MIPS
Assembly Language
using QtSpim

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MIPS R3000 Custom Chip

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1.0 Introduction

There are number of excellent, comprehensive, and in-depth texts on MIPS assembly language programming. This is not one of them.

The purpose of this text is to provide a simple and free reference for university level programming and architecture units that include a brief section covering MIPS assembly language. The text uses the QtSpim simulator. An appendix covers the downloading, installation, and basic use of the simulator.

The scope of this text addresses basic MIPS assembly language programming including instruction set basics, stack, procedure/function calls, QtSpim simulator system services, multiple dimension arrays, and basic recursion.

1.1 Additional References

Some key references for additional information are listed below:

- MIPS Assembly-language Programmer Guide, Silicon Graphics
- MIPS Software Users Manual, MIPS Technologies, Inc.
- Hennessy and Patterson, Computer Organization and Design: The Hardware/Software Interface

More information regarding these references can be found on the Internet.

2.0 MIPS Architecture Overview

The following text presents a basic, general overview of the architecture of the MIPS processor.

The MIPS architecture is a Reduced Instruction Set Computer (RISC). This means that there is a smaller number of instructions, using a uniform instruction encoding format. Each instruction/operation does one thing (memory access, computation, conditional, etc.). The idea is to make the lesser number of instructions execute faster. In general RISC architectures, and specifically the MIPS architecture, are designed for high-speed implementations.

2.1 Architecture Overview

The basic components of a computer include a Central Processing Unit (CPU), Random Access Memory (RAM), Disk Drive, and Input/Output devices (i.e., screen and keyboard), and an interconnection referred to as BUS.

A very basic diagram of a computer architecture is as follows:

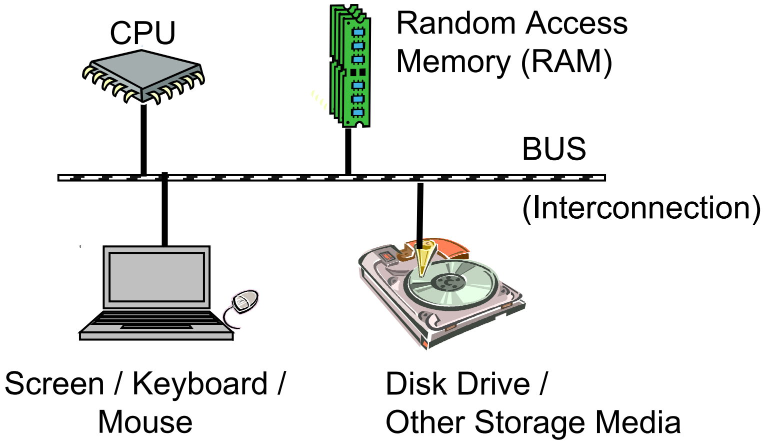


Illustration 1: Computer Architecture

Programs and data are typically stored on the disk drive. When a program is executed, it must be copied from the disk drive into the RAM memory. The CPU executes the program from RAM. This is similar to storing a term paper on the disk drive, and when writing/editing the term paper, it is copied from the disk drive into memory. When done, the updated version is stored back to the disk drive.

2.2 Data Types/Sizes

The basic data types include integer, floating point, and characters.

Data can be stored in byte, halfword, word, double-word sizes. Floating point must be in either word (32-bit) or double word (64-bit) size. Character data is typically a byte and a string is a series of sequential bytes. The MIPS architecture supports the following data/memory sizes:

Name	Size
byte	8-bit integer
half	16-bit integer
word	32-bit integer
float	32-bit floating-point number
double	64-bit floating-point number

Lists or arrays (sets of memory) can be reserved in any of these types. In addition, an arbitrary amount of space can be defined with the "space" directive.

2.3 Memory

Memory can be viewed as a series of bytes, one after another. That is, memory is *byte addressable*. This means each memory address hold one byte of information. To store a word, four bytes are required which use four memory addresses.

Additionally, the MIPS architecture as simulated in QtSpim is ***little-endian***. This means that the Least Significant Byte (LSB) is stored in the lowest memory address. The Most Significant Byte (MSB) is stored in the highest memory location.

For a word (32-bits), the MSB and LSB are allocated as shown below.

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
MSB																								**LSB**							

For example, assuming the following declarations:

```
num1:   .word    42
num2:   .word    5000000
```

Recall that 42 in hex, word size is 0x0000002A and 5,000,000 in hex, word size is 0x004C4B40.

For a little-endian architecture, the memory picture would be as follows:

variable name	value	address
	00	0x100100B
	4C	0x100100A
	4B	0x1001009
Num2 →	40	0x1001008
	00	0x1001007
	00	0x1001006
	00	0x1001005
Num1 →	2A	0x1001004

2.4 Memory Layout

The general memory layout is as shown:

stack
heap
uninitialized data
data
text (code)
reserved

Later sections will provided additional detail for the listed sections.

2.5 Registers

A CPU register, or just register, is a temporary storage or working location built into the CPU itself (separate form memory). Computations are typically performed by the CPU using registers.

The MIPS has 32, 32-bit integer registers ($0 through $31) and 32 32-bit floating point register ($f0 through $f31). Some of the integer registers are used for special purposes.

In addition, there are some miscellaneous registers, $pc, $hi, $lo, and $epc. The $pc is the Program Counter (point to the next instruction to be executed). The $hi and $lo registers are used for some integer arithmetic operations.

The registers and register usage is described in the following table.

Register Name	Register Number	Register Usage
$zero	$0	Hardware set to 0
$at	$1	Assembler temporary
$v0 - $v1	$2 - $3	Function result (low/high)
$a0 - $a3	$4 - $7	Argument Register 1
$t0 - $t7	$8 - $15	Temporary registers
$s0 - $s7	$16 - $23	Saved registers
$t8 - $t9	$24 - $25	Temporary registers
$k0 - $k1	$26 - $27	Reserved for OS kernel
$gp	$28	Global pointer
$sp	$29	Stack pointer
$fp	$30	Frame pointer
$ra	$31	Return address

The register names will used in the remainder of this document. Further sections will expand on register usage and address the usage including the 'temporary' and 'saved' registers.

2.5.1 Reserved Registers

The following register should not be used in user programs.

Register Name
$k0 - $k1
$at
$gp

The $k0 and $k1 register are reserved for use by the operating system and should not be used in user programs. The $at register is used by the assembler and should not be used in user programs. The $gp register is used point to global data (as needed) and should not be used in user programs.

3.0 Data Representation

Data representation refers to how information is stored within the computer. There is a specific method for storing integers which is different that storing floating point values which is different than storing characters. This chapter presents a brief summary of the integer, floating-point, and ASCII representation schemes. It is assumed the reader is already generally familiar with data representation issues.

3.1 Integer Representation

Representing integer numbers refers to how the computer stores or represents a number in memory. As you know, the computer represents numbers in binary. However, the computer has a limited amount of space that can be used for each number or variable. This directly impacts the size, or range, of the number that can be represented. For example, a byte (8 bits) can be used to to represent 2^8 or 256 different numbers. Those 256 different numbers can be *unsigned* (all positive) in which case we can represent any number between 0 and 255 (inclusive). If we choose *signed* (positive and negative), then we can represent any number between -128 and +127 (inclusive).

If that range is not large enough to handle the intended values, a larger size must be used. For example, a word (16 bits) can be used to to represent 2^{16} or 65,536 different numbers, and a double-word can be used to to represent 2^{32} or 4,294,967,296 different numbers. So, if you wanted to store a value of 100,000 then a double-word would be required.

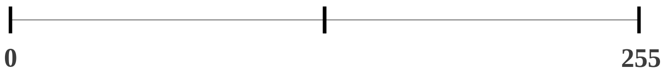
The following table shows the ranges associated with typical sizes:

Size	***Size***	***Unsigned Range***	***Signed Range***
Bytes (8 bits)	2^8	0 to 255	-128 to +127
Words (16 bits)	2^{16}	0 to 65,535	−32,768 to +32,767
Double words (32 bits)	2^{32}	0 to 4,294,967,295	−2,147,483,648 to +2,147,483,647

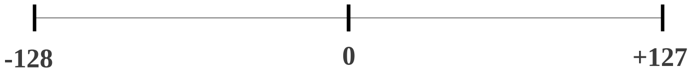
In order to determine if a value can be represented, you will need to know the size of storage (byte, word, double-word) and if the values are signed or unsigned values.

- For representing *unsigned* values within the range of a given storage size, standard binary is used.
- For representing *signed* values with the range, **two's compliment** is used. Specifically, two's compliment applies to the values in the negative range. Values within the positive range, standard binary is used.

For example, the unsigned byte range can be represented as follows:



For example, the signed byte range can be represented as follows:



The same concept applies to halfwords and words with larger ranges.

3.1.1 Two's Compliment

The following describes how to find the two's compliment representation for negative values.

To take the two's compliment of a number:

1. take the one's compliment (negate)
2. add 1 (in binary)

The same process is used to encode a decimal value into two's compliment and from two's compliment back to decimal.

3.1.2 Byte Example

For example, to find the byte size, two's compliment representation of -9 and -12.

9 (8+1) =	00001001
Step 1	11110110
Step 2	11110111
-9 (in hex) =	F7

12 (8+4) =	00001100
Step 1:	11110011
	11110100
-12 (in hex) =	F4

Note, all bits for the given size, byte in this example, must be specified.

3.1.3 Word Example

To find the word size, two's compliment representation of -18 and -40.

18 (16+2) =	0000000000010010
Step 1	1111111111101110
Step 2	1111111111101111
-18 (in hex) =	FFEE

40 (32+8) =	0000000000101000
Step 1:	1111111111010111
	1111111111011000
-40 (in hex) =	FFD8

Note, all bits for the given size, words in these examples, must be specified.

3.2 Unsigned and Signed Addition

Since *unsigned* values have a different, positive only, range than signed values, there is some overlap between the values. For example:

- A signed byte representation of -15 is $F1_{16}$
- An unsigned representation of 241 is also $F1_{16}$

However, the addition and subtraction operations are the same. For example:

241	11110001
+ 7	00000111
248	11111000
248 =	F8

-15	11110001
+ 7	00000111
-8	11111000
-8 =	F8

Additionally, $F8_{16}$ is the º (degree symbol) in the ASCII table.

As such, it is very important to have a clear definition of the sizes (byte, half, word, etc.) and types (signed, unsigned) of operations being performed.

3.3 Floating-point Representation

The representation issues for floating points numbers are more complex. There are a series of floating point representations for various ranges of the value. For simplicity, we will only look primarily at the IEEE 754 32-bit floating-point standard.

3.3.1 IEEE 32-bit Representation

The IEEE 754 32-bit floating-point standard is defined as follows:

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
s	***biased exponent***								***fraction***																						

Where ***s*** is the sign (0 => positive and 1 => negative).

When representing floating point values, the first step is to convert floating point value into binary. The following table provides a brief reminder of how binary handles fractional components:

	2^3	2^2	2^1	2^0		2^{-1}	2^{-2}	2^{-3}	
...	8	4	2	1	.	1/2	1/4	1/8	...
	0	**0**	**0**	**0**	**.**	**0**	**0**	**0**	

For example, 100.101_2 would be 4.625_{10}. For repeating decimals, calculating the binary value can be time consuming. However, there is a limit since computers have finite storage.

The next step is to show the value in normalized scientific notation in binary. This means that the number should has a single, non-zero leading digit to the left of the decimal point. For example, 8.125_{10} is 1000.001_2 (or $1000.001_2 \times 2^0$) and in binary normalized scientific notation that would be written as 1.000001×2^3 (since the decimal point was moved three places to the left). Of course, if the number was 0.125_{10} the binary would be 0.001_2 (or $0.001_2 \times 2^0$) and the normalized scientific notation would be 1.0×2^{-3} (since the decimal point was moved three places to the right). The numbers after the leading 1, ***not*** including the leading 1, are stored left-justified in the fraction portion of the word.

The next step is to calculate the *biased exponent*, which is the exponent from the normalized scientific notation with plus the bias. The bias for the IEEE 754 32-bit floating-point standard is 127_{10}. The result should be converted to a byte (8 bits) and stored in the biased exponent portion of the word.

Note, converting from the IEEE 754 32-bit floating-point representation to the decimal value is done in reverse, however leading 1 must be added back (as it is not stored in the word). Additionally, the bias is subtracted (instead of added).

3.3.1.1 IEEE 32-bit Representation Examples

This section presents several examples of encoding and decoding floating-point representation for reference.

3.3.1.1.1 Example → 7.75_{10}

For example, to find the IEEE 754 32-bit floating-point representation for -7.75_{10}:

<u>Example 1:</u> **-7.75**

- determine sign -7.75 => 1 (since negative)
- convert to binary $-7.75 = -0111.11_2$
- normalized scientific notation $= 1.1111 \times 2^2$
- compute biased exponent $2_{10} + 127_{10} = 129_{10}$
    - and convert to binary $= 10000001_2$
- write components in binary:

sign	exponent	mantissa
1	10000001	11110000000000000000000

- convert to hex (split into groups of 4)

  11000000111110000000000000000000
  1100 0000 1111 1000 0000 0000 0000 0000
  C 0 F 8 0 0 0 0

- final result: **$C0F8\ 0000_{16}$**

3.3.1.1.2 Example → 0.125_{10}

For example, to find the IEEE 754 32-bit floating-point representation for -0.125_{10}:

<u>Example 2:</u> **-0.125**

- determine sign -0.125 => 1 (since negative)
- convert to binary $-0.125 = -0.001_2$
- normalized scientific notation $= 1.0 \times 2^{-3}$
- compute biased exponent $-3_{10} + 127_{10} = 124_{10}$
    - and convert to binary $= 01111100_2$
- write components in binary:

sign	exponent	mantissa
1	01111100	00000000000000000000000

- convert to hex (split into groups of 4)

  10111110000000000000000000000000
  1011 1110 0000 0000 0000 0000 0000 0000
  B E 0 0 0 0 0 0

- final result: **$BE00\ 0000_{16}$**

3.3.1.1.3 Example → 41440000_{16}

For example, given the IEEE 754 32-bit floating-point representation 41440000_{16} find the decimal value:

<u>Example 3:</u> **41440000_{16}**

- convert to binary
  $0100\ 0001\ 0100\ 0100\ 0000\ 0000\ 0000\ 0000_2$
- split into components
  $0\ 10000010\ 10001000000000000000000_2$
- determine exponent $10000010_2 = 130_{10}$
  - and remove bias $130_{10} - 127_{10} = 3_{10}$
- determine sign 0 => positive
- write result $+1.10001 \times 2^3 = +1100.01 =$ **+12.25**

3.3.2 IEEE 64-bit Representation

The IEEE 754 64-bit floating-point standard is defined as follows:

63	62		52	51		0
s	***biased exponent***			***fraction***		

The representation process is the same, however the format allows for an 11-bit biased exponent (which support large and smaller values). The 11-bit biased exponent uses a bias of ±1023.

4.0 QtSpim Program Formats

The QtSpim MIPS simulator will be used for programs in this text. The SPIM simulator has a number of features and requirements for writing MIPS assembly language programs. This includes a properly formatted assembly source file.

A properly formatted assembly source file consists of two main parts; the data section (where data is placed) and the text section (where code is placed). The following sections summarize the formatting requirements and explains each of these parts.

4.1 Assembly Process

The QtSpim effectively assembles the program during the load process. Any major errors in the program format or the instructions will be noted immediately. Assembler errors must be resolved before the program can be successfully executed. Refer to Appendix B regarding the use of QtSpim to load and execute programs.

4.2 Comments

The "#" character represents a comment line. Anything typed after the "#" is considered a comment. Blank lines are accepted.

4.3 Assembler Directives

An assembler directive is a message to the assembler, or the QtSpim simulator, that tells the assembler something it needs to know in order to carry out the assembly process. This includes noting where the data is declared or the code is defined. Assembler directives are *not* executable statements.

Directives are required for data declarations and to define the start and end of procedures. Assembler directives start with a ".". For example, ".data" or ".text".

Additionally, directives are used to declare and defined data. The following sections provide some examples of data declarations using the directives.

4.4 Data Declarations

The data must be preceded by the ".data" directive. All variables and constants are placed in this section. Variable names must start with a letter followed by letters or numbers (including some special characters such as the "_"), and terminated with a ":". Variable definitions must include the name, the data type, and the initial value for the variable. In the definition, the variable name must be terminated with a ":".

The data type must be preceded with a ".". The general format is:

```
<variableName>:      .<dataType>     <initialValue>
```

Refer to the following sections for a series of examples using various data types.

The supported data types are as follows:

Declaration	
`.byte`	8-bit variable(s)
`.half`	16-bit variable(s)
`.word`	32-bit variable(s)
`.ascii`	ASCII string
`.asciiz`	NULL terminated ASCII string
`.float`	32 bit IEEE floating point number
`.double`	64 bit IEEE floating point number
`.space <n>`	<n> bytes of uninitialized memory

These are the primary assembler directives for data declaration. Other directives are referenced in different sections.

4.4.1 Integer Data Declarations

Integer values are defined with the *.word*, *.half*, or *.byte* directives. Two's compliment is used for the representation of negative values. For more information regarding two's compliment, refer to the Data Representation section.

The following declarations are used to define the integer variables "wVar1" and "wVar2" as 32-bit word values and initialize them to 500,000 and -100,000.

```
wVar1:     .word      500000
wVar2:     .word      -100000
```

The following declarations are used to define the integer variables "hVar1" and "hVar2" as 16-bit word values and initialize them to 5,000 and -3,000.

```
hVar1:     .half      5000
hVar2:     .half      -3000
```

The following declarations are used to define the integer variables "bVar1" and "bVar2" as 8-bit word values and initialize them to 5 and -3.

```
bVar1:     .byte      5
bVar2:     .byte      -3
```

If an variable is initialized to a value that can not be stored in the allocated space, an assembler error will be generated. For example, attempting to set a byte variable to 500 would be illegal and generate an error.

4.4.2 String Data Declarations

Strings are defined with *.ascii* or *.asciiz* directives. Characters are represented using standard ASCII characters. Refer to Appendix D for a copy of the ASCII table for reference.

The C/C++ style new line, "\n", and tab, "\t" tab are supported within in strings.

The following declarations are used to define the a string "message" and initialize it to “Hello World”.

```
message:   .asciiz    "Hello World\n"
```

In this example, the string is defined as NULL terminated (i.e., after the new line). The NULL is a non-printable ASCII character and is used to mark the end of the string. The NULL termination is standard and is required by the print string system service (to work correctly).

To define a string with multiple lines, the NULL termination would only be required on the final or last line. For example,

```
message:   .ascii     "Line 1: Goodbye World\n"
           .ascii     "Line 2: So, long and thanks "
           .ascii     "for all the fish.\n"
           .asciiz    "Line 3: Game Over.\n"
```

When printed, using the starting address of 'message', everything up-to (but not including) the NULL will be displayed. As such, the declaration using multiple lines is not relevant to the final displayed output.

4.4.3 Floating-Point Data Declarations

Floating-point values are defined with the *.float* (32-bit) or *.double* (64-bit) directives. The IEEE floating-point format is used for the internal representation of floating-point values.

The following declarations are used to define the floating-point variables "pi" to a 32-bit floating-point value initialized to 3.14159 and "tao" to a 64-bit floating-point values initialized them to 6.28318.

```
pi:        .float     3.14159
tao:       .double    6.28318
```

For more information regarding the IEEE format, refer to the Data Representation section.

4.5 Constants

Constant names must start with a letter followed by letters or numbers including some special characters such as the "_" (underscore). Constant definitions are created with an "=" sign.

For example, to create some constants named TRUE and FALSE, set to 1 and 0:

```
TRUE = 1
FALSE = 0
```

Constants are also defined in the data section. The use of all capitals for a constant is a convention and not required by the QtSpim program. The convention helps programmers more easily distinguish between variables (which can change values) and constants (which can not change values). Additionally, in assembly language constants are not typed (i.e., not predefined to be a specific size such as 8-bit, 16-bit, or 32-bits, etc.).

4.6 Program Code

The code must be preceded by the ".text" directive.

In addition, there are some basic requirements for naming a "main" procedure (i.e., the first procedure to be executed). The ".globl name" and ".ent name" directives are required to define the name of the initial or main procedure. *Note*, the **globl** is correct. Also, the main procedure must start with a label with the procedure name. The main procedure (as all procedures) should be terminated with the ".end <name>" directive.

In the following example, the <name> would be the name of the main procedure, which is “main”.

4.7 Program Template

The following is a template for QtSpim MIPS programs. This general template will be used for all programs.

```
#  Name and assignment number

.data

#    data declarations go here...

#-----------------------------------

.globl     main
.text
.ent  main
main:

# -----
#    your program code goes here.

# -----
#  Done, terminate program.

     li    $v0, 10
     syscall                    # all done!
.end  main
```

A more complete example, with working code, is located in Appendix A.

5.0 Instruction Set Overview

In assembly-language, instructions are how work is accomplished. In assembly the instructions are simple, single operation commands. In a high-level language, one line can be a series of instructions in assembly-language.

This section presents a summary of the basic, most common instructions. The ***MIPS Instruction Set*** Appendix presents a more comprehensive list of the available instructions.

5.1 Pseudo-Instructions vs Bare-Instructions

As part of the MIPS architecture, the assembly language includes a number of pseudo-instructions. A bare-instruction is an instructed that is executed by the CPU. A pseudo-instruction is an instruction that the assembler, or simulator, will recognize but then convert into one or more bare-instructions. This text will focus primarily on the pseudo-instructions.

5.2 Notational Conventions

This section summarizes the notation used within this text which is fairly common in the technical literature. In general, an instruction will consist of the instruction or operation itself (i.e., add, sub, mul, etc.) and the ***operands***. The operands refer to where the data (to be operated on) is coming from or the result will be placed.

The following table summarizes the notational conventions used in the remainder of the document.

Operand Notation	Description
`Rdest`	Destination operand. Must be a register. Since it is a destination operand, the contents will be over written with the new result.
`Rsrc`	Source operand. Must be a register. Register value is unchanged.
`Src`	Source operand. Must be a register or an immediate value. Value is unchanged.
`Imm`	Immediate value
`Mem`	Memory location. May be a variable name or an indirect reference.

Refer to the chapter on Addressing Modes for more information regarding indirection.

5.3 Data Movement

CPU computations are typically performed using registers. As such, before computations can be performed, data is typically moved into registers from variables (i.e., memory) and when the computations are completed the data would be moved out of registers into variables.

To support the loading of data from memory into registers and storing of data in register to memory, there are a series of load and store instructions.

The general form of the load and store instructions are as follows:

Instruction	Description
`l<type>    Rdest, mem`	Load value from memory location memory into destination register.
`li         Rdest, imm`	Load specified immediate value into destination register.
`la         Rdest, mem`	Load address of memory location into destination register.
`s<type>    Rsrc, mem`	Store contents of source register into memory location.
`move       Rdest, RSrc`	Copy contents of source register into destination register.

Assuming the following data declarations:

```
num:      .word     0
wnum:     .word     42
hnum:     .half     73
bnum:     .byte     7
wans:     .word     0
hnum:     .half     0
bnum:     .byte     0
```

To perform, the basic operations of:

```
num = 27
wans = wnum
hans = hnum
bans = bnum
```

The following instructions

```
li    $t0, 27
sw    $t0, num         # num = 27
lw    $t0, wnum
sw    $t0, wans        # wans = wnum
lh    $t1, hnum
```

```
sh    $t1, hans        # hans = hnum
lb    $t2, bnum
sb    $t2, bans        # bans = bnum
```

For the halfword and byte instructions, only the lower 16-bits are 8-bits are used.

5.4 Integer Arithmetic Operations

The arithmetic operations include addition, subtraction, multiplication, division, remainder (remainder after division), logical AND, and logical OR. The general format for these basic instructions is as follows:

Instruction	Description
`add<ui>   Rdest, Rsrc, Src`	Rdest = Rsrc + Src
`sub<ui>   Rdest, Rsrc, Src`	Rdest = Rsrc - Src
`mul<ui>   Rdest, Rsrc, Src`	Rdest = Rsrc * Src
`div<ui>   Rdest, Rsrc, Src`	Rdest = Rsrc / Src
`rem<ui>   Rdest, Rsrc, Src`	Rdest = Rsrc % Src
`and<ui>   Rdest, Rsrc, Src`	Rdest = Rsrc **&&** Src
`or<ui>    Rdest, Rsrc, Src`	Rdest = Rsrc || Src

Note, the && refers to the logical AND operation and the || refers to the logical OR operation (as per C/C++).

These instructions operate on 32-bit registers (even if byte or halfword values are placed in the registers).

Assuming the following data declarations:

```
wnum1:     .word      651
wnum2:     .word      42
wans1:     .word      0
wans2:     .word      0
wans3:     .word      0

hnum1:     .half      73
hnum2:     .half      15
hans:      .half      0

bnum1:     .byte      7
bnum2:     .byte      9
bans:      .byte      0
```

To perform, the basic operations of:

```
wans1 = wnum1 + wnum2
wans2 = wnum1 * wnum2
```

```
wans3 = wnum1 % wnum2
hans  = hnum1 * hnum2
bans  = bnum1 / bnum2
```

The following instructions

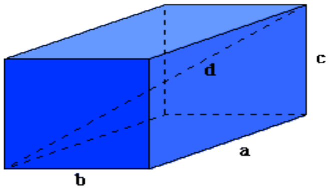
```
lw    $t0, wnum1
lw    $t1, wnum2
add   $t2, $t0, $t1
sw    $t0, wans1        # wans1 = wnum1 + wnum2

lw    $t0, wnum1
lw    $t1, wnum2
add   $t2, $t0, $t1
sw    $t0, wans2        # wans2 = wnum1 * wnum2

lw    $t0, wnum1
lw    $t1, wnum2
rem   $t2, $t0, $t1
sw    $t0, wans3        # wans = wnum1 % wnum2

lh    $t0, wnum1
lh    $t1, wnum2
mul   $t2, $t0, $t1
sh    $t0, wans         # hans = wnum1 * wnum2

lb    $t0, bnum1

lb    $t1, bnum2
div   $t2, $t0, $t1
sb    $t0, bans         # bans = bnum1 / bnum2
```

For the halfword instructions, only the lower 16-bits are used. For the byte instructions, only the lower 8-bits are used.

5.5 Example Program, Integer Arithmetic

The following is an example program to compute the volume and surface area of a rectangular parallelepiped.

The formulas for the volume and surface area are as follows:



$$\begin{aligned} volume &= aSide * bSide * cSide \\ surfaceArea &= 2\left(aSide * bSide + aSide * cSide + bSide * cSide\right) \end{aligned}$$

This example main initializes the ***a***, ***b***, and ***c*** sides to arbitrary integer values.

```
#   Example to compute the volume and surface area
```

```
#  of a rectangular parallelepiped.

# ----------------------------------------------------------
#  Data Declarations

.data

aSide:          .word      73
bSide:          .word      14
cSide:          .word      16

volume:         .word      0
surfaceArea:    .word      0

# ----------------------------------------------------------
#  Text/code section

.text
.globl     main
main:

# -----
#  Load variables into registers.

     lw    $t0, aSide
     lw    $t1, bSide
     lw    $t2, cSide

# ----
#  Find volume of a rectangular paralllelpiped.
#     volume = aSide * bSide * cSide

     mul   $t3, $t0, $t1
     mul   $t4, $t3, $t2

     sw    $t4, volume

# -----
#  Find surface area of a rectangular parallelepiped.
#     volume = 2*(aSide*bSide + aSide*cSide + bSide*cSide)

     mul   $t3, $t0, $t1         # note, redundent
     mul   $t4, $t0, $t2
     mul   $t5, $t1, $t2

     add   $t6, $t3, $t4
     add   $t7, $t6, $t5

     sw    $t7, surfaceArea
```

```
# -----
#  Done, terminate program.

     li   $v0, 10                # call code for terminate
     syscall                     # system call
.end main
```

Refer to the system services section for information on displaying the final results to the console.

5.6 Labels

Labels are code locations, typically used as the target of a jump. A typical use for a label would be the start of a loop. The conditional statements are explained in the following section.

The rules for a label are as follows:

- Must start with a letter
- May be followed by letters, numbers, or an "_" (underscore).
- Must be terminated with a ":" (colon).
- May only be define once.

Some examples of a label include:

```
mainLoop:
exitProgram:
```

Characters in a label are case-sensitive. As such, `Loop:` and `loop:` are different labels. This can be very confusing initially, so caution is advised.

5.7 Control Instructions

The control instructions refer to unconditional and conditional branching. Branching is required for basic conditional statements (i.e., IF statements) and looping.

5.7.1 Unconditional Control Instructions

The unconditional instruction provides an unconditional jump to a specific location.

Instruction	Description
`j <label>`	Unconditionally branch to the specified label.

An error is generated if the label is not defined.

5.7.2 Conditional Control Instructions

The conditional instruction provides a conditional jump based on a comparison. This is a basic IF statement.

The conditional control instructions include the standard set; branch equal, branch not equal, branch less than, branch less than or equal, branch greater than, and branch greater than or equal. The general format for these basic instructions is as follows:

Instruction	Description
`beq <Rsrc>, <Src>, <label>`	Branch to label if <Rscr> and <Scr> are equal
`bne <Rsrc>, <Src>, <label>`	Branch to label if <Rscr> and <Scr> are not equal
`blt <Rsrc>, <Src>, <label>`	Branch to label if <Rscr> is less than <Scr>
`ble <Rsrc>, <Src>, <label>`	Branch to label if <Rscr> is less than or equal to <Scr>
`bgt <Rsrc>, <Src>, <label>`	Branch to label if <Rscr> is greater than <Scr>
`bge <Rsrc>, <Src>, <label>`	Branch to label if <Rscr> is greater than or equal to <Scr>

These instructions operate on 32-bit registers (even if byte or halfword values are placed in the registers).

5.8 Example Program, Sum of Squares

The following is an example program to find the sum of squares from 1 to ***n***. For example, the sum of squares for 10 is as follows:

$$1^2 + 2^2 + \cdots + 10^2 = 385$$

This example main initializes the ***n*** to arbitrary to 10 to match the example.

```
#  Example program to compute the sum of squares.

# ----------------------------------------------------------
#  Data Declarations

.data

n:          .word 10
```

```
sumOfSquares:   .word 0

# -----------------------------------------------------------
#  text/code section

.text
.globl    main
main:

# -----
#  Compute sum of squares from 1 to n.

     lw   $t0, n               #
     li   $t1, 1               # loop index (1 to n)
     li   $t2, 0               # sum
sumLoop:
     mul  $t3, $t1, $t1        # index^2
     add  $t2, $t2, $t3

     add  $t1, $t1, 1
     ble  $t1, $t0, sumLoop

     sw   $t2, sumOfSquares

# -----
#  Done, terminate program.

     li   $v0, 10              # call code for terminate
     syscall                   # system call
.end main
```

Refer to the system services section for information on displaying the final results to the console.

5.9 Floating-Point Instructions

This section presents a summary of the basic, most common floating-point arithmetic instructions. The ***MIPS Instruction Set*** Appendix presents a more comprehensive list of the available instructions.

5.9.1 Floating-Point Register Usage

The floating-point instructions are similar to the integer instructions, however the floating-point register must be used. And, the floating-point register must be used exclusively (i.e., no ability to use the integer registers).

When single-precision (32-bit) floating-point operation is performed, the specified 32-bit floating-point register is used. When a double-precision (64-bit) floating-point operation is performed, two 32-bit floating-point registers are used; the specified 32-bit floating-point register and the next numerically sequential register is used by the instruction.

5.9.2 Floating-Point Instruction Notation

This section summarizes the notation used within this text which is fairly common in the technical literature. In general, an instruction will consist of the instruction or operation itself (i.e., add, sub, mul, etc.) and the ***operands***. The operands refer to where the data (to be operated on) is coming from or the result will be placed.

The following table summarizes the notational conventions used in the remainder of the document.

Operand Notation	Description
`FRdest`	Destination operand. Must be a floating-point register. Since it is a destination operand, the contents will be over written with the new result.
`FRsrc`	Source operand. Must be a floating-point register. Register value is unchanged.
`Mem`	Memory location. May be a variable name or an indirect reference.

Refer to the chapter on Addressing Modes for more information regarding indirection.

5.9.3 Floating-Point Data Movement

Floating-point CPU computations are typically performed using floating-point registers. As such, before computations can be performed, data is typically moved into registers from variables (i.e., memory) and when the computations are completed the data would be moved out of registers into variables.

To support the loading of data from memory into registers and storing of data in register to memory, there are a series of load and store instructions.

The general form of the load and store instructions are as follows:

Instruction	Description
`l<type>    FRdest, mem`	Load value from memory location memory into destination register.
`s<type>    FRsrc, mem`	Store contents of source register into memory location.
`mov<type>  Frdest, FRsrc`	Copy the contents of source register into the destination register.

In this case, the floating-point types are “.s” for single-precision and “.d” for double-precision.

Assuming the following data declarations:

```
fnum1:     .float          3.14
fnum2      .float          0.0
dnum1:     .double         6.28
dnum2      .double         0.0
```

To perform, the basic operations of:

```
fnum2 = fnum1
dnum2 = dnum1
```

The following instructions :

```
l.s   $f6, fnum1
s.s   $f0, fnum2            # fnum2 = fnum1

l.d   $f6, dnum1
s.d   $f0, dnum2            # dnum2 = dnum1
```

For the halfword and byte instructions, only the lower 16-bits are 8-bits are used.

5.9.4 Floating-Point Arithmetic Operations

The arithmetic operations include addition, subtraction, multiplication, division, remainder (remainder after division), logical AND, and logical OR. The general format for these basic instructions is as follows:

Instruction	Description
`add<type>  FRdest, FRsrc, FRsrc`	FRdest = FRsrc + FRsrc
`sub<type>  FRdest, FRsrc, FRsrc`	FRdest = FRsrc - FRsrc
`mul<type>  FRdest, FRsrc, FRsrc`	FRdest = FRsrc * FRsrc
`div<type>  FRdest, FRsrc, FRsrc`	FRdest = FRsrc / FRsrc
`rem<type>  FRdest, FRsrc, FRsrc`	FRdest = FRsrc % FRsrc

Assuming the following data declarations:

```
fnum1:     .float     6.28318
fnum2:     .float     3.14159
fans1:     .float     0.0
fans2:     .float     0.0

dnum1:     .double    42.3
dnum2:     .double    73.6
dans1:     .double    0.0
dans2:     .double    0.0
```

To perform, the basic operations of:

```
fans1 = fnum1 + fnum2
fans2 = fnum1 * fnum2
dans1 = dnum1 - dnum2
dans2 = dnum1 / dnum2
```

The following instructions:

```
l.s         $f4, fnum1
l.s         $f6, fnum2
add.d       $f8, $f4, $f6
s.s         $t0, fans1           # fans1 = fnum1 + fnum2

mul.s       $f10, $f4, $f6
s.s         $t0, fans2           # fans2 = fnum1 * fnum2

l.d         $f4, fnum1
l.d         $f6, fnum2
sub.d       $f8, $f4, $f6
s.d         $t0, fans1           # dans1 = dnum1 - dnum2

div.d       $f10, $f4, $f6
s.d         $t0, fans2           # dans2 = dnum1 / dnum2
```

For the double-precision instructions, the specified register and the next numerically sequential register is used. For example, the **l.d** instruction sets the $f4 and $f5 32-bit registers with the 64-bit value.

5.10 Example Program, Floating-Point Arithmetic

The following is an example program to compute the surface area and volume of a sphere.

The formulas for the surface area and volume of a sphere are as follows:

$$surfaceArea = 4.0 * pi * radius^2$$

$$volume = \frac{4.0 * pi}{3.0} * radius^3$$

This example main initializes the ***radius*** to arbitrary floating-point value.

```
#  Example program to calculate the surface area
#  and volume of a sphere given the radius.

# -----------------------------------------------------
#  Data Declarations

.data
```

```
pi:             .float     3.14159
fourPtZero:     .float     4.0
threePtZero:    .float     3.0

radius:         .float     17.25

surfaceArea:    .float     0.0
volume:         .float     0.0


# ---------------------------------------------------------
#  text/code section

.text
.globl    main
main:

# -----
#  Compute: (4.0 * pi) which is used for both equations.

     l.s   $f2, fourPtZero
     l.s   $f4, pi
     mul.s $f4, $f2, $f4             # 4.0 * pi

     l.s   $f6, radius               # radius

# -----
#  Calculate surface area of a sphere.
#    surfaceArea = 4.0 * pi * radius^2

     mul.s $f8, $f6, $f6             # radius^2
     mul.s $f8, $f4, $f8             # 4.0 * pi * radius^2

     s.s   $f8, surfaceArea     # store final answer

# -----
#  Calculate volume of a sphere.
#    volume = (4.0 * pi / 3.0) * radius^3

     l.s   $f8, threePtZero

     div.s $f6, $f4, $f8             # (4.0 * pi / 3.0)

     mul.s $f10, $f6, $f6
     mul.s $f10, $f10, $f6           # radius^3

     mul.s $f12, $f6, $f10           # (4.0 * pi / 3.0) * radius^3

     s.s   $f12, volume              # store final answer
```

```
# -----
#  Done, terminate program.

     li   $v0, 10               # call code for terminate
     syscall                    # system call
.end main
```

Refer to the system services section for information on displaying the final results to the console.

6.0 Addressing Modes

This file contains some basic information regarding addressing modes and address manipulations on the MIPS architecture.

To get an address, the "la" instruction is used. All addresses are words (32-bit) for the MIPS architecture.

6.1 Direct Mode

Direct addressing mode is when the register or memory location contains the actual values.

For example:

```
lw   $t0, var1
lw   $t1, var2
```

Registers and variables $t0, $t1, var1, and var2 are all accessed in direct mode addressing.

6.2 Immediate Mode

Immediate addressing mode is when the actual value is one of the operands.

For example:

```
li   $t0, 57
add  $t0, $t0, 57
```

The value 57 is immediate mode addressing. The register $t0 is direct mode addressing.

6.3 Indirection

The ()'s are used to denote an indirect memory access. For example, to get a value from a list of longs

```
la   $t0, lst
lw   $s1, ($t0)
```

The address, in $t0, is a word size (32-bits). Memory is byte addressable. As such, if the data items in "lst" (from above) are words, then four add must be added to get the the next element.

For example:

```
add  $t0 $t0, 4
lw   $s2, ($t0)
```

Will get the next word value in array (named ***lst*** in this example).

A form of displacement addressing is allowed. For example, to get the second item from a list of long sized values:

```
la   $t0, lst
lw   $s1, 4($t0)
```

The "4" is added to the address before the memory access. However, the register is not changed.

6.4 Examples

This section provides some example using the addressing modes to access arrays and perform basic calculations.

6.4.1 Example Program, Sum and Average

The following example computes the sum and average for an array integer values. The values are calculated and saved into memory variables.

```
#  Example to compute the sum and integer average
#  for an array of integer values.

# -----------------------------------------------------------
#  Data Declarations

.data

array:     .word       1,  3,  5,  7,  9, 11, 13, 15, 17, 19
           .word      21, 23, 25, 27, 29, 31, 33, 35, 37, 39
           .word      41, 43, 45, 47, 49, 51, 53, 55, 57, 59
length:    .word      30

sum:       .word      0
average:   .word      0

# -----------------------------------------------------------
#  text/code section

#  Basic approach:
#    - loop through the array
#         accessing each value
#         update sum
#    - calculate the average

.text
.globl    main
main:

# -----
#  Loop through the array to calculate sum
```

```
     la   $t0, array      # array starting address
     li   $t1, 0                # loop index, i=0
     lw   $t2, length           # length
     li   $t3, 0                # initialize sum=0

sumLoop:
     lw   $t4, ($t0)      # get array[i]

     add  $t3, $t3, $t4         # sum = sum + array[i]

     add  $t1, $t1, 1           # i = i+1
     add  $t0, $t0, 4           # update array address

     blt  $t1, $t2, sumLoop     # if i<length, continue looping

     sw   $t3, sum        # save sum

# -----
#  Calculate average
#    note, sum and length set in section above.

     div  $t5, $t3, $t2         # ave = sum / length
     sw   $t5, average

# -----
#  Done, terminate program.

     li   $v0, 10               # call code for terminate
     syscall                    # system call
.end main
```

This example program does not display the results to the screen. For information regarding displaying values and strings to output (console), refer to the QtSpim System Services section.

6.4.2 Example Program, Median

The following example finds the median for a sorted array of values. In this example, the length is given as always even. As such, the integer median is the integer average for the two middle values. Specifically, the formula for median is:

$$medianEvenOnly = \frac{\left(array[length/2] + array[length/2-1]\right)}{2}$$

The length/2 notation refers to generating the correct index of the appropriate value from the array. In assembly, we must convert the index into the offset from the base address (i.e., starting address) of the array. Since the data in this example is words (i.e., 4 bytes), it will be necessary to multiply by four to convert the index into an offset. That offset is from the start of the array, so the final address is the array base address plus the offset. This requires a series of calculations as demonstrated in the following example.

```
#  Example to find the median of a sorted
#  array of integer values of even length.

# ----------------------------------------------------------
#  Data Declarations

.data

array:     .word       1,  3,  5,  7,  9, 11, 13, 15, 17, 19
           .word      21, 23, 25, 27, 29, 31, 33, 35, 37, 39
           .word      41, 43, 45, 47, 49, 51, 53, 55, 57, 59
length:    .word      30

median:    .word      0

# ----------------------------------------------------------
#  text/code section

#  The median for an even length array is defined as:
#    median = ( array[len/2] + array[len/2-1] ) / 2

#  Note, the len/2 is the index.  Must convert the index
#  into the an offset from the base address (of the array.
#  Since the data is words (4 bytes), multiple the index
#  by four to convert to the offset.

.text
.globl     main
main:

# -----

     la   $t0, array            # starting address of array
     lw   $t1, length           # value of length

     div  $t2, $t1, 2           # length / 2
     mul  $t3, $t3, $t2         # convert index into offset
     add  $t4, $t0, $t3         # add base address of array to offset

     lw   $t5, ($t4)            # get array[len/2]
     sub  $t4, $t4, 4           # address of previous value in array

     lw   $t6, ($t4)            # get array[len/2-1]

     add  $t7, $t6, $t5         # array[len/2] + array[len/2-1]
```

```
     div   $t8, $t7, 2           #  / 2

     sw    $t8, median           # save median

# -----
#  Done, terminate program.

     li    $v0, 10               # call code for terminate
     syscall                     # system call
.end main
```

This example program does not display the results to the screen. For information regarding displaying values and strings to output (console), refer to the QtSpim System Services section.

Finding the median for an odd length list is left to the reader as an exercise.

7.0 Stack

In a computer, a stack is a type of data structure where items are added and them removed from the stack in reverse order. That is, the most recently added item is the very first one that is removed. This is often referred to as Last-In, First-Out (LIFO).

A stack is heavily used in programming for the storage of information during procedure or function calls. The following section provides information and examples regarding procedure and function calls.

Adding an item to a stack is refer to as a PUSH. Removing an item from a stack is referred to as a POP.

It is generally expected that the reader will be familiar with the general concept of a stack.

7.1 Stack Example

To demonstrate the usage of the stack, given an array, **`a = {7, 19, 37}`**, consider the operations:

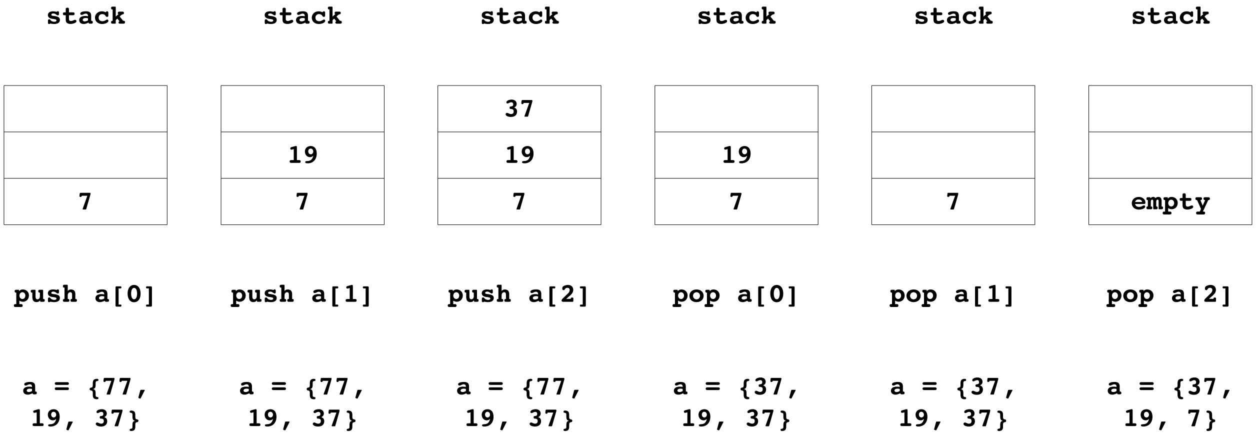
```
push  a[0]
push  a[1]
push  a[2]
```

Followed by the operations:

```
pop   a[0]
pop   a[1]
pop   a[2]
```

The initial push will push the 7, followed by the 29, and finally the 37. Since the stack is last-in, first-out, the first item pop'ed off the stack will be the last item pushed, or 37 in this example. The 37 is placed in the first element of the array (over-writing the 7). As this continues, the order of the array elements is reversed.

The following diagram shows the progress and the results.



The following sections provide more detail regarding the implementation and applicable instructions.

7.2 Stack Implementation

The current top of the stack is pointed to by the $sp register. The stack grows downward in memory and it is generally expected that all items push'ed and/or pop'ed should be of word size (32-bit).

There is no push or pop instruction. Instead, you must perform the push and pop operations manually.

While it is possible to push/pop items of various sizes (byte, halfword, etc.) it is not recommended. For such operations, it is recommended to use the entire word (4-bytes).

7.3 Push

For example, a push would subtract the $sp by 4 bytes and then copy the operand to that location. The instructions to "push $t9" would be:

```
subu   $sp, $sp, 4
sw     $t9, ($sp)
```

Which will place the contents of the $t9 register at the top of the stack.

7.4 Pop

A pop would copy the operand and then add 8 bytes. To pop $t2, the instructions would be as follows:

```
lw     $t2, ($sp)
addu   $sp, $sp, 4
```

Which will place the contents of the $t9 register at the top of the stack.

7.5 Multiple push/pop's

The preferred method of performing multiple push's or pop's is to perform the $sp adjustment only once. For example, to push registers, $s0, $s1, and $s2:

```
subu   $sp, $sp, 12
sw     $s0, ($sp)
sw     $s1, 4($sp)
sw     $s2, 8($sp)
```

And, the commands to pop registers, $9, $10, and $11 as as follows:

```
lw     $s0, ($sp)
lw     $s1, 4($sp)
lw     $s2, 8($sp)
addu   $sp, $sp, 12
```

By performing the stack adjustment only once, it is faster for the architecture to execute.

7.6 Example Program, Stack Usage

A pop would copy the operand and then add 8 bytes. To pop $t2, the i

```
#  Example to reverse values in an array
#  by using the stack.

# ----------------------------------------------------------
#  Data Declarations

.data

array:     .word       1,  3,  5,  7,  9, 11, 13, 15, 17, 19
           .word      21, 23, 25, 27, 29, 31, 33, 35, 37, 39
           .word      41, 43, 45, 47, 49, 51, 53, 55, 57, 59
length:    .word 30

# ----------------------------------------------------------
#  Text/code section

#  Basic approach:
#     - loop to push each element onto the stack
#     - loop to pop each element off the stack
#  Final result is all elements reversed.

.text
.globl     main
main:

# -----
#  Loop to read items from array and push onto stack and place.
```

```
     la    $t0, array             # array starting address
     li    $t1, 0                 # loop index, i=0
     lw    $t2, length            # length

pushLoop:
     lw    $t4, ($t0)             # get array[i]

     subu  $sp, $sp, 4            # push array[i]
     sw    $t4, ($sp)

     add   $t1, $t1, 1            # i = i+1
     add   $t0, $t0, 4            # update array address

     blt   $t1, $t2, pushLoop     # if i<length, continue looping

# -----
#  Loop to pop items from stack and write into array.

     la    $t0, array             # array starting address
     li    $t1, 0                 # loop index, i=0
     lw    $t2, length            # length (redundant line)

popLoop:
     lw    $t4, ($sp)
     addu  $sp, $sp, 4            # pop array[i]

     sw    $t4, ($t0)             # set array[i]

     add   $t1, $t1, 1            # i = i+1
     add   $t0, $t0, 4            # update array address

     blt   $t1, $t2, popLoop      # if i<length, continue looping

# -----
#  Done, terminate program.

     li    $v0, 10                # call code for terminate
     syscall                      # system call
.end main
```

It must be noted that there are easier ways to reverse a set of numbers, but they would not help demonstrate stack operations.

8.0 Procedures/Functions

This following information provides and overview of using assembly language procedures/functions. In C/C++ a procedure is referred to as a void function. Other languages refer to such functions as procedures. A function returns a single value in a more mathematical sense. C/C++ refers to functions as value returning functions.

With regard to calling a procedure/function, there are two primary activities; linkage and argument transmission. Each are explained in the following sections. Additionally, using procedures/functions in MIPS assembly assembly language requires the use of a series of special purpose registers. These special purpose registers are part of the basic integer register set but have a dedicated purpose based upon standardized and conventional usage.

8.1 MIPS Calling Conventions

When writing MIPS assembly-language procedures, the MIPS standard calling conventions should be utilized. This ensures that the code can more effectively re-used, can interact with other compiler-generated code or mixed-language programs, and utilize high-level language libraries.

The calling conventions address register usage, argument passing and register preservation.

There are two categories of procedures as follows:

- Non-leaf procedures
    - These procedures call other procedures.
- Leaf procedures
    - These procedures do not other procedures (or themselves).

The standard calling convention specified actions for the ***caller*** (routine that is calling) and the ***caller*** (routine that is being called). The specifics requirements for each are detailed in the following sections.

8.2 Procedure Format

The basic format for a procedure requires an entry point to be declared. This is done as follows.

A procedure definition uses the ".ent <procName>" directive, and ".globl <procName>" directive, and an entry label for the procedure. The general syntax is:

```
.globl  procedureName
.ent    procedureName
procedureName:

# code goes here

.end  procedureName
```

Use of the ".end <procName> directive is optional in the QtSpim simulator.

8.2.1 Procedure Format Example

The following is an example of the basic procedure format.

```
.globl     proc_name
.ent  proc_name
proc_name:

#   procedure code...

     jr    $ra
.end  proc_name
```

The “.end <procName>” directive may be omitted in the MIPS simulator.

8.3 Caller Conventions

The calling convention addresses specific requirements for the ***caller*** or routine that is calling a procedure.

- The calling procedures is expected to save any non-preserved registers ($a0-$a3, $t0-$t9, $v0, $v1, $f0-$f10 and $f16 - $f18) that are required after the call is completed.
- The calling procedure should pass all arguments.
    - The first argument is passed in either $a0 or $f12 ($a0 if integer or $f12 if float single or double precision).
    - The second argument is passed in either $a1 or $f14 ($a1 if integer or $f14 if float single or double precision).
    - The third argument is passed in $a2 (integer only).
    - If the third argument is float, it must be passed on the stack.
    - The fourth argument is passed in $a3 (integer only).
    - If the fourth argument is float, it must be passed on the stack.

Remaining arguments are passed on the stack. Arguments on the the stack should be placed on the stack in reverse order. Call by reference arguments load address (***la*** instruction) and call by value load the value.

Calling procedure should use the "jal <proc>" instruction.

Upon completion of the procedure, the caller procedure must restore any saved non-preserved registers (from 1 above) and adjust the stack point ($sp) as necessary if any arguments were passed on the stack.

Note, for floating-point arguments appearing in registers you must allocate a pair of registers (even if it's a single precision argument) that start with an even register.

8.4 Linkage

The term ***linkage*** refers to the basic process of getting to a procedure and getting back to the correct location in the calling routine. This does not include argument transmission, which is addressed in the next section.

The basic linkage operation uses the **jal** and **jr** instructions. Both instructions utilize the $ra register. This register is set to the return address as part of the procedure call.

The call to a procedure/function requires the procedure/function name, generically labeled as <procName>, as follows:

```
        jal     <procName>
```

The jal, jump and link, instruction, will copy the $pc into the $ra register and jump to the procedure <procName>. Recall that the $pc register points to the next instruction to be executed. That will be the instruction immediately after the call, which is the correct place to return to when the procedure/function has completed.

If the procedure/function does not call any other procedures/functions, nothing additional is required with regard to the $ra register.

A procedure that does not call another procedure is referred to as a "leaf procedure". A procedure that calls another procedure is referred to as a "non-leaf procedure".

The return from procedure is as follows:

```
       jr      $ra
```

If the procedure/function calls yet another procedure/function, the $ra must be preserved. Since $ra contains the return address, it will be changed when the procedure/function calls the next procedure/function. As such, it must be saved and restored from the stack in the calling procedure. This is typically performed only once at the beginning and then at the end of the procedure (for non-leaf procedures).

Refer to the example programs for a more detailed series of examples that demonstrate the linkage.

8.5 Argument Transmission

Based on the context, parameters may be transmitted to procedures/functions as either values or addresses. These basic approaches are implemented in high-level languages.

The basic argument transmission is accomplished via a combination of registers and the stack.

8.5.1 Call-by-Value

Call-by-value involves passing a copy of the information being passed to the procedure or function. As such, the original value can not be altered.

8.5.2 Call-by-Reference

Call-by-reference involves passing the address of the variables. Call-by-reference is used when passing arrays or when passing variables that will be altered or set by the procedure or function.

8.5.3 Argument Transmission Convention

The basic argument transmission is accomplished via a combination of registers and the stack.

Integer arguments can be passed in registers $a0, $a1, $a2, and $a3 and floating-point values passed in $f12 and $f14 (single or double precision floating point).

- The first argument is passed in either $a0 or $f12 ($a0 if integer or $f12 if float single or double precision).
- The second argument is passed in either $a1 or $f14 ($a1 if integer or $f14 if float single or double precision).
- The third argument is passed in $a2 (integer only).
- If the third argument is float, it must be passed on the stack.
- The fourth argument is passed in $a3 (integer only).
- If the fourth argument is float, it must be passed on the stack.

If the first argument is integer, $a0 is used and $f12 should not be used at all. If the first argument is floating-point value, $f12 is used and $a0 is not used at all. Any additional arguments are passed on the stack. The following table shows the argument order and register allocation.

	1st	2nd	3rd	4th	5th	Nth
integer	$a0	$a1	$a2	$a3	stack	stack
	or	or				
floating-point value	$f12	$f14	stack	stack	stack	stack

Recall that addresses are integers, even when pointing to floating-point values. As such, addresses are passed in integer registers.

8.6 Function Results

A function is expected to return a result (i.e., value returning function).

Integer registers $v0 or $v1/$v0 are used to return integers values from function/procedure calls. Floating point registers $f0 and $f2 are used to return floating point values from function/procedures.

8.7 Registers Preservation Conventions

The MIPS calling convention requires that only specific registers (not all) be saved across procedure calls.

- Integer registers $s0 - $s7 must be saved the procedure.
- Floating point registers $f20 - $f30 must be saved the procedure.

When writing a procedure, this will require that the registers $s0 - $s7 or $f20 - $f30 (single or double precision) be push'ed and pop'ed from the stack if those registers are utilized/changed. When calling a procedure, the main routine must be written so that any values required across procedure calls be placed in register $s0 - $s7 or $f20 - $f30 (single or double precision).

Integer registers $t0 - $t9 and floating point registers $f4 - $f10 and $f16 - $f18 (single or double precision) are used to hold temporary quantities that do not need to be preserved across procedure calls.

8.8 Miscellaneous Register Usage

Registers $at, $k0, and $k1 are reserved for the assembler and operating system and should not be used by programs. Register $fp is used to point to the procedure call frame on the stack. This can be used when arguments are passed on the stack.

Register $gp is used as a global point (to point to globally accessible data areas). This register is not typically used when writing assembly programs directly.

8.9 Summary, Callee Conventions

The calling convention addresses specific requirements for the ***callee*** or routine that is being called from another procedure (which includes the main routine).

- Push any altered "saved" registers on the stack.
  - Specifically, this includes $s0-$s7, $f20-$f30, $ra, $fp, or $gp.
  - If the procedure is a non-leaf procedure, $ra must be saved.
  - If $fp is altered, $fp must be saved which is required when arguments are passed on the stack
  - Space for local variables should be created on the stack for stack dynamic local variables.
- Note, when altering the $sp register, it should be done in a single operation (instead of a series).
- If arguments are passed on the stack, $fp should be set as follows
  - $fp = $sp + (frame size)
  - This will set $fp pointing to the first argument passed on the stack.

The procedure can access fist 4 integer arguments in registers $a0-$a3 and the first two float registers $f12-$f14.

Arguments passed on the stack can be accessed using $fp. The procedure should place returned values (if any) into $v0 and $v1.

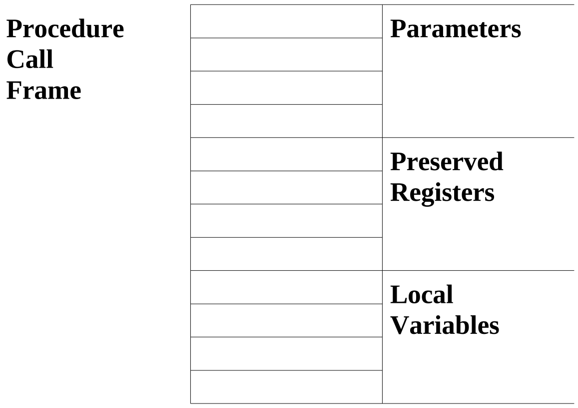
- Restore saved registers
  - Includes $s0 - $s7, $fp, $ra, $gp if they were pushed.
  - Return to the calling procedure via the "jr $ra" instruction.

The procedures example section provides a series of example procedures and functions including register usage and argument transmission.

8.10 Procedure Call Frame

The procedure call frame or activation record is what the information placed on the stack is called. As noted in the previous sections, the procedure call frame includes passed parameters (if any) and the preserved registers. In addition, space for the procedures local variables (if any) is allocated on the stack.

A general overview of the procedure call frame is show as follows:



Each part of the procedure call frame may be a different size based on home many arguments are passed (if any), which registers must be preserved (if any), or the amount and size of the local variabels (if any).

8.10.1.1 Stack Dynamic Local Variables

The local variables, also referred to as stack dynamic local variables, are typically allocated by the compiler and assigned to stack locations. This allows a more efficient use of memory for high-level languages. This can be very important in large programs.

For example, assume there are 10 procedures each with a locally declared 100,000 element array of integers. Since each integer typically requires 4-bytes, this would mean 400,000 bytes for each procedure with a combined total of 4,000,000 bytes (or about ~4MB) for all ten procedures.

For the standard method of stack dynamic local variables, each array is only allocated when the procedure is active (i.e., being executed). If none of the procedures is called, none of the memory is allocated. If only two of the arrays are active at any given time, only 800,000 bytes are allocated at any given time.

However, if the arrays were to be declared statically (i.e., not the standard local declaration), the ~4MB of memory allocated even if none of the procedures is ever called. This can lead to excessive memory usage which can slow a program down.

8.11 Procedure Examples

This section presents a series of example procedures of varying complexity.

8.11.1 Example Program, Power Function

This following is a very simple example function call. The example includes a simple main procedure and a simple function that computes x^y (i.e., x to the y power). The high-level language call, shown in C/C++ here, would be:

```
answer = power(x, y);
```

Where ***x*** and ***y*** are passed by value and the result return to the variable ***answer***. The main passes the arguments by value and receives the result in $v0 (as per the convention). The main then saves the result into the variable ***answer***.

```
#  Example function to demonstrate calling conventions
#  Function computes power (i.e., x to y power).

# ---------------------------------------------------------
#  Data Declarations

.data

x:          .word      3
y:          .word      5
answer:     .word      0

# ------------------------------------
#  Main routine.
#  Call simple procedure two add two numbers.

.text
.globl     main
.ent  main
main:
     lw    $a0, x                       # pass arg's to function
     lw    $a1, y
     jal   power
     sw    $v0, answer

     li    $v0, 10
     syscall                            # terminate program
.end  main

# ------------------------------------
# Function to find and return x^y

# -----
#  Arguments
#     $a0 – x
#     $a1 – y

#  Returns
#     $v0 - x^y

.globl     power
.ent  power
power:
```

```
     li   $v0, 1
     li   $t0, 0

powLoop:
     mul  $v0, $v0, $a0
     add  $t0, $t0, 1
     blt  $t0, $a1, powLoop

     jr   $ra
.end power
```

Refer to the next section for a more complex example.

8.11.2 Example program, Summation Function

This following is an example procedure call.

```
#  Example function to demonstrate calling conventions.
#  Simple function to sum six arguments.

# ------------------------------------
#  Data Declarations

.data

num1:      .word      3
num2:      .word      5
num3:      .word      3
num4:      .word      5
num5:      .word      3
num6:      .word      5
sum:       .word      0

# ------------------------------------
#  Main routine.
#  Call function to add six numbers.
#    First 4 arguments are passed in $a0-$a3.
#    Next 2 arguments are passed on the stack.

.text

.globl     main
.ent  main
main:
  lw       $a0, num1            # pass arg's and procedure
  lw       $a1, num2
  lw       $a2, num3
  lw       $a3, num4
  lw       $t0, num5
```

```
  lw       $t1, num6
  subu     $sp, $sp, 8
  sw       $t0, ($sp)
  sw       $t1, 4($sp)
  jal      addem
  sw       $v0, sum

  addu     $sp, $sp, 8                # clear stack

  li       $v0,10
  syscall                             # terminate
.end main

# ------------------------------------
#  Example function to add 6 numbers

# -----
#  Arguments
#    $a0 - num1
#    $a1 - num2
#    $a2 - num3
#    $a3 - num4
#    ($fp) - num5
#    4($fp) - num6

#  Returns
#    $v0 – num1+num2+num3+num4+num5+num6

.globl     addem
.ent       addem
addem:

  subu     $sp, $sp, 4                # preserve registers
  sw       $fp, ($sp)

  addu     $fp, $sp, 4                # set frame pointer

# -----
#  Perform additions.

  li       $v0, 0
  add      $v0, $v0 $a0               # num1
  add      $v0, $v0 $a1               # num2
  add      $v0, $v0 $a2               # num3
  add      $v0, $v0 $a3               # num4
  lw       $t0, ($fp)                 # num5
  add      $v0, $v0 $t0
  lw       $t0, 4($fp)                # num6
  add      $v0, $v0 $t0
```

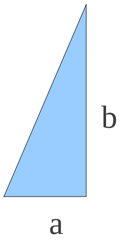
```
# -----
#  Restore registers.

  lw      $fp, ($sp)
  addu    $sp, $sp, 4

  jr  $ra
.end  addem
```

Refer to the next section for a more complex example.

8.11.3 Example Program, Pythagorean Theorem Procedure

The following is an example of a procedure that calls another function. Given the ***a*** and ***b*** sides of a right triangle, the ***c*** side can be computed as follows:

$$cSide \ = \ \sqrt{aSide^2 + bSide^2}$$



This example program will call a procedure to compute the ***c*** sides of a series of right triangles. The ***a*** sides and ***b*** sides are stored in an arrays, ***aSides[]*** and ***bSides[]*** and results stored into an array, ***cSides[]***. The procedure will also compute the minimum, maximum, sum, and average of the ***cSides[]*** values. All values are integers. In order to compute the integer square root, a ***iSqrt()*** function is used. The ***iSqrt()*** function uses a simplified versioon of Newtons method.

```
#  Example program to calculate the cSide for each
#  right triangle in a series of right triangles
#  given the aSides and bSides using the
#  pythagorean theorem.

#  Pythagorean theorem:
#    cSide = sqrt ( aSide^2 + bSide^2 )

#  Provides examples of MIPS procedure calling.

# ---------------------------------------------------------
#  Data Declarations

.data

aSides:    .word 19, 17, 15, 13, 11, 19, 17, 15, 13, 11
           .word 12, 14, 16, 18, 10
bSides:    .word 34, 32, 31, 35, 34, 33, 32, 37, 38, 39
           .word 32, 30, 36, 38, 30
cSides:    .space    60

length:    .word 15
```

```
min:        .word 0
max:        .word 0
sum:        .word 0
ave:        .word 0

# -----------------------------------------------------------
#  text/code section

#  For example

.text
.globl    main
.ent  main
main:

# -----
#  Main program calls the cSidesStats routine.
#  The HLL call is as follows:
#     cSidesStats(aSides, bSides, cSides, length, min,
#                     max, sum, ave)
#  Note:
#     The arrays are passed by reference
#     The length is passed by value
#     The min, max, sum, and ave are passed by reference.

     la    $a0, aSides                # address of array
     la    $a1, bSides                # address of array
     la    $a2, cSides                # address of array
     lw    $a3, length                # value of length

     la    $t0, min                   # address for min
     la    $t1, max                   # address for max
     la    $t2, sum                   # address for sum
     la    $t3, ave                   # address for ave

     subu  $sp, $sp, 16
     sw    $t0, ($sp)                 # push addresses
     sw    $t1, 4($sp)
     sw    $t2, 8($sp)
     sw    $t3, 12($sp)

     jal   cSidesStats                # call routine

     addu  $sp, $sp, 16               # clear arguments

# -----
#  Done, terminate program.

     li    $v0, 10                    # call code for terminate
```

```
     syscall                        # system call
.end main

# ---------------------------------------------------------
#  Procedure to calculate the cSides[] for each right
#  triangle in a series of right triangles given the
#  aSides[] and bSides[] using the pythagorean theorem.

#  Pythagorean theorem formula:
#     cSides[n] = sqrt ( aSides[n]^2 + bSides[n]^2 )

#  Also finds and returns the minimum, maximum, sum,
#  and average for the cSides.

#  Uses the iSqrt() routine to find the integer
#  square root of an integer.

# -----
#  Arguments:
#     $a0 - address of aSides[]
#     $a1 - address of bSides[]
#     $a2 - address of cSides[]
#     $a3 - list length
#     ($fp) - addr of min
#     4($fp) - addr of max
#     8($fp) - addr of sum
#     12($fp) - addr of ave

#  Returns (via passed addresses):
#     cSides[]
#     min
#     max
#     sum
#     ave

.globl    cSidesStats
.ent cSidesStats
cSidesStats:
     subu $sp, $sp, 28              # preserve registers
     sw   $a0, ($sp)
     sw   $s0, 4($sp)
     sw   $s1, 8($sp)
     sw   $s2, 12($sp)
     sw   $s3, 16($sp)
     sw   $fp, 20($sp)
     sw   $ra, 24($sp)

     add  $fp, $sp, 28              # set frame pointer
```

```
# -----
#  Loop to calculate cSides[]
#     Note, must use $s<n> registers due to iSqrt() call

     move $s0, $a0                   # starting address of aSides
     move $s1, $a1                   # starting address of bSides
     move $s2, $a2                   # starting address of cSides
     li   $s3, 0                     # index = 0

cSidesLoop:
     lw   $t0, ($s0)                 # get aSides[n]
     mul  $t0, $t0, $t0              # aSides[n]^2
     lw   $t1, ($s1)                 # get bSides[n]
     mul  $t1, $t1, $t1              # bSides[n]^2
     add  $a0, $t0, $t1
     jal  iSqrt                      # call iSqrt()

     sw   $v0, ($s2)                 # save to cSides[n]

     addu $s0, $s0, 4                # update aSides address
     addu $s1, $s1, 4                # update bSides address
     addu $s2, $s2, 4                # update cSides address
     addu $s3, $s3, 1                # index++

     blt  $s3, $a3, cSidesLoop       # if index < length, loop

# -----
#  Loop to find minimum, maximum, and sum.

     move $s2, $a2                   # starting address of cSides
     li   $t0, 0                     # index = 0
     lw   $t1, ($s2)                 # min = cSides[0]
     lw   $t2, ($s2)                 # max = cSides[0]
     li   $t3, 0                     # sum = 0

statsLoop:
     lw   $t4, ($s2)                 # get cSides[n]

     bge  $t4, $t1, notNewMin        # if cSides[n] >= item -> skip
     move $t1, $t4                   # set new min value
notNewMin:

     ble  $t4, $t2, notNewMax        # if cSides[n] <= item -> skip
     move $t2, $t4                   # set new max value
notNewMax:

     add  $t3, $t3, $t4              # sum = sum + cSides[n]

     addu $s2, $s2, 4                # update cSides address
```

```
     addu $t0, $t0, 1                 # index++

     blt  $t0, $a3, statsLoop         # if index < length -> loop

     lw   $t5, ($fp)                  # get address of min
     sw   $t1, ($t5)                  # save min

     lw   $t5, 4($fp)                 # get address of max
     sw   $t2, ($t5)                  # save max

     lw   $t5, 8($fp)                 # get address of sum
     sw   $t3, ($t5)                  # save sum

     div  $t0, $t3, $a3               # ave = sum / len

     lw   $t5, 12($fp)                # get address of ave
     sw   $t0, ($t5)                  # save ave

# -----
#  Done, restore registers and return to calling routine.

     lw   $a0, ($sp)
     lw   $s0, 4($sp)
     lw   $s1, 8($sp)
     lw   $s2, 12($sp)
     lw   $s3, 16($sp)
     lw   $fp, 20($sp)
     lw   $ra, 24($sp)
     addu $sp, $sp, 28
     jr   $ra
.end cSidesStats

# ---------------------------------------------------------
#  Function to computer integer square root for
#  an integer value.

#  Uses a simplified version of Newtons method.
#    x = N
#    iterate 10 times:
#         x' = (x + N/x) / 2
#         x = x`

# -----
#  Arguments
#    $a0 - N

#  Returns
#    $v0 - integer square root of N
```

```
.globl     iSqrt
.ent  iSqrt
iSqrt:
     move  $v0, $a0                    # $t0 = x = N
     li    $t0, 0                      # counter
sqrLoop:
     div   $v0, $a0, $v0               # N/x
     add   $v0, $v0, $a0               # x + N/x
     div   $v0, $v0, 2                 # (x + N/x)/2

     add   $t0, $t0, 1
     blt   $t0, 10, sqrLoop

     jr    $ra
.end  iSqrt
```

This example uses a simplified version of Newtons method. Further improvements are left to the reader as an exercise.

9.0 QtSpim System Service Calls

The operating system must provide some basic services for functions that a user program can not easily perform on its own. Some key examples include input and output operations. These functions are typicallt referred to as *system services*. The QtSpim simulator provides a series of operating system like services by using a **syscall** instruction.

To request a specific service from the QtSpim simulator, the 'call code' is loaded in the $v0 register. Based on the specific system service being requested, additional information may be needed which is loaded in the argument registers (as noted in the Procedures/Functions section).

9.1 Supported QtSpim System Services

A list of the supported system services are listed in the below table. A series of examples is provided in the following sections.

Service Name	**Call Code**	**Input**	**Output**
Print Integer (32-bit)	1	$a0 → integer to be printed	
Print Float (32-bit)	2	$f12 → 32-bit floating-point value to be printed	
Print Double (64-bit)	3	$f12 → 64-bit floating-point value to be printed	
Print String	4	$a0 → starting address of NULL terminated string to be printed	
Read Integer (32-bit)	5		$v0 → 32-bit integer entered by user
Read Float (32-bit)	6		$f0 → 32-bit floating-point value entered by user
Read Double (64-bit)	7		$f0 → 64-bit floating-point value entered by user
Read String	8	$a0 → starting address of buffer (of where to store character entered by user) $a1 → length of buffer	
Allocate Memory	9	$a0 → number of bytes to allocate	$v0 → starting address of allocated memory

Terminate	10		
Print Character	11	$a0 → character to be printed	
Read Character	12		$v0 → character entered by user
File Open	13	$a0 → file name string, NULL terminated $a1 → access flags $a2 → file mode, (UNIX style)	$v0 → file descripor
File Read	14	$a0 → file descriptor $a1 → buffer starting address $a2 → number of bytes to read	$v0 → number of bytes actually read from file (-1 = error, 0 = end of file)
File Write	15	$a0 → file descriptor $a1 → buffer starting address $a2 → number of bytes to read	$v0 → number of bytes actually written to file (-1 = error, 0 = end of file)
File Close	16	$a0 → file descriptor	

The file open access flags are defined as follows:

```
Read = 0x0, Write = 0x1, Read/Write = 0x2
OR Create = 0x100, Truncate = 0x200, Append = 0x8
OR Text = 0x4000, Binary = 0x8000
```

For example, for a file read operation the 0x0 would be selected. For a file write operation, the 0x1 would be selected.

9.2 QtSpim System Services Examples

This section provides a series of examples using system service calls.

The system service calls follow the standard calling convention in that the temporary registers ($t0 - $t9) may be altered and the saved registers ($s0 - $s7, $fp, $ra) will be preserved. As such, if a series of values is being printed in a loop, it saved register would be required for the loop counter and the current array address/index.

9.2.1 Example Program, Display String and Integer

The following code provides an example of how to to display a string and an integer.

```
#  Example program to display a string and an integer.
#  Demonstrates use of QtSpim system service calls.

# -------------------------------------------------------
#  Data Declarations

.data
hdr:        .ascii      "Example\n"
            .asciiz     "The meaning of life is: "
```

```
number:    .word      42

# ----------------------------------------------------------
#  text/code section

.text
.globl     main
main:
     li    $v0, 4                # call code for print string
     la    $a0, hdr              # address of NULL terminated string
     syscall                     # system call

     li    $v0, 1                # call code for print integer
     lw    $a0, number           # value for integer to be printed
     syscall                     # system call

# -----
#  Done, terminate program.

     li    $v0, 10               # call code for terminate
     syscall                     # system call
.end main
```

Note, in this example, the string definition ensures the NULL termination as required by the system service.

The output for the example would be displayed to the QtSpim console window. For example,

```
Example
The meaning of life is: 42
```

The console window can be display or hidden from the Windows menu (on the top bar).

9.2.2 Example Program, Read Integer

The following code provides an example of how to to display a prompt string, read an integer value, square that integer value, and display the final result.

```
#  Example program to display an array.
#  Demonstrates use of QtSpim system service calls.

# ----------------------------------------------------------
#  Data Declarations

.data
```

```
hdr:        .ascii     "Squaring Example\n"
            .asciiz    "Enter Value: "
ansMsg:     .ascii     "Value Squared: "
value:      .word      0

# -----------------------------------------------------------
#   text/code section

.text
.globl      main
main:
      li    $v0, 4                    # call code for print string
      la    $a0, hdr                  # address of NULL terminated string
      syscall                         # system call

      li    $v0, 5                    # call code for read integer
      syscall                         # system call (response in $v0)

      mul   $t0, $v0, $v0             # square answer
      sw    $t0, value                # save to variable

      li    $v0, 4                    # call code for print string
      la    $a0, ansMsg               # address of NULL terminated string
      syscall                         # system call

      li    $v0, 1                    # call code for print integer
      lw    $a0, value                # value for integer to be printed
      syscall                         # system call

# -----
#   Done, terminate program.

      li    $v0, 10                   # call code for terminate
      syscall                         # system call
.end main
```

The output for the example would be displayed to the QtSpim console window. For example,

```
Squaring Example
Enter Value: 12
Value Squared: 144
```

Note, the default console window size will typically be larger than what is shown above.

9.2.3 Example Program, Display Array

The following code provides an example of how to display an array. In this example, an array of numbers is displayed to the screen five number per line (arbitrarily chosen) to make the output appear more pleasing.

Since the system service call is utilized for the print function, the saved register must be used. Refer to the Procedures/Functions section for additional information regarding the MIPS calling conventions.

```
#  Example program to display an array.
#  Demonstrates use of QtSpim system service calls.

# ------------------------------------------------------
#  Data Declarations

.data
hdr:       .ascii     "Array Values\n"
           .asciiz    "-----------------------\n\n"
spaces:    .asciiz    "   "
newLine:   .asciiz    "\n"

array:     .word      11, 13, 15, 17, 19
           .word      21, 23, 25, 27, 29
           .word      31, 33, 35, 37, 39
           .word      41, 43, 45, 47
length:    .word      19

# ----------------------------------------------------------
#  text/code section

.text
.globl     main
main:
     li    $v0, 4                # print header string
     la    $a0, hdr
     syscall

     la    $s0, array
     li    $s1, 0
     lw    $s2, length

printLoop:
     li    $v0, 1                # call code for print integer
     lw    $a0, ($s0)            # get array[i]
     syscall                     # system call

     li    $v0, 4                # print spaces
     la    $a0, spaces
     syscall
```

```
        addu  $s0, $s0, 4           # update address (to next word)
        add   $s1, $s1, 1           # increment counter

        rem   $t0, $s1, 5
        bnez  $t0, skipNewLine

        li    $v0, 4                # print spaces
        la    $a0, newLine
        syscall

skipNewLine:
        bne   $s1, $s2, printLoop   # if counter<length -> loop

# -----
#  Done, terminate program.

        li    $v0, 10               # call code for terminate
        syscall                     # system call
.end main
```

The output for the example would be displayed to the QtSpim console window. For example,

```
Array Values
------------------------


11  13  15  17  19
21  23  25  27  29
31  33  35  37  39
41  43  45  47
```

The example codes does not align the values (when printed). The values above appear aligned only since they are all the same size.

10.0 Multi-dimension Array Implementation

This section provides a summary of the implementation of multiple dimension array as viewed from assembly language.

Memory is inherently a single dimension physical entity. As such, multi-dimension array is implemented as sets of single dimension array. There are two primary ways this can be performed; row major and column major. Each is explained in subsequent sections.

To simplify the explanation, this section focuses on two-dimensional arrays.The general process extents to high dimensions.

10.1 High-Level Language View

Multi-Dimension arrays are sometimes used in high level languages. For example, in C/C++, the declaration of: **`int arr [3][4]`** would declare an array as follows:

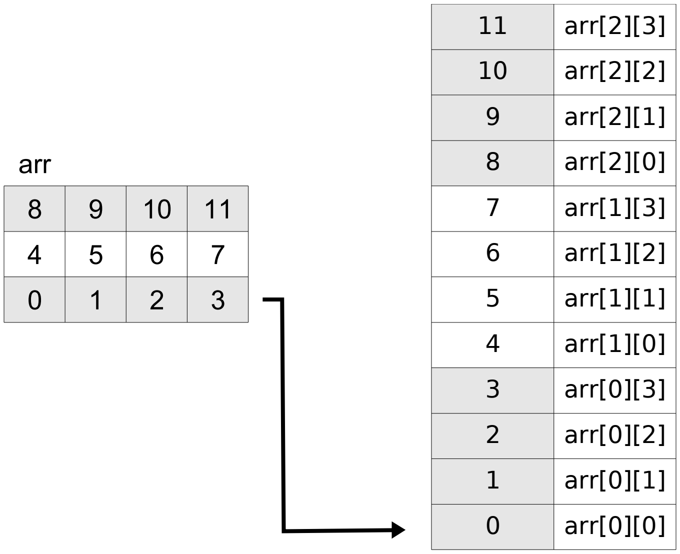
arr

arr[0][0]	arr[0][1]	arr[0][2]	arr[0][3]
arr[1][0]	arr[1][1]	arr[1][2]	arr[1][3]
arr[2][0]	arr[2][1]	arr[2][2]	arr[2][3]

It is expected that the reader is generally familiar with the high-level language use of two-dimensional arrays.

10.2 Row-Major

Row-major assigns each row as a single dimension array in memory, one row after the next until all rows are in memory.



The formula to convert two-dimensional array indexes (row, column) into a single dimension, row-major memory offset is as follows:

```
address = baseAddress + (rowIndex * colSize + colIndex) * dataSize
```

Where the *base address* is the starting address of the array, *dataSize* is the size of the data in bytes, and *colSize* is the dimension or number of the rows in the array. In this example, the number of columns in the array is 4 (from the previous high-level language declaration).

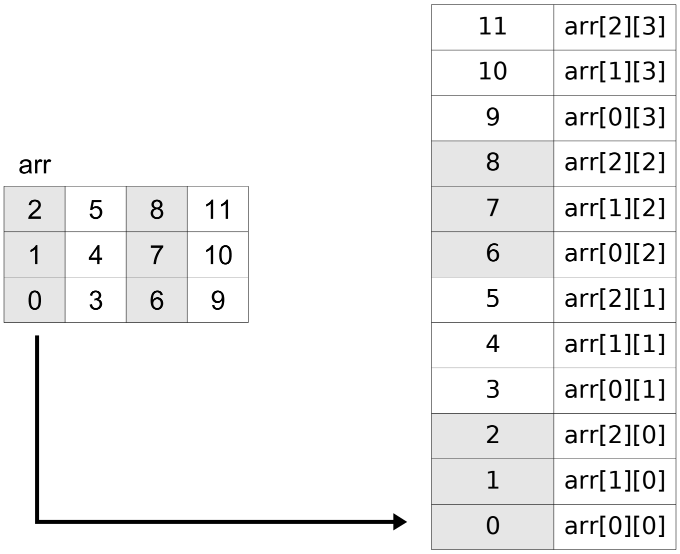
For example, to access the `arr[1][2]` element (labeled '6' in the above diagram), assuming the array is composed of 32-bit sized elements it would be:

```
address     = arr + (1 * 3 + 2) * 4 = arr + (4 + 2) * 4
            = arr + 6 * 4 = arr + 24
```

Which generates the correct, final address.

10.3 Column-Major

Column-major assigns each column as a single dimension array in memory, one column after the next until all rows are in memory.



arr

2	5	8	11
1	4	7	10
0	3	6	9

11	arr[2][3]
10	arr[1][3]
9	arr[0][3]
8	arr[2][2]
7	arr[1][2]
6	arr[0][2]
5	arr[2][1]
4	arr[1][1]
3	arr[0][1]
2	arr[2][0]
1	arr[1][0]
0	arr[0][0]

The formula to convert two-dimensional array indexes (row, column) into a single dimension, column-major memory offset is as follows:

```
address = baseAddress + (colIndex * rowSize + rowIndex) * dataSize
```

Where the base *address* is the starting address of the array, *dataSize* is the size of the data in bytes, and *rowSize* is the dimension or number of the columns in the array. In this example, the number of rows in the array is 3 (from the previous high-level language declaration).

For example, to access the **`arr[1][2]`** element (labeled '6' in the above diagram), assuming the array is composed of 32-bit sized elements it would be:

```
address    = arr + (2 * 4 + 1) * 4 = arr + (6 + 1) * 4
           = arr + 7 * 4 = arr + 28
```

Which generates the correct, final address.

10.4 Example Program, Matrix Diagonal Summation

The following code provides an example of how to access elements in a two-dimensional array. This example adds the elements on the diagonal of a two-dimensional array.

For example, given the logical view of a five-by-five square matrix:

11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30
31	32	33	34	35

The main diagonal contains the numbers, 11, 17, 23, 29, and 35.

```
#  Example program to compute the sum of diagonal
#  in a square two-dimensional array
#  Demonstrates multi-dimension array indexing.
#  Assumes row-major ordering.

# ----------------------------------------------------------
#  Data Declarations

.data

mdArray:   .word 11, 12, 13, 14, 15
           .word 16, 17, 18, 19, 20
           .word 21, 22, 23, 24, 25
           .word 26, 27, 28, 29, 30
           .word 31, 32, 33, 34, 35

size:      .word 5
dSum:      .word 0

DATASIZE = 4                    # 4 bytes for words

finalMsg:  .ascii     "Two-Dimensioanl Diagonal Summation\n\n"
           .asciiz    "Diagonal Sum = "

# ----------------------------------------------------------
#  Text/code section

.text
.globl     main
main:

# -----
#  Call function to sum the diagaonal
#     (of square two-dimensional array)

     la    $a0, mdArray         # base address of array
```

```
     lw    $a1, size             # array size

     jal   diagSummer

     sw    $v0, dSum

# -----
#  Display final result.

     li    $v0, 4                # print prompt string
     la    $a0, finalMsg
     syscall

     li    $v0, 1                # print integer
     lw    $a0, dSum
     syscall

# -----
# Done, terminate program.

     li    $v0, 10               # call code for terminate
     syscall                     # system call
.end main

# ----------------------------------------------------------
#  Simple function to sum the diagonals of a
#  square two-dimensional array.

#  Approach
#     loop i = 0 to len-1
#          sum = sum + mdArray[i][i]

#  Note, for two-dimensional array:
#    address = baseAddr + (rowIndex * colSize + colIndex) * dataSize
#  Since the two-dimensional array is given as square, the
#  row and column dimensions are the same (i.e., size).

# -----
#  Arguments
#     $a0 - array base address
#     $a1 - size (of square two-dimension array)

#  Returns
#     $v0 - sum of diagonals

.globl    diagSummer
.ent diagSummer
diagSummer:
```

```
     li    $v0, 0                 # sum=0
     li    $t1, 0                 # loop index, i=0

diagSumLoop:
     mul   $t3, $t1, $a1          # (rowIndex * colSize
     add   $t3, $t3, $t1          #              + colIndex)
                                  # note, rowIndex=colIndex
     mul   $t3, $t3, DATASIZE     #              * dataSize
     add   $t4, $a0, $t3          # + base address

     lw    $t5, ($t4)             # get mdArray[i][i]

     add   $v0, $v0, $t5          # sum = sum + mdArray[i][i]

     add   $t1, $t1, 1            # i = i + 1
     blt   $t1, $a1, diagSumLoop

# -----
#  Done, return to calling routine.

     jr    $ra
.end diagSummer
```

While not mathematically useful, this does demonstrate how elements in a two-dimensional array.

11.0 Recursion

The Google search result for recursion, shows Recursion, did you mean recursion?

Recursion is the idea that a function may call itself (which is the basis for the joke). Recursion is a powerful general-purpose programming technique and is used for some important applications including search and sorting methods.

Recursion can be very confusing in its simplicity. The simple examples in this section will not be enough in themselves for the reader to obtain recursive enlightenment. The goal of this section is to provide some insight into the underlying mechanisms that support recursion. The simple examples here which are used introduce recursion are meant to help demonstrate the form and structure for recursion. More complex examples (than will be discussed here) should be studied and implemented in order to ensure a complete appreciation for the power of recursion.

The procedure/function calling process previously described supports recursion without any changes.

A recursive function must have a recursive definition that includes:

1. base case, or cases, that provide a simple result (that defines when the recursion should stop).
2. rule, or set of rules, that reduce toward the base case.

This definition is referred to as a recursive relation.

11.1 Recursion Example, Factorial

The factorial function is mathematically defined as follows:

$$n! = \prod_{k=1}^{n} k$$

Or more familiarly, you might see 5! as:

$$n! = 5 \times 4 \times 3 \times 2 \times 1$$

It must be noted that this function could easily be computed with a loop. However, the reason this is done recursively is to provide a simple example of how recursion works.

A typical recursive for factorial is:

$$factorial(n) = \begin{cases} 1 & if\ n=0 \\ n \times factorial(n-1) & if\ n \geq 1 \end{cases}$$

This definition assumes that the value of ***n*** is positive.

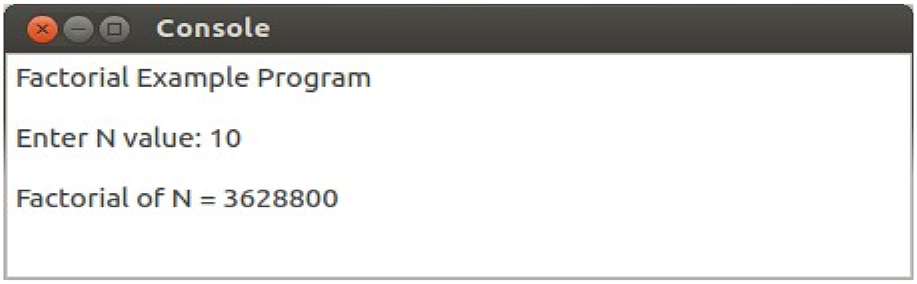
11.1.1 Example Program, Recursive Factorial Function

The following code provides an example of the recursive factorial function.

```
#  Example program to demonstrate recursion.

# -----------------------------------------------------------
#  Data Declarations

.data

prompt:    .ascii     "Factorial Example Program\n\n"
           .asciiz    "Enter N value: "

results:   .asciiz    "\nFactorial of N = "

n:         .word 0
answer:    .word 0

# -----------------------------------------------------------
#  Text/code section

.text
.globl     main
main:

# -----
#  Read n value from user

     li    $v0, 4                # print prompt string
     la    $a0, prompt
     syscall

     li    $v0, 5                # read N (as integer)
     syscall

     sw    $v0, n

# -----
#  Call factorial function.

     lw    $a0, n
     jal   fact

     sw    $v0, answer

# -----
#  Display result
```

```
     li   $v0, 4                 # print prompt string
     la   $a0, results
     syscall

     li   $v0, 1                 # print integer
     lw   $a0, answer
     syscall

# -----
#  Done, terminate program.

     li   $v0, 10                # call code for terminate
     syscall                     # system call
.end main

# -----------------------------------------------------------
#  Factorial function
#  Recursive definition:
#     = 1              if n = 0
#     = n * fact(n-1)   if n >= 1

# -----
#  Arguments
#     $a0 - n
#  Returns
#     $v0 set to n!

.globl     fact
.ent  fact
fact:
     subu $sp, $sp, 8
     sw   $ra, ($sp)
     sw   $s0, 4($sp)

     li   $v0, 1                 # check base case
     beq  $a0, 0, factDone

     move $s0, $a0               # fact(n-1)
     sub  $a0, $a0, 1
     jal  fact

     mul  $v0, $s0, $v0          # n * fact(n-1)

factDone:
     lw   $ra, ($sp)
     lw   $s0, 4($sp)
     addu $sp, $sp, 8
     jr   $ra
.end  fact
```

The output for the example would be displayed to the QtSpim console window. For example,

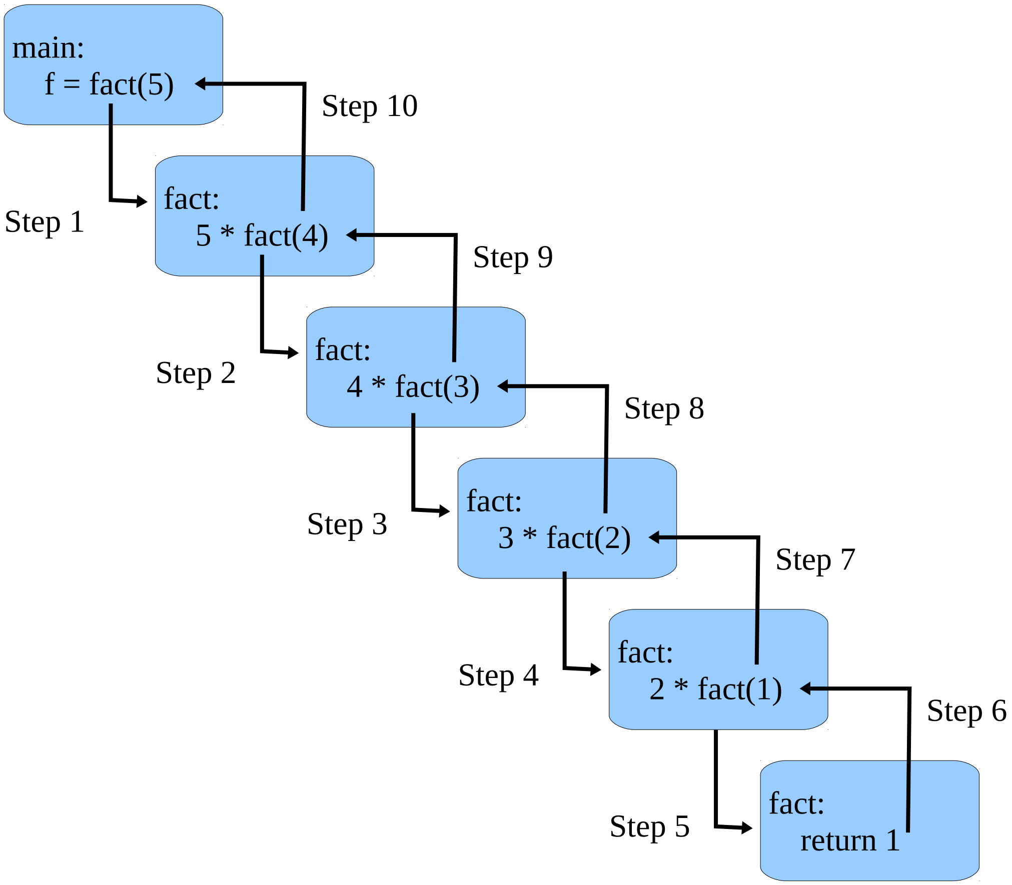


```
Factorial Example Program

Enter N value: 10

Factorial of N = 3628800
```

Refer to the next section for an explanation of how this function woks.

11.1.2 Recursive Factorial Function Call Tree

In order to help understand recursion, a recursion tree can help show how the recursive calls interact.



When the initial call occurs from main, the main will start into the fact() function (shown as step 1). Since the argument, of 5 is not a base case, the fact() function must call fact() again with the argument of ***n***-1 or 4 in this example (step 2). And, again, since 4 is not the base case, the fact() function must call fact() again with the argument of ***n***-1 or 3 in this example (step 3).

This process continues until the argument passed into the fact() function meets the base case which is when the arguments is equal to 1 (shown as step 5). When this occurs, only then is a return value provided to the previous call (step 6). This return argument is then used to calculate the previous multiplication which is 2 times 1 which will return a value to the previous call (as shown in step 7).

This returns will continue (steps 8, 9, and 10) until the main has a final answer.

Since the code being executed is the same, each instance of the fact() function is different from any other instance only in the arguments and temporary values. The arguments and temporary values for each instance are different since they maintained on the stack as required by the standard calling convention.

For example, consider a call to factorial with ***n*** = 2 (step 4 on the diagram). The return address, $ra, and previous contents of $s0 are preserver by pushing them on the stack in accordance with the standard calling convention. The base case is checked and since ***n*** ≠ 1 it continues to save the original value of 1 into $s0, decrement the original argument, ***n***, by 1 and calling the fact() function (with ***n*** = 1). The call the the fact() function (step 5 in the diagram) is like any other function call in that it must follow the standard calling convention, which requires preserving $ra and $s0. This when the function returns an answer, 1 in this specific case, that answer in $v0 is multiplied by the original ***n*** value in $s0 and returned to the calling routine.

As such the foundation for recursion is the procedure call frame or activation record. In general, it is simply stated that recursion is stack-based.

It should also be noted that the height of the recursion tree is directly associated with the amount of stack memory used by the function.

11.2 Recursion Example, Fibonacci

The Fibonacci function is mathematically defined as follows:

$$F_n = F_{n-1} + F_{n-2}$$

for positive integers with seed values of $F_0 = 0$ and $F_1 = 1$ by definition.

As such, starting from 0 the first 14 numbers in the Fibonacci series are:

0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233

It must be noted that this function could easily be computed with a loop. However, the reason this is done recursively is to provide a simple example of how recursion works.

For example, a typical recursive definition for Fibonacci is:

$$fib(n) = \begin{cases} 0 & if\ n=0 \\ 1 & if\ n=1 \\ fib(n-1) + fib(n-2) & if\ n>1 \end{cases}$$

This definition assumes that the value of ***n*** is positive.

11.2.1 Example Program, Recursive Fibonacci Function

The following code provides an example of the recursive Fibonacci function.

```
#  Recursive Fibonacci program to demonstrate recursion.

# ------------------------------------------------------------
#  Data Declarations

.data

prompt:     .ascii      "Fibonacci Example Program\n\n"
            .asciiz     "Enter N value: "

results:    .asciiz     "\nFibonacci of N = "

n:          .word 0
answer:     .word 0

# ------------------------------------------------------------
#  Text/code section

.text
.globl      main
main:

# -----
#  Read n value from user

      li    $v0, 4                  # print prompt string
      la    $a0, prompt
      syscall

      li    $v0, 5                  # read N (as integer)
      syscall

      sw    $v0, n

# -----
#  Call Fibonacci function.

      lw    $a0, n
      jal   fib

      sw    $v0, answer

# -----
#  Display result
```

```
     li   $v0, 4                # print prompt string
     la   $a0, results
     syscall

     li   $v0, 1                # print integer
     lw   $a0, answer
     syscall

# -----
#  Done, terminate program.
     li   $v0, 10               # call code for terminate
     syscall                    # system call
.end main

# ------------------------------------------------------------
#  Fibonacci function

#  Recursive definition:
#    = 0                     if n = 0
#    = 1                     if n = 1
#    = fib(n-1) + fib(n-2)   if n > 2

# -----
#  Arguments
#    $a0 - n

#  Returns
#    $v0 set to fib(n)

.globl     fib
.ent       fib
fib:
     subu $sp, $sp, 8
     sw   $ra, ($sp)
     sw   $s0, 4($sp)

     move $v0, $a0              # check for base cases
     ble  $a0, 1, fibDone

     move $s0, $a0              # get fib(n-1)
     sub  $a0, $a0, 1
     jal  fib

     move $a0, $s0
     sub  $a0, $a0, 2           # set n-2
     move $s0, $v0              # save fib(n-1)
     jal  fib                   # get fib(n-2)

     add  $v0, $s0, $v0         # fib(n-1)+fib(n-2)
```

```
fibDone:
     lw   $ra, ($sp)
     lw   $s0, 4($sp)
     addu $sp, $sp, 8
     jr   $ra
.end fib
```

The output for the example would be displayed to the QtSpim console window. For example,

```
Fibonacci Example Program

Enter N value: 13

Fibonacci of N = 233
```

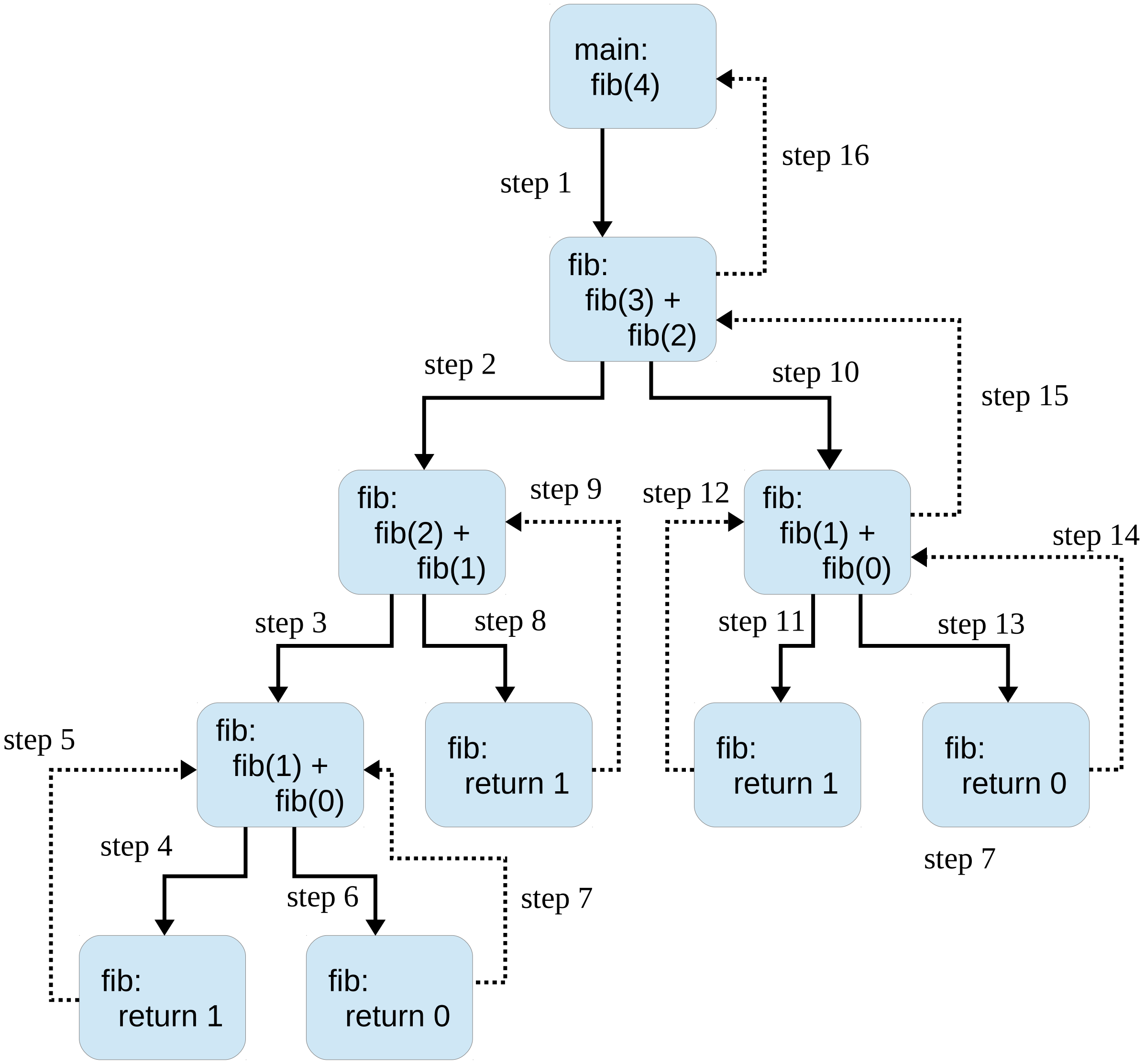
Refer to the next section for an explanation of how this function works.

11.2.2 Recursive Fibonacci Function Call Tree

The Fibonacci recursion tree appears more complex than the previous factorial tree since the Fibonacci functions uses two recursive calls. However, the general process and use of the stack for arguments and temporary values is the same.

As noted in the factorial example, the basis of recursion is the stack. In this example, since two recursive calls are made, the first call will make another call, which may make yet another call. In this manner, the call sequence will follow the order shown in the following diagram.

The following is an example of the call tree for a Fibonacci call with ***n*** = 4.



The calls are shown with a solid line and the returns are shown with a dashed line.

12.0 Appendix A – Example Program

Below is a simple example program. This program can be used to test the simulator installation and as an example of the required program formatting.

```
#  Example program to find the minimum and maximum from
#  a list of numbers.  Also displays the list of numbers.

# -------------------------------------------------------------
#  data segment

.data

array:     .word      13, 34, 16, 61, 28
           .word      24, 58, 11, 26, 41
           .word      19,  7, 38, 12, 13
len:       .word      15

hdr:       .asciiz    "\nExample program to find max and min\n\n"
newLine:   .asciiz    "\n"
a1Msg:     .asciiz    "min = "
a2Msg:     .asciiz    "max = "

# -------------------------------------------------------------
#  text/code segment
#  Note, QtSpim requires the main procedure to be named "main".

.text
.globl main
.ent main
main:

#  This program will use pointers.
#     t0 - array address
#     t1 - count of elements
#     s2 - min
#     s3 - max
#     t4 - each word from array
# -----
#  Display header
#  Uses print string system call

     la    $a0, hdr
```

```
     li   $v0, 4
     syscall                    # print header


# -----
#  Find max and min of the array.
#   Set min and max to first item in list and then
#   loop through the array and check min and max against
#   each item in the list, updating the min and max values
#   as needed.

     la   $t0, array            # set $t0 addr of array
     lw   $t1, len              # set $t1 to length
     lw   $s2, ($t0)            # set min, $t2 to array[0]
     lw   $s3, ($t0)            # set max, $t3 to array[0]

loop:
     lw   $t4, ($t0)            # get array[n]

     bge  $t4, $s2, NotMin      # is new min?
     move $s2, $t4              # set new min

NotMin:
     ble  $t4, $s3, NotMax      # is new max?
     move $s3, $t4              # set new max
NotMax:
     sub  $t1, $t1, 1           # decrement counter
     addu $t0, $t0, 4           # increment addr by word
     bnez $t1, loop

# -----
#  Display results min and max.
#   First display string, then value, then a print a
#   new line (for formatting).  Do for each max and min.

     la   $a0, a1Msg
     li   $v0, 4
     syscall                    # print "min = "

     move $a0, $s2
     li   $v0, 1
     syscall                    # print min

     la   $a0, newLine          # print a newline
     li   $v0, 4
     syscall

     la   $a0, a2Msg
     li   $v0, 4
```

```
      syscall                     # print "max = "

      move  $a0, $s3
      li    $v0, 1
      syscall                     # print max

      la    $a0, newLine          # print a newline
      li    $v0, 4
      syscall

# -----
#  Done, terminate program.
      li    $v0, 10
      syscall                     # all done!

.end main
```

13.0 Appendix B – QtSpim Tutorial

This QtSpim Tutorial is designed to prepare you to use the QtSpim simulator and complete your MIPS assignments more easily.

13.1 Downloading and Installing QtSpim

The first step is to download and install QtSpim for your specific machine. QtSpim is available for Winodws, Linux, and MAC OS's.

13.1.1 QtSpim Download URLs

The following are the current URLs for QtSpim. These are subject to change.

The QtSpim home page is located at: http://spimsimulator.sourceforge.net/

The specific download site is located at: http://sourceforge.net/projects/spimsimulator/files/

At the download site there are multiple versions for different target machines. These include Windows (all versions), linux (32-bit), linux (64-bit), and MAC OS (all versions). Download the latest version for your machine.

13.1.2 Installing QtSpim

Once the package is downloaded, follow the standard installation process for the specific OS being used. This typically will involve double-clicking the downloaded installation package and following the instructions. You will need administrator privileges to perform the installation. Additionally, some installations will require Internet access during the installation.

13.2 Sample Program

Copy the provided example file (assignment #0, asst0.asm) to a file in your working directory. This file will be used in the remainder of the tutorial. It demonstrates assembler directives, procedure calls, console I/O, program termination, and good programming practice. Notice in particular the assembler directives '.data' and '.text' as well as the declarations of program constants. Understanding the basic flow of the example program will help you to complete your SPIM assignment quickly and painlessly. Once you have created the file and reviewed the code, it is time to move onto the next section.

13.3 QtSpim – Executing Programs

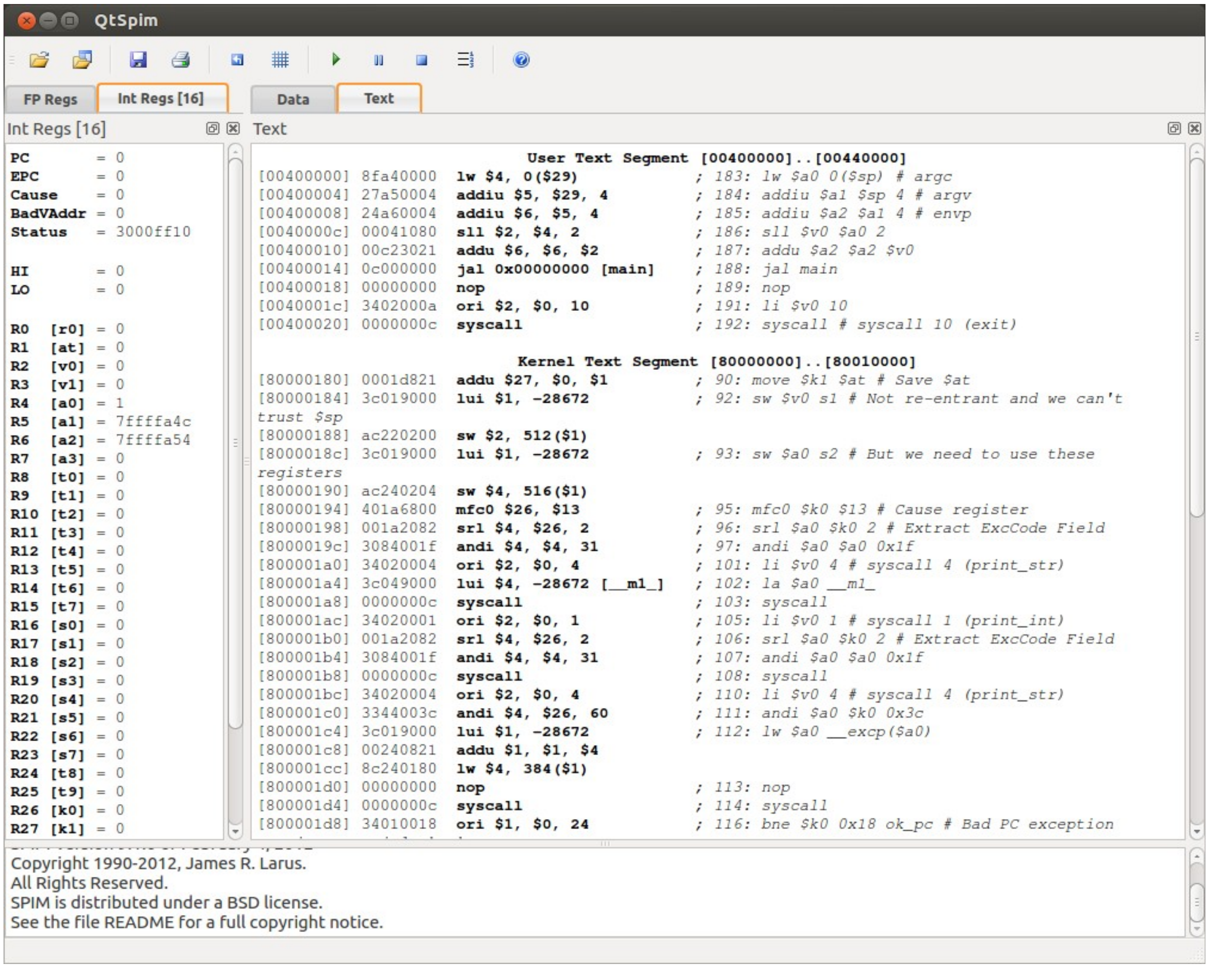
After the QtSpim application installation has been complete and the sample program has been created, you can execute the program to view the results. The use of QtSpim is described in the following sections.

13.3.1 Starting QtSpim

For Windows, this is typically, performed with the standard "Start Menu -> Programs -> QtSpim " operation. For MAC OS, enter LaunchPad and click on QtSPim. For Linux, find the QtSpim icon (location is OS distribution dependent) and click on QtSpim.

13.3.2 Main Screen

The initial QtSpim screen will appear as shown below. There will be some minor difference based on the specific Operating System being used.



```
PC       = 0
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10

HI       = 0
LO       = 0

R0  [r0] = 0
R1  [at] = 0
R2  [v0] = 0
R3  [v1] = 0
R4  [a0] = 1
R5  [a1] = 7ffffa4c
R6  [a2] = 7ffffa54
R7  [a3] = 0
R8  [t0] = 0
R9  [t1] = 0
R10 [t2] = 0
R11 [t3] = 0
R12 [t4] = 0
R13 [t5] = 0
R14 [t6] = 0
R15 [t7] = 0
R16 [s0] = 0
R17 [s1] = 0
R18 [s2] = 0
R19 [s3] = 0
R20 [s4] = 0
R21 [s5] = 0
R22 [s6] = 0
R23 [s7] = 0
R24 [t8] = 0
R25 [t9] = 0
R26 [k0] = 0
R27 [k1] = 0
```

```
                    User Text Segment [00400000]..[00440000]
[00400000] 8fa40000  lw $4, 0($29)           ; 183: lw $a0 0($sp) # argc
[00400004] 27a50004  addiu $5, $29, 4        ; 184: addiu $a1 $sp 4 # argv
[00400008] 24a60004  addiu $6, $5, 4         ; 185: addiu $a2 $a1 4 # envp
[0040000c] 00041080  sll $2, $4, 2           ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2         ; 187: addu $a2 $a2 $v0
[00400014] 0c000000  jal 0x00000000 [main]   ; 188: jal main
[00400018] 00000000  nop                     ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10          ; 191: li $v0 10
[00400020] 0000000c  syscall                 ; 192: syscall # syscall 10 (exit)

                   Kernel Text Segment [80000000]..[80010000]
[80000180] 0001d821  addu $27, $0, $1        ; 90: move $k1 $at # Save $at
[80000184] 3c019000  lui $1, -28672          ; 92: sw $v0 s1 # Not re-entrant and we can't
trust $sp
[80000188] ac220200  sw $2, 512($1)
[8000018c] 3c019000  lui $1, -28672          ; 93: sw $a0 s2 # But we need to use these
registers
[80000190] ac240204  sw $4, 516($1)
[80000194] 401a6800  mfc0 $26, $13           ; 95: mfc0 $k0 $13 # Cause register
[80000198] 001a2082  srl $4, $26, 2          ; 96: srl $a0 $k0 2 # Extract ExcCode Field
[8000019c] 3084001f  andi $4, $4, 31         ; 97: andi $a0 $a0 0x1f
[800001a0] 34020004  ori $2, $0, 4           ; 101: li $v0 4 # syscall 4 (print_str)
[800001a4] 3c049000  lui $4, -28672 [__m1_]  ; 102: la $a0 __m1_
[800001a8] 0000000c  syscall                 ; 103: syscall
[800001ac] 34020001  ori $2, $0, 1           ; 105: li $v0 1 # syscall 1 (print_int)
[800001b0] 001a2082  srl $4, $26, 2          ; 106: srl $a0 $k0 2 # Extract ExcCode Field
[800001b4] 3084001f  andi $4, $4, 31         ; 107: andi $a0 $a0 0x1f
[800001b8] 0000000c  syscall                 ; 108: syscall
[800001bc] 34020004  ori $2, $0, 4           ; 110: li $v0 4 # syscall 4 (print_str)
[800001c0] 3344003c  andi $4, $26, 60        ; 111: andi $a0 $k0 0x3c
[800001c4] 3c019000  lui $1, -28672          ; 112: lw $a0 __excp($a0)
[800001c8] 00240821  addu $1, $1, $4
[800001cc] 8c240180  lw $4, 384($1)
[800001d0] 00000000  nop                     ; 113: nop
[800001d4] 0000000c  syscall                 ; 114: syscall
[800001d8] 34010018  ori $1, $0, 24          ; 116: bne $k0 0x18 ok_pc # Bad PC exception
```

```
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```
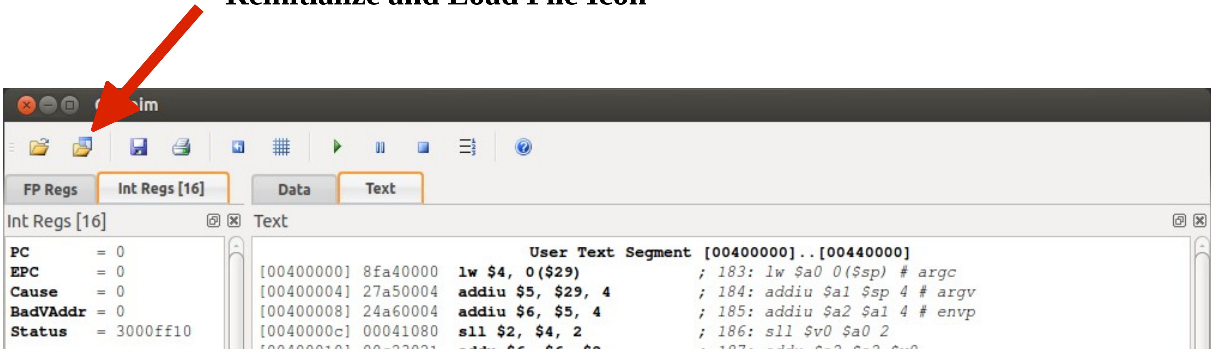

13.3.3 Load Program

To load the example program (and all programs), you can select the standard “**File→Reinitialize and Load File**” option from the menu bar. However, it is typically easier to select the **Reinitialize and Load File Icon** from the main screen (second file icon on right side).

Note, the Load File option can be used on the initial load, but subsequent file loads will need to use the Reinitialize and Load File to ensure the appropriate reinitialization occurs.

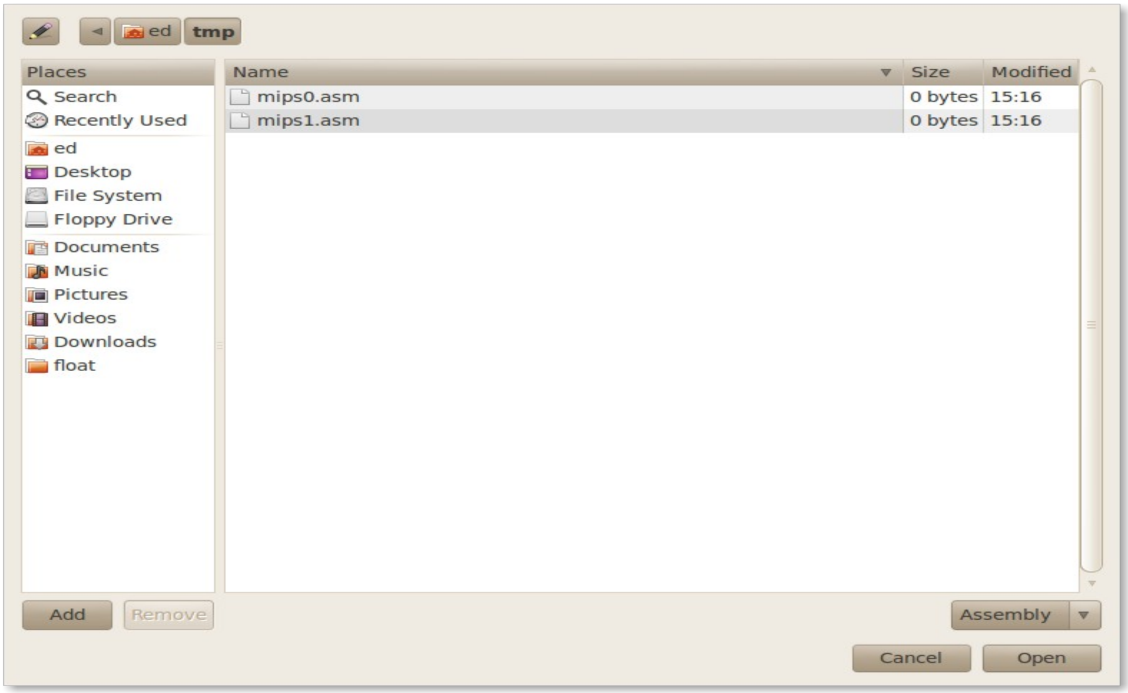


Reinitialize and Load File Icon

```
PC       = 0
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10
```

```
                              User Text Segment [00400000]..[00440000]
[00400000] 8fa40000  lw $4, 0($29)         ; 183: lw $a0 0($sp) # argc
[00400004] 27a50004  addiu $5, $29, 4      ; 184: addiu $a1 $sp 4 # argv
[00400008] 24a60004  addiu $6, $5, 4       ; 185: addiu $a2 $a1 4 # envp
[0040000c] 00041080  sll $2, $4, 2         ; 186: sll $v0 $a0 2
```

Once selected, a standard open file dialog box will be displayed. Find and select 'asst0.asm' file (or whatever you named it) created in section 3.0.

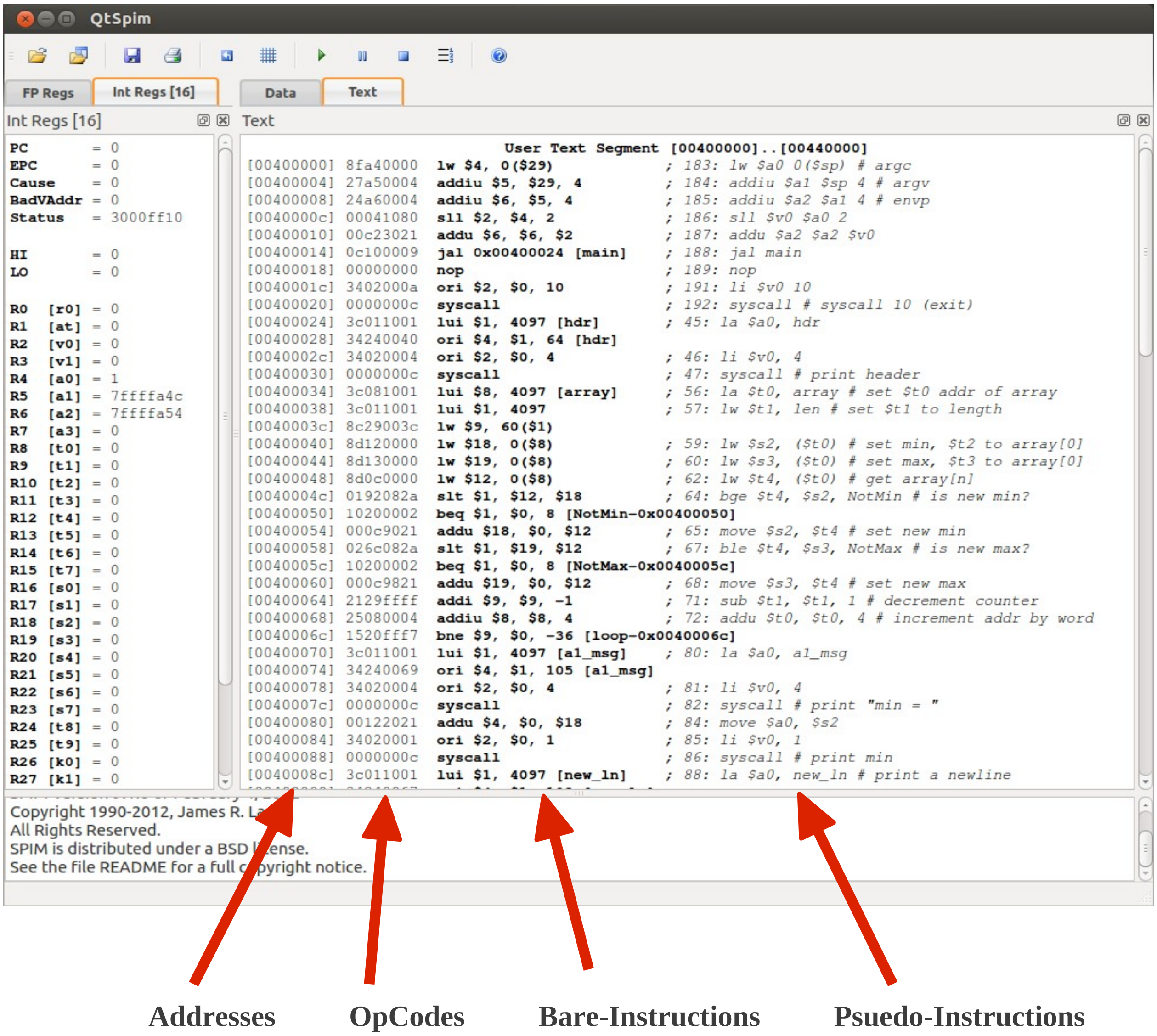


Name	Size	Modified
mips0.asm	0 bytes	15:16
mips1.asm	0 bytes	15:16

Navigate as appropriate to find the example file previously created. When found, select the file (it will be highlighted) and click Open button (lower right hand corner).

The assembly process occurs as the file is being loaded. As such, any assembly syntax errors (i.e., misspelled instructions, undefined variables, etc.) are caught at this point. An appropriate error message is provided with a reference to the line number that caused the error.

When the file load is completed with no errors, the program is ready to run, but has not yet been executed. The screen will appear something like the following image.



```
PC        = 0
EPC       = 0
Cause     = 0
BadVAddr  = 0
Status    = 3000ff10

HI        = 0
LO        = 0

R0   [r0] = 0
R1   [at] = 0
R2   [v0] = 0
R3   [v1] = 0
R4   [a0] = 1
R5   [a1] = 7ffffa4c
R6   [a2] = 7ffffa54
R7   [a3] = 0
R8   [t0] = 0
R9   [t1] = 0
R10  [t2] = 0
R11  [t3] = 0
R12  [t4] = 0
R13  [t5] = 0
R14  [t6] = 0
R15  [t7] = 0
R16  [s0] = 0
R17  [s1] = 0
R18  [s2] = 0
R19  [s3] = 0
R20  [s4] = 0
R21  [s5] = 0
R22  [s6] = 0
R23  [s7] = 0
R24  [t8] = 0
R25  [t9] = 0
R26  [k0] = 0
R27  [k1] = 0
```

```
                           User Text Segment [00400000]..[00440000]
[00400000] 8fa40000  lw $4, 0($29)             ; 183: lw $a0 0($sp) # argc
[00400004] 27a50004  addiu $5, $29, 4          ; 184: addiu $a1 $sp 4 # argv
[00400008] 24a60004  addiu $6, $5, 4           ; 185: addiu $a2 $a1 4 # envp
[0040000c] 00041080  sll $2, $4, 2             ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2           ; 187: addu $a2 $a2 $v0
[00400014] 0c100009  jal 0x00400024 [main]     ; 188: jal main
[00400018] 00000000  nop                       ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10            ; 191: li $v0 10
[00400020] 0000000c  syscall                   ; 192: syscall # syscall 10 (exit)
[00400024] 3c011001  lui $1, 4097 [hdr]        ; 45: la $a0, hdr
[00400028] 34240040  ori $4, $1, 64 [hdr]
[0040002c] 34020004  ori $2, $0, 4             ; 46: li $v0, 4
[00400030] 0000000c  syscall                   ; 47: syscall # print header
[00400034] 3c081001  lui $8, 4097 [array]      ; 56: la $t0, array # set $t0 addr of array
[00400038] 3c011001  lui $1, 4097              ; 57: lw $t1, len # set $t1 to length
[0040003c] 8c29003c  lw $9, 60($1)
[00400040] 8d120000  lw $18, 0($8)             ; 59: lw $s2, ($t0) # set min, $t2 to array[0]
[00400044] 8d130000  lw $19, 0($8)             ; 60: lw $s3, ($t0) # set max, $t3 to array[0]
[00400048] 8d0c0000  lw $12, 0($8)             ; 62: lw $t4, ($t0) # get array[n]
[0040004c] 0192082a  slt $1, $12, $18          ; 64: bge $t4, $s2, NotMin # is new min?
[00400050] 10200002  beq $1, $0, 8 [NotMin-0x00400050]
[00400054] 000c9021  addu $18, $0, $12         ; 65: move $s2, $t4 # set new min
[00400058] 026c082a  slt $1, $19, $12          ; 67: ble $t4, $s3, NotMax # is new max?
[0040005c] 10200002  beq $1, $0, 8 [NotMax-0x0040005c]
[00400060] 000c9821  addu $19, $0, $12         ; 68: move $s3, $t4 # set new max
[00400064] 2129ffff  addi $9, $9, -1           ; 71: sub $t1, $t1, 1 # decrement counter
[00400068] 25080004  addiu $8, $8, 4           ; 72: addu $t0, $t0, 4 # increment addr by word
[0040006c] 1520fff7  bne $9, $0, -36 [loop-0x0040006c]
[00400070] 3c011001  lui $1, 4097 [a1_msg]     ; 80: la $a0, a1_msg
[00400074] 34240069  ori $4, $1, 105 [a1_msg]
[00400078] 34020004  ori $2, $0, 4             ; 81: li $v0, 4
[0040007c] 0000000c  syscall                   ; 82: syscall # print "min = "
[00400080] 00122021  addu $4, $0, $18          ; 84: move $a0, $s2
[00400084] 34020001  ori $2, $0, 1             ; 85: li $v0, 1
[00400088] 0000000c  syscall                   ; 86: syscall # print min
[0040008c] 3c011001  lui $1, 4097 [new_ln]     ; 88: la $a0, new_ln # print a newline
```

```
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```

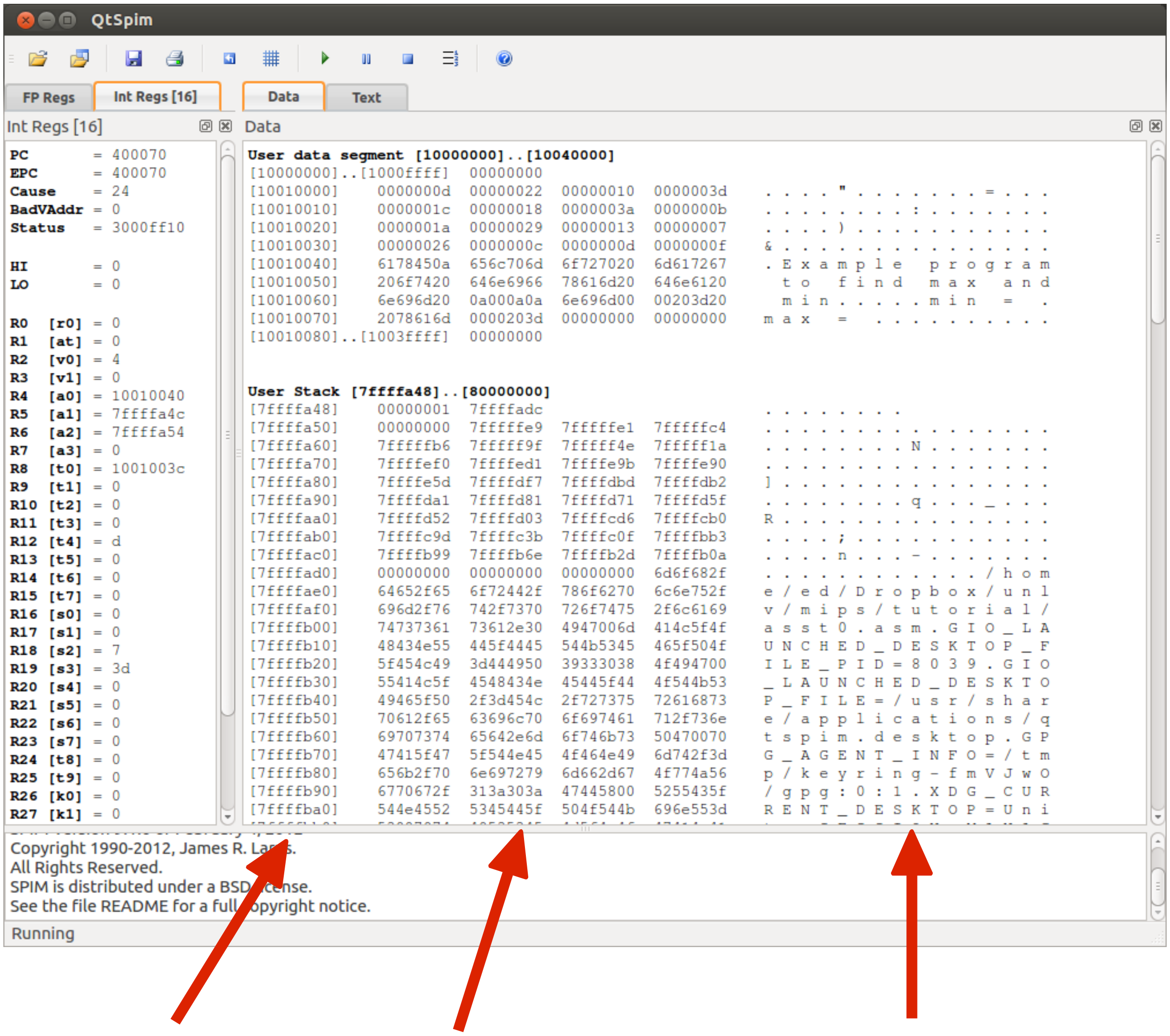
The code is placed in Text Window. The first column of hex values (in the []'s) is the address of that line of code. The next hex value is the OpCode or hex value of the 1's and 0's that the CPU understands to be that instruction.

MIPS includes psuedo-instructions. That is an instruction that the CPU does not execute, but the programmer is allowed to use. The assembler, QtSpim here, accepts the instruction and inserts the real or ***bare*** instruction as appropriate.

13.3.4 Data Window

The data segment contains the data declared by your program (if any). To view the data segment, click on the Data Icon.

The data window will appear similar to the following:



```
PC       = 400070
EPC      = 400070
Cause    = 24
BadVAddr = 0
Status   = 3000ff10

HI       = 0
LO       = 0

R0  [r0] = 0
R1  [at] = 0
R2  [v0] = 4
R3  [v1] = 0
R4  [a0] = 10010040
R5  [a1] = 7ffffa4c
R6  [a2] = 7ffffa54
R7  [a3] = 0
R8  [t0] = 1001003c
R9  [t1] = 0
R10 [t2] = 0
R11 [t3] = 0
R12 [t4] = d
R13 [t5] = 0
R14 [t6] = 0
R15 [t7] = 0
R16 [s0] = 0
R17 [s1] = 0
R18 [s2] = 7
R19 [s3] = 3d
R20 [s4] = 0
R21 [s5] = 0
R22 [s6] = 0
R23 [s7] = 0
R24 [t8] = 0
R25 [t9] = 0
R26 [k0] = 0
R27 [k1] = 0
```

```
User data segment [10000000]..[10040000]
[10000000]..[1000ffff]  00000000
[10010000]    0000000d  00000022  00000010  0000003d    . . . . " . . . . . . . = . . .
[10010010]    0000001c  00000018  0000003a  0000000b    . . . . . . . . : . . . . . . .
[10010020]    0000001a  00000029  00000013  00000007    . . . . ) . . . . . . . . . . .
[10010030]    00000026  0000000c  0000000d  0000000f    & . . . . . . . . . . . . . . .
[10010040]    6178450a  656c706d  6f727020  6d617267    . E x a m p l e   p r o g r a m
[10010050]    206f7420  646e6966  78616d20  646e6120      t o   f i n d   m a x   a n d
[10010060]    6e696d20  0a000a0a  6e696d00  00203d20      m i n . . . . . m i n   =   .
[10010070]    2078616d  0000203d  00000000  00000000    m a x   =   . . . . . . . . . .
[10010080]..[1003ffff]  00000000


User Stack [7ffffa48]..[80000000]
[7ffffa48]    00000001  7ffffadc                        . . . . . . . .
[7ffffa50]    00000000  7ffffe9  7fffffe1  7fffffc4     . . . . . . . . . . . . . . . .
[7ffffa60]    7fffffb6  7fffff9f  7fffff4e  7fffff1a    . . . . . . . . N . . . . . . .
[7ffffa70]    7ffffef0  7ffffed1  7ffffe9b  7ffffe90    . . . . . . . . . . . . . . . .
[7ffffa80]    7ffffe5d  7ffffdf7  7ffffdbd  7ffffdb2    ] . . . . . . . . . . . . . . .
[7ffffa90]    7ffffda1  7ffffd81  7ffffd71  7ffffd5f    . . . . . . . . q . . . _ . . .
[7ffffaa0]    7ffffd52  7ffffd03  7ffffcd6  7ffffcb0    R . . . . . . . . . . . . . . .
[7ffffab0]    7ffffc9d  7ffffc3b  7ffffc0f  7ffffbb3    . . . . ; . . . . . . . . . . .
[7ffffac0]    7ffffb99  7ffffb6e  7ffffb2d  7ffffb0a    . . . . n . . . - . . . . . . .
[7ffffad0]    00000000  00000000  00000000  6d6f682f    . . . . . . . . . . . . / h o m
[7ffffae0]    64652f65  6f72442f  786f6270  6c6e752f    e / e d / D r o p b o x / u n l
[7ffffaf0]    696d2f76  742f7370  726f7475  2f6c6169    v / m i p s / t u t o r i a l /
[7ffffb00]    74737361  73612e30  4947006d  414c5f4f    a s s t 0 . a s m . G I O _ L A
[7ffffb10]    48434e55  445f4445  544b5345  465f504f    U N C H E D _ D E S K T O P _ F
[7ffffb20]    5f454c49  3d444950  39333038  4f494700    I L E _ P I D = 8 0 3 9 . G I O
[7ffffb30]    55414c5f  4548434e  45445f44  4f544b53    _ L A U N C H E D _ D E S K T O
[7ffffb40]    49465f50  2f3d454c  2f727375  72616873    P _ F I L E = / u s r / s h a r
[7ffffb50]    70612f65  63696c70  6f697461  712f736e    e / a p p l i c a t i o n s / q
[7ffffb60]    69707374  65642e6d  6f746b73  50470070    t s p i m . d e s k t o p . G P
[7ffffb70]    47415f47  5f544e45  4f464e49  6d742f3d    G _ A G E N T _ I N F O = / t m
[7ffffb80]    656b2f70  6e697279  6d662d67  4f774a56    p / k e y r i n g - f m V J w O
[7ffffb90]    6770672f  313a303a  47445800  5255435f    / g p g : 0 : 1 . X D G _ C U R
[7ffffba0]    544e4552  5345445f  504f544b  696e553d    R E N T _ D E S K T O P = U n i
```

```
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```

Running

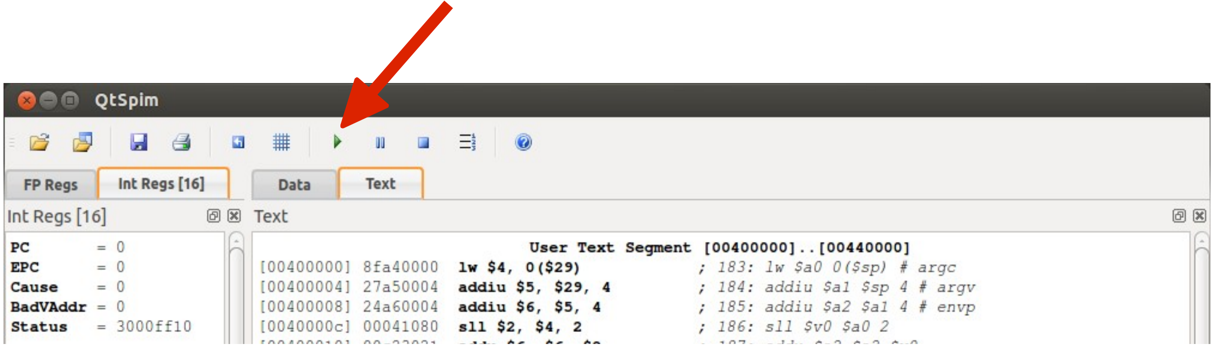
Addresses **Data (Hex Representation)** **Data (ASCII Representation)**

As before, the addresses are shown on the left side (with the []'s). The values at that address are shown in hex (middle) and in ASCII (right side). Depending on the specific type of data declarations, it may be easier to view the hex representation (i.e., like the array of numbers from the example code) or the ASCII representation (i.e., the declared strings).

Note, right clicking in the Data Window will display a menu allowing the user to change the default hex representation to decimal representation (if desired).

13.3.5 Program Execution

To execute the entire program (uninterrupted), you can select the standard "**Simulator → Run/Continue**" option from the menu bar. However, it is typically easier to select the **Run/Continue Icon** from the main screen or to type the **F5** key.



Run/Continue

```
PC       = 0
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10
```

```
                              User Text Segment [00400000]..[00440000]
[00400000] 8fa40000  lw $4, 0($29)              ; 183: lw $a0 0($sp) # argc
[00400004] 27a50004  addiu $5, $29, 4           ; 184: addiu $a1 $sp 4 # argv
[00400008] 24a60004  addiu $6, $5, 4            ; 185: addiu $a2 $a1 4 # envp
[0040000c] 00041080  sll $2, $4, 2              ; 186: sll $v0 $a0 2
```

Once typed, the program will be execution.

If a program performs input and/or output, it will be directed to the Console window. For example, the sample program (from Appendix B) will display the following in the Console window when executed.

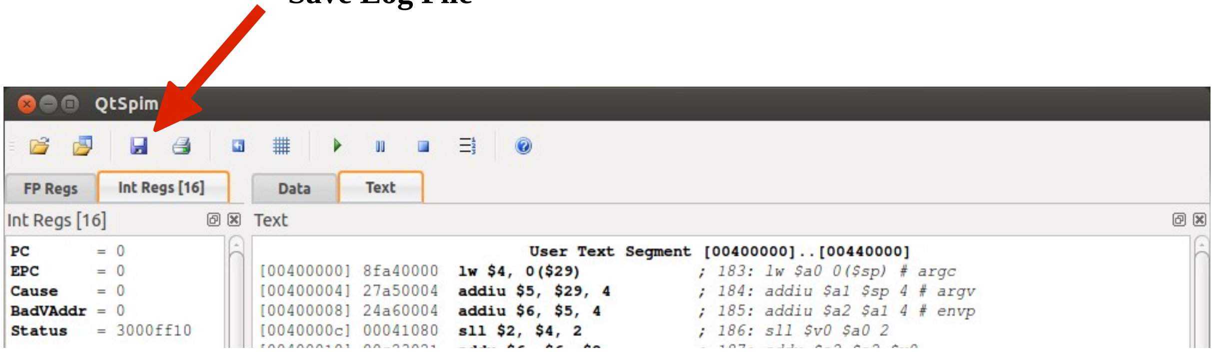
```
Example program to find max and min

min = 7
max = 61
```

For the sample program and the initial data set, these are the correct results.

13.3.6 Log File

QtSpim can create a log file documenting of the program results. To create a log file, you can select the standard "**File** → **Save Log File**" option from the menu bar. However, it is typically easier to select the **Save Log File Icon** from the main screen.

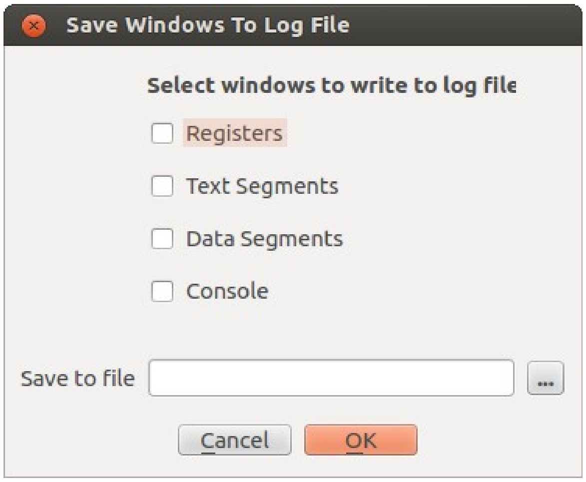
Save Log File



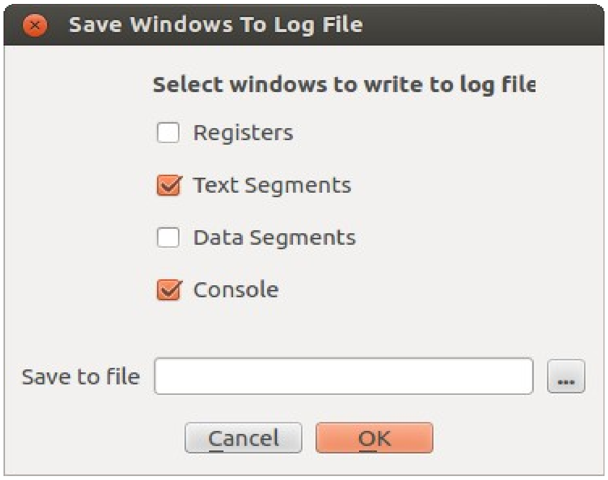
```
PC       = 0
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10
```

```
                          User Text Segment [00400000]..[00440000]
[00400000] 8fa40000  lw $4, 0($29)          ; 183: lw $a0 0($sp) # argc
[00400004] 27a50004  addiu $5, $29, 4       ; 184: addiu $a1 $sp 4 # argv
[00400008] 24a60004  addiu $6, $5, 4        ; 185: addiu $a2 $a1 4 # envp
[0040000c] 00041080  sll $2, $4, 2          ; 186: sll $v0 $a0 2
```

When selected, the Save Windows to Log File dialog box will be displayed as shown below on the left.



☐ Registers
☐ Text Segments
☐ Data Segments
☐ Console

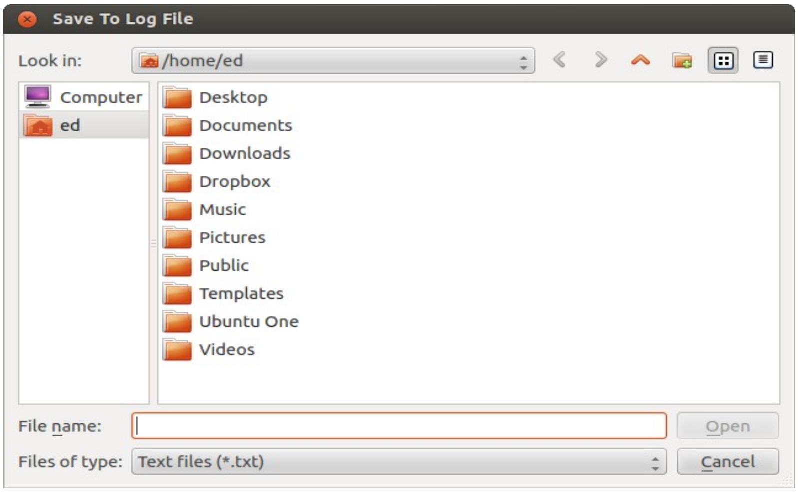


☐ Registers
☑ Text Segments
☐ Data Segments
☑ Console

In general, the Text Segments and Console options should be selected as shown on the left. Basedon the current version, selecting all will cause the simulator to crash.

Additionally, there is no default file name or location (for the log file). As such, a file name must be entered before it can be saved. This can done by manually entering the name in the Save to file box or by selecting the **...** box (on the lower right side).

When the **...** option is selected, a Save to Log File dialog box is displayed allowing selection of a location and the entry of a file name.

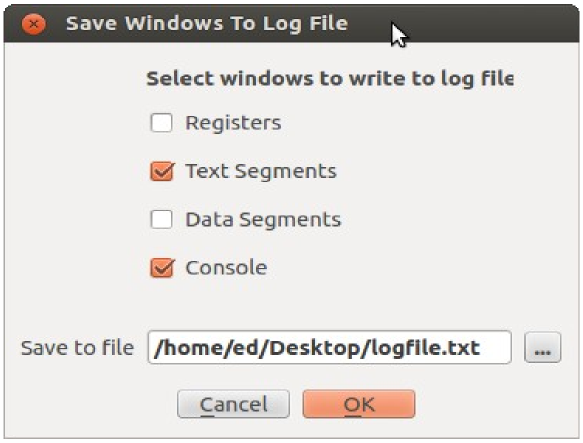


Look in: /home/ed

File name:

Files of type: Text files (*.txt)

When completed correctly, the Save Windows To Log File box will appear similar the the below image.



Select windows to write to log file

☐ Registers

☑ Text Segments

☐ Data Segments

☑ Console

Save to file /home/ed/Desktop/logfile.txt ...

When the options are selected and the file name entered, the OK box can be selected which will save the log file. This log file will need to be submitted as part the assignment submission.

13.3.7 Making Updates

In the highly unlikely event that the program does not work the first time or the program requirements are changed, the source file will need to be updated in a text editor. After the program source file is updated, it must be explicitly reloaded into QtSpim. The Reinitialize and Load File option must be used as described in section 4.3. Every change made to the source file must be re-loaded into QtSpim.

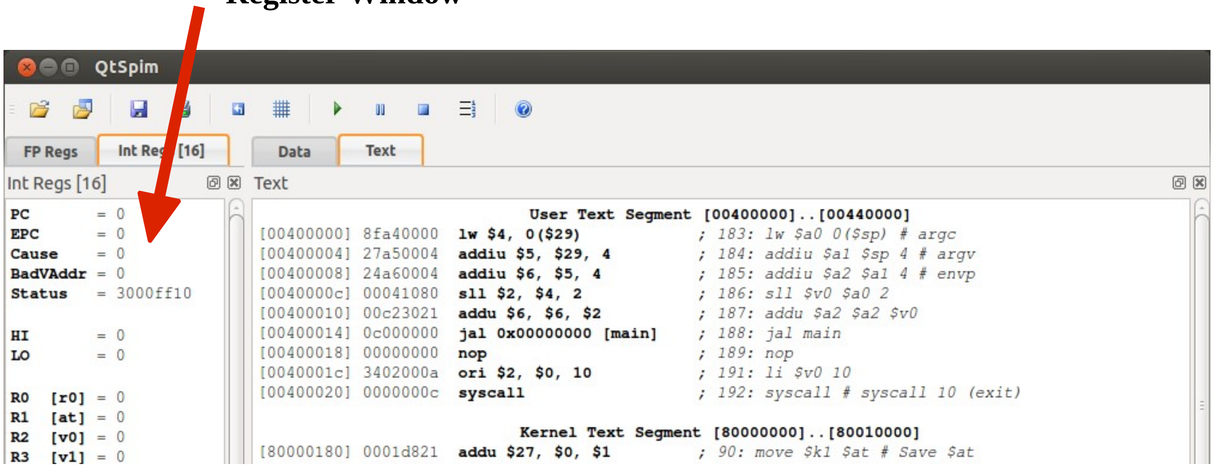
Once re-loaded, the program can be re-executed as noted in section 4.5. Refer to section 5.0 for information regarding debugging and controlled program execution.

13.4 Debugging

Often, looking at program source code will not help to find errors. The first step in debugging is to ensure that the file assembles correctly (or "reads" in the specific case of QtSpim). However, even if the file assembles, it still may not work correctly. In this case, the program must be debugged. In a broad sense, debugging is comparing the expected program results to actual program results. This requires a solid understanding of what the program is supposed to do and the specific order in which it does it → that is understanding the algorithm being used to solve the program. The algorithm should be noted in the program comments and can be used as a checklist for the debugging process.

One potentially useful way to check the program status is to view the register contents. The current register contents are show in registers window (left side) as shown in the image below.

Register Window



```
PC       = 0
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10

HI       = 0
LO       = 0

R0  [r0] = 0
R1  [at] = 0
R2  [v0] = 0
R3  [v1] = 0
```

```
                              User Text Segment [00400000]..[00440000]
[00400000] 8fa40000  lw $4, 0($29)             ; 183: lw $a0 0($sp) # argc
[00400004] 27a50004  addiu $5, $29, 4          ; 184: addiu $a1 $sp 4 # argv
[00400008] 24a60004  addiu $6, $5, 4           ; 185: addiu $a2 $a1 4 # envp
[0040000c] 00041080  sll $2, $4, 2             ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2           ; 187: addu $a2 $a2 $v0
[00400014] 0c000000  jal 0x00000000 [main]     ; 188: jal main
[00400018] 00000000  nop                       ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10            ; 191: li $v0 10
[00400020] 0000000c  syscall                   ; 192: syscall # syscall 10 (exit)

                            Kernel Text Segment [80000000]..[80010000]
[80000180] 0001d821  addu $27, $0, $1          ; 90: move $k1 $at # Save $at
```

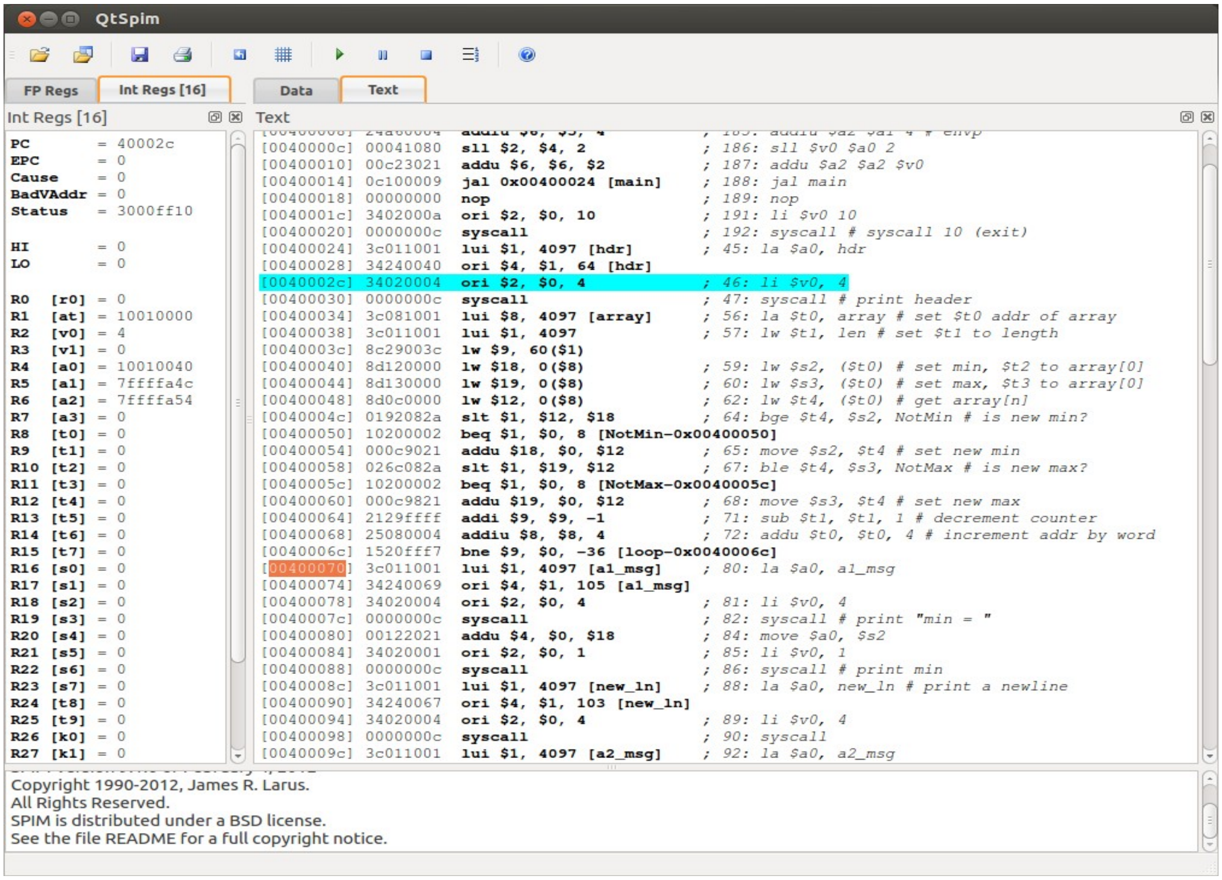
The overall debugging process can be simplified by using the QtSpim controlled execution functions. These functions include single stepping through the program and using one or more breakpoints. A breakpoint a programmer selected location in the program where execution will be paused. When the program is paused the current program status can be checked by viewing the register contents and/or the data segment. Typically, a breakpoint will be set, the program executed (to that point), and from there single stepping through the program watching execution and checking the results (via register contents and/or data segment).

When stepping through the program, the *next instruction to be executed* is highlighted. As such, that instruction has **not** yet been executed. This highlighting is how to track the progress of the program execution.

To set a breakpoint, select an appropriate location. This should be chosen with a specific expectation in mind. For example, if a program does not produce the correct average for a list of numbers, a typical debugging strategy would be to see of the sum is correct (as it is required for the average calculation). As such, a breakpoint could be set after the loop and before the average calculation.

As an example, to set a breakpoint after the loop in the sample program (from Appendix B), the first instruction after the loop can be found in the Text Window. This will require looking at the pseudo-instructions (on the right side of the Text Window).

The first instruction after the loop in the example program is highlighted in orange (for reference) in the image below.



```
PC       = 40002c
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10

HI       = 0
LO       = 0

R0  [r0] = 0
R1  [at] = 10010000
R2  [v0] = 4
R3  [v1] = 0
R4  [a0] = 10010040
R5  [a1] = 7ffffa4c
R6  [a2] = 7ffffa54
R7  [a3] = 0
R8  [t0] = 0
R9  [t1] = 0
R10 [t2] = 0
R11 [t3] = 0
R12 [t4] = 0
R13 [t5] = 0
R14 [t6] = 0
R15 [t7] = 0
R16 [s0] = 0
R17 [s1] = 0
R18 [s2] = 0
R19 [s3] = 0
R20 [s4] = 0
R21 [s5] = 0
R22 [s6] = 0
R23 [s7] = 0
R24 [t8] = 0
R25 [t9] = 0
R26 [k0] = 0
R27 [k1] = 0
```

```
[0040000c] 00041080  sll $2, $4, 2                ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2              ; 187: addu $a2 $a2 $v0
[00400014] 0c100009  jal 0x00400024 [main]        ; 188: jal main
[00400018] 00000000  nop                          ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10               ; 191: li $v0 10
[00400020] 0000000c  syscall                      ; 192: syscall # syscall 10 (exit)
[00400024] 3c011001  lui $1, 4097 [hdr]           ; 45: la $a0, hdr
[00400028] 34240040  ori $4, $1, 64 [hdr]
[0040002c] 34020004  ori $2, $0, 4                ; 46: li $v0, 4
[00400030] 0000000c  syscall                      ; 47: syscall # print header
[00400034] 3c081001  lui $8, 4097 [array]         ; 56: la $t0, array # set $t0 addr of array
[00400038] 3c011001  lui $1, 4097                 ; 57: lw $t1, len # set $t1 to length
[0040003c] 8c29003c  lw $9, 60($1)
[00400040] 8d120000  lw $18, 0($8)                ; 59: lw $s2, ($t0) # set min, $t2 to array[0]
[00400044] 8d130000  lw $19, 0($8)                ; 60: lw $s3, ($t0) # set max, $t3 to array[0]
[00400048] 8d0c0000  lw $12, 0($8)                ; 62: lw $t4, ($t0) # get array[n]
[0040004c] 0192082a  slt $1, $12, $18             ; 64: bge $t4, $s2, NotMin # is new min?
[00400050] 10200002  beq $1, $0, 8 [NotMin-0x00400050]
[00400054] 000c9021  addu $18, $0, $12            ; 65: move $s2, $t4 # set new min
[00400058] 026c082a  slt $1, $19, $12             ; 67: ble $t4, $s3, NotMax # is new max?
[0040005c] 10200002  beq $1, $0, 8 [NotMax-0x0040005c]
[00400060] 000c9821  addu $19, $0, $12            ; 68: move $s3, $t4 # set new max
[00400064] 2129ffff  addi $9, $9, -1              ; 71: sub $t1, $t1, 1 # decrement counter
[00400068] 25080004  addiu $8, $8, 4              ; 72: addu $t0, $t0, 4 # increment addr by word
[0040006c] 1520fff7  bne $9, $0, -36 [loop-0x0040006c]
[00400070] 3c011001  lui $1, 4097 [a1_msg]        ; 80: la $a0, a1_msg
[00400074] 34240069  ori $4, $1, 105 [a1_msg]
[00400078] 34020004  ori $2, $0, 4                ; 81: li $v0, 4
[0040007c] 0000000c  syscall                      ; 82: syscall # print "min = "
[00400080] 00122021  addu $4, $0, $18             ; 84: move $a0, $s2
[00400084] 34020001  ori $2, $0, 1                ; 85: li $v0, 1
[00400088] 0000000c  syscall                      ; 86: syscall # print min
[0040008c] 3c011001  lui $1, 4097 [new_ln]        ; 88: la $a0, new_ln # print a newline
[00400090] 34240067  ori $4, $1, 103 [new_ln]
[00400094] 34020004  ori $2, $0, 4                ; 89: li $v0, 4
[00400098] 0000000c  syscall                      ; 90: syscall
[0040009c] 3c011001  lui $1, 4097 [a2_msg]        ; 92: la $a0, a2_msg
```

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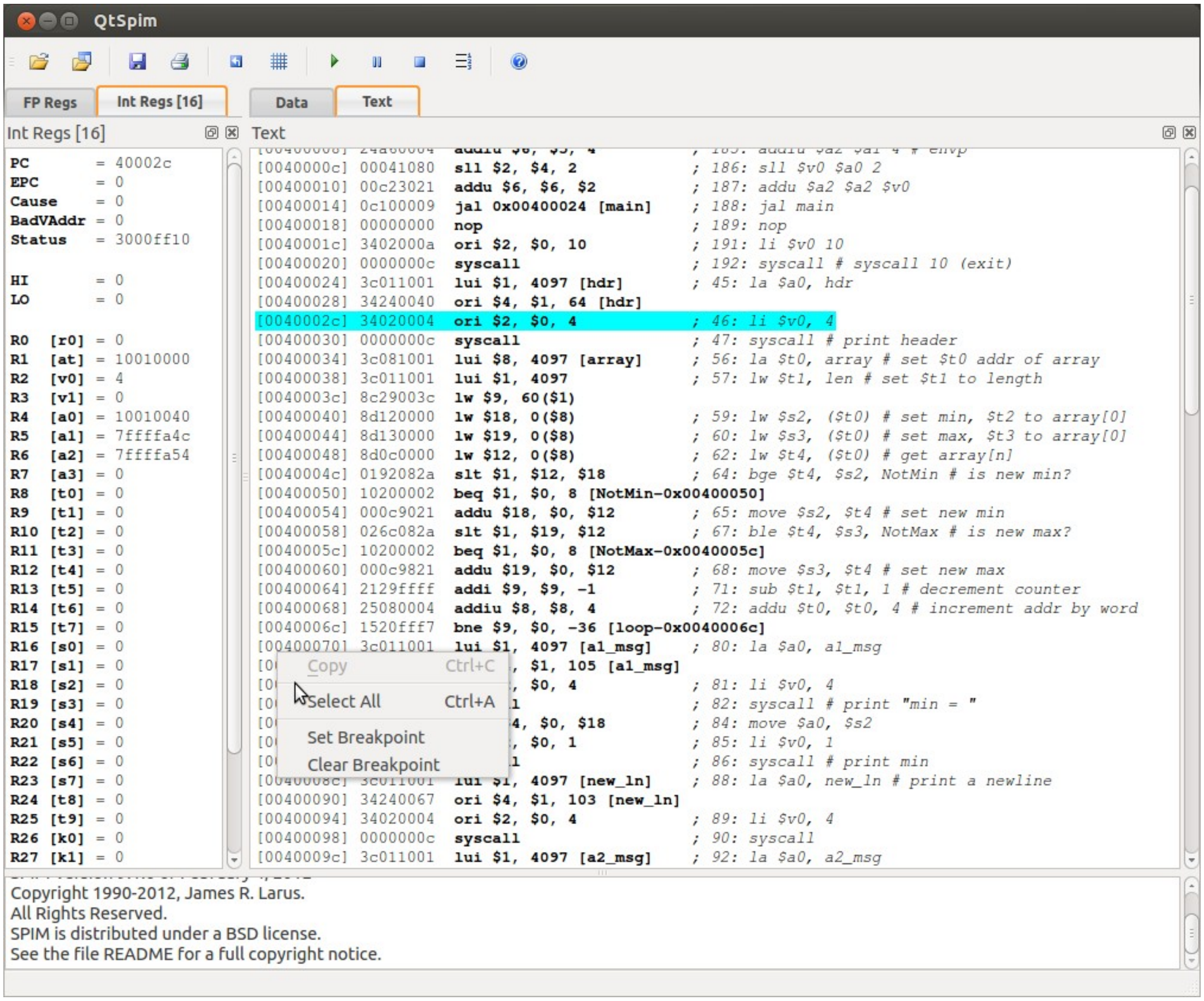
Note, the orange highlighting was added in this document for reference and will not be displayed in QtSpim during normal execution.

When an appropriate instruction is determined, move the cursor to the instruction address and right-click. The right-click will display the breakpoint menu as shown in the image below.



Int Regs [16]

```
PC        = 40002c
EPC       = 0
Cause     = 0
BadVAddr  = 0
Status    = 3000ff10

HI        = 0
LO        = 0

R0  [r0] = 0
R1  [at] = 10010000
R2  [v0] = 4
R3  [v1] = 0
R4  [a0] = 10010040
R5  [a1] = 7ffffa4c
R6  [a2] = 7ffffa54
R7  [a3] = 0
R8  [t0] = 0
R9  [t1] = 0
R10 [t2] = 0
R11 [t3] = 0
R12 [t4] = 0
R13 [t5] = 0
R14 [t6] = 0
R15 [t7] = 0
R16 [s0] = 0
R17 [s1] = 0
R18 [s2] = 0
R19 [s3] = 0
R20 [s4] = 0
R21 [s5] = 0
R22 [s6] = 0
R23 [s7] = 0
R24 [t8] = 0
R25 [t9] = 0
R26 [k0] = 0
R27 [k1] = 0
```

Text

```
[0040000c] 00041080  sll $2, $4, 2                ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2              ; 187: addu $a2 $a2 $v0
[00400014] 0c100009  jal 0x00400024 [main]        ; 188: jal main
[00400018] 00000000  nop                          ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10               ; 191: li $v0 10
[00400020] 0000000c  syscall                      ; 192: syscall # syscall 10 (exit)
[00400024] 3c011001  lui $1, 4097 [hdr]           ; 45: la $a0, hdr
[00400028] 34240040  ori $4, $1, 64 [hdr]
[0040002c] 34020004  ori $2, $0, 4                ; 46: li $v0, 4
[00400030] 0000000c  syscall                      ; 47: syscall # print header
[00400034] 3c081001  lui $8, 4097 [array]         ; 56: la $t0, array # set $t0 addr of array
[00400038] 3c011001  lui $1, 4097                 ; 57: lw $t1, len # set $t1 to length
[0040003c] 8c29003c  lw $9, 60($1)
[00400040] 8d120000  lw $18, 0($8)                ; 59: lw $s2, ($t0) # set min, $t2 to array[0]
[00400044] 8d130000  lw $19, 0($8)                ; 60: lw $s3, ($t0) # set max, $t3 to array[0]
[00400048] 8d0c0000  lw $12, 0($8)                ; 62: lw $t4, ($t0) # get array[n]
[0040004c] 0192082a  slt $1, $12, $18             ; 64: bge $t4, $s2, NotMin # is new min?
[00400050] 10200002  beq $1, $0, 8 [NotMin-0x00400050]
[00400054] 000c9021  addu $18, $0, $12            ; 65: move $s2, $t4 # set new min
[00400058] 026c082a  slt $1, $19, $12             ; 67: ble $t4, $s3, NotMax # is new max?
[0040005c] 10200002  beq $1, $0, 8 [NotMax-0x0040005c]
[00400060] 000c9821  addu $19, $0, $12            ; 68: move $s3, $t4 # set new max
[00400064] 2129ffff  addi $9, $9, -1              ; 71: sub $t1, $t1, 1 # decrement counter
[00400068] 25080004  addiu $8, $8, 4              ; 72: addu $t0, $t0, 4 # increment addr by word
[0040006c] 1520fff7  bne $9, $0, -36 [loop-0x0040006c]
[00400070] 3c011001  lui $1, 4097 [a1_msg]        ; 80: la $a0, a1_msg
[0                   , $1, 105 [a1_msg]
[0                   , $0, 4                      ; 81: li $v0, 4
[0                   1                            ; 82: syscall # print "min = "
[0                   4, $0, $18                   ; 84: move $a0, $s2
[0                   , $0, 1                      ; 85: li $v0, 1
[0                   1                            ; 86: syscall # print min
[0040008c] 3c011001  lui $1, 4097 [new_ln]        ; 88: la $a0, new_ln # print a newline
[00400090] 34240067  ori $4, $1, 103 [new_ln]
[00400094] 34020004  ori $2, $0, 4                ; 89: li $v0, 4
[00400098] 0000000c  syscall                      ; 90: syscall
[0040009c] 3c011001  lui $1, 4097 [a2_msg]        ; 92: la $a0, a2_msg
```

```
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```
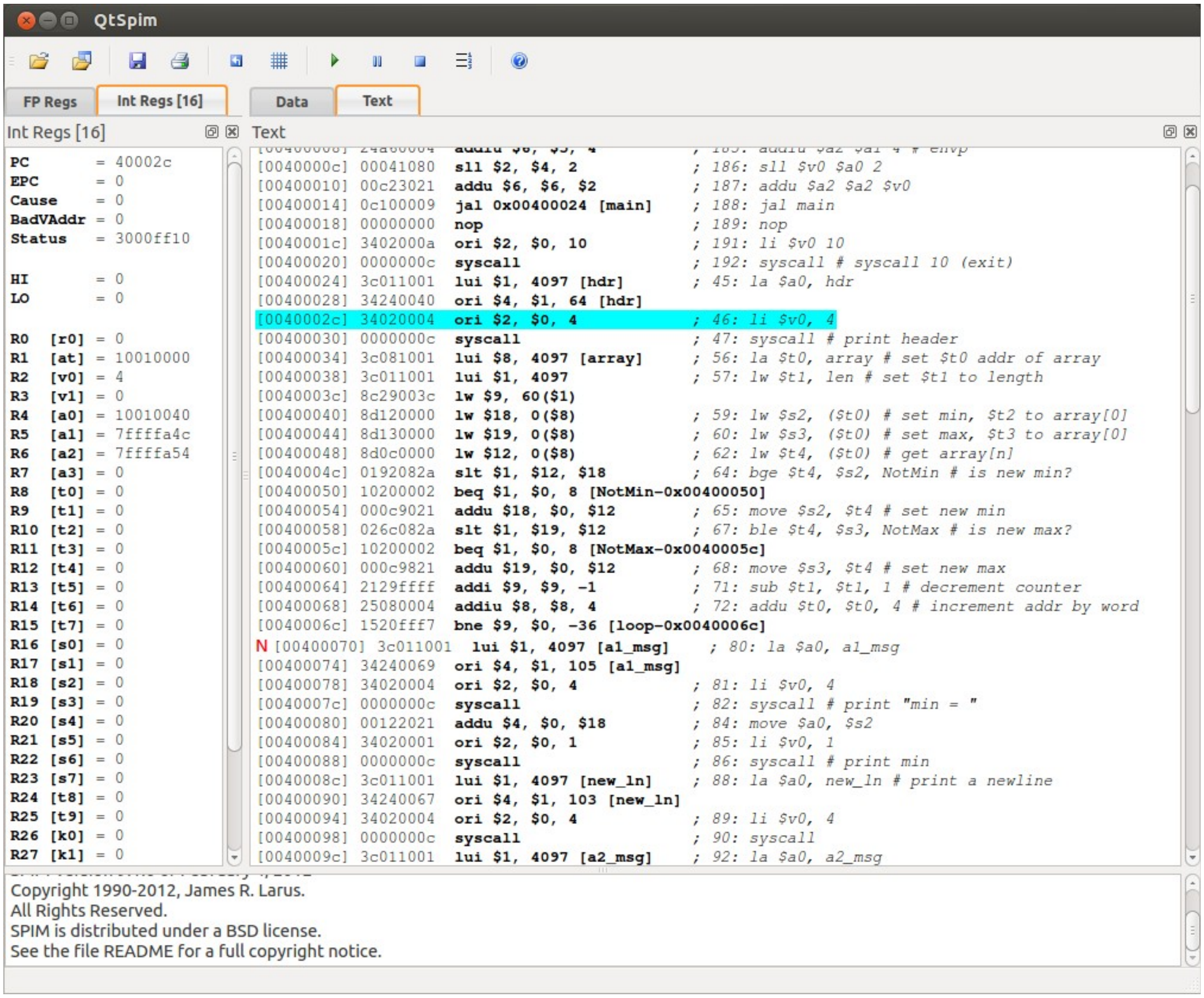

To set a breakpoint, select the Set Breakpoint option. If a breakpoint has already been set, it can be cleared by selecting the Clear Breakpoint option.

Once the breakpoint has been set, it will be highlighted with a small red icon such as an **N** as shown in the following image. *Note*, different operating systems may use a different icon.



```
PC       = 40002c
EPC      = 0
Cause    = 0
BadVAddr = 0
Status   = 3000ff10

HI       = 0
LO       = 0

R0  [r0] = 0
R1  [at] = 10010000
R2  [v0] = 4
R3  [v1] = 0
R4  [a0] = 10010040
R5  [a1] = 7ffffa4c
R6  [a2] = 7ffffa54
R7  [a3] = 0
R8  [t0] = 0
R9  [t1] = 0
R10 [t2] = 0
R11 [t3] = 0
R12 [t4] = 0
R13 [t5] = 0
R14 [t6] = 0
R15 [t7] = 0
R16 [s0] = 0
R17 [s1] = 0
R18 [s2] = 0
R19 [s3] = 0
R20 [s4] = 0
R21 [s5] = 0
R22 [s6] = 0
R23 [s7] = 0
R24 [t8] = 0
R25 [t9] = 0
R26 [k0] = 0
R27 [k1] = 0
```

```
[0040000c] 00041080  sll $2, $4, 2              ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2            ; 187: addu $a2 $a2 $v0
[00400014] 0c100009  jal 0x00400024 [main]      ; 188: jal main
[00400018] 00000000  nop                        ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10             ; 191: li $v0 10
[00400020] 0000000c  syscall                    ; 192: syscall # syscall 10 (exit)
[00400024] 3c011001  lui $1, 4097 [hdr]         ; 45: la $a0, hdr
[00400028] 34240040  ori $4, $1, 64 [hdr]
[0040002c] 34020004  ori $2, $0, 4              ; 46: li $v0, 4
[00400030] 0000000c  syscall                    ; 47: syscall # print header
[00400034] 3c081001  lui $8, 4097 [array]       ; 56: la $t0, array # set $t0 addr of array
[00400038] 3c011001  lui $1, 4097               ; 57: lw $t1, len # set $t1 to length
[0040003c] 8c29003c  lw $9, 60($1)
[00400040] 8d120000  lw $18, 0($8)              ; 59: lw $s2, ($t0) # set min, $t2 to array[0]
[00400044] 8d130000  lw $19, 0($8)              ; 60: lw $s3, ($t0) # set max, $t3 to array[0]
[00400048] 8d0c0000  lw $12, 0($8)              ; 62: lw $t4, ($t0) # get array[n]
[0040004c] 0192082a  slt $1, $12, $18           ; 64: bge $t4, $s2, NotMin # is new min?
[00400050] 10200002  beq $1, $0, 8 [NotMin-0x00400050]
[00400054] 000c9021  addu $18, $0, $12          ; 65: move $s2, $t4 # set new min
[00400058] 026c082a  slt $1, $19, $12           ; 67: ble $t4, $s3, NotMax # is new max?
[0040005c] 10200002  beq $1, $0, 8 [NotMax-0x0040005c]
[00400060] 000c9821  addu $19, $0, $12          ; 68: move $s3, $t4 # set new max
[00400064] 2129ffff  addi $9, $9, -1            ; 71: sub $t1, $t1, 1 # decrement counter
[00400068] 25080004  addiu $8, $8, 4            ; 72: addu $t0, $t0, 4 # increment addr by word
[0040006c] 1520fff7  bne $9, $0, -36 [loop-0x0040006c]
N [00400070] 3c011001  lui $1, 4097 [a1_msg]    ; 80: la $a0, a1_msg
[00400074] 34240069  ori $4, $1, 105 [a1_msg]
[00400078] 34020004  ori $2, $0, 4              ; 81: li $v0, 4
[0040007c] 0000000c  syscall                    ; 82: syscall # print "min = "
[00400080] 00122021  addu $4, $0, $18           ; 84: move $a0, $s2
[00400084] 34020001  ori $2, $0, 1              ; 85: li $v0, 1
[00400088] 0000000c  syscall                    ; 86: syscall # print min
[0040008c] 3c011001  lui $1, 4097 [new_ln]      ; 88: la $a0, new_ln # print a newline
[00400090] 34240067  ori $4, $1, 103 [new_ln]
[00400094] 34020004  ori $2, $0, 4              ; 89: li $v0, 4
[00400098] 0000000c  syscall                    ; 90: syscall
[0040009c] 3c011001  lui $1, 4097 [a2_msg]      ; 92: la $a0, a2_msg
```

```
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```
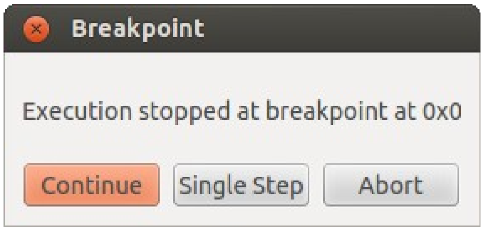
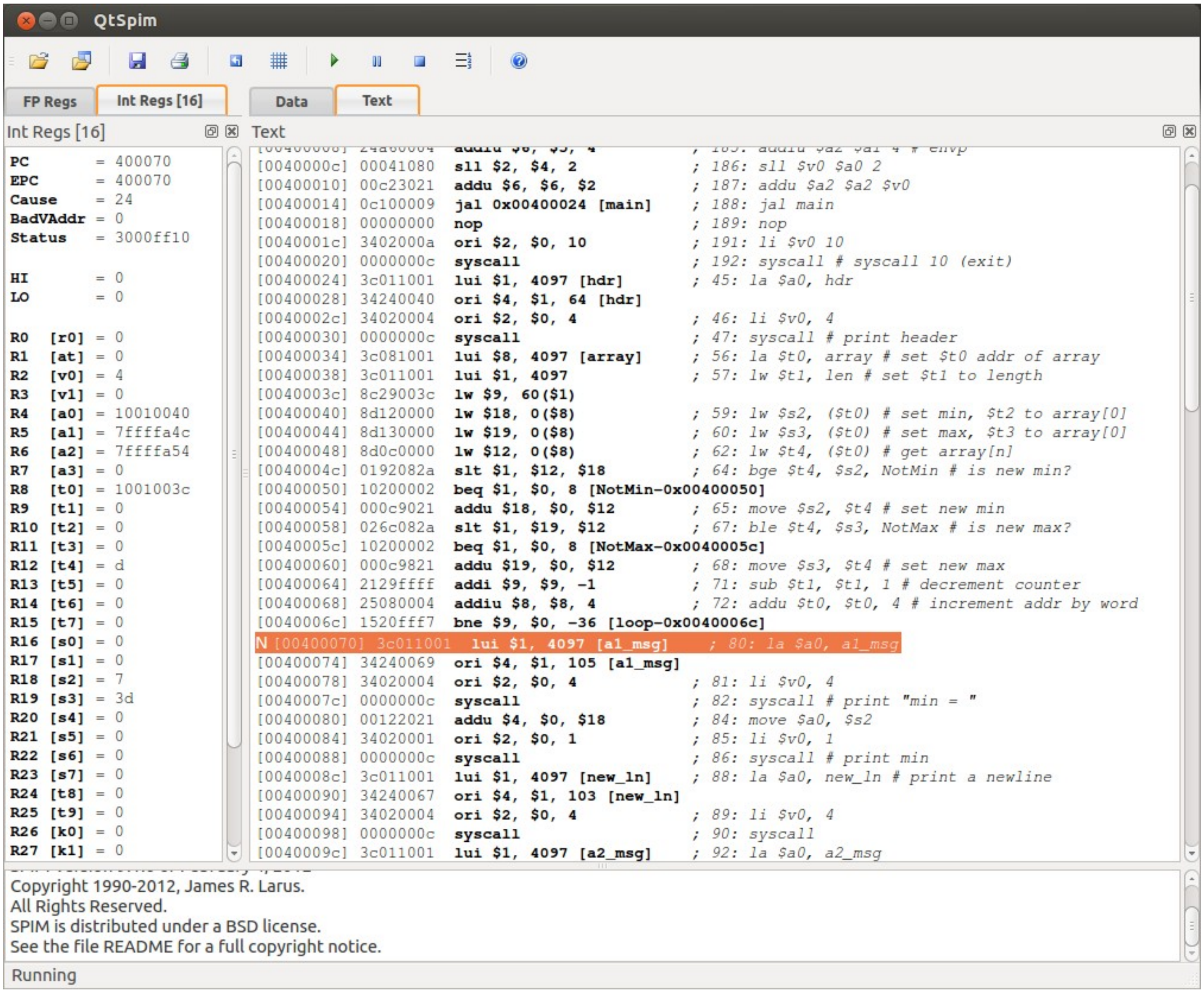

Select the Run/Continue option (as described in section 4.5) which will execute the program up to the selected breakpoint. When program execution reaches the breakpoint, it will be paused and a Breakpoint diaglog box display as shown in the below image.



Execution stopped at breakpoint at 0x0

The program execution can be halted by selecting the Abort box. The breakpoint can be ignored, thus continuing to the next breakpoint or program termination, whichever comes first.

However, typically the Single Step box will be selected enter the single step mode. The following image shows the result of selecting Single Step. Note, the highlighted instruction represents the next instruction to be executed and thus has not yet been executed.



```
PC       = 400070
EPC      = 400070
Cause    = 24
BadVAddr = 0
Status   = 3000ff10

HI       = 0
LO       = 0

R0  [r0] = 0
R1  [at] = 0
R2  [v0] = 4
R3  [v1] = 0
R4  [a0] = 10010040
R5  [a1] = 7ffffa4c
R6  [a2] = 7ffffa54
R7  [a3] = 0
R8  [t0] = 1001003c
R9  [t1] = 0
R10 [t2] = 0
R11 [t3] = 0
R12 [t4] = d
R13 [t5] = 0
R14 [t6] = 0
R15 [t7] = 0
R16 [s0] = 0
R17 [s1] = 0
R18 [s2] = 7
R19 [s3] = 3d
R20 [s4] = 0
R21 [s5] = 0
R22 [s6] = 0
R23 [s7] = 0
R24 [t8] = 0
R25 [t9] = 0
R26 [k0] = 0
R27 [k1] = 0
```

```
[0040000c] 00041080  sll $2, $4, 2             ; 186: sll $v0 $a0 2
[00400010] 00c23021  addu $6, $6, $2           ; 187: addu $a2 $a2 $v0
[00400014] 0c100009  jal 0x00400024 [main]     ; 188: jal main
[00400018] 00000000  nop                       ; 189: nop
[0040001c] 3402000a  ori $2, $0, 10            ; 191: li $v0 10
[00400020] 0000000c  syscall                   ; 192: syscall # syscall 10 (exit)
[00400024] 3c011001  lui $1, 4097 [hdr]        ; 45: la $a0, hdr
[00400028] 34240040  ori $4, $1, 64 [hdr]
[0040002c] 34020004  ori $2, $0, 4             ; 46: li $v0, 4
[00400030] 0000000c  syscall                   ; 47: syscall # print header
[00400034] 3c081001  lui $8, 4097 [array]      ; 56: la $t0, array # set $t0 addr of array
[00400038] 3c011001  lui $1, 4097              ; 57: lw $t1, len # set $t1 to length
[0040003c] 8c29003c  lw $9, 60($1)
[00400040] 8d120000  lw $18, 0($8)             ; 59: lw $s2, ($t0) # set min, $t2 to array[0]
[00400044] 8d130000  lw $19, 0($8)             ; 60: lw $s3, ($t0) # set max, $t3 to array[0]
[00400048] 8d0c0000  lw $12, 0($8)             ; 62: lw $t4, ($t0) # get array[n]
[0040004c] 0192082a  slt $1, $12, $18          ; 64: bge $t4, $s2, NotMin # is new min?
[00400050] 10200002  beq $1, $0, 8 [NotMin-0x00400050]
[00400054] 000c9021  addu $18, $0, $12         ; 65: move $s2, $t4 # set new min
[00400058] 026c082a  slt $1, $19, $12          ; 67: ble $t4, $s3, NotMax # is new max?
[0040005c] 10200002  beq $1, $0, 8 [NotMax-0x0040005c]
[00400060] 000c9821  addu $19, $0, $12         ; 68: move $s3, $t4 # set new max
[00400064] 2129ffff  addi $9, $9, -1           ; 71: sub $t1, $t1, 1 # decrement counter
[00400068] 25080004  addiu $8, $8, 4           ; 72: addu $t0, $t0, 4 # increment addr by word
[0040006c] 1520fff7  bne $9, $0, -36 [loop-0x0040006c]
N [00400070] 3c011001  lui $1, 4097 [a1_msg]   ; 80: la $a0, a1_msg
[00400074] 34240069  ori $4, $1, 105 [a1_msg]
[00400078] 34020004  ori $2, $0, 4             ; 81: li $v0, 4
[0040007c] 0000000c  syscall                   ; 82: syscall # print "min = "
[00400080] 00122021  addu $4, $0, $18          ; 84: move $a0, $s2
[00400084] 34020001  ori $2, $0, 1             ; 85: li $v0, 1
[00400088] 0000000c  syscall                   ; 86: syscall # print min
[0040008c] 3c011001  lui $1, 4097 [new_ln]     ; 88: la $a0, new_ln # print a newline
[00400090] 34240067  ori $4, $1, 103 [new_ln]
[00400094] 34020004  ori $2, $0, 4             ; 89: li $v0, 4
[00400098] 0000000c  syscall                   ; 90: syscall
[0040009c] 3c011001  lui $1, 4097 [a2_msg]     ; 92: la $a0, a2_msg
```

```
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```

Running

14.0 Appendix C – MIPS Instruction Set

This appendix presents a summary of the MIPS instructions as implemented within the QtSpim simulator. The instructions a grouped by like-operations and presented alphabetically.

The following table summarizes the notational conventions used.

Operand Notation	Description
`Rdest`	Destination operand. Must be a register. Since it is a destination operand, the contents will be over written with the new result.
`FRdest`	Destination operand. Must be a floating-point register. Since it is a destination operand, the contents will be over written with the new result.
`Rsrc`	Source operand. Must be a register. Register value is unchanged.
`FRscr`	Source operand. Must be a floating-point register. Register value is unchanged.
`Src`	Source operand. Must be a register or an immediate value. Value is unchanged.
`Imm`	Immediate value
`Mem`	Memory location. May be a variable name or an indirect reference.

Refer to the chapter on Addressing Modes for more information regarding indirection.

14.1 Arithmetic Instructions

Below are a summary of the basic integer arithmetic instructions.

`abs Rdest, Rsrc`	Absolute Value Sets Rdest = absolute value of integer in Rsrc
`add Rdest, Rsrc, Src`	Addition (with overflow) Sets Rdest = Rscr + Src (or imm)
`addu Rdest, Rsrc, Src`	Addition (without overflow) Sets Rdest = Rscr + Src (or imm)

`div Rsrc1, Rsrc`	Divide (with overflow) Set $lo = Rscr / Src (or imm) Remainder is placed in $hi
`divu Rsrc1, Rsrc`	Divide (without overflow) Set $lo = Rscr / Src (or imm) Remainder is placed in $hi
`div Rdest, Rsrc, Src`	Divide (with overflow) Sets: Rdest = Rscr / Src (or imm)
`divu Rdest, Rsrc, Src`	Divide (without overflow) Sets: Rdest = Rscr / Src (or imm)
`mul Rdest, Rsrc, Src`	Multiply (without overflow) Sets: Rdest = Rscr (Src (or imm)
`mulo Rdest, Rsrc, Src`	Multiply (with overflow) Sets: Rdest = Rscr * Src (or imm)
`mulou Rdest, Rsrc, Src`	Unsigned Multiply (with overflow) Sets: lo = Rscr * Src (or imm)
`mult Rsrc, Rsrc`	Multiply Sets $hi:$lo = Rscr / Src (or imm)
`multu Rsrc, Rsrc`	Unsigned Multiply Sets $hi:$lo = Rscr / Src (or imm)
`neg Rdest, Rsrc`	Negate Value (with overflow) Rdest = negative of integer in register Rsrc
`negu Rdest, Rsrc`	Negate Value (without overflow) Rdest = negative of integer in register Rsrc
`rem Rdest, Rsrc, Src`	Remainder after division Rdest = remainder from Rscr / Src (or imm)
`remu Rdest, Rsrc, Src`	Unsigned Remainder Rdest = remainder from Rscr / Src (or imm)
`sub Rdest, Rsrc, Src`	Subtract (with overflow) Rdest = Rsrc – Src (or imm)

`subu Rdest, Rsrc, Src`	Subtract (without overflow) Rdest = Rsrc – Src (or imm)

14.2 Comparison Instructions

Below are a summary of the basic integer comparison instructions. Programmers generally use the conditional branch and jump instructions as detailed in the next section.

`seq Rdest, Rsrc1, Src2`	Set Equal - Sets register Rdest to 1 if register Rsrc1 equals Src2 and to be 0 otherwise
`sge Rdest, Rsrc1, Src2`	Set Greater Than Equal - Sets register Rdest to 1 if register Rsrc1 greater than or equal Src2 and to 0 otherwise
`sgeu Rdest, Rsrc1, Src2`	Set Greater Than Equal Unsigned - Sets register Rdest to 1 if register Rsrc1 is greater than or equal to Src2 and to 0 otherwise
`sgt Rdest, Rsrc1, Src2`	Set Greater Than - Sets register Rdest to 1 if register Rsrc1 greater than Src2 and to 0 otherwise
`sgtu Rdest, Rsrc1, Src2`	Set Greater Than Unsigned - Sets register Rdest to 1 if register Rsrc1 is greater than Src2 and to 0 otherwise
`sle Rdest, Rsrc1, Src2`	Set Less Than Equal - Sets register Rdest to 1 if register Rsrc1 is less than or equal to Src2 and to 0 otherwise
`sleu Rdest, Rsrc1, Src2`	Set Less Than Equal Unsigned - Sets register Rdest to 1 if register Rsrc1 is less than or equal to Src2 and to 0 otherwise
`slt Rdest, Rsrc1, Src2`	Set Less Than - Sets register Rdest to 1 if register Rsrc1 is less than to Src2 and to 0 otherwise
`slti Rdest, Rsrc1, Imm`	Set Less Than Immediate - Sets register Rdest to 1 if register Rsrc1 is less than or equal to Imm and to 0 otherwise

`sltu  Rdest, Rsrc1, Src2`	Set Less Than Unsigned - Sets register Rdest to 1 if register Rsrc1 is less than to Src2 and to 0 otherwise
`sltiu  Rdest, Rsrc1, Imm`	Set Less Than Unsigned Immediate - Sets register Rdest to 1 if register Rsrc1 is less than Src2 (or Imm) and to 0 otherwise
`sne  Rdest, Rsrc1, Src2`	Set Not Equal - Sets register Rdest to 1 if register Rsrc1 is not equal to Src2 and to 0 otherwise

14.3 Branch and Jump Instructions

Below are a summary of the basic conditional branch and jump instructions.

`b  label`	Branch instruction - Unconditionally branch to the instruction at the label
`bczt  label`	Branch Coprocessor *z* True - Conditionally branch to the instruction at the label if coprocessor *z*'s condition flag is true (false)
`bczf  label`	Branch Coprocessor *z* False - Conditionally branch to the instruction at the label if coprocessor *z*'s condition flag is true (false)
`beq  Rsrc1, Src2, label`	Branch on Equal - Conditionally branch to the instruction at the label if the contents of register Rsrc1 equals Src2
`beqz  Rsrc, label`	Branch on Equal Zero - Conditionally branch to the instruction at the label if the contents of Rsrc equals 0
`bge  Rsrc1, Src2, label`	Branch on Greater Than Equal - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are greater than or equal to Src2
`bgeu  Rsrc1, Src2, label`	Branch on GTE Unsigned - Conditionally branch to the instruction at the

	label if the contents of register Rsrc1 are greater than or equal to Src2
bgez Rsrc, label	Branch on Greater Than Equal Zero - Conditionally branch to the instruction at the label if the contents of Rsrc are greater than or equal to 0
bgezal Rsrc, label	Branch on Greater Than Equal Zero - 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 $ra
bgt Rsrc1, Src2, label	Branch on Greater Than - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are greater than Src2
bgtu Rsrc1, Src2, label	Branch on Greater Than Unsigned - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are greater than Src2
bgtz Rsrc, label	Branch on Greater Than Zero - Conditionally branch to the instruction at the label if the contents of Rsrc are greater than 0
ble Rsrc1, Src2, label	Branch on Less Than Equal - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are less than or equal to Src2
bleu Rsrc1, Src2, label	Branch on LTE Unsigned - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are less than or equal to Src2
blez Rsrc, label	Branch on Less Than Equal Zero - Conditionally branch to the instruction at the label if the contents of Rsrc are less than or equal to 0
bgezal Rsrc, label	Branch on Greater Than Equal Zero And Link - Conditionally branch to the instruction at the label if the contents of Rsrc are greater or

	equal to 0 or less than 0, respectively. Save the address of the next instruction in register $ra
`bltzal  Rsrc, label`	Branch on Less Than And Link - Conditionally branch to the instruction at the label if the contents of Rsrc are less than 0 or less than 0, respectively. Save the address of the next instruction in register $ra
`blt  Rsrc1, Src2, label`	Branch on Less Than - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are less than Src2
`bltu  Rsrc1, Src2, label`	Branch on Less Than Unsigned - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are less than Src2
`bltz  Rsrc, label`	Branch on Less Than Zero - Conditionally branch to the instruction at the label if the contents of Rsrc are less than 0
`bne  Rsrc1, Src2, label`	Branch on Not Equal - Conditionally branch to the instruction at the label if the contents of register Rsrc1 are not equal to Src2
`bnez  Rsrc, label`	Branch on Not Equal Zero - Conditionally branch to the instruction at the label if the contents of Rsrc are not equal to 0
`j  label`	Jump - Unconditionally jump to the instruction at the label
`jal  label`	Jump and Link - Unconditionally jump to the instruction at the label or whose address is in register Rsrc. Save the address of the next instruction in register $ra
`jalr  Rsrc`	Jump and Link Register - Unconditionally jump to the instruction at the label or whose address is in register Rsrc.

	Save the address of the next instruction in register $ra
`jr  Rsrc`	Jump Register - Unconditionally jump to the instruction whose address is in register Rsrc

14.4 Load Instructions

Below are a summary of the basic load instructions.

`la  Rdest, address`	Load Address - Load computed *address*, not the contents of the location, into register Rdest
`lb  Rdest, address`	Load Byte - Load the byte at *address* into register Rdest. The byte is sign-extended by the lb, but not the lbu, instruction
`lbu  Rdest, address`	Load Unsigned Byte - Load the byte at *address* into register Rdest. The byte is sign-extended by the lb, but not the lbu, instruction
`ld  Rdest, address`	Load Double-Word - Load the 64-bit quantity at *address* into registers Rdest and Rdest + 1
`lh  Rdest, address`	Load Halfword - Load the 16-bit quantity (halfword) at *address* into register Rdest. The halfword is sign-extended
`lhu  Rdest, address`	Load Unsigned Halfword - Load the 16-bit quantity (halfword) at *address* into register Rdest. The halfword is not sign-extended
`lw  Rdest, address`	Load Word - Load the 32-bit quantity (word) at *address* into register Rdest
`lwcz  Rdest, address`	Load Word Coprocessor *z* - Load the word at address into register Rdest

	of coprocessor z (0-3)
`lwl  Rdest, address`	Load Word Left - Load the left bytes from the word at the possibly-unaligned *address* into register Rdest
`lwr  Rdest, address`	Load Word Right - Load the right bytes from the word at the possibly-unaligned *address* into register Rdest
`ulh  Rdest, address`	Unaligned Load Halfword - Load the 16-bit quantity (halfword) at the possibly-unaligned *address* into register Rdest. The halfword is sign-extended.
`ulhu  Rdest, address`	Unaligned Load Halfword Unsigned - Load the 16-bit quantity (halfword) at the possibly-unaligned *address* into register Rdest. The halfword is not sign-extended
`ulw  Rdest, address`	Unaligned Load Word - Load the 32-bit quantity (word) at the possibly-unaligned *address* into register Rdest
`li  Rdest, imm`	Load Immediate - Move the immediate imm into register Rdest
`lui  Rdest, imm`	Load Upper Immediate - 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

14.5 Logical Instructions

Below are a summary of the basic logical instructions.

`and  Rdest, Rsrc1, Src2`	AND
`andi  Rdest, Rsrc1, Imm`	AND Immediate - Put the logical AND of the integers from register Rsrc1 and Src2 (or Imm) into register Rdest
`nor  Rdest, Rsrc1, Src2`	NOR - Put the logical NOR of the integers from

	register Rsrc1 and Src2 into register Rdest
not Rdest, Rsrc	NOT - Put the bitwise logical negation of the integer from register Rsrc into register Rdest
or Rdest, Rsrc1, Src2	OR - Put the logical OR of the integers from register Rsrc1 and Src2 into register Rdest
ori Rdest, Rsrc1, Imm	OR Immediate - Put the logical OR of the integers from register Rsrc1 and Imm into register Rdest
rol Rdest, Rsrc1, Src2	Rotate Left - Rotate the contents of register Rsrc1 left by the distance indicated by Src2 and put the result in register Rdest
ror Rdest, Rsrc1, Src2	Rotate Right - Rotate the contents of register Rsrc1 left (right) by the distance indicated by Src2 and put the result in register Rdest
sll Rdest, Rsrc1, Src2	Shift Left Logical - Shift the contents of register Rsrc1 left by the distance indicated by Src2 and put the result in register Rdest
sllv Rdest, Rsrc1, Rsrc2	Shift Left Logical Variable - Shift the contents of register Rsrc1 left by the distance indicated by Rsrc2 and put the result in register Rdest
sra Rdest, Rsrc1, Src2	Shift Right Arithmetic - Shift the contents of register Rsrc1 right by the distance indicated by Src2 and put the result in register Rdest
srav Rdest, Rsrc1, Rsrc2	Shift Right Arithmetic Variable - Shift the contents of register Rsrc1 right by the distance indicated by Rsrc2 and put the result in register Rdest
srl Rdest, Rsrc1, Src2	Shift Right Logical

	- Shift the contents of register Rsrc1 right by the distance indicated by Src2 and put the result in register Rdest
`srlv  Rdest, Rsrc1, Rsrc2`	Shift Right Logical Variable - Shift the contents of register Rsrc1 right by the distance indicated by Rsrc2 and put the result in register Rdest
`xor  Rdest, Rsrc1, Src2`	XOR - Put the logical XOR of the integers from register Rsrc1 and Src2 into register Rdest
`xori  Rdest, Rsrc1, Imm`	XOR Immediate - Put the logical XOR of the integers from register Rsrc1 and Imm into register Rdest

14.6 Store Instructions

Below are a summary of the basic store instructions.

`sb  Rsrc, address`	Store Byte - Store the low byte from register Rsrc at *address*
`sd  Rsrc, address`	Store Double-Word - Store the 64-bit quantity in registers Rsrc and Rsrc + 1 at *address*
`sh  Rsrc, address`	Store Halfword - Store the low halfword from register Rsrc at *address*
`sw  Rsrc, address`	Store Word - Store the word from register Rsrc at *address*
`swcz  Rsrc, address`	Store Word Coprocessor *z* - Store the word from register Rsrc of coprocessor z at address
`swl  Rsrc, address`	Store Word Left - Store the left bytes from register Rsrc at the possibly-unaligned *address*
`swr  Rsrc, address`	Store Word Right

	- Store the right bytes from register Rsrc at the possibly-unaligned *address*
`ush  Rsrc, address`	Unaligned Store Halfword - Store the low halfword from register Rsrc at the possibly-unaligned *address*
`usw  Rsrc, address`	Unaligned Store Word - Store the word from register Rsrc at the possibly-unaligned *address*

14.7 Data Movement Instructions

Below are a summary of the basic data movement instructions. The data movement implies data movement between registers.

`move Rdest, Rsrc`	Move the contents of Rsrc to Rdest. - The multiply and divide unit produces its result in two additional registers, hi and lo. These instructions move values to and from these registers. The multiply, divide, and remainder instructions described above are pseudoinstructions that make it appear as if this unit operates on the general registers and detect error conditions such as divide by zero or overflow.
`mfhi Rdest`	Move from hi - Move the contents of the hi register to register Rdest
`mflo Rdest`	Move from lo - Move the contents of the lo register to register Rdest
`mthi Rdest`	Move to hi - Move the contents register Rdest to the hi register. - *Note*, Coprocessors have their own register sets. This instructions move values between these registers and the CPU's registers.
`mtlo Rdest`	Move to lo - Move the contents register Rdest to the lo register.

	- *Note*, Coprocessors have their own register sets. This instructions move values between these registers and the CPU's registers.
`mfcz Rdest, CPsrc`	Move From Coprocessor *z* - Move the contents of coprocessor z's register CPsrc to CPU register Rdest
`mfc1.d Rdest, FRsrc1`	Move Double From Coprocessor 1 - Move the contents of floating point registers FRsrc1 and FRsrc1 + 1 to CPU registers Rdest and Rdest + 1
`mtcz Rsrc, CPdest`	Move To Coprocessor *z* - Move the contents of CPU register Rsrc to coprocessor z's register CPdest

14.8 Floating Point Instructions

The MIPS has a floating point coprocessor (numbered 1) that operates on single precision (32-bit) and double precision (64-bit) floating point numbers. This coprocessor has its own registers, which are numbered *f0-f31*. Because these registers are only 32-bits wide, two of them are required to hold doubles. To simplify matters, floating point operations only use even-numbered registers - including instructions that operate on single floats. Values are moved in or out of these registers a word (32-bits) at a time by lwc1, swc1, mtc1, and mfc1 instructions described above or by the l.s, l.d, s.s, and s.d pseudoinstructions described below. The flag set by floating point comparison operations is read by the CPU with its bc1t and bc1f instructions. In all instructions below, FRdest, FRsrc1, FRsrc2, and FRsrc are floating point registers (e.g., *$f2*).

`abs.d  FRdest, FRsrc`	Floating Point Absolute Value Double - Compute the absolute value of the floating float double in register FRsrc and put it in register FRdest
`abs.s  FRdest, FRsrc`	Floating Point Absolute Value Single - Compute the absolute value of the floating float single in register FRsrc and put it in register FRdest
`add.d  FRdest, FRsrc1, FRsrc2`	Floating Point Addition Double - Compute the sum of the floating float doubles in registers FRsrc1 and FRsrc2 and put it in register FRdest
`add.s  FRdest, FRsrc1, FRsrc2`	Floating Point Addition Single

	- Compute the sum of the floating float singles in registers FRsrc1 and FRsrc2 and put it in register FRdest
`c.eq.d  FRsrc1, FRsrc2`	Compare Equal Double - 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  FRsrc1, FRsrc2`	Compare Equal Single - 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  FRsrc1, FRsrc2`	Compare Less Than Equal Double - 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  FRsrc1, FRsrc2`	Compare Less Than Equal Single - Compare the floating point simgle 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  FRsrc1, FRsrc2`	Compare Less Than Double - 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  FRsrc1, FRsrc2`	Compare Less Than Single - 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  FRdest, FRsrc`	Convert Single to Double - Convert the single precision floating point number in register FRsrc to a double precision number and put it in register FRdest

cvt.d.w FRdest, FRsrc	Convert Integer to Double - Convert the integer in register FRsrc to a double precision number and put it in register FRdest
cvt.s.d FRdest, FRsrc	Convert Double to Single - Convert the double precision floating point number in register FRsrc to a single precision number and put it in register FRdest
cvt.s.w FRdest, FRsrc	Convert Integer to Single - Convert the integer in register FRsrc to a single precision number and put it in register FRdest
cvt.w.d FRdest, FRsrc	Convert Double to Integer - Convert the double precision floating point number in register FRsrc to an integer and put it in register FRdest
cvt.w.s FRdest, FRsrc	Convert Single to Integer - Convert the single precision floating point number in register FRsrc to an integer and put it in register FRdest
div.d FRdest, FRsrc1, FRsrc2	Floating Point Divide Double - Compute the quotient of the floating float doubles in registers FRsrc1 and FRsrc2 and put it in register FRdest.
div.s FRdest, FRsrc1, FRsrc2	Floating Point Divide Single - Compute the quotient of the floating float singles in registers FRsrc1 and FRsrc2 and put it in register FRdest.
l.d FRdest, address	Load Floating Point Double - Load the floating float double at address into register FRdest
l.s FRdest, address	Load Floating Point Single - Load the floating float single at address into register FRdest
mov.d FRdest, FRsrc	Move Floating Point Double - Move the floating float double from register

	FRsrc to register FRdest
`mov.s  FRdest, FRsrc`	Move Floating Point Single - Move the floating float single from register FRsrc to register FRdest
`mul.d  FRdest, FRsrc1, FRsrc2`	Floating Point Multiply Double - Compute the product of the floating float doubles in registers FRsrc1 and FRsrc2 and put it in register FRdest
`mul.s  FRdest, FRsrc1, FRsrc2`	Floating Point Multiply Single - Compute the product of the floating float singles in registers FRsrc1 and FRsrc2 and put it in register FRdest
`neg.d  FRdest, FRsrc`	Negate Double - Store the floating float double in register FRdest at address
`neg.s  FRdest, FRsrc`	Negate Single Store the floating float single in register FRdest at address
`s.d  FRdest, address`	Store Floating Point Double - Store the floating float double in register FRdest at address
`s.s  FRdest, address`	Store Floating Point Single - Store the floating float single in register FRdest at address
`sub.d  FRdest, FRsrc1, FRsrc2`	Floating Point Subtract Double - Compute the difference of the floating float doubles in registers FRsrc1 and FRsrc2 and put it in register FRdest
`sub.s  FRdest, FRsrc1, FRsrc2`	Floating Point Subtract Single - Compute the difference of the floating float singles in registers FRsrc1 and FRsrc2 and put it in register FRdest

14.9 Exception and Trap Handling Instructions

Below are a summary of the exception and trap instructions.

`rfe`	Return From Exception - Restore the Status register
`syscall`	System Call - Transfer control to system routine. Register $*v0* contains the number of the system call
`break n`	Break - Cause exception *n*. - *Note*, Exception 1 is reserved for the debugger
`nop`	No operation - Do nothing

15.0 Appendix D – ASCII Table

This appendix provides a copy of the ASCII Table for reference.

Char	Dec	Hex
NUL	0	0x00
SOH	1	0x01
STX	2	0x02
ETX	3	0x03
EOT	4	0x04
ENQ	5	0x05
ACK	6	0x06
BEL	7	0x07
BS	8	0x08
TAB	9	0x09
LF	10	0x10
VT	11	0x0A
FF	12	0x0B
CR	13	0x0C
SO	14	0x0D
SI	15	0x0E
DLE	16	0x0F
DC1	17	0x11
DC2	18	0x12
DC3	19	0x13
DC4	20	0x14
NAK	21	0x15
SYN	22	0x16
ETB	23	0x17
CAN	24	0x18
EM	25	0x19
SUB	26	0x1A
ESC	27	0x1B
FS	28	0x1C
GS	29	0x1D
RS	30	0x1E
US	31	0x1F

Char	Dec	Hex
space	32	0x20
!	33	0x21
"	34	0x22
#	35	0x23
$	36	0x24
%	37	0x25
&	38	0x26
'	39	0x27
(	40	0x28
)	41	0x29
*	42	0x2A
+	43	0x2B
,	44	0x2C
-	45	0x2D
.	46	0x2E
/	47	0x2F
0	48	0x30
1	49	0x31
2	50	0x32
3	51	0x33
4	52	0x34
5	53	0x35
6	54	0x36
7	55	0x37
8	56	0x38
9	57	0x39
:	58	0x3A
;	59	0x3B
<	60	0x3C
=	61	0x3D
>	62	0x3E
?	63	0x3F

Char	Dec	Hex
@	64	0x40
A	65	0x41
B	66	0x42
C	67	0x43
D	68	0x44
E	69	0x45
F	70	0x46
G	71	0x47
H	72	0x48
I	73	0x49
J	74	0x4A
K	75	0x4B
L	76	0x4C
M	77	0x4D
N	78	0x4E
O	79	0x4F
P	80	0x50
Q	81	0x51
R	82	0x52
S	83	0x53
T	84	0x54
U	85	0x55
V	86	0x56
W	87	0x57
X	88	0x58
Y	89	0x59
Z	90	0x5A
[	91	0x5B
\	92	0x5C
]	93	0x5D
^	94	0x5E
_	95	0x5F

Char	Dec	Hex
`	96	0x60
a	97	0x61
b	98	0x62
c	99	0x63
d	100	0x64
e	101	0x65
f	102	0x66
g	103	0x67
h	104	0x68
i	105	0x69
j	106	0x6A
k	107	0x6B
l	108	0x6C
m	109	0x6D
n	110	0x6E
o	111	0x6F
p	112	0x70
q	113	0x71
r	114	0x72
s	115	0x73
t	116	0x74
u	117	0x75
v	118	0x76
w	119	0x77
x	120	0x78
y	121	0x79
z	122	0x7A
{	123	0x7B
|	124	0x7C
}	125	0x7D
~	126	0x7E
DEL	127	0x7F

For additional information and a more complete listing of the ASCII codes (including the extended ASCII characters), refer to http://www.asciitable.com/