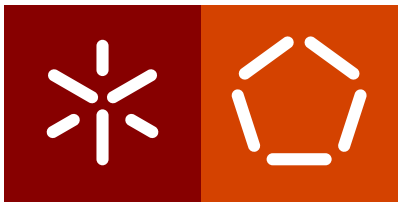

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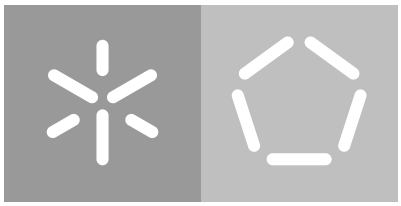

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Implementing an Integrated Syntax Directed Editor for LISS.

Master dissertation
Master Degree in Computer Science

Dissertation supervised by
Professor Pedro Rangel Henriques
Professor Daniela da Cruz

December 2016

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And last but not least, I would like to dedicate this thesis to my, particularly, most beautiful mother. Despite you couldn't be here to watch me conclude my studies. Wherever you are, I hope that you are proud of me. None of this could have been made without their unconditional help.

ABSTRACT

The aim of this master work is to implement LISS language in ANTLR compiler generator system using an attribute grammar which create an abstract syntax tree (AST) and generate MIPS assembly code for MARS (MIPS Assembler and Runtime Simulator) . Using that AST, it is possible to create a Syntax Directed Editor (SDE) in order to provide the typical help of a structured editor which controls the writing according to language syntax as defined by the underlying context free grammar.

RESUMO

O tema desta dissertação é implementar a linguagem LISS em ANTLR com um gramática de atributos e no qual, irá criar uma árvore sintática abstrata e gerar MIPS assembly código para MARS (MIPS Assembler and Runtime Simulator). Usando esta árvore sintática abstrata, criaremos uma SDE (Editor Dirigido a Sintaxe) no qual fornecerá toda a ajuda típica de um editor estruturado que controlará a escrita de acordo com a gramática.

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INTRODUCTION

In informatics, solving problems with computers is related to the necessity of helping the end-users, facilitating their life. And all these necessities pass through developers who creates programs for this purpose.

However, developing programs is a difficult task; analyzing problems, and debugging software takes effort and time.

And this is why we must find a solution for these problems.

Developing a software package requires tools to help the developers to maximize their programming productivity. These tools are: on one hand, compilers to generate lower-level code (machine code) from the high-level source code (the input program written in an high-level programming language); on the other hand, editors to create that source code. And to make easier and safer the programmers work, high-level programming languages were created for facilitating their work.

This is not enough to overcome all the difficulties for creating a program in a safety way and having a high level productivity!

This is why we need to have fresh ideas and to implement more features to help on solving these problems.

1.1 OBJECTIVES

In this work, this project aims to develop an editor with the concept of a SDE (Syntax Directed Editor).

It is intended that the editor works with language designed by the members of the Language Processing group at UM which is called LISS.

LISS language will be specified by an attribute grammar that will be passed, as input, to ANTLR. The compiler generated by ANTLR will generate MIPS assembly code (lower-level source code).

The front-end and the back-end of that compiler will be explained and detailed along the next pages.

1.2 RESEARCH HYPOTHESIS

It is possible to synthesize a complete source program, ready to be compiled and executed, selecting the appropriate alternative language constructors and writing literals in the right positions in a special editor guided by the source language structure, or syntax.

1.3 DOCUMENT STRUCTURE

In this section, the project planned for this master thesis will be explained.

First, create an ANTLR version of the CFG grammar for LISS language.

Second, extend the LISS CFG to an AG in order to specify throw it the generation of MIPS assembly code. Then verify the correctness of the assembly code generated with a simple MIPS simulator, named MARS, that will be selected to provide all the tools for checking it.

Third, the desired Structure-Editor, SDE, will be developed based on ANTLR. It will be implemented with Java (JAVAFX) because ANTLR has always been implemented via Java and it is said, also, to use Java target as a reference implementation mirrored by other targets. At this phase, we will create an IDE similar to other platforms but with the capacity of being a syntax-directed editor.

Finally, exhaustive and relevant tests will be made with the tool created and, the outcomes will be analyzed and discussed.

2

LISS LANGUAGE

LISS (da Cruz and Henriques, 2007a) -that stands for Language of Integers, Sequences and Sets- is an imperative programming language, defined by the Language Processing members (Pedro Henriques and Leonor Barroca) at UM for teaching purposes (compiler course).

The idea behind the design of LISS language was to create a simplified version of the more usual imperative languages although combining functionalities from various languages.

It is designed to have atomic or structured integer values, as well as, control statements and block structure statements.

Before explaining the basic statements of the language and its data types using a context free grammar, let's remember briefly the basilar concepts related to formal programming languages and their definition using grammars (context free and attribute grammars).

2.1 FORMAL LANGUAGES AND GRAMMAR

A grammar (Chomsky, 1962; Gaudel, 1983; Waite and Goos, 1984; Aho et al., 1986; Kastens, 1991b; Muchnick, 1997; Hopcroft et al., 2006; Grune et al., 2012) is a set of derivation rules (or production) that explains how words are used to build the sentences of a language.

A grammar (Deransart et al., 1988; Alblas, 1991; Kastens, 1991a; Swierstra and Vogt, 1991; Deransart and Jourdan, 1990; Räihä, 1980; Filè, 1983; Oliveira et al., 2010) is considered to be a language generator and also a language recognizer (checking if a sentence is correctly derived from the grammar).

The rules describe how a string is formed using the language alphabet, defining the sentences that are valid according to the language syntax.

One of the most important researchers in this area was Noam Chomsky. He defined the notion of grammar in computer science's field.

He described that a formal grammar is composed by a finite set of production rules

$$(\text{left hand side} \mapsto \text{right hand side})$$

where each side is composed by a sequence of symbols.

These symbols are split into two sets : non terminals, terminals; the start symbol is a special non-terminal.

There is, always, at least one rule for the start symbol (see Figure 1) followed by other rules to derive each non-terminal. The non terminals are symbols which can be replaced and terminals are symbols which cannot be.

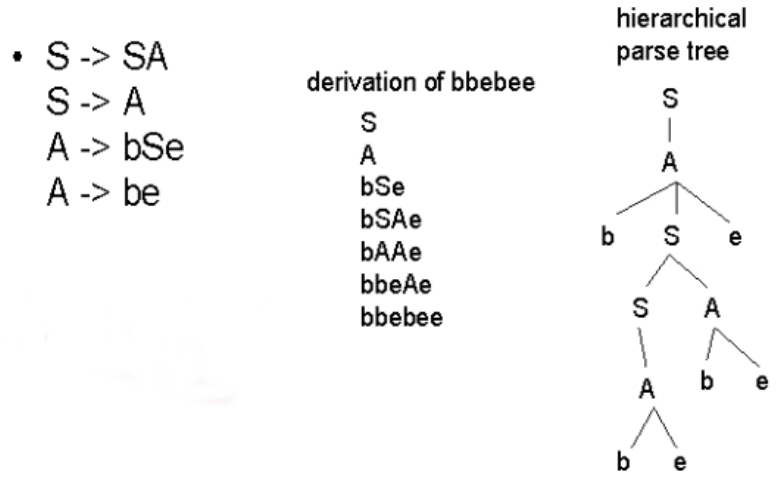


Figure 1.: CFG example [1]

One valid sentences (Example in Figure 1), could be : bbebee .

In the compilers area two major classes of grammars are used : CFG (Context-free grammar) and AG (Attribute Grammar).

The difference between these two grammars are that a CFG is directed to define the syntax (only) and, AG contains semantic and syntax rules.

An AG is , basically, a GFC grammar extended with semantic definitions. It is a formal way to define attributes for the symbols that occur in each production of the underlying grammar. We can associate values to these attributes later, after processed with a parser; the evaluation will occur applying those semantic definition to any node of the abstract syntax tree. These attributes are divided into two groups: synthesized attributes and inherited attributes.

The synthesized attributes are the result of the attribute evaluation rules for the root symbol of each subtree, and may also use the values of the inherited attributes. The inherited attributes are passed down from parent nodes to children or between siblings.

Like that it is possible to transport information anywhere in the abstract syntax tree which is one of the strength for using an AG.

2.2 LISS DATA TYPES

There are 5 types available. From atomic to structured types, they are known as : integer, boolean, array, set and sequence.

Used for declaring a variable in a program, the data type gives us vital information for understanding what kind of value we are dealing with.

Let's obverse a LISS code example:

```
a -> integer;
b -> boolean;
c -> array size 5,4;
d -> set;
e -> sequence;
```

Listing 2.1: Declaring a variable in LISS

As we can see in Listing 2.1, some variables ('a','b','c','d' and 'e') are being declared each one associated to a type ('integer', 'boolean', 'array', 'set' and 'sequence'). Syntactically, in LISS, this is done by writing the variable name followed by an arrow and the type of the variable (see Listing 2.2).

```
variable_declaration : vars '->' type ';'
                     ;
vars : var (',' var )*
   ;
var : identifier value_var
  ;
value_var :
        | '=' inic_var
        ;
type : 'integer'
   | 'boolean'
   | 'set'
   | 'sequence'
   | 'array' 'size' dimension
   ;
dimension : number (',' number )*
        ;
inic_var : constant
       | array_definition
       | set_definition
       | sequence_definition
       ;
constant : sign number
```

Table 1.: LISS data types

Type	Default Value
boolean	false
integer	0
array	[0,...,0]
set	{}
sequence	nil

```
24          | 'true'
25          | 'false'
26          ;
27  sign :
28      | '+'
29      | '-'
30      ;
```

Listing 2.2: CFG for declaring a variable in LISS

Variables that are not initialized, have a default value (according to Table 1).

Table 2.: Operations and signatures in LISS

Operators && Functions	**Signatures**
+ (add)	integer x integer -> integer
- (subtract)	integer x integer -> integer
|| (or)	boolean x boolean -> boolean
++ (union)	set x set -> set
/ (division)	integer x integer -> integer
* (multiply)	integer x integer -> integer
&& (and)	boolean x boolean -> boolean
** (intersection)	set x set -> set
== (equal)	integer x integer -> integer; boolean x boolean -> boolean
!= (not equal)	integer x integer -> integer; boolean x boolean -> boolean
<(less than)	integer x integer -> boolean
>(greater than)	integer x integer -> boolean
<= (less than or equal to)	integer x integer -> boolean
>= (great than or equal to)	integer x integer -> boolean
in (contains)	integer x set -> boolean
tail	sequence -> sequence
head	sequence -> integer
cons	integer x sequence -> sequence
delete	integer x sequence -> sequence
copy	sequence x sequence -> void
cat	sequence x sequence -> void
isEmpty	sequence -> boolean
length	sequence -> integer
isMember	integer x sequence -> boolean

Additionally, we may change the default values of the variables by initializing them with a different value (see an example in Listing 2.3). This can be made by writing an equal symbol after the variable name and, then, inserting the right value according to the type (see example in Listing 2.2).

```
1 a = 4, b -> integer;
2 t = true -> boolean;
3 vector1 = [1,2,3], vector2 -> array size 5;
4 a = { x | x<10} -> set ;
5 seq1 = <<10,20,30,40,50>>, seq3 = <<1,2>>, seq2 -> sequence;
```

Listing 2.3: Initialize a variable

Now, let's define which types are, correctly, associated with the arithmetic operators and functions in LISS (see Table 2).

So, in Table 2, we list the operators and functions, available in LISS, and their signature. In order to understand the table better, we will explain how to read the table and its signature with one example.

Consider the symbol '+' (Table 2), indicates that both operands must be of type integer. The result of that operation, indicated by the symbol '->', will be an integer. Semantically, operations must be valid according to Table 2; otherwise the operations would be incorrect and throw an error.

Arrays. LISS supports a way of indexing a collection of integer values such that each value is uniquely addressed. LISS also supports an important property of multidimensionality.

Called as 'array', it is considered to be a static structured type due to the fact that its dimensions and maximum size of elements in each dimension is fixed at the declaration time.

The operations defined over arrays are:

1. *indexing*
2. *assignment*

Arrays can be initialized, in the declaration section, partially or completely in each dimension. For example, consider an array of dimension 3x2 declared in the following way:

```
array1 = [[1,2],[5]] -> array size 3,2;
```

Thi is equivalent to the initialization below:

```
array1 = [[1,2],[5,0],[0,0]] -> array size 3,2;
```

Notice that the elements that are not explicitly assigned, are initialized with the value 0 (see Table 1).

The grammar for array declaration and initialization is shown below.

```
array_definition : '[' array_initialization ']'
                 ;

array_initialization : elem (',' elem)*
                     ;

elem : number
```

```
8       | array_definition
9       ;
```

Sets. The type *set*, in LISS, is a collection of integers with no repeated numbers.

It is defined by an expression, in a comprehension, instead of by enumeration of its element. A *set* variable can have an empty value and, syntactically, this is done by writing '{}'.

To define a set by comprehension, the free variable and the expression shall be return between curly brackets. The 'identifier' (free variable) is separated from the expression by an explicit symbol '|'.

The expression is built up from relational and boolean operators to define an integer interval.

The operations defined for sets are :

1. *union*
2. *intersection*
3. *in* (membership)

Let's see an example of its syntax below:

```
1   set1 = {x | x < 6 && x > -7} -> set;
```

This declaration defines a set including all the integers from -7 to 6 (open interval) and other numbers are not included in the set.

The syntax for set declaration and initialization is :

```
1   set_definition : '{' set_initialization '}'
2                  ;
3
4   set_initialization :
5                      | identifier '|' expression
6                      ;
```

Sequences. Considered as a dynamic array of one dimension, the type sequence is a list of ordered integers. But, in opposition to the concept of an array, its size is not fixed; this means that it grows dinamicallly at run time like a linked list. A sequence can have the empty value (syntactically done by writing '<<>>'). If not empty, the sequence value is defined by enumerating its components (integers) in the right order. Let's see deeper with one example:

```
1 c=<<1,2,3>> -> sequence;
```

Listing 2.4: Example of valid operations using sequence on LISS

In the example of Listing 2.4 the sequence is defined by three numbers (3,2,1).
The operations defined for the sequence are:

1. *tail* (all the elements but the first)
2. *head* (the first element of the sequence)
3. *cons* (adds an element in the head of the sequence)
4. *delete* (remove a given element from the sequence)
5. *copy* (copies all the elements to another sequence)
6. *cat* (concatenates the second sequence at the end of the first sequence)
7. *isEmpty* (true if the sequence is empty)
8. *length* (number of elements of the sequence)
9. *isMember* (true if the number is an element of the sequence)

Those operations will be explained further and deeper.

The grammar below defines how to declare a sequence:

```
1 sequence_definition : '<<' sequence_initialization '>>'
2                     ;
3
4 sequence_initialization :
5                         | values
6                         ;
7
8 values : number (',' number )*
9        ;
```

2.2.1 *LISS lexical conventions*

Once you've declared a variable of a certain type, you cannot redeclare it again with the same name.

The variable name must be unique (see Listing 2.5).

```
program single_variable_name{
  declarations
    int=1 -> integer;
    int=true -> boolean; //cannot declare this variable with this name
       (already exists)
  statements
}
```

Listing 2.5: Conflicts with variable names

Keywords cannot be used as variable names.

For example, you cannot declare a variable with the name *array* due to the fact that *array* is a keyword in LISS (in this case, a type).

See the example in Listing 2.6.

```
array -> array size 3,4; //variable 'array' cannot be declared as a
   name
integer -> integer;
```

Listing 2.6: Conflicts with keyword names

Variable names contain only letters and numbers, or the underscore sign. However the first character of the variable name must be a letter (lower or upper case). See the example below:

```
My_variable_1
MyVariable1
```

Numbers are composed of digits (one or more). Nothing more is allowed.

See example below:

```
1562
1
```

A string is a sequence of n-characters enclosed by double quotes.

See example below:

```
"This is a string"
```

2.3 LISS BLOCKS AND STATEMENTS

A LISS program is always composed of two parts: declarations and statements (a program block). LISS language is structured with a simple hierarchy. And this is done by structuring LISS code as a block.

Any program begins with a name then appear the declaration of variables and subprograms. After that appear the flow of the program by writing statements.

Let's see one example (see Listing 2.7).

```
program sum{
  declarations
      int=2 -> integer;
  statements
      writeln(int+3);
}
```

Listing 2.7: The structure of a LISS program (example)

So a program in LISS begins by, syntactically, writing 'program' and then the name of the program (in this case, the name is 'sum'). A pair of curly braces delimits the contents of the program; that is done by opening it after the name of the program and closing it at the end of the program. After the left brace, appear the declaration and statement blocks.

As in a traditional imperative language (let's compare 'C language'), if we don't take the habit of declaring the variable always in a certain part of the code, it becomes confusing. This makes the programmer's life harder to understand the code when the code is quite long.

So, in LISS, we always declare variables first (syntactically written by 'declarations') and then the statements (syntactically written by 'statements'). This is due to the fact that LISS wants to help the user to create solid and correct code. And in this case, the user will always know that all the variable declarations will be always at the top of the statements and not randomly everywhere (see grammar in Listing 2.8).

```
liss : 'program' identifier body
   ;

body : '{'
     'declarations' declarations
     'statements'   statements
     '}'
   ;
```

Listing 2.8: CFG for program in LISS

2.3.1 *LISS declarations*

The declaration part is divided into two other parts: variable declarations and subprogram declarations, both optional.

The first part is explained in section 2.2; the subprogram part will be discussed later in section 2.4.

This part is specified by the following grammar (see Listing 2.9).

```
declarations : variable_declaration* subprogram_definition*
             ;
```

Listing 2.9: CFG for declarations in LISS

2.3.2 *LISS statements*

As said previously, under the statements part, we control and implement the flow of a LISS program. In LISS, we may write none or, one or more statements consecutively.

Every statement ends with a semicolon, unless two type of statements (conditional and cyclic statements) as shown in Listing 2.10.

```
statements : statement*
           ;
statement : assignment ';'
          | write_statement ';'
          | read_statement ';'
          | function_call ';'
          | conditional_statement
          | iterative_statement
          | succ_or_pred ';'
          | copy_statement ';'
          | cat_statement ';'
          ;
```

Listing 2.10: CFG for statements in LISS

Let's see one example of a LISS program which shows how the language shall be used (see Listing 2.11).

```
program factorial{
  declarations
      res=1, i -> integer;
  statements
      read(i);
```

```
6         for(j in 1..i){
7             res=res*j;
8         }
9         writeln(res);
10    }
```

Listing 2.11: Example of using statements in LISS

Assignment. This statement assigns, as it is called, values to a variable and it is defined for every type available on LISS. This operation is done by writing the symbol "=" in which a variable is assigned to the left side of the symbol and a value to the right side of the symbol.

Notice that an assignment requires that the variable on the left and the expression on the right must agree in type.

Let's see in Listing 2.12 an example.

```
1  program assignment1{
2    declarations
3      intA -> integer;
4      bool -> boolean;
5    statements
6      intA = -3 + 5 * 9;
7      bool = 2 < 8;
8  }
```

Listing 2.12: Example of assignment in LISS

In Listing 2.12, we can see assignment statements of integers and boolean types. Those assignments are correct, as noticed in the previous paragraphs, because they have the same type on the left and right side of the symbol equals (operations of integers assigned to a variable of integer type and operation of booleans assigned to a variable of boolean type).

The grammar that rules the assignment is shown at Listing 2.13.

```
1  assignment : designator '=' expression
2             ;
```

Listing 2.13: CFG for assignment in LISS

I/O. The input and output statements are also available in LISS.

The *read* operations, called syntactically as 'input' in LISS, assign a value to a variable obtained from the standard input and require to be an atomic value (in this case, only an integer value).

```
1  program input1{
```

```
  declarations
    myInteger -> integer;
  statements
    input(myInteger);
}
```

Listing 2.14: Example of input operation in LISS

Notice that, in Listing 2.14, the variable *myInteger* must be declared and must be integer otherwise the operations fails. The grammar that rules the input statement, is shown in Listing 2.15.

```
read_statement : 'input' '(' identifier ')'
               ;
```

Listing 2.15: CFG for input operation in LISS

The *write* operations, called syntactically as 'write' or 'writeln' in LISS, print an integer value in the standard output. Notice that 'write' operation only prints the value and doesn't move to a new line; instead, 'writeln' moves to a new line at the end.

Listing 2.16 shows some more examples.

```
writeln(4*3);
writeln(2);
writeln();
```

Listing 2.16: Example of output operations in LISS

Note that the write statement may have as assignment, an atomic value as well as an empty value or some complex arithmetic expression (see grammar in 2.17).

```
write_statement : write_expr '(' print_what ')'
                ;

write_expr : 'write'
           | 'writeln'
           ;

print_what :
           | expression
           ;
```

Listing 2.17: CFG for output operation in LISS

Function call. The function call is a statement that is available for using the functions created in the program under the section 'declarations' (as described in Section 2.3.1). This will allow reusing functions that were created by calling them instead of creating duplicated code.

See Listing 2.18 for a complete example.

```
program SubPrg {

 declarations

   a = 4, b= 5, c= 5 -> integer;
   d = [10,20,30,40], ev -> array size 4;


   subprogram calculate() -> integer
   {
     declarations
           fac = 6 -> integer;
           res = -16 -> integer;

       subprogram factorial(n -> integer; m -> array size 4) -> integer
           {
             declarations
                   res = 1 -> integer;
             statements
                   while (n > 0)
                   {
                       res = res * n;
                       n = n -1;
                   }

                   for (a in 0..3) stepUp 1
                   {
                     d[a] = a*res;
                   }
                   return res;
           }
     statements
           res = factorial(fac,d);
           return res/2;
   }


 statements
```

```
39
40      a = calculate();
41      writeln(a);
42      writeln(d);
43  }
```

Listing 2.18: Example of call function in LISS

In Listing 2.18, we can see that the function *calculate()*, called in the main program, and that is created under the declarations section.

The grammar who rules the function call is shown in Listing 2.19.

```
1   function_call : identifier '(' sub_prg_args ')'
2                 ;
3   sub_prg_args :
4                | args
5                ;
6   args : expression (',' expression )*
7      ;
```

Listing 2.19: CFG for call function in LISS

2.3.3 *LISS control statements*

LISS language includes some statements for controlling the execution flow at runtime with two different kind of behaviour.

The first one is called conditional statement and it has only one variant in LISS language (see Listing 2.20).

The second one is called cyclic statement or iterative statement, and it has two variants (see Listing 2.20).

```
1   conditional_statement : if_then_else_stat
2                         ;
3   iterative_statement : for_stat
4                       | while_stat
5                       ;
```

Listing 2.20: CFG for control statement in LISS

These control statements, mimics the syntax and the behaviour of other modern imperative language.

CONDITIONAL The if-statement, which is common across many modern programming languages, performs different actions according to decision depending on the truth value of a control conditional expression: an alternative 'else' block is also allowed (optional).

If the conditional expression evaluates 'true', the content of 'then' block will be executed. Otherwise, if the condition is 'false', the 'then' block is ignored; and if an 'else' block is provided it will be executed alternatively.

Let's see an example in Listing 2.21.

```
1 if(y==x)
2 then{
3   x=x+1;
4 }else{
5   x=x+2;
6 }
```

Listing 2.21: LISS syntax of a if statement

The code shown in Listing 2.21, means that the if-statement evaluates the conditional expression 'y==x'. If the expression, which must be boolean, is true, then every action in the 'then' block will be executed and the block 'else' will be ignored. Otherwise, if the condition is false, every action in the 'else' block is executed ignoring the 'then' block.

If the else-statement is not provided, the if-statement will finish and do not perform any actions.

The syntax of the if-statement in LISS is shown in Listing 2.22.

```
1 if_then_else_stat : 'if' '(' expression ')'
2                     'then' '{' statements '}'
3                     else_expression
4                     ;
5
6 else_expression :
7               | 'else' '{' statements '}'
8               ;
```

Listing 2.22: CFG for iterative statement in LISS

ITERATIVE We should take a look at the behaviour of each iterative control statement to understand it deeper.

The for-statement offers two variants to control the repetition. Normally, in a conventional way, the for-loop has a control variable which takes a value in a given range and step up or step down by a default or an explicit value.

In LISS, the control variable is set in a given integer interval defined by the lower and upper bounds. By default, the step is one, which means that the control variable is incremented by one at the end of each iteration but it is possible to increment or decrement it by a different value, setting it explicitly. Additionally, we may write a condition for filtering the values in the interval. This can be done as shown in the following example:

```
for(a in 1..10) stepUp 2 satisfying elems[a]==1{
  ...
}
```

Listing 2.23: LISS syntax of a for-loop statement

In Listing 2.23, the control variable 'a' is set to a range 1 to 10 and would be increased (due to the 'stepUp' constructor) by 2. Also there is a filter condition (after the 'satisfying' keyword) that restricts the values of 'a' to those that makes the condition 'elems[a]==1' true. Notice that the filter expression must be boolean.

After each cycle, the control variable will be incremented with value 2 and the filter condition tested again.

This is the first way of expressing the control in a for-loop statement. Let's see the second way in the sequel.

There is also the possibility to assign to the control variable the values in an array, like illustrated in the following example:

```
for(b inArray elems){
      ...
}
```

Listing 2.24: LISS syntax of a for-each statement on array

In Listing 2.24, the control variable 'b' is assigned with all of the elements of the array and begins with his lower index (zero) until his upper index (size of the array minus one). Notice that, in this case, we cannot apply an increment or decrement neither a filter condition.

The next grammar fragment describes the cycle 'for' in LISS:

```
for_stat : 'for' '(' interval ')' step satisfy
         '{' statements '}'
       ;
interval : identifier type_interval
       ;
type_interval : 'in' range
            | 'inArray' identifier
            ;
range : minimum '..' maximum
    ;
```

```
minimum : number
        | identifier
        ;
maximum : number
        | identifier
        ;
step :
    | up_down number
    ;
up_down : 'stepUp'
        | 'stepDown'
        ;
satisfy :
        | 'satisfying' expression
        ;
```

Listing 2.25: CFG for for-statement in LISS

Finally, the while-statement consists in a block of code that is executed repeatly until the control condition evaluates 'false'.

Each time that the 'while' block is performed, the conditional expression associated will be evaluated again to decide whether to repeat the execution of the statements in the block or to continue the normal program flow.

Let's see an example in Listing 2.26.

```
while (n > 0)
{
  res = res * n;
  pred n;
}
```

Listing 2.26: LISS syntax of a while-statement in LISS

In Listing 2.26, the while-statement is controled by the conditional expression 'n>0' that is evaluated at the beginning. If the condition is true, then all the actions that are inside the braces will be performed. Later, after executing all the actions, the condition will be evaluated again. If the condition remains 'true', then those actions would be executed again otherwise if the condition is false, the while-statement will be exited.

The syntax that rule the while-statement is shown below:

```
while_stat : 'while' '(' expression ')'
           '{' statements '}'
           ;
```

Listing 2.27: CFG for while-statement in LISS

2.3.4 *Other statements*

LISS language offers other statements to make it more expressive easing the codification of any imperative algorithm.

Succ/Pred. Those statements are available for incrementing or decrementing a variable. This is a common situation in modern programming languages, making life easier for the developers.

The keyword 'succ' means increment (successor) and the syntax 'pred' means decrease (predecessor). Only integer variables can be used with those constructors.

Listing 2.28 illustrates both statements.

```
1 succ int1;
2 pred int1;
```

Listing 2.28: Example of using succ/pred in LISS

As we can see in Listing 2.28, variable 'int1' is, first, incremented by 1 and then it is decremented also by 1.

Grammar of 'succ' and 'pred' in LISS is shown in Listing 2.29.

```
1 succ_or_pred : succ_pred identifier
2               ;
3 succ_pred : 'succ'
4           | 'pred'
5           ;
```

Listing 2.29: CFG for succ and pred in LISS

Copy statement. This statement is applied only to variables of type sequence. Basically, it copies one sequence to another sequence. Let's see an example in Listing 2.30.

```
1 copy(seq1,seq2);
```

Listing 2.30: Example of copy statement in LISS

Notice that 'copy' is a statement and not a function: it modifies the arguments but does not return any value.

In Listing 2.30, the statement 'copy' copies the content of the variable *seq1* to *seq2*.

The grammar for 'copy' statement is in Listing 2.31.

```
copy_statement : 'copy' '(' identifier ',' identifier ')'
               ;
```

Listing 2.31: CFG for copy statement in LISS

Cat statement.

'Cat' statement is simular to 'copy', it only operates with variables of type sequence. The behaviour of this statement is to concatenate a sequence to another sequence. Let's see an example in Listing 2.32).

```
cat(seq1,seq2);
```

Listing 2.32: Example of cat statement in LISS

In Listing 2.32, 'cat' concatenates the content of *seq2* to *seq1*. Again, 'cat' is not a function; it modifies the arguments instead of returning a value.

The grammar for cat-statement is shown in Listing 2.33.

```
cat_statement : 'cat' '(' identifier ',' identifier ')'
              ;
```

Listing 2.33: CFG for cat statement in LISS

2.4 LISS SUBPROGRAMS

In LISS, it is possible to organize the code by splitting the general block of statements into sub-programs. This allows the programmer to reuse or to give more clarity to his code by creating functions or procedures. Also, it is possible to create sub-programs inside sub-programs by using a nesting strategy.

The syntax that defines a sub-program in LISS is shown in Listing 2.34.

```
subprogram_definition: 'subprogram' identifier '(' formal_args ')'
   return_type f_body
                    ;
f_body : '{'
       'declarations' declarations
       'statements' statements
       returnSubPrg
       '}'
     ;
formal_args :
          | f_args
```

```
11              ;
12  f_args   : formal_arg (',' formal_arg )*
13        ;
14  formal_arg : identifier '->' type
15             ;
16  return_type :
17              | '->' typeReturnSubProgram
18              ;
19  returnSubPrg :
20               | 'return' expression ';'
21               ;
```

Listing 2.34: CFG for block structure in LISS

Note that every variable declared inside of a sub-program is local, and it can be accessed only by other nested sub-programs. However, variables declared in the program (not in a sub-program) are considered global and can be accessed by any sub-program. The usual scope rules are applied to LISS.

As can be inferred from the syntax above (Listing 2.34), the body of a sub-program is identical to the body of a program — the same declarations can be made and similar statements can be used.

2.5 EVOLUTION OF LISS SYNTAX

Due to the maturity of the language already done along the years, we have added some few but extra changes for a better experience of the programming language.

One of the first changes was concerned with declarations in order to avoid mixing functions and variable declarations. We, indirectly, teach the programmer by doing it in the right way. So we declare, first, the variables and then the functions.

```
declaration : variable_declaration * subprogram_definition *
            ;
```

Another change was to add punctuation after each statement (see Figure 2.35).

```
statement : assignment  ';'
          | write_statement  ';'
          | read_statement  ';'
          | conditional_statement
          | iterative_statement
          | function_call ';'
          | succ_or_pred  ';'
          | copy_statement  ';'
          | cat_statement  ';'
          ;
```

Listing 2.35: Function statement

Another change was adding also a 'cat_statement' rule which works with only sequences. It concatenates a sequence with another sequence.

Regarding arrays, it was previously possible to use any expression to access elements of the array. So it was possible to index with a boolean expression what does not make any sense. Now only integers are allowed (see in Listing 2.36).

```
elem_array : single_expression (',' s2=single_expression )*
           ;
```

Listing 2.36: Rule element of array

In the previous version of LISS, it was allowed to create a boolean expression associating relational operators, but we decided to change that and not permit associativity; only able to create one boolean expression (see Listing 2.37). It does not make sense to have an expression like that : '3 == 4 == 5 != 6'.

```
expression : single_expression (rel_op single_expression )?
           ;
```

Listing 2.37: Rule for Boolean expression

We added the possibility of using parenthesis on expressions (see Listing 2.38).

```
factor: '(' expression ')'
      ;
```

Listing 2.38: Rule factor

We changed the rules of two pre-defined functions: 'cons' and 'del'. These functions were working both in the same way. Waiting for an expression and a variable as arguments. Now, we decide to change that allowing to expression as arguments giving more expressive power to those functions (see Listing 2.39).

```
cons // integer x sequence -> sequence
     : 'cons' '(' expression ',' expression ')'
     ;

delete // del : integer x sequence -> sequence
       : 'del' '(' expression ',' expression ')'
       ;
```

Listing 2.39: Rule cons and delete

Besides adding some improvements to the grammar, we additionally deleted a rule which we thought not necessary to control the for-statement (see Listing 2.40).

```
type_interval : 'in' range
              | 'inArray' identifier
              //| 'inFunction' identifier
              ;
```

Listing 2.40: Rule type interval

Last but not least, we also added comments to the programming language, giving more power to the programmer.

```
fragment
COMMENT
    : '/*'.*?'*/' /* multiple lines comment*/
    | '//'~('\r' | '\n')* /* single line comment*/
    ;
```

Listing 2.41: Lexical rule for Comment

3

TARGET MACHINE: MIPS

MIPS, from Microprocessor without Interlocked Pipeline Stages, is a Reduced Instruction Set Computer (RISC) developed by MIPS Technologies. Born in 1981, a team led by John L. Hennessy at Stanford University began to work on the first MIPS processor.

The main objective for creating MIPS, was to increase performance with deep pipelines, a main problem back to the 80's. Some instructions, as division, take a longer time to complete; if the CPU needs to wait that the division ends before passing to the next instruction into the pipeline, the total time is greater. If it can be done without that waiting time, the total process will be faster.

As MIPS solved those problems, it was primarly used for embedded systems and video games consoles (which requires a lot of arithmetic computation).

Now, the architecture of MIPS, along the years, has gained maturity and provides different versions of it (MIPS32, MIPS64....) [1].

Figure 2 [2] illustrate the architecture of MIPS.

1 according to https://imgtec.com/mips/architectures (See also wikipedia https://en.wikipedia.org/wiki/MIPS_instruction_set)

2 from https://upload.wikimedia.org/wikipedia/commons/thumb/e/ea/MIPS_Architecture_(Pipelined).svg/300px-MIPS_Architecture_(Pipelined).svg.png

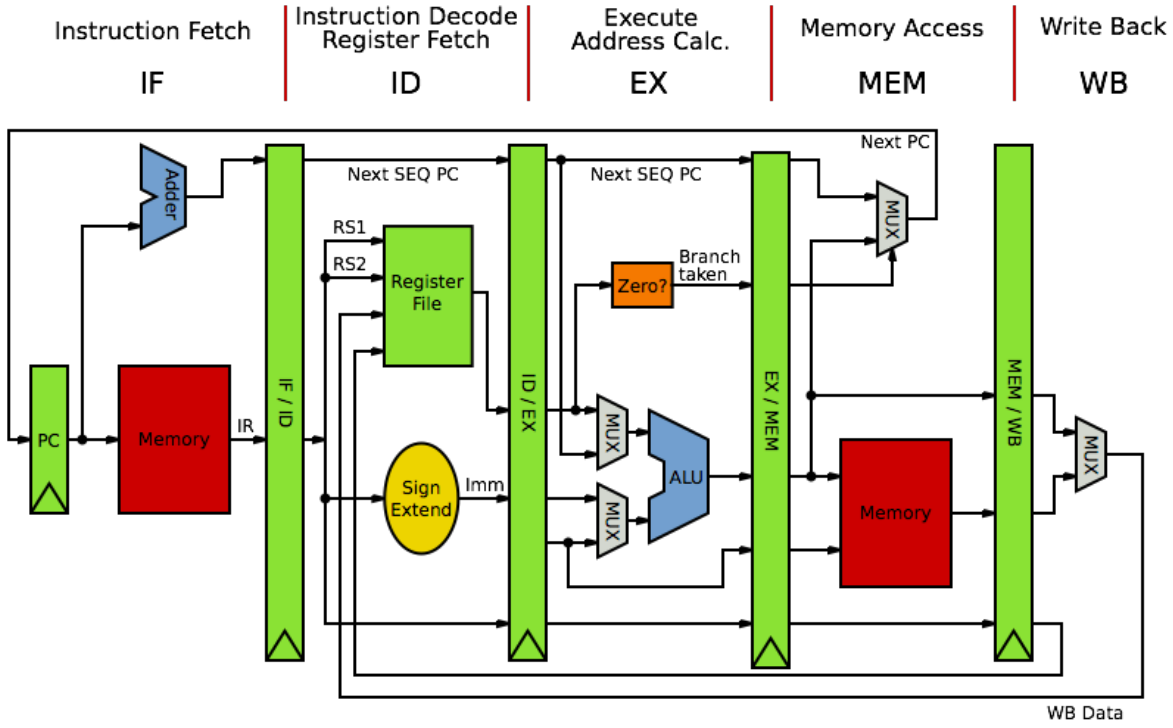


Figure 2.: MIPS architecture

In this chapter, we will talk about the architecture components and assembly of MIPS 32-bit version.

3.1 MIPS COPROCESSORS

MIPS was born for solving complex arithmetic problems by reducing the time consumed in those operations. This is attained through the implementation of coprocessors within MIPS.

MIPS architecture includes four coprocessors respectively, CP0, CP1, CP2 and CP3:

1. Coprocessor 0, denoted by *CP0*, is incorporated in the CPU chip; it supports the virtual memory system and exception handling (also known as the *System Control Coprocessor*).
2. Coprocessor 1, denoted by *CP1*, is reserved for floating point coprocessor.
3. Coprocessor 2, denoted by *CP2*, is reserved for specific implementations.
4. Coprocessor 3, denoted by *CP3*, is reserved for the implementations of the architecture.

Notice that coprocessor *CP0*, translates virtual addresses into physical addresses, manages exceptions, and handles switch between kernel, supervisor and user modes.

3.2 MIPS CPU DATA FORMATS

The CPU of MIPS defines four differents formats:

- *Bit* (1 bit, b)
- *Byte* (8 bits, B)
- *Halfword* (16 bits, H)
- *Word* (32 bits, W)

3.3 MIPS REGISTERS USAGE

MIPS architecture has 32 registers dedicated and there are some conventions to use those registers correctly. Table 3 summarizes those registers, and their usage.

Table 3.: MIPS registers

Name	Number	Use	Callee must preserve?
$zero	$0	has constant 0	No
$at	$1	register reserved for assembler (temporary)	No
$v0 - $v1	$2 - $3	register reserved for returning values of functions, and expression evaluation	No
$a0 - $a3	$4 - $7	registers reserved for function arguments	No
$t0 - $t7	$8 - $15	temporary registers	No
$s0 - $s7	$16 - $23	saved temporary registers	Yes
$t8 - $t9	$24 - $25	temporary registers	No
$k0 - $k1	$26 - $27	register reserved for OS kernel	N/A
$gp	$28	global pointer	Yes
$sp	$29	stack pointer	Yes
$fp	$30	frame pointer	Yes
$ra	$31	return address	N/A

Note: N/A (Not applicable)

Table 3 is composed of 4 columns:

1. *Name* displays the identifier of the registers available in MIPS. Those identifiers will be used as operands of MIPS instructions.

2. *Number* column defines the number of each register. This number can also be used to refer to the register in an instruction.
3. *Use* column refers to the meaning/definition of each register.
4. *Callee must preserve?* column provides information about the volatility of the register (used when a function is called).

Beside those 32 registers, 3 more registers are dedicated to the CPU.
And they are known by:

- *PC* - Program Counter register
- *HI* - Multiply and Divide register higher result
- *LO* - Multiply and Divide register lower result

PC is the register which holds the address of the instruction that is being executed at the current time; *HI* and *LO* registers have different usage according to the instruction that is being executed. In this case, let's see what context they have:

- when there is a multiply (*mul* instruction) operation, the *HI* and *LO* registers store the result of integer multiply.
- when there is a multiply-add (*madd* instruction) or multiply-subtract (*msub* instruction) operation, the *HI* and *LO* register store the result of integer multiply-add or multiply-subtract.
- when there is a division (*div* instruction) operation, the *HI* register store the remainder of the division and the *LO* register store the quotient of the division operation.
- when there is a multiply-accumulate (instruction) operation, the *HI* and *LO* registers store the accumulated result of the operation.

See an overview of the MIPS registers in Figure 3.

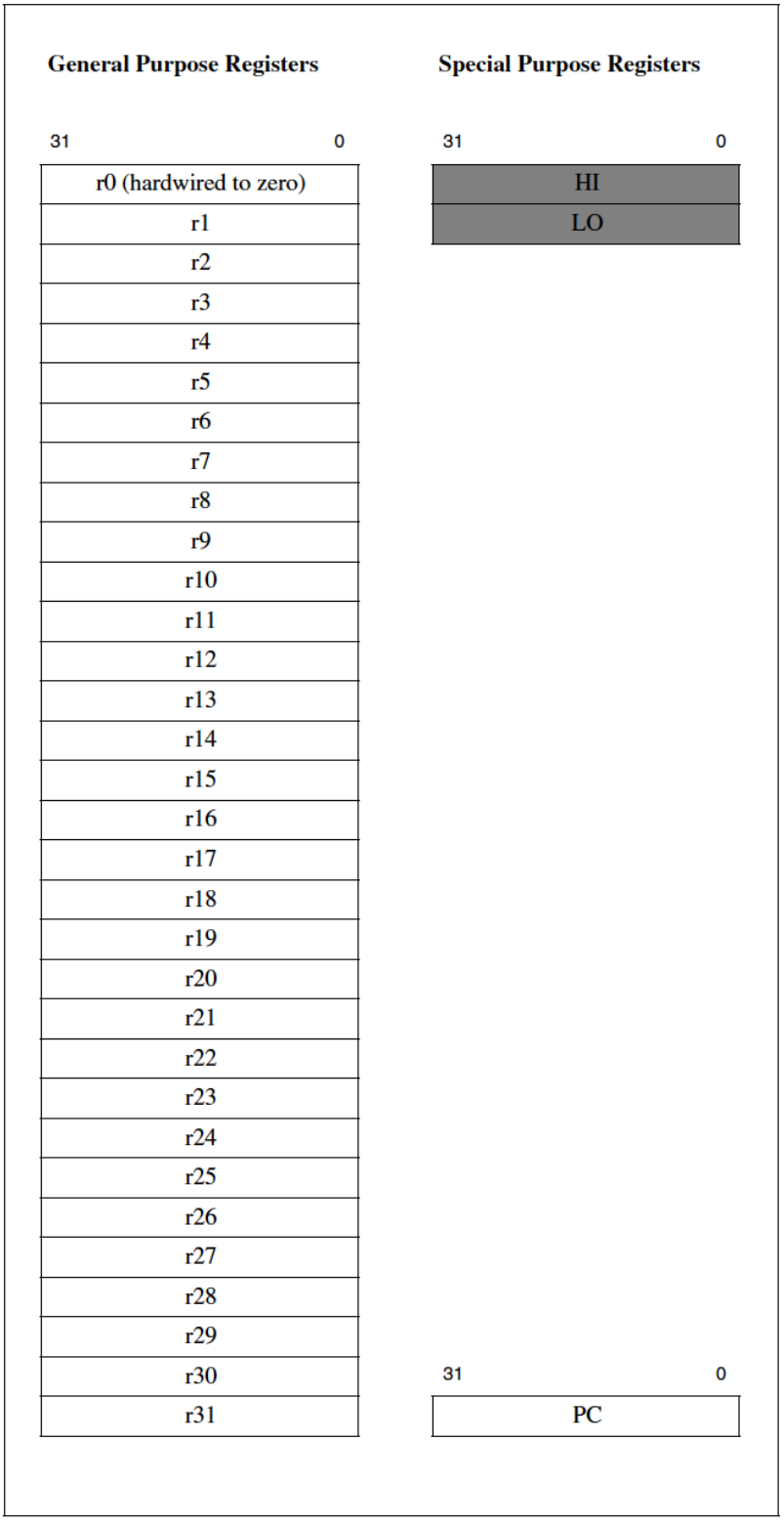


Figure 3.: MIPS register

3.4 MIPS INSTRUCTION FORMATS

Instructions, in MIPS, are divided into three types:

- R-Type
- I-Type
- J-Type

Each instruction is denoted by an unique mnemonic that represents the correspondent low-level machine instruction or operation.

Next sections provide the necessary details.

3.4.1 *MIPS R-Type*

R-Type instruction refers a register type instruction (it is the most complex type in MIPS). The idea behind that instruction is to operate with registers only.

This type has the following format in MIPS (see Listing 3.1).

```
1 OP rd, rs, rt
```

Listing 3.1: R-Type instruction format

In Listing 3.1, the instruction is composed of one mnemonic, denoted by *OP*, and three operands, denoted by *rd* (destination register), *rs* (source register), *rt* (another source register).

The R-Type instruction format as the following mathematical semantics:

```
1 rd = rs OP rt
```

To understand better this instruction, let's see an example of one R-Type instruction in MIPS (see Listing 3.2).

```
1 add $t1, $t1, $t2
```

Listing 3.2: Example of a R-Type instruction

The instruction shown in Listing 3.2 means that register $t1 shall be added (due to *add* mnemonic) to register $t2 and their sum (the result) stored in register $t1.

The following equivalence explains that meaning.

$$
\begin{aligned}
OP\ rd,\ rs,\ rt &\iff rd\ =\ rs\ OP\ rt \\
&\Downarrow \\
add\ \$t1,\ \$t1,\ \$t2 &\iff \$t1\ =\ \$t1\ add\ \$t2 \\
&\Downarrow \\
\$t1\ &=\ \$t1\ +\ \$t2
\end{aligned}
$$

Table 4 defines the bit-structure of a R-Type instruction in a 32-bit machine.

Table 4.: R-Type binary machine code

opcode	**rs**	**rt**	**rd**	**shift (shamt)**	**funct**
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

Let's explain each of the columns in Table 4.

- **opcode** defines the instruction type. For every R-Type instruction, *opcode* is set to the value 0. The *opcode* field is 6 bits long (bit 31 to bit 26).
- **rs** this is the first source register; it is the register where it will load the content of the register to the operation.The *rs* field is 5 bits long (bit 25 to bit 21).
- **rt** this is the second source register (same behaviour as *rs* register). The *rt* field is 5 bits long (bit 20 to bit 16).
- **rd** this is the destination register; it is the register where the results of the operation will be stored. The *rd* field is 5 bits long (bit 15 to bit 11).
- **shift amount** the amount of bits to shift for shift instructions. The *shift* field is 5 bits long (bit 10 to bit 6).
- **function** specify the operation in addition to the *opcode* field. The *function* field is 6 bits long (bit 5 to bit 0).

Let's see an example of a R-Type instruction and its transformation to machine code in Table 5.

$$add\ \$t0,\ \$t0,\ \$t1$$
$$\Downarrow$$
$$add\ \$8,\ \$8,\ \$9$$
$$\Downarrow$$
$$(8)_{10} = (01000)_2$$
$$(9)_{10} = (01001)_2$$
$$add\ instruction\ (funct\ field) = (100000)_2$$
$$\Downarrow$$

opcode (6bits)	rs (5bits)	rt (5bits)	rd (5bits)	shift (shamt) (5bits)	funct (6bits)
000000	01000	01001	01000	00000	100000

Table 5.: Transformation of R-Type instruction to machine code

In Table 5, the instruction 'add $to, $to, $t1' will be normalized with the name of the register according to the number associated for the register in MIPS (see Table 3). Then a conversion operation is applied to the two register numbers (*8* and *9*), translating them into their binary number with 5 bits long. Also we give the information for the *add* instruction, which is set for the MIPS architecture (not predictable).

After that, we complete the table for R-Type instruction according to Table 4 with the informations available and the restriction/rules associated to R-Type instruction in MIPS.

Notice that the *opcode* field for R-Type instruction are set to the value 0 (according to the explanation in Table 4).

3.4.2 *MIPS I-Type*

I-Type instruction is a set of instructions which operate with an immediate value and a register value.

Several different Immediate (*I-Type*) instructions formats are available.

Let's see those diferents formats for this type in Table 6.

31 – 26	25 —- 21	20 – 16	15 ——— 11	10 ——- 6	5 —— 0
opcode	rs	rt	immediate		
opcode	rd	offset			
opcode	offset				
opcode	rs	rt	rd	offset	
opcode	base	rt	offset		function

Table 6.: Distinct I-Type instruction formats

In Table 6, there are 5 differents instruction formats which corresponds to different bit structures as illustrated.

The most frequent MIPS I-Type instruction is the first one, denoted as Imm16 (Immediate instruction with 16 bits immediate value), is used for logical operands, arithmetic signed operands, load/store address byte offsets and PC-relative branch signed instruction displacements (see Table 7).

31 — 26	25 — 21	20 — 16	15 ————— 0
opcode	rs	rt	immediate

Table 7.: Immediate (I-Type) Imm16 instruction format

Let's see examples of Imm16 instruction:

```
addi $to, $to, 10 // Arithmetic operation
ori $to, $t1, 5   // Logical operation
beq $to, $t1, 1    // Conditional branch operation
lw $to, array1($to) //Data transfer operation
```

The second instruction, denoted as Immediate Off21 instruction (Immediate instruction with 21bits offset), is used for comparing a register against zero and branch (offset field is larger than the usual 16-bit field (immediate field of the first instruction from the table above)). See Table 8.

31 — 26	25 — 21	20 ————— 0
opcode	rd	offset

Table 8.: Immediate (I-Type) Off21 instruction format

The third instruction, denoted as Immediate Off26 instruction (Immediate instruction with 26 bits offset), is used for PC-relative branches with very large displacements (unconditional branches (BC mnemonic instruction) & branch-and-link (BALC mnemonic instruction) with a 26-bit offset,). See Table 9.

31 — 26	25 ——————————— 0
opcode	offset

Table 9.: Immediate (I-Type) Off26 instruction format

The fourth instruction, denoted as Immediate Off11 instruction (Immediate instruction with 11 bits offset), is used for the newest encodings of coprocessor 2 load and store instructions (LWC2, SWC2, LDC2, SWC2). See Table 10.

31 — 26	25 —— 21	20 ——— 16	15 ——— 11	10 ————— 0
opcode	rs	rt	rd	offset

Table 10.: Immediate (I-Type) Off11 instruction format

Finally, the last one (fifth instruction), denoted as Immediate Off9 instruction (Immediate instruction with 9 bits offset), is used for SPECIAL3 instructions such as EVA memory access (*LBE* mnemonic). Also this is primarly used for instruction encodings that have been moved, such as *LL* menmonic and *SC* mnemonic instruction. See Table 11.

31 — 26	25 —— 21	20 ——— 16	15 ————— 7	6	5 ————— 0
opcode	base	rt	offset	0	function

Table 11.: Immediate (I-type) Off9 instruction format

Notice that, for the project related to the thesis, only the first instruction type (Immediate (I-Type) Imm16 instruction format) was used. The other instruction formats are not really important for this project.

3.4.3 *MIPS J-Type*

J-Type instructions are instructions which jump to a certain address. Let's see his format in Table 12.

31 — 26	25 ——————————————————————— 0
opcode	address

Table 12.: J-Type instruction format

In Table 12, 6 bits are associated to the *opcode* field and 26 bits for the *address* field. But notice that in MIPS, addresses are 32 bits long.

For solving that, MIPS use a technique which leads to shift the address left by 2 bits and then combine 4 bits with the 4 high-order bits of the PC in front of the address.

Examples of J-Type formats can be seen in Listing 3.3.

```
1  jal writeln  // Jump and link instruction
```

```
2  jr $ra    // Jump register instruction
3  j writeln      // Jump instruction
```

Listing 3.3: Examples of J-Type instruction

In Listing 3.3, we see three different types of jump instruction. The first one example, is a *jal* instruction and it means 'jump and link' in an extensive way. Basically, it jump to the branch written in front of the *jal* nomenclature and stores the return address (instantly) to the return address register ($ra; $31). In this way, the programmer don't need to use some instructions for saving the return address and continue the flow of the execution code.

The second example, is a *jr* instruction and it means 'jump to an address stored in a register'. Notice that registers are available in the MIPS architecture.

The third and last example is a *j* instruction and this is a 'jump instruction'. Summing it up, it jumps to the branch written in front of the letter *j*, which is in this case *writeln*.

3.5 MIPS ASSEMBLY LANGUAGE

MIPS language is divided into 2 parts (Data and Text parts).

3.5.1 *MIPS data declarations*

This section is used for declaring variable names used in the program. Variables declared are allocated in the main memory (RAM) and must be identified with a particular nomenclature denoted as *.data*. It is used for declaring global variables, principally.

Then comes the part when the variable names are declared.

Let's see the format for declaring a variable name in Listing 3.4.

```
1  name: storage_type value(s)
```

Listing 3.4: Syntax format of data declarations in MIPS

In Listing 3.4, the *name* field refers to the name of the variable.

The *storage_type* refers to the type of the variable that can be:

- *.ascii* store a string in memory without a null terminator.
- *.asciiz* store a string in memory with the null terminator.
- *.byte* store 'n' bytes contiguously in memory.
- *.halfword* store 'n' 16-bit halfwords contiguously in memory.
- *.word* store 'n' 32-bit words contiguously in memory.

- *.space* store a certain number of bytes of space in memory.

Last, the *value(s)* field refers to the value of the type associated.

Let's see some example for declaring some variables in MIPS in Listing 3.5.

```
1  .data  # Tells assembler we're in the data segment
2    val:  .word  10
3    str:  .ascii  "Hello, world"
4    num:  .byte  0x01, 0x02
5    arr:  .space 100
```

Listing 3.5: Examples for declaring variables in MIPS

In Listing 3.5, there are 4 different types under the *data* section.

The variable *val* contains the value '10' and the size of the variable is 32 bits.

The variable *str* contains the string 'Hello World' and the size of the variable is the same size as the string.

The variable *num* stores the listed value(s) (which appears after the *.byte* nomenclature) as 8 bit bytes. In this example, it will be '0x00000201'.

The variable *arr* reserves the next specified number of bytes in the memory, which will be 100 bytes reserved for that variable.

3.5.2 *MIPS text declarations*

This section contains the program code and follows a specific syntax starting with the keyword *.text*.

As all programming languages, there is a starting point in the code that must be designated as *main:*. Each of the assembly language statements in MIPS (written after the *main:* field) are executed sequentially (excepted loop and conditional statements).

Let's see an example in Listing 3.6.

```
1  .text
2    main:
3      li $t0, 5
4      li $t1, 10
5      mul $t0, $t0, $t1
```

Listing 3.6: Example of Text declarations in MIPS

In Listing 3.6, we see the *.text* which begins the code of the program and the *main:* which shows where the code execution must start.

Below the keyword *main:* appears all the instruction of the program code.

In this case, it will load two numbers in different registers and multiply them (see Section 3.6 to understand those instructions).

Notice that the code will execute sequentially.

Also, in the text part beside of the code execution flow, we can write the name of branches for executing some jump instructions. This means that every jump instruction with a name associated, will see if that name is under the text part. Like that when a jump instruction is available it can jump to the name associated.

And for this purpose, we need to add some context to the MIPS jump instruction code and understand it better.

In this case, we need to replicate the same syntax as the *main:* field but with the correct name of the condition or the loop (also inside of the text declarations parts). Like that, MIPS knows where it must jump for the next instruction. Let's look an example in Listing 3.7.

```
1  .data
2  .text
3    main:
4      li $to, 5
5      li $t1, 5
6      mul $to, $to, $t1
7      jal jump_condition #needs to jump to the field jump_condition
8      li $to, 4
9      li $vo, 10
10     syscall
11   jump_condition:  #syntax for jump and conditional instruction in mips
12     li $t1, 5
13     jr $ra
```

Listing 3.7: Example of a loop declaration in MIPS

As we can see in Listing 3.7, we have a *jal* instruction available and a name associated next to the instruction. This name must be included under the *.text* section, because the name is the name of the branch from where the jump instruction will jump. If the name isn't in the MIPS assembly code, then the program cannot execute the assembly code. But in the example case, we can see that the name is available below as *jump_condition:*. So this means that the *jal* instruction will jump to that line and continue the code execution flow there.

Also, in MIPS, there is the possibility to include inline comments in the code using the symbol **#** on a line (see Listing 3.8).

```
1  var1:    .word 3 # create a single integer variable with initial value 3
```

Listing 3.8: Example of a comment in MIPS

Let's see the template for a MIPS assembly language program in Listing 3.9.

```
# Comment giving name of program and description of function
# Template.s
# Bare-bones outline of MIPS assembly language program

    .data       # variable declarations follow this line
                # ...

    .text       # instructions follow this line

      main:     # indicates start of code (first instruction to execute)
                # ...
```

Listing 3.9: Template of a MIPS assembly language

3.6 MIPS INSTRUCTIONS

MIPS has 6 type of instructions :

- instructions for data transfer
- instructions for arithmetic operations
- instructions for logical operations
- instructions for bitwise shift
- instructions for conditional branch
- instructions for unconditional branch

Let's see some examples of those instructions and their meanings.

Table 13.: Example of Data transfer instruction in MIPS

Name	Instruction Syntax	Meaning	Format	Opcode	Funct
Store word	sw $t,C($s)	Memory[$s + C] = $t	I	0x2B	N/A
Load word	lw $t,C($s)	$t = Memory[$s + C]	I	0x23	N/A
Load immediate	li $t, C	$t = C	I	0x9	N/A

Table 14.: Example of Arithmetic instruction in MIPS

Name	Instruction Syntax	Meaning	Type	Opcode	Funct
Add	add $d, $s, $t	$d = $s + $t	R	0x0	0x20
Add immediate	addi $t, $s, C	$t = $s + C (signed)	I	0x8	N/A
Subtract	sub $d, $s, $t	$d = $s - $t	R	0x0	0x22
Move	move $to, $t1	$to = $t1	R	0x0	0x21
Multiply	mul $s, $t, $d	$s = $t * $d LO = $t * $d (upper 32bits) HI = $t * $d (lower 32bits)	R	0x0	0x19
Divide	div $s, $t, $d	$s = $t / $d LO = $t / $d HI = $t % $d	R	0x0	0x1A

Table 15.: Example of Logical instruction in MIPS

Name	Instruction Syntax	Meaning	Format	Opcode	Funct
Set on less than	slt $d,$s,$t	$d = ($s <$t)	R	0x0	0x2A
Or	or $d,$s,$t	$d = $s || $t	R	0x0	0x25
And	and $d,$s,$t	$d = $s & $t	R	0x0	0x24
Set on less than unsigned	sltu $d,$s,$t	$d = ($s <$t)	R	0x0	0x2B
Exclusive or immediate	xori $d,$s,C	$d = $s ^C	I	0xE	N/A

Table 16.: Example of Bitwise Shift instruction in MIPS

Name	Instruction Syntax	Meaning	Format	Opcode	Funct
Shift left logical immediate	sll $d,$t,shamt	$d = $t <<shamt	R	0x0	0x0
Shift right logical immediate	srl $d,$t,shamt	$d = $t >>shamt	R	0x0	0x2
Shift left logical	sllv $d,$t,$s	$d = $t <<$s	R	0x0	0x4
Shift right logical	srlv $d,$t,$s	$d = $t >>$s	R	0x0	0x6

Some explanation must be provided for understanding the tables shown previously:

- **PC** means Program Counter.
- **target** means the name of the target (used for jump instructions).
- **C** means constants.
- `0x..` means a hexadecimal format number.
- **N/A** means Not Applicable.

Table 17.: Example of Conditional Branch instruction in MIPS

Name	Instruction Syntax	Meaning	Format	Opcode	Funct
Branch if equal zero	beqz $s, jump	if($s==0) go to jump address	I	0x4	N/A
Branch on not equal	bne $s, $t, C	if ($s != $t) go to PC+4+4*C	I	0x5	N/A
Branch on equal	beq $s, $t,C	if ($s == $t) go to PC+4+4*C	I	0x4	N/A

Table 18.: Example of Unconditional Branch instruction in MIPS

Name	Instruction Syntax	Meaning	Format	Opcode	Funct
Jump	j target	PC = PC+4[31:28] . target*4	J	0x2	N/A
Jump register	jr $s	goto address $s	R	0x0	0x8
Jump and link	jal target	$31 ($ra) = PC + 4; PC = PC+4[31:28] . target*4	J	0x3	N/A

- **shamt** means the number to shift (used in shift instructions).

Note that the *Format*, *Opcode* and *Funct* are the information of each field for each format instruction as explained in Section 3.4.

Beside those instructions, some other instructions are sequences of instructions and they are called as pseudo instructions (see in Table 19).

Table 19.: Example of Pseudo Instructions in MIPS

Name	Instruction Syntax	Real instruction translation	Meaning
Move	move $d, $s	add $d, $s, $zero	$d=$s
Load Address	la $d, LabelAddr	lui $d, LabelAddr[31:16] ori $d, $d, LabelAddr[15:0]	$d = Label Address
Multiplies and returns only first 32 bits	mul $d, $s, $t	mult $s, $t mflo $d	$d = $s * $t
Divides and returns quotient	div $d, $s, $t	div $s, $t mflo $d	$d = $s / $t
Branch if equal to zero	beqz $s, Label	beq $s, $zero, Label	if ($s==0) PC=Label

Additionally, MIPS includes a number of system services for input and output interaction, denoted as **SYSCALL**. Let's see an example of those services in Table 20.

To understand better Table 20, we need to give some explanation of it. The *service* column gives us the context of the service; the *code* column explains which value must be

Table 20.: Example of SYSCALL instruction in MIPS

Service	Code in $vo	Arguments	Result
print integer	1	$ao = integer to print	
print string	4	$ao = address of null-terminated string to print	
read integer	5		$vo contains integer read
sbrk (allocate heap memory)	9	$ao = number of bytes to allocate	$vo contains address of allocated memory
exit (terminate execution)	10		

set into register $vo (associated to the service wished); the *arguments* column specify the argument values that must be loaded depending on the service and last; the *result* column gives some informations about the return value of the service (if available or not).

Let's see an example of one service in Listing 3.10.

```
1 li $to, 3              #adding the number 3 to register to
2 li  $vo, 1            # loading the service number 1 (print integer) to
    register vo
3 add $ao, $to, $zero  # loading the argument value to register ao
4 syscall  #calling the syscall for printing the integer.
```

Listing 3.10: Example of printing integer in MIPS

Notice that every instructions shown in the tables, are instructions which were used for the project.

3.7 MIPS MEMORY MANAGEMENT

MIPS has the possibility to control and coordinate the computer memory by two ways:

1. L'Isle-Adam
2. heap

3.7.1 *MIPS stack*

When a program is being executed, a portion of memory is set aside for the program and it is called the **stack**.

The stack is used for functions and it set some spaces for local variables of the functions.

Internally, MIPS doesn't have real instructions for pushing or popping the stack. But this can be made with a sequences of instructions and using the stack pointer register.

Let's see an example in Listing 3.11.

```
1 push:  addi $sp, $sp, -4  # Decrement stack pointer by 4
2        sw   $vo, 0($sp)   # Save register vo to stack
3
4 pop:   lw   $vo, 0($sp)   # Copy from stack to register vo
5        addi $sp, $sp, 4   # Increment stack pointer by 4
```

Listing 3.11: Example of push and pop instructions in MIPS

3.7.2 *MIPS heap*

Beside a stack, we might need to allocate some dynamic memory. And this can be done by using a **Heap**.

For this purpose, in MIPS, we only need to say how much bytes we want to allocate in the heap.

Let's see an example in Listing 3.12.

```
1 .text
2   main:
3     li $ao, 4 #we want to allocate 4 bytes in the heap.
4     li $vo, 9 # we load the value 9 in register vo for calling the heap
          instruction.
5     syscall   # calling the system call instruction for allocating 4
          bytes into the heap. The register vo contains the address of
          allocated memory.
```

Listing 3.12: Example of code for allocating in the heap

3.8 MIPS SIMULATOR

Several simulators are available in the market for executing MIPS assembly code, and some are free.

For this project, we considered two nice free simulators:

- MARS simulator [3]
- SPIM simulator [4]

3 http://courses.missouristate.edu/KenVollmar/MARS/
4 http://spimsimulator.sourceforge.net

Both simulators are for education purposes and built with a GUI.

They execute and debug MIPS assembly code but only MARS simulator has the possibility to write some live-code MIPS assembly code. This explains why MARS was the one selected for this project.

3.8.1 *MARS at a glance*

MARS from *Mips Assembly and Runtime Simulator*, assembles and simulates the execution of MIPS assembly language programs. The strength of MARS comes from the interaction between the user and the program through its integrated development environment (IDE) and the tools available there (program editing, assembling code, interactive debugging...).

Let's see MARS IDE in Figure 4.

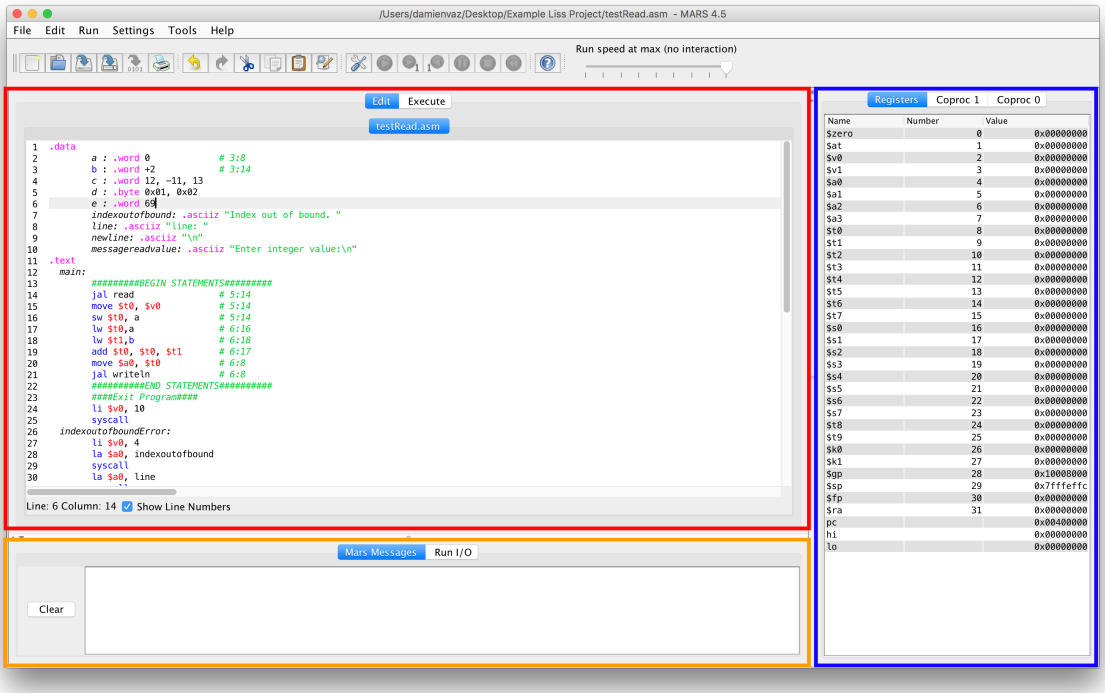


Figure 4.: MARS GUI

In Figure 4, we have 3 different boxes. The red box offers two possible views (two different perspective by switching between the tabs available at the top). In this case, the view is opened for programing some live MIPS assembly code (MIPS assembly code is colored along the left part of the window). But if we open the second tab view, then it will change to the execution mode of the MIPS assembly code (if no syntatic or semantic errors are found).

The orange box also has two possible views (Mars Messages or Run I/O tabs). It is used to display error messages regarding the syntax and semantic of MIPS assembly code, or error messages regarding the execution of the MIPS assembly code.

Last, the blue box has three different views: Registers, Co-processor1 and Co-processor 2. In the Figure above, it shows the states of the registers available in MIPS architecture but if we change the view it can show the states of each co-processor (related to division, multiplication).

If the MIPS assembly code typed in (or loaded from a file) is correct (no errors detected), we can assemble it and execute it.

Figure 5 illustrates the new view offered by the IDE after assembling the source program.

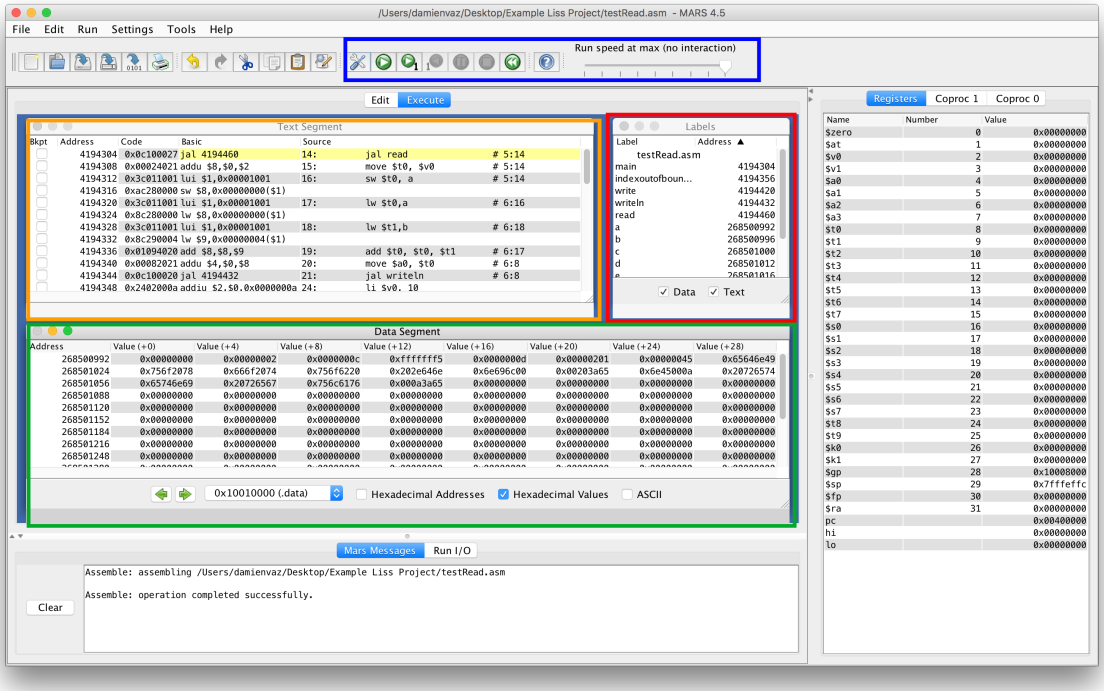


Figure 5.: MARS GUI (Execution mode)

In Figure 5, it is possible to identify the main window (the red one in Figure 4) now split into three subwindows: orange, red and green.

Notice that above the main red window, a small blue box contains buttons to activate tools for assembling MIPS assembly code, executing MIPS assembly code totally or step by step (one instruction at a time) and also the possibility to change the speed execution of the MIPS assembly code if we want to run it completely.

The orange box contains the MIPS assembly code assembled and ready to execute. It shows the MIPS assembly code instructions, the correspondent code in hexadecimal, the respective address in the memory, and eventually some breakpoints associated with cer-

tain MIPS assembly instructions. Also notice that MIPS assembly code has some pseudo-instructions; and in the orange box, there is a part where we can see the translation of the MIPS assembly code to another lower MIPS assembly code (with no pseudo-instruction). The yellow bar, or cursor, displayed in the figure above enhances the next instruction to be executed.

The red box is the identifier table for the MIPS assembly code. It contains the variables existing in the MIPS assembly code and displays their respective address in the memory.

The green box represents the virtual memory of the MIPS architecture. It displays the stack and the heap memory, as well as other informations not relevant in this context. Basically, we see the value being changed throw the iteration of the MIPS assembly code being executed. This mean that if there is a store instruction for a certain variable, it will look up for the identifer table (red box), search the address associated to the variable and store to that address the value associated to the variable.

4

COMPILER DEVELOPMENT

Earlier in the history of computers, software was primarily written in assembly language. Due to the low productivity of programming assembly code, researchers invented a way that add some more productivity and flexibility for programmers; they created the compiler allowing to wire programs in high level programming languages.

A compiler is a software program which converts a high-level programming language (source code) into a lower level programing language for the target machine (known as machine code or assembly language).

The compiler task is divided into several steps (see Figure 6):

1. Lexical analysis
2. Syntactic analysis or parsing
3. Semantic analysis
4. Optimization
5. Code generation

First, the lexical analysis must recognize words; these words are a string of symbols each of which is a letter, a digit or a special character. The Lexical analysis divides program text into ”words” or ”tokens” and once words are identified, the next step is to understand sentence structure (role of the parser). We can think the parsing as an analogy of our world by constructing phrases which requires a subject, verb and object. So, basically, the parser do a diagramming of sentences.

Once the sentence structure is understood, we must extract the ”meaning” with the semantic analyzer. The duty of the semantic analyzer is to perform some contextual checks to catch language inconsistencies and build an intermediate representation to store the meaning of the source text. After that, it may or may not have some optimization regarding the source code.

Finally, the code generator translates the intermediate representation of the high-level programming into assembly code (lower level programming). At this stage, a new opti-

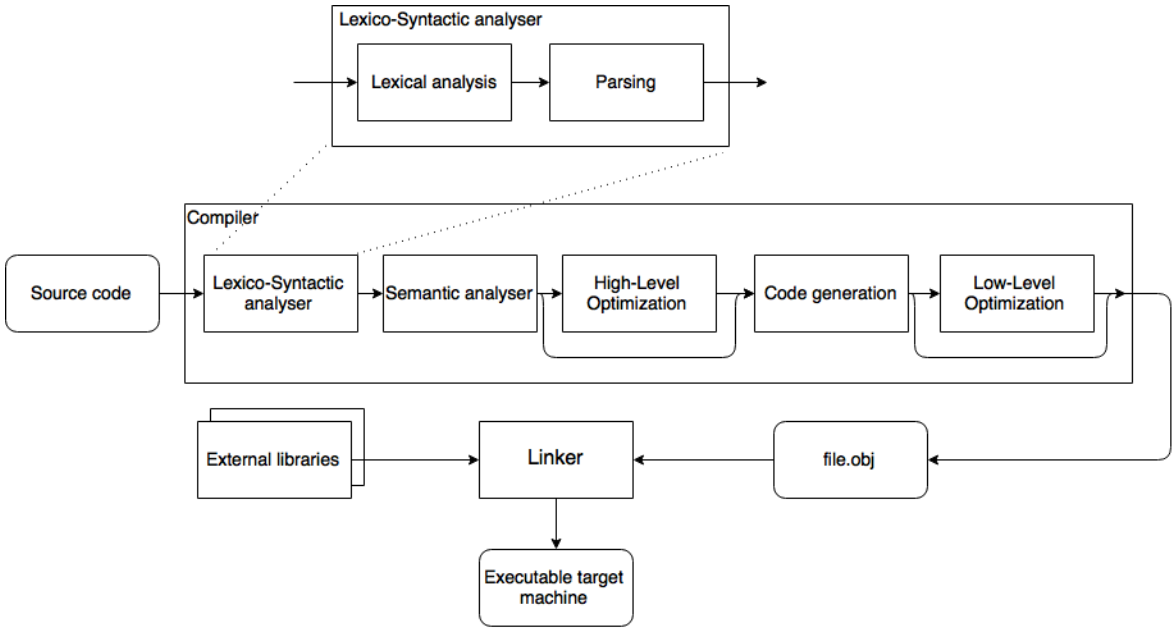


Figure 6.: Traditional compiler

mization phase can occur to deliver an object code shorter and faster than the original one.

Notice that the task of constructing a compiler for a particular source language is complex. To simplify this task, it is usual to resort to a compiler generator that is a system able to build automatically a language processor from the language grammar. In this master project, the compiler generator ANTLR was used, as we will be described in section 4.1.

The first tool steps, lexical and syntatical analysis, will be briefly discussed in section 4.2. Then section 4.3 explains in detail the implementation of LISS semantic analyzer. To conclude the chapter, section 4.4 provides also details about the implementation of the LISS code generator.

4.1 COMPILER GENERATION WITH ANTLR

Terence Parr, the man who is behind ANTLR (ANother Tool for Language Recognition (Parr, 2007, 2005)) made a parser (or more precisely, a compiler) generator that reads a context free grammar, a translation grammar, or an attribute grammar and produces automatically a processor (based on a LL(k) recursive-descent parser) for the language defined by the input grammar.

An ANTLR specification is composed by two parts : the one with all the grammar rules and the other one with lexer grammar.

Listing 4.1 is the one with the grammar rules; in that case it is an example of an AG (Attribute Grammar).

```
facturas : fatura +
         ;
fatura   : 'FATURA' cabec 'VENDAS' corpo
         ;
cabec    : numFat idForn 'CLIENTE' idClie
         { System.out.println("FATURA num: " + $numFat.text);}
         ;
numFat   : ID
         ;
idForn   : nome morada 'NIF:' nif  'NIB:' nib
```

Listing 4.1: AG representation on ANTLR

On the other hand, the lexer grammar defines the lexical rules which are regular expressions as can be seen in Listing 4.2. They define the set of possible character sequences that are used to form individual tokens. A lexer recognizes strings and for each string found, it produces the respective tokens.

```
/*————————————— Lexer ———————————————————————————————————*/

ID  :   ('a'..'z'|'A'..'Z'|'_') ('a'..'z'|'A'..'Z'|'0'..'9'|'_'|'-')*
    ;

NUM :   '0'..'9'+
```

Listing 4.2: Lexer representation

4.2 LEXICAL AND SYNTATICAL ANALYSIS

The parser generator by ANTLR will be able to create an abstract syntax tree (AST) which is a tree representation of the abstract syntactic structure of source code written in a programming language (see Figure 7).

ANTLR will be used to generate MIPS assembly code according to the semantic rule specified in the AG for LISS language.

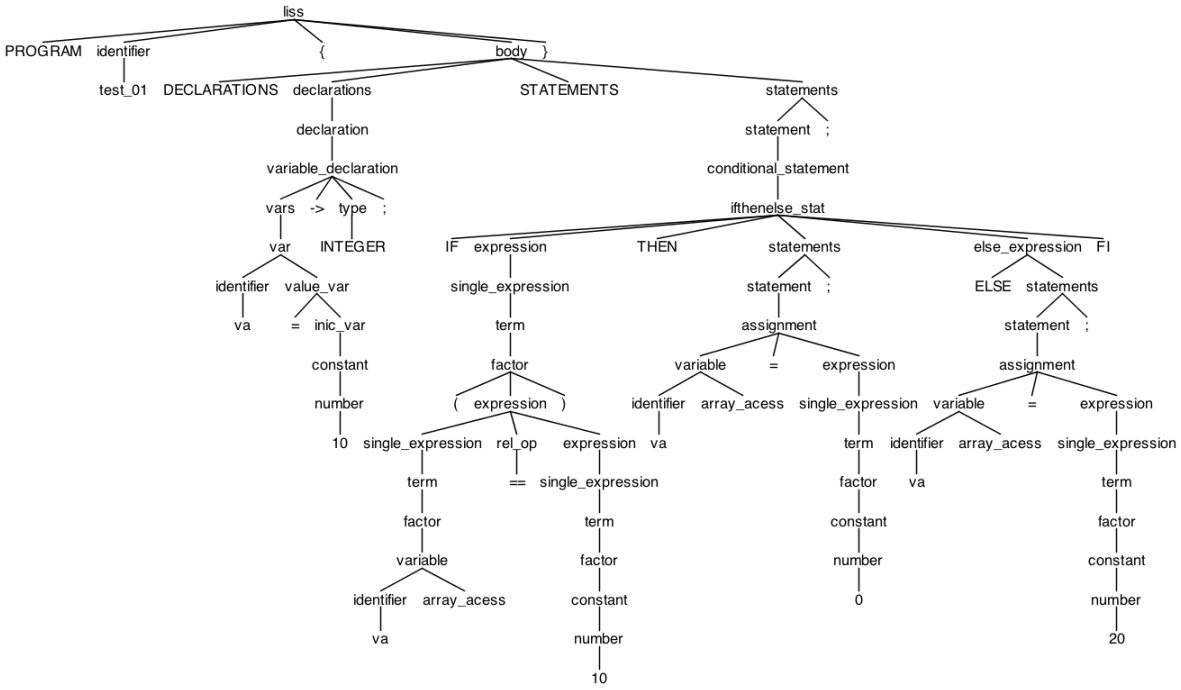


Figure 7.: AST representation

4.3 SEMANTIC ANALYSIS

In programming language theory, the word *semantics* is concerned by the field of studying the meaning of programming languages. And in this field, it concerns about a lot of area.

For our project, every time that we see an inconsistency, we use some structures that helps the compiler for getting those inconsistencies and also informs the user about those inconsistencies.

And the kind of inconsistency that can be found in the project are listed above:

1. Finding inconsistency in types and their related specifications.
2. Finding inconsistency in variables declared or not.
3. Finding inconsistency regarding to the use of multiple expressions.
4. Finding inconsistency for returning types of functions created.

Now, let's talk about the structures that were made for the project.

4.3.1 *Symbol Table*

A symbol table is a data structure used for the compiler, which helps to store some valuable informations for identifiers in a program's source code. Basically, it helps the compiler for

finding some semantic errors regarding to the translation of the program which will be done later.

There are a lot of types of data structure for creating a symbol table. From one large symbol table for all symbols or separated, hierarchical symbol tables for different scopes.

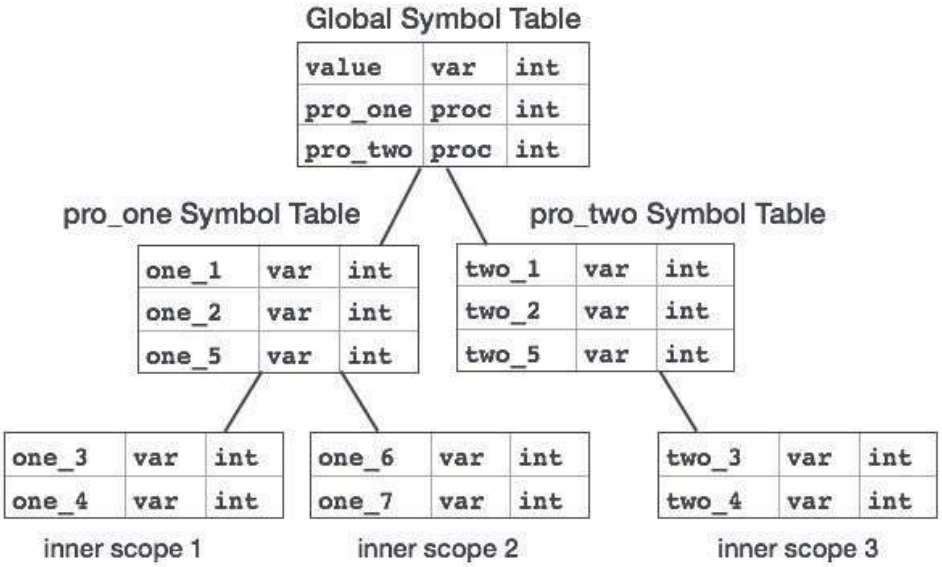


Figure 8.: Example of hierarchical symbol table

Symbol Table in LISS

For this project, we used only one symbol table (ST) for all symbols.

Let's explain throw Figure 9, the usage of the symbol table in LISS.

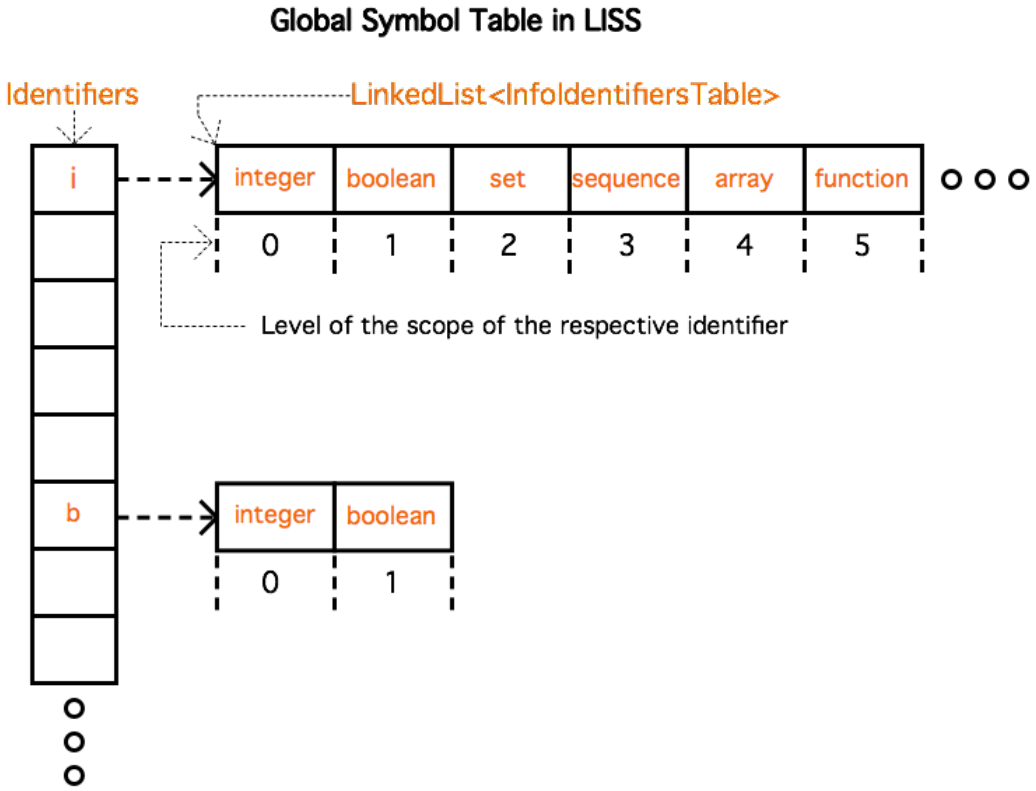


Figure 9.: Global symbol table in LISS

For our project we implemented the symbol table with a HashMap where the key is an identifier and the value is a LinkedList of variables information associated with the identifier.

```
1 HashMap<String, LinkedList<InfoIdentifiersTable>>
```

Listing 4.3: Data structure of the symbol table in LISS

The identifier (of type *String*, as shown in Listing 4.3) must be unique (concept of using a HashMap) and the *LinkedList* must be an ordered list.

Basically, the identifier is associated to a *LinkedList* of information related to the identifier that explains among other things the category and type of the identifier.

For our project, we have 3 different categories:

1. TYPE

2. VAR
3. FUNCTION

TYPE category

The *TYPE* category aggregates all the identifiers that denote the primitive (or pre-defined) types available in LISS. In our language, they are: set, integer, sequence and boolean. In this case, the ST contains information about the fixed size of each type in MIPS representation, as well as their scope level as summarized in Table 21.

Table 21.: TYPE category information

Identifier	Category	Level	Space (Bytes)
set	TYPE	0	0
integer	TYPE	0	4
boolean	TYPE	0	4
sequence	TYPE	0	4

VAR category

The *VAR* category aggregates all the identifiers that denote the variables declared in LISS (in the program *declarations* part). The variable type may be integer, boolean, array, set or sequence. The information associated with each variable depends on its type.

Let's see and explain in detail the information per type.

Table 22.: ST information for an integer variable

Identifier	Category	Level	Type	Address
x	VAR	0	integer	0

In Table 22, we can see the information stored in ST for an integer variable:

- *Identifier* - name of the variable.
- *Category* - the category of the identifier: VAR.
- *Level* - the scope level of the variable.
- *Type* - the type of the variable (integer).
- *Address* - the address of the variable in the stack memory.

Table 23.: ST information for a boolean variable

Identifier	Category	Level	Type	Address
bool	VAR	1	boolean	4

In Table 23, it can be seen the information stored in ST for a boolean variable:

- *Identifier* - name of the variable.
- *Category* - the category of the identifier: VAR.
- *Level* - the scope level of the variable.
- *Type* - the type of the variable (boolean).
- *Address* - the address of the variable in the stack memory.

Table 24.: ST information for an array variable

Identifier	Category	Level	Type	Address	Dimension	Limits
array_1	VAR	0	array	8	2	[2|3]

In Table 24, it can be seen information stored in ST for an array.

- *Identifier* - name of the variable.
- *Category* - the category of the identifier: VAR.
- *Level* - the scope level of the variable.
- *Type* - the type of the variable (array).
- *Address* - the address of the variable in the stack memory.
- *Dimension* - the number of dimension for the array.
- *Limits* - the limits of each dimension of the array.

Table 25.: ST information for a set variable

Identifier	Category	Level	Type	Address	Tree Allocated
set_1	VAR	0	set	NULL	[x]

In Table 25, it can be seen the information stored in ST for a set.

- *Identifier* - name of the variable.
- *Category* - the category of the identifier: VAR.

- *Level* - the scope level of the variable.
- *Type* - the type of the variable (set).
- *Address* - not used (no memory address).
- *Tree Allocated* - indicates if the set has an initiate value associated. Letter 'X' means that the set was initialized.

Table 26.: ST information for a sequence variable

Identifier	Category	Level	Type	Address	Elements_type
sequence_1	VAR	0	sequence	32	integer

In Table 26, it can be seen the information stored in ST for a set.

- *Identifier* - name of the variable.
- *Category* - the category of the identifier: VAR.
- *Level* - the scope level of the variable.
- *Type* - the type of the variable (sequence).
- *Address* - address in the stack memory.
- *Elements_type* - indicates the type of the elements.

FUNCTION category

The *FUNCTION* category contains informations about the subprograms created in a LISS code.

Table 27.: ST information for a function

Identifier	Category	Level	Type	Address	Nº Arguments	Type List Arguments
calculate	FUNCTION	0	NULL	32	2	[integer, boolean]

In Table 27, it can be seen the information stored in ST for a function.

- *Identifier* - name of the function.
- *Category* - the category of the identifier: FUNCTION.
- *Level* - the scope level of the function.
- *Type* - field not used.

- *Address* - size of the function stack in the stack memory (includes the arguments list, the variables declared in the subprogram and the return value).
- *Nº Arguments* - indicates how many arguments the function does have.
- *Type List Arguments* - indicates the type of each argument.

Let's see in Figure 10, the abstract data structure of InfoIdentifiersTable implemented.

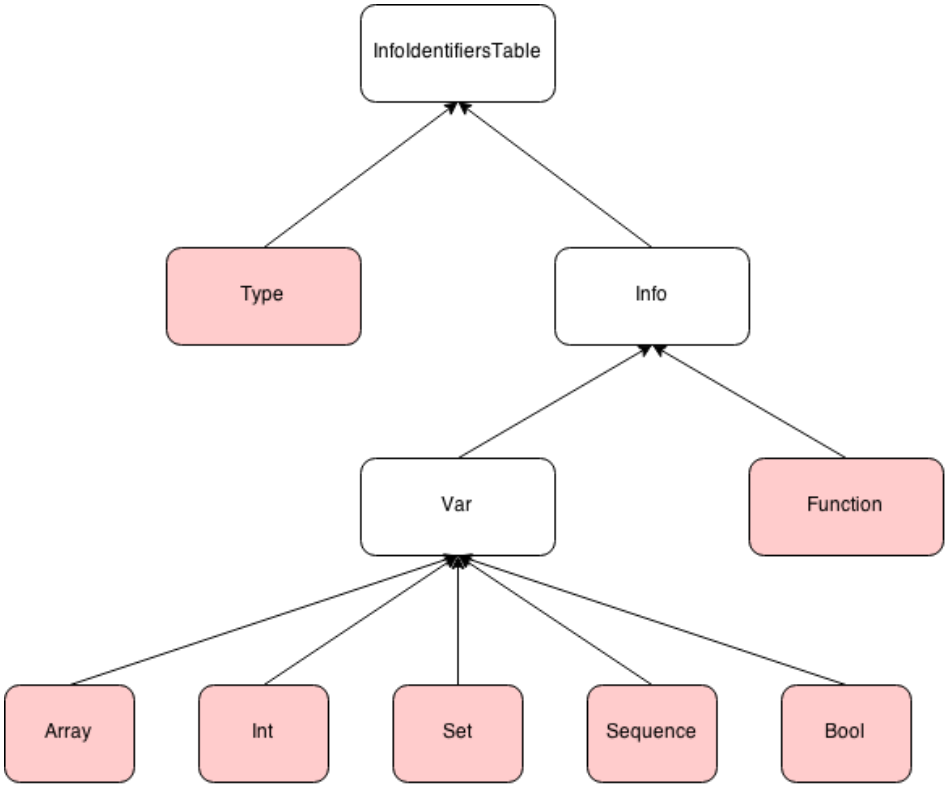


Figure 10.: InfoIdentifiersTable structure

Each time that an identifier is inserted into the HashMap, the information described related to that identifier is inserted according to its category.

The usage of a *LinkedList<InfoIdentifiersTable>* has the notion of being an ordered list, and this is very important due to the fact that it reveals the level of a given identifier found.

In Figure 9, the identifier **b** was found in two differents scope level.

- Level 0 - Identifier **b** found with type *integer*
- Level 1 - Identifier **b** found with type *boolean*

Notice that every time, we look for an identifier and its respective info in the symbol table, the most recent (the one that was the latest inserted) info in the *LinkedList* will be inserted.

In the case of the identifier **b** in Figure 9, it will be the **boolean** info.

Every time that a function (*subprogram* in LISS) is exited, we remove every information associated with the scope level of the function from the symbol table.

The JAVA functions created and available in the project, regarding the symbol table handling.

- getSymbolTable - gets the symbol table.
- doesExist - checks whether a certain identifier is in ST.
- getInfoIdentifier - gets the most recent information associated with a certain identifier.
- removeLevel - removes from the symbol table every information related to a given scope level.
- getAddress - gets the most recent address (this address is related to the next position of an identifier that will be added to the symbol table).
- setAddress - sets a new address.
- add - adds an identifier into the symbol table.
- toString - gets the representation of the symbol table as a string.

4.3.2 *Error table in LISS*

The error table let the user to understand the problems that he is having with the code when he is trying to create (write) a LISS program. In this way, it will facilitate the user to fix the errors found in his code.

Figure 11 shows the structure of the error table built for our project.

We managed to create a data structure which can handle some error messages and also store some information related to the error message (line and column number).

This was done by creating the following data structure in JAVA:

```
1 TreeMap<Integer ,TreeMap<Integer ,ArrayList<String>>>
```

Listing 4.4: Data structure of the error table in LISS

Basically, this data structure is divided into two *TreeMaps* (as can be seen in Figure 11, black and white) and a list (*ArrayList* data structure) of some error messages.

We chose the *TreeMap* data structure for one reason, the map is sorted according to the natural ordering of its keys. This means that each time we insert a pair <key, value> in the *TreeMap* data structure, the information is ordered by the unique key. In this case, the first

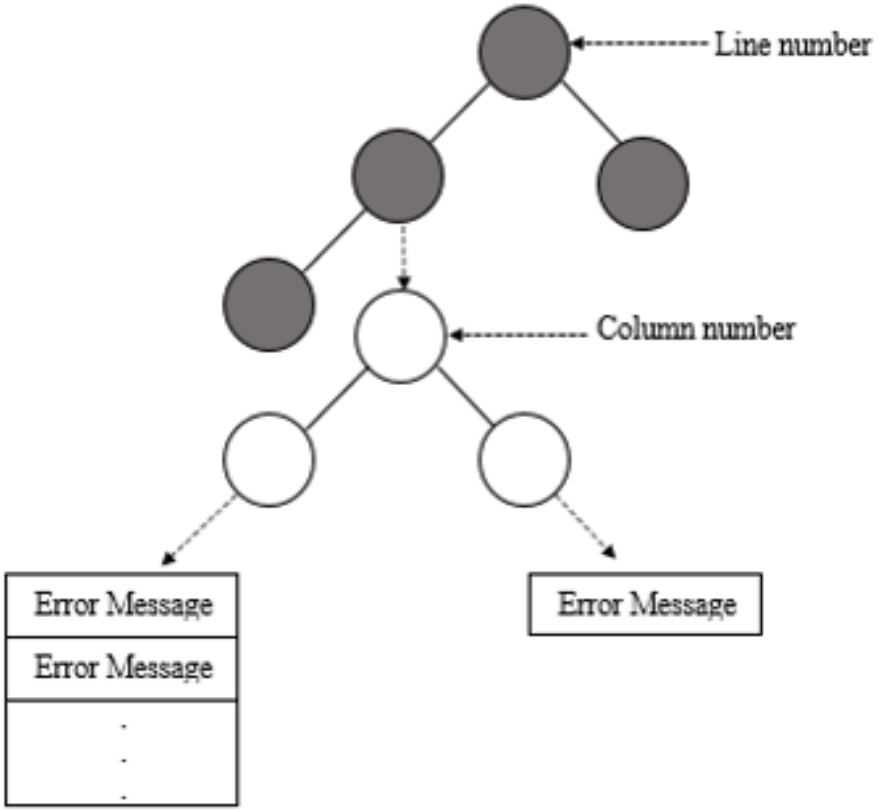


Figure 11.: ErrorTable structure

TreeMap is intended for ordering the line number of the error message (black tree in Figure 11).

Then when the line number is added and ordered, we add some information linked to the line number and this is the column number of the line (white tree in Figure 11).

Finally, we add the error messages to the list related to a certain line and column.

With that data structure, we are sure that it can have a list of error messages for a certain line and column numbers and that the line and the column number are ordered for an easy reading.

Listing 4.5 shows some error message issued after processing a LISS program.

```
1 ERROR TABLE:
2   line: 5:18  Expression 'b' has type 'boolean',when It should be '
      integer'.
3   line: 6:11  Expression 'flag' has type 'integer',when It should be '
      boolean'.
4   line: 7:1 Expression 'array1=[[1,2],[2,3,4,5]],vector' has a problem
      with his limits.
5   line: 8:1 Expression 'vector' already exists.
```

```
6     line: 10:4  Expression 'seq1' already exists.
7     line: 14:4  Expression 'b' already exists.
```

Listing 4.5: Example of an error table

Regarding the data structure explained above, Figure 12 shows an example of how the error messages are being handled, displaying the storage of the first two messages in Listing 4.5.

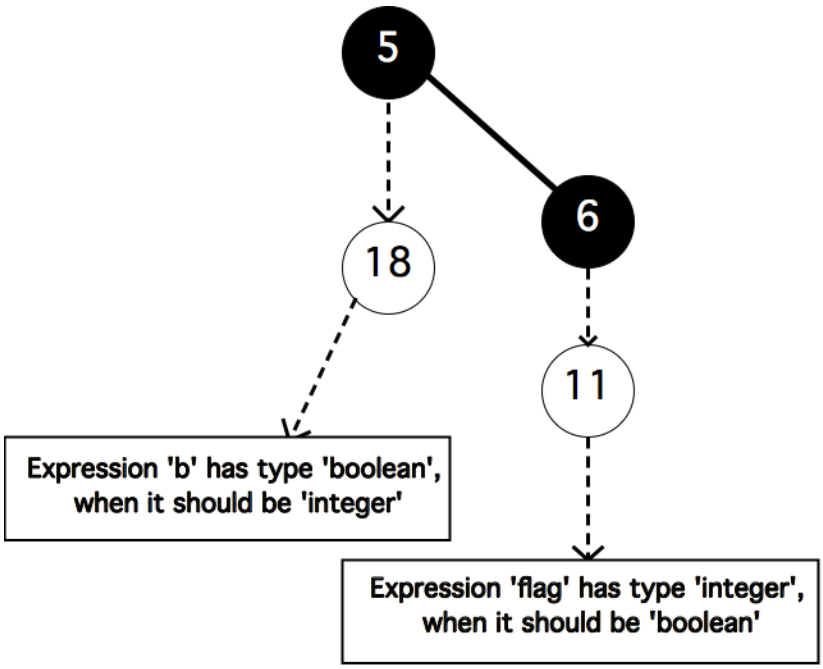


Figure 12.: ErrorTable structure instantiated for example in Listing 4.5

4.3.3 *Types of error message*

As said, previously, we have different kinds of error messages, that can be seen in Table 28.

Notice that in Table 28, we have all the messages used and thrown (when necessary) by the compiler that we need to explain the notation used. For example, the mark:

```
1   <...>
```

represents a placeholder; it means that it must be replaced by the correct name according to the environment where the error was found.

To understand better the usage of the mark, let's consider the program example in Listing 4.6.

Table 28.: Types of error message in LISS

Error type number	Error message
1	Variable <name_of_variable >isn't declared
2	Variable <name_of_the_variable >already exists.
3	Variable <name_of_the_array_variable >must be an 'array'.
4	Variable <name_of_the_array_variable >has a problem with his limits.
5	Variable <name_of_the_variable >has type <type_found >, when it should be <type_expected >.
6	Incompatible types in Assignment.
7	Expression <expression_string >has type <type_found >, when it should be <type_expected >.
8	Function <name_of_the_function >has return type <type_found >, when it should be <type_expected >.
9	Variable <name_of_the_function >is not a function.
10	Expression <expression_string >has type <left_type_found > <operator_string ><right_type_found >, required type <left_type_required ><operator_string ><right_type_required >.
11	Expression <name_of_the_array_variable >has dimension <dimension_found >, when it should be equal to <dimension_required >.
12	'stepUp' or 'stepDown' expression, not valid with "inArray" operation.
13	'satisfying' expression, not valid with "inArray" operation.
14	Function <name_of_the_function >does not exist.
15	Expression <name_of_the_array_variable >doesn't have the same limits or dimensions.

```
1 program Errors{
2   declarations
3     seq1 =<<1,2,3,4>> -> sequence;
4     seq1 = <<1,4,7>> -> sequence;
5   statements
6 }
```

Listing 4.6: Partial Listing

The LISS program in Listing 4.6 declares two variables with the same name in the declarations part. As in all programming language, in LISS it is not allowed to declare two variables in the same scope level. So the compiler must throw an error, printing the message in Listing 4.7.

```
1   ERROR TABLE:
2   line: 4:2 Variable 'seq1' already exists.
```

Listing 4.7: Error table related to Listing 4.6

The error message in Listing 4.7 has a type with the number 2 message in Table 28. We can see that the mark was replaced by the name of the variable. The same exactly happens regarding the other messages in the Table 28.

Now, let's explain Table 28 for an easy interpretation of those messages.

1. Message for a variable not declared.
2. Message for a variable already declared.
3. Message for a variable that must be an array and is not.
4. Message for a variable that is of type array and its limits that doesn't match.
5. Message for a variable that has a certain type, but should have another type.
6. Message regarding an assignment found with different types. For example : 'integer' = 'boolean'.
7. Message for an expression that contains operand with different types.
8. Message for a function when the return type must be different.
9. Message for a function where the name of the function doesn't have the type function and does have another type.
10. Message for expressions which has different types according to the operator who is being used. For example: 'integer' + 'boolean'.
11. Message for an array that has a different number of dimensions, according to its declaration.
12. Message for an unconditional loop that use 'stepUp' or 'stepDown' expression.
13. Message for an unconditional loop that use 'satisfying' expression.
14. Message for a function when its name do not exist.
15. Message for an array where the limits or the dimension do not agree with it.

4.3.4 *Validations Implemented*

In this section, we are going to report where the error message will be thrown by the compiler according to contextual conditions expressed in the attribute grammar that we have.

Variable declaration

```
variable_declaration : vars '->' type ';'
```

Listing 4.8: Variable declaration rule in LISS

Listing 4.8, shows the declaration part where the programmer declares variables with the respective type. Processing this part, the compiler adds the information into the symbol table. As variable can be initialized at this stage, before adding the information into the symbol table, we need to check if every variable has the correct type regarding the type of literal value assigned. If not, error message 5 (see Table 28) must be printed.

Let's see in Listing 4.9, an error that may happen in this case.

```
b = boolean -> integer;
```

Listing 4.9: Example of an error message in variable declaration

While processing this section, the compiler creates the mips code for each variable. There is one type which can throw an error message too in this section, it is called the *array* type. For this type, we need to check if the index respects the limits (the index value is in bounds); if not then error message number 4 must be issued (see Table 28).

Regarding to the other types, we don't check values in this section. Notice that the *array* type is the hardest one to deal (needs to calculate the position of the array) for creating the mips code instruction.

Let's see an example of an array type error message regarding to this case in Listing 4.10.

```
array1 = [[1,2],[2,3,4,5]], vector -> array size 4,3;
```

Listing 4.10: Example of an error message in variable declaration for the array type

In the left side of a declaration, before the type name the programmer can define one or more variables. Listing 4.11 shows the grammar rule for *Vars*.

Vars

```
vars : v1 (',' v2)*
```

Listing 4.11: Vars rule in LISS

The grammar rule in Listing 4.11 refers to the declaration of multiple variables of the same type.

In this case, the compiler needs to check if the variables that will be added to the symbol table have been already declared. If one variable has been previously declared, then an

error message type number 2 will be thrown (see Table 28). Let's see an example of a LISS program that illustrates this error in Listing 4.12.

```
a = 4, a = 5 -> integer;
```

Listing 4.12: Example of an error message in LISS for vars non-terminal

In Listing 4.12, there is a problem regarding that two variables with the same name are being created. This must throw an error as we said previously, and an error message related to the second variable.

Set initialization

```
set_definition : '{' set_initialization '}'
               ;
set_initialization :
                   | identifier '|' expression
```

Listing 4.13: Set initialization rule in LISS

In Listing 4.13, we can see how to declare a set under the declarations section in LISS. And it has two choices for declaring a set: empty set or some content in the set. If there is some content available, this content must be defined by a boolean expression. In case the expression is not a boolean, an error message with the number 7 (see Table 28) will be thrown. Let's see an example of this error with a piece of LISS code related to set initialization in Listing 4.14.

```
set6 = { z | (z+tail(z)) < 5} -> set;
```

Listing 4.14: Example of an error in LISS for set_initialization

In Listing 4.14, we can see that the variable won't be declared due to the fact that the content isn't correct. The function *tail* is a function for sequence and it needs a sequence variable as an argument, not an integer variable (as we can see). The compiler will return the type of that operation as 'null' because he can't execute that operation.

Moreover, there is another error concerned with the add operator that defines both operands of type integer. But, due to the previous statements made, the types that the add operator will see: integer (from *z* variable) and a null (from *tail(z)*). The compiler can't execute it too, so the error is being spread throw the entire operation of the set content.

In the end, after calculating the content of the set initialization, an error message will be printed out, as can be seen in Listing 4.15.

```
line: 20:18 Expression '(z+tail(z))<5' has type 'null',when It should
    be 'boolean'.
```

Listing 4.15: Error message for the set_initialization

Subprogram definition

```
subprogram_definition : 'subprogram' identifier '(' formal_args ')'
    return_type f_body
```

Listing 4.16: Subprogram definition rule in LISS

In Listing 4.16, we can see how to declare subprogram (function) under the declaration section in LISS. In this case, we need to check the return type of the subprogram.

If the type of the returned expression is different from the type declared (for example, the return expression is of type boolean, but the return type declared is integer) then an error message number 7 (see Table 28) is thrown.

Let's see an example of this case in Listing 4.17.

```
subprogram f(amen->boolean)->integer{
        declarations
                b -> boolean;
        statements
        return b;
}
```

Listing 4.17: Example of error message in LISS for subprogram_definition non_terminal

In Listing 4.17, we can see that the return type declared is integer. However in this example, the subprogram returns a variable called 'b' that has boolean type. In this case, an error message will be reported due to the incompatible types.

Assignment

```
assignment : designator '=' expression
```

Listing 4.18: Assignment rule in LISS

In Listing 4.18, we can see the syntax for assigning some content to a variable or an array under the statement section in LISS. For this part we need to check some possible error regarding to the context available. Let's explain those differents contexts below.

Suppose the designator non-terminal in Listing 4.18, is a variable of type *array*; In that case, the content that we can assign to that variable is restricted (see an example in Listing 4.19).

```
1  array1 = [1,2,3];
```

Listing 4.19: Example of assigning a constant value to an array variable

In Listing 4.19, we see a variable named *array1* with the type *array* and it will be assigned to some values shown in the example, *[1,2,3]*. For this example, we need to check if the value has the correct dimensions and limits regarding the variable declaration. In this case, if it isn't correct then the number 15 error message will be outputed (see Table 28).

Also the same error message is reported for the case of the next example in Listing 4.20.

```
1  array[3] = 1;
```

Listing 4.20: Example of storing a value to a certain position in the array

In Listing 4.20, suppose that the variable *array* has one dimension with only two position available. In this case, the access to the fourth position (index 3, as shown in the example), is behind the limits regarding to the specification of the variable. And, in this case, it must thrown the number 15 error message too (see Table 28).

The last case for this part concerns in general the types of *designator* and *expression* that must be equal. The compiler can't generate code for the assignment operation.

If they do not conform this general rules, then this will throw the number 6 error message (see Table 28).

Let's see an example of this case in Listing 4.21.

```
1  boolean1 = integer1;
```

Listing 4.21: Example of assignment with differents types

In Listing 4.21, the example shows us that assignment operation is trying to store an integer value in *boolean1* variable (which has boolean type). As we know, if the types aren't equal then the operations cannot be executed and an error must be reported.

Designator

```
1  designator : identifier array_access
```

Listing 4.22: Designator rule in LISS

In Listing 4.22, we can see the syntax to refer to an atomic variable or an array variable under the statement section in LISS. In this case, we need to check some errors depending on the context: atomic variable or array variable.

Let's explain first the case of a simple variable.

Every variable used must be declared and so it must be in the symbol table. If it doesn't exist in the symbol table, it means that variable doesn't exist and we need to throw an error number 1 (see Table 28).

We need to check if the name of the *identifier* isn't the same as the name of a type in LISS (see Table 21). If it is, then an error message number 1 must throw (see Table 28).

Now regarding the array variable context, we need to check a lot of conditions.

First, we need to check if the identifier is in the symbol table; otherwise the compiler will throw the number 1 error message (see Table 28).

Second, we need to check if the name of the identifier isn't the same name of another type variable in LISS (see Table 21). If it is, then the compiler must throw the number 1 error message (see Table 28).

Third, we need to check the type of identifier. If the type isn't an array then we need to throw the error message number 3 (see Table 28).

And finally, we need to check if the *identifier* and the *array_access* agreed in number of dimensions. If not, then it must be thrown the number 11 error message (see Table 28).

Elem array

```
1  elem_array : single_expression ( ',' single_expression )*
```

Listing 4.23: Elem_array rule in LISS

In Listing 4.23, we can see how to handle an element of an array. For this part we need to check if every element (represented by the *single_expression* non-terminal) has the correct type.

In an array context, the type of each element must be an integer. If it isn't then the compiler must throw the number 7 error message (see Table 28).

Function call

```
1  function_call : identifier '(' sub_prg_args ')'
```

Listing 4.24: Function_call rule in LISS

In Listing 4.24, we can see the syntax to call a function under the statement section in LISS. In this context, we need to check two error situations.

First, we need to check if the *identifier* (function name) is in the symbol table. If it isn't then it must throw the number 14 error message (see Table 28).

Last, the compiler checks if the *identifier* has the correct category (it must belong to the category *Function*). If it doesn't have then it must throw the number 9 error message (see Table 28).

Expression

```
1 expression : single_expression (rel_op single_expression )?
```

Listing 4.25: Expression rule in LISS

Listing 4.25, defines the syntax to write an expression, that can be used in many different contexts in LISS. In this case, we need to check the type of both operands (the *single_expression* are correct regarding the type required by *rel_op*). If they are not, then we throw the number 10 error message (see Table 28).

Notice that it is the *rel_op* non-terminal that determines the type that the left and right *single_expression* must have.

Let's see an example in Listing 4.26.

```
1 2 < true
```

Listing 4.26: Example of an error message in expression rule

In Listing 4.26, we can see the number two (left single_expression) then the less-than sign (the rel_op) and finally the true value (the right single_expression annotation). We can see immediately that the operand types doesn't match. In that case the less-than sign requires both expressions (left and right) of type integer, and actually one is integer and the other is boolean — an error number 10 will be generated.

Single expression

```
1 single_expression : term ( add_op term)*
```

Listing 4.27: Single_expresion rule in LISS

Listing 4.27 defines how to expand a *single_expression* non-terminal in LISS. In a similar way, we need to check the types of the operands required by the *add_op*. If the *terms* type don't agree with the required type regarding to the *add_op*, then the compiler must throw the number 10 error message.

Term

```
term : factor ( mul_op factor)*
```

Listing 4.28: Term rule in LISS

In Listing 4.28 is specified the syntax to expand a *term* in LISS. In a similar way, we need to check the types of the operands required by the *mul_op*. If the *factors* type don't agree with the required type regarding *mul_op*, then it must throw the number 10 error message.

Factor

```
factor : inic_var
          | designator
          | '(' expression ')'
          | '!' factor
          | function_call
          | specialFunctions
```

Listing 4.29: Factor rule in LISS

In Listing 4.29, we can see the syntax to expand a *factor* in LISS. As it can be seen, there are a lot of alternative rules; however the majority do not require any special check.

We will only discuss a particular one:

```
'!' factor
```

In this option there is an exclamation mark sign and then a *factor* non-terminal. In programming languages, the exclamation mark represents the negation of the expression. So, the negation operation requires an operand of boolean type in order to work correctly. If the type of the *factor* is not a boolean, then the number 7 error message will be added to the error table.

Print_what

```
print_what :
          | expression
          | string
```

Listing 4.30: Print_what rule in LISS

In Listing 4.30, it is shown the syntax for printing a value (numeric or alphanumeric) in the output in LISS language.

In this case, we need to check the type of the *expression* in the context of the first alternative. If the type is a *set* then it must throw the number 7 error message (see Table 28).

Notice that the type allowed for the *expression* are :

- integer
- boolean
- sequence
- array

Read

```
read_statement : 'input' '(' identifier ')'
```

Listing 4.31: Read rule in LISS

In Listing 4.31, it is shown the syntax for reading the input to get the value from the user to be stored in the given *identifier* in LISS. In this case, we need to check some possible errors.

If the *identifier* doesn't exist in the symbol table, then we must thrown the number 1 error message (see Table 28). If the *identifier* exists in the symbol table, we must check the type of it. If the type isn't an integer, then we must throw the number 5 error message (see Table 28).

If_then_else_stat

```
if_then_else_stat : 'if' '(' expression ')'
                    'then' '{' statements '}'
                     else_expression
```

Listing 4.32: If_then_else_stat rule in LISS

Listing 4.32 defines the syntax of a conditional statement, in particular, for the 'if' statement.

As for all programming languages, the behaviour of an 'if' statement is the same. It means that the *expression* non-terminal must be of boolean type, in order to be possible to decide if it will enter to the next branch (*then*) or has to jump to the *else* branch. If the

expression type isn't a boolean, then it must throw the number 7 error message (see Table 28).

For_stat

```
for_stat : 'for' '(' interval ')' step satisfy
           {
             statements
           }
interval : identifier type_interval
         ;
type_interval : 'in' range
              | 'inArray' identifier
              ;
range : minimum '..' maximum
      ;
minimum : number
        | identifier
        ;
maximum : number
        | identifier
        ;
satisfy :
        | 'satisfying' expression
    ;
```

Listing 4.33: For_stat rule in LISS

Listing 4.33 defines the use of a 'for-loop' statement in LISS.

A particular case of this statement is the use of 'for-each' interval which is denoted with the keyword *inArray*.

In LISS, we are able to use a 'for-loop' which can access all the elements of an array, also called 'for-each'. In that 'for-each' context, we cannot use *step* non-terminal nor *satisfy* non-terminal.

Let's see an example of that case in Listing 4.34.

```
for(b inArray vector) stepDown 1 satisfying vector[0] == a
```

Listing 4.34: Example of an error message in for_stat rule

In Listing 4.34, the fact that there is an *inArray* keyword means that the statement is a 'for-each' loop and for this case we cannot use *step* or *satisfying* construct.

If the *step* non-terminal is present then we must throw the number 12 error message (see Table 28); if the *satisfy* non-terminal is present then we must throw the number 13 error message (see Table 28).

However, if the 'for-each' statement isn't used, we can use the known and normal behaviour of a 'for-loop' statement by using the *in* keyword instead of *inArray*.

Range

Listing 4.33 is specified how to expand the *interval* non-terminal in the context of the *for_stat* in LISS.

We need to check if the *identifier* is in the symbol table, If it isn't then it must throw the number 1 error message (see Table 28).

If the *identifier* is in the symbol table, we need to check its type. If it isn't a variable of type integer, then it must throw the number 5 error message (see Table 28).

The *type_interval* non-terminal of the *interval* rule in LISS (Listing 4.33) tells us which kind of operation can be a 'for-loop' in LISS. As we can see there are two choices, the normal behaviour of the 'for-loop' statement (represented by *in range*) and the 'for-each' statement (represented by *inArray identifier*). In the case of the constructor, we need to check if the *identifier* variable is in the symbol table and if it isn't, the number 1 error message will be thrown (see Table 28). Then we need to check the type that *identifier* variable has. If the variable isn't an *array* then it must throw the number 5 error message (see Table 28).

The *range* rule indicates us the limit bounds of a 'for-loop' statement and it is syntatically represented by: a limit inferior (*minimum*), two dots and a limit superior (*maximum*).

Minimum rule have two options; the first one is to write a constant number, the second one is to write a variable. Regarding the variable, we need to check if it is in the symbol table. If it isn't then it means that it isn't declared and must be thrown the number 1 error message (see Table 28). But if the variable is in the symbol table, we need to check its type. If the type isn't an *integer* then it must throw the number 5 error message (see Table 28).

In a similar way, *maximum* rule has the same behaviour as *minimum* rule. This means that we need to check if the *identifier* (variable) is in the symbol table. If it isn't then it means that the variable isn't declared and the compiler must throw the number 1 error message (see Table 28). However if the variable exists, we need to check its type. If the type isn't an *integer* then it must throw the number 5 error message (see Table 28).

Satisfy

Listing 4.33 is shown the syntax to define a condition *satisfy* in the context of the *for_stat* in LISS. Basically, the *satisfying* keyword means that there is a condition that must be evaluated and should be 'true' in order to proceed.

In this case, the *expression* is the condition and it must have a boolean type. If the *expression* type isn't a boolean then it must throw the number 7 error message (see Table 28).

While_stat

```
1 while_stat : 'while' '(' expression ')'
2              '{' statements '}'
```

Listing 4.35: While_stat rule in LISS

In Listing 4.35 is shown the syntax to write the interation control flow statement *while*.

For this case, we need to check if the condition (represented above by the non-terminal *expression*) has the correct type. Notice that a condition must be an expression with *boolean* type. If it isn't then it must throw the number 7 error message (see Table 28).

Succ_or_pred

```
1 succ_or_pred : succ_pred identifier
```

Listing 4.36: Succ_or_pred rule in LISS

Listing 4.36 defines the syntax of the increment or decrement statement in LISS. In this case, we need to check two things.

First, we need to check if the *identifier* (also known as variable) is in the symbol table. If it isn't then it must throw the number 1 error message (see Table 28).

In case that the variable is in the symbol table, we need to check its type. If the type isn't an *integer*, then it must throw the number 5 error message (see Table 28).

Tail

```
1 tail : 'tail' '(' expression ')'
```

Listing 4.37: Tail rule in LISS

Concerning the operations of sequences, Listing 4.37 defines the syntax for the tail function for sequences.

For this case, we need to see if the *expression* type has the correct type. If the *expression* doesn't have *sequence* type, then it must throw the number 7 error message (see Table 28).

Head

```
head : 'head' '(' expression ')'
```

Listing 4.38: Head rule in LISS

Similarly, Listing 4.38 defines the syntax for the *Head* function for sequences.

For this case, we need to see if the *expression* type has the correct type. If the *expression* doesn't have *sequence* type, then it must throw the number 7 error message (see Table 28).

Cons

```
cons : 'cons' '(' expression ',' expression ')'
```

Listing 4.39: Cons rule in LISS

In Listing 4.39, we can see how to write the *Cons* function for sequences.

For this case, we need to see if both *expression* have the correct type. If the first *expression* (the left one) doesn't have *integer* type, then it must throw the number 7 error message (see Table 28). If the second *expression* (the right one) doesn't have *sequence* type, then it must throw the number 7 error message (see Table 28).

Delete

```
delete : 'del' '(' expression ',' expression ')'
```

Listing 4.40: Delete rule in LISS

In Listing 4.40 is presented the syntax for the *delete* function for sequences.

For this case, we need to see if both *expressions* have the correct type. If the first *expression* (the left one) doesn't have *integer* type, then it must throw the number 7 error message (see Table 28). If the second *expression* (the right one) doesn't have *sequence* type, then it must throw the number 7 error message (see Table 28).

Copy_statement

```
copy : 'copy' '(' identifier ',' identifier ')'
```

Listing 4.41: Copy_statement rule in LISS

In Listing 4.41 is presented the syntax for the *copy* statement. For this case, we need to see if both the *identifiers* are in the symbol table and have the correct type. If one of the

identifier is not in the symbol table, then it must throw the number 1 error message (see Table 28). After checking the availability of both *identifiers* in the symbol table, we need to check their type. If a variable is not of *sequence* type, then it must throw the number 5 error message (see Table 28).

Cat_statement

```
1  cat_statement : 'cat' '(' identifier ',' identifier ')'
```

Listing 4.42: Cat_statement rule in LISS

In Listing 4.42 is shown the syntax for *cat* statement and it has the same behaviour as the *copy* statement.

This means that we need to check if both *identifiers* are in the symbol table and have the correct type. If one of the *identifiers* is not in the symbol table, then it must throw the number 1 error message (see Table 28). Then, after checking the availability of both *identifiers* in the symbol table, we need to check their type. If a variable is not of *sequence* type, then it must throw the number 5 error message (see Table 28).

Is_empty

```
1  is_empty : 'isEmpty' '(' expression ')'
```

Listing 4.43: Is_empty rule in LISS

In Listing 4.43, we can see the syntax for function *is_empty* for sequences. In this case, we need to check, only, the type of *expression* that must be a *sequence*. If it isn't, then it must throw the number 7 error message (see Table 28).

Length

```
1  length : 'length''(' expression ')'
```

Listing 4.44: Length rule in LISS

In Listing 4.44 is shown the syntax for function *length*, that is the same behaviour as *is_empty* function.

We need to check, only, the type of *expression* that must be sequence type. If it isn't, then it must throw the number 7 error message (see Table 28).

Member

```
member : 'isMember''(' expression ',' identifier ')'
```

Listing 4.45: Member rule in LISS

At last, Listing 4.45 defines the function *member* sequences. For this case, we need to check first the *identifier* and then the *expression*. If the *identifier* terminal is not in the symbol table, then we must throw the number 1 error message (see Table 28). Otherwise, if the variable is in the symbol table, we need to check the type of both (*identifier* and *expression*). *Identifier* must be an *sequence*, if it isn't then it must throw the number 5 error message (see Table 28). If *expression* isn't an *integer*, then it must throw the number 7 error message (see Table 28).

4.4 CODE GENERATION

In the compiler process, after adding informations to the *symbol table* and searching some inconsistencies to the LISS language (semantic). It is now time to convert the LISS language representation (higher level language) to MIPS assembly code (lower level language).

In the process of converting the language, there is a lot of tasks that will be executed:

- Instruction selection : choosing which type of instruction to use.
- Register allocation : choosing the right register to use for a certain instruction.
- Instruction scheduling : choosing the right time for the instruction to be added in the code.

Let's discuss along this section about strategy and operations used for the code generation.

4.4.1 *Strategy used for the code generation*

In chapter 3, we talked about the MIPS architecture. In this section we will talk about the strategy used for generating the MIPS assembly code regarding the processor's specific architecture.

Data and text part

The compiler creates two variables called *data* and *text* and those two variables have type *String*. Each time that it is needed to generate a new assembly code fragment, it will be

added to one of those variables depending on the context. Each variable created at scope level 0 (corresponding to a declaration) will be added to the *data* variable. Similarly, each statement is transformed into MIPS code that is added to *text* variable.

Notice that a *subprogram* declaration (also known as function) is the only thing that is not added to the *data* variable string.

Compiler register strategy

The MIPS architecture has a limited number of registers and it is a necessity to use it wisely for generating the code.

So we created, in our project, an array structure with 8 positions which tells us which registers are free (array type is boolean). From 0 to 7, it will represent the state of each MIPS register.

In this case, the association of the registers with the array component is:

- Position 0 : register $t0
- Position 1 : register $t1
- Position 2 : register $t2
- Position 3 : register $t3
- Position 4 : register $t4
- Position 5 : register $t5
- Position 6 : register $t6
- Position 7 : register $t7

Each time that the compiler needs to occupy a register, it will always check the state of each register by ascending order. Like that, the compiler knows that the next register to be allocated will always be the latest and not in a random order.

Then we need to apply a strategy to avoid an overflow of registers being used. Let's explain this situation with an example in Listing 4.46:

```
1  4 + 5 + 6 + 7 + 8 + 9 + 10 + 11 + 12
```

Listing 4.46: Example of a sum operation with some numbers

In Listing 4.46, we see a long addition with 9 numbers as operands. If we wanted to store the 9 numbers in the available registers, it will be impossible due to the limitation of the MIPS architecture (only 8 temporary register). So we need to apply a strategy for solving

this situation, and it passes by removing information when it is no more needed. For this case, we can move value 4 to the first register ($to) and move value 5 to the second register ($t1). Then we add the values, stored in the two registers, and store the result in register $to. Notice that by doing that, we set position 1 of the control array to *false* (because register $t1 is free) and $t1 will be available for storing the next value 6; after that we apply the same strategy to continue the sum. By using this strategy, we won't have an overflow of registers.

Also, notice that the MIPS architecture has some other registers available (saved temporary registers (reserved across call)) and we could use them to increase the number of registers. But even if we increase the number of registers, the problem is still there and that is why we need to apply a strategy to handle properly the registers allocation task.

Additionally, those saved temporary registers are reserved for jump instructions and in our case we use them for sequence operations only. Regarding to calling functions, which uses also jump instruction, we use a different algorithm. We use the stack for storing the information about the function and that is why we don't need to use the saved temporary registers.

Finally, concerning the usage of temporary registers, we have a law that dictate that when a statement is finished (a statement ends with a semicolon), the state of those temporary registers must be set to false. This means that each temporary register is free to be used again.

Address size

In MIPS architecture, we have the ability to optimize the instruction that will be used. But in our case, we won't optimize anything and we will use a fixed address size. So, we created an *integer* variable that tells us how many bytes does have an address in the MIPS architecture (4 bytes).

The size of the address will be used to allocate variables in the heap or in the *stack*.

Notice that MIPS architecture does a fetch with address alignment of the instructions being executed. And that is why we set up a fixed size address and we don't do optimizations for ease debugging and code generation.

Conditional statement

In LISS language, there are different kinds of conditional statements (if-statement, while-statement and for-statement) that will be implemented in MIPS assembly code, using some jump instructions.

As said previously in Chapter 3 (MIPS assembly), there is a code pattern to adopt when a jump instruction is being used. So we need to define a strategy for those conditional statements.

It is created two variables, one of type *LinkedList<Integer>* named as *counterJumpStack* and another one of type *Integer* named as *counterJump*.

Each time that a conditional statement is new, the variable *counterJump* will be concatenated to the name of the condition statement and then it is incremented. This is done because in MIPS architecture code label: name must be unique so that inconditional jump instructions are not ambiguous. If the name was the same then MIPS won't be able to know to which code label it should jump. So, when we concatenate the number with the name of the conditional statement (and then it increments), the assembly code labels will be unambiguous.

Regarding *counterJumpStack* (the *LinkedList<integer>* variable), this is a stack for saving informations about the conditional statements when there are nested control statements. The stack uses a LIFO (Last In First Out) system.

Let's see an example in Listing 4.47.

```
1  program test{
2      declarations
3          i -> integer;
4          array1=[1,2,3] -> array size 3;
5      statements
6          if(true)
7          then{
8              for(i inArray array1){
9                  writeln(i);
10             }
11         }
12 }
```

Listing 4.47: Example of conditional statements in LISS language

In Listing 4.47, we can see that we use a lot of nested conditional statement. So we need to save the information of each conditional statement anywhere and that is why we use a stack. Each time that a conditional statement appears, the compiler pushes the *counterJump* value (associated to the conditional statement) to the stack *counterJumpStack*. If inside of the conditional statement, there is another conditional statement, then its *counterJump* value, meanwhile incremented, will be added to the top of the stack.

Like that we don't loose the information and we have traceability regarding to the conditional statement that the compiler has passed throw. Following this strategy, MIPS assembly code generation will be easier and correct.

Notice that each time the compiler exits from a conditional statement, it removes the information from the stack but the *counterJump* variable won't be decremented.

Subprogram

To handle appropriately subprograms in LISS, we created three structure:

1. LinkedList<String> **functionName**
2. HashMap<String,String> **mipsCodeFunctionCache**
3. String **functionMipsCode**

The variable *functionName* is a *LinkedList<String>* structure that stores the name of each subprogram that the compiler finds. It uses a FILO system and acts as a stack.

Basically, we created the same system as the one used for conditional statements. To implement subprograms it is necessary to use also a jump instruction and so the name of the function must be also unique to avoid ambiguity in the MIPS assembly code.

Each time, that the compiler finds a subprogram name in the LISS code, it pushes it to the *LinkedList* structure. If there is, also, the nesting effect by having a multiplicity of subprograms inside each one, then it will add all those informations to the stack.

When we need to add some MIPS assembly code, we just need to take the entire string available in the stack by using the concatenate method and associate the MIPS assembly code to that name.

The variable *mipsCodeFunctionCache* is a *HashMap<String,String>* structure and the key of the HashMap refers to the name of a subprogram (it is the name that is catched in the *LinkedList* structure explained before) and the value is the MIPS assembly code associated to the name of the function.

Basically, that structure saves the information of each subprogram with their MIPS assembly code associated. The fact that we use a *HashMap* structure is to comply with the requirement that the name of a subprogram must be unique, and this constraint is perfect with a *HashMap* because the keys are always unique.

Finally, the variable *functionMipsCode* is a String which hold the MIPS assembly code of a subprogram. When the compiler is creating the MIPS assembly code of a subprogram, it will add to that variable. At the end, it will be added to the HashMap structure whenever it is necessary.

Notice that when the compiler finishes to pass the entire LISS code, it will remove all the informations available in the *HashMap* structure and add it to the string variable *text* (referred previously in the subsection **Data and text part**).

State of functions

In LISS language, some statements or operators are not translated directly into MIPS assembly code. Instead, they are already predefined. It happens with:

- Sequence operations (tail, head, etc...)
- Printing statement (write, writeln)
- Read statement (input)
- Index out of bound check on validation (related to the array type)

Instead of translanting those functions to MIPS assembly code, the predefined code is invoked. So when they are not used in the LISS code, it is not necessary to add that code to the target file. We created a structure which tells us if those functions will be used or not.

- HashMap<String, Integer> **functionStateUsedOrNot**

Basically, the idea behind that structure is that if a function was used, it will set the function entry (available in the *HashMap* structure) to 1(1 means true). When the compiler finishs the code generation, it will check the variable *functionStateUsedOrNot* and see if some functions are set to 1. If it is the case, then it will add at the end of the generated MIPS assembly code, the appropriated and defined MIPS assembly code for that function. Notice that the variable *functionStateUsedOrNot* is always initialized with 0 before the compiler begins the code generation.

Stack

To complement the Symbol Table and deal easily with variables declared in scopes with level greater than 0 (inside a function) we use a stack depicted in Figure 13, where we can see two components: *levelStackSP* and *stackSP*.

1. ArrayList<Integer> **levelStackSP**
2. ArrayList<Integer> **stackSP**

levelStackSP is a stack where the index is associated with the scope level of a LISS subprogram. The value stored in each index corresponds to the information about the index of the *stackSP* array. Meanwhile the value in each index of the *stackSP* array store information about the space that the compiler required when a stack operation was used in a LISS program to deal with function calls as explained in the next section.

By creating that structure, the compiler will use an algorithm for finding a specific position relatively to a variable in the stack faster, instead of creating multiple lines of MIPS assembly code for finding that position. In this case, it is done an optimization aimed at executing a LISS program faster.

For example, in Figure 13, if the compiler needs to figure out the address of a variable in scope level 2, it will use *levelStackSP*, access to its index 2 and get the value 4. Then with the value 4, it will access index 4 of the *stackSP* array and get the address number 64.

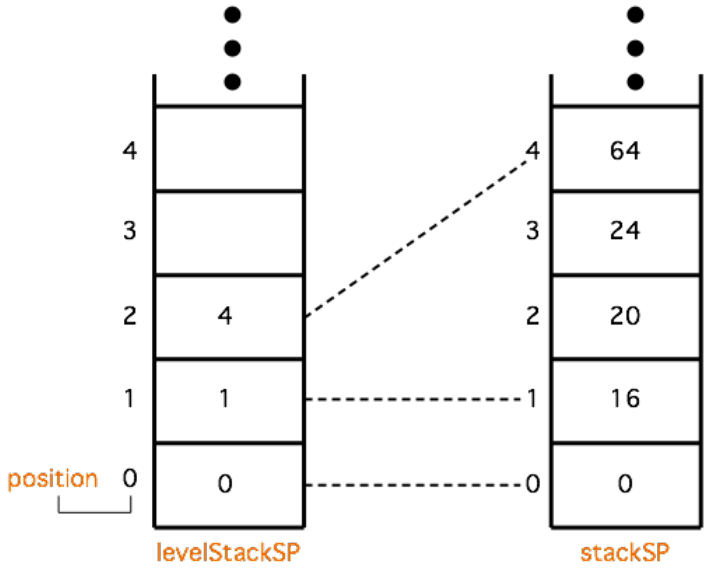


Figure 13.: Stack structure

With that address, we can calculate the position of that variable with a specific algorithm which will generate only one MIPS assembly code.

Calling a function

Calling a function requires some jump instruction. Those jump instructions may or may not loose the information available in the registers before processing the function.

That is why we need to create a mechanism to avoid loosing that information before processing a function in MIPS assembly code.

Let's first explain the use of the stack regarding to function call in expression. But before starting the explanation, notice that the arguments in function call doesn't allow the use of functions.

If a function call is used in an expression, it needs to check first the availability of the temporary registers.

If a temporary register contains a value (isn't empty) then it must be saved into the stack before calling the function (example can be seen in Listing 4.49).

```
1  i = 2 + calculate();
```

Listing 4.48: Example of a function call in an expression statement

In Listing 4.49, the information that is stored into stack is the number 2. This is a valuable information that needs to be stored in order to continue and generate the correct code. At the end, after return from the function, it will be restored into the register.

Let's see the code generated in Listing 4.49.

```
1 li $to,2
2 addi $sp, $sp, -4
3 sw $to, 0($sp)
4 jal calculate
5 lw $to, 0($sp)
6 addi $sp, $sp, 4
7 move $t1, $vo
8 add $to, $to, $t1
9 sw $to, i
```

Listing 4.49: Code generated for the Listing 4.49

In Listing 4.49, the value 2 is loaded to register $to (line 1); then, the compiler knows that a function call will occur so it needs to save the number two into the stack (line 2 and 3); the next instruction calls function *calculate()* (line 4); after the return (when the function ends), the state saved previously into the stack (actually, number two) is loaded again to the register $to (line 5 and 6); then it loads the result of the function to the next register available, $t1 (line 7); and finally, it executes the arithmetic operation, addition (line 8), and the result is in variable *i* (line 9).

However, if the temporary registers are empty before the function call, then this save mechanism will not be applied.

Let's see an example in Listing 4.50.

```
1 i = calculate();
```

Listing 4.50: Example of a function call in an assignment

As we can seen, in Listing 4.50, no information is stored in the temporary registers before the call of function *calculate()*; this means that the mechanism for saving valuable information won't be applied (see the code generated for example 4.51).

```
1 jal calculate
2 move $to, $vo
3 sw $to, i
```

Listing 4.51: Code generated for Listing 4.51

Concerning the functions to operate with sequences, the function call mechanism is applied in the same way. The difference is that with sequence functions this mechanism can also be applied to arguments that have an expression.

For example, let's consider the function *cons()* to operate with sequences (see Listing 4.52).

```
1 sequence2 = cons(3+head(sequence2),sequence2);
```

Listing 4.52: Example of using a sequence function in LISS

In Listing 4.52, the mechanism will be applied to both of the arguments passed to *cons* function. The second argument of function *cons()*, it must be a sequence and can be an expression (this means that we can nest more sequence functions in this argument). The first argument must be an integer and can be an expression too (this mean that it can nest sequence functions in there (if they return an integer)).

To cope with this situation, the compiler needs to store all the values into the stack to avoid loosing them.

Let's see and explain the code generated from the example in Listing 4.52 (see Listing 4.53).

```
1  lw $to,sequence2
2  addi $sp, $sp, -4
3  sw $to, 0($sp)
4  li $to,3
5  addi $sp, $sp, -4
6  sw $to, 0($sp)
7  lw $to,sequence2
8  move $so, $to
9  jal head_sequence
10 lw $to, 0($sp)
11 addi $sp, $sp, 4
12 move $t1, $vo
13 add $to, $to, $t1
14 move $s1, $to
15 lw $to, 0($sp)
16 addi $sp, $sp, 4
17 move $so, $to
18 jal cons_sequence
19 move $to, $vo
20 sw $to, sequence2
```

Listing 4.53: Example of code generated for Listing 4.52

In Listing 4.53, we load the variable *sequence2* corresponding to the second argument of function *cons()* (line 1); then we store that information to the stack (line 2 to 3); then, we process the first argument of the *cons()* function (loading the number 3 to a temporary register $to)(line 4); now, the compiler knows that it must add that number with the result of *head()* function (which will use a jump instruction), it will save the number 3 to the stack before calling that function (line 5 to 6); then the compiler will generate the calling function (line 7 to 9); after return from the function, the compiler knows that it needs to load the previous state stored before calling the function, so it gets back the number 3 from the stack into $to (line 10 to 11); then the result of the *head()* function is stored in the next register available $t1 and executes the addition (line 12 to 13); finally, the compiler will move the sum to the appropriated register to call the *cons()* function (line 14) and reload the information that he stored previously to the stack (related with the second argument of the *cons()* function) (line 15 to 17); last, it will process the call of the *cons()* function and store the result into the variable *sequence2* (line 18 to 20).

4.4.2 *LISS language code generation*

This part will discuss the code generation implemented for every statements in LISS language. It is divided by paragraphs, one for each statements; when appropriate, it is again subdivided to discuss the process for scope level 0 and for scope level greater than 0.

4.4.3 *Creating a variable in LISS*

Scope level equals to zero

Let's see an example of LISS code in Listing 4.54.

```
1  program liss{
2    declarations
3      a, b = 4, c = -1, d = +2 -> integer;
4      flag, flag1 = false, flag2 = true -> boolean;
5      array1, array2 = [2,1,1], array3 = [1] -> array size 3;
6      array4 = [[1,2],[3]] -> array size 3,3;
7      set1, set2 = { y | y+1 < y+4}, set3 = {} -> set;
8      seq1, seq2 = <<1,2>> -> sequence;
9    statements
10 }
```

Listing 4.54: Declaration block in LISS, to illustrate the creation of variables

In Listing 4.54, we can see some variables being declared in a LISS program in the level 0 (global scope). In this case, the compiler needs to identify the name and type of each variable and its initial values that will generate respective MIPS assembly code. Let's go line by line and explain each one.

In line 3 of Listing 4.54, we see 4 different named variables being declared with the type *integer*. The compiler adds them to the symbol table and does some checkings according to the semantic system implemented. Then, if everything is all right, it associates each variable with a certain address. Remember that the type *integer* requires 4 bytes in the memory as explained before. So, in this case, it will generate the address 0, 4, 8 and 12 for those variables.

Later, we need to generate the assembly code if everything worked as planned. And this is done by declaring them in the data section of the MIPS assembly code (see in Listing 4.55).

```
1  .data
2  a : .word 0
3  b : .word 4
4  c : .word -1
5  d : .word +2
```

Listing 4.55: Code generation of integer variables in MIPS assembly code

So creating variables in the level 0, means to add them to the *data* section (otherwise it will be in the stack) associating the name of the variables (*a*) with their size (*.word* (4 bytes)) and the value that the variable will store. Notice that a variable not initialized store the value 0.

In line 4 of Listing 4.54, we declare boolean variables and this is processed in the same way as we did for *integer* variables. Remember that *boolean* types cost 4 bytes in the memory. So we just need to do the same as if it was of *integer* type.

We add the name of the variable (*flag*), then its size (*.word* (4 bytes)) and then we write the value of the boolean (true is 1, false is 0) (see in Listing 4.56).

```
1  flag : .word 0
2  flag2 : .word 1
3  flag1 : .word 0
```

Listing 4.56: Code generation of boolean variables in MIPS assembly code

Notice that a boolean variable not initialized has the default value false.

Arrays

In lines 5 and 6 of Listing 4.54, we declare some array type variables. The idea of *array* type is a fixed-size sequential collection of elements with the same type. In MIPS assembly code, there is a specific way of creating this type by doing as follows (see in Listing 4.57).

```
1 array2 : .space 12
2 array1 : .space 12
3 array3 : .space 12
4 array4 : .space 36
```

Listing 4.57: Code generation of array variables in MIPS assembly code

In Listing 4.57, we declare the name of the variable, then its size (sequence of memory, *.space*) (due to the fact that it is an *array* type) and finally, how much space that the array will store. Notice that *array* type in LISS, only stores integer values and for calculating the space required by the *array* variable, we need to do some calculation.

The calculation is done by multiplying all the limits of each dimension of the *array* variable and with that result we multiply by the number 4 (space of an *integer* variable). Regarding to the line 5 in Listing 4.54, the calculation for the variables *array1*, *array2* and *array3* is done by taking the limit 3 (they are a one-dimension array) and multiply it by 4 (space of an integer), which is equal to 12. However regarding to line 6 in Listing 4.54, the calculation for the variable *array4* (that is a bi-dimensional array) is done by multiplying all the limits associated to the variable (3x3 which is 9) and then, multiplying by 4 (space of an integer), which is equal to 36. And the strategy is the same if the dimension of the *array* variable is greater.

Now that we declared the space of those variables in MIPS assembly code, we need to declare the values associated to those variables.

So we implemented a system which takes the information of each position of the array regarding to the value that was declared in the array.

For example, if we have a multidimensional array with 3 dimensions like that :

```
1 array1 = [[[12]],[[5,6],[7]]] -> array size 2,2,3;
```

Listing 4.58: Example of an array with 3 dimensions

We need to create a system which will take the information regarding the array initialization to generate the appropriated code (see Figure 14). So we created the following structure (see in Listing 4.59).

```
1 ArrayList<ArrayList<Integer>> accessArray
```

Listing 4.59: Structure of saving informations of each index in JAVA

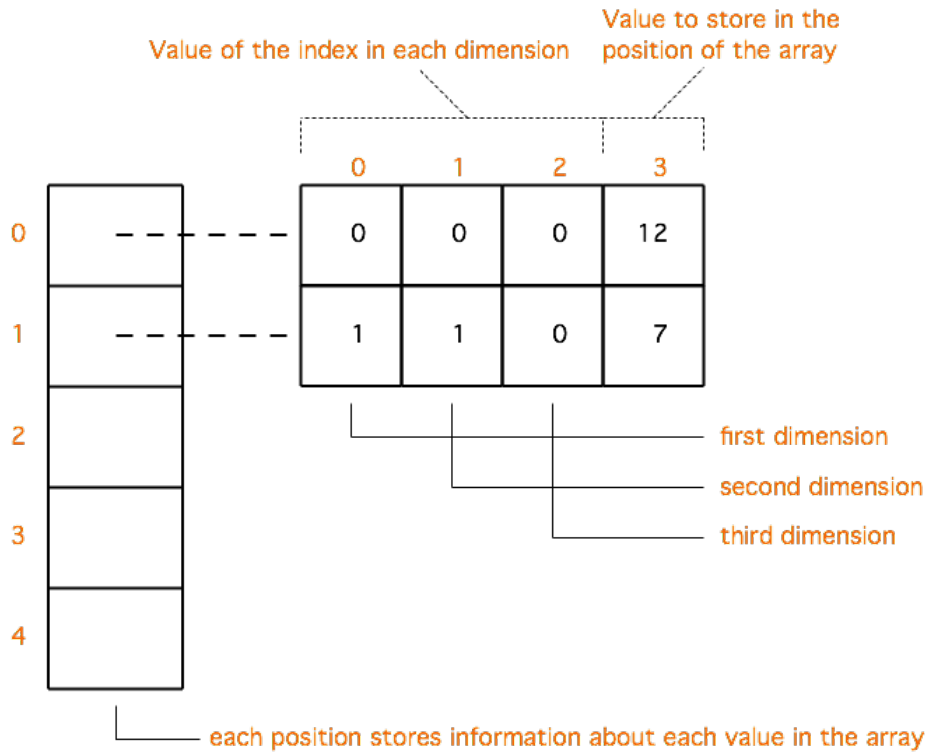


Figure 14.: Structure for saving information of each value declared in a array

Basically, it is a structure where one *ArrayList* holds the information of one index of the array processed and add it to the other *ArrayList* whenever it completes to process the information (it behaves like a stack).

So, in Figure 14, we can see clearly that the left rectangle is the stack where each position of it holds information (a *ArrayList* of integers) regarding each dimension declared in the array. This *LinkedList* has a certain architecture which must be explained. The size of that *ArrayList* is equal to the dimension of the *array* plus one (refers to the value available in the index processed). Then, the first positions of the *ArrayList* are reserved for each dimension of the array and the last position of the *ArrayList* is the value which needs to be stored in that index of the array. Each dimension will inform us which position has the value. For example, in Figure 14, the first information available in the stack is in the position 0 and this information is telling us that there is a value (12) to be stored at the position [0,0,0]. The second information, available in the index 1 of the stack, is telling us that there is another value (7) to be stored at the position [1,1,0]. After getting all those informations, we need to generate the instructions and for that we need to calculate the right position of each value

with the information that it was processed. The calculation is done with the formula in Equation 1.

$$p(l,a) = \sum_{i=0,\ i\neq n-1}^{n-2} (a[i] \times \prod_{j=i+1}^{n-1} l[j]) + a[n-1] \tag{1}$$

Equation 1 needs two inputs:

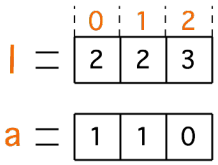
- **l** - array variable which has the informations about the bounds of the array in question.
- **a** - array variable with the indexes of the position of the array that need to be accessed.

Notice that the variable **n**, in the equation, is equal to the number of dimensions of the array.

Then after getting those inputs variables, it calculates the position of an element for any n-dimensional array size. If the dimension of the array is 1, the equation doesn't compute the first part (due to the restriction of the equation).

And to understand the formula, let's explain it with an example supposing that we need to access a[1,1,0] of an array tridimensional with 2,2,3 boundaries.

In that case, the input variables for the formula (examples taken from Figure 14 and Listing 4.58) are:



By using the equation above with that example, let's unfold it.

$$\begin{aligned} p(l,a) &= a[0] \times l[1] \times l[2] + a[1] \times l[2] + a[2] \\ p(l,a) &= 1 \times 2 \times 3 + 1 \times 3 + 0 \\ p(l,a) &= 6 + 3 + 0 \\ p(l,a) &= 9 \end{aligned} \tag{2}$$

So, with that calculation we can see that the memory sequential position for the array component selected (0,1,0) is the offset 9.

Using Figure 15 let's check if the calculation was done correctly.

Using the positions of the variable array **l** and using them to find the right position in the array structure in Figure 15, we go first to the right position of the first dimension (number 1 (l[0] = 1)). Then, we go to the second dimension of the part that belongs the number 1 in the first dimension, in this case it is the number 1 (l[1] = 1). Finally, we go to the last

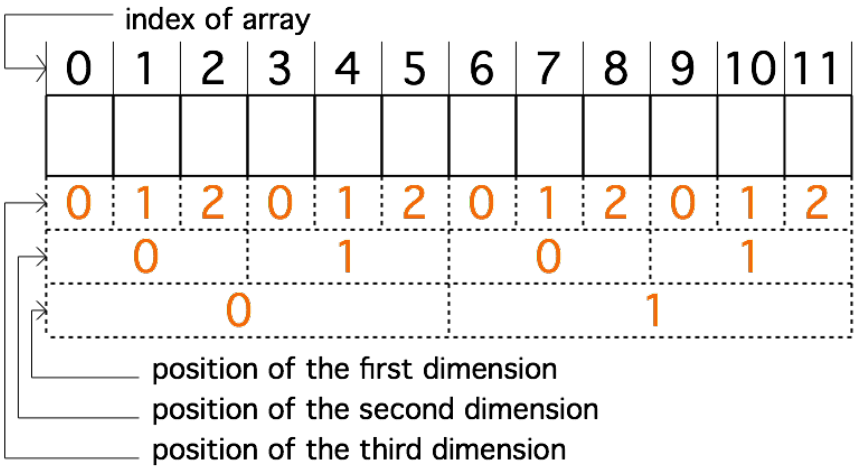


Figure 15.: Array structure with size 2,2,3.

dimension and go to the number 0 (l[2] = 0). As we can see, it goes directly to the index number 9 of the array.

This proves that the algorithm works properly and explains how it calculates the memory position for any array component given its index.

Back to the analysis of line 5 and line 6 in Listing 4.54, and after creating the space for the variables *array2*, *array3* and *array4*, we need to initialize them.

Let's see in Listing 4.60 an example of the code generation for the initialization of *array2*

```
1  .text
2    main:
3       ##### Initialize Value Array :array2#####
4       li $to,2    # 5:12
5       li $t1,0    # 5:12
6       sw $to, array2($t1)
7       li $to,1    # 5:12
8       li $t1,4    # 5:12
9       sw $to, array2($t1)
10      li $to,1    # 5:12
11      li $t1,8    # 5:12
12      sw $to, array2($t1)
13      ########################################
```

Listing 4.60: MIPS assembly code generated for the variable array2

In MIPS architecture, it is impossible to declare the array with the values associated in the declaration part. So, we need to overcome this problem and this is done by creating MIPS assembly code in the *text* part to be added to the flow of the program execution.

In this case, we can see in Listing 4.60 that the MIPS assembly code for the initialization of *array2* comes first in the flow of the program execution. Then after that code fragment for initialization of arrays, comes the mark fragment to control the flow of the program execution.

Let's explain how the code generated in Listing 4.60 works.

- line 4 - Loading the value 2, this is the value to be stored in the array.
- line 5 - Loading the position 0, this is the position which the value will be stored (use the algorithm for calculating the position).
- line 6 - Store the value 2 to the position 0 in the array2 memory.
- line 7.... - Continue to use the same strategy with the next values that needs to be added.

Storing one value in an array needs three MIPS instructions.

Notice that the position calculated is always multiplied, at the end, by the size of an *integer* (number 4).

As we can see in Listing 4.60, the positions are :

- line 5 - the value is 0 => position 0 (0/4 = 0)
- line 8 - the value is 4 => position 1 (4/4 = 1)
- line 11 - the value is 8 => position 2 (8/4 = 2)

The other array elements (on components) have the initial value 0 and that is why we don't need to create MIPS instructions for them, because the default value is 0 in an array non-initialized (the story changes when those arrays are created in a level scope greater than 0, but it will be discussed further).

Sets

In line 7 of Listing 4.54, we see two different named variables being declared with the type *set*.

That type basically doesn't create any informations in the MIPS assembly code for the declarations parts. Instead it saves the information in a specific structure created for that purpose. The structure is made with the concept of a Tree structure where there are some nodes with branches or not, associated to other nodes.

And this structure is made by two JAVA class:

- Node Class

- Set Class

The Node JAVA class is a class that represents the concept of a node structure in a tree, with three components:

1. String data
2. Node left
3. Node right

The variable **data** refers to the value associated with that node, the variables **left** and **right** refers to a node who might be to the left or right side of the present node.

Now, the Set class is a class that saves the information of the set in a tree structure and the free variable associated with that set declaration. The Set class uses the Node class.

1. ArrayList<Node> identifier
2. Node head

The variable **identifer** refers to a list of occurencies of the set free variable in the tree nodes. This is done for one particularly reason, instead of browsing the entire tree and looking for those free variable occurences, we can change their state along the list and directly, it changes also in the tree. The advantage of that structure is that we don't need to execute a tree search to look for and change those free variable occurences, who will be a time consuming by doing that operation.

Then we have the variable **head** which points to the root node of the tree structure.

Let's see the Set structure in Figure 16.

We implemented that list for free variables for one reason and this reason comes with the fact that we can join multiple sets. Notice that each set has its own free variable which means that each free variable is distinct from set to set when trees are merged in a set operation.

Let's see an example of joining two sets in Figure 17.

In Figure 17, we can see that the root of the **Set** is connected with two sets (left and right). This means that we are joining two sets (*Set1* and *Set2*).

Doing this change to upgrade the complexity of the tree structure will need some attention to fix the free variables of each set. This is why we have created the set class with a list of free variables. Like that, we can get the free variables from the other sets and add them to the list of the **Set**.

The compiler creates a Set class for each set variable declared, and it will associate that structure to the variable added in the symbol table.

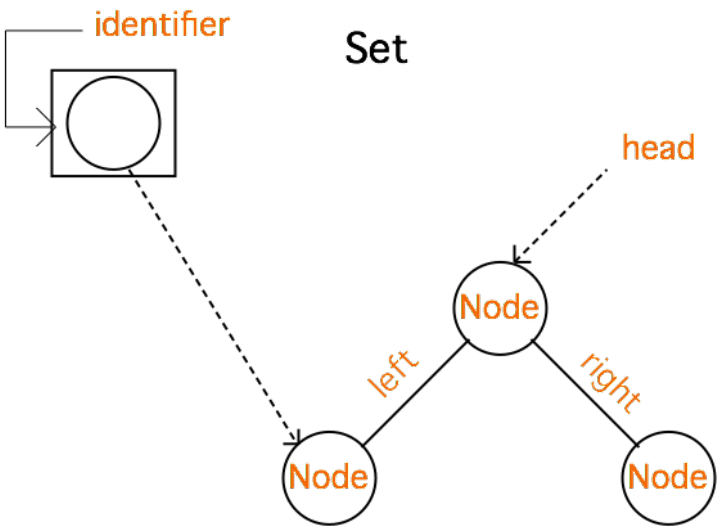


Figure 16.: Set structure in JAVA

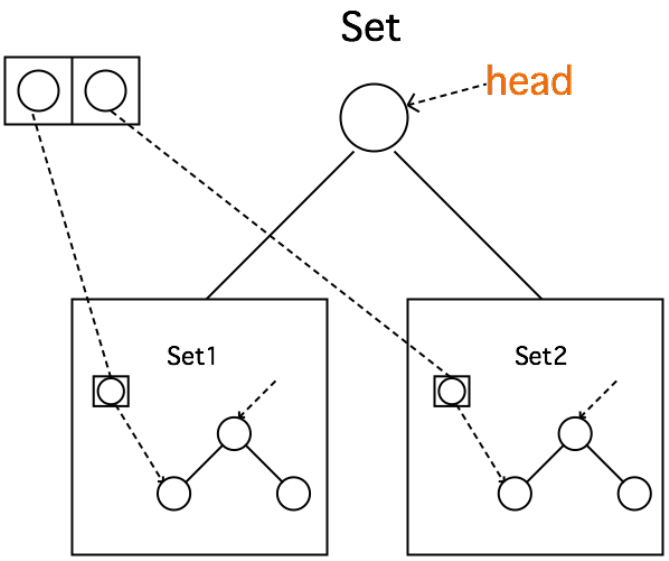


Figure 17.: Set structure in JAVA

Notice that the compiler will generate some assembly code only when it will be needed to implement a set logical expression in the *statements* part of the LISS program.

Last, we need to talk about the different states that a set can have regarding to the declaration part.

Set variable can have three different states:

- Universe set
- Empty set
- Defined set

The **universe** set is a set which represents the whole number system and it is declared in a LISS program as follows:

```
1  set1 -> set;
```

The **empty** set is a set which represents a collection without any number. It is declared a LISS program as follows:

```
1  set1 = {} -> set;
```

The **defined** set is a set which represents a collection containing the numbers generated by the logical expression associated with the set. It is declared in a LISS program as follows:

```
1  set1 = {y | y+1 < y+4} -> set;
```

Sequences

Let's talk finally about the last line 8 in Listing 4.54 that represents the declaration of variables of type *sequence*. The idea of generating the code for that type, is almost the same as for the type *array*.

Basically, the type *sequence* creates one position of memory for each variable declared and will store the value -1 in there (value -1 is equal to NULL). By setting the value to -1, it means that the variable sequence is empty, no values are associated to that variable (the same as saying that the sequence wasn't intialized).

Let's see the code generated for the example available on line 8 of Listing 4.54:

```
1  seq2 : .word -1
2  seq1 : .word -1
```

As we can see, we write the name of the variable first, then the space needed to store that variable (*.word)* and the initial value associated to that variable (NULL value (-1)). Notice that for that type of variables we allocate 4 bytes, for one main raison. The *sequence* type is a linkedlist of integer numbers and those numbers will be stored in the *heap* section. So, in this case, we need to know in which address the first element of the sequence is stored. This initial address must be stored at one place that can be known and this goes by storing that address to the variable name associated. Because the size of an address in the MIPS architecture is 4 bytes, so in this case the variable must be 4 bytes long and that is why we chose the type *.word*.

After creating the variables, we need to check if the sequence is initialized or not. If it is initialized, we need to generate MIPS assembly code.

For generating the code, we need to insert the values defined in the sequence writing the appropriate MIPS assembly code for each value.

Notice also, that the MIPS assembly code that will be generated, will also be placed in the same area as the initialization of an array (before the code corresponding to the statement in the program *body*).

Let's analyze in Listing 4.61, the code generated for the variable **seq2** declared in Listing 4.54.

```
1 lw $so, seq2
2 li $s1, 1
3 jal cons_sequence
4 move $so, $vo
5 li $s1, 2
6 jal cons_sequence
7 sw $vo, seq2
```

Listing 4.61: Code generated for the sequence variable

Basically, we need some inputs in order to add some values to a sequence and those informations are:

1. the name of the sequence variable.
2. the value that needs to be added to the sequence.
3. the function that will add the number to the heap and link it to the *sequence*.

So, regarding to the variable **seq2** in Listing 4.54, the compiler needs to take the value 1 and 2 and generate code to insert them in the sequence.

In Listing 4.61, the compiler first creates an instruction which puts the address of the sequence variable to a saved register ($ *so*), then it loads the value 1 (first number that must

be added to the sequence) to the next saved register ($ *s1*) and finally it calls the function that will insert in the sequence (*cons_sequence*).

Notice that those steps are always the same; regarding the use of those saved registers, the reason is that we don't need to use the stack for storing the information. Instead we take profit of the MIPS architecture, and we use those saved registers.

Normally we use the saved registers for calling some functions due to the fact that those registers won't be modified during the jumping to those functions, and in that case, we call the function that will add the number to the sequence.

cons_sequence function will return and set register $vo to the return value that is the address of the first element of the sequence. Then in line 5, it will move the address in register $vo to the register $so, due to the fact that it needs to add the second number (number 2) to the sequence. Finally, at the end it will store the address of the first element in the sequence variable (line 8).

Level scope greater than zero

Creating variables in an inner scope (with a level greater than 0) is necessary when those variables are declared inside of a function, like the one exemplified in Listing 4.62.

```
1  program liss{
2    declarations
3      subprogram test(){
4        declarations
5          a, b = 4, c = -1, d = +2 -> integer;
6          flag, flag1 = false, flag2 = true -> boolean;
7          array1, array2 = [2,1,1], array3 = [1] -> array size 3;
8          array4 = [[1,2],[3]] -> array size 3,3;
9          set1, set2 = { y | y+1 < y+4}, set3 = {} -> set;
10         seq1, seq2 = <<1,2>> -> sequence;
11       statements
12     }
13   statements
14 }
```

Listing 4.62: Example of declaring variables in a level greater than 0 in a subprogram

As we can see in Listing 4.62, variables are declared in the same way as they are at level 0 (program code). The only thing that is different is that they are created in a different area (subprogram area) and this means that those variables need to be allocated in the stack memory.

When the compiler processes a function, it will process first the arguments and then, every variable declared in the *declarations* part.

After adding the arguments and the variables to the symbol table, it will also calculate the total size that needs to be allocated in the runtime stack.

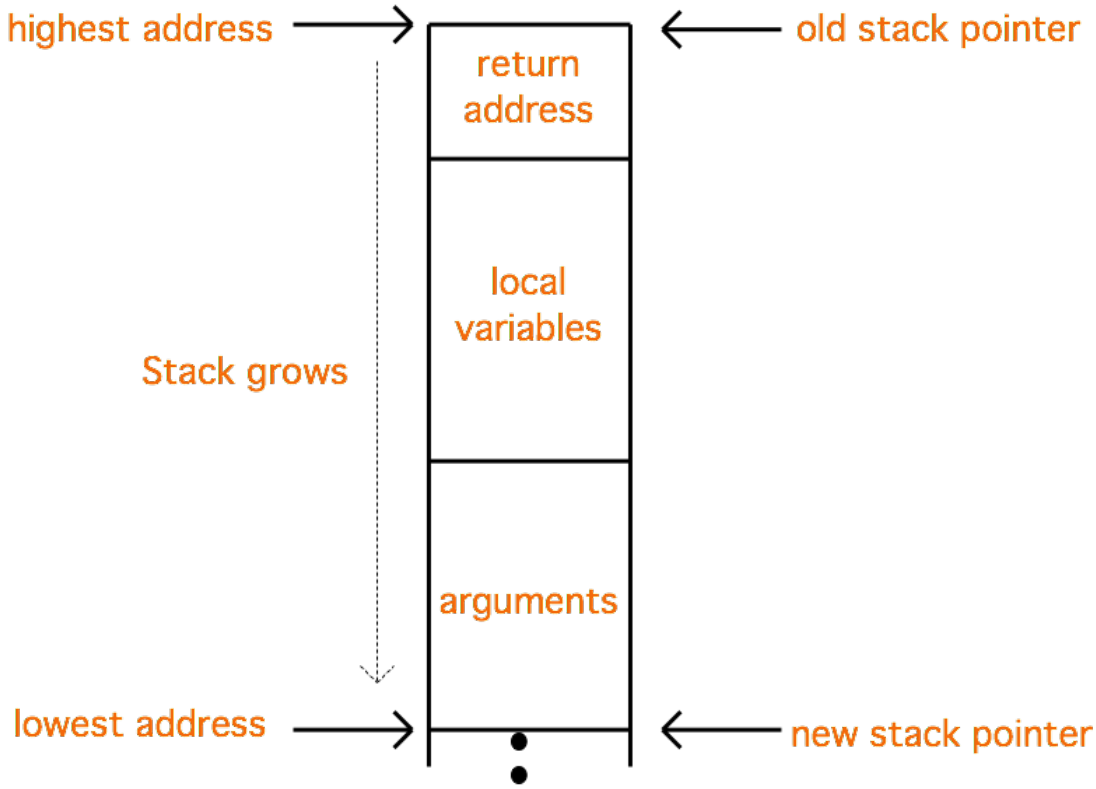


Figure 18.: Architecture of the stack relatively to a function in LISS

As can be seen in Figure 18, the stack is organized as follows:

- First, a position for the return address is allocated;
- Then, the local variables are allocated;
- At the top, we allocate space for the arguments of the function.

Notice that the stack grows from the highest address to the lowest one and that there is also a reason for this choice. The variables that the compiler finds and needs to add to the symbol table have an address automatically generated by incrementing a global space counter. When the compiler enters a function (a subprogram in LISS), this address counter is reset to zero.

So, if we want to access a variable in that stack, we just need to get the address of the variable from the symbol table and add it to the *new stack pointer*.

Notice that, in Figure 18, it is possible that the arguments section, or the local variables section, does not appear in the stack (if the function in the LISS program does not have arguments, or does not declare variable).

Now, let's explain the code generated in MIPS relatively to the Listing 4.62.

The fact that it is a subprogram (function) implies that the code generated will be added to the branch associated with the function name in MIPS and the first thing that must be done under that branch is to increase the stack relatively to the size of data that needs to be allocated (see in Listing 4.63).

```
1    test:
2      addi $sp, $sp, -160
3      sw $ra, 156($sp)
```

Listing 4.63: Initialization of MIPS code generated for a function branch

In Listing 4.63, we see in the first line a code label that is the name of the branch associated with that function. Then appears the instruction for adding to the stack-pointer the stack size that the function needs. In this case, we have one instruction *add* (line 2) which explains us that the function needs to allocate 160 bytes in the stack memory regarding to the stack pointer and updating the value of the new stack pointer. Finally, we save the return address of the function into the stack (line 3).

This example follows the general MIPS schema that is always used for the initialization of a function code branch. After that, comes the MIPS assembly code relative to the variables declared under the *declarations* part of the function; notice that local variables are allocated in the top of the runtime stack instead of being allocated in the global static memory. So these initialization requires the generation of proper instructions.

In line 5 of Listing 4.62, we are declaring integer variables and the code generated for those variables is shown in Listing 4.64.

```
1  li $to,0
2  sw $to, 0($sp)
3  li $to,4
4  sw $to, 4($sp)
5  li $to,-1
6  sw $to, 8($sp)
7  li $to,+2
8  sw $to, 12($sp)
```

Listing 4.64: Declaring integer variables in level scope greater than 0 on MIPS.

In Listing 4.64, lines 1 and 2 are related with the declaration of the variable **a**. Basically, the idea is:

1. load the value to store in the variable to a temporary register.

2. store that value in that register to the position allocated to the variable in the stack.

Notice that the position is given by the algorithm that we explained in a previous section (stack structure).

Lines 3 and 4 are the code generated for the variable **b**; lines 5 and 6 are the code generated for the variable **c**; lines 7 and 8 are the code generated for the variable **d**.

Line 6 of Listing 4.62, refers to variables declared with type boolean and the code generated for that type can be seen in Listing 4.65.

```
1  li $to,0
2  sw $to, 16($sp)
3  li $to,1
4  sw $to, 20($sp)
5  li $to,0
6  sw $to, 24($sp)
```

Listing 4.65: Declaring boolean variables in scope level greater than 0

In Listing 4.65, the methodology for creating boolean variables at a level greater than 0 is the same used for level zero. The only thing that differs, is the instruction for storing the value that is associated to the variable.

Lines 1 and 2 of Listing 4.65 refers to the declaration of the variable **flag**; lines 3 and 4 corresponds to the declaration of the variable **flag2**; and lines 5 and 6 corresponds to the declaration of the variable **flag1**.

Lines 7 and 8 of Listing 4.62, declare variables of type array; the code generated for the variable **array2** is shown in Listing 4.66.

```
1  ##### Initialize Array :array2#####
2  li $to,0
3  sw $to, 28($sp)
4  li $to,0
5  sw $to, 32($sp)
6  li $to,0
7  sw $to, 36($sp)
8  ##### Initialize Value Array :array2#####
9  li $to,2
10 li $t1,0
11 li $t2,28
12 add $t1, $t1, $t2
13 add $t1, $t1, $sp
14 sw $to, ($t1)
15 li $to,1
```

```
16  li $t1,4
17  li $t2,28
18  add $t1, $t1, $t2
19  add $t1, $t1, $sp
20  sw $to, ($t1)
21  li $to,1
22  li $t1,8
23  li $t2,28
24  add $t1, $t1, $t2
25  add $t1, $t1, $sp
26  sw $to, ($t1)
```

Listing 4.66: Declaring array variables in a level greater than 0

The creation of a variable of type array is done almost in the same way as if it was a variable declared at level zero. But it differs in some points explained below.

Regarding variables of type array, we need to set to zero all the position of the array in the stack (done on line 2 to 7 of Listing 4.66). Then, we need to store the values that were declared in the array into their right position. Let's explain how this is done for value 2 of **array2**, considering the program in Listing 4.66:

1. line 10 : Store value 2 in register $to.
2. line 11 : Store index of value 2 regarding to the array declared to register $t1.
3. line 12 : Store address of the array to register $t2.
4. line 13 : Add the index with the address of the array for getting the relative address of the component.
5. line 14 : Add that address with the stack pointer, for getting the final address in the stack.
6. line 15 : Store the value 2 into that computed address in the stack.

Repeat the same algorithm for the next values that need to be stored. Also notice that the index of the array is calculated throw the algorithm mentioned previously and that the address of the array is associated to the variable and caught from the symbol table.

Line 9 of Listing 4.62, declares variables of type set and it only creates the tree structure which will be associated to each variable in the compiler's Symbol Table. Nothing more will be generated as code, unless if it is used in the *statements* section.

Line 10 of Listing 4.62 declares variables of type sequence and the code generated for the variable **seq2** is shown in Listing 4.67.

```
1  li $t2,-1
2  sw $t2, 148($sp)
3  lw $so, 148($sp)
4  li $s1, 1
5  jal cons_sequence
6  move $so, $vo
7  li $s1, 2
8  jal cons_sequence
9  sw $vo, 148($sp)
```

Listing 4.67: Declaring sequence variable in level scope greater than 0

The idea of generating the code for a sequence is the same used for an array variable. First, we need store the value NULL in the stack memory (lines 2 and 3 of Listing 4.67) and then, if some initiate values are associated to the variable, we need to generate the code (which is almost the same as the one generated for a sequence in level 0).

So, first we get the address of the sequence (line 4 of Listing 4.67), then we load the value to a register (line 5 of Listing 4.67) and finally, we call the function that will process the concatenation of the value to the sequence.

Notice that after creating the code corresponding to those variable declarations, appears the MIPS code for the body of the subprogram. Finally, at the end of the execution, we need to remove the stack allocated to the function and return, as shown in Listing 4.68.

```
1  lw $ra, 156($sp)
2  addi $sp, $sp, 160
3  jr $ra
```

Listing 4.68: Exiting the function in MIPS assembly code

In Listing 4.68, line 1 will get the return address of the function; then at line 2 it will remove the stack allocated to the function and finally at line 3, it will prepare to exit the function with the return address.

4.4.4 *Loading a variable or a value*

Loading a variable depends only on one factor, the level of the variable.

If the level of the variable is zero then it will load the value of the variable by using its name (see in Listing 4.69).

```
1  lw $to,b
```

Listing 4.69: Loading a variable with level scope equals to zero

Otherwise if the level is greater than zero, then it must use the algorithm which will find the position in the stack and then load the value at that position in the stack (see in Listing 4.70).

```
lw $to, 4($sp)
```

Listing 4.70: Loading a variable with level scope greater than zero

To load a value, the only possible values that can be loaded are of integer and boolean types; this operation doesn't depend on the level. The instruction for loading is the same, it just depends on the type that will be used. If it is a boolean type, the value *true* will be loaded as one; otherwise the value *false* will be loaded as zero (see in Listing 4.71).

```
li $to,1    # true value being loaded
li $to,0    # false value being loaded
```

Listing 4.71: Loading a boolean value

If it is an integer type, then it will load the value that it will be declared (see in Listing 4.72).

```
li $to, 5           # loading the number 5
```

Listing 4.72: Loading an integer value

4.4.5 *Assigning in LISS*

An assignment in LISS has three parts: the sign equals, the left operands and the right expression.

In order to make the operations consistant (coherent), the types in the left and right sides must be equal. Let's show, in Listing 4.73, some cases of assignment statements in LISS.

```
i = 1 + 2 + 3;
flag1 = 1 < 3;
array1[1] = 10;
array1 = array2;
array1 = [2];
set1 = set2;
sequence1 = sequence2;
```

Listing 4.73: Examples of assignment for different types in LISS

Assignment for integer

In Listing 4.73, lines 1 and 3 are statement that deal with integer type; however the process for generating MIPS assembly code is distinct and needs to be discussed. The normal and general way consists in assigning the content to an integer variable. Let's explain it by analyzing the code generated for both lines 1 and 3.

```
1  li $to,1
2  li $t1,2
3  add $to, $to, $t1
4  li $t1,3
5  add $to, $to, $t1
6  sw $to, i
```

Listing 4.74: Code generated for line 1 in Listing 4.73

For example, to translate an arithmetic operations of type integer variable, it must create the code for the arithmetic operation (lines 1 to 5 of Listing 4.74) and then store it into the variable (line 6 of Listing 4.74).

If we want to assign a value to an array, the code generated can be seen in Listing 4.75.

```
1  li $to,1
2  ####Verify limits of the array####
3  li $t1,0
4  slt $t2, $to, $t1
5  sltu $t2, $zero, $t2
6  xori $t2, $t2, 1
7  li $so, 7
8  beqz $t2, indexoutofboundError
9  li $t1,4
10 slt $t2, $to, $t1
11 li $so, 7
12 beqz $t2, indexoutofboundError
13 ####End of the verification####
14 li $t1,4
15 mul $to, $to, $t1
16 li $t1,10
17 sw $t1, array1($to)
```

Listing 4.75: Code generated for line 3 in Listing 4.73

First, it loads the position where the value will be stored (in this case, it loads the number 1 (line 1 of Listing 4.75). Then some code is included for checking if the position is inside the boundaries of the array (line 3 to 12 of Listing 4.75). Basically, it tests if the position

value is between 0 and 4; if it is not, then it will raise an index out of bounds error and will stop the program. Though, if the position is inside the limits then it will multiply the position by four (line 14 to 15 of Listing 4.75) and after, it will load the respective content (line 16 of Listing 4.75). Finally, it will store the content to the position of the array (line 17 of Listing 4.75).

Notice that the right side of assignment statement can be an expression. This means that it can use some operators to build a complex arithmetic expression (only integer operators); below is a list of those operators:

- + (plus sign)
- - (minus sign)
- * (multiply sign)
- / (division sign)

Concerning those operators, each one has one corresponding instruction in MIPS as can be seen in Listing 4.76.

```
1 add $to, $to, $t1 # plus instruction
2 sub $to, $to, $t1 # minus instruction
3 mul $to, $to, $t1 # multiply instruction
4 div $to, $to, $t1 #division instruction
```

Listing 4.76: Code generated for arithmetic operators

So, the mechanism of generating the code for an expression is always the same: generate the code for the left operand of the operator, then generate the code for the right operand, and finally generate the appropriate operator instruction.

Assignment for boolean

In Listing 4.73, line 2 is a statement that deals with boolean type.

The method for processing the values of their type is simular to the one followed for arithmetic operations with integer variables: first it generate the code for the right side and then generate the code for the left side.

Let's see the code generated for a boolean assignment (see in Listing 4.77).

```
1 li $to,1
2 li $t1,3
3 slt $to, $to, $t1
4 sw $to, flag1
```

Listing 4.77: Code generated for line 2 of Listing 4.73

In Listing 4.77, it is processed the expression on the right side (lines 1 to 3), and then store the result in the variable associated to the assignment statement (line 4).

As explained before, some operators are available for boolean expressions which are listed below:

- == (double equal sign)
- != (different sign)
- < (less sign)
- > (greater sign)
- <= (less or equal sign)
- >= (greater or equal sign)
- || (or sign)
- ! (negation sign)

Concerning those operators, only three of them have one corresponding instruction(<, >, ||), and the other require a logic mechanism with more than one instruction. Notice that this is due to the fact that MIPS architecture doesn't have all the logic instruction implemented. Let's see the code generated for each one.

```
1  slt $t2, $to, $t1
2  sltu $t2, $zero, $t2
3  xori $t2, $t2, 1
4  slt $t3, $t1, $to
5  sltu $t3, $zero, $t3
6  xori $t3, $t3, 1
7  and $t2, $t2, $t3
```

Listing 4.78: Code generated for 'equal' operator in MIPS

In Listing 4.78, we translate the behaviour of the equal operator according to the equation below:

$$x == y \iff (\neg(x < y)) \wedge (\neg(x > y)) \tag{3}$$

```
1  slt $t2, $to, $t1
2  slt $t3, $t1, $to
3  or $t2, $t2, $t3
```

Listing 4.79: Code generated for 'not equal' operator in MIPS

In Listing 4.79, we translate the semantics of the 'not equal' operator according to the equation below:

$$x! = y \iff (x < y \vee x > y) \tag{4}$$

```
slt $to, $t1, $to
sltu $to, $zero, $to
xori $to, $to, 1
```

Listing 4.80: Code generated for 'less or equal' operator in MIPS

In Listing 4.80, we translate the semantics of the 'less or equal' operator according to the following equation:

$$x <= y \iff \neg(x > y) \tag{5}$$

```
slt $to, $to, $t1
sltu $to, $zero, $to
xori $to, $to, 1
```

Listing 4.81: Code generated for 'greater or equal' operator in MIPS

In Listing 4.81, we translate the semantics of the 'greater or equal' operator according to the equation below:

$$x >= y \iff \neg(x < y) \tag{6}$$

Now, let's see the code generated for the 'not' operator (see Listing 4.82).

```
sltu $to, $zero, $to
xori $to, $to, 1
```

Listing 4.82: Code generated for 'not' operator in MIPS

And finally, the three operators which are translated directly to MIPS:

```
slt $to, $to, $t1 # less instruction
slt $to, $t1, $to # greater instruction
or $to, $to, $t1  # or instruction
```

Notice that the difference between a 'less' and a 'greater' instruction is only in the use of the registers. The mechanism for generating MIPS code for the boolean assignment follows

the pattern introduced above for the integer assignment: first, generate the code for the left side of the operator; second, generate the code for the right side and third, generate the code for the operator involved.

Assignment for array

Assigning arrays in LISS can be made in two ways (see lines 4 and 5 in Listing 4.73).

One way is to assign an array variable to another array variable with the purpose of copying the entire array to the other array. The MIPS code for that case can be seen in Listing 4.83.

```
1  li $to,0
2  lw $t1, array2($to)
3  sw $t1, array1($to)
4  li $to,4
5  lw $t1, array2($to)
6  sw $t1, array1($to)
```

Listing 4.83: Code generated for line 4 in Listing 4.73

In Listing 4.83, an array with size two is copied to another array. Before to begin the process of copying, it is necessary to check if the boundaries and the size are the same. Otherwise, the copy will not be executed and an error will be raised.

Basically, the idea is to copy the content of each position in array2 to the same position in array1. First, it loads the position (line 1 of Listing 4.83), then it loads the value available at that position in array2 (line 2 of Listing 4.83) and finally it stores the value to the same position in array1 (line 3 of Listing 4.83). The same process will be repeated for the next remaining positions of the array in order to complete the copy process.

The other way for assign an array is by declaring the content of each position of the array (line 5 of Listing 4.73). And the process is different because it needs to do some calculations for knowing the position of each value that needs to be stored. Notice that the calculation to determine the position of an array component is the same one explained in the *declarations* part for initialization. Once again the array limits (dimensions and boundaries) must be checked.

The code generated for that situation can be seen in Listing 4.84.

```
1  li $to,2
2  li $t1,0
3  sw $to, array1($t1)
4  li $to,0
5  li $t1,4
6  sw $to, array1($t1)
```

Listing 4.84: Code generated for line 5 of Listing 4.73

In Listing 4.84, we first load the value that needs to be stored (line 1), then comes the position of the array (line 2) and finally, the storage of that value to the required position in array1 (line 3). If some positions weren't declared or missed then it will put them with the value zero. For instance, the case of the last position (line 4 to 6) of array1 because his size is equal to two and it was declared only one value in the assignment statement.

Assignment for set

Assigning sets is a little different from the other assignments (see line 6 of Listing 4.73).

Basically, in this case the compiler generate any instructions but, instead, it reorganize the JAVA tree structure associated with the set variable, available in the symbol table, changing it to the correct structure according to the expression. The operators available for the set type are listed below:

- ++ (union sign)
- ** (intersection sign)

Using those operators with sets doesn't imply to generate any instructions but instead reorganize the tree structure for the set, according to the mathematical meaning of each one (see equations below).

$$A \cup B = \{x : x \in A \; or \; x \in B\} \tag{7}$$

$$A \cap B = \{x : x \in A \; and \; x \in B\} \tag{8}$$

Assignment for sequence

The idea of assigning two sequences is to change the pointer of one sequence to the other sequence and, in this case, the sequence on the left side will change the address (where it is pointing to in the heap memory) to the address of the sequence on the right side of the assignment.

Let's see the code generated to assign a sequence to another one in Listing 4.85.

```
1 lw $to,sequence2
2 sw $to, sequence1
```

Listing 4.85: Code generated for line 7 of Listing 4.73

In Listing 4.85, we load the address that the variable *sequence2* is pointing to in the heap memory (line 1) and then, it stores that address to the variable *sequence1* (line 2).

Notice that assigning sequences, doesn't copy every elements of one sequence to the other one. To do that (sequence cloning), there is a function in LISS which does that (*copy* function).

4.4.6 *Set operations*

Variables of type sets can be assigned and used as operands in expression made out of union and intersections operators. Moreover there is a special operator that takes an integer and a set, and returns a boolean: the 'in' operator (allows to test if a value is contained in the set). See Listing 4.86 for an example.

```
1 program test{
2     declarations
3         flag -> boolean;
4         set1 = {x | x>1} -> set;
5     statements
6         flag = 4 in set1;
7 }
```

Listing 4.86: Example of using a set in LISS

The example in line 6 of Listing 4.86 will test if the number 4 is contained in the elements of the set named *set1*.

This is the only situation that requires the generation of MIPS code to implement the referred test (check the truth of that expression). The idea is to create a boolean expression replacing the free variable, in the set tree, by the value that we want to check.

Let's look the code generated in Listing 4.87.

```
1 li $to,4
2 li $t1,1
3 slt $to, $t1, $to
4 sw $to, flag
```

Listing 4.87: Code generated for line 6 of Listing 4.86

The compiler traverses the tree associated to the free variable *set1* and replaces each occurences of the free variable 'x' by the value 4, then it generates code for that boolean expression. Lines 1 to 3 in Listing 4.87 correspond to that code produced (boolean expression), the result of the boolean operator (great) is then stored in the variable 'flag' (line 4 in Listing 4.87).

4.4.7 *Sequence operations*

To operate with variables of type sequence, LISS language offers a set of predefined:

1. statements
2. functions

that are summarized in Table 29:

Table 29.: Sequence predefined operations

Mode	Name of the sequence operator in LISS	Name of the sequence operator in MIPS
expression	tail	tail_sequence
	head	head_sequence
	cons	cons_sequence
	isMember	member_sequence
	isEmpty	is_empty_sequence
	length	length_sequence
	del	delete_sequence
statement	copy	copy_sequence
	cat	cat_sequence

Each operator listed in Table 29 is implemented as a predefined function in MIPS assembly code. This means that each time the compiler recognizes a sequence operator it needs to use a jump instruction for processing the sequence. Notice that it uses the name of the sequence function in MIPS (available in Table 29) for generating the appropriated sequence jump instruction (see an example in Listing 4.88).

```
1  jal head_sequence
```

Listing 4.88: Example of processing a head function in MIPS

Before invoking the jump instruction; it is necessary to load the respective argument of type sequence. This process for loading the arguments, follows the schema below:

1. load the register $so with the name of the sequence variable.
2. load, in a sequential way, the rest of the arguments (depending on the sequence operator) into the next saved temporary registers ($s1, $s2,...).

For example, *cons* function has two arguments. Let's see how is the code generated for the case *cons(3,sequence2)* in Listing 4.89.

```
1  lw $to,sequence2
2  addi $sp, $sp, -4
3  sw $to, 0($sp)
4  li $to,3
5  move $s1, $to
6  lw $to, 0($sp)
7  addi $sp, $sp, 4
8  move $so, $to
9  jal cons_sequence
```

Listing 4.89: Example of a code generated for the function *cons*

In Listing 4.89, we load the *sequence2* variable (line 1) in a first step; then we push that information into the stack (line 2 to 3); after, we process the other argument (second one) and we move to the correct register (register $s1) (line 4 and 5); then, we get back the value that we stored earlier in the stack and we put it to the register $so (line 6 and 8). Last, we call the function *cons_sequence* to execute the function (line 9).

Let's see an example of a function that receives arguments that are other sequence functions for understanding it better (see Listing 4.90).

```
1  head(cons(3,cons(4,cons(5,sequence2))));
```

Listing 4.90: Example of using a function call as argument

We must process the information for the inner function in Listing 4.90, in this case *cons(5,sequence2)*, and then getting back and process the other functions. Let's see how it is done below:

1. cons(5,sequence2)
2. cons(4,cons(5,sequence2))
3. cons(3,cons(4,cons(5,sequence2)))
4. head(cons(3,cons(4,cons(5,sequence2))))

Concerning *copy* and *cat* operations, as they are not used in an expression but as a statement. To generate code for them we use a simple mechanism that consists in loading the sequence variable to the respective saved temporary register before calling the respective predefined function.

Let's see the code generated for those two operators (*copy(sequence1,sequence2)* and *cat(sequence1,sequence2)*) in Listing 4.91.

```
1  lw $s0, sequence1
2  li $s1, -1
3  jal copy_sequence
4  sw $v0, sequence2
5  li $v0, 0
6  lw $s0, sequence1
7  lw $s1, sequence2
8  jal cat_sequence
9  sw $v0, sequence1
10 li $v0, 0
```

Listing 4.91: Example of code generated for copy and cat statement

Concerning the translation of *copy* statement (from lines 1 to 4 of Listing 4.91): load the first argument (line 1); load an empty sequence (line 2) (remind that an empty sequence holds the value NULL which is minus one); call the *copy_sequence* function (line 3); store the new address into the variable *sequence2* (line 4). Finally, we reset the content of the register $v0 for internal reasons (line 5).

Remember that the copy statement copies every element of a sequence to another sequence.

Concerning the translation of *cat* statement (from lines 6 to 10 of Listing 4.91), it is applied the same schema as the one used for *copy*. But instead of loading an empty sequence as second argument, it loads the appropriated sequence (line 7).

4.4.8 *Implementing Function calls*

Calling a function, which code was already created by the compiler, requires some appropriated mechanism.

As we know, functions deal with the stack available in MIPS architecture and the stack will hold information about the function arguments, local variables and return adress.

This means that if a function has one or more arguments, it is necessary to use a certain strategy for passing that information to the stack.

Listing 4.92 shows the code for passing parameters.

```
1 lw $t0,a
2 sw $t0, -12($sp)
3 jal factorial
```

Listing 4.92: Code generated for calling a function in MIPS

The idea of calling a function is: if there are arguments, then it is needed to generate code to store them in the right position of the stack and finally, call the function. Otherwise if there are no arguments, then the code must only call the function.

In Listing 4.92, lines 1 and 2 load the variable *a* and then stores it in the right position of the stack. Finally, it calls the function with a jump instruction (line 3).

4.4.9 *Implementing Input/Output*

Let's see in Listing 4.93 an example of a fragment of a LISS program to write and read data from/to the console device.

```
1 write();
2 write(a);
3 write("hello");
4 writeln();
5 writeln(a);
6 writeln("hello");
7 input(a);
```

Listing 4.93: Example of I/O statements in LISS

First, let's talk about the output statements: *write* and *writeln*.

Write statement prints the content of its arguments but doesn't add the return carriage. However *writeln* statement is similar, it prints the content of its arguments and add the carriage return at the end of the output string.

The arguments of the output statement can be:

1. empty (lines 1 and 4 of Listing 4.93)
2. an integer expression (lines 2 and 5 of Listing 4.93)
3. a string (lines 3 and 6 of Listing 4.93)

To translate the 'write()' statement, we need to generate first the code to process the arguments and then the code to call the appropriate output instruction.

If the output statement is *write*, then the code will be :

```
1 jal write
```

Otherwise if the output statement is *writeln*, then the code will be :

```
1  jal writeln
```

Notice that the translation of the output statement, *writeln*, reuses the code for *write* statement and adds the instruction to print the new line (see Listing 4.94).

```
1  la $ao, writestringo
2  li $vo, 4
3  jal write
4  jal writeln
```

Listing 4.94: Code generated for line 6 in Listing 4.93

The predefined code corresponding to the print action is shown in Listing 4.95.

```
1  write:
2  syscall
3  jr $ra
4  writeln:
5  li $vo, 4
6  la $ao, newline
7  syscall
8  jr $ra
```

Listing 4.95: MIPS assembly code for write and writeln

Now, let's talk about the input statement.

To translate it, the idea is to call the MIPS function to read a value and then store this value into the variable that is referenced in the *input* statment, inside the parentheses.

Let's see below the code generated for line 7 in Listing 4.93:

```
1  jal read
2  move $to, $vo
3  sw $to, a
```

As we can see, after processing the read statement, we need to move the return value to another register and finally, store it the value to the respective variable. Below is the predefined code for the read statement (see in Listing 4.96).

```
1  read:
2    li $vo,4
3    la $ao,messagereadvalue
```

```
4     syscall
5     li $vo,5
6     syscall
7     jr $ra
```

Listing 4.96: Read statement code in MIPS

4.4.10 *Implementing Conditional statements*

The syntax to write a conditional statement in LISS has been introduced in Chapter 2, however it is illustrated again in Listing 4.97 to refresh the memory. The schema of Figure 19 depicts its semantics.

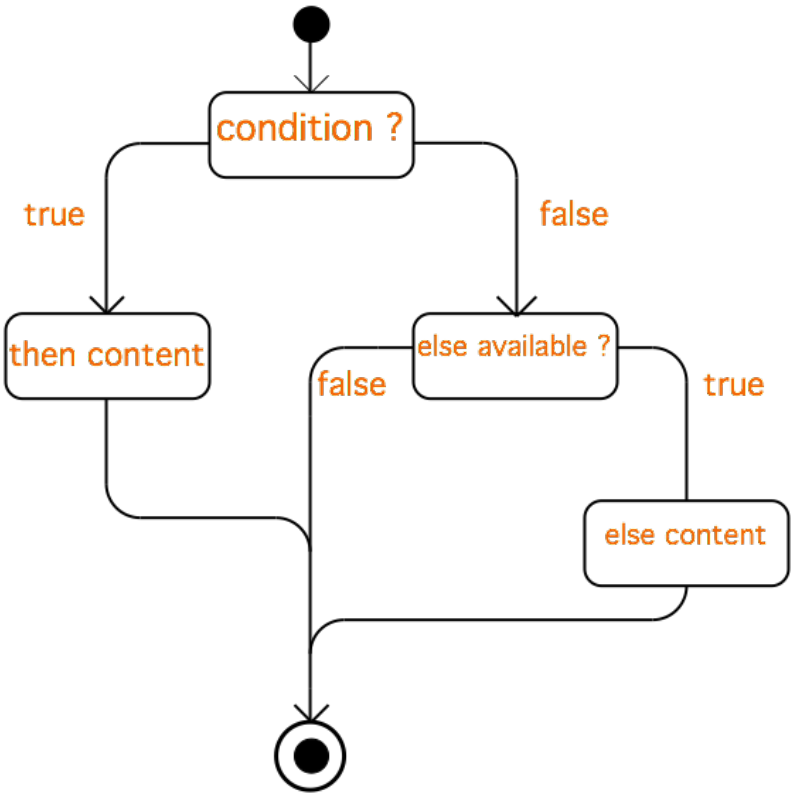


Figure 19.: Schema of the conditional statements in LISS

Basically we have, in Listing 4.97, a conditional statement with an if and an else statement.

```
1  if(flag)
2  then{
```

```
3     writeln("Then content.");
4   }else{
5     writeln("Else content.");
6   }
```

Listing 4.97: Example of conditional statement in LISS

Now let's see how the conditional code is generated in Listing 4.98.

```
1     lw $to,flag
2     bne $to, 1, else1
3     la $ao, writestringo
4     li $vo, 4
5     jal write
6     jal writeln
7     j l1
8   else1:
9     la $ao, writestring1
10    li $vo, 4
11    jal write
12    jal writeln
13  l1:
```

Listing 4.98: Code generated for conditional statement in MIPS

In Listing 4.98, line 1 is the piece of code that translates the boolean expression of the conditional statement: line 2 contains the instruction which compares the value of that with the value True. If the values are different then it must jump to the else-condition. Otherwise if the values are equal, then the program execution continues in the next instruction available in line 3 which is the code that translates the content of the then-statment. At the end of the then-statement, the program exits the conditional statement (line 7) jumping over the else part to line 13.

If the boolean expression evaluates to False, then it will jump to the branch of the else-statement (line 8) and execute every instruction available from that line on; the code execution will flow to the end of the if-statement (line 13) wihtout any extra jump.

Let's consider now the case that in the LISS program, no else-statement is used. Then the only thing that disappears is the whole code corresponding to the else branch in Listing 4.98.

Let's see in Listing 4.99 an example of the code above (Listing 4.98) without the else-statement.

```
1     lw $to,flag
2     bne $to, 1, l1
```

```
3     la $a0, writestring0
4     li $v0, 4
5     jal write
6     jal writeln
7   l1:
```

Listing 4.99: Code generated for conditional statements without an else-statement in MIPS

4.4.11 *Implementing Iterative statements*

As already introduced in Chapter 2, in LISS, we have three different to wrote an iterative statement:

1. For-loop with 'in' condition.
2. For-loop with 'inArray' condition.
3. While-loop.

In Figure 20, we can see the diagrammatic schema of a for-loop with an 'in' condition.

Notice that the black circle is where the flow of the for-loop statement begins and that the double circle is where it finishs executing the for-loop statement.

Let's see in Listing 4.100 a fragment of s LISS program containing a for-loop statement with an 'in' condition.

```
1  for(a in 1..5) stepUp 1 satisfying flag==true{
2    writeln(a);
3  }
```

Listing 4.100: Example of a for-loop statement with 'in' condition in LISS

We can see in Listing 4.100, a for-loop statement controlled by an 'in' condition to test the inclusion in a given range (1 to 5) and also by a logical expression that must be satisfied. Moreover the control flow statement listed also defines explicitly the method for incrementing (*stepUp*) the control variable (by one) after each iteration.

Let's see in Listing 4.101 the iterative code generated for that piece of LISS program.

```
1     li $t0,1
2     sw $t0, a
3   for_loop1:
4     lw $t0,a
5     li $t1,5
6     slt $t0, $t1, $t0
```

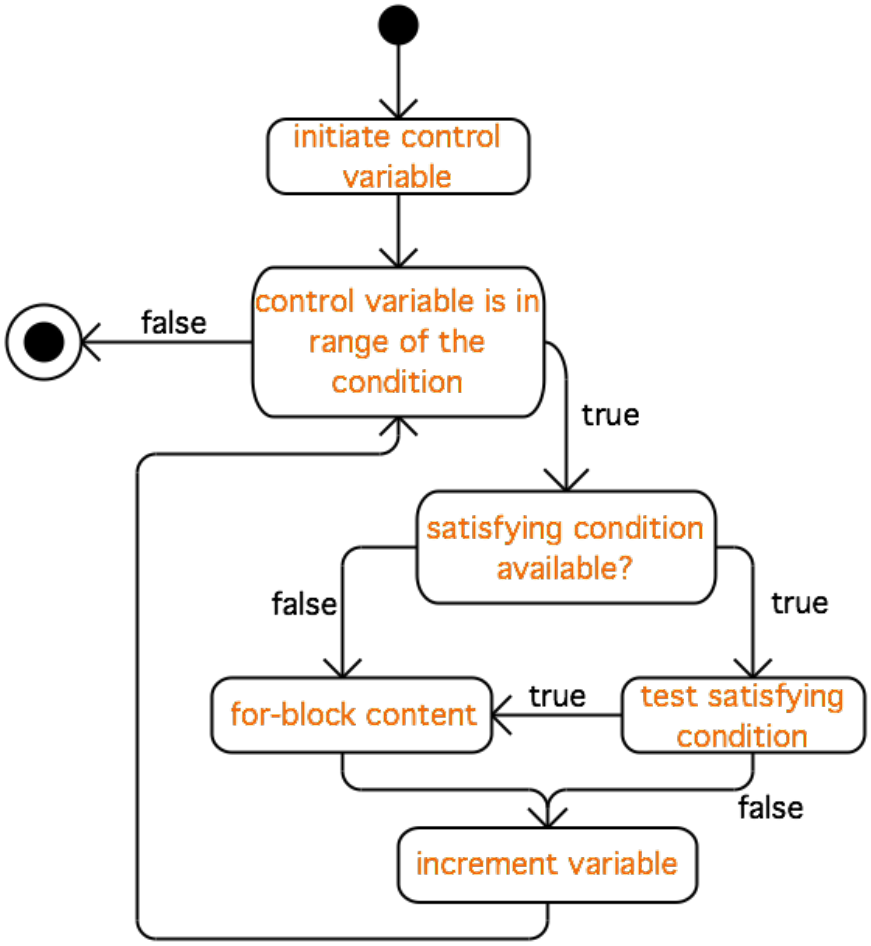


Figure 20.: Schema of the for-loop statement using the condition 'in'

```
7     sltu $to, $zero, $to
8     xori $to, $to, 1
9     bne $to, 1, for_exit1
10    lw $to,flag
11    li $t1,1
12    slt $t2, $to, $t1
13    sltu $t2, $zero, $t2
14    xori $t2, $t2, 1
15    slt $t3, $t1, $to
16    sltu $t3, $zero, $t3
17    xori $t3, $t3, 1
18    and $t2, $t2, $t3
19    move $to, $t2
20    bne $to, 1, satisfying_exit1
21    lw $to,a
```

```
22      move $ao, $to
23      li $vo, 1
24      jal write
25      jal writeln
26  satisfying_exit1:
27      lw $t1,a
28      li $t2,1
29      add $t1, $t1, $t2
30      sw $t1, a
31      j for_loop1
32   for_exit1:
```

Listing 4.101: Iterative code generated for the LISS program in Listing 4.100

In Listing 4.101, lines 1 to 2 creates the variable *a*; line 3 creates the for-loop branch; lines 4 to 9 tests if the value of the variable *a* is in the range of the for-loop condition. If the variable is not in the range, the program exits the for-loop flow by going to the branch named *for_exit1*(line 32); otherwise it continues the flow of the for-loop execution by going to line 10. Lines 10 to 20 refers to the *satisfying* condition. If the condition isn't satisfied then it goes to the branch named *satisfying_exit1*, otherwise it continues the flow of the execution in line 21. Lines 21 to 25 is the code contained in the block of the for-loop statement. Notice that lines 27 to 30 is the piece of code who will increment the variable *a* relatively to *stepUp*. At the end (line 31), it jumps to the branch of the for-loop statement *for_loop1*(line 3).

Notice also, that *stepUp* and *satisfying* information are optional statement. If the satisfying statement is not available then the lines from 10 to 20 and line 26 of Listing 4.101 will be removed. Regarding to the *step* statement, even if the information is not available, by definition a for-loop statement needs to have a step by step iteraction. So, by omission, it will increment the variable by one; otherwise if the information is available, it will increment or decrease relatively to the information shown.

In Figure 22, we can see the routine of a for-loop with an 'inArray' condition.

The idea of that for-loop statement is to have some kind of a foreach statement in LISS. Basically, the for-loop statement will pass to every positions of the array. Notice that when it is used, the for-loop statement disables the user by declaring any *step* or *satisfying* statement.

Let's see in Listing 4.102 a piece of a LISS program containing a for-loop statement with an 'inArray' condition.

```
1  for(a inArray array1){
2      writeln(a);
3  }
```

Listing 4.102: Example of a for-loop statement with 'inArray' condition in LISS

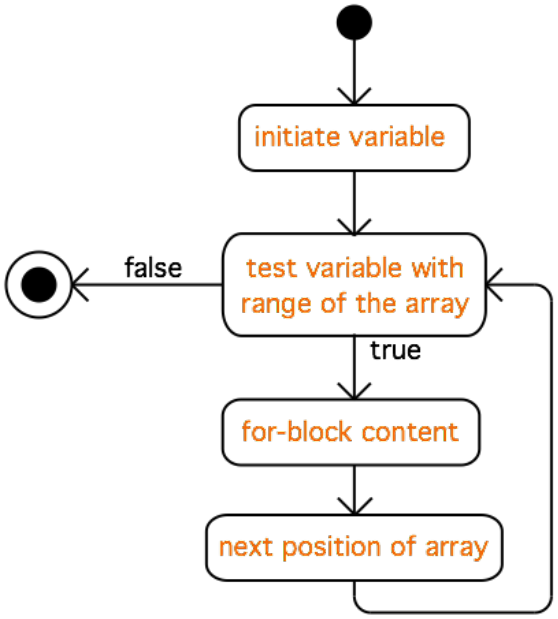


Figure 21.: Schema of the for-loop statement using the condition 'inArray'

We can see in Listing 4.102, a for-loop statement where the *array1* is the variable of type array and the variable *a* will have the value of each position of the variable *array1*.

By doing a *writeln(a)* in line 2 of Listing 4.102, it will output the value of each position of the array named *array1*.

Let's see in Listing 4.103 the iterative code generated for the piece of LISS program in Listing 4.102.

```
1     li $to,0
2     sw $to, for_var4
3   for_loop4:
4     lw $to,for_var4
5     li $t1,16
6     slt $to, $t1, $to
7     sltu $to, $zero, $to
8     xori $to, $to, 1
9     bne $to, 1, for_exit4
10    lw $to,for_var4
11    lw $to, array1($to)
12    sw $to, a
13    lw $to,a
14    move $ao, $to
15    li $vo, 1
16    jal write
17    jal writeln
```

```
18      lw $t1,for_var4
19      li $t2,4
20      add $t1, $t1, $t2
21      sw $t1, for_var4
22      j for_loop4
23    for_exit4:
```

Listing 4.103: Iterative code generated for the LISS program in Listing 4.102

In Listing 4.103, lines 1 to 2 creates a variable named *for_var4* which will be used for accessing each index of the array; line 3 creates the branch name relatively to the for-loop statement; lines 4 to 9 test the variable *for_var4* with the bounds associated to the variable. If it does not agree then it must exit the for-loop statement by going to the branch named *for_exit4* (line 23), otherwise it continues the flow of the execution of the code to line 10. Lines 10 to 12, the program refreshes the value of the variable *a* by getting the value throw the index (variable *for_var4*) of the array. Lines 13 to 17, contains the code relative to the content in the body of the for-loop statement. In this case, it is the code instruction for writing to the output, the variable *a*. Lines 18 to 21, refreshes the variable *for_var4* to the next position of the array by summing up with 4 bytes relatively to the old value of the variable. Finally, line 22 jumps to the branch *for_loop4* and continue the flow of the execution of the for-loop statement.

In Figure 22, we can see the diagrammatic schema that depicts the semantics of a while-loop.

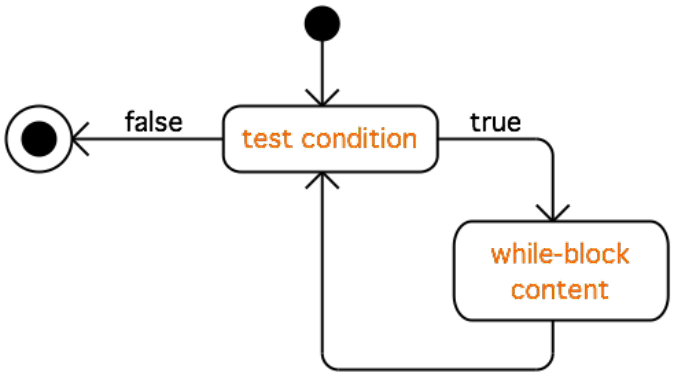


Figure 22.: Schema of the while-loop statement

Basically, behind the idea of being the most simple iterative statement, the behavior of the while-loop statement is to check the truth of the condition on every iteraction. If it is True, then the content who is inside will be executed otherwise it will be exited.

Let's see in Listing 4.104 a fragment of a LISS program containing a while-loop statement.

```
1 while(flag){
2     writeln("Hello");
3 }
```

Listing 4.104: Example of a while-loop statement in LISS

In Listing 4.104, the program has a variable *flag* with the value set to True. With that case, the condition will be True and should proceed to the content available inside of the parentheses. Otherwise if the condition is False, the program will exit.

Let's see in Listing 4.105 the iterative code generated for the fragment of LISS program of Listing 4.104.

```
1 while5:
2   lw $to,flag
3   bne $to, 1, while_exit5
4   la $ao, writestringo
5   li $vo, 4
6   jal write
7   jal writeln
8   j while5
9 while_exit5:
```

Listing 4.105: Iterative code generated for the LISS program in Listing 4.104

In Listing 4.105, line 1 is created for the branch name of the while-loop statement. First, we incorporate the code of the condition associated to the while-loop statement (line 2), then we test the truth of the condition in line 3. If the condition is False, it will jump to the branch *while_exit5* (line 9) for exiting the while-loop statement; otherwise, it will continue the flow of the execution proceeding to line 4. In this part, it is included all the code relative to the content in the body of the while-loop statement (lines 4 to 7). Finally, at line 8, it will jump back to the branch *while5* and repeat all the process.

4.4.12 *Implementing increment or decrement operators*

Listing 4.106 shows the LISS statements to increment a variable ('i').

```
1 succ i;
```

Listing 4.106: Increment variable in LISS

In Listing 4.107, it is shown the code generated for 'succ' statement.

```
1 lw $to,i
```

```
2  li $t1,1
3  add $to, $to, $t1
4  sw $to, i
```

Listing 4.107: Code generated for the LISS code in Listing 4.106

In Listing 4.107, line 1 load the variable *i* to register $to; line 2 load the constant value 1 to register $t1; line 3 sums both registers (value of the variable and the value 1); line 4 refresh and store the result into variable *i*.

Similarly, in Listing 4.108 shows the LISS statement to decrement a variable ('i').

```
1  pred i;
```

Listing 4.108: Decrement variable in LISS

The MIPS assembly code to implement the statement 'pred' is shown in Listing 4.109.

```
1  lw $to,i
2  li $t1,1
3  sub $to, $to, $t1
4  sw $to, i
```

Listing 4.109: Code generated for the LISS code in Listing 4.109

In Listing 4.109, line 1 loads the variable *i* to register $to; line 2 loads the value 1 to register $t1; line 3 subtract both registers (value of the variable and the value 1); line 4 refresh and store the result into variable *i*.

5

SDE: DEVELOPMENT

Before we try to explain the concept of a Syntax-Directed Editor (SDE) (Reps and Teitelbaum, 1989b; Ko et al., 2005; MI-students et al., 2010; Teitelbaum and Reps, 1981; Reps et al., 1986; Reps and Teitelbaum, 1989a; Arefi et al., 1989), let's start defining what is an Integrated Development Environment (IDE).

An IDE is described as a software application that provides facilities to computer programmers for software development. It consists , normally, of a source code editor, a compiler or interpreter, a debugger, and other tools. IDEs are designed for maximizing the productivity of programmers with visual interface (see Figure 23).

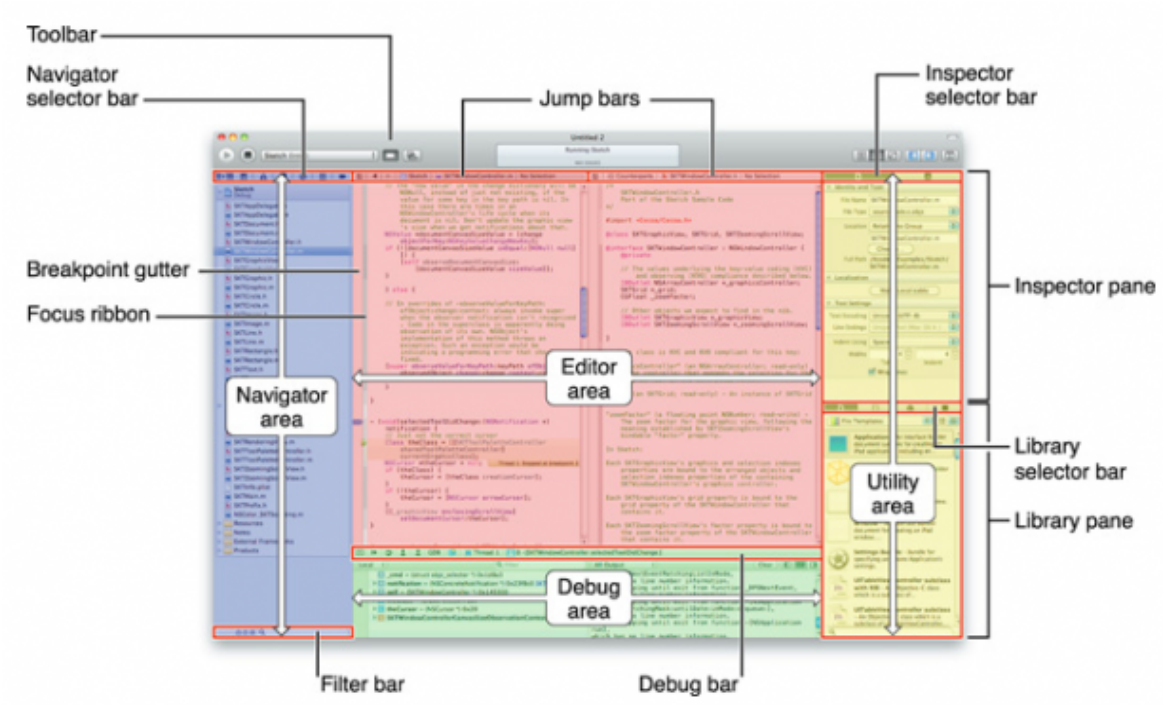


Figure 23.: Example of an IDE visual interface (XCode) [1]

Programs are created top down in the editor window by inserting statements and expressions at the right cursor position of the current syntactic template and we can, by the cursor, change simply from one line of text to another one.

A SDE has the same approach of an IDE which is (as said above) an interactive programming environment with integrated facilities to create, edit, execute and debug programs. The difference between them is that SDE encourages the program writing at a high level of abstraction, and promotes the programming based on a step by step refinement process guided by the language syntax.

It liberates the user from knowing the language syntactic details while editing programs.

SDE is basically guided by the syntactic structure of a programming language. It is a hybrid system between a tree editor and a text editor.

The notion of cursor is really important in the context of SDE because, when the editing mode is on, the cursor is always located in a placeholder of a correct template (see next section) and the programmer may only change to another correct template at that placeholder or to its constituents.

It reinforces the idea that the program is a hierarchical composition of syntactic objects, rather than a sequence of characters.

5.1 WHAT IS A TEMPLATE?

The grammar of a programming language is a collection of production (or derivation rules) that state how a non-terminal symbol (LHS) is decomposed in a sequence of other symbols (RHS). A template is just the RHS of a grammar rule. Templates cannot be altered, they have placeholders for inserting a value (word, number, or string) or another template and they are generated by editor commands, according to the grammar production.

```
1 IF( condition )
2   THEN statement
3   ELSE statement
```

Listing 5.1: Example of a IF Conditional template

In Listing 5.1 we can see the editor template for the if-statement, where *condition* and *statement* are placeholders.

The notion of template is very important because templates are always syntactically correct for two reasons:

1. First, the command is validated to guarantee that it inserts a template permitted.
2. Second, the template is not typed, so it contains no lexical errors.

So a correct program (i.e., a valid sentence of the programming language) is created by choosing templates and replacing placeholders by other templates or by concrete values (numeric or string constants or identifiers).

To clarify the definition of SDE, we will explain it with the help of an example.

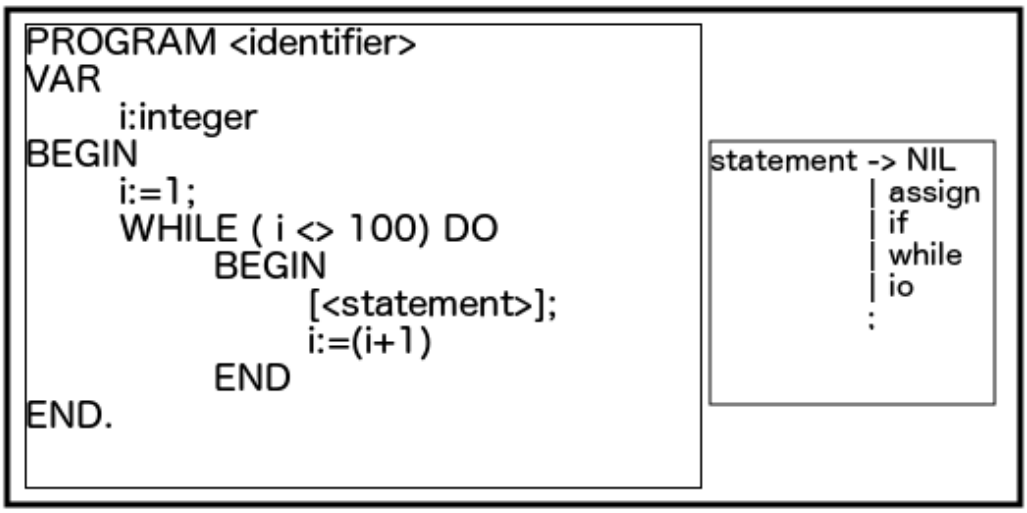


Figure 24.: SDE example

Figure 24 shows the main window of a standard Syntax-Directed Editor. In this figure, two boxes are displayed. The left one is the editor window where we code the program, and the right one exhibits template choices.

Every <...> tag represents a placeholder, and [...] represents the actual cursor position.

As the cursor changes its position, moving from one placeholder to another placeholder, the right box will be updated according to the grammar rules in the context of the new cursor position. In this example, the cursor in Figure 24 is placed at the placeholder corresponding to a *statement*; at the same time, the right box was updated to show all the possible next templates according to the *statement* derivation rules (RHS).

To sum up, this is how a SDE works.

5.2 CONCEPTION OF THE SDE

By taking the ideas explained in the previous section, we managed to create a simple and easy to use Syntax Directed Editor based on the principles:

- having a window for visualization of the rules of the language grammar and the templates associated to the ”LISS” program under development.

- showing the source code produced until the moment by choosing templates and fulfilling placeholder according to the rules generated.
- displaying semantic or runtime errors, and outputing the results of the execution.

These guidelines led the creation of the program called *liss|SDE* (see Figure 25).

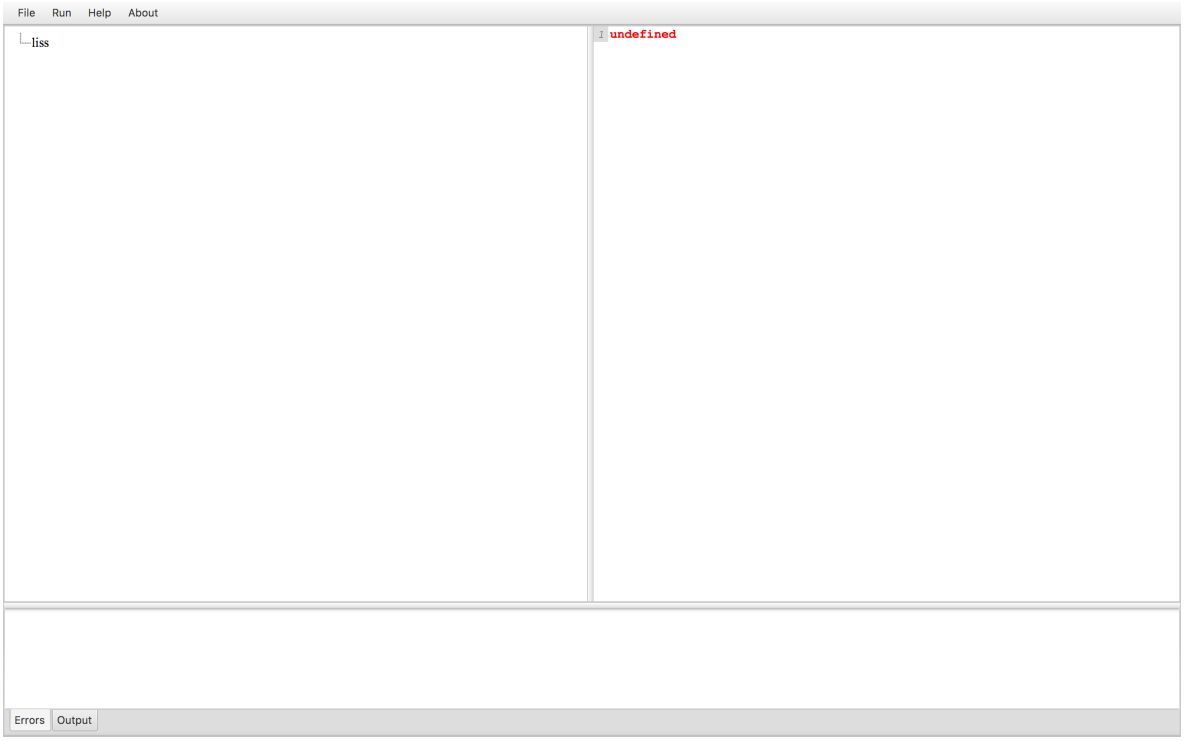


Figure 25.: liss|SDE

liss|SDE system interface is divided in three main areas (see Figure 26).

The number 1, in Figure 26, is where the templates, or the rules of the language LISS, are displayed. This part was implemented with the technology called HTML and Javascript, and the main reason of implementing that part with that technology was the fact that we needed to implement a tree visualization structure.

Creating some visualization content within the JAVA context is really hard. For that reason we decided to use another technology where JAVA could handle it; HTML and Javascript were the perfect key for creating those contents, due to their powerful and easy use to create some visualization content.

Also, notice that, we implemented a tree visualization structure for one simple reason: a programming language is represented by a tree structure. So we decided to adapt it and create a tree visualization structure.

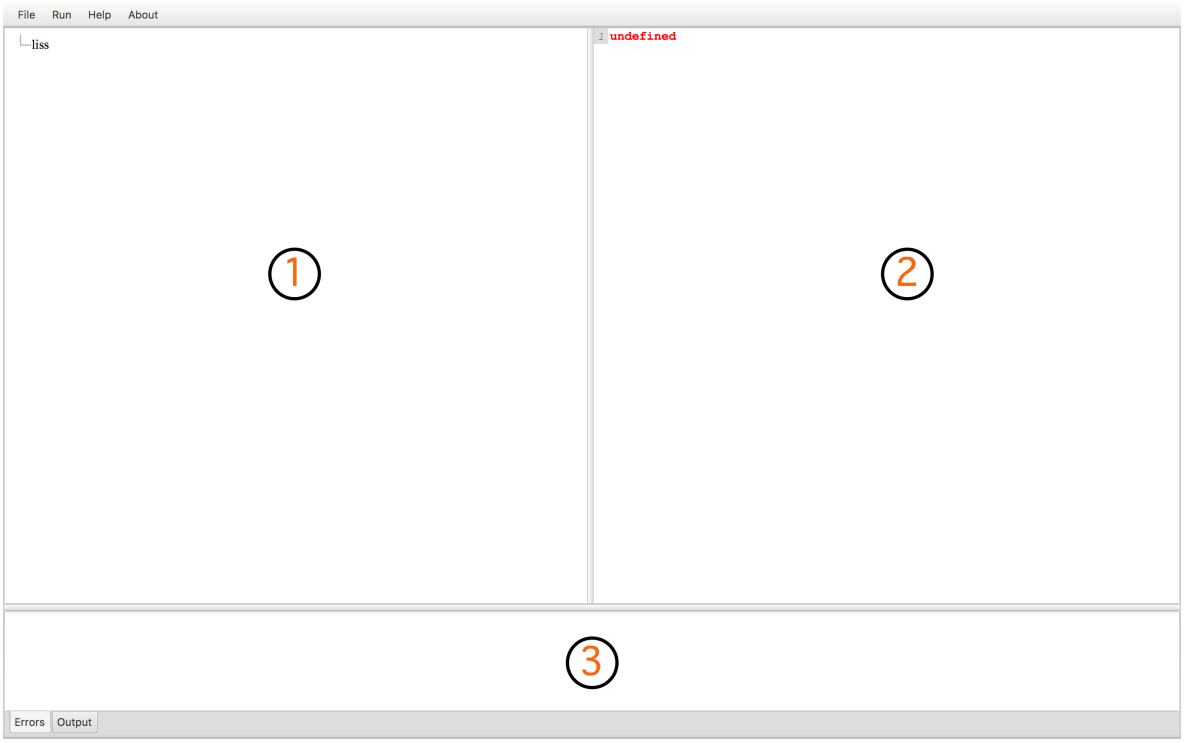


Figure 26.: liss|SDE structure

The number 2, in Figure 26, is where the code of the language is processed regarding to the rules generated to the view number 1. Each time, the user selects a rule, the view in the window number 2 will be represented to reflect the new program code synthesized.

Last, the window number 3 is related to every syntax and semantic errors, as well as, the output of the execution.

5.2.1 *Toolbar meaning*

The toolbar in *liss|SDE* is available at the top of the program and it control various functions of the program.

It is divided in four boxes (see Figure 27).

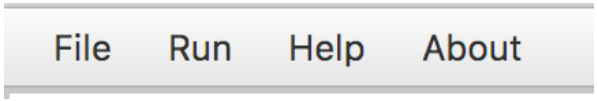


Figure 27.: Toolbar of *liss|SDE*

The *File* button shows the commands for creating new projects, saving/loading projects and exiting the application (see Figure 28).

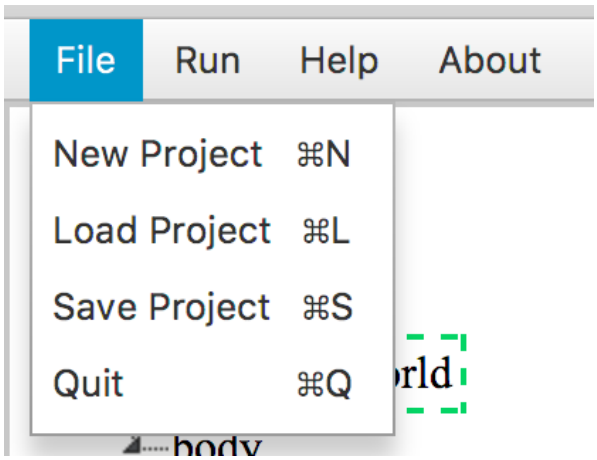


Figure 28.: File option of toolbar in *liss|SDE*

The *Run* button activates the compiler (this means that the semantic system will be run and if everything is correct, the code is generated, getting the MIPS assembly code) and executes the code created (see Figure 29).

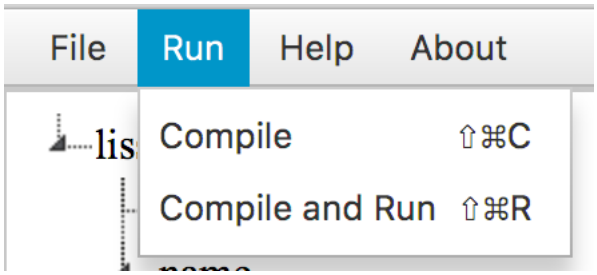


Figure 29.: Run option of toolbar in *liss|SDE*

The *Help* button shows information about the use of the editor and about a LISS program structure (see Figure 30).

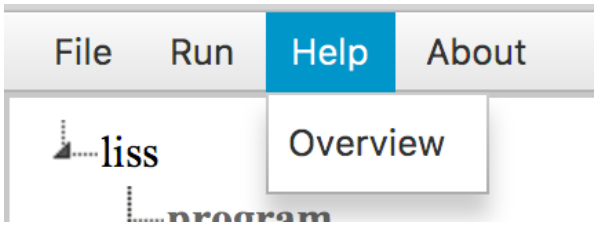


Figure 30.: Help option of toolbar in *liss|SDE*

About button displays information about the program: which technology and plugins were used; the name of the program creator; etc.. (see Figure 31).

Notice that some shortcuts for the most used functions were implemented in the toolbar, as can be seen in Figures 28 and 29.

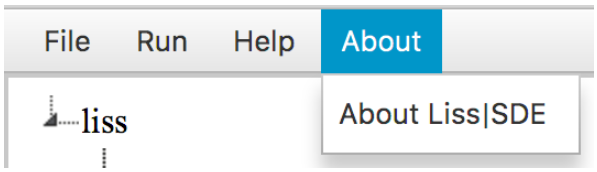


Figure 31.: About option of toolbar in *liss|SDE*

5.2.2 *Creating a program*

For a better understanding of this section, let's see a simple piece of LISS code in Listing 5.2.

```
1 program helloWorld{
2   declarations
3   statements
4     writeln("Hello World!");
5 }
```

Listing 5.2: LISS code

In Listing 5.2, we created a 'hello world' program in LISS which basically outputs the string "Hello World!".

Now, let's try and create the same LISS program using *liss|SDE*.

In Figure 32, we left click on the non-terminal *liss*; this selects the *liss* rule and expands the non-terminal with three branches:

- program
- name
- body

program is a terminal of type keyword: this can be seen by its bold and blurry visual; the other branches are non-terminal (*name* and *body*) and they are not bolded nor blurried. Those visual effects are really important for the user because it means that terminals aren't clickable and non-terminal are clickable.

Notice, also, that by selecting the *liss* rule, the right window is refreshed with the code that is possible to synthesize until that moment the keyword is printed correctly and the label 'undefined' is displayed in red for each non-terminal not yet expanded. This means that the non-terminal must be selected and derived and that the code isn't valid in this state.

Figure 32.: Creating a LISS program (1/17)

So, in this case, we need to expand those two non-terminal rules and we will do it by clicking with the left mouse button on the *name* branch. This generates a rectanglular box with a name inside (*IDENTIFIER*), see Figure 33.

Basically, a rectangle as the one shown in Figure 33 means that this is a placeholder of that kind "input interaction" and the label *IDENTIFIER* informs the kind of value that must be typed.

In this case, the *IDENTIFIER* label specifies that it must be typed a text matching the following pattern:

```
1  ('a'..'z'|'A'..'Z')('a'..'z'|'A'..'Z'|'0'..'9'|'_')*
```

Figure 33.: Creating a LISS program (2/17)

If the text typed in by the user does not match the pattern, then the box will change the color to red (see Figure 34).

Red color means that there is a lexical error in the input; instead, green color means that the input is correct.

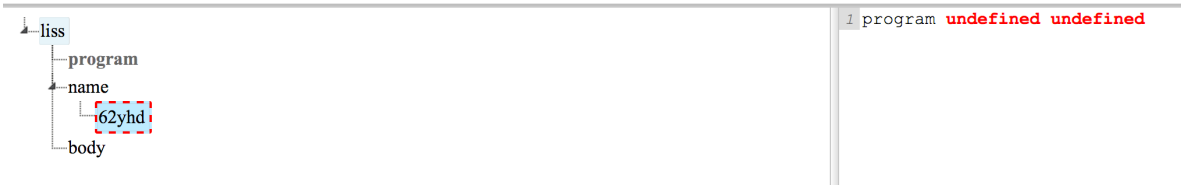


Figure 34.: Creating a LISS program (3/17)

If the color of the box is green (see Figure 35) then the input is correct and the *undefined* word seen in the right window previously (see Figure 34), will change to the value of the input.

Now, let's proceed with the other branch *body* by clicking it with the left mouse button.

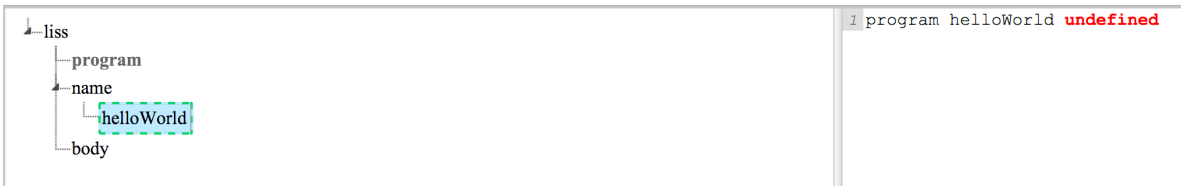


Figure 35.: Creating a LISS program (4/17)

As can be seen, in Figure 36, this non-terminal symbol expands to more rules and notice, that in the right windows, the code is changed. The next step is always the same, generating the rules in order to synthesize a correct program (no *undefined* must be displayed in the right window).

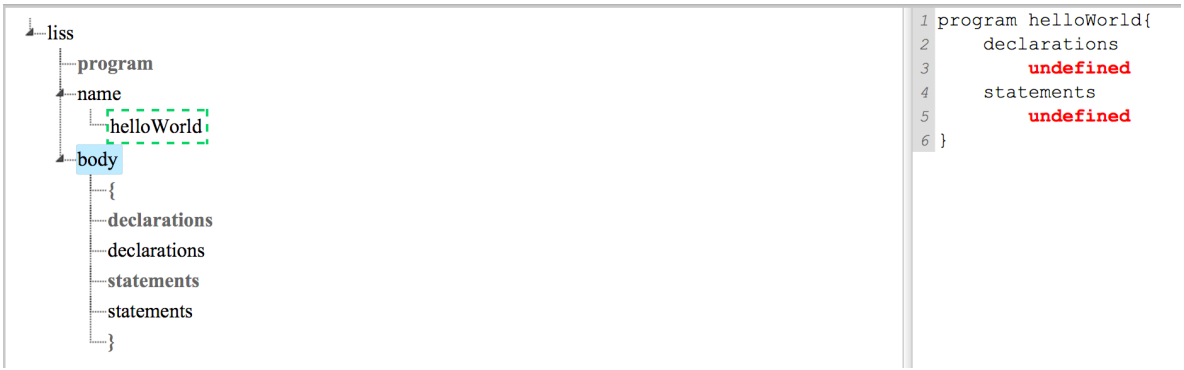


Figure 36.: Creating a LISS program (5/17)

By clicking with the left mouse button over the rule called *declarations* in Figure 36, it will generate more branches (see Figure 37). Notice that, in the right window, the first *undefined* word disappeared and that in the left window, two branches were created (the two possible kind of *declarations*) with a star at the end of their names. That star means that the non-terminal symbol can be expanded to zero or more elements.

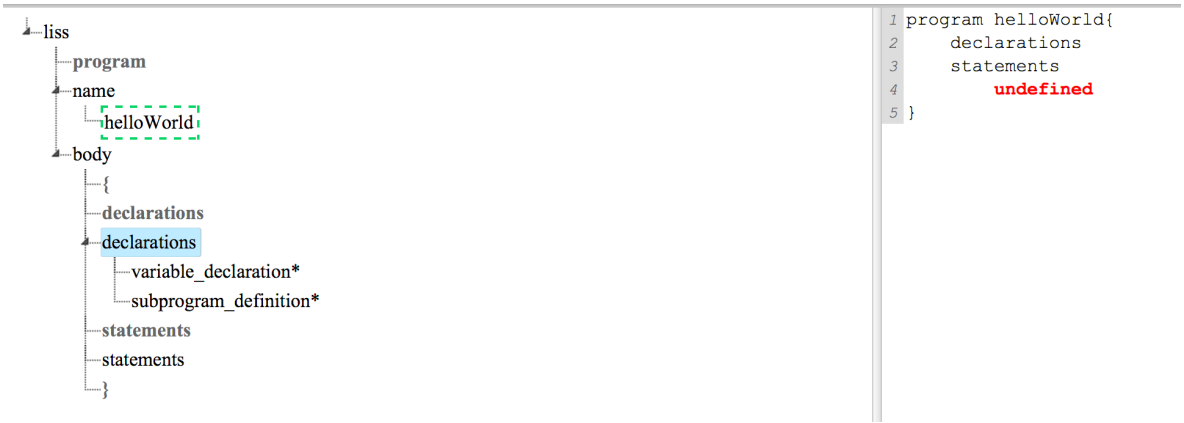


Figure 37.: Creating a LISS program (6/17)

The program created until this stage is similar to the first part of the one in Listing 5.2; let's now work out the rules for the *statements* part by left clicking on that symbol (see Figure 38).

At this moment, no *undefined* label is displayed in the right window which means that the code can be compiled. But the problem is that it is not yet finished relatively to the program in Listing 5.2.

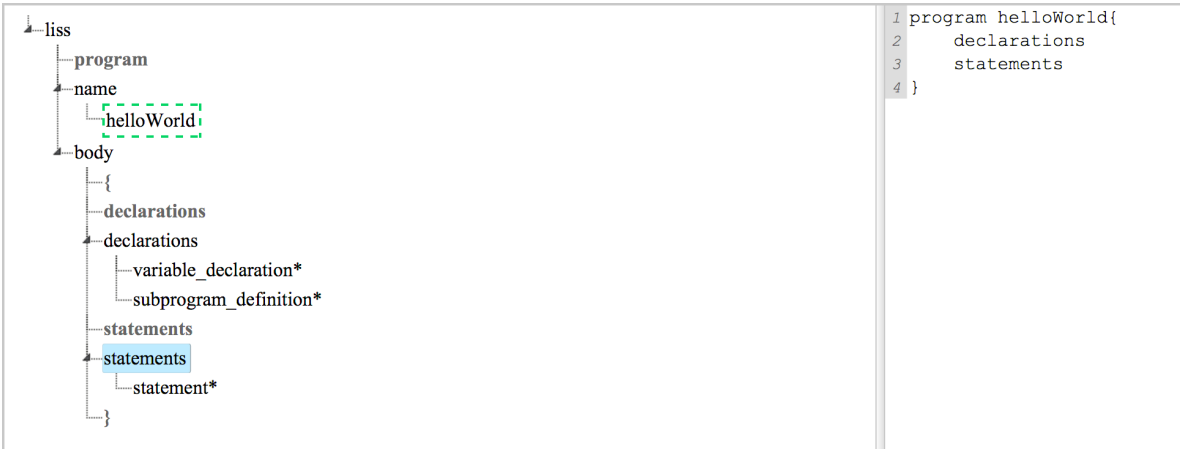


Figure 38.: Creating a LISS program (7/17)

So, we need to expand the *statement** rule by left clicking it. Then a pop-up menu will appear (see Figure 39).

This pop-up menu (that exhibits just one option "Add" at the beginning) is available for one reason: if the user creates a lot of branches under the *statement**, after the second branch created that pop-up box will show another option for deleting all the branches created. And this is why we needed to create a menu for adding those two options (thinking on the easy use of the program).

Each time a statement is added, it will be appended to the previous ones, at the bottom place of the program.

Regarding the code in Listing 5.2, we just need to create one statement (writeln statement); so we only need to add one statement to the program (see Figure 40).

By adding that statement, we see that in the right window, the program becomes incorrect (an *undefined* label appears aggain).

By left clicking on the *statement* rule, a pop-up menu appears and we can see the rules that a *statement* can expand to (see Figure 41).

So, left click on the option of adding the write statement to expand to the appropriate rule (see Figure 42).

After left clicking over the *write* statement rule, the content of that rule is generated and the right window is refreshed accordingly (see Figure 43).

Figure 39.: Creating a LISS program (8/17)

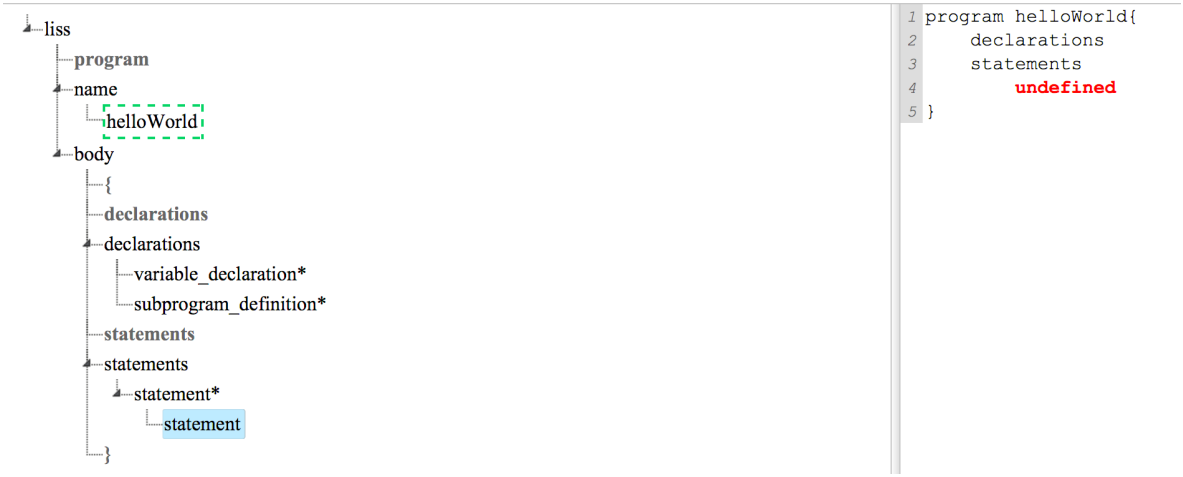


Figure 40.: Creating a LISS program (9/17)

First it is necessary to expand the *write_expr* rule by left clicking on it; it will open another pop-up menu to choose the desired output statment (Figure 44).

To clone the program in Listing 5.2, we must choose the *Writeln* option.

So, left clicking on that option, the right part will be refreshed accordingly to the terminal keyword. Then it is needed to process the rule *print_what* for finishing the code (see Figure 45).

The *print_what* non-terminal shows a pop-up menu with three options (see Figure 46); for our case, we need to choose the option of adding a string.

By clicking on that option, a rectangle with the label **STRING** appears below (see Figure 47), following the same idea talked previously for the *IDENTIFIER* box. The only thing that differs is the pattern that now is:

```
1  '"' ( ESC_SEQ | ~('"') )* '"'
```

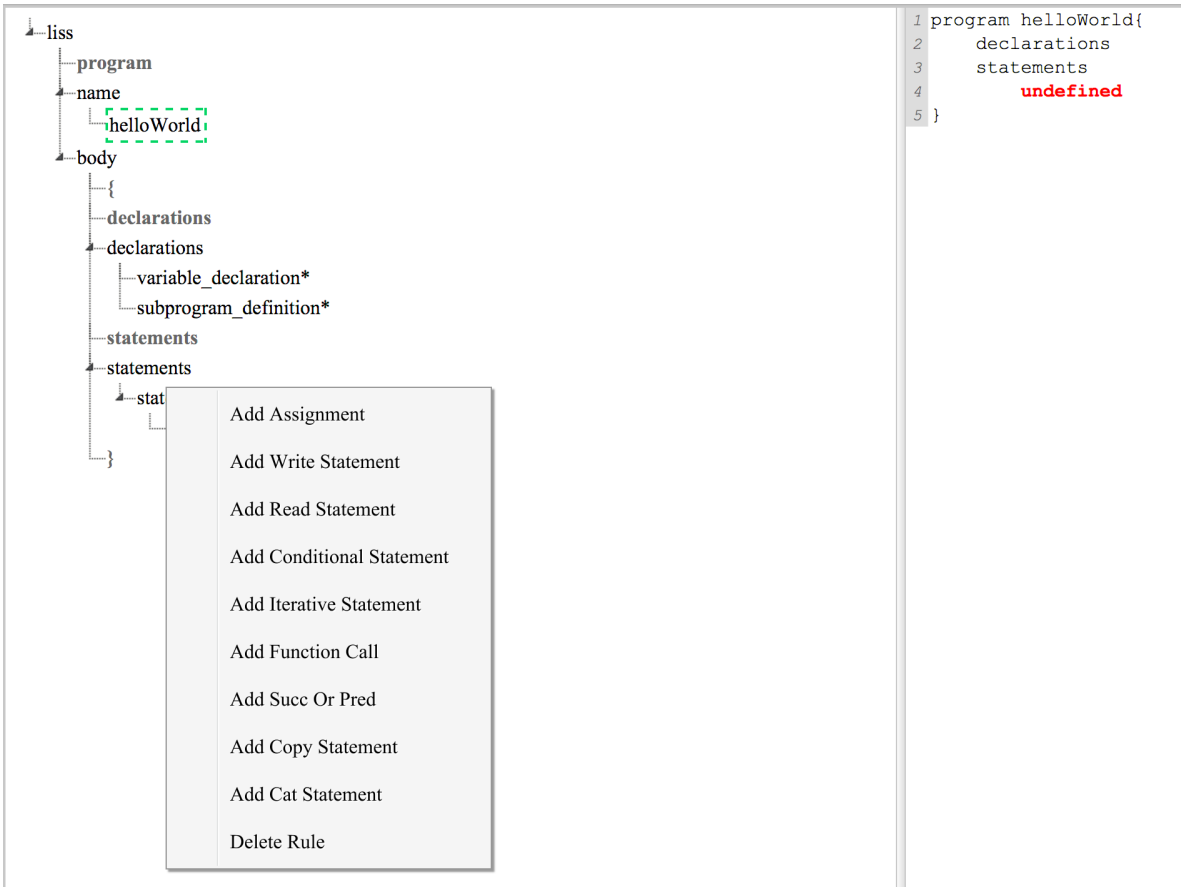


Figure 41.: Creating a LISS program (10/17)

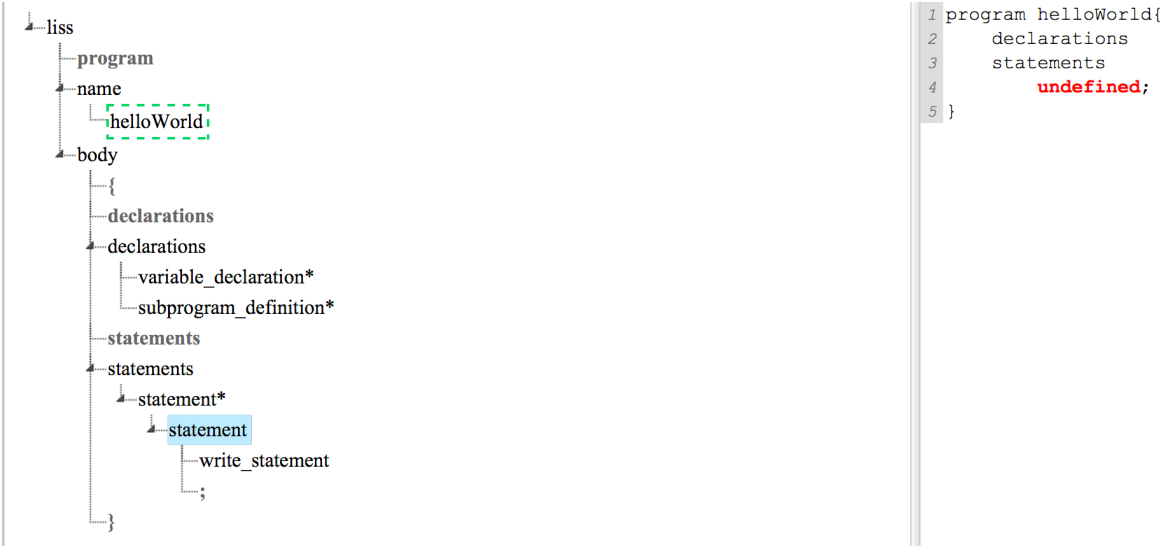


Figure 42.: Creating a LISS program (11/17)

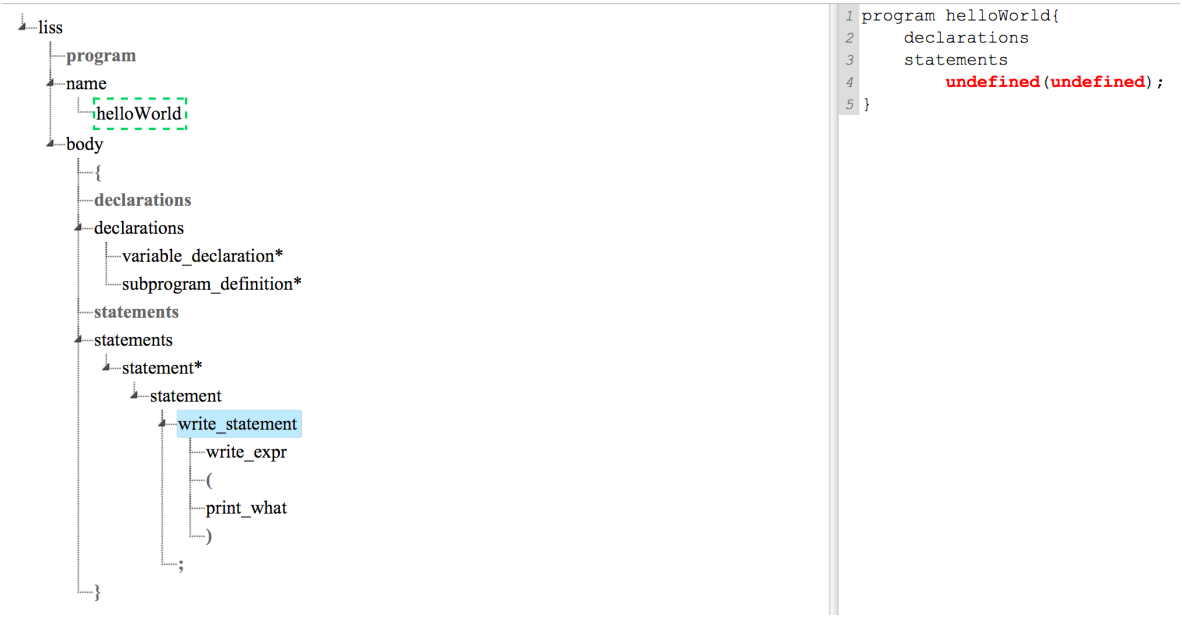


Figure 43.: Creating a LISS program (12/17)

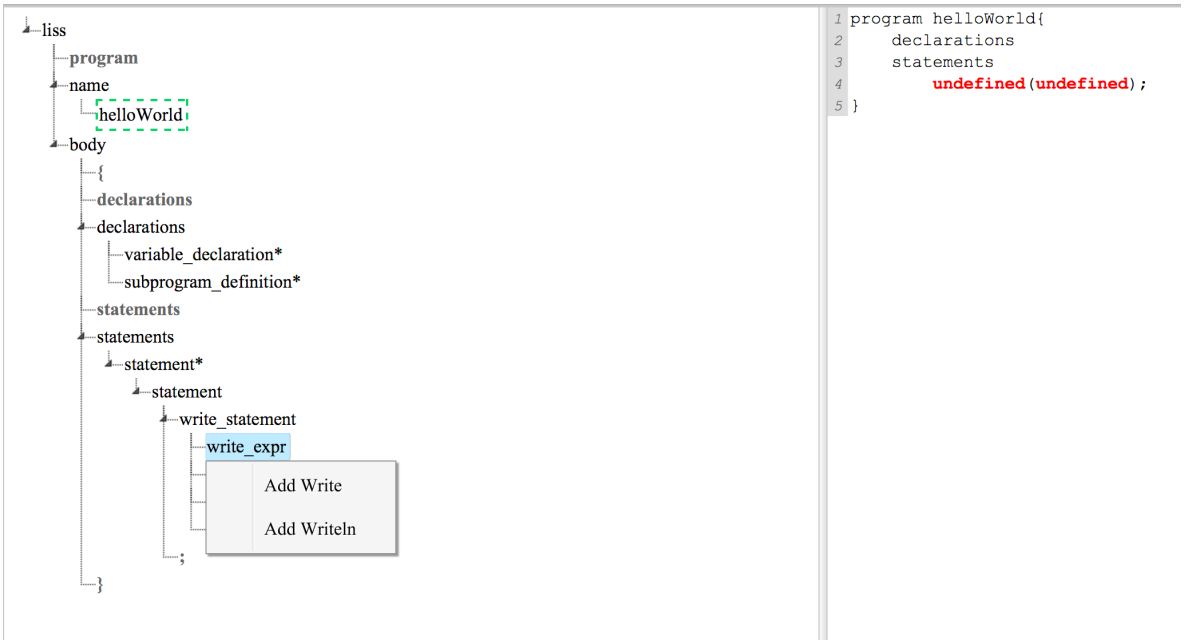


Figure 44.: Creating a LISS program (13/17)

Basically the idea of that pattern is that the string must be a sequence of any characters inside quotation marks.

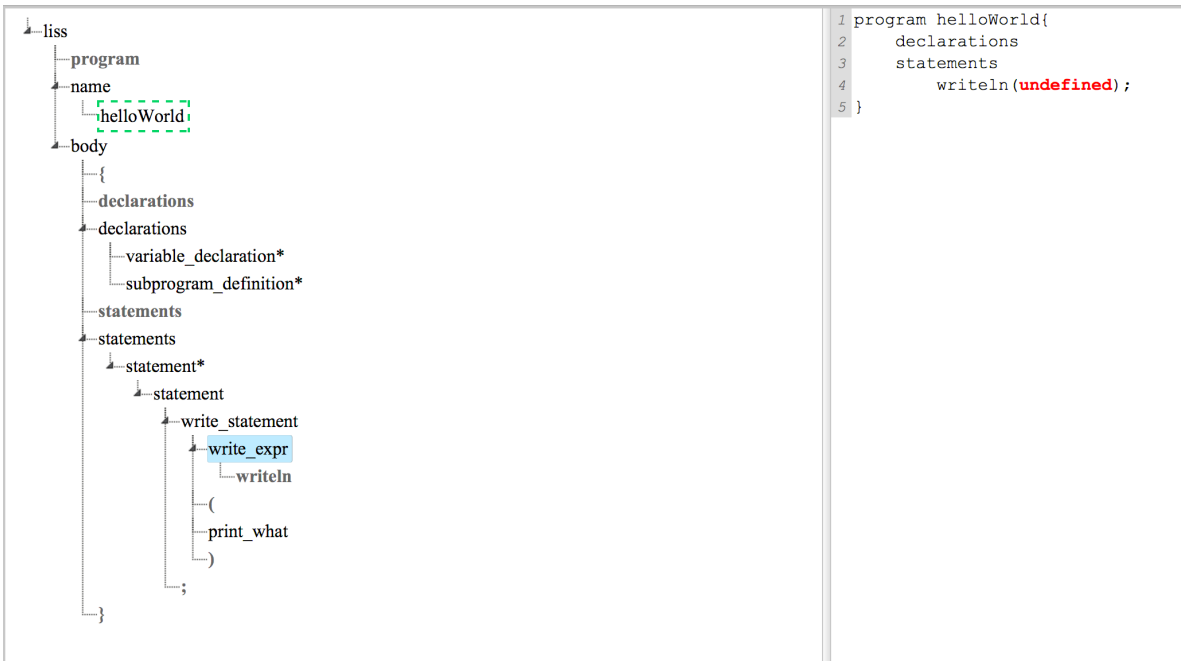


Figure 45.: Creating a LISS program (14/17)

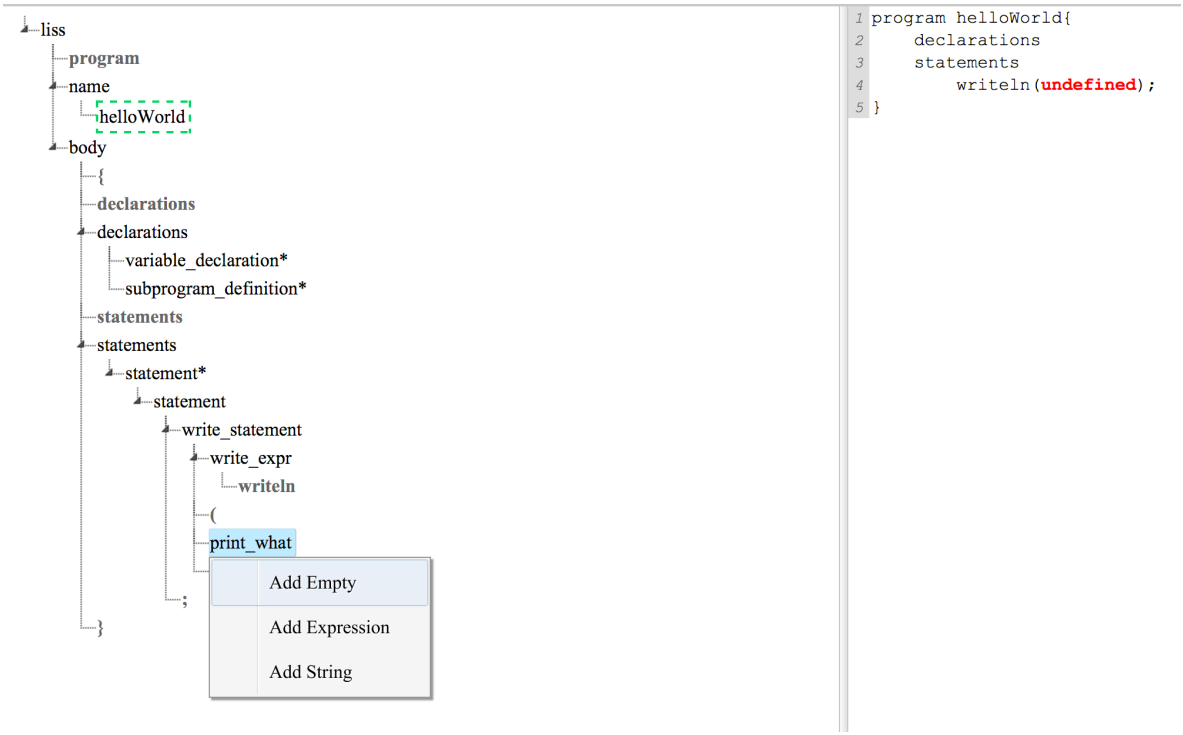


Figure 46.: Creating a LISS program (15/17)

And so, for the last step, we manage to write the string *"Hello World!"* in that rectangular box for finishing the creation of the program in Listing 5.2.

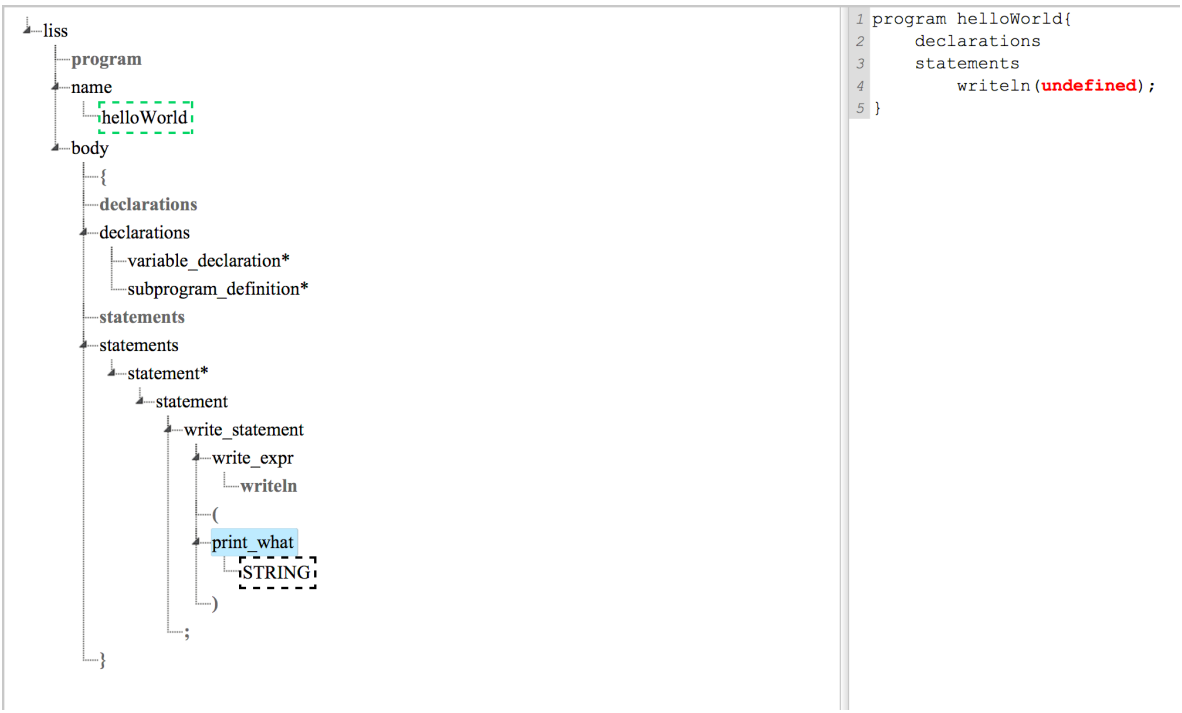


Figure 47.: Creating a LISS program (16/17)

Notice that in the right window of Figure 48, no *undefined* label is shown, what means that the code can be compiled and executed.

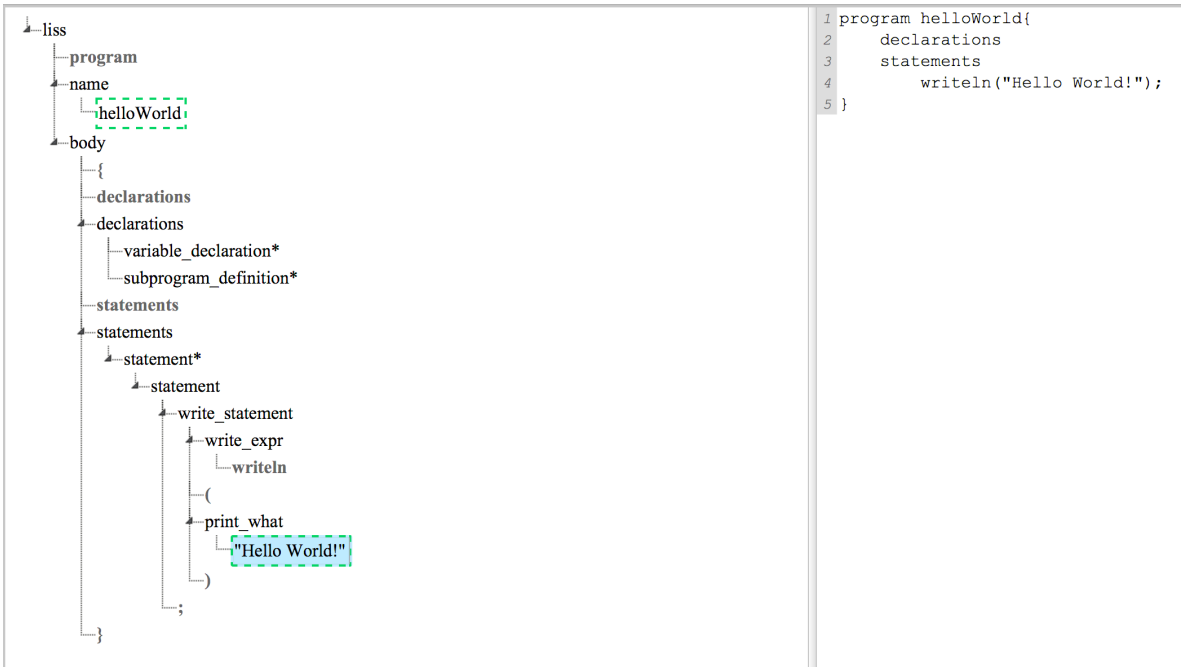


Figure 48.: Creating a LISS program (17/17)

Finally, notice that the user can at any time delete rules by clicking on every non-terminal in the tree structure.

And this is how the user can interact and create a program in *liss*|*SDE*.

5.2.3 *Executing a program*

For executing a program in *liss|SDE*, we just need to go to the toolbar, press the *Run* button and then choose the *Compile and Run* option (remember Figure 29).

By doing that, it will pass throw a lot of steps (see Figure 49).

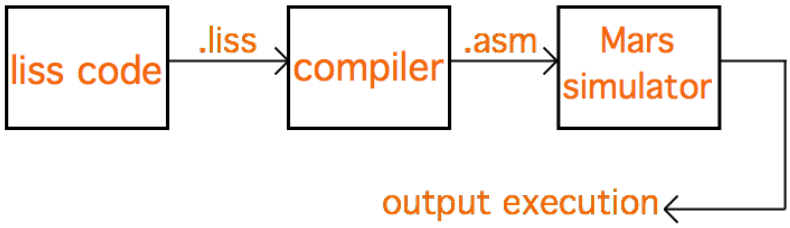


Figure 49.: Flow of the execution of a liss code in the *liss|SDE*

The first step is to take the liss program and pass it to the compiler. In this moment, the compiler will check the consistency of the code (semantic system); then, if everything is fine, it will pass the MIPS assembly code generated (at the end of the process of the compiler) to the simulator (Mars Simulator) and execute the code. Finally, it will print the output of the execution of the liss code to the window number 3 (see Figure 26).

For a visual example, let's execute the program created above with the *liss|SDE* tool.

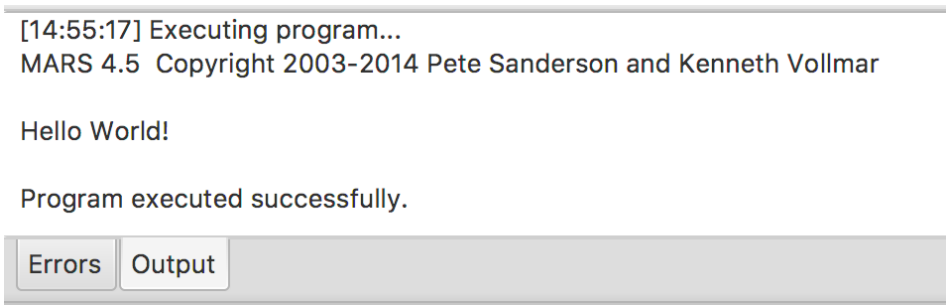


Figure 50.: Output of the execution of the *HelloWorld* program

In Figure 50, we can see that the string *"Hello World!"* is printed and that the program was executed and terminates successfully.

5.2.4 *Error System in liss|SDE*

Each time a LISS program is compiled, an error table is built. All the semantic error that are found in the LISS program, will be added to that error table.

If the error table is empty, then the code can be executed. Otherwise, if the error table contains some errors, then those errors must be outputed in the tab *Errors* at the window number 3 (see Figure 26).

Let's see an example of the error system in *liss|SDE*.

Consider the program below created with *liss|SDE* environment:

```
1 program test{
2   declarations
3     int=2->boolean;
4   statements
5     writeln(int+3);
6 }
```

Listing 5.3: Example of a liss code that isn't semantically correct

Now, if we try to run the compiler in *liss|SDE*, the compiler will throw error messages due to the inconsistencies that were found (see in Listing 5.4).

```
1 [16:10:40] Semantics errors found:
2 [16:10:40] line: 3:8  Variable 'int' has type 'integer',when It should
      be 'boolean'.
3 [16:10:40] line: 5:16  Expression 'int + 3' has type 'boolean +
    integer',required type 'integer + integer'.
4 [16:10:40] line: 5:16  Expression 'int+3' has type 'null',when It
    should be 'integer | boolean | sequence | array'.
```

Listing 5.4: Error messages in *liss|SDE*

The notation conventions used for those messages, in Listing 5.4, is as follows: first, is shown the time that the error was found (embraced by square brackets); second, the line number of the error regarding to the liss code in window number 2 (see Figure 26) and finally, the error message text.

Notice that the line number is very important to locate and understand the error and correct it.

6

CONCLUSION

In this final chapter, it will be summarized the information that was exposed throughout this document in order to remember the aims of the project and how they were achieved.

First, it begins by contextualizing the reasons of helping the developers for being more productive regarding the creation of some programs for computers. This was attained by creating a software system (a compiler) which makes the life of a developer easier by allowing him to write programs at a high level of productivity. But as always there is the necessity of achieving more (creating a program with a high level language and in a safety way) and that is why, we introduce the notion of Syntax Directed Editor, an editor that helps the programmer writing his code guiding him through the language syntax.

The main idea underlying of a SDE is to create programs whithout the use of the keyboard avoiding syntax errors; instead, the programmer will use the mouse and create the code by selecting some rules available in the grammar of the language. For this project, it was aimed to create a SDE for the language called LISS.

So, it was needed to first understand that language, writting some test programs. After understanding the syntax of the language, some improvements were introduced in the language (due to its old age) by changing or deleting some rules.

After designing those improvements in the grammar, it was necessary to develop the compiler to analyse and check the LISS programs and generate the associated assembly code. For that purpose, the original grammar (a CFG - Context-Free Grammar) was evolved to another type (an AG - Attribute Grammar).

Before creating the compiler, it was needed to understand the MIPS architecture which is the chosen target machine (the compiler will generate MIPS assembly code). The architecture is a RISC architecture which makes the learning phase easier. After understanding the architecture, it was necessary to test it, writting some programs in MIPS assembly code for a better view of that programming language.

With those knowledge acquired relatively to the MIPS architecture, it was essential to create some adapted data structures (stack, registers) to support the code generation and the execution of LISS program.

As a result of all the research and reasoning made, we began by creating the compiler. It is important to remember that the compiler only pass once throw the LISS code which has some pros and cons. In that single pass, two tasks are performed by the compiler's back-end; the semantic analysis and the code generation.

The semantic analysis requires some structures that are a symbol table and an error table. The symbol table save information about all the LISS identifiers; the error table stores the error messages to inform the user relatively to the semantic analysis (both of those structures are in a sense connected). The symbol table is also used to support the most complex stage in the project, the code generation.

The code generation rose up a lot of difficulties and this is due to some hard issues listed below:

- processing the LISS code only once and caring about the order that it is processing relatively for generating the code.
- saving some informations in the memory relatively for generating the code in the correct order (due to the specifications of the MIPS architecture).
- creating a linked-list in MIPS assembly code to implement the sequence type.
- creating MIPS code with alignment address.
- defining a certain architecture for generating the code relatively to the context that the compiler is dealing with (using which register, stack or heap).
- creating some complex algorithm for the use of some structure available in the project.

After developing the compiler there is the need of testing it and checking the correctness of the code generated. 18 LISS programs prepared specifically to cover the different types and statements that were tested and approved.

Once the compiler was created, it was built the visual (Syntax Directed Editor - SDE) program. By studying and reading some articles about the concept of SDE, we managed to draw the interface and its visual appearance, focusing on the most important notions of such an editor:

- having a visualization of the abstract syntax tree for the LISS language.
- having a window where the LISS code being created can be seen.
- having an output window where the error messages found at runtime by the compiler are displayed as well as the ouput produced by the execution.

After developing the visual editor and integrating it with the LISS compiler, it was needed to connect the compiler and the MARS simulator. This task for connecting the MARS

simulator with the SDE environment, was one of the hardest parts of the project due to the complexity of using processes and threads in JAVA for sending some input and getting the output.

The last step was the final, testing of the SDE environment to check if everything works properly.

It was made an inquiry for testing the application and learn more about the usability of the syntax direct editor. It was concluded that this concept is a must for learning a new programming language due to the fact of getting a better perception of the syntax of the programming language and the easy way for creating some code. However when the user has better and deeper knowledge of the programming language, that approach is not the most appropriated.

The project is available to test on github throw this link https://github.com/damienvaz/Liss-SDE.

6.1 FUTURE WORK

To conclude that dissertation, it is intended to discuss some future work that might be done for improving the application concerning the productivity of the programmer and the compiler efficiency.

- Adding some semantic to the abstract syntax tree available in the visual for generating the rules. This means that if we declare a variable where it is initialized with an integer value, it should know that the variable will be an integer type. In this case, we could create a SSDE (Semantic Syntax Directed Editor).
- Optimizing the code generated by the compiler.
- Adding the possibility of moving statements in the abstract syntax tree. For instance, if you want to swap two statements, you cannot do it.
- Adding a feature for incremental compilation.
- Adding a feature to the editor (SDE) to be adaptable to any programming language who deal with other programs not written in LISS.

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A

LISS CONTEXT FREE GRAMMAR

LISS (da Cruz and Henriques, 2007a) is an imperative programming language, defined by the Language Processing members (Pedro Henriques and Leonor Barroca) at UM for teaching purposes. It allows handling integers, sets of integers, dynamic sequences, complex numbers, polynomials, etc., etc (da Cruz and Henriques, 2007b,a, 2006a,b, 2005).

The idea behind the design of LISS language was to create a simplified version of the more usual imperative languages although combining functionalities from various languages.

```
grammar LissGIC;

/* ****** Program ****** */

liss : 'program' identifier body
     ;


body : '{'
       'declarations' declarations
       'statements'   statements
       '}'
     ;

/* ****** Declarations ****** */

declarations : variable_declaration* subprogram_definition*
             ;

/* ****** Variables ****** */

variable_declaration : vars '->' type ';'
                     ;

```

```
25 vars : var (',' var )*
26      ;
27
28 var : identifier value_var
29     ;
30
31 value_var :
32           | '=' inic_var
33           ;
34
35 type : 'integer'
36      | 'boolean'
37      | 'set'
38      | 'sequence'
39      | 'array' 'size' dimension
40      ;
41
42 typeReturnSubProgram : 'integer'
43                      | 'boolean'
44                      ;
45
46 dimension : number (',' number )*
47           ;
48
49 inic_var : constant
50          | array_definition
51          | set_definition
52          | sequence_definition
53          ;
54
55 constant : sign number
56          | 'true'
57          | 'false'
58          ;
59
60 sign :
61      | '+'
62      | '-'
63      ;
64
65 /* ****** Array definition ****** */
66
67 array_definition : '[' array_initialization ']'
```

```
68                  ;
69
70 array_initialization : elem (',' elem)*
71                       ;
72
73 elem : number
74      | array_definition
75      ;
76
77 /* ****** Sequence definition ****** */
78
79 sequence_definition : '<<' sequence_initialization '>>'
80                      ;
81
82 sequence_initialization :
83                          | values
84                          ;
85
86 values : number (',' number )*
87        ;
88
89 /* ****** Set definition ****** */
90
91 set_definition : '{' set_initialization '}'
92                ;
93
94 set_initialization :
95                    | identifier '|' expression
96                    ;
97
98 /* ****** SubProgram definition ****** */
99
100 subprogram_definition: 'subprogram' identifier '(' formal_args ')'
    return_type f_body
101                      ;
102
103 f_body : '{'
104          'declarations' declarations
105          'statements' statements
106          returnSubPrg
107          '}'
108        ;
109
```

```
110 /* ****** Formal args ****** */
111
112 formal_args :
113             | f_args
114             ;
115
116 f_args  : formal_arg (',' formal_arg )*
117         ;
118
119 formal_arg : identifier '->' type
120            ;
121
122 /* ****** Return type ****** */
123
124 return_type :
125             | '->' typeReturnSubProgram
126             ;
127
128 /* ****** Return ****** */
129
130 returnSubPrg :
131              | 'return' expression ';'
132              ;
133
134 /* ****** Statements ****** */
135
136 statements : statement*
137            ;
138
139 statement : assignment ';'
140           | write_statement ';'
141           | read_statement ';'
142           | conditional_statement
143           | iterative_statement
144           | function_call ';'
145           | succ_or_pred ';'
146           | copy_statement ';'
147           | cat_statement ';'
148           ;
149
150 /* ****** Assignment ****** */
151
152 assignment : designator '=' expression
```

```
153             ;
154
155 /* ****** Designator ****** */
156
157 designator : identifier array_access
158             ;
159
160 array_access :
161               | '[' elem_array ']'
162               ;
163
164 elem_array : single_expression (',' single_expression )*
165             ;
166
167 /* ****** Function call ****** */
168
169 function_call : identifier '(' sub_prg_args ')'
170                ;
171
172 sub_prg_args :
173               | args
174               ;
175
176 args : expression (',' expression )*
177      ;
178
179 /* ****** Expression ****** */
180
181 expression : single_expression ( rel_op single_expression )?
182             ;
183
184 /* ****** Single expression ****** */
185
186 single_expression : term ( add_op term )*
187                   ;
188
189 /* ****** Term ****** */
190 term : factor ( mul_op factor )*
191      ;
192
193 /* ****** Factor ****** */
194
195 factor : inic_var
```

```
196         | designator
197         | '(' expression ')'
198         | '!' factor
199         | function_call
200         | specialFunctions
201         ;
202
203 specialFunctions : tail
204                   | head
205                   | cons
206                   | member
207                   | is_empty
208                   | length
209                   | delete
210                   ;
211
212 /* ****** add_op, mul_op, rel_op ****** */
213
214 add_op : '+'
215        | '-'
216        | '||'
217        | '++'
218        ;
219
220 mul_op : '*'
221        | '/'
222        | '&&'
223        | '**'
224        ;
225
226 rel_op : '=='
227        | '!='
228        | '<'
229        | '>'
230        | '<='
231        | '>='
232        | 'in'
233        ;
234
235 /* ****** Write statement ****** */
236
237 write_statement : write_expr '(' print_what ')'
238                 ;
```

```
239
240 write_expr : 'write'
241           | 'writeln'
242           ;
243
244 print_what :
245           | expression
246           ;
247
248 /* ****** Read statement ****** */
249
250 read_statement : 'input' '(' identifier ')'
251               ;
252
253 /* ****** Conditional & Iterative ****** */
254
255 conditional_statement : if_then_else_stat
256                       ;
257
258 iterative_statement : for_stat
259                     | while_stat
260                     ;
261
262 /* ****** if_then_else_stat ****** */
263
264 if_then_else_stat : 'if' '(' expression ')'
265                     'then' '{' statements '}'
266                     else_expression
267                   ;
268
269 else_expression :
270                 | 'else' '{' statements '}'
271                 ;
272
273 /* ****** for_stat ****** */
274
275 for_stat : 'for' '(' interval ')' step satisfy
276           '{' statements '}'
277         ;
278
279 interval : identifier type_interval
280         ;
281
```

```
type_interval : 'in' range
              | 'inArray' identifier
              ;

range : minimum '..' maximum
      ;

minimum : number
        | identifier
        ;

maximum : number
        | identifier
        ;

step :
     | up_down number
     ;

up_down : 'stepUp'
        | 'stepDown'
        ;

satisfy :
        | 'satisfying' expression
        ;

/* ****** While_Stat ****** */
while_stat : 'while' '(' expression ')'
             '{' statements '}'
           ;

/* ****** Succ_Or_Predd ****** */

succ_or_pred : succ_pred identifier
             ;

succ_pred : 'succ'
          | 'pred'
          ;

/* ****** SequenceOper ****** */

```

```
tail // tail : sequence -> sequence
     : 'tail' '(' expression ')'
     ;

head // head : sequence -> integer
     : 'head' '(' expression ')'
     ;

cons // integer x sequence -> sequence
     : 'cons' '(' expression ',' expression ')'
     ;

delete // del : integer x sequence -> sequence
       : 'del' '(' expression ',' expression ')'
       ;

copy_statement // copy_statement : seq x seq -> void
               : 'copy' '(' identifier ',' identifier ')'
               ;

cat_statement //cat_statement : seq x seq -> void
              : 'cat' '(' identifier ',' identifier ')'
              ;

is_empty // is_empty : sequence -> boolean
         : 'isEmpty' '(' expression ')'
         ;

length // length : sequence -> integer
       : 'length' '(' expression ')'
       ;

/* ****** set_oper ****** */

member // isMember : integer x sequence -> boolean
       : 'isMember' '(' expression ',' identifier ')'
       ;



/*
   ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    */
```

```

string : STR
       ;

number : NBR
       ;

identifier : ID
           ;
/* ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++ */


/* ****** Lexer ****** */

NBR : ('0'..'9')+
    ;

ID : ('a'..'z'|'A'..'Z')('a'..'z'|'A'..'Z'|'0'..'9'|'_')*
   ;

WS  :   ( [ \t\r\n] | COMMENT) -> skip
    ;

STR :  '"' ( ESC_SEQ | ~('"') )* '"'
    ;


fragment
COMMENT
    : '/*'.*?'*/' /* multiple comments*/
    | '//'~('\r' | '\n')* /* single comment*/
    ;

fragment
ESC_SEQ
    :   '\\' ('b'|'t'|'n'|'f'|'r'|'\"'|'\''|'\\')
    ;
```

lissGIC.g4