RISC-V Assembly Programmming

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Info

This book is available online in both HTML and PDF form.

You can support the book and purchase the chapter exercise solutions here.

The repo for the book, where you can get the code referenced and report any errors (submit an issue or even a pull request) is here.

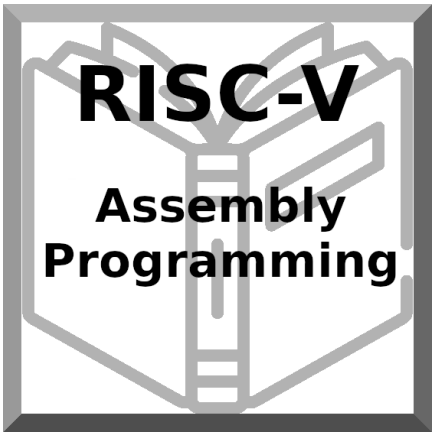
If you're interested in contacting me regarding MIPS tutoring or any other business request related to the book, you can reach me at mips@robertwinkler.com.

Dedication

This book is dedicated to all its supporters and all the students I've helped with RISC-V over the years who inspired me to create it.

Thank you.

An extra thank you goes to the corporate level sponsors below:



Chapter 0: Hello World

In which we lay the groundwork for the rest of the book…

Prereqs

While someone with no programming experience could probably learn RISC-V from this book, it is definitely preferable to have at least some experience in a higher level imperative programming language. I say imperative, because programming in assembly is the antithesis of functional programming; everything is about state, with each line changing the state of the CPU and sometimes memory. Given that, experience in functional languages like Lisp, Scheme etc. are less helpful than experience in C/C++, Java, Python, Javascript etc.

Of all of the latter, C is the best, with C++ being a close second because at least all of C exists in C++. There are many reasons C is the best prior experience when learning assembly (any assembly, not just RISC-V), including the following:

- pointers, concepts and symmetry of "address of" and "dereference" operators
- pointer/array syntax equivalence
- stack allocation as the default
- manual memory management, no garbage collector
- global data
- rough equivalence in structure of a C program and an assembly program (vs. say Java)
- pass by value

There is some overlap between those and there are probably more, but you can see that most other languages that are commonly taught as first languages are missing most, if not all of those things.

Even C++, which technically has all of them being a superset of C, is usually taught in a way that mostly ignores all of those things. They teach C++ as if it's Java, never teaching the fundamentals. In any case this is getting into my problems with CS pedagogy of the last 20 years based on my experience as a CS major myself ('12) and as a programming tutor helping college students across the country since 2016, and I should save it for a proper essay/rant sometime.

Long story short, I use C code and C syntax to help explain and teach RISC-V. I'll try to provide enough explanation regardless of past experience as best I can.

System Setup

As I tell all of my tutoring students, if you're majoring in CS or anything related I highly recommend you use Linux. It's easier in every way to do dev work on Linux vs Windows or Mac. Many assignments require it, which often necessitates using a virtual machine (which is painful, especially on laptops) and/or ssh-ing into a school Linux server, which is also less than ideal. In general, you'll have to learn how to use the unix terminal eventually and will probably use it to some extent in your career so it also makes sense to get used to it asap.

That being said, Windows does now have WSL so you can get the full Ubuntu or Debian or Fedora etc. terminal based system on Windows without having to setup a real virtual machine (or dealing with the slowdown that would cause). I've even heard that they'll get support for Linux GUI programs soon.

MacOS on the other hand, is technically a Unix based system and you can use their terminal and install virtually any program from there using Macports or Homebrew or similar.

There are a few RISC-V simulators that I know of and h

- RARS is a RISC-V port of MARS, a Java GUI based simulator with dozens of extra environment calls, syntactic sugar and features like graphics, memory mapped I/O, etc.
- Venus, a web based simulator used by Berkeley (also has a downloadable jar)
- Ripes, a graphical processor simulator and assembly editor for bare bones assembly programming

Of those three, RARS is by far the most full featured and user friendly for learning since it forked from the venerable MARS MIPS simulator. It is also the most commonly used by students outside of Berkeley. Given that, this book will focus primarily on RARS, though it almost all of it should apply equally well to Venus.

You can download/access both at the following links:

- RARS
- Venus

Handy Resources

There are a few references that you should bookmark (or download) before you get started. The first is the RISC-V Greensheet. It's possible you already have a physical copy of this as it's actually the tearout from the Patterson and Hennessey textbook *Computer Architecture and Design* that is commonly used in college courses.

There is also a large format of the greensheet.

The second thing is the list of environment calls (aka ecalls, system calls, syscalls) from the RARS wiki.

I recommend you download/bookmark both and keep them open while working because you'll be referencing them often to remind yourself which instructions and ecalls you have available and how they work.

Hello World

Let's start with the classic hello world program, first in C, then in RISC-V, and go over all the pieces in overview. You can copy paste these into your editor of choice (mine being neovim), or use the files in the associated repo to follow along.

```c
#include <stdio.h>

int main()
{
    printf("Hello World!\n");
    return 0;
}
```

It is pretty self explanatory. You have to include stdio.h so you can use the function printf (though in the real world I'd use puts here), the function main is the start of any C/C++ program, which is a function that returns an int. We call printf to display the string "Hello World!\n" to the user and then return 0 to exit. Returning 0 indicates success and there were no errors.

You can compile and run it in a linux/unix terminal as shown below. You can substitute clang or another compiler for gcc if you want.

```
$ gcc -o hello hello.c
$ ./hello
Hello World!
```

Now, the same program in RISC-V:

```
1  .data
2  hello:   .asciz "Hello World!\n"
3
4  .text
5  main:
6      li   a7, 4      # load immediate, a7 = 4 (4 is print string system call)
7      la   a0, hello  # load address of string to print into a0
8      ecall
9
10     li   a7, 10     # exit ecall
11     ecall
```

The `.data` section is where you declare global variables, which includes string literals as in this case. We'll cover them in more detail later.

The `.text` section is where any code goes. Here we declare a single label `main:`, indicating the start of our main function.

We then put the number 4 in the `a7` register to select the print string system call. The print string system call takes one argument, the address of the string to print, in the `a0` register. We do that on the next line. On line 8, we call the system call using the ecall instruction.

Finally we call the exit system call which takes no arguments and exits the program.

Again, we'll cover system calls in a later chapter. This is just an intro/overview so don't worry if

some things aren't completely clear. This chapter is about getting you up and running, not really about teaching anything specific yet.

Building and Running

Now that we have our hello world MIPS program, how do we run it? Well the easiest and quickest[1] way is of course to do it on the command line, which can be done like this:

```
$ java -jar ~/rars_latest.jar hello.s
RARS 1.5  Copyright 2003-2019 Pete Sanderson and Kenneth Vollmar

Hello World!

Program terminated by calling exit
```

The name of your RARS jar file may be different[2], so be sure to use the correct name and path. For myself, I keep the jar file in my home directory so I can use tilde to access it no matter where I am. You can also copy it into your working directory (ie wherever you have your source code) so you don't have to specify a path at all. There are lots of useful command line options that you can use[3], some of which we'll touch on later.

Running the jar directly on the command line works even in the Windows/DOS command line though I've never done it and it's probably not worth it.

Alternatively, you can start up RARS like a normal GUI application and then load your source file. RARS requires you to hit "assemble" and then "run".

Conclusion

Well, there you have it, you have written and run your first RISC-V program. Another few chapters and you will have no trouble with almost anything you would want to do in RISC-V, whether for a class, or on your own for fun.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Modify the hello world program to print something different, perhaps your name.
2. Run it with both RARS and Venus.

[1] Starting up the RARS GUI (an old style Java app) is often annoyingly slow

[2] Some schools/professors have their own versions with extra features and other improvements over the official releases

[3] https://github.com/TheThirdOne/rars/wiki/Using-the-command-line

Chapter 1: Data

In RISC-V, you can declare global variables in the `.data` section.

At a minimum, this is where you would declare/define any literal strings your program will be printing, since virtually every program has at least 1 or 2 of those.

When declaring something in the `.data` section, the format is

```
variable_name: .directive value(s)
```

where whitespace between the 3 is arbitrary. The possible directives are listed in the following table:

Table 1. RISC-V data types

Directive	Size	C equivalent
.byte	1	char
.half	2	short
.word	4	int, all pointer types
.float	4	float
.double	8	double
.ascii	NA	char str[5] = "hello"; (no '\0')
.asciz	NA	char str[] = "hello"; (includes the '\0')
.string	NA	alias for .asciz
.space	NA	typeless, unitinialized space, can be used for any type/array

As you can see it's pretty straightforward, but there are a few more details about actually using them so let's move onto some examples.

Say you wanted to convert the following simple program to RISC-V:

```c
#include <stdio.h>

int main()
{
    char name[30];
    int age;
    printf("What's your name and age?\n");
    scanf("%s %d", name, &age);
    printf("Hello %s, nice to meet you!\n", name);
    return 0;
}
```

The first thing you have to remember is that when converting from a higher level language to

assembly (any assembly) is that what matters is whether it's functionally the same, not that everything is done in exactly the same way. In this instance, that means realizing that your literal strings and your local variables `name` and `age` become globals in RISC-V.

```
1  .data
2  age:          .word 0  # can be initialized to anything
3
4  ask_name:     .asciz "What's your name and age?\n"
5  hello_space:  .asciz "Hello "
6  nice_meet:    .asciz ", nice to meet you!\n"
7
8  name:         .space 30
9
10 .text
11
12 # main goes here
```

As you can see in the example, we extract all the string literals and the character array `name` and int `age` and declare them as MIPS globals. One thing to note is the second `printf`. Because it prints a variable, `name`, using the conversion specifier, we break the literal into pieces around that. Since there is no built-in `printf` function in RISC-V, you have to handle printing variables yourself with the appropriate system calls.

Arrays

Obviously strings are special cases that can be handled with `.ascii` or `.asciz` (or the alias `.string`) for literals, but for other types or user inputed strings how do we do it?

The first way, which was demonstrated in the snippet above is to use `.space` to declare an array of the necessary byte size. Keep in mind that the size is specified in bytes not elements, so it only matches for character arrays. For arrays of ints/words, floats, doubles etc. you'd have to multiply by the sizeof(type).

"But, `.space` only lets you declare uninitialized arrays, how do I do initialized ones?"

Actually, it appears `.space` initializes everything to 0 similar to global/static data in C and C++, though I can't find that documented anywhere.

Aside from that, there are two ways depending on whether you want to initialize every element to the same value or not.

For different values, the syntax is an extension of declaring a single variable of that type. You specify all the values, comma separated. This actually gives you another way to declare a string or a character array, though I can't really think of a reason you'd want to. You could declare a `.byte` array and list all the characters individually.

However, if you want an array with all elements initialized to the same value there is a more convenient option that I learned very recently. After the type you put the value you want, a colon, and then the number of elements. So `a: .word 123 : 10` would declare a 10 integer array with all

elements set to 123. TODO check if venus supports this syntax.

Given what we just covered, this:

```
int a[20];
double b[20];
int c[10] = { 9,8,7,6,5,4,3,2,1,0 };
int d[5] = { 42, 42, 42, 42, 42 };
char e[3] = { 'a', 'b', 'c' };
```

becomes

```
.data
a:        .space 80
b:        .space 160
c:        .word 9,8,7,6,5,4,3,2,1,0
d:        .word 42 : 5
e:        .byte 'a', 'b', 'c'
```

For more examples of array declarations, see array_decls.s. You don't have to understand the rest of the code, just that it prints out each of the arrays.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Create a MIPS data section that declares variables equivalent to the following. This will not be a runnable program without a main.

    ```
        float a;
        float b = 2.71;
        int myarray[10] = { 9, 8, 7, 6, 5, 4, 3, 2, 1 };
        short array2[10];

        char mips_str[] = "MIPS assembly is awesome!";
    ```

2. How would you declare an array of 500 points? The point structure is tightly packed and defined like this:

    ```
    struct point {
        float x;
        float y;
        float z;
    };
    ```

Chapter 2: Environment Calls

We mentioned environment calls (aka ecalls, though they're also called system calls or syscalls in other languages like MIPS) in chapter 0 when we were going over our "Hello World" program, but what exactly are they?

Essentially, they are the built in functions of a operating system; in this case, the simple operating system of the RISC-V simulators. They provide access to all the fundamental features, like input and output to/from both the console and files, allocating memory, and exiting. That covers the basics but RARS supports many more, for things ranging from playing MIDI sounds, to getting a random number, to creating GUI dialogs.[1]

Table 2. Basic RARS supported ecalls

Name	a7	Arguments	Result
print integer	1	a0 = integer to print	
print float	2	fa0 = float to print	
print double	3	fa0 = double to print	
print string	4	a0 = address of string	
read integer	5		a0 = integer read
read float	6		fa0 = float read
read double	7		fa0 = double read
read string	8	a0 = address of input buffer a1 = buffer size	works like C's fgets
sbrk	9	a0 = size in bytes to allocate	a0 = address of allocated memory (sbrk is basically malloc but there is no free)
exit	10		program terminates
print character	11	a0 = character to print (ascii value)	
read character	12		a0 = character read
open file	1024	a0 = address of filename $a1 = flags	a0 = file descriptor (negative if error)
lseek	62	a0 = file descriptor, a1 = offset from base, a2 = beginning(0), current(1), or end of the file(2)	a0 = selected position from beginning of the file or -1 if error
read from file	63	a0 = file descriptor a1 = address of input buffer a2 = max characters to read	a0 = number of characters read, -1 if error
write to file	64	a0 = file descriptor a1 = address of output buffer a2 = number of characters to write	a0 = number of characters written

Name	a7	Arguments	Result
close file	57	a0 = file descriptor	
exit2	93	a0 = termination result	program terminates, returning number in a0 (only meaningful when run in the terminal, ignored in GUI)

As you can see, they really only cover the basics. You can read or write the different types, do file I/O using calls identical to POSIX functions (open, read, write, close; see man pages), allocate memory, and exit. Even so, they're sufficient to build anything you want.

So, what does that table mean? How do these actually work?

The process is:

1. Put the number for the ecall you want in `a7`
2. Fill in the appropriate arguments, if any
3. Execute the ecall with `ecall`

```
    li    a7, 1   # 1 is print integer
    li    a0, 42  # takes 1 arg in a0, the number to print
    ecall         # actually execute ecall
```

You can think of the above as `print_integer(42);`. Let's look at an actual program that uses a few more ecalls next.

Examples

```c
#include <stdio.h>

int main()
{
    int age;
    int height;
    char name[50];
    printf("What's your name? ");
    fgets(name, 50, stdin);

    printf("Hello %s", name);

    printf("How old are you? ");
    scanf("%d", &age);

    printf("Enter your height in inches: ");
    scanf("%d", &height);

```

```
    printf("Your age + height = %d\n", age + height);

    return 0;
}
```

I'm using `fgets()` instead of `scanf("%s", name)` because fgets works the same as the read string ecall (8).

```
.data

name:     .space 50

nameprompt:  .asciz "What's your name? "
hello_space: .asciz "Hello "
how_old:     .asciz "How old are you? "
ask_height:  .asciz "Enter your height in inches: "
ageplusheight: .asciz "Your age + height = "


.text
main:
    li    a7, 4      # print string
    la    a0, nameprompt  # load address of string to print into a7
    ecall

    li    a7, 8      # read string
    la    a0, name
    li    a1, 50
    ecall

    li    a7, 4
    la    a0, hello_space
    ecall

    la    a0, name  # note 4 is still in a7
    ecall

    # don't print a newline here because
    # one will be part of name unless they typed >48 characters

    li    a7, 4
    la    a0, how_old
    ecall

    li    a7, 5   # read integer
    ecall
    mv    t0, a0  # save age in t0

    li    a7, 4
    la    a0, ask_height
```

```
43      ecall
44
45      li    a7, 5   # read integer
46      ecall
47      add   t0, t0, a0 # t0 += height
48
49
50      li    a7, 4
51      la    a0, ageplusheight
52      ecall
53
54      li    a7, 1  # print int
55      mv    a0, t0  # t0 = age + height
56      ecall
57
58      # print newline
59      li    a7, 11   # print char
60      li    a0, 10   # ascii value of '\n'
61      ecall
62
63
64      li    a7, 10     # exit ecall
65      ecall
```

There a few things to note from the example.

We don't declare global variables for age or height. We could, but there's no reason to since we have to have them in registers to do the addition anyway. Instead, we copy/save age to `t0` so we can use `a0` for 2 more ecalls, then add height to `t0`.

This is generally how it works. Use registers for local variables unless required to do otherwise. We'll cover more about register use when we cover the RISC-V calling convention.

Another thing is when we print their name, we don't put 4 in `a7` again because it is still/already 4 from the lines above.

Lastly, many people will declare a string `"\n"` and use print string to print a newline, but it's easier to use the print char ecall as we do right before exiting.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Convert the following C code to MIPS

```c
#include <stdio.h>

int main()
{
```

```
    float price;
    double golden = 1.618;
    int ret;

    printf("Enter what the price of gas was last time you filled up: ");
    scanf("%f", &price);

    printf("%f is too expensive!\n", price);

    printf("The golden ratio is roughly %f\n", golden);


    printf("Enter an integer for the program to return: "
    scanf("%d", &ret);
    return ret;
}
```

2. Write a program that asks the user for their name, reads it in, and then prints "Hello [user's name]!"

[1] https://github.com/TheThirdOne/rars/wiki/Environment-Calls

Chapter 3: Branches and Logic

We can't go much farther in our RISC-V programming journey without covering branching. Almost every non-trivial program requires some logic, even if it's only a few `if` or `if-else` statements. In other words, almost every program requires branching, a way to do a instead of b, or to do a only if certain conditions are met.

You already know how to do this in higher level languages, the aforementioned `if` statement. In assembly it's more complicated. Your only tool is the ability to jump to a label on another line based on the result of various comparisons. The relevant instructions are listed in the following table:

Table 3. RISC-V branching related instructions (and some pseudoinstructions)

Name	Opcode	Format	Operation
Branch On Equal	beq	beq rs, rt, label	if (rs == rt) goto label
Branch On Not Equal	bne	bne rs, rt, label	if (rs != rt) goto label
Branch Less Than	blt	blt rs, rt, label	if (rs < rt) goto label
Branch Greater Than	bgt	bgt rs, rt, label	if (rs > rt) goto label
Branch Less Than Or Equal	ble	ble rs, rt, label	if (rs ⇐ rt) goto label
Branch Greater Than Or Equal	bge	bge rs, rt, label	if (rs >= rt) goto label
Set Less Than	slt	slt rd, rs, rt	rd = (rs < rt) ? 1 : 0
Set Less Than Immediate	slti	slt rd, rs, imm	rd = (rs < imm) ? 1 : 0
Set Less Than Immediate Unsigned	sltiu	slt rd, rs, imm	rd = (rs < imm) ? 1 : 0
Set Less Than Unsigned	sltu	sltu rd, rs, imm	rd = (rs < imm) ? 1 : 0

You can see the same information and more on the RISC-V greensheet and the RARS Supported Instructions list.[1][2]

There are additional pseudoinstructions in the form of beq/bne/blt/bgt/ble/bge + 'z' which are syntactic sugar to compare a register against 0, ie the 0 register.

So the following:

```
beq      t0, x0, label
bne      t1, x0, label
blt      t2, x0, label
```

would be equivalent to:

```
beqz     t0, label
bnez     t1, label
bltz     t2, label
```

Note `x0` is the same as `zero` and is the hard coded 0 register. I'll cover registers in more detail in the chapter on functions and the calling conventions.

One final thing is that labels have the same naming requirements as C variables and functions. They must start with a letter or underscore and the rest can be letters, underscores, or digits.

Practice

The rest of this chapter will be going over many examples, looking at snippets of code in C and translating them to RISC-V.

Basics

Let's start with the most basic if statement. The code in and after the if statement is arbitrary.

```
1     if (a > 0) {
2         a++;
3     }
4     a *= 2;
```

Now in RISC-V, let's assume that a is in `t0`. The tranlation would look like this:

```
1     ble    t0, x0, less_eq_0   # if (a <= 0) goto less_eq_0
2     addi   t0, t0, 1           # a++
3 less_eq_0:
4     slli   t0, t0, 1           # a *= 2  (shifting left by n is multiplying by 2^n)
```

There are a few things to note in this example. The first is that in assembly we test for the opposite of what was in the if statement. This will always be the case when jumping forward because (if we want to keep the same order of code) we can only jump *over* a block of code, whereas in C we fall into the block if the condition is true. In the process of mentally compiling a bit of C to assembly, it can be helpful to change to jump based logic first. For example the previous C would become:

```
1     if (a <= 0)
2         goto less_eq_0;
3     a++;
4 less_eq_0:
5     a *= 2;
```

This is obviously still valid C but matches the branching behavior of assembly exactly. You can see I put comments for the equivalent C code in my assembly; it helps with readability to comment every line or group of lines that way.

The second thing to notice is how we handled the multiplication. This has nothing to do with branching but is something we'll touch on multiple times throughout the book. Your job when acting as a human compiler is to match the *behavior*. You are under no obligation to match the

structure or operations of the higher level code exactly (unless your professor stupidly forces you to).

Given that, it is in your best interest to change and rearrange things in order to simplify the assembly as much as possible to make your life easier. Generally speaking, this also tends to result in more performant code, since using fewer instructions and fewer branches (the most common outcomes) saves execution time.

In this case, using the standard `mul` instruction would actually take 2 instructions:

```
1     li     t1, 2
2     mul    t0, t0, t1   # a *= 2
```

This is why, when multiplying or dividing by a constant power of 2 it's common practice to use `slli` or `srai`. This is true in all assembly languages because multiplication and division are relatively costly operations so using shifts when you can saves performance even if you didn't actually save instructions.

Ok, let's look at an `if-else` example. Again, the actual code is arbitrary and we're assuming a and b are in `t0` and `t1` respectively

```
1     if (a > 0) {
2         b = 100;
3     } else {
4         b -= 50;
5     }
```

You could do it something like these two ways

```
 1     bgt     t0, x0, greater_0   # if (a > 0) goto greater_0
 2     addi    t1, t1, -50        # b -= 50
 3     j       less_eq_0
 4 greater_0:
 5     li      t1, 100             # b = 100
 6 less_eq_0:
 7
 8     # or
 9
10     ble     t0, x0, less_eq0    # if (a <= 0) goto less_eq_0
11     li      t1, 100             # b = 100
12     j       greater_0
13 less_eq_0:
14     addi    t1, t1, -50        # b -= 50
15 greater_0:
```

You can see how the first swaps the order of the actual code which keeps the actual conditions the same as in C, while the second does what we discussed before and inverts the condition in order

keep the the blocks in the same order. In both cases, an extra unconditional branch and label are necessary so we don't fall through the else case. This is inefficient and wasteful, not to mention complicates the code unecessarily. Remember how our job is to match the behavior, not the exact structure? Imagine how we could rewrite it in C to simplify the logic:

```
    b -= 50;
    if (a > 0) {
        b = 100;
    }
```

which becomes

```
    addi    t1, t1, -50        # b -= 50;
    ble     t0, x0, less_eq_0   # if (a <= 0) goto less_eq_0
    li      t1, 100             # b = 100
less_eq_0:
```

That is a simple example of rearranging code to make your life easier. In this case, we are taking advantage of what the code is doing to make a default path or default case. Obviously, because of the nature of the code subtracting 50 has to be the default since setting b to 100 overwrites the original value which we'd need if we were supposed to subtract 50 instead. In cases where you can't avoid destructive changes (like where the condition and the code are using/modifying the same variable), you can use a temporary variable; i.e. copy the value into a spare register. You still save yourself an unecessary jump and label.

Compound Conditions

These first 2 examples have been based on simple conditions, but what if you have compound conditions? How does that work with branch operations that only test a single condition? As you might expect, you have to break things down to match the logic using the operations you have.

Let's look at **and** first. Variables a, b, and c are in t0, t1, and t2.

```
    if (a > 10 && a < b) {
        c += 20;
    }
    b &= 0xFF;
```

So what's our first step? Like previous examples, we need to test for the opposite when we switch to assembly, so we need the equivalent of

```
    if (!(a > 10 && a < b))
        goto no_add20;
    c += 20;
no_add20:
```

```
5     b &= 0xFF;
```

That didn't help us much because we still don't know how to handle that compound condition. In fact we've made it more complicated. If only there were a way to convert it to **or** instead of **and**. Why would we want that? Because, while both **and** and **or** in C allow for short circuit evaluation (where the result of the whole expression is known early and the rest of expression is not evaluated), with **or**, it short circuits on success while **and** short circuits on failure. What does that mean? It means that with **or**, the whole expression is true the second a single true term is found, while with **and** the whole expression is false the second a single false term is found.

Let's look at the following code to demonstrate:

```
1     if (a || b || c) {
2         something;
3     }
4
5     // What does this actually look like if we rewrote it to show what it's
6     // actually doing with short circuit evaluation?
7
8     if (a) goto do_something;
9     if (b) goto do_something;
10    if (c) goto do_something;
11    goto dont_do_something;
12
13 do_something:
14    something;
15
16 dont_do_something:
17
18    // You can see how the first success is all you need:
19    // Compare that with and below
20
21    if (a && b && c) {
22        something;
23    }
24
25    if (a) {
26        if (b) {
27            if (c) {
28                something;
29            }
30        }
31    }
32    // which in jump form is
33
34    if (a)
35        goto a_true;
36    goto failure;
37 a_true:
```

```
38      if (b)
39          goto b_true;
40      goto failure;
41
42  b_true:
43      if (c)
44          goto c_true:
45      goto failure;
46
47  c_true:
48      something;
49  failure:
50
51      // Man that's ugly, overcomplicated, and hard to read
52      // But what if we did this instead:
53
54      if (!a) goto dont_do_something;
55      if (!b) goto dont_do_something;
56      if (!c) goto dont_do_something;
57
58      something;
59
60  dont_do_something:
61
62      // Clearly you need all successes for and.  In other words
63      // to do and directly, you need state, knowledge of past
64      // successes.  But what about that second translation of and?
65      // It looks a lot like or?
```

You're exactly right. That final translation of **and** is exactly like **or**.

It takes advantage of De Morgan's laws.[3] For those of you who haven't taken a Digital Logic course (or have forgotten), De Morgan's laws are 2 equivalencies, a way to change an **or** to an **and**, and vice versa.

They are (in C notation):

```
!(A || B) == !A && !B
```

```
!(A && B) == !A || !B
```

Essentially you can think of it as splitting the not across the terms and changing the logical operation. The law works for arbitrary numbers of terms, not just 2:

```
(A && B && C)
is really
((A && B) && C)
so when you apply De Morgan's Law recursively you get:
!((A && B) && C) == !(A && B) || !C == !A || !B || !C
```

Let's apply the law to our current compound **and** example. Of course the negation of greater or less than comparisons means covering the rest of the number line so it becomes:

```
    if (a <= 10 || a >= b))
        goto no_add20;
    c += 20;
no_add20:
    b &= 0xFF;
```

which turns into:

```
    li      t6, 10
    ble     t0, t6, no_add20      # if (a <= 10) goto no_add20
    bge     t0, t1, no_add20      # if (a >= b)  goto no_add20

    addi    t2, t2, 20            # c += 20
no_add20:
    andi    t1, t1, 0xFF          # b &= 0xFF
```

See how that works? **Or**'s do not need to remember state. Just the fact that you reached a line in a multi-term **or** expression means the previous checks were false, otherwise you'd have jumped. If you tried to emulate the same thing with an **and**, as you saw in the larger snippet above, you'd need a bunch of extra labels and jumps for each term.

What about mixed compound statements?

```
    if (a > 10 || c > 100 && b >= c)
        printf("true\n");

    b |= 0xAA;
```

Well, the first thing to remember is that `&&` has a higher priority than `||`, which is why most compilers these days will give a warning for the above code about putting parenthesis around the `&&` expression to show you meant it (even though it's completely legal as is).

So with that in mind, let's change it to jump format to better see what we need to do. While we're at it, let's apply De Morgan's law to the `&&`.

```
    if (a > 10)
        goto do_true;
    if (c <= 100)
        goto done_if;
    if (b < c)
        goto done_if;
do_true:
    printf("true\n");

```

```
done_if:
    b |= 0xAA;
```

This one is trickier because we don't flip the initial expression like normal. Instead of jumping *over* the body which would require testing for the opposite, we jump to the true case. We do this because we don't want to have multiple print statements and it lets us fall through the following conditions. We would need multiple print statements because failure for the first expression *is not* failure for the entire expression. Here's how it would look otherwise:

```
    if (a <= 10)
        goto check_and;
    printf("true\n");
    goto done_if;
check_and:
    if (c <= 100)
        goto done_if;
    if (b < c)
        goto done_if;

    printf("true\n");

done_if:
    b |= 0xAA;
```

That is harder to read and has both an extra print and an extra jump.

So let's convert the better version to RISC-V (a,b,c = `t0`, `t1`, `t2`):

```
.data
true_str: .asciz "true\n"

.text
    li     t5, 10   # get the necessary literals in some unused regs
    li     t6, 100

    bgt    t0, t5, do_true   # if (a > 10) goto do_true
    ble    t2, t6, done_if   # if (c <= 100) goto done_if
    blt    t1, t2, done_if   # if (b < c) goto done_if

do_true:
    li     a7, 4           # print string
    la     a0, true_str    # address of str in a0
    ecall

done_if:
    ori    t1, t1, 0xAA   # b |= 0xAA
```

If-Else Chain

Ok, let's look at a larger example. Say you're trying to determine a student's letter grade based on their score. We're going to need a chain of `if-else-if`'s to handle all cases. Assume `score` is declared and set somewhere before.

```
    char letter_grade;
    if (score >= 90) {
        letter_grade = 'A';
    } else if (score >= 80) {
        letter_grade = 'B';
    } else if (score >= 70) {
        letter_grade = 'C';
    } else if (score >= 60) {
        letter_grade = 'D';
    } else {
        letter_grade = 'F';
    }

    printf("You got a %c\n", letter_grade);
}
```

With chains like these, if you follow everything we've learned, it comes out looking like this (assuming score is `t0` and letter_grade is `t1`):

```
.data
grade_str: .asciz "You got a "

.text
    li      t1, 70   # letter_grade default to 'F' ascii value

    li      t2, 90
    blt     t0, t2, not_a    # if (score < 90) goto not_a
    li      t1, 65           # leter_grade = 'A'
    j       grade_done

not_a:
    li      t2, 80
    blt     t0, t2, not_b    # if (score < 80) goto not_b
    li      t1, 66           # leter_grade = 'B'
    j       grade_done

not_b:
    li      t2, 70
    blt     t0, t2, not_c    # if (score < 70) goto not_c
    li      t1, 67           # leter_grade = 'C'
    j       grade_done

not_c:
```

```
    li      t2, 60
    blt     t0, t2, grade_done   # if (score < 60) goto grade_done
    li      t1, 68               # leter_grade = 'D'

grade_done:
    li      a7, 4       # print str
    la      a0, grade_str
    ecall

    li      a7, 11       # print character
    mv      a0, t1       # char to print
    ecall

    mv      a0, 10    # print '\n'
    ecall
```

You can see how we set a default value and then test for the opposite of each condition to jump to the next test, until we get one that fails (aka was true in the original C condition) and set the appropriate grade.

You can arrange chains like this in either direction, it doesn't have to match the order of the C code. As long as it works the same, do whatever makes the code simpler and more sensible to you.

Conclusion

Branching and logic and learning to translate from higher level code to assembly is something that takes a lot of practice, but eventually it'll become second nature. We'll get more practice in the chapter on looping which naturally also involves branching.

One final note, there's rarely any reason to use the `slt` family of opcodes *unless* your professor requires it for some strange reason. Even if your professor says you can't use pseudoinstructions, that would still leave you with `beq`, `bne`, `blt`, `bge`, which covers every possibility even if you sometimes have to switch the order of the operands.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Convert the following C code to MIPS.

```c
#include <stdio.h>

int main()
{
    int num;
    printf("Enter an integer: ");
    scanf("%d", &num);

```

```
    if (num > 50) {
        puts("The number is greater than 50");
    } else if (num < 50) {
        puts("The number is less than 50");
    } else {
        puts("You entered 50!");
    }

    return 0;
}
```

2. Prompt for the user's name, then tell them whether their name starts with a letter from the first or second half of the alphabet. Be sure to handle both upper and lower case correctly, but assume they entered a valid letter.

[1] https://inst.eecs.berkeley.edu/~cs61c/fa17/img/riscvcard.pdf

[2] https://github.com/TheThirdOne/rars/wiki/Supported-Instructions

[3] https://en.wikipedia.org/wiki/De_Morgan%27s_laws

Chapter 4: Loops

> "Insanity is doing the same thing over and over again and expecting different results."
>
> — Unknown, Often misattributed to Albert Einstein

Before we get into the RISC-V, I want to cover something that may be obvious to some but may have never occurred to others. Any loop structure can be converted to any other (possibly with the addition of an `if` statement). So a `for` can be written as a `while` and vice versa. Even a `do-while` can be written as a `for` or `while` loop. Let's look at some equivalencies.

```
    for (int i=0; i<a; i++) {
        do_something;
    }

    int i = 0;
    while (i < a) {
        do_something;
        i++;
    }

    int i = 0;
    if (i < a) {
        do {
            do_something;
            i++;
        } while (i < a);
    }
    // you could also have an if (i >= a) goto loop_done; to jump over do-while
```

In general, when writing assembly, it can help to think more in terms of `while` or `do-while` rather than `for` because the former more closely resemble what the assembly looks like in terms of what goes where. Like in the last chapter, where we would think of the `if-else` statements in "jump-form" or "branch-form", we can do the same here, converting for to while in our head as an intermediary step before going to assembly.

Speaking of "jump-form", lets apply it to the loop above:

```
    int i=0;
    if (i >= a)
        goto done_loop;
loop:
    do_something;
    i++
    if (i < a)
        goto loop;
```

```
 9
10 done_loop:
```

You can see how that starts to look more like assembly. Another thing to note is that unlike with `if` statements where we test for the opposite to jump over the block of code, when you're doing the loop test at the bottom like with a `do-while`, it is unchanged from C because you are jumping to *continue* the loop. If you put the test at the top it becomes inverted, and you put an unconditional jump at the bottom:

```
1     int i=0;
2 loop:
3     if (i >= a)
4         goto done_loop;
5     do_something;
6     i++
7     goto loop:
8
9 done_loop:
```

In general it's better to test at the bottom, both because the condition matches the higher level form, and because when you know the loop is going to execute at least once it requires only one jump + label, rather than 2 since you can forgo the the initial `if` check:

```
1     for (int i=0; i<10; i++)
2         do_something;
3
4     // becomes
5
6     int i=0;
7 loop:
8     do_something;
9     i++
10    if (i < a)
11        goto loop;
```

Ok, now that we've got the theory and structure out of the way, let's try doing a simple one in RISC-V.

```
1     int sum = 0;
2     for (int i=0; i<100; i++) {
3         sum += i;
4     }
```

That's about as basic as it gets, adding up the numbers 0 to 99.

```
1     li     t0, 0   # sum = 0
```

```
    li     t1, 1   # i = 1  we can start at 1 because obviously adding 0 is
  pointless
    li     t2, 100
loop:
    addi   t0, t0, t1     # sum += i
    addi   t1, t1, 1      # i++
    blt    t1, t2, loop   # while (i < 100)
```

Ok I don't think there's much point in doing any more without getting to what loops are most often used for, looping through data structures, most commonly arrays.

Looping Through Arrays

Looping and arrays go together like peanut butter and jam. An array is a sequence of variables of the same type, almost always related in some way. Naturally, you want to operate on them all together in various ways; sorting, searching, accumulating, etc. Given that the only way to do that is with loops, in this section we'll cover different ways of looping through arrays, and dealing with multi-dimentional arrays.

1D Arrays

Let's pretend there's an array `int numbers[10];` filled with 10 random numbers.

```
    int total = 0;
    for (int i=0; i<10; i++) {
        total += numbers[i];
    }
```

There are several ways to do this. The first is the most literal translation.

```
    li    t0, 0     # total = 0
    li    t1, 0     # i = 0
    la    t2, numbers   # t2 = numbers
    li    t3, 10
sum_loop:
    slli  t4, t1, 2   # t4 = i*sizeof(int) == i*4
    add   t4, t4, t2  # t4 = &numbers[i]
    lw    t4, 0(t4)   # t4 = numbers[i]
    add   t0, t0, t4  # total += numbers[i]

    addi  t1, t1, 1   # i++
    blt   t1, t3, sum_loop   # while (i < 10)
```

We initialize the relevant variables beforehand (`numbers` and `t3` could be set every iteration but that's less efficient). Now what's with the `i*4`? We already discussed using shifts to multiply and divide by powers of 2 in a previous chapter, but here we're doing something that higher level languages do automatically for you every time you do an array access. When you access the *i*'th

element, under the hood it is multiplying `i` by the size of the type of the array and adding that number of bytes to the base address and then loading the element located there.

If you're unfamiliar with the C syntax in the comments, `&` means "address of", so `t4` is being set to the address of the *i*'th element. Actually that C syntax is redundant because the the `&` counteracts the brackets. In C adding a number to a pointer does pointer math (ie it multiplies by the size of the items as discussed above). This means that the following comparison is true:

```
&numbers[i] == numbers + i
```

which means that this is true too

```
&numbers[0] == numbers
```

The reason I use the form on the left in C/C++ even when I can use the right is it makes it more explicit and obvious that I'm getting the address of an element of an array. If you were scanning the code quickly and saw the expression on the right, you might not realize that's an address at all, it could be some mathematical expression (though the array name would hopefully clue you in if it was picked well).

Anyway, back to the RISC-V code. After we get the address of the element we want, we have to actually read it from memory (ie load it). Since it's an array of words (aka 4 byte ints) we can use load word, `lw`.

Finally, we add that value to `total`, increment `i`, and perform the loop check.

Now, I said at the beginning that this was the most literal, direct translation (not counting the restructuring to a `do-while` form). However, it is not my preferred form because it's not the simplest, nor the shortest.

Rather than calculate the element address every iteration, why not keep a pointer to the current element and iterate through the array with it? In C what I'm suggesting is this:

```
1     int* p = &numbers[0];
2     int i = 0, total = 0;
3     do {
4         total += *p;
5         i++;
6         p++;
7     } while (i < 10);
```

In other words, we set `p` to point at the first element and then increment it every step to keep it pointing at `numbers[i]`. Again, all mathematical operations on pointers in C deal in increments of the byte syze of the type, so `p++` is really adding `1*sizeof(int)`.

```
1     li      t0, 0     # total = 0
2     li      t1, 0     # i = 0
3     la      t2, numbers   # p = numbers
4     li      t3, 10
5 sum_loop:
```

```
    lw      t4, 0(t2)    # t4 = *p
    add     t0, t0, t4   # total += *p

    addi    t1, t1, 1    # i++
    addi    t2, t2, 4    # p++  ie p += sizeof(int)
    blt     t1, t3, sum_loop   # while (i < 10)
```

Now, that may not look much better, we only saved 1 instuction, and if we were looping through a string (aka an array of characters, `sizeof(char) == 1`) we wouldn't have saved any. However, imagine if we weren't using `slli` to do the multiply but `mul`. That would take 2 instructions, even if one could be above the loop. And remember we *would* have to use `mul` instead of `slli` if we were iterating through an array of structures with a size that wasn't a power of 2, so using this method saves even more in that rare case.

However, there is one more variant that you can use that can save a few more instructions. Instead of using `i` and `i<10` to control the loop, use `p` and the address just past the end of the array. In C it would be this:

```
    int* p = &numbers[0];
    int* end = &numbers[10];
    int total = 0;
    do {
        total += *p;
        p++;
    } while (p < end);
```

You could also use `!=` instead of `<`. This is similar to using the `.end()` method on many C++ data structures when using iterators. Now the RISC-V version:

```
    li      t0, 0        # total = 0
    la      t2, numbers  # p = numbers
    addi    t3, t2, 40   # end = &numbers[10] = numbers + 10*sizeof(int)
sum_loop:
    lw      t4, 0(t2)    # t4 = *p
    add     t0, t0, t4   # total += *p

    addi    t2, t2, 4    # p++  ie p += sizeof(int)
    blt     t2, t3, sum_loop   # while (p < end)
```

So we dropped from 10 to 7 instructions, 6 to 4 in the loop itself which is the most important for performance. And this was for a 1D array. Imagine if you had 2 or 3 indices you had to use to calculate the correct offset. That's what we go over in the next section.

2D Arrays

The first thing to understand is what's really happening when you declare a 2D array in C. The contents of a 2D array are tightly packed, in row-major order, meaning that all the elements from

the first row are followed by all the elements of the second row and so on. What this means is that a 2D array is equivalent to a 1D array with rows*cols elements in the same order:

```
    // The memory of these two arrays are identical
    int array2d[2][4] = { { 1, 2, 3, 4 }, { 5, 6, 7, 8 } };
    int array1d[8] = { 1, 2, 3, 4, 5, 6, 7, 8 };
```

See the code example 2d_arrays.c for more details.

What this means is that when we declare a 2D array, it's basically a 1D array with the size equal to the rows * columns. Also, when we loop through a 2D array, we can often treat it like a 1D array with a single loop. So everything that we learned before applies.

Let's do an example.

```
    for (int i=0; i<rows; i++) {
        for (int j=0; j<cols; ++j) {
            array[i][j] = i + j;
        }
    }

    // becomes

    int r, c;
    for (int i=0; i<rows*cols; i++) {
        r = i / cols;
        c = i % cols;
        array[i] = r + c;
    }
```

So assuming `rows` and `cols` are in `a0` and `a1` (and nonzero), it would look like this:

```
    la     t0, array    # p = &array[0]
    li     t1, 0        # i = 0
    mul    t2, a0, a1   # t2 = rows * cols
loop:
    div    t3, t1, a1   # r = i / cols
    rem    t4, t1, a1   # c = i % cols
    add    t3, t3, t4    # t3 = r + c

    sw     t3, 0(t0)      # array[i] = *p = r + c

    addi   t1, t1, 1      # i++
    addi   t0, t0, 4      # p++ (keep pointer in sync with i, aka p = &array[i])
    blt    t1, t2, loop   # while (i < rows*cols)
```

You might ask if it's it worth it to convert it to a single loop when you still need the original `i` and `j`

as if you were doing nested loops. Generally, it is much nicer to avoid nested loops in assembly if you can. There are many cases when you get the best of both worlds though. If you're doing a clear for example, setting the entire array to a single value, there's no need to calculate the row and column like we did here. I only picked this example to show how you could get them back if you needed them.

For comparison here's the nested translation (while still taking advantage of the 1D arrangement of memory and pointer iterators):

```
    la     t0, array    # p = &array[0]
    li     t1, 0        # i = 0
looprows:
    li     t2, 0        # j = 0
loopcols:
    add    t3, t1, t2     # t3 = i + j
    sw     t3, 0(t0)      # array[i][j] = *p = i + j

    addi   t2, t2, 1         # j++
    addi   t0, t0, 4         # p++ (keep pointer in sync with i and j, aka p =
&array[i][j])
    blt    t2, a1, loopcols  # while (j < cols)

    addi   t1, t1, 1          # i++
    blt    t1, a0, looprows   # while (i < rows)
```

It's the same number of instructions, but with an extra label and branch. I prefer this version. On the other hand, either of the last 2 versions are better than the literal translation below:

```
    la     t0, array    # p = &array[0]
    li     t1, 0        # i = 0
looprows:
    li     t2, 0        # j = 0
loopcols:
    add    t3, t1, t2    # t3 = i + j

    # need to calculate the byte offset of element array[i][j]
    mul    t4, t1, a1      # t4 = i * cols
    add    t4, t4, t2      # t4 = i * cols + j
    slli   t4  t4, 2       # t4 = (i * cols + j) * sizeof(int)

    add    t4, t4, t0      # t4 = &array[i][j] (calculated as array + (i*cols +
j)*4)

    sw     t3, 0(t4)       # array[i][j] = i + j

    addi   t2, t2, 1         # j++
    blt    t2, a1, loopcols  # while (j < cols)

    addi   t1, t1, 1          # i++
```

```
21      blt     t1, a0, looprows    # while (i < rows)
```

That chunk in the middle calculating the offset of every element? Not only is it far slower than iterating the pointer through the array, but you can imagine how much worse it would be for a 3D array with 3 nested loops.

Conclusion

Hopefully after those examples you have a more solid understanding of looping in RISC-V and how to transform various loops and array accesses into the form that makes your life the easiest. There is more we could cover here, like looping through a linked list, but I think that's beyond the scope of what we've covered so far. Perhaps in a later chapter.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Convert the following C code to MIPS. If using SPIM, you can just hard code a "random" number between 0 and 100.

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    int num = rand() % 101
    int guess;
    puts("I'm thinking of a number 0-100.  Try to guess it!");
    while (1) {
        printf("Guess a number: ");
        scanf("%d", &guess);

        if (guess > num) {
            puts("Too high!");
        } else if (guess < num) {
            puts("Too low!");
        } else {
            break;
        }
    }

    printf("Correct, it was %d!\n", num);

    return 0;
}
```

2. Write a MIPS program to find and print the average of the following array. Just use integer division.

```
1 .data
2 array:         .word 93,8,78,-6,51,49,3,2,128,0
```

3. Write a program to find the min and max of the array in the previous exercise

Chapter 5: Functions and the RISC-V Calling Convention

While I'm sure everyone here probably knows what functions are, and we'll cover them in assembly shortly, you might be wondering what a "Calling Convention" is. In short, it is an agreement between the caller and callee about how to treat/use certain registers. We'll get to the why and how later.

Functions

In assembly, a function is simply a label with a return instruction associated with it; because this is far more ambiguous than a function in a higher level language, it is good practice to only have a single return instruction associated with a function.[1] A comment above the label is also helpful. Together those help you quickly see the start and end of the function.

```
1 void func1() {}
```

would be

```
1 # void func1()
2 func1:
3     # body goes here
4     ret
```

As you can see my policy is to put a single line comment of the C prototype above label.

But how do you call a function in assembly? You use the instruction Jump and Link: `jal func_label`. Let's change the hello world program from chapter 0 to call a function:

```
 1 .data
 2 hello:   .asciz "Hello World!\n"
 3
 4 .text
 5 main:
 6     jal   hello_world
 7
 8     li    v0, 10     # exit ecall
 9     ecall
10
11
12 # void hello_world()
13 hello_world:
14     li    a7, 4      # print string ecall
15     la    a0, hello  # load address of string to print into a0
16     ecall
```

```
17
18      ret
```

What `jal` actually does, is save the address of the next instruction to `ra` and then do an unconditional jump to the function label. So you could achieve the same results with the following:

```
    jal    func

    # is equivalent to

    la     ra, next_instr
    j      func
next_instr:
```

That would get tiring and ugly fast though, having to come up with unique labels for the next instruction every time. You also might be confused about why the greensheet says `jal` saves PC+4 in an arbitrary register R[rd] instead of `ra` specifically (R[1]). The instruction does actually take a register argument but since it's most commonly used to call a function if you don't specify a register it will use `ra` as if you did `jal ra, func`. This works in conjunction with the pseudoinstruction `ret` which does PC=R[1] using the instruction jalr (`jalr x0, ra, 0`) to easily return from functions.

The Convention

We've gone as far as we can without starting to talk about registers and their purposes in functions. You can think of registers as variables[2] that are part of the CPU. In this case, since we're dealing with a 32-bit RISC-V architecture, they are 32-bit (aka 4 bytes, 1 word) variables.[3] Since they're part of the CPU, they exist for the life of the program and the whole program shares the same registers.

But how does that work? If all parts of the program use the same 32 registers, how does one function not stomp all over what another was doing when it uses them? In fact, how do functions communicate at all? How do they pass arguments or return results? All these questions are solved by deciding on a "Calling Convention". It's different for different architectures and even different operating systems on the same architecture. This is because different architectures have different numbers of registers, and some registers like `ra` semi-hardcoded uses. The the pseudoinstruction `ret` uses `ra`, and `x0` is a constant 0 and there's no way to change either of those facts. That still leaves a lot of flexibility about designing a calling convention. While they mostly match, you can probably find several variations of RISC-V calling conventions online. They usually differ in how they setup a stack frame. The convention covered in this chapter is consistent with, and sufficient for, almost every college course I've ever heard of.

Regardless, what matters is that the calling convention works by setting rules (and guidelines) for register use, and when/how to use the stack.

If you're unfamiliar with the runtime stack, it's exactly what it sounds like. It's a Last-In-First-Out (LIFO) data structure that you can use to store smaller values in a program. It grows in a negative direction, so to allocate 12 bytes, you would subtract 12 from the stack pointer (in RISC-V that's `sp`).

RISC-V specifically designates certain registers to be used for passing arguments (at least the first 8), a couple for return values, and others for misc. temporary or saved values. The rest are special use registers like `ra`.

The quickest way to summarize is to look at the table on the greensheet which is reproduced (with some modifications) below:

Table 4. RISC-V Registers and Uses

Name	Number	Use	Preserved Across a Call
zero	0	Constant 0	N.A.
ra	1	Return address	No
sp	2	Stack pointer	Yes
gp	3	Global pointer	—
tp	4	Thread pointer	—
t0-t2	5-7	Temporaries	No
s0/fp	8	Saved register/Frame pointer	Yes
s1	9	Saved register	Yes
a0-a1	10-11	Function arguments/Return values	No
a2-a7	12-17	Function arguments	No
s2-s11	18-27	Saved registers	Yes
t3-t6	28-31	Temporaries	No

To summarize, you have 15 registers that can be used anytime for temporary values, though some have special uses too (the a and t registers). You have 12 s registers that have to be saved on the stack if you use them, plus `ra` as well. The `zero` register is obviously a special case.

The `sp` register is technically preserved but not in the same way. Basically what you allocate (subtract) you have to deallocate (add) before returning from a function, thus preserving the original value.

You can ignore `gp, tp`, and most of the time `fp` too. Also, with 8 registers to pass arguments, you'll almost never need to pass arguments on the stack.

Basic example

Let's start with something simple that doesn't use the stack.

```
int hello_name_number(char* name, int number)
{
    printf("Hello %s!\n", name);
    return number + 10;
}
```

According to the convention that becomes:

```
.data
hello_space:  .asciz "Hello "
exclaim_nl:   .asciz "!\n"

.text
# int hello_name_number(char* name, int number)
hello_name_number:
    mv       t0, a0   # save name in t0 since we need a0 for the ecall

    li       a7, 4        # print string
    la       a0, hello_space
    ecall

    mv       a0, t0    # print name (a7 is still 4)
    ecall

    la       a0, exclaim_nl  # print "!\n"
    ecall


    addi     a0, a1, 10  # return number + 10
    ret
```

Some things to note, ecalls are not function calls so we can "save" `a0` in a t register and know that it'll still be there when the ecall is done. In the same way, we know that `a7` is still the same so we don't have to keep setting it to 4 for print string. Lastly, to return a value, we make sure that value is in `a0` before returning.

Using the Stack

First, let's establish the rules on when you *have* to use the stack (You can always use it for arbitrary local variables, like a local array for example, but generally don't if you don't have a good reason).

1. **You call another function, ie you're a non-leaf function.**

   This means you have to save `ra` on the stack at the very least, otherwise when you do your `ret` you'd jump back into yourself (right after the last `jal` instruction). This does not apply to main because you don't/shouldn't return from main, you should call the exit (or exit2) ecall (10 or 93).

2. **You need to save values across a function call (automatically includes reason 1).**

   This is fairly common for non-trivial functions. Obvious examples are calling a function in a loop or loops (you'd have to preserve the iterator(s)), and many recursive functions.

3. **You run out of temporary registers and overflow into the s registers.**

   This is very rare. The most common reason this "happens" is people forget they have 8 a registers, in addition to the 7 t registers, that they can also use for temporaries. 15 is more than

enough to handle pretty much any function because you rarely need 16 discrete values at the same time.

Let's look at an example for the first two. Any example for the last rule would be prohibitively large and complicated.

```
1 int non_leaf()
2 {
3     func1();
4     return 42
5 }
```

This calls the empty function discussed at the top of this chapter.

```
1 #int non_leaf()
2 non_leaf:
3     addi     sp, sp, -4  # space to save 1 register, ra
4     sw       ra, 0(sp)   # store ra in the newly allocated stack space
5
6     jal      func1
7
8     li       a0, 42       # return 42
9
10    lw       ra, 0(sp)   # restore original $ra
11    addi     sp, sp, 4   # pop the stack
12    ret
```

The bit of code at the top and bottom of the function are called the prologue and epilogue respectively for obvious reasons. We allocate 4 bytes on the stack by subtracting 4 (I add a negative rather than subtract because I can copy-paste the line with a single character change for the epilogue). Then we store the current `ra` in that space at the new top of the stack. Then before we exit we have to load it back and pop the stack.

If we didn't save and restore `ra` we would jump to line 7 when we do our `ret` and then we'd be in an infinite loop.

Next we have the second case, where we need to preserve regular local values across a function call.

```
1 void print_letters(char letter, int count)
2 {
3     for (int i=0; i<count; i++) {
4         putchar(letter);
5     }
6     putchar('\n');
7 }
8
9 int save_vals()
```

```
{
    for (int i=0; i<10; i++) {
        print_letters('A'+i, i+1);
    }
    return 8;
}
```

That becomes this in RISC-V:

```
#void print_letters(char letter, int count)
print_letters:
    ble      a1, $0, exit_pl   # if (count <= 0) goto exit_pl
    li       a7, 11            # print character
pl_loop:
    ecall
    addi     a1, a1, -1        # count--
    bgt      a1, x0, pl_loop   # while (count > 0)

    li       a0, 10            # '\n'
    ecall

exit_pl:
    ret


#int save_vals()
save_vals:
    addi     sp, sp, -12
    sw       ra, 0(sp)
    sw       s0, 4(sp)
    sw       s1, 8(sp)

    li       s0, 0  # i = 0
    li       s1, 10
sv_loop:
    addi     a0, s0, 65   # i + 'A'
    addi     a1, s0, 1    # i + 1
    jal      print_letters

    addi     s0, s0, 1        # i++
    blt      s0, s1, sv_loop  # while (i < 10)

    lw       ra, 0(sp)
    lw       s0, 4(sp)
    lw       s1, 8(sp)
    addi     sp, sp, 12
    ret
```

Notice that for print_letters, we not only convert the loop to a `do-while`, but we also use the

parameter `count` as the iterator to count *down* to 0. It saves us an instruction initializing an `i`.

Second, for `save_vals`, we save not only `ra` because we call another function, but also two s registers to save `i` and our stopping point. The second is not actually necessary; because it's a constant, we could load 10 into a register right before the check every iteration of the loop. Which version is better depends on several factors, like how long or complex the loop is, how many times it executes, and of course personal preference.

Recursive Functions

Let's do a classic recursive function, the fibonacci sequence.

```
1 int fib(int n)
2 {
3     if (n <= 1)
4         return n;
5
6     return fib(n-2) + fib(n-1);
7 }
```

You can see how, at the very least, we'll have to save `ra` and `n`, because we need the original even after the first recursive call. It's not as obvious, but we'll also have to save the return value of the first call so we'll still have it to do the addition after the second. You might think this would require using two s regs, but does it? Let's see...

```
 1 #int fib(int n)
 2 fib:
 3     addi    sp, sp, -8
 4     sw      ra, 0(sp)
 5     sw      s0, 4(sp)
 6
 7     # n already in a0 for immediate return
 8     li      t0, 1
 9     ble     a0, t0, exit_fib  # if (n <= 1) goto exit_fib (ie return n)
10
11     mv      s0, a0        # save n
12
13     addi    a0, a0, -2
14     jal     fib           # fib(n-2)
15
16     addi    t0, s0, -1    # calc n-1 first so we can use s0 to save fib(n-2)
17     mv      s0, a0        # save return of fib(n-2) in s0
18     mv      a0, t0        # copy n-1 to a0
19     jal     fib           # fib(n-1)
20
21     add     a0, a0, s0    #  a0 = fib(n-1) + fib(n-2)
22
23 exit_fib:
24     lw      ra, 0(sp)
```

```
25      lw      s0, 4(sp)
26      addi    sp, sp, 8
27      ret
```

Notice how we don't have to save `n` any sooner than necessary, ie right before we have to use `a0` to setup the first recursive call. Also, the ordering of lines 15-17 is important. We needed the original `n` to calculate `n-1` but once that's in `a0` ready for the call, because we won't need `n` again afterward, we can now use `s0` to preserve the return value of the first call.

Some of you, if you were paying attention, might point out that you could save a few instructions of performance if you moved the base case testing before the prologue as long as you put the exit label after the epilogue. This is true, but I'd recommend against it unless you were really trying to eke out every last microsecond. It's nicer/cleaner to keep the prologue and epilogue as the first and last things; they're one more thing to catch your eye and help delineate where functions start and end. Regardless, if you're curious, you can see that version, along with every other function in this chapter in the included program calling.s.

Conclusion

While grasping the basics of a calling convention is not too difficult, it takes practice to get used to it. There are many things that we haven't covered in this chapter, like how to pass more than 8 arguments, or use `fp`, or handle floating point arguments or return values. The latter at least, will be covered in the next chapter.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Implement the following functions in MIPS and write a program to demonstrate their use. You can reuse much of your code from the previous chapter's exercises.

```
1 // return the min or max
2 int get_min(int* array, int size);
3 int get_max(int* array, int size);
4
5 // return the index of the min/max
6 int locate_min(int* array, int size);
7 int locate_max(int* array, int size);
8
9 // return the average of the array
10 int calc_average(int* array, int size);
```

2. The Collatz conjecture is defined as follows: start with any positive integer n, if n is even, divide by 2, otherwise, multiply by 3 and add 1. The conjecture is that all sequences will eventually reach 1. Write 2 versions of the collatz function, one iterative and one recursive. Print out the sequence as they go.

```
1 void collatz_iterative(int n);
2 void collatz_recursive(int n);
3
4 // for an added challenge return the number of steps taken to reach 1
5 // you can remove the printing of the steps
6 int collatz_iterative2(int n);
7 int collatz_recursive2(int n);
```

[1] I do not agree with an ironclad "one return" policy in higher level languages. Sometimes returning early results in cleaner code, sometimes not. Similarly, `goto` is not evil and there are rare cases where using it creates the best code.

[2] Obviously the zero register is not really a variable. I never understood how people could say "const variable" with a straight face, it's literally an oxymoron.

[3] RARS does support 64 bit I think TODO

Chapter 6: Floating Point Types

Up to this point we haven't really mentioned floating point values or instructions at all, except how to declare them in the `.data` section and the ecalls for reading and printing them. There are two reasons we've left them alone till now. First, they use a whole separate set of registers and instructions. Second, and partly because of the first reason, most college courses do not ever require you to know or use floating point values. Since this book is targeted at college students, if you know you won't need to know this feel free to skip this chapter.

Floating Point Registers and Instructions

The greensheet contains all the floating point registers and their uses but you can also see them in the table below:

Table 5. RISC-V Floating Point Registers and Uses

Name	Number	Use
Preserved Across a Call	ft0-ft7	f0-f7
Temporaries	No	fs0-fs1
f8-f9	Saved registers	Yes
fa0-fa1	f10-f11	Arguments/Return values
No	fa2-fa7	f12-f17
Arguments	No	fs2-fs11
f18-f27	Saved registers	Yes
ft8-ft11	f28-f31	Temporaries

Likewise, you can look to the greensheet to see all the floating point instructions but here are the most important/useful ones:

Table 6. RISC-V floating point instructions (and pseudoinstructions)

Name	Opcode	Format	Operation
Load	flw,fld	`flw ft, n(rs)`	F[ft] = M[R[rs]+n]
Store	fsw,fsd	`fsw ft, n(rs)`	M[R[rs]+n] = F[ft]
Move from Integer	fmv.[sd].x	`fmv.s.x ft, rs`	F[ft] = R[rs]
Move to Integer	fmv.x.[sd]	`fmv.x.s rs, ft`	R[rs] = F[ft]
Move	fmv.[sd]	`fmv.s fd, fs`	F[fd] = F[fs]
Convert to SP from DP	fcvt.s.d	`fcvt.s.d fd, fs`	F[fd] = (float)F[fs]
Convert to DP from SP	fcvt.d.s	`fcvt.d.s fd, fs`	F[fd] = (double)F[fs]
Convert from 32b Integer	fcvt.[sd].w	`fcvt.s.w fd, rs`	F[fd] = (float)R[rs]
Convert to 32b Integer	fcvt.w.[sd]	`fcvt.w.s rd, fs`	R[rd] = (int)F[fs]

Name	Opcode	Format	Operation
Compare Equal	feq.[sd]	`feq.s rd, fs1, fs2`	R[rd] = (F[fs1] == F[fs2]) ? 1 : 0
Compare Less Than	flt.[sd]	`flt.s rd, fs1, fs2`	R[rd] = (F[fs1] < F[fs2]) ? 1 : 0
Compare Less Than Equal	fle.[sd]	`fle.s rd, fs1, fs2`	R[rd] = (F[fs1] ⇐ F[fs2]) ? 1 : 0
Absolute Value	fabs.[sd]	`fabs.s fd, fs`	F[fd] = (F[fs] < 0) ? -F[fs] : F[fs]
Add	fadd.[sd]	`fadd.s fd, fs, ft`	F[fd] = F[fs] + F[ft]
Subtract	fsub.[sd]	`fsub.s fd, fs, ft`	F[fd] = F[fs] - F[ft]
Multiply	fmul.[sd]	`fmul.s fd, fs, ft`	F[fd] = F[fs] * F[ft]
Divide	fdiv.[sd]	`fdiv.s fd, fs, ft`	F[fd] = F[fs] / F[ft]
Negation	fneg.[sd]	`fneg.s fd, fs`	F[fd] = -F[fs]

Anywhere you see a [sd], use s or d for single or double precisision.

You only get equal, less than, and less than equal, but it's easy enough to flip the operands or test for the opposite result to cover the others.

Practice

We're going to briefly go over some of the more different aspects of dealing with floating point numbers, but since most of it is the same but with a new set of registers and calling convention, we won't be rehashing most concepts.

Getting Floating Point Literals

The first thing to know when dealing with floats is how to get float (or double) literals into registers where you can actually operate on them.

There are two ways. The first, and simpler way, is to declare them as globals and then use the `flw` and `fld` instructions:

```
1 .data
2 a:     .float 3.14159
3 b:     .double 1.61
4
5 .text
6 main:
7
8     la      t0, a
9     flw     ft0, 0(t0)   # get a into ft0
10
```

```
    la      t0, b
    fld     ft1, 0(t0)   # get b into ft1

    # other code here
```

The second way is to use the regular registers and convert the values. Of course this means unless you want an integer value, you'd have to actually do it twice and divide, and even that would limit you to rational numbers. It looks like this:

```
    fmv.s.x   ft0, x0     # move 0 to ft0 (0 integer == 0.0 float)

    # get 4 to 4.0 in ft1
    li        t0, 4
    fcvt.s.w  ft1, t0     # ft1 = (float)t0
```

As you can see, other than 0 which is a special case, it requires at least 2 instructions.

NOTE There is a 3rd way that is easier, but it's only supported in RARS, not Venus. RARS lets you use `flw` and `fld` like this `flw ft0, label, t0` where t0 is used as a temporary, ie it's doing the load address into t0 for you before doing the actual flw

Branching

Branching based on floating point values is slightly different than normal. Instead of being able to test and jump in a single convenient instruction, you have to test first and then jump in a second instruction if the test was true or not. This is similar to the way x86 and MIPS (for floats) do it. For them, the test sets a special control/flag register (or a certain bit or bits in the register) and then all jumps are based on its state.

With RISC-V there is no special control register. The float comparisons are like the `slt` instructions where you choose a destination register to set to 1 (true) or 0 (false).

Using them looks like this:

```
    flt.s    t0, ft0, ft1   # t0 = ft0 < ft1
    bne      t0, x0, was_less   # if (t0 != 0 aka ft0 < ft1) goto was_less

    # do something for ft0 >= ft1

    j       blah
was_less:

    # do something for ft0 < ft1

blah:
```

Functions

Finally, lets do a simple example of writing a function that takes a float and returns a float. I'm not going to bother doing one for doubles because it'd be effectively the same, or doing one that requires the stack, because the only differences from normal are a new set of registers and knowing which ones to save or not from the table above.

So, how about a function to convert a fahrenheit temperature to celsius:

```
.data

# 5/9 = 0.5 with 5 repeating
fahrenheit2celsius: .float 0.5555555

.text
# float convert_F2C(float degrees_f)
convert_F2C:
    la       t0, fahrenheit2celsius
    flw      ft0, 0(t0)    # get conversion factor

    # C = (F - 32) * 5/9
    li       t0, 32
    fcvt.s.w ft1, t0       # convert to 32.0

    fsub.s   fa0, fa0, ft1  # fa0 = degrees_f - 32
    fmul.s   fa0, ft0, fa0  # fa0 = 0.555555 * fa0

    ret
```

You can see we follow the convention with the argument coming, and the result being returned, in `fa0`. In this function we use both methods for getting a value into float registers; one we load from memory and the other, being an integer, we convert directly.

Conclusion

As I said before, it is rare for courses to even bother covering floating point instructions or assign any homework or projects that use them, but hopefully this brief overview, combined with the knowledge of previous chapters is sufficient.

There are also 2 example programs conversions.s and calc_pi.s for you to study.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Write a program to convert an input in minutes to hours.
2. Write the following functions and use them in a program.

```
1 float miles2kilometers(float miles);
2 float pounds2kilograms(float pounds);
```

Chapter 7: Tips and Tricks

This chapter is a grab bag of things you can do to improve your RISC-V programs and make your life easier.

Formatting

You may have noticed I have a general format I like to follow when writing RISC-V (or any) assembly. The guidelines I use are the following

1. **1 indent for all code excluding labels/macros/constants.**

   I use hard tabs set to a width of 4 but it really doesn't matter as long as it's just 1 indent according to your preferences.

2. **Use *spaces* to align the first operand of all instructions out far enough.**

   Given my 4 space tabs, this means column 13+ (due to longer floating point instructions like fcvt.s.w, though I often stop at 10 or 11 when that's sufficient). The reason to use spaces is to prevent the circumstances that gave hard tabs a bad name. When you use hard tabs for alignment, rather than indentation, and then someone else opens your code with their tab set to a different width, suddenly everything looks terrible. Thus, tabs for indentation, spaces for alignment. Or as is increasingly common (thanks Python), spaces for everything but I refuse to do that to the poor planet.[1]

3. **A comma and a single space between operands.**

   The simulators don't actually require the comma but since other assembly languages/assemblers do, you might as well get used to it. Besides I think it's easier to read with the comma, though that might be me comparing it to passing arguments to a function.

4. **Comment every line or group of closely related lines with the purpose.**

   This is often simply the equivalent C code. You can relax this a little as you get more experience.

5. **Use a blank line to separate logically grouped lines of code.**

   While you can smash everything together vertically, I definitely wouldn't recommend it, even less than I would in a higher level language.

6. **Put the `.data` section at the top, similar to declaring globals in C.**

   There are exceptions for this. When dealing with a larger program with lots of strings, it can be convenient to have multiple `.data` sections with the strings you're using declared close to where you use them. The downside is you have to keep swapping back and forth between `.text` and `.data`.

Misc. General Tips

1. **Try to use registers starting from 0 and working your way up.**

   It helps you keep track of where things are (esp. combined with the comments). This can fall apart when you discover you forgot something or need to modify the code later and it's often not worth changing all the registers you're already using so you can maintain that nice sequence. When that happens I'll sometimes just pick the other end of sequence (ie `t6`, `a7`, or `s11`) since if it's out of order I might as well make it obvious.

2. **Minimize your jumps, labels, and especially your level of nested loops.**

   This was already covered in the chapters on branching and loops but it bears repeating.

3. **In your prologue save `ra` first, if necessary, then all s regs used starting at `s0`.**

   Then copy paste the whole thing to the bottom, move the first line to the bottom and change the number to positive and change all the `sw` to `lw`.

```
func:
    addi     sp, sp, -20
    sw       ra, 0(sp)
    sw       s0, 4(sp)
    sw       s1, 8(sp)
    sw       s2, 12(sp)
    sw       s3, 16(sp)

    # body of func here that calls another function or functions
    # and needs to preserve 4 values across at least one of those calls

    lw       ra, 0(sp)
    lw       s0, 4(sp)
    lw       s1, 8(sp)
    lw       s2, 12(sp)
    lw       s3, 16(sp)
    addi     sp, sp, 20
```

Constants

One of the easiest things you can do to make your programs more readable is to use defined constants in your programs. RARS has a way of defining constants similar to how C defines macro constants; ie they aren't "constant variables" that take up space in memory, it's as if a search+replace was done on them right before assembling the program.

Let's look at our Hello World program using constants:

```
1 .eqv sys_print_str 4
2 .eqv sys_exit 10
```

```
3
4 .data
5 hello:   .asciz "Hello World!\n"
6
7 .text
8 main:
9     li   a7, sys_print_str
10    la   a0, hello  # load address of string to print into a0
11    ecall
12
13    li   a7, sys_exit
14    ecall
```

Macros

RARS supports function style macros that can shorten your code and improve readability in some cases (though I feel it can also make it worse or be a wash).

The syntax looks like this:

```
1 .macro macroname
2     instr1  a, b, c
3     instr2, b, d
4 # etc.
5 .end_macro
6
7 # or with parameters
8 .macro macroname(%arg1)
9     instr1    a, %arg1
10    instr2    c, d, e
11 # etc.
12 .end_macro
```

Some common examples are using them to print strings:

```
1 .macro print_str_label(%x)
2     li     a7, 4
3     la     a0, %x
4     ecall
5 .end_macro
6
7 .macro print_str(%str)
8 .data
9 str: .asciz %str
10 .text
11    li     a7, 4
12    la     a0, str
13    ecall
```

```
14 .end_macro
15
16 .data
17
18 str1:   .asciz "Hello 1\n"
19
20 .text
21 # in use:
22     print_str_label(str1)
23
24     print_str("Hello World\n")
25
26     ...
```

You can see an example program in macros.s.

Switch-Case Statements

It is relatively common in programming to compare an integral type variable (ie basically any built-in type but float and double) against a bunch of different constants and do something different based on what it matches or if it matches none.

This could be done with a long `if-else-if` chain, but the longer the chain the more likely the programmer is to choose a `switch-case` statement instead.

Here's a pretty short/simple example in C:

```
1     printf("Enter your grade (capital): ");
2     int grade = getchar();
3     switch (grade) {
4     case 'A': puts("Excellent job!"); break;
5     case 'B': puts("Good job!"); break;
6     case 'C': puts("At least you passed?"); break;
7     case 'D': puts("Probably should have dropped it..."); break;
8     case 'F': puts("Did you even know you were signed up for the class?"); break;
9     default: puts("You entered and invalid grade!");
10    }
```

You could translate this to its eqivalent `if-else` chain and handle it like we cover in the chapter on branching. However, imagine if this switch statment had a dozen cases, two dozen etc. The RISC-V code for that quickly becomes long and ugly.

So what if we implemented it in RISC-V the same way it is semantically in C? The same way compilers often (but not necessarily) use? Well, before we do that, what is a switch actually doing? It is *jumping* to a specific case label based on the value in the specified variable. It then starts executing, falling through any other labels, till it hits a `break` which will jump to the end of the switch block. If the value does not have its own case label, it will jump to the default label.

Compilers handle it by creating what's called a jump table, basically an array of label addresses, and using the variable to calculate an index in the table to use to jump to.

The C eqivalent of that would look like this:

```c
#include <stdio.h>


// This compiles with gcc, uses non-standard extension
// https://gcc.gnu.org/onlinedocs/gcc/Labels-as-Values.html

int main()
{

    // jump table
    void* switch_table[] =
    { &&a_label, &&b_label, &&c_label, &&d_label, &&default_label, &&f_label };

    printf("Enter your grade (capital): ");
    int grade = getchar();
    grade -= 'A';  // shift to 0

    if (grade < 0 || grade > 'F'-'A')
        goto default_label;

    goto *switch_table[grade];

a_label:
    puts("Excellent job!");
    goto end_switch;

b_label:
    puts("Good job!");
    goto end_switch;

c_label:
    puts("At least you passed?");
    goto end_switch;

d_label:
    puts("Probably should have dropped it...");
    goto end_switch;

f_label:
    puts("Did you even know you were signed up for the class?");
    goto end_switch;

default_label:
    puts("You entered an invalid grade!");

```

```
46
47 end_switch:
48
49
50     return 0;
51 }
```

The `&&` and `goto *var` syntax are actually not standard C/C++ but are GNU extensions that are supported in gcc (naturally) and clang, possibly others.[2]

First, notice how the size of the jump table is the value of the highest valued label minus the lowest + 1. That's why we subtract the lowest value to shift the range to start at 0 for the indexing. Second, any values without labels within that range are filled with the `default_label` address. Third, there has to be an initial check for values outside the range to jump to default otherwise you could get an error from an invalid access outside of the array's bounds.

The same program/code in RISC-V would look like this:

```
 1 .data
 2
 3 a_str:  .asciz "Excellent job!\n"
 4 b_str:  .asciz "Good job!\n"
 5 c_str:  .asciz "At least you passed?\n"
 6 d_str:  .asciz "Probably should have dropped it...\n"
 7 f_str:  .asciz "Did you even know you were signed up for the class?\n"
 8
 9 invalid_str:  .asciz "You entered an invalid grade!\n"
10
11 enter_grade:  .asciz "Enter your grade (capital): "
12
13 switch_labels: .word a_label, b_label, c_label, d_label, default_label, f_label
14
15 .text
16
17 main:
18
19     li      a7, 4
20     la      a0, enter_grade
21     ecall
22
23     li      a7, 12    # read char
24     ecall
25
26     li      t2, 5    # f is at index 5
27
28     la      t0, switch_labels
29     addi    t1, a0, -65   # t1 = grade - 'A'
30     blt     t1, x0, default_label   # if (grade-'A' < 0) goto default
31     bgt     t1, t2, default_label  # if (grade-'A' > 5) goto default
32
```

```
33      slli    t1, t1, 2     # offset *= 4 (sizeof(word))
34      add     t0, t0, t1    # t0 = switch_labels + byte_offset =
    &switch_labels[grade-'A']
35      lw      t0, 0(t0)     # load address from jump table
36      jr      t0            # jump to address
37
38  a_label:
39      la      a0, a_str
40      j       end_switch
41
42  b_label:
43      la      a0, b_str
44      j       end_switch
45
46  c_label:
47      la      a0, c_str
48      j       end_switch
49
50  d_label:
51      la      a0, d_str
52      j       end_switch
53
54  f_label:
55      la      a0, f_str
56      j       end_switch
57
58  default_label:
59      la      a0, invalid_str
60
61
62  end_switch:
63      li      a7, 4
64      ecall
65
66      li      a7, 10   # exit
67      ecall
```

You can see we can use the pseudoinstruction `jr` (jump register) to do the eqivalent of the computed goto statement in C.

This example probably wasn't worth making switch style, because the overhead and extra code of making the table and preparing to jump balanced out or even outweighed the savings of a branch instruction for every case. However, as the number of options increases, the favor tilts toward using a jump table like this as long as the range of values isn't too sparse. If the range of values is in the 100's or 1000's but you only have cases for a dozen or so, then obviously it isn't worth creating a table that large only to fill it almost entirely with the default label address.

To reiterate, remember it is not about the magnitude of the actual values you're looking for, only the difference between the highest and lowest because high - low + 1 is the size of your table.

Command Line Arguments

Command line arguments, also known as program arguments, or command line parameters, are strings that are passed to the program on startup. In high level languages like C, they are accessed through the parameters to the main function (naturally):

```
#include <stdio.h>

int main(int argc, char** argv)
{
    printf("There are %d command line arguments:\n", argc);

    for (int i=0; i<argc; i++) {
        printf("%s\n", argv[i]);
    }

    return 0;
}
```

As you can see, `argc` contains the number of parameters and `argv` is an array of those arguments as C strings. If you run this program you'll get something like this:

```
$ ./args 3 random arguments
There are 4 command line arguments:
./args
3
random
arguments
```

Notice that the first argument is the what you actually typed to invoke the program, so you always have at least one argument.

RISC-V works the same way. The number of arguments is in `a0` and an array of strings is in `a1` when main starts. So the same program in RISC-V looks like this:

```
.data

there_are:  .asciz "There are "
arguments:  .asciz " command line arguments:\n"


.text

main:
    mv        t0, a0  # save argc

    li        a7, 4
```

```
13      la        a0, there_are
14      ecall
15
16      mv        a0, t0
17      li        a7, 1   # print int
18      ecall
19
20      li        a7, 4
21      la        a0, arguments
22      ecall
23
24      li        t1, 0   # i = 0
25      j         arg_loop_test
26
27  arg_loop:
28      li        a7, 4
29      lw        a0, 0(a1)
30      ecall
31
32      li        a7, 11
33      li        a0, 10    # '\n'
34      ecall
35
36      addi      t1, t1, 1   # i++
37      addi      a1, a1, 4    # argv++ ie a1 = &argv[i]
38  arg_loop_test:
39      blt       t1, t0, arg_loop  # while (i < argc)
40
41      li        a7, 10
42      ecall
```

Unfortunately, RARS works slightly differently, probably because it's more GUI focused. It does not pass the program/file name as the first argument, so you can actually get 0 arguments:

```
$ java -jar ~/rars_latest.jar args.s pa 3 random arguments
RARS 1.5  Copyright 2003-2019 Pete Sanderson and Kenneth Vollmar

There are 3 command line arguments:
3
random
arguments

Program terminated by calling exit
```

You can see that you have to pass "pa" (for "program arguments") to indicate that the following strings are arguments. In the GUI, there is an option in "Settings" called "Program arguments provided to progam" which if selected will add a text box above the Text Segment for you to enter in the arguments to be passed.

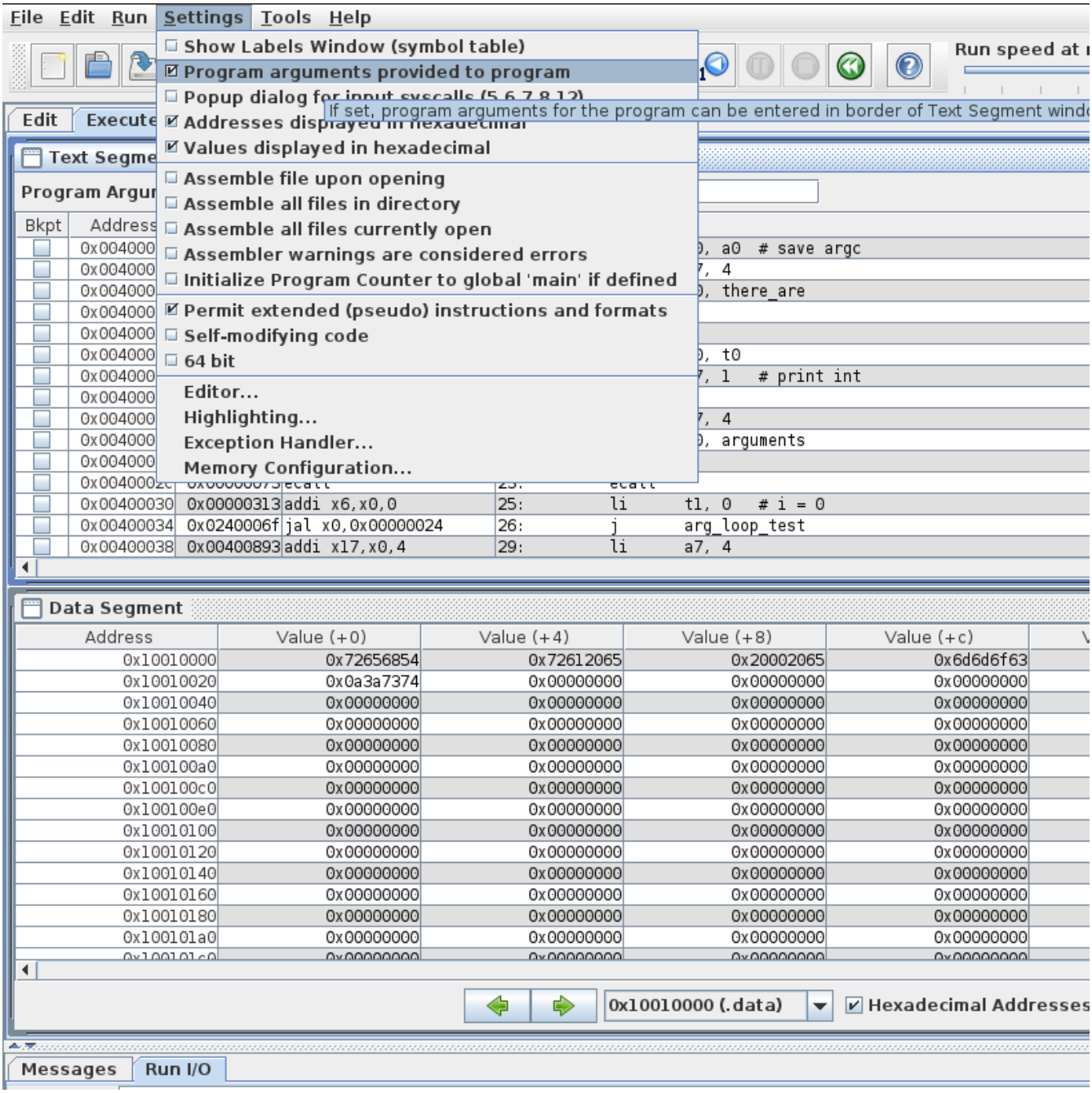


Figure 1. Enable program arguments in RARS GUI

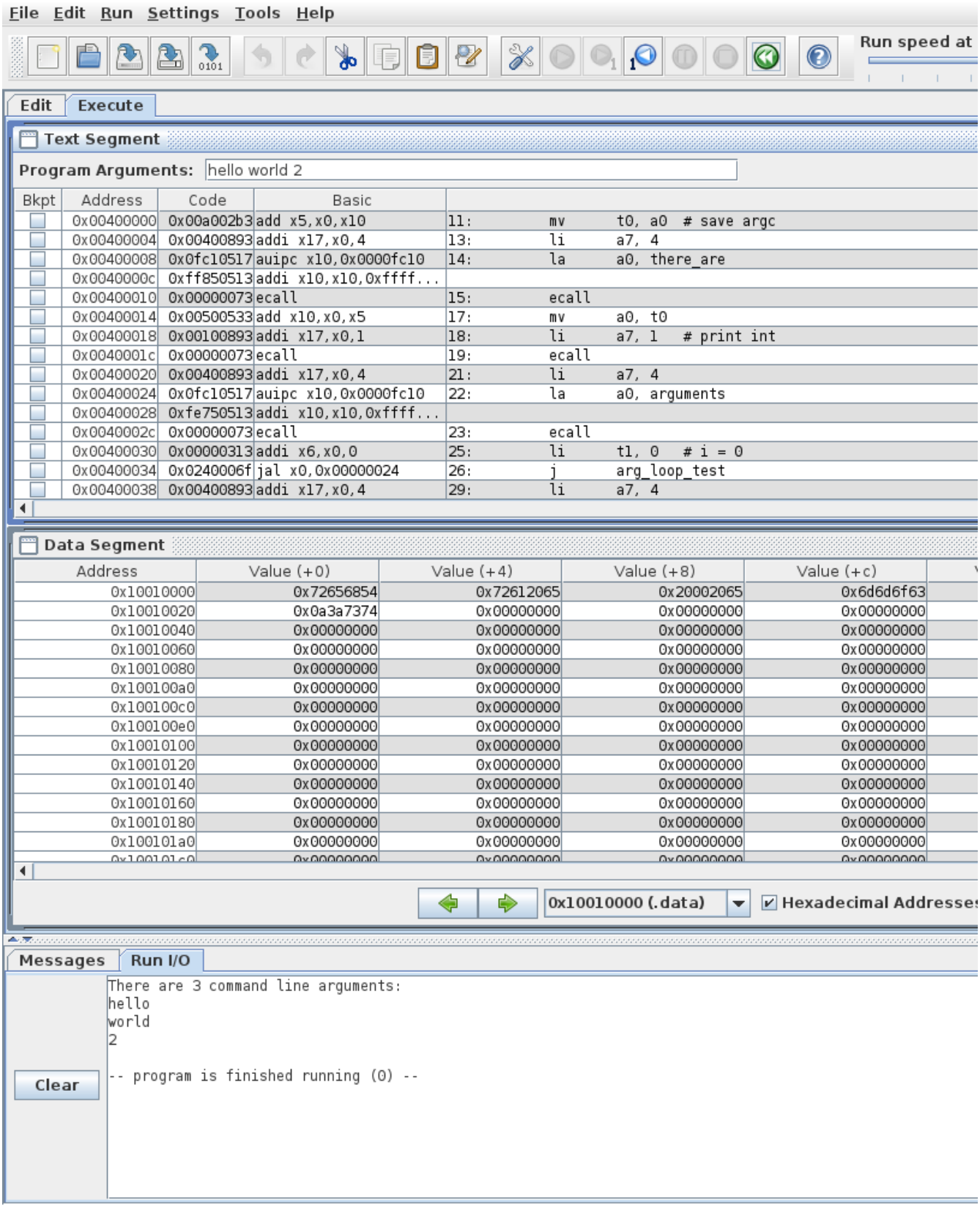


Figure 2. Example using program arguments in RARS GUI

No Pseudoinstructions Allowed

One relatively common assignment requirement is forbidding pseudoinstructions, either all of them, or some subset of them. This forces us to explicitly write what those pseudoinstructions are translated into (or could be translated into since there are often several alternatives).

Table 7. Pseudoinstruction Equivalents

Pseudoinstruction	Example Use	Equivalence

Load Immediate	`li $t0, 42`	`ori $t0, $0, 42`
		`# or`
		`addi $t0, $0, 42`

Move	`move $t0, $t1`	`or $t0, $0, $t1`
		`# or`
		`add $t0, $0, $t1`

Load Address	`la $t0, label`	`lui $t0, 0x10010` `ori $t0, $t0, byte_offset`

Branch Less Than	`blt $t0, $t1, label`	`# t2 = t0 < t1`
		`slt $t2, $t0, $t1`
		`bne $t2, $0, label`
		
		`# or if you're counting up and`
		`# you know they'll be equal,`
		`# you can simplify to`
		`bne $t0, $t1, label`

Branch Greater Than	`bgt $t0, $t1, label`	`# flip order to get >`
		`slt $t2, $t1, $t0`
		`bne $t2, $0, label`

Branch Less Than or Equal	`ble $t0, $t1, label`	`# test for < and = separately`
		`slt $t2, $t0, $t1`
		`bne $t2, $0, label`
		`beq $t0, $t1, label`
		
		`# or add 1 to change <= to <`
		`# use a spare reg if you need`
		`# to preserve the original value`
		`addi $t3, $t1, 1`
		`slt $t2, $t0, $t3`
		`bne $t2, $0, label`

Pseudoinstruction	Example Use	Equivalence

Branch Greater Than or Equal	`bge  $t0, $t1, label`	`# test for opposite`
		`# and branch on failure`
		`slt  $t2, $t0, $t1`
		`beq  $t2, $0, label`

You can see how you use the non-pseudoinstructions to match the same behavior, and there's often (usually) more than one way. Of all of them, `ble` is the worst, because what was 1 instruction becomes 3, and you'll sometimes need an extra register to hold the "plus 1" value if you still need the original.

Another thing I should comment on is the `la` equivalence. The reason it is a pseudoinstruction in the first place is that an address is 32 bits. That's also the size of a whole instruction. Clearly there's no way to represent a whole address and anything else at the same time. The lower left corner of the greensheet has the actual formats of the 3 different types of instructions and even the jump format still needs 6 bits for the opcode. This is why `lui` exists, in order to facilitate getting a full address into a register by doing it in two halves, 16 + 16. The lower 16 can be placed with `addi` or `ori` after the `lui`.

That begs the question, what actually goes in the upper half? Well, since we're dealing with addresses in the `.data` section, the upper portion should match the upper part of address of the `.data` section. In SPIM the `data` section starts at `0x10000000` in bare mode. In normal mode it is `0x10010000`, but you'd be able to use `la` in normal mode. However, in MARS it is always `0x10010000`, so you won't be able to have it work correctly in bare SPIM and MARS without changing that back and forth.

But what about the lower part of the address? This involves counting the bytes from the top of `.data` to the label you want. If all you have is words, halfs, floats, doubles, or space (with a round number), that's fairly easy, but the second you have strings between the start and the label you want, it's a bit more painful. This is why I recommend putting any string declarations at the bottom so at least any other globals will have nice even offsets. Also, if you have a bunch of globals, it doesn't hurt to count once and put the offsets in comments above each label so you don't forget. Of course, none of this matters if you're allowed to just use `la` which is true the vast majority of the time.

Let's look at a small example. We'll convert the args.s from above (reproduced here for convenience) to bare mode:

```
1 .data
2
3 there_are:  .asciz "There are "
4 arguments:  .asciz " command line arguments:\n"
5
6
7 .text
8
9 main:
```

```
    mv        t0, a0  # save argc

    li        a7, 4
    la        a0, there_are
    ecall

    mv        a0, t0
    li        a7, 1   # print int
    ecall

    li        a7, 4
    la        a0, arguments
    ecall

    li        t1, 0   # i = 0
    j         arg_loop_test

arg_loop:
    li        a7, 4
    lw        a0, 0(a1)
    ecall

    li        a7, 11
    li        a0, 10    # '\n'
    ecall

    addi      t1, t1, 1   # i++
    addi      a1, a1, 4    # argv++ ie a1 = &argv[i]
arg_loop_test:
    blt       t1, t0, arg_loop  # while (i < argc)

    li        a7, 10
    ecall
```

So we need to change the `mv`, the `li`'s, the `j`, and the `la`.

```
# RARS .data (like MARS) always starts at 0x10010000, whether pseudoinstructions
# are on or not.

.data

there_are:  .asciz "There are "
arguments:  .asciz " command line arguments:\n"

.text

.globl main
main:
    or        t0, x0, a0  # save argc

```

```
15      ori       a7, x0, 4
16
17      #la        a0, there_are
18      lui       a0, 0x10010    # there_are is at beginning of data so just lui, lower
    is 0
19      ecall
20
21      or        a0, x0, t0
22      ori       a7, x0, 1   # print int
23      ecall
24
25      ori       a7, x0, 4
26      lui       a0, 0x10010
27      ori       a0, a0, 11   # 11 is length in bytes of "There are " 10 chars + '\0'
28      #la        a0, arguments
29      ecall
30
31      ori       t1, x0, 0   # i = 0
32      #j         arg_loop_test
33      jal       x0, arg_loop_test
34
35  arg_loop:
36      ori       a7, x0, 4     # print string for argv[i]
37      lw        a0, 0(a1)
38      ecall
39
40      ori       a7, x0, 11
41      ori       a0, x0, 10    # '\n'
42      ecall
43
44      addi      t1, t1, 1    # i++
45      addi      a1, a1, 4    # argv++ ie a1 = &argv[i]
46  arg_loop_test:
47      blt       t1, t0, arg_loop  # while (i < argc)
48
49      ori       a7, x0, 10
50      ecall
```

Following the table, you can see the `mv` became `or`, the `li` became `ori`, the `j` became `jal` with `x0` as the destination register, and lastly the `la` became `lui` plus an `ori` if necessary for the byte offset.

Exercises

You can support the book and purchase the chapter exercise solutions here.

1. Convert the exercises from chapter 5 to run in `spim -bare` mode and/or in MARS with delayed branches and no pseudoinstructions (`java -jar ~/Mars_4.5.jar db np file.s` on the command line).
2. Convert the following C code to MIPS using a jump table (Note in C/C++ enum values start at 0

and go up by one unless the user manually assigns a value, in which case it continues counting up from there).

```
enum { STATE0, STATE1, STATE2, STATE3, STATE14 = 14, STATE42 = 42, STATE43,
STATE44 };


int main()
{
    int num;
    do {
        printf("Enter a number between 0 and 50: ");
        scanf("%d", &num);
    } while (num < 0 || num > 50);

    switch (num) {
    case STATE0:
        puts("Zilch");
        break;
    case STATE1:
        puts("Uno");
        break;
    case STATE2:
        puts("Dos");
        break;
    case STATE3:
        puts("Tres");
        break;
    case STATE14:
        puts("Catorce");
    case STATE42:
        puts("The answer to life, the universe, and everything.");
    case STATE43:
        puts("Off by one");
    case STATE44:
        puts("4 * 11?");
        break;
    }

    puts("Thanks for playing!");


    return 0;
}
```

[1] When I find the post I read years ago about how using tabs saves CO2 I'll put it here, but I'm joking. I use tabs because it makes sense and there are accessibility reasons too: https://www.reddit.com/r/javascript/comments/c8drjo/nobody_talks_about_the_real_reason_to_use_tabs/

[2] https://gcc.gnu.org/onlinedocs/gcc/Labels-as-Values.html

References and Useful Links

- Greensheet
- MARS syscall list
- learnxinyminutes page
- Randolph-Macon College MIPS Reference
- CCSU MIPS Reference

Supporters

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supporter17	supporter18	supporter19
supporter20		

Bronze

supporter21	supporter22	supporter23
supporter24	supporter25	supporter26
supporter27	supporter28	supporter29
supporter30		