiz "\n"
##
## End of file loop8.a
```

A.3.4 QUESTION LOOP9

```
## Start of file loop9.a
##
## Question:
## Replace the second last character in the
## string "charstr" with the last character.
## The string will contain at least 2 characters.
##
## Then print the resulting string.
##
## Output format must be:
## "abcdff"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------


```

```

#-----------  end cut  -------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
charstr:
        .asciiz "abcdef"
endl:   .asciiz "\n"
##
## End of file loop9.a
```

A.3.5 QUESTION LOOPA

```
## Start of file loopa.a
##
## Question:
## Replace the first character in the
## string "charstr" with the last character.
## The string will contain at least 2 characters.
##
## Then print the resulting string.
##
## Output format must be:
## "fbcdef"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
```

```
#----------- start cut -------------------------



#-----------  end cut  -------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
charstr:
        .asciiz "abcdef"
endl:   .asciiz "\n"
##
## End of file loopa.a
```

A.3.6 QUESTION TCOMP

```
## Start of file tcomp.a
##
## Question:
## Print the absolute value of the element in
## "array" with the largest absolute value.
## "count" holds the number of elements in "array"
##
## Output format must be:
## "max absolute value is = 43"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
array:  .word 3,0xffffffd5,2,6
count:  .word 4
ans1:   .asciiz "max absolute value is = "
endl:   .asciiz "\n"
##
## End of file tcomp.a
```

A.3.7 QUESTION TCOMP1

```
## Start of file tcomp1.a
##
## Question:
## calculate the sum of the elements in "array"
## whose absolute value is greater than forty
## "count" holds the number of elements in "array"
##
## Output format must be:
## "sum is = -60"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                    # execution starts here

```

```

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#                data segment                   #
#                                               #
#################################################

        .data
array:  .word 3,0xffffffd5,2,6,50,-67
count:  .word 6
ans1:   .asciiz "sum is = "
endl:   .asciiz "\n"
##
## End of file tcomp1.a
```

A.4 EXAM QUESTION USING BIT MANIPULATION

This section shows an example program that tests your knowledge of the logical, shift and rotate instructions.

A.4.1 QUESTION LOGIC3

```
## Start of file logic3.a
##
## Question:
## "number" is a word.
## If bits 3 and 6 are set then
## set bits 0, 1 and 2 and print out
## the result.
## If bits 3 and 6 are not set then
## print out the number unchanged.
##
## Output format must be:
## "result is = 79"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here


# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
number: .word 0x48
ans:    .asciiz "result is = "
endl:   .asciiz "\n"
##
## End of file logic3.a
```

A.5 EXAM QUESTIONS USING THE STACK

This section shows some example programs that test your ability to use the stack data structure.

A.5.1 QUESTION STACK2

```
## Start of file stack2.a
##
## Question:
## The program must sum a sequence of numbers
## stored on the stack. The word
## on the top of the stack tells you how
## many numbers are in the sequence.
## Do not include this first word in the sum.
##
## Do not rely on the existence of the "test"
## variable, or the code above the
## dashed line.
##
## Output format must be:
## "sum is = 23"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here

        la $t0,test     # This code sets up the stack
        lw $t1,($t0)    # Do not alter
        add $t0,$t0,4
loop:   lw $t2,($t0)
        sub $sp,$sp,4
        sw $t2,($sp)
        add $t0,$t0,4
        add $t1,$t1,-1
        bnez $t1,loop
        la $t0,test
        lw $t1,($t0)
        sub $sp,$sp,4
        sw $t1,($sp)

                        # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
```

```
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
test:   .word 4,6,7,8,2
ans:    .asciiz "sum is = "
endl:   .asciiz "\n"
##
## End of file stack2.a
```

A.5.2 QUESTION STACK3

```
## Start of file stack3.a
##
## Question:
## The program must sum a sequence of numbers
## stored on the stack. "num"
## tells you how many numbers are in the sequence.
##
## Do not rely on the existence of the "test"
## variable, or the code above the
## dashed line.
##

## Output format must be:
## "sum is = 15"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
```

```
__start:                # execution starts here

        la $t0,test     # This code sets up the stack
        lw $t1,num
loop:   lw $t2,($t0)
        sub $sp,$sp,4
        sw $t2,($sp)
        add $t0,$t0,4
        add $t1,$t1,-1
        bnez $t1,loop

                        # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

       .data
test:  .word 4,-6,7,8,2
num:   .word 5
ans:   .asciiz "sum is = "
endl:  .asciiz "\n"
##
## End of file stack3.a
```

A.5.3 QUESTION STACK4

```
## Start of file stack4.a
##
## Question:
## The program must find the smallest number in
## a sequence of ten numbers stored on the stack.
##
```

```
## Do not rely on the existence of the "test"
## variable, or the code above the
## dashed line.
##

## Output format must be:
## "min is = -8"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here

        la $t0,test     # This code sets up the stack
        li $t1,10
loop:   lw $t2,($t0)
        sub $sp,$sp,4
        sw $t2,($sp)
        add $t0,$t0,4
        add $t1,$t1,-1
        bnez $t1,loop

                        # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

       .data
```

```
test:   .word 4,-6,7,8,0,6,6,-8,6,6
ans:    .asciiz "min is = "
endl:   .asciiz "\n"
##
## End of file stack4.a
```

A.5.4 QUESTION STACK5

```
## Start of file stack5.a
##
## Question:
## The program must sum numbers
## stored on the stack
## that have bit 6 set.
## The word
## on the top of the stack tells you how
## many numbers are in the sequence.
## Do not include this first word in the sum.
##
## Do not rely on the existence of the "test"
## variable, or the code above the
## dashed line.
##
## Output format must be:
## "sum is = 169"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here

        la $t0,test     # This code sets up the stack
        lw $t1,($t0)    # Do not alter
        add $t0,$t0,4
loop:   lw $t2,($t0)
        sub $sp,$sp,4
        sw $t2,($sp)
        add $t0,$t0,4
        add $t1,$t1,-1
        bnez $t1,loop
        la $t0,test
        lw $t1,($t0)
        sub $sp,$sp,4
        sw $t1,($sp)

                        # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
test:   .word 4,0x96,0x47,0x28,0x62
ans:    .asciiz "sum is = "
endl:   .asciiz "\n"
##
## End of file stack5.a
```

A.5.5 QUESTION STACK7

```
## Start of file stack7.a
##
## Question:
##
## Pop the stack until a
## word is found which if printed out
## in hex would contain a "C", and print
## out that word in decimal.
##
## Do not rely on the existence of the "test"
## or "num" variables, or the code above the
## dashed line.
##
```

```
## Output format must be:
## "Number is = 192"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

        .text
        .globl __start
__start:                # execution starts here

        la $t0,test     # This code sets up the stack
        lw $t1,num      # Do not alter
loop:   lw $t2,($t0)
        sub $sp,$sp,4
        sw $t2,($sp)
        add $t0,$t0,4
        add $t1,$t1,-1
        bnez $t1,loop
                        # Stack set up now....

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#----------- start cut --------------------------



#-----------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
test:   .word 0x99,0xc0,0xf,0xa,1,0xd
num:    .word 6
ans:    .asciiz "Number is = "
endl:   .asciiz "\n"
##
## End of file stack7.a
```

A.6 EXAM QUESTIONS USING FUNCTIONS

This section shows some example programs that test your ability to use the MIPS function call mechanism.

A.6.1 QUESTION FUNCT3

```
## Start of file funct3.a
##
## Question:
## Write a function "setbits" that takes a
## number in $a0 and sets all the bits from
## the most significant bit down.
## Return the resulting number in the register $v0.
## For example 100111 base two becomes 111111.
##
## Output format must be:
## "Number is = 63"

#################################################
#                                               #
#                text segment                   #
#                                               #
#################################################

         .text
         .globl __start
__start:                 # execution starts here


         la $a0,ans
         li $v0,4
         syscall

         li $a0,39
         jal setbits     # call function

         move $a0,$v0
         li $v0,1
         syscall

         la $a0,endl     # system call to print
         li $v0,4        # out a newline
         syscall

```

```
exit:    li $v0,10
         syscall        # au revoir...

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#                data segment                   #
#                                               #
#################################################

         .data
ans:     .asciiz "Number is = "
endl:    .asciiz "\n"
##
## End of file funct3.a
```

A.6.2 QUESTION FUNCT4

```
## Start of file funct4.a
##
## Question:
## Write a function "findpat" that takes a
## long binary pattern in $a0 and a smaller
## binary pattern in $a1, and returns true
## if the long binary pattern contains the
## smaller one.
## For example 100111 base two contains 1001.
##
## Output format must be:
## "Pattern found"

#################################################
#                                               #
#                text segment                   #
#                                               #
#################################################

```

```
         .text
         .globl __start
__start:                # execution starts here


         li $a0,39
         li $a1,9
         jal findpat    # call  function

         beqz $v0,notthere

         la $a0,yes
         li $v0,4
         syscall
         b exit

notthere:
         la $a0,no
         li $v0,4
         syscall

exit:    li $v0,10
         syscall        # au revoir...

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
yes:    .asciiz "Pattern found\n"
no:     .asciiz "Pattern not found\n"

##
## End of file funct4.a
```

A.6.3 QUESTION FUNCT5

```
## Start of file funct5.a
##
## Question:
## Write a function "check3" that takes a
## number in $a0 and returns that number if
## three consecutive bits are set. Otherwise
## it returns zero.
##
## Output format must be:
## "Number is = 39"

#################################################
#                                               #
#               text segment                    #
#                                               #
#################################################

         .text
         .globl __start
__start:                 # execution starts here


         la $a0,ans
         li $v0,4
         syscall

         li $a0,39
         jal check3      # call  function

         move $a0,$v0
         li $v0,1
         syscall

         la $a0,endl     # system call to print
         li $v0,4        # out a newline
         syscall

exit:    li $v0,10
         syscall         # au revoir...

# Any changes above this line will be discarded by
# mipsmark. Put your answer between dashed lines.
#------------ start cut --------------------------
```

```



#------------  end cut  --------------------------
# Any changes below this line will be discarded by
# mipsmark. Put your answer between dashed lines.

#################################################
#                                               #
#               data segment                    #
#                                               #
#################################################

        .data
ans:    .asciiz "Number is = "
endl:   .asciiz "\n"
##
## End of file funct5.a
```

APPENDIX B

MIPS/SPIM instruction quick reference

This appendix contains a quick reference for the MIPS/SPIM instruction set, grouped together by instruction type. The † symbol denotes a pseudo-instruction.

Table B.1 Arithmetic and logical instructions.

Description	Opcode	Operands
Absolute value	`abs`†	`Rdest, Rsrc`
Addition (with overflow)	`add`	`Rdest, Rsrc1, Src2`
Addition immediate (with overflow)	`addi`	`Rdest, Rsrc1, Imm`
Addition (without overflow)	`addu`	`Rdest, Rsrc1, Src2`
Addition immediate (without overflow)	`addiu`	`Rdest, Rsrc1, Imm`
AND	`and`	`Rdest, Rsrc1, Src2`
AND immediate	`andi`	`Rdest, Rsrc1, Imm`
Divide (signed)	`div`	`Rsrc1, Rsrc2`
Divide (unsigned)	`divu`	`Rsrc1, Rsrc2`
Divide (signed, with overflow)	`div`†	`Rdest, Rsrc1, Src2`
Divide (unsigned, without overflow)	`divu`†	`Rdest, Rsrc1, Src2`
Multiply (without overflow)	`mul`†	`Rdest, Rsrc1, Src2`
Multiply (with overflow)	`mulo`†	`Rdest, Rsrc1, Src2`
Unsigned multiply (with overflow)	`mulou`†	`Rdest, Rsrc1, Src2`
Multiply	`mult`	`Rsrc1, Rsrc2`
Unsigned multiply	`multu`	`Rsrc1, Rsrc2`
Negate value (with overflow)	`neg`†	`Rdest, Rsrc`
Negate value (without overflow)	`negu`†	`Rdest, Rsrc`
NOR	`nor`	`Rdest, Rsrc1, Src2`
NOT	`not`†	`Rdest, Rsrc`
OR	`or`	`Rdest, Rsrc1, Src2`
OR immediate	`ori`	`Rdest, Rsrc1, Imm`
Remainder	`rem`†	`Rdest, Rsrc1, Src2`

Table B.1 – continued

Description	Opcode	Operands
Unsigned remainder	`remu`†	`Rdest, Rsrc1, Src2`
Rotate left	`rol`†	`Rdest, Rsrc1, Src2`
Rotate right	`ror`†	`Rdest, Rsrc1, Src2`
Shift left logical	`sll`	`Rdest, Rsrc1, Src2`
Shift left logical variable	`sllv`	`Rdest, Rsrc1, Rsrc2`
Shift right arithmetic	`sra`	`Rdest, Rsrc1, Src2`
Shift right arithmetic variable	`srav`	`Rdest, Rsrc1, Rsrc2`
Shift right logical	`srl`	`Rdest, Rsrc1, Src2`
Shift right logical variable	`srlv`	`Rdest, Rsrc1, Rsrc2`
Subtract (with overflow)	`sub`	`Rdest, Rsrc1, Src2`
Subtract (without overflow)	`subu`	`Rdest, Rsrc1, Src2`
XOR	`xor`	`Rdest, Rsrc1, Src2`
XOR immediate	`xori`	`Rdest, Rsrc1, Imm`

Table B.2 Branch and jump instructions.

Description	Opcode	Operands
Branch instruction	`b`	`label`
Branch coprocessor *z* true	`bc`*z*`t`	`label`
Branch coprocessor *z* false	`bc`*z*`f`	`label`
Branch on equal	`beq`	`Rsrc1, Src2, label`
Branch on equal zero	`beqz`†	`Rsrc, label`
Branch on greater than equal	`bge`†	`Rsrc1, Src2, label`
Branch on GTE unsigned	`bgeu`†	`Rsrc1, Src2, label`
Branch on greater than equal zero	`bgez`	`Rsrc, label`
Branch on greater than equal zero and link	`bgezal`	`Rsrc, label`
Branch on greater than	`bgt`†	`Rsrc1, Src2, label`
Branch on greater than unsigned	`bgtu`†	`Rsrc1, Src2, label`
Branch on greater than zero	`bgtz`	`Rsrc, label`
Branch on less than equal	`ble`†	`Rsrc1, Src2, label`
Branch on LTE unsigned	`bleu`†	`Rsrc1, Src2, label`
Branch on less than equal zero	`blez`	`Rsrc, label`
Branch on greater than equal zero and link	`bgezal`	`Rsrc, label`
Branch on less than and link	`bltzal`	`Rsrc, label`
Branch on less than	`blt`†	`Rsrc1, Src2, label`
Branch on less than unsigned	`bltu`†	`Rsrc1, Src2, label`
Branch on less than zero	`bltz`	`Rsrc, label`
Branch on not equal	`bne`	`Rsrc1, Src2, label`
Branch on not equal zero	`bnez`†	`Rsrc, label`
Jump	`j`	`label`
Jump and link	`jal`	`label`
Jump and link register	`jalr`	`Rsrc`
Jump register	`jr`	`Rsrc`

Table B.3 Data movement instructions.

Description	**Opcode**	**Operands**
Move	move†	Rdest, Rsrc
Move from hi	mfhi	Rdest
Move from lo	mflo	Rdest
Move to hi	mthi	Rdest
Move to lo	mtlo	Rdest
Move from coprocessor *z*	mfc*z*	Rdest, CPsrc
Move double from coprocessor 1	mfc1.d†	Rdest, FRsrc1
Move to coprocessor *z*	mtc*z*	Rsrc, CPdest

Table B.4 Comparison instructions.

Description	**Opcode**	**Operands**
Set equal	seq†	Rdest, Rsrc1, Src2
Set greater than equal	sge†	Rdest, Rsrc1, Src2
Set greater than equal unsigned	sgeu†	Rdest, Rsrc1, Src2
Set greater than	sgt†	Rdest, Rsrc1, Src2
Set greater than unsigned	sgtu†	Rdest, Rsrc1, Src2
Set less than equal	sle†	Rdest, Rsrc1, Src2
Set less than equal unsigned	sleu†	Rdest, Rsrc1, Src2
Set less than	slt	Rdest, Rsrc1, Src2
Set less than immediate	slti	Rdest, Rsrc1, Imm
Set less than unsigned	sltu	Rdest, Rsrc1, Src2
Set less than unsigned immediate	sltiu	Rdest, Rsrc1, Imm
Set not equal	sne†	Rdest, Rsrc1, Src2

Table B.5 Constant-manipulating instructions.

Description	**Opcode**	**Operands**
Load immediate	li†	Rdest, imm
Load upper immediate	lui	Rdest, imm

Table B.6 Load instructions.

Description	Opcode	Operands
Load address	`la`†	`Rdest, address`
Load byte	`lb`	`Rdest, address`
Load unsigned byte	`lbu`	`Rdest, address`
Load double-word	`ld`†	`Rdest, address`
Load halfword	`lh`	`Rdest, address`
Load unsigned halfword	`lhu`	`Rdest, address`
Load word	`lw`	`Rdest, address`
Load word coprocessor	`lwc`*z*	`Rdest, address`
Load word left	`lwl`	`Rdest, address`
Load word right	`lwr`	`Rdest, address`
Unaligned load halfword	`ulh`†	`Rdest, address`
Unaligned load halfword unsigned	`ulhu`†	`Rdest, address`
Unaligned load word	`ulw`†	`Rdest, address`

Table B.7 Store instructions.

Description	Opcode	Operands
Store byte	`sb`	`Rsrc, address`
Store double-word	`sd`†	`Rsrc, address`
Store halfword	`sh`	`Rsrc, address`
Store word	`sw`	`Rsrc, address`
Store word coprocessor	`swcz`	`Rsrc, address`
Store word left	`swl`	`Rsrc, address`
Store word right	`swr`	`Rsrc, address`
Unaligned store halfword	`ush`†	`Rsrc, address`
Unaligned store word	`usw`†	`Rsrc, address`

Table B.8 Floating point instructions.

Description	Opcode	Operands
Floating point absolute value double	`abs.d`	`FRdest, FRsrc`
Floating point absolute value single	`abs.s`	`FRdest, FRsrc`
Floating point addition double	`add.d`	`FRdest, FRsrc1, FRsrc2`
Floating point addition single	`add.s`	`FRdest, FRsrc1, FRsrc2`
Compare equal double	`c.eq.d`	`FRsrc1, FRsrc2`
Compare equal single	`c.eq.s`	`FRsrc1, FRsrc2`
Compare less than equal double	`c.le.d`	`FRsrc1, FRsrc2`
Compare less than equal single	`c.le.s`	`FRsrc1, FRsrc2`
Compare less than double	`c.lt.d`	`FRsrc1, FRsrc2`
Compare less than single	`c.lt.s`	`FRsrc1, FRsrc2`
Convert single to double	`cvt.d.s`	`FRdest, FRsrc`
Convert integer to double	`cvt.d.w`	`FRdest, FRsrc`
Convert double to single	`cvt.s.d`	`FRdest, FRsrc`
Convert integer to single	`cvt.s.w`	`FRdest, FRsrc`
Convert double to integer	`cvt.w.d`	`FRdest, FRsrc`
Convert single to integer	`cvt.w.s`	`FRdest, FRsrc`
Floating point divide double	`div.d`	`FRdest, FRsrc1, FRsrc2`
Floating point divide single	`div.s`	`FRdest, FRsrc1, FRsrc2`
Load floating point double	`l.d`†	`FRdest, address`
Load floating point single	`l.s.`†	`FRdest, address`
Move floating point double	`mov.d`	`FRdest, FRsrc`
Move floating point single	`mov.s`	`FRdest, FRsrc`
Floating point multiply double	`mul.d`	`FRdest, FRsrc1, FRsrc2`
Floating point multiply single	`mul.s`	`FRdest, FRsrc1, FRsrc2`
Negate double	`neg.d`	`FRdest, FRsrc`
Negate single	`neg.s`	`FRdest, FRsrc`
Store floating point double	`s.d`†	`FRdest, address`
Store floating point single	`s.s`†	`FRdest, address`
Floating point subtract double	`sub.d`	`FRdest, FRsrc1, FRsrc2`
Floating point subtract single	`sub.s`	`FRdest, FRsrc1, FRsrc2`

Table B.9 Exception and trap instructions.

Description	Opcode	Operands
Return from exception	`rfe`	
System call	`syscall`	
Break	`break`	`n`
No operation	`nop`	

APPENDIX C

MIPS/SPIM instruction reference

The † symbol denotes a pseudo-instruction.

`abs.d`

Floating point absolute value double

```
abs.d FRdest, FRsrc
```

Compute the absolute value of the floating point double in register `FRsrc` and put it in register `FRdest`.

`abs.s`

Floating point absolute value single

```
abs.s FRdest, FRsrc
```

Compute the absolute value of the floating point single in register `FRsrc` and put it in register `FRdest`.

`abs`†

Absolute value

```
abs Rdest, Rsrc
```

Put the absolute value of the integer from register `Rsrc` in register `Rdest`.

`add.d` — Floating point addition double

```
add.d FRdest, FRsrc1, FRsrc2
```

Compute the sum of the floating point doubles in registers `FRsrc1` and `Frsrc2` and put it in register `FRdest`.

`add.s` — Floating point addition single

```
add.s FRdest, FRsrc1, FRsrc2
```

Compute the sum of the floating point singles in registers `FRsrc1` and `FRsrc2` and put it in register `FRdest`.

`addiu` — Addition immediate (without overflow)

```
addiu Rdest, Rsrc1, Imm
```

Put the sum of the integers from register `Rsrc1` and `Imm` into register `Rdest`.

`addi` — Addition immediate (with overflow)

```
addi Rdest, Rsrc1, Imm
```

Put the sum of the integers from register `Rsrc1` and `Imm` into register `Rdest`.

`addu` — Addition (without overflow)

```
addu Rdest, Rsrc1, Src2
```

Put the sum of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

`add` — Addition (with overflow)

```
add Rdest, Rsrc1, Src2
```

Put the sum of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

`andi` AND immediate

```
andi Rdest, Rsrc1, Imm
```

Put the logical AND of the integers from register `Rsrc1` and `Imm` into register `Rdest`.

`and` AND

```
and Rdest, Rsrc1, Src2
```

Put the logical AND of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

`bc`*z*`f` Branch coprocessor *z* false

```
bczf label
```

Conditionally branch to the instruction at the label if coprocessor *z*'s condition flag is false.

`bc`*z*`t` Branch coprocessor *z* true

```
bczt label
```

Conditionally branch to the instruction at the label if coprocessor *z*'s condition flag is true.

`beqz`† Branch on equal zero

```
beqz Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` equal 0.

beq
Branch on equal

```
beq Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` equals `Src2`.

bgeu†
Branch on GTE unsigned

```
bgeu Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are greater than or equal to `Src2`.

bgezal
Branch on greater than equal zero and link

```
bgezal Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are greater than or equal to 0. Save the address of the next instruction in register 31.

bgezal
Branch on greater than equal zero and link

```
bgezal Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are greater than or equal to 0. Save the address of the next instruction in register 31.

bgez
Branch on greater than equal zero

```
bgez Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are greater than or equal to 0.

bge† Branch on greater than equal

```
bge Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are greater than or equal to `Src2`.

bgtu† Branch on greater than unsigned

```
bgtu Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are greater than `Src2`.

bgtz Branch on greater than zero

```
bgtz Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are greater than 0.

bgt† Branch on greater than

```
bgt Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are greater than `Src2`.

bleu† Branch on LTE unsigned

```
bleu Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are less than or equal to `Src2`.

blez

Branch on less than equal zero

```
blez Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are less than or equal to 0.

ble†

Branch on less than equal

```
ble Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are less than or equal to `Src2`.

bltu†

Branch on less than unsigned

```
bltu Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are less than `Src2`.

bltzal

Branch on less than and link

```
bltzal Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are less than 0. Save the address of the next instruction in register 31.

bltz

Branch on less than zero

```
bltz Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are less than 0.

blt† — Branch on less than

```
blt Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are less than `Src2`.

bnez† — Branch on not equal zero

```
bnez Rsrc, label
```

Conditionally branch to the instruction at the label if the contents of `Rsrc` are not equal to 0.

bne — Branch on not equal

```
bne Rsrc1, Src2, label
```

Conditionally branch to the instruction at the label if the contents of register `Rsrc1` are not equal to `Src2`.

break — Break

```
break n
```

Cause exception *n*. Exception 1 is reserved for the debugger.

b — Branch instruction

```
b label
```

Unconditionally branch to the instruction at the label.

c.eq.d — Compare equal double

```
c.eq.d FRsrc1, FRsrc2
```

Compare the floating point double in register `FRsrc1` against the one in `FRsrc2` and set the floating point condition flag true if they are equal.

c.eq.s

Compare equal single

```
        c.eq.s FRsrc1, FRsrc2
```

Compare the floating point single in register `FRsrc1` against the one in `FRsrc2` and set the floating point condition flag true if they are equal.

c.le.d

Compare less than equal double

```
        c.le.d FRsrc1, FRsrc2
```

Compare the floating point double in register `FRsrc1` against the one in `FRsrc2` and set the floating point condition flag true if the first is less than or equal to the second.

c.le.s

Compare less than equal single

```
        c.le.s FRsrc1, FRsrc2
```

Compare the floating point single in register `FRsrc1` against the one in `FRsrc2` and set the floating point condition flag true if the first is less than or equal to the second.

c.lt.d

Compare less than double

```
        c.lt.d FRsrc1, FRsrc2
```

Compare the floating point double in register `FRsrc1` against the one in `FRsrc2` and set the condition flag true if the first is less than the second.

c.lt.s

Comapre less than single

```
        c.lt.s FRsrc1, FRsrc2
```

Compare the floating point single in register `FRsrc1` against the one in `FRsrc2` and set the condition flag true if the first is less than the second.

cvt.d.s

Convert single to double

```
cvt.d.s FRdest, FRsrc
```

Convert the single precision floating point number in register `FRsrc` to a double precision number and put it in register `FRdest`.

cvt.d.w

Convert integer to double

```
cvt.d.w FRdest, FRsrc
```

Convert the integer in register `FRsrc` to a double precision number and put it in register `FRdest`.

cvt.s.d

Convert double to single

```
cvt.s.d FRdest, FRsrc
```

Convert the double precision floating point number in register `FRsrc` to a single precision number and put it in register `FRdest`.

cvt.s.w

Convert integer to single

```
cvt.s.w. FRdest, FRsrc
```

Convert the integer in register `FRsrc` to a single number and put it in register `FRdest`.

cvt.w.d

Convert double to integer

```
cvt.w.d FRdest, FRsrc
```

Convert the double precision floating point number in register `FRsrc` to an integer and put it in register `FRdest`.

`cvt.w.s` Convert single to integer

```
cvt.w.s FRdest, FRsrc
```

Convert the single precision floating point number in register `FRsrc` to an integer and put it in register `FRdest`.

`div.d` Floating point divide double

```
div.d FRdest, FRsrc1, FRsrc2
```

Compute the quotient of the floating point doubles in registers `FRsrc1` and `FRsrc2` and put it in register `FRdest`.

`div.s` Floating point divide single

```
div.s FRdest, FRsrc1, FRsrc2
```

Compute the quotient of the floating point singles in registers `FRsrc1` and `FRsrc3` and put it in register `FRdest`.

`divu`† Divide (unsigned, without overflow)

```
divu Rdest, Rsrc1, Src2
```

Put the quotient of the integers from register `Rsrc1` and `Src2` into register `Rdest`. `divu` treats its operands as unsigned values.

`divu` Divide (unsigned)

```
divu Rsrc1, Rsrc2
```

Divide the contents of the two registers. `divu` treats its operands as unsigned values. Leave the quotient in register `lo` and the remainder in register `hi`. Note that if an operand is negative, the remainder is unspecified by the MIPS architecture and depends on the conventions of the machine on which SPIM is run.

`div`† Divide (signed, with overflow)

```
div Rdest, Rsrc1, Src2
```

Put the quotient of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

`div` Divide (signed)

```
div Rsrc1, Rsrc2
```

Divide the contents of the two registers. Leave the quotient in register `lo` and the remainder in register `hi`. Note that if an operand is negative, the remainder is unspecified by the MIPS architecture and depends on the conventions of the machine on which SPIM is run.

`jalr` Jump and link register

```
jalr Rsrc
```

Unconditionally jump to the instruction whose address is in register `Rsrc`. Save the address of the next instruction in register 31.

`jal` Jump and link

```
jal label
```

Unconditionally jump to the instruction at the label. Save the address of the next instruction in register 31.

`jr` Jump register

```
jr Rsrc
```

Unconditionally jump to the instruction whose address is in register `Rsrc`.

j — Jump

```
j label
```

Unconditionally jump to the instruction at the label.

l.d† — Load floating point double

```
l.d FRdest, address
```

Load the floating point double at `address` into register `FRdest`.

l.s† — Load floating point single

```
l.s FRdest, address
```

Load the floating point single at `address` into register `FRdest`.

la† — Load address

```
la Rdest, address
```

Load computed *address*, not the contents of the location, into register `Rdest`.

lbu — Load unsigned byte

```
lbu Rdest, address
```

Load the byte at *address* into register `Rdest`. The byte is not sign-extended by the `lbu` instruction.

lb — Load byte

```
lb Rdest, address
```

Load the byte at *address* into register `Rdest`. The byte is sign-extended by the `lb` instruction.

`ld`† Load double-word

```
ld Rdest, address
```

Load the 64-bit quantity at *address* into registers `Rdest` and `Rdest + 1`.

`lhu` Load unsigned halfword

```
lhu Rdest, address
```

Load the 16-bit quantity (halfword) at *address* into register `Rdest`. The halfword is not sign-extended by the `lhu` instruction.

`lh` Load halfword

```
lh Rdest, address
```

Load the 16-bit quantity (halfword) at *address* into register `Rdest`. The halfword is sign-extended by the `lh` instruction.

`li`† Load immediate

```
li Rdest, imm
```

Move the immediate `imm` into register `Rdest`.

`lui` Load upper immediate

```
lui Rdest, imm
```

Load the lower halfword of the immediate `imm` into the upper halfword of register `Rdest`. The lower bits of the register are set to 0.

`lwcz` Load word coprocessor

```
lwcz Rdest, address
```

Load the word at *address* into register `Rdest` of coprocessor *z* (0–3).

`lwl` — Load word left

```
lwl Rdest, address
```

Load the left bytes from the word at the possibly-unaligned *address* into register `Rdest`.

`lwr` — Load word right

```
lwr Rdest, address
```

Load the right bytes from the word at the possibly-unaligned *address* into register `Rdest`.

`lw` — Load word

```
lw Rdest, address
```

Load the 32-bit quantity (word) at *address* into register `Rdest`.

`mfc1.d`† — Move double from coprocessor 1

```
mfc1.d Rdest, FRsrc1
```

Move the contents of floating point registers `FRsrc1` and `FRsrc1 + 1` to CPU registers `Rdest` and `Rdest + 1`.

`mfc`*z* — Move from coprocessor *z*

mfc*z* Rdest, CPsrc

Move the contents of coprocessor *z*'s register `CPsrc` to CPU register `Rdest`.

`mfhi` — Move from `hi`

```
mfhi Rdest
```

Move the contents of the `hi` register to register `Rdest`.

`mflo` — Move from `lo`

```
mflo Rdest
```

Move the contents of the `lo` register to register `Rdest`.

`mov.d` — Move floating point double

```
mov.d FRdest, FRsrc
```

Move the floating point double from register `FRsrc` to register `FRdest`.

`mov.s` — Move floating point single

```
mov.s FRdest, FRsrc
```

Move the floating point single from register `FRsrc` to register `FRdest`.

`move`† — Move

```
move Rdest, Rsrc
```

Move the contents of `Rsrc` to `Rdest`.

`mtc`*z* — Move to coprocessor *z*

```
mtcz Rsrc, CPdest
```

Move the contents of CPU register `Rsrc` to coprocessor *z*'s register `CPdest`.

`mthi` — Move to `hi`

```
mthi Rdest
```

Move the contents register `Rdest` to the `hi` register.

mtlo

Move to lo

```
mtlo Rdest
```

Move the contents register `Rdest` to the `lo` register.

mul.d

Floating point multiply double

```
mul.d FRdest, FRsrc1, FRsrc2
```

Compute the product of the floating point doubles in registers `Frsrc1` and `FRsrc2` and put it in register `FRdest`.

mul.s

Floating point multiply single

```
mul.s FRdest, FRsrc1, FRsrc2
```

Compute the product of the floating point singles in registers `FRsrc1` and `FRsrc2` and put it in register `FRdest`.

mulou†

Unsigned multiply (with overflow)

```
mulou Rdest, Rsrc1, Src2
```

Put the product of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

mulo†

Multiply (with overflow)

```
mulo Rdest, Rsrc1, Src2
```

Put the product of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

multu

Unsigned multiply

```
multu Rsrc1, Rsrc2
```

Multiply the contents of the two registers. Leave the low-order word of the product in register `lo` and the high-word in register `hi`.

mult

Multiply

```
mult Rsrc1, Rsrc2
```

Multiply the contents of the two registers. Leave the low-order word of the product in register `lo` and the high-word in register `hi`.

mul†

Multiply (without overflow)

```
mul Rdest, Rsrc1, Src2
```

Put the product of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

neg.d

Negate double

```
neg.d FRdest, FRsrc
```

Negate the floating point double in register `FRsrc` and put it in register `FRdest`.

neg.s

Negate single

```
neg.s FRdest, FRsrc
```

Negate the floating point single in register `FRsrc` and put it in register `FRdest`.

negu†

Negate value (without overflow)

```
negu Rdest, Rsrc
```

Put the negative of the integer from register `Rsrc` into register `Rdest`.

neg†

Negate value (with overflow)

```
neg Rdest, Rsrc
```

Put the negative of the integer from register `Rsrc` into register `Rdest`.

nop

No operation

```
nop
```

Do nothing.

nor

NOR

```
nor Rdest, Rsrc1, Src2
```

Put the logical NOR of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

not†

NOT

```
not Rdest, Rsrc
```

Put the bitwise logical negation of the integer from register `Rsrc` into register `Rdest`.

ori

OR immediate

```
ori Rdest, Rsrc1, Imm
```

Put the logical OR of the integers from register `Rsrc1` and `Imm` into register `Rdest`.

or

OR

```
or Rdest, Rsrc1, Src2
```

Put the logical OR of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

remu†

Unsigned remainder

```
remu Rdest, Rsrc1, Src2
```

Put the remainder from dividing the integer in register `Rsrc1` by the integer in `Src2` into register `Rdest`. Note that if an operand is negative, the remainder is unspecified by the MIPS architecture and depends on the conventions of the machine on which SPIM is run.

rem† Remainder

```
rem Rdest, Rsrc1, Src2
```

Put the remainder from dividing the integer in register `Rsrc1` by the integer in `Src2` into register `Rdest`. Note that if an operand is negative, the remainder is unspecified by the MIPS architecture and depends on the conventions of the machine on which SPIM is run.

rfe Return from exception

```
rfe
```

Restore the Status register.

rol† Rotate left

```
rol Rdest, Rsrc1, Src2
```

Rotate the contents of register `Rsrc1` left by the distance indicated by `Src2` and put the result in register `Rdest`.

ror† Rotate right

```
ror Rdest, Rsrc1, Src2
```

Rotate the contents of register `Rsrc1` right by the distance indicated by `Src2` and put the result in register `Rdest`.

s.d† Store floating point double

```
s.d FRdest, address
```

Store the floating point double in register `FRdest` at `address`.

s.s† Store floating point single

```
s.s FRdest, address
```

Store the floating point single in register `FRdest` at `address`.

sb Store byte

```
sb Rsrc, address
```

Store the low byte from register `Rsrc` at *address*.

sd† Store double-word

```
sd Rsrc, address
```

Store the 64-bit quantity in registers `Rsrc` and `Rsrc + 1` at *address*.

seq† Set equal

```
seq Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` equals `Src2` and to be 0 otherwise.

sgeu† Set greater than equal unsigned

```
sgeu Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is greater than or equal to `Src2` and to 0 otherwise.

sge† Set greater than equal

```
sge Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is greater than or equal to `Src2` and to 0 otherwise.

`sgtu`† Set greater than unsigned

```
sgtu Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is greater than `Src2` and to 0 otherwise.

`sgt`† Set greater than

```
sgt Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is greater than `Src2` and to 0 otherwise.

`sh` Store halfword

```
sh Rsrc, address
```

Store the low halfword from register `Rsrc` at *address*.

`sleu`† Set less than equal unsigned

```
sleu Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is less than or equal to `Src2` and to 0 otherwise.

`sle`† Set less than equal

```
sle Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is less than or equal to `Src2` and to 0 otherwise.

`sllv` — Shift left logical variable

```
sllv Rdest, Rsrc1, Rsrc2
```

Shift the contents of register `Rsrc1` left by the distance indicated by `Rsrc2` and put the result in register `Rdest`.

`sll` — Shift left logical

```
sll Rdest, Rsrc1, Src2
```

Shift the contents of register `Rsrc1` left by the distance indicated by `Src2` and put the result in register `Rdest`.

`sltiu` — Set less than unsigned immediate

```
sltiu Rdest, Rsrc1, Imm
```

Set register `Rdest` to 1 if register `Rsrc1` is less than `Imm` and to 0 otherwise.

`slti` — Set less than immediate

```
slti Rdest, Rsrc1, Imm
```

Set register `Rdest` to 1 if register `Rsrc1` is less than `Imm` and to 0 otherwise.

`sltu` — Set less than unsigned

```
sltu Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is less than `Src2` and to 0 otherwise.

`slt` — set less than

```
slt Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is less than `Src2` and to 0 otherwise.

`sne`† Set not equal

```
sne Rdest, Rsrc1, Src2
```

Set register `Rdest` to 1 if register `Rsrc1` is not equal to `Src2` and to 0 otherwise.

`srav` Shift right arithmetic variable

```
srav Rdest, Rsrc1, Rsrc2
```

Shift the contents of register `Rsrc1` right by the distance indicated by `Rsrc2` and put the result in register `Rdest`.

`sra` Shift right arithmetic

```
sra Rdest, Rsrc1, Src2
```

Shift the contents of register `Rsrc1` right by the distance indicated by `Src2` and put the result in register `Rdest`.

`srlv` Shift right logical variable

```
srlv Rdest, Rsrc1, Rsrc2
```

Shift the contents of register `Rsrc1` right by the distance indicated by `Rsrc2` and put the result in register `Rdest`.

`srl` Shift right logical

```
srl Rdest, Rsrc1, Src2
```

Shift the contents of register `Rsrc1` right by the distance indicated by `Src2` and put the result in register `Rdest`.

`sub.d` Floating point subtract double

```
sub.d FRdest, FRsrc1, FRsrc2
```

Compute the difference of the floating point doubles in registers `FRsrc1` and `FRsrc2` and put it in register `FRdest`.

`sub.s` Floating point subtract single

```
sub.s FRdest, FRsrc1, FRsrc2
```

Compute the difference of the floating point singles in registers `FRsrc1` and `FRsrc2` and put it in register `FRdest`.

`subu` Subtract (without overflow)

```
subu Rdest, Rsrc1, Src2
```

Put the difference of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

`sub` Subtract (with overflow)

```
sub Rdest, Rsrc1, Src2
```

Put the difference of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

`swc`*z* Store word coprocessor

```
swcz Rsrc, address
```

Store the word from register `Rsrc` of coprocessor *z* at *address.*

`swl` Store word left

```
swl Rsrc, address
```

Store the left bytes from register `Rsrc` at the possibly unaligned *address.*

`swr` Store word right

```
swr Rsrc, address
```

Store the right bytes from register `Rsrc` at the possibly unaligned *address*.

`sw` Store word

```
sw Rsrc, address
```

Store the word from register `Rsrc` at *address*.

`syscall` System call

```
syscall
```

Register `$v0` contains the number of the system call provided by SPIM.

`ulhu`† Unaligned load halfword unsigned

```
ulhu Rdest, address
```

Load the 16-bit quantity (halfword) at the possibly unaligned *address* into register `Rdest`. The halfword is not sign-extended by the `ulhu` instruction.

`ulh`† Unaligned load halfword

```
ulh Rdest, address
```

Load the 16-bit quantity (halfword) at the possibly unaligned *address* into register `Rdest`. The halfword is sign-extended by the `ulh` instruction.

`ulw`† Unaligned load word

```
ulw Rdest, address
```

Load the 32-bit quantity (word) at the possibly unaligned *address* into register `Rdest`.

`ush`† Unaligned store halfword

```
ush Rsrc, address
```

Store the low halfword from register `Rsrc` at the possibly unaligned *address*.

`usw`† Unaligned store word

```
usw Rsrc, address
```

Store the word from register `Rsrc` at the possibly unaligned *address*.

`xori` XOR immediate

```
xori Rdest, Rsrc1, Imm
```

Put the logical XOR of the integers from register `Rsrc1` and `Imm` into register `Rdest`.

`xor` XOR

```
xor Rdest, Rsrc1, Src2
```

Put the logical XOR of the integers from register `Rsrc1` and `Src2` into register `Rdest`.

Index

Computer Architecture / Assembly Language Programming

Introduction to RISC Assembly Language Programming

As the best way to gain an understanding of how a computer processor works at the lower levels, assembly language programming is essential background for every computer science and electronic engineering student. It is, however, often considered an arcane and complex discipline, because many first encounter it through the daunting instructions and registers of the Intel 8086 family.

Programming in a simple RISC architecture is very different due to the elegant and compact instruction set. Students of this text who have never programmed before and who study it simultaneously with a course on a higher-level language report that it is easier and more logical to program in assembly!

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John Waldron

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