Lola 0.064

A Programming Language for Augmenting Programming Languages

Research Thesis

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Abstract

LOLA, *the* **L**anguage **O**f **L**anguage **A**ugmentation, *is the topic of this master of science in computer science thesis.* LOLA *is a modern, language-independent, preprocessor, for* language extension. *Inspired by the island grammars trend,* LOLA *makes many non-trivial language extensions possible with no more than a handful lines of code.*

LOLA *was used for tasks such as augmenting* JAVA *with keywords* `This` *(bound to the name of current class) and* `Super` *(invoke the overridden method), and positional arguments, for adding a range based* `for` *loop construct to C, for AOP like features and even for computing code metrics. In fact,* LOLA *is expressive enough for users to define their own variant of the C-preprocessor and other preprocessors, including the immediate and delayed semantics of the preprocessor of Unix "*`make`*".*

A user-accessible configuration file defines the tokens of the host language. LOLA *analyzes the token stream (rather than the raw character stream) with extended regular expressions, and employs "generating expressions" to replace, delete, or otherwise amend pieces of its input. A language is augmented by appropriate use of "lexies", where each lexi is a semi-declarative module describing a certain code-transformation.*

Underlying LOLA *is a* PYTHON *engine, and* LOLA *programmers are allowed full access to* PYTHON *language features. With this model the definition of* LOLA *can be kept short, concentrating in weaving together, as seamlessly as possible,* LOLA *keywords, the stream of tokens of the augmented language, and the* PYTHON *code the programmer chooses to use.*

Glossary

Chapter 1

Introduction

Everyone knows how risky is the business of adding features to existing successful languages.

> *"When in doubt, always abstain."* ,

one well known language designer [39, p.497–508] decreed after explaining that even innocent changes very often interfere at the least expected places.

Abstention leads to delays. A case in point is a **`switch`** over strings in JAVA, which seems so natural, especially after reading the repetitive code of Listing 1.1.

Listing 1.1 JAVA code with multiple comparisons of the same string variable with a sequence of string literals

```java
public static void main(String[] args) {
  for (String arg: args)
    if (arg.equals("-c") || arg.equals("--bytes"))
      …
    else if (arg.equals("-m") || arg.equals("--chars"))
      …
    else if (arg.equals("-w") || arg.equals("--words"))
      …
    else if (arg.equals("-l") || arg.equals("--lines"))
      …
    else if (arg.equals("--help"))
      …
    else if (arg.equals("--version"))
      …
  …
}
```

It took 20 years from the time requests started accumulating[1] until the language extension was finally implemented[2].

Designer's prudence and delays can have a non-negligible toll on resources, i.e., the relatively late addition of generics to JAVA forced programmer to use the unsafe **`Vector`** substitution that was available at the time.

[1] `http://bugs.java.com/bugdatabase/view_bug.do?bug_id=1223179`
[2] `http://docs.oracle.com/javase/7/docs/technotes/guides/language/strings-switch.html`

Yet, this price seems to be unavoidable. A programming language that haphazardly accepts changes, cannot be trusted by its clients. The design of a programming language is a delicate art of balancing between conflicting trade-offs and all changes must be weighed carefully. On the one hand, to make the language appealing, the language designer would like to equip future programmers with a variety of powerful and useful abstractions. On the other hand, the folk-lore of language design is that any feature added to a language has its price: reduced elegance of the design, a steeper language learning curve, and complication of the construction of language processing tools.

LOLA, the ***L**anguage **of** **L**anguage **A**ugmentation*, was designed with this dilemma in mind: The approach it offers is of empowering the language users, the programmers in the trenches, by making it easier for them to introduce lightweight, and not so lightweight, extensions to the programming language they use.

Figure 1.1 Hare Lola Bunny. ♀ *1996–*

Readers eager to get a quick taste of LOLA, and its somewhat unusual syntax, may check out the mostly self-explanatory "hello world" example in Listing 1.2.

Listing 1.2 Basic matching and replacing of the highlighted code

```
#include <stdio.h>
#include "HelloWorld.ms"
int main()
{
  float f = 0.0f;
  int   a = 5;
  return 0;
}
```

(a) C source code, in which the highlighted code is to be replaced. We insert the LOLA code using the C preprocessor for clarity.

```
HelloWorld.ms
@Find(HelloWorld) int a = 5;
@replace printf("int a = 5; was here");
```

(b) LOLA macro definition to match the highlighted code (in file "HelloWorld.ms")

```
#include <stdio.h>
@Find(HelloWorld) int a = 5;
@replace printf("int a = 5;
   was here");
int main()
{
  float f = 0.0f;
  int   a = 5;
  return 0;
}
```

(c) Files (a) and (b) combined into a single file.

```
#include <stdio.h>
int main()
{
  float f = 0.0f;
  printf("int a = 5; was here");
  return 0;
}
```

(d) The output of LOLA with the input file from (c).

1.1 Thesis

The thesis that this research promotes is that with the aid of a powerful preprocessing tool, programmers would be able to add and experiment with new abstractions to support the programming language they use, without waiting years for the language to evolve. LOLA was designed to make this alternative viable. LOLA makes it easy for programmers to enhance and extend the programming language they use, without making any changes to the language core.

We describe a large number of innovative language extensions made possible with LOLA. We also show how C [29] might be enhanced with high level constructs, while preserving the language efficiency and its underlying principle of *no hidden cost* [52, p.43].

On course, we demonstrate the application of PYTHON [37] as a language for meta-programming. LOLA was designed in accordance with the vision that PYTHON code embedded in it would provide C programmers with higher abstractions, all implemented in C, and all realized using the familiar metaphor of a text preprocessor.

This document describes LOLA in detail. In a nutshell, we can say now that the modular unit of computation in LOLA is a lexi. Lexies employ *patterns*, which are rather extended regular expressions defined on tokens. Patterns define points where a lexi is triggered on the input to take some appropriate action. Actions can be code replacements, but also short snippets of PYTHON code.

Figure 1.2 Hare Lexi Bunny. ♀ *September 17, 2005 – May 5, 2007*

LOLA achieves the end of language independence by using an XML configuration file defining the breaking of source code of the *host language* into lexical units, including tokens, spaces and comments.[3]

The configuration file also defines a *hierarchical taxonomy* of tokens, e.g., the classification of identifiers into `@CamelCase`, `@camelCase`, `@UPPER_CASE` (and other capitalization and naming conventions), grouping of selected tokens into categories `@Operator` and `@Punctuation`, etc.

Some other unique features of LOLA include the *blending of declarative and imperative approaches* in the definition of lexies (going beyond assertions and JAVADOC [33], and reminiscent of EIFFEL [28]'s **`ensure`**, **`require`**, **`invariant`** and **`variant`**), *lightweight language definition* borrowing as much as possible from PYTHON, *seamless weaving of code of three languages*, and a novel, *modular means* for the definition of LOLA's own grammar.

The remainder of this introductory chapter is organized as follows: Section 1.2 compares the LOLA approach with that of traditional pre-processing. This comparison is furthered in Section 1.3 which shows how LOLA compares with the C preprocessor in the implementation of the vanilla **`max`** macro. Section 1.4 disrupts the comparison to provide the reader an initial intuition of LOLA's use of indentation. Section 1.5 continues the comparison by showing how LOLA can be used for extending the C programming language, while Section 1.6 provides a table of comparison between LOLA directives and C preprocessor directives.

1.2 The Lola Approach

In a sense, the approach that LOLA takes is not new. Macros of the ancient C preprocessor made it possible to make certain additions to C. However, the many limitations of the C preprocessor and of other macro systems (such as M4 [20]), may be the reason that modern programming languages tend less to rely on a preprocessing stage.

Yes, LOLA is a preprocessor in the sense that its input is source code intermixed with *directives*, and its output is the source code after the application of the directives. Yes, LOLA is a macro system in the sense that directives manipulate the source without fully parsing it, figuring its semantics, inferring types etc.

However, in contrast with other macro and preprocessing systems, LOLA is specifically designed for the task of language extension. To this end, instead of macros, LOLA's code is organized in *lexies*, where each lexi is a modular specification, including both imperative and declarative *sections*, of some source code transformation. As we shall see, a lexi augmenting JAVA with a **`switch`** construct on strings can be done in a lexi comprised of just a handful of lines.

The syntax of the C preprocessor's macros is that of function calls. Lexies are different in that they rely on extended regular expressions, called *patterns* in the LOLA lingo, to determine code locations in which they should be applied. Arguments to macros are typically expressions, or a specific syntactical unit of the programming language they tend. In contrast, LOLA is language independent, and arguments to macros can be any sequence of tokens.

LOLA lexies are a bit similar to AWK [1] line patterns, except that unlike AWK (and the C preprocessor, M4, and other such systems) LOLA refuses to take the trouble of defining its own syntax for arithmetical expressions, variables, arrays, control flow constructs and other commodities that concern most programming languages. Instead, LOLA relies on PYTHON

[3]Henceforth, the term *input stream*, or just *input* refers to the text of the program processed by LOLA and the term "host language" refers to the programming language that LOLA processes its source files, C being our primary example.

for defining these, and concentrates on defining its central unique language constructs: lexies, patterns and *generating expressions*.

As it turns out, computation carried out by short PYTHON snippets makes it possible to analyze the host code more thoroughly than possible with traditional macro systems.

1.3 The Max Lexies

To demonstrate the difference between LOLA and traditional preprocessors, consider the problem of implementing a `max` macro. In the C preprocessor a `max` macro would look like the code in Listing 1.3.

Listing 1.3 Max macro in the C preprocessor

```
#define max(X,Y) ((X) > (Y) ? (X) : (Y))
```

As usual with C preprocessor macros, the body of macro `max` wraps the arguments in parenthesis to protect against the predicament of a substitution being incorrect due to operator precedence.

Arguments to `max`, just like all other macros of the C preprocessor, are expressions separated by commas. Since LOLA knows nothing about the tokens of C, to define a similar macro, it is first necessary to define the syntactical construct which macros take as arguments. This is done in Listing 1.4.

Listing 1.4 A lexi for the comma argument (similar to C preprocessor macro's)

```
@Find(NoCommasExpression)
  @Match @Any @exceptFor @Any, @Any

@Find(Expression)
  @Either @NoCommasExpression @or (@Any)

@Find(Expressions)
  @OneOrMore @Expression @separator,
```

The first lexi in the listing,

```
@Find(NoCommasExpression)
  @Match @Any @exceptFor @Any, @Any
```

makes use of `@Any`, a LOLA builtin, which matches any *balanced* sequence of *tokens* of C, the *host language*. Tokens of the host language are defined in a language-specific *configuration file*. This configuration file also specifies which tokens of the language come in balanced pairs. There are three such pairs in C (and other curly brackets languages): "`(`" must be balanced against "`)`", "`[`" against "`]`, and, the "`{`" token which must match against its "`}`" counterpart

Pattern `@Any` matches therefore, e.g.,

```
(2,3),
```

but not

```
(2,3), f(
```

The pattern in the first lexi of the listing thus means: Any sequence of tokens, which does *not* match `@Any, @Any`, i.e., cannot be written as a balanced sequence of tokens, followed by a comma, and then followed by another balanced tokens' sequence. Notice the use of conjunctions in LOLA patterns, an operator not available in most regular expression languages.

Note that pattern `@Any, @Any` matches token sequences such as

```
(2,3),f(4,5)
```

but not

```
f(4,5)
```

since neither "`f(4,`" nor "`,5)`" are balanced sequences that match `@Any`.

The interpretation of the phrase `@Match @Any @exceptFor @Any, @Any` as "any balanced sequence of tokens, *except* for those sequences which can be broken into two such balanced sequences separated by a comma token" is made by LOLA by identifying these elements in it:

- Keyword `@Match` is a constructor which creates a conjunctive regular expression out of its constituents.

- Keyword `@Any` is a *parameterless constructor* as described above.

- Keyword `@exceptFor` is an *elaborator*. Elaborators are similar to constructors in their grammatical structure, except that they do not make a pattern on their own, and must be associated with a constructor, `@Match` in this case.

  Despite a couple of exceptions, constructors use the "CameCase" capitalization and case convention and elaborators the "cameCase" convention.

- Host token `,` which is the second of the three parameters to elaborator `@exceptFor`.

Writing

```
@Find(NoCommasExpression)
```

binds the name `NoCommasExpression` to this pattern.

This name or, more accurately, its "plural" form, `NoCommasExpressions` can be used in PYTHON. Variable `NoCommasExpressions` is made up of a list of all cases in which `@NoCommasExpression` was matched.

Another possible use of the binding is in defining LOLA patterns that use the user defined pattern `@NoCommasExpression` as a building block.

In general, LOLA keywords fall into one of three categories:

1. *Builtin.* A category includes keywords such as `@Match`, `@exceptFor`, `@Any`, which are part of LOLA and can be used in any host programming language.

2. *Host Specific.* In this category, we find names of individual tokens, such as `@Integer`, and of classes of tokens, such as `@Operator`, all being defined in the configuration file of the host language.

3. *User Defined.* Three examples of this category, pattern `@NoCommasExpression`, pattern `@Expression`, and pattern `@Expressions` are shown in Listing 1.5.

We see the user defined pattern `@NoCommasExpression` being employed in the second lexi of Listing 1.5: User defined pattern `@Expression`, is either a `@NoCommasExpression` or, `(@Any)`, i.e., a balanced sequence of tokens wrapped in parenthesis.

Accordingly `@Expression` matches

```
f(4,5)
```

and

```
(f(4),5)
```

but not

```
3,f(4, 5)
```

Thus, `@Expression` specifies a valid argument to a C preprocessor macros.[4]

The third lexi of Listing 1.4 uses pattern `@Expression` to define pattern `@Expressions` which matches a comma separated, non-empty list of `@Expression`s. The Lola *builtin constructor* `@OneOrMore` takes elaborator `@separator` with its argument "`,`" that, together, tell that the recurring expressions in the list are comma separated.

Listing 1.5 builds on the infrastructure of Listing 1.4 to define the Lola equivalent of the C preprocessor `max` macro.

Listing 1.5 Max lexi in Lola

```
@Find
    max(@Expression(x), @Expression(y))
  @run {
    x = '(' + str(x) + ')'
    y = '(' + str(y) + ')'
  }
  @replace
    (@(x) > @(y) ? @(x) : @(y))
```

The lexi in the listing has three sections: the starting `@Find` section defines the pattern which *triggers* the proxy, the `@run` section which defines a bunch of Python commands to be executed upon triggering, and the `@replace` section defining the replacement of the matched sequence.

Sections are just elaborators of a lexi. A section whose name is capitalized, `@Find` in the listing, creates an empty lexi, and attaches itself to it as one of its elaborators. Non-capitalized sections, `@run` and `@replace` here, attach as elaborators to the preceding lexi.

[4]In fact, the Lola specification is slightly different, since C preprocessor does not worry about square- nor curly- brackets

The pattern in the `@Find` section matches a sequence beginning with the `max` identifier, followed by an opening parenthesis, an expression as previously defined, a comma, another such expression and ending with a closing parenthesis.

Whenever a pattern is matched, LOLA creates a PYTHON object, called the *reifying object*, which can be manipulated in the `@run` section. The `@Expression(x)` sub-pattern in the `@Find` section invokes the `@Expression` pattern defined above, and storing the result of the match into an instance variable named `x` in this reifying object. Instance variable `y` is similarly defined in this object.

Now, the `@run` section wraps these two instance variables in parenthesis. The `@(x)` and `@(y)` references to these variables in the `@replace` section yield the correct parenthetical version of these.

LOLA makes it easy to define a version of `max` taking a variable number of arguments, as done in Listing 1.6. Notice that even though variadic macros exist in the C preprocessor, they cannot be used to create a variadic `max` macro.

Listing 1.6 Max lexi in LOLA with variable number of arguments

```
@Find
    max(
      @OneOrMore @Expression(x) @separator,
    )
  @run {
    xs = ['(' + str(x) + ')' for x in xs]
  }
  @replace
    @ForEach(xs[:-1])
      (@(xs[0]) < @(_) ? @(_) : @(xs[0]) @(')'*(len(xs)-1))
```

The pattern in this listing is exactly what it reads to be: a sequence of tokens starting with the `max` identifier followed by open parenthesis, and ending with closing parenthesis. In between the parenthesis pair there are one or more occurrences of the user defined `@Expression` pattern, separated by commas.

Occurrences of `@Expression` in the pattern are repeatedly stored in instance variable `x`, so at time of triggering `x` will store the last matched `@Expression`. However, LOLA automatically defines an instance variable which contains the list of all assignments to `x` during the match. This name of this variable, `xs`, is obtained by adding the plural suffix `s` to the user defined name `x`. The `@run` section uses a PYTHON programming idiom to parenthesize all elements of list `xs`.

The `@replace` section of the lexi uses a *generating expression* to produce C code that implements the variadic max semantics. A generating expression is a LOLA expression that generates code. The `@ForEach` builtin employed in this section is a useful operator in generating expressions; it uses a PYTHON *iterable*[5] to iterate over the list. The iteration variable is named `_` and it can be accessed in the body of the `@ForEach` by means of LOLA's operator for escaping a PYTHON identifier, `@(·)`.

[5]e.g., expression `xrange` yielding multiple values by means of the PYTHON `yield` keyword

1.4 Indentation

Before proceeding to more motivational examples, note that Lola relies on indentation for block definitions, much in the spirit of Python and Occam [16]. In Listing 1.6 the body of the `@replace` section is the two indented lines that follow it, and the body `@replace` is the subsequent indented line.

Lola's syntax is a combination of free style with indentation and line breaking rules. The details of implementation may be a bit complicated, but to understand Lola code, the reader should only keep these simple rules in mind:

- the *no lower indentation argument rule* stating that the arguments of any Lola keyword are never found at an indentation level which is lower than that of the keyword itself.

- the *eager association rule* states that keywords that elaborate other keywords (e.g., `@else` elaborating an `@If`) always attach to inner most candidate.

- the *right associativity rule* says that tokens and keywords found in a line associate to the left. In other words, the interpretation of the isolated such as

  ```
  @X a b c @Y d e f @g h i @Z
  ```

  is as if the following virtual Lisp [22] like parenthesis were written:

  ```
  ( @X a b c ( @Y d e f ( @g h i @Z ) ) )
  ```

  The above should be read with Lisp convention in mind: the first item in a list is a function whose arguments are the remainder of the list.

  Right associativity in this example means that constructor **`@X`** takes four arguments: host tokens "**`a`**", "**`b`**", "**`c`**", and the result of applying constructor **`@Y`** to its own arguments.

  Constructor **`@Y`** also takes four arguments: host tokens "**`d`**", "**`e`**", "**`f`**", and, the result of application of elaborator **`@g`** to its own arguments.

  Finally, elaborator **`@g`** takes three arguments: host tokens "**`h`**" and "**`i`**", and the parameterless constructor **`@Z`**.

1.5 Ranged Loops and Loop Unrolling

Listing 1.7 illustrates the use of Lola for adding two new language constructs to C: ranged loops and loop unrolling.

Listing 1.7 Using **@replace** for defining a loop based on range syntax

```
@Find                                                              1
    for @Identifier(i) in @Literal(start) .. @Literal(end)         2
  @replace                                                         3
     for (int @(i) = @(start); @(i) < @(end); @(i)++)              4

@Find                                                              6
    unroll @Identifier(i) in @Literal(start) .. @Literal(end) {    7
      @Any(body)                                                   8
    }                                                              9
  @replace                                                        10
     @ForEach (range(start,end))                                  11
       {                                                          12
         int @(i) = @(_);                                         13
         @(body)                                                  14
       }                                                          15

int main() {                                                      17
  for iter in 0..2 {                                              18
    printf("now at %d", iter);                                    19
  }                                                               20

  unroll iter in 0..2 {                                           22
    printf("now at %d", iter);                                    23
  }                                                               24

  unroll i in 0..2 {                                              26
    unroll j in 0..3 {                                            27
      printf("now at %d", iter);                                  28
    }                                                             29
  }                                                               30
}                                                                 31
```

A usage of the ranged loop is highlighted in green in line 18. We see in the code the **for** keyword of C, the name of the iterator variable, and the literals that indicate the bounds of the loop (i.e., **iter** $= 0, 1$), separated by two dots.

The use of the **unroll** loop can be seen in line 22, highlighted in red. The main difference in this added syntax is that the lexi triggers on **unroll**, rather than on **for**. The semantics is also similar. The loop body is executed the number of times as declared by the range. The loop is unrolled, where each iteration is provided with the correct value of **iter**, the iteration variable. Lastly, starting at line 24 are two nested **unroll** loops. These will be expanded as expected.

Now, having reviewed the use examples of both constructs, we return to the first lexi definition, that is, the ranged loop lexi definition. It searches for C's keyword `for`, followed by an identifier (that will be declared as a C variable in the rewritten code, as explained later). Then, we see the `in` word and two literals, separated by two consecutive "`.`" tokens. Variables `i`, `start` and `end` in PYTHON denote the text matched by the `@Identifier` and the two occurrences of `@Literal`s, respectively.

The processing of the text in the `@replace` section also reminds the processing of string literals in shell, e.g., BASH. Default processing is verbatim. There are provisions for substitutions, most important of which is string expansion using the `@` keyword.

Here we see that the previously defined `i` variable is used to name the loop iterator. The `start` variable is used to set the initialization value of the iterator, and the `end` variable is used to test in the `for` loop condition.

The output of Listing 1.7 is presented in Listing 1.8.

The second lexi, `unroll`, starts very similarly to the first, except it looks for the word `unroll`, and in the end a following curly-braced block. It is then replaced by a series of blocks, where each represents a single execution of the loop body. Each block is prepended with the iterator definition, initialized to the current value.

1.6 Directives

All LOLA code is contained in *directives*, which are those instructions that can be placed at the upper most, file, level of the source. A directive is either a lexi, which is typically executed at a later stage, or a generating expression which is executed immediately—the output of the generating expression replacing the generating expression directive.

Table 1.1 shows a sample of LOLA directives, comparing each of these with the corresponding C preprocessor approximation.

A lexi may start with any of its sections. Therefore, any lexi section may serve as a directive. The upper block of the table gives a sample of lexi sections and their use as directives. (The full list of sections can be found below in Table 4.3.)

Similarly, any generating expression might be used as a directive. The lower block of Table 1.1 shows a sample of constructors of generating expressions used as directives. (The full list of constructors of generating expressions can be found below in Table 4.1.)

Lexies can only appear at the top level of a file. Three exceptions exist to this rule: Directives `@Include`, `@Import` and `@Splice` may introduce new lexies to LOLA, only as long as these directives are in the top level of the file. I particular, lexies may not be created by other lexies.

1.7 Contributions, Challenges and Achievements

I believe that LOLA bears the potential of evolving into a tool that would be used by many programmers. In many ways, LOLA supersedes everyday tools such as "grep", "sed", AWK, PERL [57], PYTHON and others, in the context of their application to software. In this sense, LOLA is a software engineering tool: When put in the hands of able programmers it makes it possible to "engineer" the software itself, modify it, enhance it, measure it, and reason about it. And, it makes it possible to do all that in a reproducible, concise and modular fashion.

Listing 1.8 The output of Listing 1.7 produced by Lola.

```
int main() {
  for (int iter = 0; iter < 2; iter++) {
    printf("now at %d", iter);
  }

  {
    int i = 0;
    printf("now at %d", iter);
  }
  {
    int i = 1;
    printf("now at %d", iter);
  }

  {
    int i = 0;
    {
      int j = 0;
      printf("now at %d", iter);
    }
    {
      int j = 1;
      printf("now at %d", iter);
    }
    {
      int j = 2;
      printf("now at %d", iter);
    }
  }
  {
    int i = 1;
    {
      int j = 0;
      printf("now at %d", iter);
    }
    {
      int j = 1;
      printf("now at %d", iter);
    }
    {
      int j = 2;
      printf("now at %d", iter);
    }
  }
}
```

LOLA *keyword*	PYTHON *parameter*	***Purpose***	C preprocessor *approximation*
`@Find`		Find an extended regular expression in the input stream, and trigger actions such as `@run`, `@replace`, `@delete` and `@log`.	`#define VERSION 4`
`@Description`	`"""`*Multi-line string literal*`"""`	A textual description (comment) which may span several paragraphs.	
`@Note`	`"`*Short string literal*`"`	A short, typically, one-line description.	
`@Affirm`	`(`*Expression*`)`	Issue a warning if PYTHON expression evaluates to `False`.	`#if VERSION < 4` `#warning "oh"` `#endif`
`@Assert`	`(`*Expression*`)`	Issue an error if PYTHON expression evaluates to `False`.	`#if VERSION < 4` `#error "bad"` `#endif`
`@Run`	`{`*Command(s)*`}`	A PYTHON script to execute on match.	
`@Import`	`"`*Short string literal*`"`	Insert the contents of the given filename (a file is only imported once, obviating the need for header protection).	`#ifndef STDIO_H` `#define STDIO_H` `#include <stdio.h>` `#endif`
`@Include`	`"`*Short string literal*`"`	Insert the contents of the given filename.	`#include <stdio.h>`
`@Splice`	`(`*Expression*`)`	Execute a system, shell command, and insert its output.	
`@If`	`(`*Expression*`)`	Insert replacement if expression evaluates to `True`.	`#if VERSION < 4` `...` `#endif`

Table 1.1: A sample of LOLA directives

A combination of external script and other software tools can, and are used, to, e.g., compute the Halstead metrics, or enforce the style rule (practiced mercilessly in Google) that C++ [53] classes should never inherit from more than one class. With LOLA, the same deeds are carried out in a tongue that programs already speak: the host programming language itself, albeit augmented with LOLA's syntax.

The central objective of my work was to make LOLA elegant, readable but also writable. Great effort was made to make LOLA terse yet not cryptic, and, above all, as language independent as possible. I learned the hard way that relying on existing language paradigms is not the way to go. I believe that LOLA invents its own little paradigm made of by assembling concepts such as patterns, generating expressions, lexies, etc.

Concepts such as regular expressions and language embedding are more familiar, other, such as generating expressions are less, and others, such as elaborators, “match all possible” (rather than lazy or eager) semantics of regular expressions, or fixed point semantics of search and replace are quite novel. The particular way in which LOLA puts all of these together is what makes it special.

Outline

Having seen a bit of LOLA's expressive power, we first turn to comparing it in greater detail to related work (Chapter 2). More of LOLA capabilities are demonstrated in the series of examples in Chapter 3.

Chapter 4 presents the main grammatical elements of LOLA, furthering the discussion of notions such as patterns (extended regular expressions) lexies, generative expressions, etc. This section also explains two architectural issues: how LOLA interacts with PYTHON, and how LOLA is configured to recognize the tokens of a specific host language. More details on host-language configuration can be found in Chapter 5.

Chapter 6 explains the novel modular means for the definition of LOLA's own grammar. In Chapter 7 the order in which rewritings are applied is described.

Chapter 8 concludes, discussing the current implementation, and drawing directions for future work.

Chapter 2

Related Work

2.1 Embedded Languages

Preprocessors are traditionally implemented as embedded languages. In the C preprocessor, for example, the embedded text begins with the hash character and ends with an un-escaped end-of-line character. We see implementation as an embedded languages also in other preprocessors, mentioned hereafter.

The concept of embedded languages is not limited to preprocessors. In several ways, string literals and comments in programming languages are an example of embedded languages: they begin at a designated and easy to recognized point (e.g., in the character sequence `/*` in the case of C comments); they end at a likewise distinguishable location (character sequence `*/` in the case of C comments); and, their content is governed by rules which are different than those of the host language (think, e.g., of JavaDoc comments).

But, the concept of *embedded languages* reaches far beyond comments and string literals. Perhaps the most famous example is underlying concept of PHP [35] , by which commands in a full blown programming language can be embedded in HTML [8] pages. It would not be an exaggeration to say that together with ASP [2] and JSP [5] which adopted the same idea, they revolutionized the design of Internet servers.

Lola in comparison, is not an embedded language on itself. To the contrary, it is a language that embeds in it not one but two languages: the host language it processes and Python. Snippets of the host language do not represent computation to Lola, nor can they be viewed as ordinary text. To Lola, the host language is a stream of tokens which can be manipulated by extended regular expressions.

Similarly, Python code is embedded in Lola; this code makes almost all computation that Lola does: variables, iterations, function calls etc. The only executional part of the Lola are generating expressions. By shamelessly borrowing from on Python, the design of Lola was less excruciating than what it had to be if Lola had to define the syntax of arithmetical expressions (as done in the C preprocessor), or include a full blown language features such as variables and control flow (as in AWK).

2.2 Preprocessing

The most famous text preprocessor, at least in the domain of programming languages, is arguably the C preprocessor [18], often identified by its acronym, CPP. It was introduced in the early stages of its host language, C.

According to D. M. Ritchie [46]:

> *"Many other changes occurred around 1972–3, but the most important was the introduction of the preprocessor, partly at the urging of Alan Snyder [50], but also in recognition of the utility of the file-inclusion mechanisms available in* BCPL [44] *and* PL/1 [27]. *Its original version was exceedingly simple, and provided only included files and simple string replacements:* `#include` *and* `#define` *of parameterless macros. Soon thereafter, it was extended, mostly by Mike Lesk and then by John Reiser, to incorporate macros with arguments and conditional compilation. The preprocessor was originally considered an optional adjunct to the language itself. Indeed, for some years, it was not even invoked unless the source program contained a special signal at its beginning. This attitude persisted, and explains both the incomplete integration of the syntax of the preprocessor with the rest of the language and the imprecision of its description in early reference manuals."*

(references added in above, I.E.Z).

The mentioned features, importing files (`#include`), `#define` macros and conditional compilation (`#if`, ...) are the key preprocessing abilities of the C preprocessor.

The C preprocessor is almost entirely independent of the host programming language [19], and can be used for other purposes. Therefore, it can be viewed as an independent programming language.

As a programming language, the C preprocessor is limited. It is possible to name parameters to a macro, however, the C preprocessor cannot perform iterations (loops) and no conditionals (on macro parameters). As well, C preprocessor does not allow recursive structure, i.e., one cannot call the macro in its own definition (without some "magic"[1]), and has a minimal "library" (the C preprocessor supports only `__FILE__`, `__LINE__` and very few more).

C preprocessor somewhat compensates for features of missing in C, liked named-values and module and file management. However C is not only very specific to C, but also very specialized for doing C enhancements but not other, Syntactic sugars such as operators `#` and `##` and variadic macros, are the exception, demonstrating the limitations, not the rule.

The PL/1 preprocessor has several built-in types (**`CHARACTER`** and **`FIXED`**) and directives, and is somewhat similar to the C preprocessor in several respects.

M4 [20] is a more general preprocessor, not related to any specific language. It accepts only strings and manipulates them. It allows a more complete preprocessing, by allowing recursive calls for macros, and thus enabling loops. It also adds conditionals. The M4 preprocessor manual [21] describes some preprocessors related to M4. An attempt to improve it was made, named M5 [47].

A literature search revealed many preprocessors using a general purpose programming language for creating code by redirecting the output to the source code file. A simple example is using PHP as a preprocessor, as in the following example:

[1] `http://jhnet.co.uk/articles/cpp_magic`

```
#include <stdio.h>

int main()
{
    <?php
        for($i = 0; $i < 20; $i++)
            echo 'printf("%d\n",␣'.$i.');';
    ?>
}
```

Some preprocessors use Python (e.g., Cog[2], jinja[3], django[4], PYM [54], pyexpander[5], pypreprocessor[6], Preprocessor in Python[7] and Cheetah[8]) to run and expand macros. As such, they provide powerful tools for macros. Others, such as PerlPP[9], use Perl.

The *Generic Preprocessor*[10] offers yet another approach, by which code segments marked by `#exec command`, are executed by the preprocessor and are replaced by their output.

Gema[11], also called "The general purpose macro processor", is a veteran (first public release of Gema was in 1995) open-source project which extends the notion of preprocessing in the following way: instead of firing the preprocessor only at specific, well marked locations within the code, Gema applies a *context matching* preprocessor. To define a macro one would declare a rule to match. Then a matched input in the file will be replaced with the appropriate output. E.g., defining the macro

```
ADD * TO *.=$2 \:\=~$2 +~$1\;
```

over the input

```
ADD ITEM TO SUM.
```

would yield

```
SUM := SUM + ITEM;.
```

The JPP: A Java Preprocessor [31] suggests a preprocessor for Java that modifies and analyses the code. It, as it states, beautifies the code by reformatting it. It also does code evaluation in the sense of checking conformance to standards, analysis according to complexity metrics of the code and the documentation and conformance to object-oriented design principles. It can encourage specifying contracts (preconditions, postconditions and invariants) for classes, interfaces. The preprocessor can also generate documentation in HTML format.

[2] http://nedbatchelder.com/code/cog/, Cog by Ned Batchelder.
[3] http://jinja.pocoo.org/, jinja by Armin Ronacher.
[4] https://docs.djangoproject.com/en/1.7/topics/templates/, Django Software Foundation.
[5] http://pyexpander.sourceforge.net/, pyexpander by Goetz Pfeiffer.
[6] https://code.google.com/p/pypreprocessor/, pypreprocessor by Evan Plaice.
[7] http://orbeckst.github.io/GromacsWrapper/gromacs/core/fileformats/preprocessor.html, Preprocessor in Python by Evan Plaice and Oliver Beckstein.
[8] http://www.cheetahtemplate.org/, Cheetah by Tavis Rudd.
[9] https://github.com/d-ash/perlpp, PerlPP by Andrew Shubin.
[10] https://math.berkeley.edu/~auroux/software/gpp.html, GPP—General Purpose Preprocessor by Denis Auroux.
[11] http://gema.sourceforge.net/new/index.shtml

C++ offers a template system that instantiates at compile time. This mechanism has been proved to enable Turing complete computations in compile time [55]. As a consequence of this given power, a major effort has been invested in developing more and more tools to use this feature. The main advantage of using templates for compile time programming is their availability. However, it is very complex to write such programs, and maybe even more to debug [43] them. An example of its usage is found in the Boost Meta-program Library and in extensions [49] made for it.

The importance of the ability to expand a language is derived from several issues. Suppose a programming language does not provide a syntax to initialize a list (for example `[1, 2, 3]`). Programmers might decide to use strings for initialization (e.g. `"[1, 2, 3]"`), and therefore leading to correctness, performance, security, and usability issues.

Hygienic Macro Expansion. A common problem with macros is that they might capture names that are already used in context. This issue can lead to hiding variables and referring to the wrong variable. This is the kind of mistakes hygienic macros [32] are meant to solve. Sometimes it imposes a larger problem, where ambiguities in the lexical analysis stage force the JavaScript [15] lexical analyzer and parser to be intertwined [10]. A solution for program transformations (that may cause problems when variables hide other variables with the same name) was introduced [13].

Macro Safety. Most macro systems treat arguments as strings. They do not know the host programming language, and do not type the arguments to macros—they do not consider whether the argument is an expression, an identifier, a constant or something else. The Marco preprocessor [34] wishes to add this distinction to the macro language, while not strongly coupled with the language. The users of macros are struggling with the usage of the macros (and it's error reporting). Writing a macro system for each language from scratch is hard and unnecessary. Marco introduces a way to reduce the coupling of the language to the macro system.

Preprocessors are a useful tool. There is a degenerate version (mainly including `#define` and `#ifdef`) built-in in C# [25] and similar versions for Java[12] [13], one also enables `#include`[14].

Similar preprocessors[15] [16] to the C preprocessor assembly languages [3]), further stressing its importance. More preprocessors resemble the C preprocessor, allowing to define variables and to use if statements, include files, add to the start or end of a file, generate messages and warnings and use defined strings in source[17].

2.3 Other Related Fields

Domain Specific Languages The usage of PHP above relates to another subject, Domain Specific Languages, such as PHP. The above example shows some usage of PHP as a

[12]`http://www.slashdev.ca/javapp/`, SLASHDEV by Josh Kropf.

[13]`https://code.google.com/p/pre-processor-java/`

[14]`http://eclipseme.org/docs/preprocessing.html`, EclipseME Developer Community.

[15]`http://sourceforge.net/projects/jsesoft/`, Java Macro Preprocessor by JSESoft.

[16]`http://antenna.sourceforge.net/wtkpreprocess.php`, Preprocessor by Omry Yadan.

[17]`https://github.com/raydac/java-comment-preprocessor`, Java Comment Preprocessor by Igor Maznitsa, .

preprocessor for C, but it demonstrated a larger idea. In PHP, code is generated using blocks of code written inside the surrounding HTML code (in a `<php>` tag in code):

```
<html>
Hello
<php>
    c=c+1; print c;
</php>
</html>
```

Reflection. The ability to inspect the written program through code is a very strong feature, however costly in runtime. A solution was suggested for both Java [26,40] and C# [14]. Both use a predefined syntax for code generation. A similar solution is the Lombok project[18], that uses Java's annotations syntax to create source code transformations.

Python Indentation Lola uses indentation to define blocks of code, as in Python. The idea is simple, and familiar also in other programming languages. Traditionally, a code block is started with a keyword such as `begin` and ends with a `end` (or similarly `{ }`). However, a common convention is to indent the text in the block to align. The idea is to discard the keywords and use the indentation to define a block, where a new level of indentation starts a block, until the next non-empty line of an older indentation.

Code transformation. Coccinelle [42] is a transformation engine which provides the language SmPL (Semantic Patch Language) for specifying desired matches and transformations in C code. It resembles to Lola in that it recognizes patterns in the host language source code and outputs an automated result. Coccinelle can also be used to find bugs in the code.

Aspect Oriented Programming. Aspect-Oriented Programming [30] can also be thought of a means for automatic code transformation, code is generated to be appended before and after a call (from a certain place or from all) to a function:

```
int main() {
    printf("world");
}

before(): execution(int main()) {
    printf("Hello␣");
}

after(): execution(int main()) {
    printf("␣from␣ACC␣!␣\n");
}
```

The idea is to separate code which is different in essence, but should be executed one after the other. A key example is a logger, which should execute immediately after the code that performs the logged action, but is not directly related to the log. This is also useful for debugging (to print something when a function is executed to notify the programmer).

[18] https://projectlombok.org

Language Extension. Language extensions come as a language evolves. However, there are solutions that embed language extensibility in the language definition itself. SugarJ [12] is a language extension tool that allows extending JAVA using libraries. However, a tailor made version of JAVA compiler was used in order to make SugarJ possible.

AST Transformation. Programming languages usually use a context free grammar in order to build an AST.

An example of an AST transformation tool is JAVASCRIPT. The HTML code constitute the DOM [38] tree, while JAVASCRIPT manipulates it. JAVASCRIPT is forgiving in regard to the DOM tree.

LOLA does not use an AST of the host language. Rather, it treats the code as a token stream. The reason for this decision is that AST transformation imposes a higher overhead for each lexi definition. Transforming the AST would first require building an AST. Hence, lexies would define new context free grammar rules that define the AST.

LOLA is designed to fill the gap between a simplistic preprocessor and a full code analyzer and transformation tool. LOLA promotes a simpler approach where it uses regular expressions and balanced parenthesis, that covers many cases.

Several tools enable the transformation of the AST. However, all these tools are spectacularly cumbersome, and are very sensitive to language dialects.

Examples of these include Refine [56], Ecipse's JDT[19], and C to C transformation tools.

In addition, Michael Ernst had some full issue with non-standard types for JAVA[20].

EMF Disaster. LOLA is not designed to create wide-scale changes. Such changes are hard to track and reason about. Therefore, lexies should be simple, otherwise the transformation is probably not in the right plane. A possibly solution is to limit the number of tokens that one substitution may generate. In addition, lexies should be designed in a way so that the output is readable. In this case, one may only use the resultant code, and the written could would still be usable.

Since LOLA's lexies are short, we are not likely to get another Eclipse EMF [51] disaster, where code became unusable due to abandoning the technology. EMF generates code as if there is no tomorrow, and indeed, there was no tomorrow for EMF. It is yesterday now.

??. The CILK [6] programming language adds the `spawn` and `sync` keywords to C. Removing these keywords does not influence the semantics of the program (erasure semantics).

The revolution of binary rewriting. PIN [36].

[19] `http://www.eclipse.org/jdt/apt/index.php`

[20] Some claim on the AST: look for michael's jrc java change request.

Chapter 3

Examples Gallery

Sections 1.3 and 1.5 were our crash course of LOLA. This chapter teaches LOLA some more, and presents its capabilities through a series of examples.

3.1 Introductory Examples

3.1.1 Comparison with the C Preprocessor

Listing 3.1 shows a simple use of LOLA, much in the fashion of the C preprocessor.

Listing 3.1 Making C look like PASCAL (the LOLA equivalents of "`#define`")

```
@Find Life    @replace 42                                    1
@Find program @replace void                                  2
@Find begin   @replace {                                     3
@Find end     @replace }                                     4

@Find write(@Any(parameters))                                6
@replace ((void) printf(@(parameters)))                      7
                                                             8
program main()                                               9
begin                                                        10
  printf("answer = %d!\n", Life);                            11
end                                                          12
```

We see a series of definitions of lexies, each includes **`@Find`** and **`@replace`** sections. After the first lexi was defined (in line 1 of Listing 3.1), every subsequent occurrence of the word "**`Life`**" in the text (but not in other LOLA definitions) is replaced by "**`42`**".

The C preprocessor equivalent of the five lexies in the listing is

```
#define Life    42
#define program void
#define begin   {
#define end     }

#define write(...) ((void)printf(__VA_ARGS__))
```

We thus saw some superficial, syntactical differences between LOLA and the C preprocessor: Definitions use `@Find` rather than `#define`, and an explicit `@replace` keyword is written (instead of the implicit break at a whitespace); the C preprocessor offers the variadic argument construct "`...`", which matches a sequence of zero or more parenthesis balanced expressions separated by commas, a purpose served by `@Any(...)`; etc.

A more fundamental difference is that LOLA's definitions are of tokens (rather than identifiers in the C preprocessor). With definitions such as

```
@Find { @replace BEGIN
```

one can use LOLA for the converse of Listing 3.1, that is, writing C in a PASCAL'*ish* style.

3.1.2 Halstead's Code Metrics

Tokens in LOLA are organized in a hierarchical taxonomy (see Section 5.4), e.g., tokens "`!`" and "`sizeof`" belong in class `@UnaryOperator`, which is a subclass of `@Operator`.

Figure 3.1 employs this taxonomy in three simple lexies, which together compute (one particular variant of) Halstead's metrics [24] of the code in a C file. The subject files are the C files in the current directory. These are `@Splice`d into the current file by the forth directive.

Figure 3.1 Halstead complexity measures.

```
@Find(HalsteadOperand)
  @Either @Identifier
  @or @Literal
  @or @TypeKeyword
```

(a) A pattern to detect Halstead's operands

```
@Find(HalsteadOperator)
  @Either @Operator
  @or @Punctuation
  @or @NonTypeKeyword
```

(b) A pattern to detect Halstead's operators

```
@Find @EndOfFile @run {
    operands = [str(x) for x in HalsteadOperands]
    operators = [str(x) for x in HalsteadOperators]
    from math import log
    N1 = len(operands)
    N2 = len(operators)
    n1 = len(set(operands))
    n2 = len(set(operators))
    n = n1 + n2
    N = N1 + N2
    V = N * log(n, 2)
    D = (n1/2) * (N2 / n2)
    E = D * V
  }
  @log (
    __FILENAME__, N1, N2, n1, n2, n, N, V, D, E
  )
```

(c) Print a summary of all of Halstead metrics when the end-of-file is reached

```
@ForEach(glob.glob("*.c"))
  @Splice('cat ' + _)
```

(d) Includes all C files in the current directory

The lexi named `HalsteadOperand` (Figure 3.1 **(a)**) matches all subsequent occurrences in the input of tokens in the `@Identifier`, `@Literal` and `@TypeKeyword` classes. Lexi `HalsteadOperator` (Figure 3.1 **(b)**) matches tokens in the `@Operator`, `@Punctuation`, and `@NonTypeKeyword` classes.

With the absence of a `@replace` clause (section in the Lola lingo), the two patterns do not modify the code. However, each match of the lexi named `HalsteadOperand` creates an instance of a Python object. These instances can be accessed through a list stored in a global variable, whose name is the (simple[1]) plural form of the name of the lexi, `HalsteadOperands`. Whenever a match is made, the new object is appended to the list. A similar global list exists for the `HalsteadOperator` lexi.

The third lexi (Figure 3.1 **(c)**) matches at the end of the file (`@EndOfFile`), and then it calculates Halstead's metrics (in the Python code listed in the `@run` section). Storing the text of the operators and the operands in two appropriate lists, it uses the length of the set of those variables to access the number of distinct items in those lists, as required by the metrics. The `@log` outputs the string representation of the tuple composed of the filename and the different measures to `stderr`.

After the three lexies comes the subject code. The `@ForEach` directive in Figure 3.1 **(d)** is used to iterate over the files in the current directory with `.c` extension. Then, they are `@Spliced` into the current files by invoking the `cat` utility.

3.2 Implementing New Language Constructs

A significant virtue of Lola is the freedom to create constructs which look natural in the host language. In these examples we would like to emphasis this characteristic. Each example adds a new feature to the host language, while they all blend seamlessly.

3.2.1 Switch Construct

In Chapter 1 we saw an example where it took 20 years to add the `switch` on `String`s to the Java language. Listing 3.2 implements it using Lola.

[1]the plural form of x is xs (the simple addition of the letter s) regardless of the English grammar that may rule otherwise

Listing 3.2 Augmenting JAVA with string `switch`

```
@Find
    stritch(@Identifier(switchee)) {
      @NoneOrMore
        @Sequence(block)
          @OneOrMore case @Literal(switcher):
          @Any(body)
          break;
    }
  @replace
    @ForEach(blocks)
      if (@ForEach(_.switchers)
            @(switchee).equals(@(_))
          @separator ||
          { @(_.body) }

  @anchor stritch
  @assert (len(set([str(x) for x in switchers])) == len(switchers))
```

In this example a lexi is defined to match a `stritch` construct (**str**ing sw**itch**), that is very similar to a regular `switch` is JAVA: A `stritch` keyword, followed by what we wish to switch over, and then `@NoneOrMore` `block`s, each contains several (`@OneOrMore`) `case`s, and a `body` to execute in each case, terminated by the word break.

However, we `@replace` a matched code by a series of appropriate `if` statements, serving the same purpose of a `switch` (we do not use `if else` statements). `@ForEach` of the `blocks` (the iterated value is named `_`) an `if` statement is generated, separating the cases (each is a single call to `equals`) with a `||` operator. If the JAVA condition will evaluate to `true`, the body of the case will be executed.

Notice that this lexi can be added to any version of JAVA—either before or after the addition of the `switch` on `String`s to the language. In addition, an advanced user may decide to implement this lexi so that the code would execute a more efficient algorithm at runtime.

To ensure a match whenever the `stritch` word appears, the lexi `@anchor`s it[2]. In addition, an `@assert` section is added, assuring that any string case appears only once.

Keep in mind that in LOLA we use the plural form of a variable name in order to access the list of variables with that name. Here, the `@Sequence` keyword creates a new PYTHON variable, named `block`. It captures the scope of its inner pattern into the variable. However, since it is expected to appear several times in the pattern, there might be more than one instance of this variable. A list of the instances is accessible via `blocks` (a simple addition of the letter `s` to the variable's name). Using the former means the last entry of the list.

Notice the usage of `@` followed by an expression on PYTHON. It outputs the `__str__`[3] result of the expression. This is convenient enough for the majority of cases.

[2]meaning that if the word will appear, and the pattern will not match, we will be notified

[3]the PYTHON predefined method for converting an object to a string

3.2.2 Poor Man's Inheritance in C

The C programming language is not object oriented, but a poor-man's substitute for inheritance can be manually added to the language. Listing 3.3 demonstrates how we can automatically add fields to a **struct** in C to emulate inheritance.

Listing 3.3 Poor man's inheritance in C

```
@Find(Struct) struct @Identifier(name) { @Any(fields) }

@Find(InheritanceStruct)
    struct @Optional @Identifier(name) extends @Identifier(inherited) {
      @Any(fields)
    }
  @anchor extends
  @run {
    fields = fields +
      next([x.fields] for x in Structs + InheritanceStructs
            if x.name is inherited])
  }
```

The example consists of two lexies. The first searches for any new **struct** definition. Whenever a match is found, the new instance is added to the **Structs** global list.

The second lexi adds the inherited fields to the extended **struct**. It looks for a pattern to that of the first lexi, except that it searches for the token **extends** followed by an **@Identifier**. Only then we expect the fields to be listed. In the case an extending **struct** is left unmatched, an error will be issued: The **@anchor** on the token **extends** flags an error whenever the token was found in the text, but the pattern did not match.

Recall that a list named **InheritanceStructs** is also created.

The addition of the inherited fields occurs at the **@run** section. By setting the **fields** variable we change the appropriate part of the matched text. We use the fields of the parent **struct**, while seeking for it both within the regular **struct**s and the **struct**s recorded by the second pattern.

3.2.3 Sets as Bit Masks

Sets can be represented by a bit vector, or in the case of less than 32 possible members, a single integer (assuming an integer consists of 32 bits). The integer can store for each of the possible members of the set a bit value that indicates whether is it indeed a member of the set or not. These values are stored as a bitwise or of constant values, each with a single bit on. The concept is commonly known in C as flag constants. Listing 3.4 creates a specialized **enum** for the use case.

Listing 3.4 Augmenting C with enumerated bit positions

```
@Find
    bitenum @Identifier(enum_name) {
      @NoneOrMore @Identifier(entry)
        @separator ,
        @closer @Optional ,
    }
  @assert (len(entrys) <= 32)
  @replace
    enum @(enum_name) {
      @ForEach (enumerate(entrys))
        @(_[1]) = (0x1 << @(a[0])),
  }
```

In the **`bitenum`** construct we catch **`@NoneOrMore`** entries, separated, and possibly terminated, by a comma. For each of these entries, we create an entry in an **`enum`** whose value is a bit-shift of `0x1` by the index of the entry. The lexi **`@assert`**s that no more than 32 entries are declared.

3.3 New Keywords in Java

In order to reduce code dependency and for the comfort of the programmer, several new lexies are introduced in this section. The first introduced lexies are used in those that follow.

3.3.1 Auxiliary Lexies for Java

In Listing 3.5 sets some auxiliary lexies, each defines a pattern to match a part of the Java programming language. The lexies' names describe their appropriate roles.

Listing 3.5 Auxiliary lexi for lexies for methods in Java

```
@Find(JavaType)
  @Either(type) @TypeKeyword @or @Identifier
  @Optional <@Any>
  @NoneOrMore [@Any]

@Find(JavaMethodArguments)
  @NoneOrMore @JavaType(argType) @Identifier(argName)
  @separator,

@Find(JavaMethodDecl)
  @JavaType(returnType) @Identifier(name)(@JavaMethodArguments)

@Find(JavaMethodBegin) @JavaMethodDecl {

@Find(JavaMethodWhole) @JavaMethodDecl { @Any(body) }
```

The lexies will not be explained. However, a worthwhile mention is that each named lexi (where a name is specified in `@Find`) can be referenced, and serve as a sub-pattern of the defined pattern. Moreover, this sub-pattern may be named, e.g., `@JavaType(returnType)` defines a sub-pattern named `returnType` that matches the pattern defined in `JavaType`.

Listing 3.6 uses the defined lexies to build the compile time global stack (named `java_methods`) of methods in the code. Whenever we meet a method start we record the new method, and when the method definition is complete we pop the definition from the stack.

Listing 3.6 Auxiliary stack of methods in JAVA

```
@Run {global java_methods; java_methods = []}

@Find @JavaMethodBegin @run {java_methods.append(self)}

@Find @JavaMethodWhole @run {java_methods.pop()}
```

3.3.2 Invoke an Overridden Method (`Super`)

The first lexi we see is one that makes it possible to delegate to an overridden method. The newly created `Super` keyword, defined in Listing 3.7, invokes the parent's overridden method with the arguments of the current method.

Listing 3.7 Augmenting JAVA with a `Super` keyword

```
@Find Super @run {m = java_methods[-1]}
  @replace super.@(m.name) (@(','.join(m.argNames)))
```

3.3.3 Current Method Name (`me`)

To get the name of the current method one may use the `me` lexi, defined in Listing 3.8.

Listing 3.8 Augmenting JAVA with a `me` keyword

```
@Find me
  @run {m = java_methods[-1]}
  @replace @(m.name)
```

3.3.4 Numbered Arguments

In many scripting languages one may access the arguments of a method using their index. We present a lexi (Listing 3.9) that makes it possible to use a similar concept in JAVA. Negative numbers index the arguments the same way as in PYTHON[4], and requires no special handling.

[4]access elements from the end of the list, counting backwards

Listing 3.9 Augmenting JAVA with numbered arguments

```
@Find
    @OneOrMore @Sequence(hash) #
    @Optional @Integer(i)
  @run {
    m = java_methods[-len(hashs)]
    i = i if hasattr(self, 'i') else 1
    v = ','.join(args) if i is 0 else args[i-1]
  }
  @replace @(v)
```

A sequence of one or more hash characters is matched. We optionally match a following integer. The number of hash characters indicates the method we refer to—the current method is addressed using one hash character, while the outer method is addressed using two, and so forth. If no integer was specified we have the first argument of the method. We check this condition using the `hasattr` function in PYTHON. Otherwise we access the `i`'th argument, where `i` is the specified integer, as long as `i` is not `0`. Using the integer 0 means we wish the lexi to be replaced by the entire list of arguments of the method.

3.3.5 Current Class Name (`This`)

The name of the current class can be retrieved in a similar way to the way we track methods. Listing 3.10 shows how to create a lexi that matches the identifier `This` and changes it to the current class name. The lexi uses very similar concepts to those portrayed earlier.

Listing 3.10 Augmenting JAVA with a `This` keyword

```
@Run {global class_names; class_names = []}

@Find class @Identifier (className)
  @run {class_names.append(className)}

@Find
    class @Identifier (className)
      @Optional @ExtendsPattern
      @Optional @ImplementsPattern
    { @Any }
  @run { class_names.pop() }

@Find This @replace @(class_names[-1])
```

3.4 Miscellaneous Examples

We end our tour in the gallery with two examples, where the purpose of the first is debugging, and the second handles a very repetitive source code.

3.4.1 Monitor an Expression (`monitor`)

Listing 3.11 demonstrates a method to create a `monitor` function—the preprocessor passes an expression's describing a string and its value. A function, defined in the beginning of the file, is passed both these parameters, prints the former followed by the latter, and returns the latter. It creates the effect of logging the expression and its value.

Listing 3.11 Augmenting JAVA with a `monitor` method

```
template<typename T>
static auto &__monitor__(const char * x, T && y) {
  std::cout << x << y << std::endl;
  return y;
}

@Find monitor(@Any(arg))
  @replace
    __monitor__(@('"' +
                  arg.replace('\\', '\\\\').replace('"', '\"') +
                  '"')
)
```

Notice that the lexi escapes certain characters in order to create the appropriate C++ string literal.

3.4.2 Avoid Repetitive Code

In Listing 3.12 we create lexies. These lexies are used in Listing 3.13 to immensely shorten the repetitive code of a class that boxes JAVA's value types into reference types[5].

[5]https://bitbucket.org/yossi_gil/services/src/c8bb342e5ea89c91931e078a7a8a6bf7f7be7112/trunk/src/il/ac/technion/cs/ssdl/utils/Box.java?at=master fileviewer=file-view-default

Listing 3.12 Box it lexi for boxing JAVA's value types into reference types

```
@Find
    BOX_IT @Identifier(boxType) @Optional to  @Identifier(boxToType);
@run {
  if not hasattr(self, 'boxToType'):
    boxToType = boxType.title()
}
@run {
  v = str(boxType)[0]
  vs = v + 's'
  comment = \
    ("""
      /**
       * Box a <code><b>{0}</b></code> into a {{@link {1}}}
       * object.
       *
       * @param {2} some <code><b>{0}</b></code> value
       * @return a non-<code><b>null</b></code> {{@link {1}}}
       * with the value of <code>val</code>
       */""").format(boxType, boxToType, v)
  commentArr = \
    ("""
      /**
       * Box an array of <code><b>{0}</b></code>s into an array
       * of {{@link {1}}}s.
       *
       * @param {2} an array of <code><b>{0}</b></code>s
       * @return an array of {{@link {1}}} of the same length
       * as that of the parameter, and such that it in its
       * <tt>i</tt><em>th</em> position is the boxed value of
       * the <tt>i</tt><em>th</em> of the parameter
       */""").format(boxType, boxToType, vs)
}
@replace
  @(comment)
  public static @(boxToType) it(final @(boxType) @(v)) {
    return cantBeNull(@(boxToType).valueOf(@(v)));
  }

  @(commentArr)
  public static @(boxToType)[] it(final @(boxType) @(vs)[]) {
    final @(boxToType)[] $ = new @(boxToType)[@(vs).length];
    for (int i = 0; i < $.length; ++i)
      $[i] = it(@(vs)[i]);
    return $;
  }
```

Listing 3.13 A use of the BOX_IT lexi introduced in Listing 3.12

```
public enum Box {
  BOX_IT boolean;
  BOX_IT byte;
  BOX_IT char to Character;
  BOX_IT double;
  BOX_IT float;
  BOX_IT int to Integer;
  BOX_IT long;
  BOX_IT short;
}
```

The lexi matches a BOX_IT statement which is followed by the type to box[6], and an optionally supplied type to box to. If the boxToType is not specified, the code just titles the boxType. The code for the comments is generated solely using PYTHON.

3.5 Rewriting

Recall the example in Listing 1.7. Another course of action to achieve the same effect of a range based loop is by using the code in Listing 3.14.

Listing 3.14 Using @run for defining a loop based on range syntax.

```

#include <stdio.h>

@Find
    for @Identifier(i) in @Literal(start) .. @Literal(end)
  @run {
    self = 'for (int ' + str(i) + ' = ' + str(start) + '; ' \
      + str(i) + ' < ' + str(end) + '; ' + str(i) + '++)'
  }


int main() {
  for iter in 0..2 {
    printf("now at %d", iter);
  }
}
```

A local variable named self is initialized to the match's reifying object. At the end of the execution of all of the code that is associated with a match, the contents of this variable are written to the output file, replacing the text that was matched. If self, or any of its attributes, indeed was changed, than the replacement changes the text (otherwise, if no changes were made to self, then nothing will change in the output file).

[6]for the sake of this example we assume value types names are defined as identifier tokens.

In the example, the code sets the string that was matched by the pattern to a new string, and therefore a replacement of the code occurs.

3.6 Reflection

Listing 3.15 defines a lexi that matches an **enum**[7].

Listing 3.15 Assertion using meta-programming

```
@Find(EnumPattern)
  enum @Identifier(name) {
    @NoneOrMore @Identifier(item) @Optional = @Literal(value)
    @separator ,
    @closer @Optional ,
  }
```

Listing 3.16 is triggered upon encounter of a C preprocessor-macro-call like pattern named **CREATE_DICTIONARY**, receiving two parameters. The first parameter is the name of an **enum**, and the second is an identifier that will hold a resultant array.

The lexi generates a C array that will hold information on each of an **enum**'s entries. Each element of the array stores the name and the numerical value of an entry of the **enum**. Code can then iterate over the array, create "**to_string**" and "**from_string**" functions, and more.

The example builds upon Listing 3.15 in assuming there is a list that describes the declared enumerations. Indeed, each match of the previous lexi adds an instance to the list named **EnumPatterns**.

The **@ForEach** keyword accepts a PYTHON expression to iterate on. The loop variable is named **_**, and we use the expression evaluation keyword (**@(E)**).

[7] note that the lexi is not fully comprehensive, since it assumes the values are only literals

Listing 3.16 A lexi that uses reflection

```
@Find CREATE_DICTIONARY(@Identifier(dictionaryName), @Identifier(enumName));
@note "Create a dictionary that describes the given enum."
@replace
  struct {
    char *name;
    int value;
  } @(dictionaryName) = {
    @ForEach (next(x for x in EnumPatterns
                   if x.name == enumName).items)
      { @ ('"' + str(_) + '"') , @(_) },
  };
@example
  CREATE_DICTIONARY(myenumDict, myenum);
@resultsIn
  struct {
    char *name;
    int value;
  } myenumDict = {
    { "SUNDAY" , SUNDAY },
    { "MONDAY" , MONDAY },
  };
```

3.7 Island Grammars and typedef

Island grammars [41] focus on the parts of the programming language that are of interest to the current task, rather than describing the entire programming language syntax tree.

In Java, one can use the same name for a class and for a function or variable. However, it is possible, in most cases, to deduce the role of an identifier by other criteria. This makes it possible to identify with island grammars all cases of a names used as a name of a type. We can create Lola lexies to identify these, as in Listing 3.17.

Listing 3.17 A lexi that simulates `typedef` in Java

```
@Find
     @Either @ClassPattern
     @or @JavaType @Identifier =
     @or @JavaType @Identifier ;
     @or new @JavaType
     @or @JavaMethodDecl
  @run {
    types = [typedefed[t] if t in typedefed else t
                                   for t in types]
  }
```

The lexi in the figure is not complete; it fails to identify occurrences of the aliased type in dot separated names, e.g., `il.ac.technion.cs.Lola.go`, and in type parameters of generics, e.g., `List<T super Lola>` or even in `Cell<Lola>`.

The latter failure can be remedied with a bit of definitional effort. However, with Lola unable to do full type analysis, it is impossible to automatically distinguish type-name components in dotted names from other kinds of components such as package- and field- names. This predicament however may be ameliorated by assuming capitalization conventions.

3.8 Before Function

Aspect oriented programming enables inserting code before another function, where the former is written in another function. Listing 3.18 demonstrates a simplified similar effect using Lola.

Listing 3.18 A lexi that simulates aspect oriented programming

```
@Find(FunctionPattern)
    @Identifier(retValue)
    @Identifier(functionName) ( @Any ) {
      @Empty(beforeFunctionBody)
      @Any
    }
  @run {
    beforeFunctionBody = 'printf("got here!\n");'
  }
```

3.8.1 Adding an Anchor

Listing 3.19 demonstrates Lola's expressiveness by matching the structure of a class declaration in Java. However, it also demonstrates the difficulty in writing patterns. The **`@anchor`** keyword assumes all occurrences of the provided word are captured by the pattern. This is useful to avoid unnoticed errors. For example, there is an "error" in the pattern (well, at least one). The keyword **`public`** does not have to appear before the **`final`** keyword. However, if these keywords are only used in the source code under this convention, the lexi is suitable. Moreover, if we do not follow this convention, an error is issued. This allows us to write patterns for the host programming language even if we do not know it in its entirety.

Listing 3.19 JAVA class pattern

```
@Find(ExtendsPattern) extends @JavaType
@Find(ImplementsPattern)
  implements @OneOrMore @JavaType @separator,

@Find(ClassPattern)
  @Optional static
  @Optional @Either public @or private @or protected
  @Optional @Either final @or abstract
  class @Identifier(className)
    @Optional @ExtendsPattern
    @Optional @ImplementsPattern
    {
      @Any
    }
@anchor class
```

3.8.2 Adding an Example

Writing unit tests is a useful tool for the pattern writer to make some "sanity checks" to check the correctness of the pattern. The code accepted by the `@Example` message is tested to match the specified pattern. If the test fails, LOLA issues a warning.

In Listing 3.20 the test fails since there is no definition of the integer `i` in the example, but just usage of the variable. We can also add a `@resultsIn` section, where we can specify the output of the example (in Listing 3.20, since we did not change the text, the output should be the same as the input).

Listing 3.20 An example of the usage of the `@example` (the test fails)

```
@Find for (int @Identifier(i) = @Literal(start);
           @Identifier(i) < @Literal(end);
           @Identifier(i) ++)
@example for (i = 0; i < 10; i++)
@resultsIn for (i = 0; i < 10; i++)
```

3.9 P4 Checksum

P4 [7] is a domain specific language for programming network data forwarding. In being such, it allows specifying headers for packets, and their checksummed fields.

Listings 3.21 and 3.22 portrays a lexi for a checksummed field in an IPv4 header[8]. The required outcome can be seen in the `@resultsIn` section in Listing 3.22. Observe how repetitive the code is. Compare to the code in the `@example` section in the same listing. The suggested code is both readable and concise. It draws inspiration from the concept of attributes in other programming languages. However, it is merely a lexi that was added without any P4 language extension.

[8]https://github.com/p4lang/tutorials/blob/master/p4v1_1/simple_router/p4src/simple_router.p4

The main sections of the definition of the lexi are given in Listing 3.21. As necessary, a programmer may add more options to customize the lexi to support other “attributes”.

Listing 3.21 An example of a lexi for creating a checksummed field in P4 (continued in Listing 3.22)

```
@Find header_type @Identifier(header_type) {
    fields {
    @OneOrMore
      @Sequence(field)
        @Optional
          [checksum(algorithm=@Identifier(algorithm))]
        @Sequence(native_field)
          bit<@Literal(nbits)> @Identifier(name);
    }
  } instantiate into @Identifier(instance_name);
@anchor instantiate
@run {checksumed = [f for f in fields if hasattr(f, 'algorithm')]}
@assert (len(checksumed) is 1)
@run {checksumed = next(checksumed)}
@replace
  header_type @Identifier(header_type) {
    fields {
      @ForEach (native_fields)
        @(_)
    }
  }
  header @(header_type) @(instance_name);
  field_list @(instance_name)_checksum_list {
    @ForEach (
      [f.name for f in fields if not hasattr(f, 'algorithm')]
    ) @(header_type).@(_);
  }
  field_list_calculation @(instance_name)_checksum {
    input {
        @(instance_name)_checksum_list;
    }
    algorithm : @(algorithm);
    output_width : @(checksumed.nbits);
  }
  calculated_field @(instance_name).@(checksumed.name)  {
    verify @(instance_name)_checksum;
    update @(instance_name)_checksum;
  }
...
```

Listing 3.22 The **@example** and **@resultsIn** sections of Listing 3.21

```
...
@example
  header_type ipv4_t {
    fields {
      bit<4> version;           bit<4> ihl;
      bit<8> diffserv;          bit<16> totalLen;
      bit<16> identification;   bit<3> flags;
      bit<13> fragOffset;       bit<8> ttl;
      bit<8> protocol;
      [checksum(algorithm=csum16)] bit<16> hdrChecksum;
      bit<32> srcAddr;          bit<32> dstAddr;
    }
  } instantiate into ipv4;
@resultsIn
  header_type ipv4_t {
    fields {
      bit<4> version;           bit<4> ihl;
      bit<8> diffserv;          bit<16> totalLen;
      bit<16> identification;   bit<3> flags;
      bit<13> fragOffset;       bit<8> ttl;
      bit<8> protocol;          bit<16> hdrChecksum;
      bit<32> srcAddr;          bit<32> dstAddr;
    }
  }
  header ipv4_t ipv4;
  field_list ipv4_checksum_list {
    ipv4.version;             ipv4.ihl;
    ipv4.diffserv;            ipv4.totalLen;
    ipv4.identification;      ipv4.flags;
    ipv4.fragOffset;          ipv4.ttl;
    ipv4.protocol;            ipv4.srcAddr;
    ipv4.dstAddr;
  }
  field_list_calculation ipv4_checksum {
    input { ipv4_checksum_list; }
    algorithm : csum16;       output_width : 16;
  }
  calculated_field ipv4.hdrChecksum  {
    verify ipv4_checksum;     update ipv4_checksum;
  }
```

3.9.1 Calling Convention

C compilers define compiler specific ways of declaring the calling convention used for invoking a function. To create a cross-compiler solution for using the fast call convention, suitable for both the `gcc` and `cl` (Visual C/C++) compilers, one can use the C preprocessor in the following manner[9]:

Listing 3.23 A C preprocessor macro definition and usage for a cross-compiler **`fastcall`** calling convention

```
#if defined(__GNUC__)
#   define MSFASTCALL __fastcall
#   define GCCFASTCALL
#elif defined(_MSC_VER)
#   define MSFASTCALL
#   define GCCFASTCALL __attribute__((fastcall))
#endif

int MSFASTCALL magic() GCCFASTCALL;
```

Lola presents a more concise solution:

Listing 3.24 Lola's Listing 3.23 equivalent for a lexi definition and usage for a cross-compiler **`fastcall`** calling convention

```
@Find
  @Sequence(before) fastcall
  @Identifier (@Any)
  @Empty(after)
@anchor fastcall
@run {
  if _MSC_VER: before, after = '__fastcall', ''
  if __GNUC__: before, after = '', '__attribute__((fastcall))'
}

int fastcall magic();
```

[9] http://stackoverflow.com/a/10253546

Chapter 4

Lola Concepts and Elements

Lola execution model is that of a filter [45] (see also [17, Sect. 3.1]) converting an input stream into an output stream. In Lola, the input stream is comprised of tokens of the host language (*host-tokens*), Python code *snippets* and Lola *keywords*. Just like the C preprocessor, the output stream is obtained from the input by applying "directives" found in the input on subsequent input.

A Lola keyword is an identifier prefixed by the "`@`" escape character. The escape character on its own is also a keyword.

All Python snippets must immediately follow a keyword, and must be appropriately *bracketed*. The semantics of the snippet (expression, literal, commands, etc.) is determined by the way it is bracketed (parenthesis, quotes, curly braces).

4.1 The Host Language Configuration File

Certain Lola keywords, such as `@Find` and `@replace` are (as in Listing 1.5) reserved; other keywords can be defined by the user, just as `@Expression` was defined in Listing 1.4.

In addition, there is a language-dependent set of *predefined* keywords, denoting *lexical tokens* and *classes* of lexical tokens. The pre-definition are made in an XML configuration file. This file also defines the *trivia* of the host language, its *comments* (currently viewed as trivia by Lola), special tokens, such as parenthesis, which must be *balanced*, and *literal* tokens (e.g., integers, strings, etc.) whose value is computed as part of the lexical analysis.

Figure 4.1 is a screen-shot taken the GUI for authoring files.

4.2 Directives

Host-tokens are normally passed on as is to the output stream. In contrast, keywords make *directives* out of subsequent keywords, tokens and snippets. Directives are parsed and executed as necessary by Lola. There are two kinds of these:

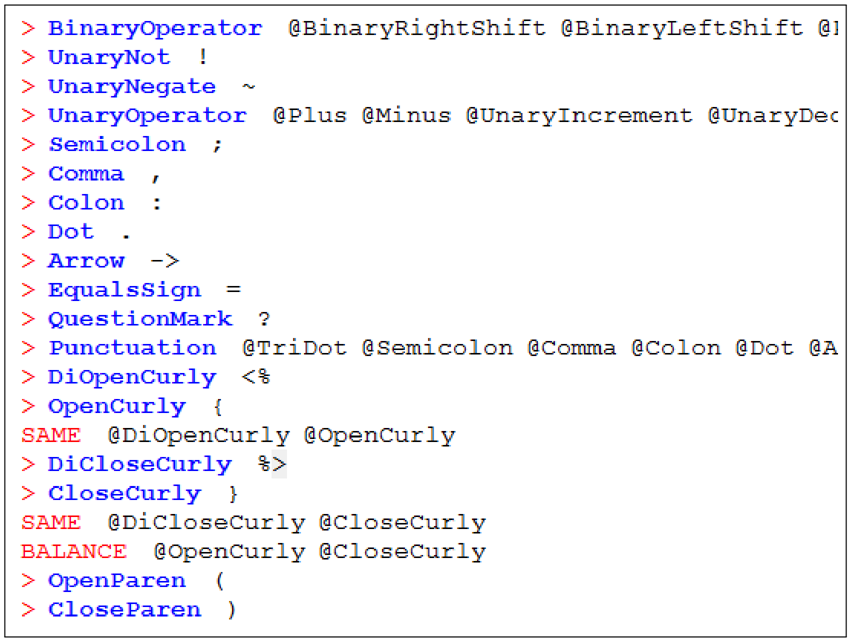
Generators A generator is a Lola generating expression (henceforth, *GE*) whose evaluation returns a sequence of host-tokens, to be placed in the output stream.

Lexies Lexies are a bunch of structured modules that describe augmentations to the host language.

	LOLA *keyword*	PYTHON *parameter*	*Elaborators*	*Purpose*	C preprocessor *approximation*
	host-tokens				
Atomic	`@`	`(`*Expression*`)`		Insert the `__str__` result of the evaluated expression.	
	`@`	`{`*Command(s)*`}`		Execute the PYTHON code.	
	`@Import`	"*Short string literal*"		Insert the contents of the given filename (a file is only imported once, obviating the need for header protection).	`#ifndef STDIO_H` `#define STDIO_H` `#include <stdio.h>` `#endif`
	`@Include`	"*Short string literal*"		Insert the contents of the given filename.	`#include <stdio.h>`
	`@Splice`	`(`*Expression*`)`		Execute a system, shell command, and insert its output.	
	`@Nothing`			Generates nothing for use as a place holder.	
Constructors	`@If`	`(`*Expression*`)`	`@else`, `@elseIf`	Insert replacement if expression evaluates to `True`.	`#if VERSION < 4` `...` `#endif`
	`@Unless`	`(`*Expression*`)`		Insert replacement if expression evaluates to `False`	`#ifndef FOO` `...` `#endif`
	`@Case`	`(`*Expression*`)`	`@of`, `@otherwise`	Switch over the evaluated expression.	
	`@ForEach`	`(`*Generating expression*`)`	`@ifNone`, `@separator`	Insert replacement for each entry in the iterable.	

Table 4.1: The recursive structure of LOLA generators

Figure 4.1 A screen-shot of an editing session of a LOLA configuration file for C



```
> BinaryOperator  @BinaryRightShift @BinaryLeftShift @
> UnaryNot  !
> UnaryNegate  ~
> UnaryOperator  @Plus @Minus @UnaryIncrement @UnaryDec
> Semicolon  ;
> Comma  ,
> Colon  :
> Dot  .
> Arrow  ->
> EqualsSign  =
> QuestionMark  ?
> Punctuation  @TriDot @Semicolon @Comma @Colon @Dot @A
> DiOpenCurly  <%
> OpenCurly  {
SAME  @DiOpenCurly @OpenCurly
> DiCloseCurly  %>
> CloseCurly  }
SAME  @DiCloseCurly @CloseCurly
BALANCE  @OpenCurly @CloseCurly
> OpenParen  (
> CloseParen  )
```

A lexi is composed of *sections*. The most important section is **@find**, which defines an *extended regular expression* (*RE* for short) to be searched in the input stream. This term and the term pattern will be used interchangeably.

Other more useful sections are **@replace**, **@log**, and **@run**. Lexies may also include declarative sections such as **@description** and **@see**.

When a generator directive (such as **@Include**) is encountered, LOLA pauses the habit of copying host tokens from the input stream to the output stream, injects into the output the sequence of tokens made by the generating expression, and then resumes its copying habit.

A lexi with no **@find** section matches exactly once, immediately after it is parsed. Otherwise, a lexi directive in the input is saved for later execution.

LOLA tries to match the *RE* provided in the **@find** section of the lexi against subsequent host tokens in the input stream. When a match is found, the lexi triggers and may invoke actions such as insertion of more tokens, deletion of others, record information for further processing, or, more generally, execute arbitrary PYTHON code.

4.3 Compound Objects

*GE*s and *RE*s are compound objects in the LOLA language, made by the application of *constructors* to *atomic* elements and to results of prior constructors.

Atomic elements. Atomic elements of both *GE*s and *RE*s come in three varieties: *(i)* a sequence of one or more tokens of the host language, *(ii)* keywords of LOLA taking an *optional* PYTHON argument, and, *(iii)* keywords of LOLA taking a *mandatory* PYTHON argument.

Examples of token sequences are "**{**" (encountered above in Listing 3.1),

```
= (0x1 <<
```

(ditto, Listing 3.4) and "`super`" (Listing 3.7).

Examples of keywords with optional parameter are `@Any`, `@EndOfLine`, and `@Identifier`. The atomic *RE* `@Any`, can be written as

```
@Any
```

meaning a sequence of any length of host tokens, or as

```
@Any(foo)
```

with the same meaning, except that the result of the match is stored in a field named "`foo`" in the reifying object (more on the subject later).

Examples of keywords taking a mandatory argument are `@run` (encountered above in Listing 3.6) and `@assert` (Listing 3.4).

An optional argument must be an identifier wrapped in parenthesis.[1] However, there are several kinds of PYTHON arguments to keywords which take a mandatory argument:

- a *sequence of* PYTHON *commands*, to be executed, as in the case of `@run`,
- a PYTHON *expression* to be evaluated as in the case of `@assert`,
- a *short* PYTHON *string literal*, used in conjunction with the LOLA keyword introducing short comments

  ```
  @Note "Lexi matches also nested and inner class"
  ```

  and in file inclusions directives

  ```
  @Import "augmented-Java.lol"
    @Include "boilerplate.lol"
  ```

- a *multi-line string literals of* PYTHON (for long comments), used in conjunction with the `@Description` LOLA keyword

  ```
  @Description """ Lorem ipsum dolor sit amet,
      consectetur adipiscing elit. Etiam interdum,
      tellus in maximus tristique, sapien mauris
      accumsan odio, quis rhoncus velit eu eros. """
  ```

- PYTHON *iterable*, used in `@ForEach`, as in

  ```
  @ForEach (range(1,3)) x,
  ```

  or as in Listing 3.2 above.

[1]for technical reason, it is required that no spaces occur before the opening parenthesis.

Constructors. Constructors make compound objects out of atoms and other, smaller, compound objects. The compound objects are either *RE*s or *GE*s.

A constructor is identifier by a capitalized *keyword* such as `@Optional`, `@OneOrMore` and `@If`. A constructor takes up to three arguments, which must occur in this order

- a PYTHON *snippet*
- a LOLA *argument* which is a (possibly empty) list of host tokens and smaller compound objects,
- a (possibly empty) list of *elaborators*, such as `@else` and `@elseIf` (for `@If`), `@separator` (for `@OneOrMore`), etc.

For example, the *GE* in Listing 4.1, is made by applying constructor `@If` to arguments:

- PYTHON snippet: `os == "DOS"`
- list of host-tokens and other atoms
  ```
  #error AD @(date.today().year) DOS no longer supported
  ```
- elaborators `@elseIf` and `@else`

Listing 4.1 Using LOLA to produce C preprocessor code

```
@If(os == "DOS")
    #error AD @(date.today().year): DOS no longer supported
  @elseIf(os == "WIN31")
    #warning Windows 3.1 will be phased out soon
  @else
    #
```

Elaborators. As can be seen in Listing 4.1, elaborators are similar to constructors in that an elaborator is made by a keyword, sometimes followed by a PYTHON snippet, and then by a possibly empty list of atoms and compound objects.

However, elaborators usually take no elaborator arguments, and an elaborator never makes, on it own, a complete *RE* or *GE*.

By convention, names of elaborators are "`@camelCase`"; all other keywords follow the "`@CamelCase`" convention.

Different constructors take different elaborators, and may place different constraints on their order. For example, `@If` requires that the elaborators it takes follow the pattern

$$f_1 \cdots f_n \, [\, e\,].$$

where $n \geq 0$, and where each f_i, $i = 1, \ldots, n$, is an `@elseIf` elaborator (taking a mandatory parenthesized PYTHON expression and a possibly empty list of host-tokens and other *GE*s) and e is an `@else` elaborator (taking no PYTHON snippet argument; taking a possibly empty list of host-tokens and *GE*s).

No elaborators and no LOLA argument are taken by *RE*s atoms, such as `@Any` and `@NewLine`. These can be thought of as degenerate constructors.

Similarly, keywords like `@` (in the second line of Table 4.1), which is an atomic *GE*, can be thought of as constructors that take no LOLA arguments and no-elaborators.

4.4 Generating Expressions

The recursive structure of *GE*s is specified completely by Table 4.1.

Other than host tokens, atoms of *GE*s include `@` constructs, which either splice the string value of a PYTHON expression (parenthesized form), or the standard output of several PYTHON commands (curly braces form).

The `@Nothing` constructor is included mainly for completeness; it produces no tokens.

Three other atoms of *GE*s are `@Include` (similar to `#include` of the C preprocessor), `@Import` (same as `#include`, but with builtin protection against multiple inclusions), and `@Splice`, which inserts the output of a system command into the output stream.

There are four constructors of *GE*s. Three of these are variations on the archetypal conditional commands: *(i)* constructor `@If` taking any number of `@elseIf` elaborators followed by an optional `@else`; *(ii)* constructor `@Unless`, the inverse of `@If`, which takes no elaborators; and, *(iii)* constructor `@Case`, which takes no LOLA argument, but requires one or more `@of` elaborators followed by an optional `@otherwise` elaborator.

The semantics should be obvious: `@If` takes a PYTHON expression as argument, evaluates it, and if the result is `True`, it generates its “LOLA argument” (which in the context of *GE*s means a list of smaller *GE*s). Similarly, the “LOLA argument” to `@Unless` is generated only if the PYTHON expression argument to the `@Unless` evaluates to `False`.

Constructor `@Case` realizes a multi-way conditional comparing, in order, its PYTHON expression argument with the PYTHON expression argument of each of its `@of`s.

The fourth constructor of *GE*s is `@ForEach`, taking *a* PYTHON *iterable* as argument, and a “LOLA argument”. The “LOLA argument” is regenerated for each value that the PYTHON iterable `yield`s.

This constructor takes also an optional `@separator` elaborator, specifying the *GE* to be used for separating items in the generated list, *and*, an `@ifNone` elaborator, specifying the output in the case that the list of the values `yield`ed by the PYTHON expression is empty.

4.5 Extended Regular Expressions

Table 4.2 specifies the recursive structure of the *RE*s of LOLA. It should be added to what that is said in the table that *all* constructors, just as all atomic *RE*s (but not elaborators), take an optional PYTHON name, wrapped in parenthesis.

When an *RE* matches, LOLA creates a PYTHON object that reifies the match, henceforth named F. This F contains all information about the location in the input in which the match occurred, and makes this information available to `@run` and other sections of the containing lexi.

In particular, if a certain constructor uses a name, then LOLA creates a variable carrying that name in F, which will contain the matched input (or throws an `AttributeError` if the triggering match did not make use of the constructor).

Let us describe F's attributes:

`self` A reference that points to the F instance. Setting this attribute directly will replace the matched text (and will not change the self reference).

`id` Each variable that is defined using the various sub-pattern definition keywords imposes another attribute, by which one may access the sub-pattern.

`__iter__` The instance is iterable (i.e., it implements the `__iter__` method). Each entry of the iterator is another token, or a sub-match, that groups more tokens. The iteration contains entries for trivia (explained shortly), but the function has a default filter argument that filters these tokens. Therefore, in order to filter some of the tokens from the iteration, provide the optional filter overload.

`__str__` The `__str__` function of the object instance returns the text that was matched. The Therefore, the text is accessible both in plain text mode and in parsed form.

`__name__` Stores the name given to this match (in the case it is a sub-pattern of a match).

`__type__` Use the `__type__` attribute to access the type according to which the match was made, i.e., the name of the pattern as provided in `@Find` or the token name or classification name as specified in the configuration file. Another two options are `"Any"` if it was captured using `@Any`, or similarly `"Empty"` if it was captured using `@Empty`.

`__pyobj__` One can access the PYTHON representation object for the match using the result of the `__pyobj__` function, in the cases of tokens that were defined with a `<convert>` element. This can also serve as a convenient convention for patterns (i.e., one can define this method to provide a relevant PYTHON object).

`__FILENAME__`, `__LINE__` and `__COLUMN__` Access the name of the file, line and column of the first character of the matched text, respectively.

An F can be referenced in two ways. The first is to access the variable named `self` from within `@run` or a similar keyword. In addition, each time an F is instantiated (i.e., each time the pattern is matched), it is appended to a list of instantiations, named after the name of the lexi, and defined as a variable in the global symbols table[2].

Atomic *RE*s. In the top block of the table we see the atomic *RE*s. Any atom of the host language is an atomic *RE*, matching only itself. The second line in the table tells us that `@SomeIdentifier` invokes the *RE* previously defined in a configuration file, or by the programmer, as in

```
@Find(SomeIdentifier) ···
```

A sequence of atoms is an *RE* that matches the same sequence of tokens in the input. It matches a span of tokens (defining a range); atomic *RE* `@Empty` matches the empty span, while `@Any` matches a span of any length[3].

When examined closely, the stream of input tokens, appears as an interleaved list of tokens and "trivia"[4] which are the thing that separates successive tokens. Trivia are typically the space or new line characters, comments, spans of these, and even the empty string. There is also a trivia at the beginning and at the end of the stream.

Normally, a trivia in an *RE* matches a trivia in the input. The LOLA programmer need not worry about these. The four remaining atomic *RE*s make an exception to this rule:

[2] https://docs.python.org/2/library/functions.html globals

[3] a pattern to match precisely one don't-care-token never came useful in earned experience

[4] see, e.g., in the implementation of the C$^{\#}$ compiler, Roslyn https://github.com/dotnet/roslyn/wiki/Roslyn 20Overview syntax-trivia

		LOLA ***keyword***	***Elaborators***
Atomic		*h o s t - t o k e n s*	
		@*SomeIdentifier*	
		@Empty	
		@Any	**@without**
		@EndOfFile	
		@NewLine	
		@BeginningOfLine	
		@EndOfLine	
Constructors	*traditional*	**@Sequence**	**@followedBy**
		@Optional	
		@OneOrMore	**@separator**, **@opener**, **@closer**
		@NoneOrMore	**@separator**, **@opener**, **@closer**, **@ifNone**
		@Either	**@or**
	power	**@Xither**	**@xor**
		@Neither	**@nor**
		@Match	**@andAlso**, **@exceptFor**
		@SubsetOf	
		@NonEmptySubsetOf	**@and**
		@ProperSubsetOf	**@and**
		@PermutationOf	**@with**
		@Not	
	modifying	**@SameLine**	
		@Unbalanced	

Table 4.2: The recursive structure of LOLA's extended regular expressions

@EndOfFile matches the last trivia in the input stream. **@NewLine** matches the new line marker (typically `\n` or `\r\n`) in the trivia it occurs in. Keyword **@BeginningOfLine** matches this empty sized interval in a trivia which occurs right at the beginning of a file or after a new line marker, and **@EndOfLine** matches this empty sized interval in a trivia which occurs right before end-of-line or end-of-file.

Traditional Constructors. The lower block of the table lists the constructors of *RE*s. The first group of these, the traditional constructors includes the essence of the repertoire of all *RE* languages. Note that the **@Sequence** constructor is present mostly for the sake of completeness. The verbose writing

```
@Sequence hello @followedBy world
```

may be preferable at times, but it is identical to

```
hello world
```

and to

```
@Sequence hello world
```

for that matter.

LOLA's variants to the Kleene closure operator include an optional `@separator` elaborator, specifying the *RE* that separates the items in the repetition, and optional `@opener` and `@closer` variants, specifying what should occur before and after a non-empty list.

There is also an elaborator `@ifNone` to the `@NoneOrMore` constructor. With these elaborators, the complete specification of the label section of a PASCAL program[5] (see also [58, p.32]) can be written as compactly as:

```
@Find(Label) @Identifier

@Find(LabelDeclarationPart)
  @NoneOrMore @Label
  @opener @Label,
  @separator,
  @closer ;
  @ifNone @Empty
```

RE disjunction uses `@Either`, the last among traditional constructors. Here is an example of how it might be used,

```
@Find(LabelDeclarationPart)
  @Either @Empty
  @or
    @Label
    @OneOrMore @Label
    @separator,
    ;
```

Power Constructors. LOLA uses a regular expression analysis engine that can deal with negation. Relying on negation, power constructor `@Neither` makes it possible to use phrases such as

```
@Neither (@nor) @nor { @nor }
```

while with the `@Xither`, the exclusive disjunction constructor, the template of use is `@Xither`… `@xor`… `@xor`… · · · .

Conjunction is made possible by the `@Match` constructor and its `@andAlso` and `@exceptFor` elaborators. The semantics of *RE*

```
@Match @Identifier @andAlso @UPPER_CASE @exceptFor @CamelCase
```

[5]http://www.fit.vutbr.cz/study/courses/APR/public/ebnf.html label-declaration-part

	LOLA *keyword*	PYTHON *parameter*	***Multiple occurrences***	LOLA *parameter*	***Purpose***
Declarative Header	`@find`			*RE*	Find an extended regular expression in the input stream, and trigger actions such as `@run`, `@replace`, `@delete` and `@log`.
	`@description`	`"""`***Multi-line string literal***`"""`	✓		A textual description (comment) which may span several paragraphs.
	`@note`	`"`***Short string literal***`"`			A short, typically, one-line description.
Action	`@run`	`{`***Command(s)***`}`	✓		A PYTHON script to execute on match.
	`@replace`			*GE*	Alter the matched text.
	`@delete`			*RE*	Delete the matched text.
	`@append`		✓	*GE*	Add after the matched text[a]
	`@prepend`		✓	*GE*	Add before the matched text [b] always appending to to prior output.
	`@filter`	`"`***Short string literal***`"`	✓		Filter the matched text through a system shell, just before printing it[c].
	`@anchor`		✓	*RE*	Produce an error if the pattern is matched where the defined pattern is not.
Declarative Footer	`@example`[d]		✓	*RE*	State that the pattern matches the code.
	`@log`	`(`***Expression***`)`	✓		Evaluate the expression and print the result to standard error stream.
	`@see`	***Identifier***	✓		Refer to the specified pattern..

[a] `@append`s accumulate: a second `@append` adds its arguments *after* the first `@append`
[b] `@prepend`s accumulate: a second `@prepend` places its argument *before the first* `@prepend`
[c] multiple `@filter` directives accumulate in the order they are written
[d] Has the elaborator `@resultsIn`.

Table 4.3: Sections in a LOLA pattern definition

is precisely what it reads to be. (Keywords `@Identifier`, `@UPPER_CASE`, and `@CamelCase` are defined in the language configuration file.)

Constructors `@SubsetOf`, `@NonEmptySubsetOf`, are syntactic sugar to be used at occasions when plain regular expressions become clumsy, such as the complex rules of specifications of modifiers in JAVA. Figure 4.2 demonstrates.

Figure 4.2 An extended regular expression, specifying that "`#find`", "`#replace`", and "`#delete`" may occur at any order, but at most once, and that "`#replace`" and "`#delete`" cannot both occur[a]

```
@Find(atMostOnceSections}
  @SubsetOf
    #Find
  @and
     @Either
        #replace
     @or
        #delete
```

[a]recall that if possible, LOLA does not issue errors for non-intuitive lexi definitions

The figure uses the `@SubsetOf` constructor in the definition of *RE* `atMostOnceSections` which specifies the condition that a lexi may not contain more than one occurrence of `@find`, `@replace` and `@delete` elaborators, and that if a lexi contains a `@replace` elaborator, it cannot include `@delete` elaborator, and vice versa.

The purpose of constructor `@Not` is mostly served by the `@exceptFor` elaborator to `@Match`; it is included for the sake of completeness.

Modifying Constructors. These are included for technical reason. Modifying constructor `@SameLine` modifies the trivia in it, so that they never match an `@EndOfLine`. This constructor becomes handy when augmenting a language with feature which must be contained in one line.

The `@Unbalanced` modifier is discussed bellow, in conjunction with the classification of tokens.

4.6 Lexies

A lexi definition is made of *sections*, such as `@find`, `@replace`, `@description`, etc. Sections may occur in any order, and certain sections may occur more than once. Table 4.3 lists all lexi sections, in their (approximate) recommended order, and their multiplicity constraints.

Table 1.1 tells us that lexi sections `@Run`, `@Find`, `@Note`, `@Affirm`, `@Assert` and `@Description` may occur at the topmost file level, serving as LOLA directives. In truth *all* sections mentioned in Table 4.3 may serve as directives; Table 1.1 mentions only the more useful ones.

A section name must be capitalized for it to serve as a directive. Creation of the pattern object begins with this section. All lower-case named sections that follow are considered elaborators that add sections to the pattern being created.

All sections of a lexi definition are optional. Even the `@Find` section is optional, in which case the lexi is *degenerate*. A degenerate lexi matches precisely once, at the location it is defined. Since degenerate lexies are allowed at the file level, we can find any section at this level.

4.6.1 Declarative Header Sections

There are three conceptual blocks in Table 4.3: *declarative header* sections tend to appear first. Sections **`@note`** and **`@description`** are for documentation purposes; they fire in cases of errors, at which time they print their contents, with the hope that this might come in handy to the client.

4.6.2 Action Sections

The *action* sections start with **`@run`**, which allows for arbitrary computation. Any change made to F is implicitly reflected in the output.

Following is the familiar **`@replace`**, then **`@delete`** (which is just an alias for

```
@replace @Empty
```

and **`@prepend`** and **`@append`** (whose semantics should be obvious).

The **`@filter`** is used for hacks, e.g., pretty-printing the text just before producing it, converting special characters to trigraphs, etc. Sections are applied in the order they are defined. Filters are different. Regardless of their location in the lexi, filters are applied last. Specifically, any substitutions made by **`@prepend`**, **`@append`**, **`@delete`** and **`@replace`** to the captured text are made before.

The **`@anchor`** section typically defines a less demanding *RE*, than that of **`@find`**. It is an error for the **`@anchor`** to match without the **`@find`** matching as well. As demonstrated in Listing 3.2, the section can be used as safety measure, warning users of Lola code that they may have used the host language in a manner not anticipated by the designer of the language augmentation.

4.6.3 Declarative Footer

The **`@example`** section is used for debugging and documentation. It is an error if the *RE* in the **`@find`** does not match the output of a **`@example`** section. It is also an error if the output produced by the lexi does not match the **`@resultsIn`** elaborator of an **`@example`**.

More generally, if the "Lola argument" of an **`@example`** is a regular expression, then this regular expression must be contained in the *RE* of the **`@find`** section. (Containment of regular-expressions is computed in Lola with conjunction and negation, and tests for emptiness of underlying finite automata underlying the regular expressions.[6]

The use of the **`@log`** section was demonstrated above in Figure 3.1.

The **`@see`** section serves only a documentation purpose, referring the reader to other, related lexies.

[6] Lola refuses to negate expressions which involve pair balancing.

Chapter 5

The Host Language Configuration File

A host programming language has to be described in a configuration file in order for Lola to execute. Figure 5.1 presents the full list of rules in the schema of the file. Later, each rule is explained separately.

Figure 5.1 Full EBNF grammar of configuration file

$$
\begin{array}{rcl}
\textit{configuration-file} & ::= & \textit{configuration-element}\,^{*} \\
\textit{configuration-element} & ::= & \textit{balance} \\
 & | & \textit{super-balance} \\
 & | & \textit{token} \\
 & | & \textit{classification} \\
 & | & \textit{regular-expressions-definition} \\
\textit{regular-expressions-definition} & ::= & \textit{name}\;\; \textit{regular-expression} \\
\textit{regular-expression} & ::= & \textit{pattern-reference} \\
 & | & \textit{range} \\
 & | & \textit{string} \\
 & | & \textit{special-character} \\
 & | & \textit{or} \\
 & | & \textit{sequence} \\
 & | & \textit{until} \\
 & | & \textit{character-negation} \\
\textit{token} & ::= & \textit{name} \\
 & & \textit{regular-expression} \\
 & & \textit{method}\,? \\
\textit{translate} & ::= & \textit{from}\;\; \textit{to} \\
\textit{classification} & ::= & \textit{name}\,^{+}\; \textit{name}\,^{+} \\
\textit{balance} & ::= & \textit{begin}\,^{+},\;\; \textit{end}\,^{+}
\end{array}
$$

5.1 A High-Level Description of the Configuration File

At the root of the abstract syntax, we find a *configuration-file* , which is nothing but a list of *configuration-element* s, i.e.,

$$\mathit{configuration\text{-}file} ::= \mathit{configuration\text{-}element}^{*} \tag{5.1}$$

where the notation x^* is to say that the syntactical element x may occur zero, one or more times. Thus, a *configuration-file* is composed by a (possibly empty) list of *configuration-element* s, where a *configuration-element* is either a *regular-expressions-definition* , a *classification* , a *balance* or a *token* :

$$\begin{aligned} \mathit{configuration\text{-}element} ::= {} & \mathit{balance} \\ | {} & \mathit{token} \\ | {} & \mathit{classification} \\ | {} & \mathit{regular\text{-}expressions\text{-}definition} \end{aligned} \tag{5.2}$$

5.2 Regular Expressions

To define and name a regular expression, use

$$\mathit{regular\text{-}expressions\text{-}definition} ::= \mathit{name}\ \ \mathit{regular\text{-}expression} \tag{5.3}$$

The regular expression itself is described using

$$\begin{aligned} \mathit{regular\text{-}expression} ::= {} & \mathit{pattern\text{-}reference} \\ | {} & \mathit{range} \\ | {} & \mathit{string} \\ | {} & \mathit{special\text{-}character} \\ | {} & \mathit{or} \\ | {} & \mathit{sequence} \\ | {} & \mathit{until} \\ | {} & \mathit{character\text{-}negation} \end{aligned} \tag{5.4}$$

where each of the names explains the role of the respective element. A building block worth mentioning is *until* , which was specially added for the case of comments. Using this element, we can specify up to two characters to read until, such as in the case of comments in C . For a single line comment we would use "//" until new-line, and for a multi-line comment—"`/*`" until "`*/`". In the case of two characters, this is a shorthand for the regular expression

$$\texttt{([/z]|(z}^{+}\texttt{([/az])))}^{*}\texttt{z}^{+}\texttt{a}$$

where we wish to continue the regular expression up to a sequence `za`.

For more information about each individual way of constructing the regular expression, see the XML schema.

5.3 Tokens

To declare a token, specify a token name and a regular expression. Optionally, specify a method to convert the text value of the token to a useful PYTHON object. The token name can consist only of lowercase characters and underscores.

$$\begin{aligned} \textit{token} ::= \; & \textit{name} \\ & \textit{regular-expression} \\ & \textit{method}\,? \end{aligned} \tag{5.5}$$

The method is some PYTHON code to convert the token to a PYTHON object. To specify the method, define a PYTHON function named convert, e.g.,

```
<method>
  def convert(text):
    return float(text)
</method>
```

Examples of good candidates for token definitions are assignment-operators (`<<=`, ...), unary-operators (`!`, `~`, ...) and binary-operators (`|`, `==`, ...).

5.3.1 Digraphs and Trigraphs

Programming languages define sequences of characters to use instead of other characters. For example, in C, one can use the string `<:` for `[`. To support this feature, use the translate rule:

$$\textit{translate} ::= \textit{from} \;\; \textit{to} \tag{5.6}$$

This technique makes it easier for the programmer in LOLA to define patterns in a more concise way, without taking into consideration those rules.

5.4 Token Classifications

One may wish to refer to a token in more than one name. Moreover, one may wish to refer to several tokens in the same name. To support this functionality in the configuration file, use token classifications. Associate several names with several new names:

$$\textit{classification} ::= \textit{name}^{+} \; \textit{name}^{+} \tag{5.7}$$

The source names appear first, and then the new names.

Common classifications may be a keywords class (tokens that are reserved from use by the programmer, and identify an entity in the host language, e.g., `public` and `short`) and a punctuation class (specifies punctuation marks such as `,` and `;` in C).

5.4.1 Reserved Token Classifications

Two reserved token classifications exist. They are used to indicate special semantics.

Ignore classification The first reserved token classification is the "ignore" classification. In many programming languages, whitespace is used to separate tokens, and is disallowed, e.g., in identifiers. Configuring LOLA to ignore whitespace in the host language is done using the reserved ignore token specification.

Comment classification The second reserved token classification is the "comment" classification. This classification is used to specify comments.

5.5 Balanced Pairs

Many programming languages use balancing pairs, such as curly braces `{...}`, parenthesis `(...)`, brackets `[...]`, and in more verbose languages, `do...done` and `if...fi` pairs.

To match constructs that use these, we wish to match only text that is balanced in this sense.

To escape this behavior, one may use the `@Unbalanced` keyword. In addition, and as a matter of convenience, if a pattern includes an odd number of balanced tokens (in the lexi definition itself), a `@Unbalanced` is implicit.

To specify pairs of tokens to be matched as a start and an end of a sequence, *balance* is used

$$\textit{balance} ::= \textit{begin}^{+}, \textit{end}^{+} \tag{5.8}$$

The *begin* element specifies the token to match as the starting sequence, and the *end* element specifies the ending token.

The PASCAL programming language is slightly special in that the `end` terminator is usually balanced against `begin`, but, the language also admits `record...end` and `case...end` pairs. For this reason, we allow both the *begin* and *end* components of a *balance* to include more than one token. The semantics is that each of the tokens in the *begin* component is balanced with any of the tokens in the *end* component. Multiple tokens in a *begin* or *end* clause should not be used for non-mixable pairs such as square brackets and curly brackets. Each of these pairs must be defined in a distinct *balance* clause.

LISP uses parenthesis to the extreme. To help the LISP programmer, the language offers a the syntax of

```
[(((...]
```

which means that the closing bracket `]` balances all of the previous parenthesis. This syntax implies the semantics of

```
[(((...)))]
```

To this end, one may use

$$\textit{super-balance} ::= \textit{begin}^{+}, \textit{end}^{+} \tag{5.9}$$

so that balancing pairs that appear in this specification balance every inner balancing pairs.

5.6 Configuration to an Input Language Convention

Many programming languages have a single identifier class. This means that a single token, usually named identifier, and usually take the lexical structure of

`[a-zA-Z_][a-zA-Z0-9_]`*,

is responsible for representing any new object—either a class, a variable or something else. However, in PROLOG [9], variable names start with an upper-case letter, whereas atom names start with a lower-case letter.

Though many programming languages do not use several identifiers, we see groups of identifiers in those languages, emerging by the use of conventions. Several of the conventions are discussed shortly in Table 5.1.

Name	***Usage***	***Regular expression***[a]
`UPPER_CASE`	C constants, mainly `enum` values, are all upper-case	`[A-Z_]`*
`CamelCase`	JAVA classes are upper camel case	`([A-Z][a-z]`*`)`$^+$
`camelCase`	JAVA methods are lower camel case	`([a-z][a-z]`*`)([A-Z][a-z]`*`)`$^+$
`mCamelCase`	JAVA member fields (mainly in android programming), start with an `m`	`m([a-z][a-z]`*`)([A-Z][a-z]`*`)`$^+$
`lower_case`	C++ standard template library uses lower case characters and underscores	`[a-z_]`*
`Camel_Case`	similar to the previous convention	`([A-Z][a-z]`*`)(_([A-Z][a-z]`*`))`*
`ICamelCase`	C# interfaces start with an `I`	`I([a-z][a-z]`*`)([A-Z][a-z]`*`)`$^+$
`m_FeralCamel` `m_feralCamel`	C++ member fields start with a `m_`	`m_([A-Z][a-z])`$^+$ `m_[a-z]`$^+$`([A-Z][a-z]`*`)`*

[a]digits are disregarded

Table 5.1: Examples of identifier groups

LOLA is configured by the user to a specific programming language, but there is no reason not to develop for a specific convention. Therefore, one may write a configuration file where the lexical analyzer distinguishes between different identifier groups.

Hungarian notation [48] is another great example of a convention of writing identifiers, though it is harder to track.

Chapter 6

Lexical and Syntactical Analysis

Having seen the showcase in Chapter 3 and reading discussion in Chapter 4 should have stated that LOLA's grammar is pretty regular. The syntactical constructs are quite repetitive. In this chapter, we shall see how this regular structure is used in parsing, and understand how the parsing of **@Find**, **@ForEach** and **@Case** can be made in essentially the same manner, without relying on traditional grammar based parser, despite the fact that their syntax is not identical and the fact that **@Find** creates a lexi, **@ForEach** is a *RE*s' constructor and **@ForEach** is a constructor of *GE*s.

In the introductory chapter (Section 1.4) it was mentioned that elaborators such as **@elseIf**, **@of**, **@and**, and **@ifNone** attach to the inner most LOLA constructor to which they fit. This chapter explains how this binding is made.

Also, recall that **@Find** just as many other keywords, takes (after an optional parenthesized PYTHON identifier) sequence of tokens (and compound objects). Upfront, this definition is ambiguous. Consider this example, in which both keywords **@Find** and **OneOrMore** expect a sequence of tokens:

```
@Find @OneOrMore token1 token2
```

One interpretation of the above is:

```
@Find {@OneOrMore {token1} token2}
```

However, The *right associativity rule* (taking aide at time from the *no lower indentation argument*) aggregates differently the arguments: the list argument to a keyword is the sequence of tokens (and compound objects) that starts at the first token after the keyword and ends just before the token in which the current indentation is resumed. In the example

```
@Find {@OneOrMore {token1 token2}}
```

More generally, aggregation technique means that a keyword accepts the longest possible sequence of tokens. LOLA uses nor parenthesis like characters neither **begin** $\cdots$ **end** and **fi** $\cdots$ **fi** like pairs for blocking and aggregation. (This means that these are free to use as keywords and characters of the host tokens). Blocking and aggregation are achieved in LOLA by indentation. This chapter also describes how the parser maintains the other rules of indentation mentioned in Section 1.4. The fine details are in this chapter which also explains how the parser

6.1 Lexical Analysis

The input to LOLA is a file consisting host-language code intermixed with LOLA directives. The configuration file tells LOLA how to group characters in the input into *tokens*, either of the host-language or of LOLA, and which characters (or sequences of characters) are *trivia*. For this purpose LOLA tokens are either keywords or keywords along with the PYTHON snippets attached to them. LOLA's lexical analyzer produces a stream of what we call "*bunnies*", which is just a collective name for trivia and tokens (of either language). This stream of bunnies makes the input to LOLA's parser.

Consider for example the code in Listing 6.1.

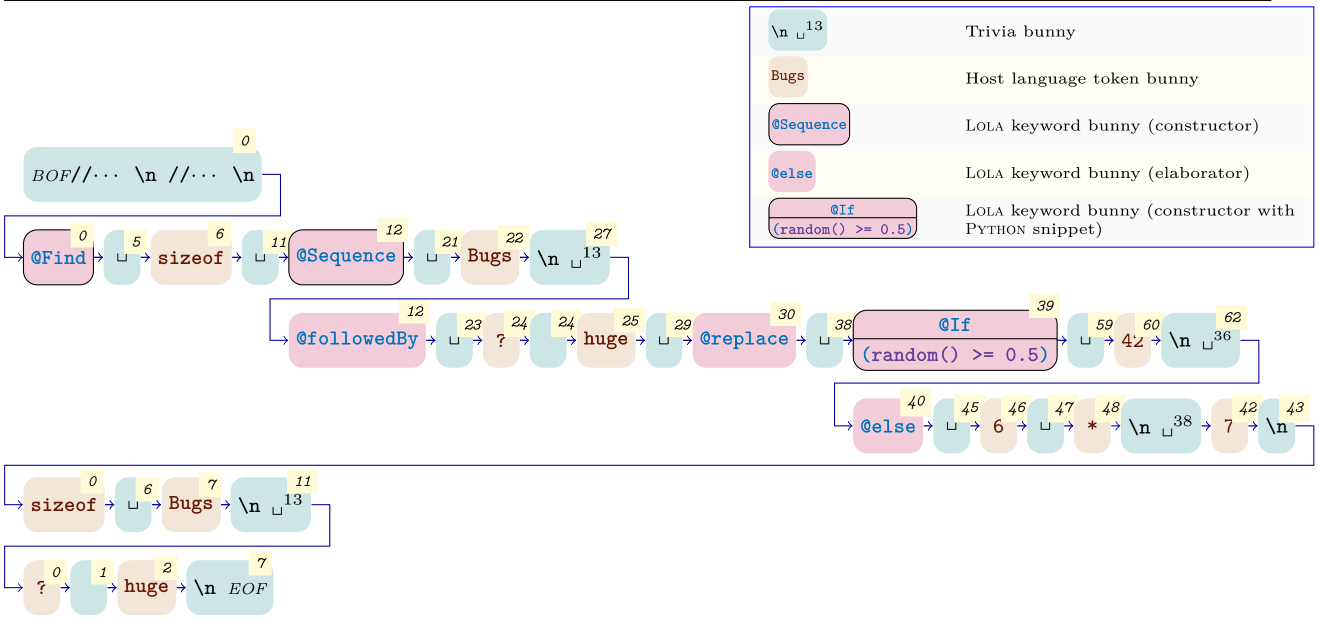
Listing 6.1 A contrived LOLA lexi demonstrating how elaborators attach to their respective constructors

```
//        1         2         3         4         5         6         7          1
// 3456789 123456789 123456789 123456789 123456789 123456789 123456789 123456789 2
@Find sizeof @Sequence Bugs                                                      3
          @followedBy ?huge @replace @If(random() >= 0.5) 42                     4
                                     @else 6 *                                   5
                                       7                                         6
sizeof Bugs                                                                      7
? huge                                                                           8
                                                                                 9
```

The listing shows a short source file, containing a lexi (lines 3–6) surrounded by C++ code: comments in lines 1–2 and an illegal expression followed by an empty line (lines 7–9).

The stream of bunnies produced from this file is depicted in Figure 6.1.

Figure 6.1 The stream of lexical units (bunnies) produced from the code in Listing 6.1



In the figure, bunnies are portrayed as a nodes in a linked list. The figure's legend shows how frame and color determine the bunny's type: bunny `␣` is a trivia, `Bugs` bunny[1], a host-token; etc.

Figure 6.2 Hare Bugs Bunny. ♂ *April 30, 1938–* (shown with Lola Bunny (Figure 1.1))

All three kinds of bunnies are demonstrated in the figure:

Trivia A trivia is a (potentially empty) sequence of comments, non-visual characters such as spaces, tabulation, new lines, carriage returns etc., or whatever is defined as such in the configuration file.

In Listing 6.1 we see a trivia at the beginning and at the end of the stream, and a trivia between any two other bunnies. Also, observe that Lola coalesces all consecutive occurrences of these into a single trivia.

[1]pun intended, *huh*, *huh*.

Note that the trivia between the C++ tokens "`?`" and "`huge`" is empty; its sole purpose is to separate these two tokens. Other tokens in the listing contain one space (line 5), multiple spaces, several new line characters and even comments.

Host Tokens These are the tokens of the host language, including identifiers, keywords, literals, etc., as defined in the configuration file.

The first five host tokens in the figure are "`sizeof`", "`Bugs`", "`?`", "`huge`", and, "`42`".

Lola Keywords which may be followed by properly bracketed PYTHON code snippets. We shall think of the keyword, along with the bracketed PYTHON snippet, and the brackets themselves, as one.

In the figure, we see the following keywords in order: `@Find` and `@replace` (which are sections of a lexi), `@Sequence` followed by the `@followedBy` elaborator, and `@If` (a constructor of *GE*), and its `@else` elaborator.

Observe that the bunny of `@If` carries with it the PYTHON code snippet, including the brackets (parenthesis in this case).

The lexical analyzer also attaches to each token a column number, to be used later in the parsing phase. The column number of a token is simply the number of characters that precede the first character of this token in the line in which it occurs.

Column numbers are depicted as little labels in Figure 6.1. For example the column of `@If` and its `@else` elaborator is 41, and the column number of the host token `7` is 43.

In processing the stream of bunnies LOLA does two things:

- identification of directives, and removing these from the input stream, and,
- application of directives to the remaining bunnies (which must be either trivia bunnies or host-language tokens)

Figure 6.3 shows the stream of bunnies generated from Figure 6.1 after the lexi in lines 3–6 is removed from it.

Figure 6.3 The stream of remaining lexical units (bunnies) after removing the lexi from Figure 6.1

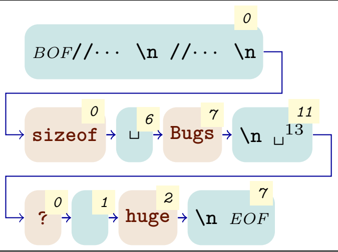
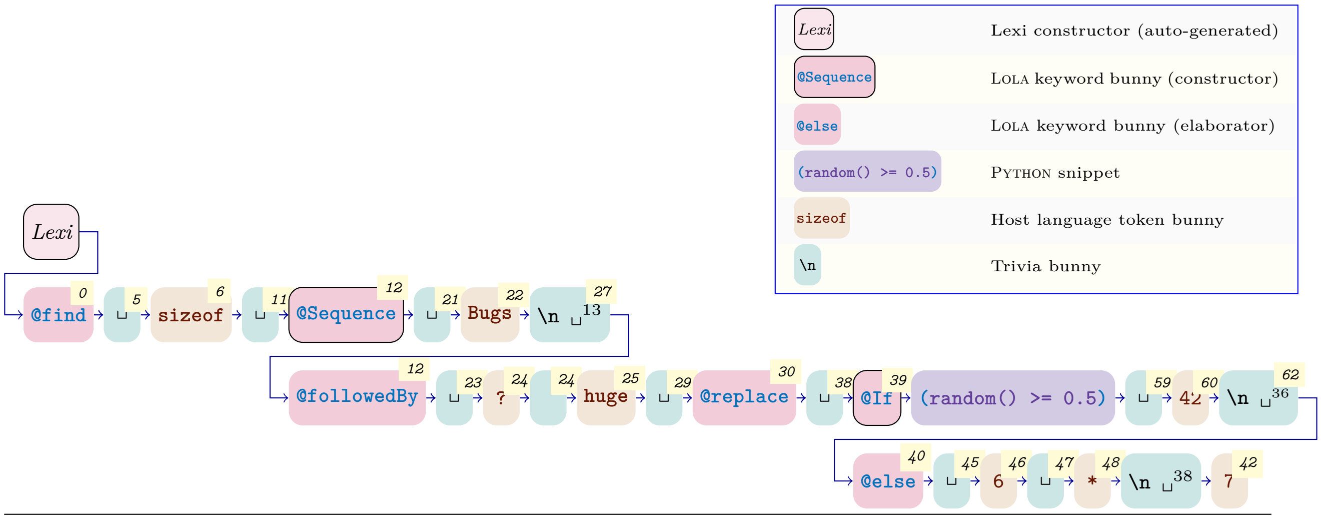


Figure 6.4 shows the stream of bunnies of the lexi in lines 3–6 of Listing 6.1. This stream is later fed to LOLA's parser which will turn it into a directive.

Figure 6.4 The stream of lexical units (bunnies) of the lexi in Listing 6.1, to be later parsed as Lola directive



Comparing the figure to the original stream (Figure 6.1) we observe that the constructor bunny marked **@Find** in the original stream was converted to two bunnies: an automatically generated constructor, named *Lexi*, followed by a **@find** modifier. This conversion is carried out at the lexical phase to save the parser from special-casing sections whose name is capitalized.

Another conversion carried out by the lexical analyzer is the conversion of the bunny composed of a keyword decorated with a snippet, e.g., **@If** in Figure 6.1, into two bunnies: a constructor named **@If**, followed by a new kind of bunny marking Python snippets, e.g., the bunny with the snippet

```
random() >= 5
```

in Figure 6.4.

Again, this conversion of snippets is carried out for non-profound reasons: Some Lola keywords such as **@Find** and **@Sequence** take an *optional* snippet. This optional snippet may look as a list of tokens. For example,

```
@Find (a) b
```

might be interpreted both as a search for host tokens **(a) b**, and as a search for host token **b** to be stored in Python variable **a**. The lexical analyzer resolves the ambiguity by selecting the first alternative if one or more space characters follows the keyword. So the above input is interpreted as per the first alternative. The second alternative is selected in case no such space occurs, e.g., if the input is

```
@Find(a) b
```

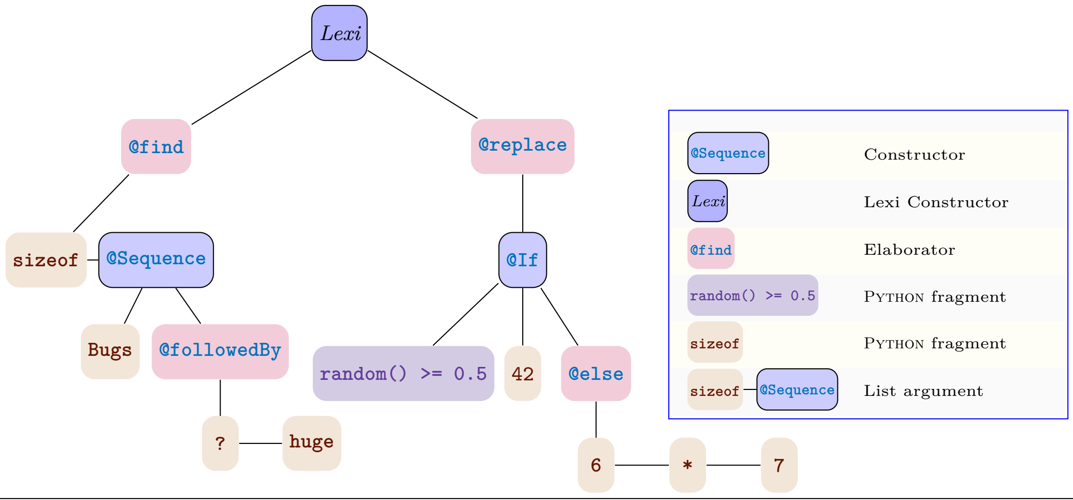
then "**a**" is interpreted as a Python identifier into which the result of the search is stored, rather than a host token to be found in the input stream.

6.2 The Abstract Syntax Tree

It is the duty of the Lola parser to generate from all other bunnies the ***A**bstract **S**yntax **T**ree* (AST) of directives embedded in the code.

The AST for the running example (Listing 6.1) is portrayed in Figure 6.5. It is created from the stream in Figure 6.4.

Figure 6.5 The abstract syntax tree created for the lexi in Listing 6.1



The most important kind of a nodes in the AST is that of *cosntructors*. In the figure we see three of these. The node labeled **`@Sequence`** represents a constructor of a *RE*; the node labeled **`@If`** represents a *GE*. The root of the AST in Figure 6.5, denoted the word *lexi* is also a constructor.

Second in importance are elaborator nodes. In the figure we see four of these, labeled **`@find`**, **`@replace`**, **`@followedBy`**, and, **`@else`**.

Figure 6.5 shows two other kinds of nodes: host-tokens such as **`sizeof`**, **`Bugs`**, etc., and nodes with Python code snippets (the only such node in the figure contains the snippet

`random() >= 5`).

6.3 Children of Constructors and Elaborators

A general constructor node has three kinds of children which must occur in a very specific order:

1. a Python *snippet*, which may occur at most once, and must be the first child when it occurs;

2. a *list* of host tokens and constructors, which may occur at most once, and must immediately follow the snippet or be the first child if no snippet occurs; and,

3. any number (including none) of *elaborators*, which must occur last.

A general elaborator node has the same kinds of children, and these which must follow the same order as in constructor nodes. Elaborators may even have elaborators of their own.

The only difference between constructors and elaborators is that elaborators are not allowed to occur in the list child.

Each individual constructor or elaborator may impose its own specific requirements on its children, including a specification on the order, kind and cardinality of its elaborators. A lexi for example, does not admit a snippet, nor a list, while an **`@If`** does not allow an **`@else`** elaborator to occur before an **`@elseIf`** elaborator.

Table 6.1 below specifies these restrictions for some common constructors including all those occurring in Figure 6.5[2].

	Snippet	**List**	**Elaborators**
Lexi	✗	✗	*all lexi sections of Table 4.3, with the respective restrictions*
`@Nothing`	✗	✗	✗
`@Include`	String	✗	✗
`@If`	Boolean-Expression	*GE*s	**`@Sequence`**
			`@NoneOrMore`
			`#elseIf`
			`@followedBy`
			`@Optional`
			`#else`
`@NoneOrMore`	Identifier$_{opt}$	*RE*s	**`@SubsetOf`**
			`#opener`
			`@and`
			`#closer`
			`@and`
			`#separator`
			`@and`
			`#ifNone`
`@Either`	✗	*RE*s	**`@OneOrMore`**
			`@or`
`@Case`	Expression	✗	**`@Sequence`**
			`@OneOrMore`
			`#of`
			`@followedBy`
			`@Optional`
			`#otherwise`
`@SameLine`	Identifier$_{opt}$	*RE*s	✗
`@Sequence`	Identifier$_{opt}$	*RE*s	**`@NoneOrMore`**
			`#followedBy`

Table 6.1: Variety in restrictions placed on children by different constructors

The table demonstrates the great variety of restrictions placed on children by constructors: A lexi has many elaborators but does not admit neither a snippet nor a list. Another

[2]The full list of restrictions is implicit in tables 4.1 to 4.3

constructor that allows only one kind of children is `@Include`, which only allows a snippet[3].

In contrast, `@If` has all three children. Constructor `@NoneOrMore` also has all three, but in this constructor, the PYTHON snippet is optional.

Constructor `@Nothing` is restrictive as it can be: it forbids all three kinds of children: snippet, list and elaborators.

Three constructors in Table 6.1 allow only two out of three kinds of children: `@Either` has no snippet, `@Case` has no list, and `@SameLine` which has no elaborators.

Table 6.2 below repeats Table 6.1, but for selected elaborators, demonstrating the variety of requirements placed by elaborators.

	Snippet	**List**	**Elaborators**
`@delete`	✗	✗	✗
`@run`	Commands	✗	✗
`@else`	✗	*GE*s	✗
`@example`	✗	*RE*s	`@Optional` `#resultsIn`
`@to`	String-Expression	*GE*s	✗
`@elseIf`	Boolean-Expression	*GE*s	✗
`@log`	Identifier$_{opt}$	*GE*s	`@Optional` `#to`
`@of`	Expression	*GE*s	✗

Table 6.2: Variety in restrictions placed on children by different elaborators

Both tables 6.1 and 6.2 employ LOLA syntax to specify the order of elaborators. This specification turns out to be quite readable, e.g., the elaborators of `@Case` are a sequence of one or more `@of`, followed by an optional `@otherwise`.

In the table (and henceforth) meta-specifications of this sort use the "`@`" notation for keywords such as `@Sequence` that defines regular expressions, and the "`#`" notation (e.g., `#case`, `#of`, `#otherwise`) notation for LOLA elaborators whose order, multiplicity and other restrictions are being specified.

Table 6.1 only hints on restrictions placed on the elaborators (sections) of a lexi. The full list of these restrictions is:

1. at least one elaborator,
2. at most one `@find`, one `@delete` and one `@replace`,
3. `@delete` and `@replace` are mutually exclusive, and,
4. otherwise, elaborators may occur any number of times and in any order.

Listing 6.2 is a meta-lexi filling this gap. The meta-lexi in it specifies, using LOLA syntax, the requirements that a LOLA lexi places on its elaborators.

[3]None of LOLA current constructors is one that only allows a list.

Listing 6.2 A meta-lexi specifying restrictions on sections of a lexi

```
@Note "A meta-lexi specifying the constraints on sections of a lexi"
@find
  @Match
    @OneOrMore
      @Either
        #find @or #replace @or #delete @or #append @or #prepend
      @or
        #description @or #note @or #log @or #see @or #example
      @or
        #anchor @or #run @or #filter
    @exceptFor
        @Any #find @Any #find @Any
    @exceptFor
        @Any #delete @Any #delete @Any
    @exceptFor
        @Any #replace @Any #replace @Any
    @exceptFor
        @Any #replace @Any #delete @Any
    @exceptFor
        @Any #delete @Any #replace @Any
@anchor
  @Either
    #find @or #replace @or #delete @or #append @or #prepend
  @or
    #description @or #note @or #log @or #see @or #example
  @or
    #anchor @or #run @or #filter
```

6.4 Parsing without Explicit Grammar

Having seen in Chapter 4 the large number of constructors and elaborators, and having seen in the above section the rich set of requirements on elaborators (e.g., Listing 6.2), and the variety on requirements on children, both in constructors (Table 6.1) and elaborators (Table 6.2) it should be clear that:

- the syntax of Lola can be written with a context free grammar notation such as EBNF, but,
- the resulting syntax definition is likely to be large and cumbersome, and that,
- anticipated changes and additions to Lola are likely to break this definition.

Thus, instead of the traditional approach of feeding a grammar specification to a parser generator, Lola uses a different approach: A universal parser reads the bunnies. The grammar specification for keywords is made in a modular fashion: the module that realizes a keyword specifies its syntax.

Lola thus encapsulates the idiosyncrasies of each of the constructors and elaborators in their respective builder objects. When the Lola parser encounters a keyword, it creates a corresponding builder, whose life purpose is maturing into the correct AST node.

Builders support these methods:

Query b.`accepts`(c) which determines whether builder b can adopt a child c, which can be a bunny, a compound, or a compound elaborator.

Operation b.`adopt`(c) which, on the presumption b.`accepts`(c), adds child c to builder b.

Query b.`mature`$()$ which returns `True` if, and only if, builder b matured into an AST node.

Operation b.`done`$()$ telling b that it may expect no more b.`adopt`$(\cdot)$ nor `accept`$(\cdot)$ invocations.

If at the time of a `done`$(\cdot)$, b notices that it still needs more children, it emits an appropriate error message. After the call, b.`mature`$()$s shall affirm that the b is complete, regardless of error messages.

Grammatical derivation rules are thus imitated by the behavior of specific builders, e.g., `@If` builder refusing to receive any more elaborators after seeing an `@else` elaborator, and a `@Case` builder issuing an error message if told it is `done`$()$ prior to seeing an `@of` elaborator.

Since the order of children is fixed, builders follow a similar protocol. Initially, a builder is in a “**Snippet**” state expecting a snippet. When the snippet is accepted, the builder moves to a “**List**” state, expecting and accepting any number of host tokens and compound objects. When the first elaborator child comes, this list is locked and the builder moves to the “**Elaborators**” state, expecting and accepting elaborators.

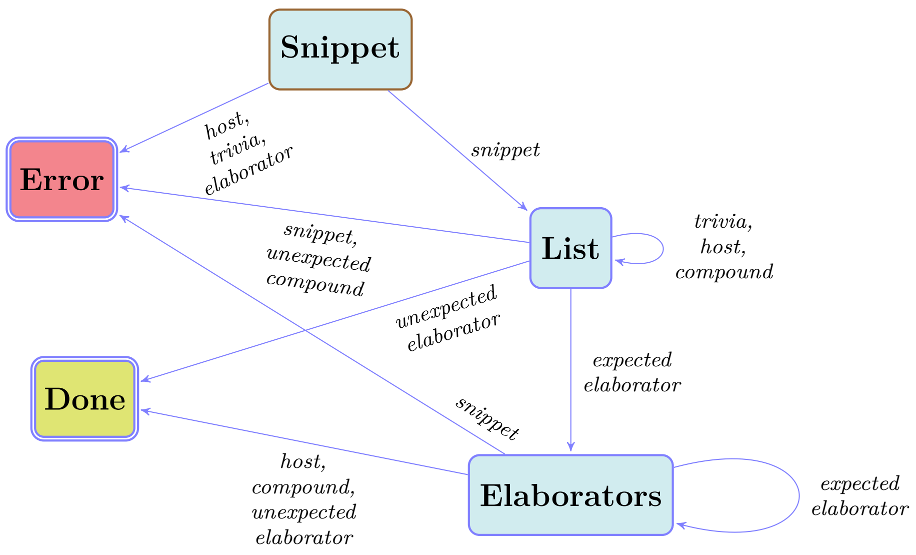
When an unexpected child arrives, the builder goes into a final state “**Done**” or to final state “**Error**”. In both cases, the builder matures into an AST node, and will take no more children. State “**Done**” is reached if two conditions are met:

- The current builder received all the children it needs to become a valid AST node of the appropriate kind.
- The pending child is of type elaborator, which might be taken by a pending builder in which the current builder is nested.

Hence, when the builder sees the first elaborator, the general list is locked.

Figure 6.6, showing the automaton behind the implementation of some generic builder, demonstrates how function b.`accepts`(x) is implemented.

Figure 6.6 An automaton describing the grammar of some generic builder



The generic builder in the figure taking a mandatory snippet argument, followed by a list of trivia, host tokens, and compound objects, followed by zero or more elaborators.

For the purpose of presentation it is tacitly assumed that the automaton knows which elaborators are expected; no automaton states are allocated to represent the underlying logic (which may be as complicated as in Listing 6.2).

The automaton follows an eager policy of trying to collect children as long as it is possible to do so, and only declare an error if the builder cannot possibly be made into a legal AST node.

Since the AST node must start with a snippet, any other input at the starting state "**Snippet**" leads to an error. Also, an occurrence of a second snippet, i.e., in states "**List**" and "**Elaborator**", leads to an error.

However, when the accepted x is an elaborator which the builder does not recognize, and the builder has already seen and stored its (i.e., it is in the either the "**List**" or the "**Elaborator**" state), the builder moves into a "**Done**" state, refusing to collect any more children.

Still if the builder sees an unrecognized elaborator prior to seeing all elaborators it must see, it moves into the "**Error**" state. This stops the builder from taking any more children, and effectively lets other builders try to accommodate the unfamiliar elaborator.

Another case of error in the building process may occur in the "**List**" state. If a builder of a *GE* receives into the list a compound of *RE*s, it takes it, reports an error, and moves into the "**Error**" state.

Of course, the implementations of the variety of builders (tables 6.1 and 6.2) are slightly different, to deal with the cases of optional snippet, no snippet at all, no list, etc., but the eager child collection policy is shared by all.

6.5 The Stack of Pending Builders

Lola's parser maintains a stack of pending builders, and tries to add children to the top most builder. If this builder refuses to adopt an additional child, the parser pops the stack, and tries to add the child to the next pending builder.

Function percolate(c), processing c, a child to be fitted with the stack of pending builders, listed in Algorithm 6.1 describes the details.

Algorithm 6.1 Procedure percolate(c), processing c, a child to be fitted with the stack of pending builders.

```
1:  While ¬empty() do                                          // builders awaiting arguments still
2:    Let b ← top()                                            // current candidate builder
3:    If column(c) < column(b) orElse ¬b.accepts(c) then       // not the right builder
4:      b.done()                                               // tell b it can expect no more arguments
5:      pop()                                                  // b is complete now; remove it from the stack
6:      percolate(b)                                           // send b to its destined builder
7:      continue                                               // percolating c to builders on stack
8:    b.adopt(c)                                               // save complete object c in builder b
9:    If ¬b.mature() then                                      // b may take further arguments
10:     Return                                                 // proceed to next token in the input
11:   pop()                                                    // b matured, percolate completed b
12:   c ← b                                                    // old c consumed; proceed with completed b
                                                               // empty stack; no more builders to take argument c
```

if c is not an elaborator then it is tested using $\leq$

Procedure percolate($\cdot$) uses operation pop() and queries empty() and top() on an implicit, global, stack data-structure of builders whose actions action was suspended.

The loop in percolate(b) tries to fit a prospective child c with b, the builder on top of the stack. If the indentation of the child is lower than that of the builder, or the builder cannot accept the child (line 3 in Algorithm 6.1), the procedure loops again, trying to send the child to the next builder pending on top of the stack.

Take note that before a child is sent for adoption by a builder deeper int the stack, all builders on top of this builder must be declared as done. In particular, procedure percolate($\cdot$) declares the current builder b as done (line 4), since once a prospective child is sent to an ancestor, the current parent cannot expect any more children. For this reason, it is pop()ed from the stack at line 5.

The recursive call (line 6 in the algorithm) is crucial, and it must be made *before* the prospective child c is tried against the builders deep in the stack. Since the current builder b can take no more children, b must be adopted itself before c, which follows it, can finds its adopting parent.

Procedure percolate($\cdot$) is used by Lola to generate an AST node for directives. Concretely, percolate($\cdot$) serves as a subroutine of directive($\cdot$), portrayed in Algorithm 6.2 below, which is in charge of creating the AST of directives.

Function directive($\cdot$) is called whenever Lola's main notices on the input stream a bunny which might be a builder, i.e., a "`@CamelCase`" keyword, or the special "Lexi" bunny (generated, as explained above, from a capitalized section such as `@Find`).

If the input is legal, directive(c) returns the AST for the directive created by constructor c. If the input is illegal, an AST is still returned, but it might be invalid.

Algorithm 6.2 Function directive(c), returning the AST for the directive created by constructor c

```
 1: push(c)                              // collect c's children
 2: While ¬eof() do                      // More bunnies pending
 3:   Let b ← getBunny()
 4:   If leaf(b) then                    // host, trivia, or snippet token
 5:     percolate(b)                     // try to find a parent for b
 6:   else                               // must be a constructor or an elaborator
 7:     push(c)                          // will be done when children are collected
 8:   If empty() then                    // all c's children were collected
 9:     ungetBunny(b)                    // a directive can only end with a bunny it cannot adopt
10:     Return c
         // end of file reached, must notify all pending builders they are done
11: While ¬empty() do                    // builders awaiting arguments still
12:   Let b ← top()                      // current unfinished builder
13:   pop()                              // b is complete now; remove it from the stack
14:   b.done()                           // tell b it can expect no more arguments
15:   pop()                              // b is complete now; remove it from the stack
16:   percolate(b)                       // send b to its destined builder
17: Return c                             // all children of argument c were collected
```

Function directive(c) employs

- query leaf(b) determining whether bunny b is trivia, host or snippet,
- operation push(t) on the implicit global stack of builders whose actions action was suspended, and,
- function percolate(t) for sending complete object to these, potentially creating more complete objects in the process, and, trying to determine their matching, incomplete builders in the stack.

Elaborators, which are also builders, typically following the "`@camelCase`" convention, can never start a directive. Whenever an elaborator occurs with no preceding constructor, the input is erroneous. Still, for the purpose of better error recovery and reporting, the main loop invokes function directive($\cdot$) on these as well.

The computation in Figure 6.4 consumes bunnies until argument c can collect no more children. If the bunny is a trivia, a host token, or snippet, it cannot serve as an internal node, and it is sent for finding a parent by invoking function percolate($\cdot$).

If however the next bunny is an elaborator or a constructor (line 6 in the algorithm), i.e., it is a prospective parent, it is pushed into the builders stack (line 7). This push means that on later steps of the parsing, percolate($\cdot$) will find the children for this parent (assuming that the input is syntactically correct). Later on, this parent bunny will become a child or a farther descendant of argument c.

6.6 Trivia Management

The AST depicted in Figure 6.5 does not portray and trivia nodes. These are generally omitted when creating ASTs of patterns. The truth of the matter is that trivia nodes receive special cases in several occasions:

- When Lola creates an AST of a regular expression, it does not save in it bunnies found in the input. But, special keywords `@NewLine`, `@EndOfFile`, etc., can be used to match designated trivia in the input.
- When scanning for a match, Lola ignores for the purpose of the matching the trivia between matched tokens, but this trivia is recorded for a later use. If any two or more consecutive tokens are printed, the printout includes also the trivia(s) that separate them.
- A trivia in the input can be matched specifically by the special keywords (parameterless constructors), that match them. A trivia in the input can be unmatched, i.e., cause the current match to fail, if it contains a new line, and the matching object is qualifies with a `@SameLine` keyword.
- In contrast with regular expression, trivia bunnies found in generating expressions are kept and used.

  However, if a trivia that includes a beginning of a line (optionally followed by spaces) is stored with a generating expression, this trivia is truncated, bringing its column down to that of the outer most operator of the generating experession.

Chapter 7

Pruning, Matching and Triggering

7.1 Input Pruning

The previous chapter explained how directives in the input stream are identified, converted into ASTs, and pruned out of the input stream. After this pruning, Lola applies the directives on the pruned input.

Immediates are directives that execute immediately. A directive that does not execute immediately can only be a non-degenerate, i.e., a lexi which has a `@find` section. Henceforth, unless otherwise specified, the term "lexi" refers to non-degenerate lexies.

Immediates are either *degenerate lexies*, i.e., lexies missing a `@find` section, or, *generative directives* such as `@Include` and `@If`. Immediates executed right after their parsing is complete. The output produced by this execution is interpolated, as is, into the input stream.

The interpolated output may contain more Lola directives: This is because interpolation into input stream means that the characters in this output are tokenized and parsed exactly like characters that originate from the main stream. Therefore, if directives are found in the interpolation, they are processed in the same way that directives on the main input stream are processed.

Specifically, a lexi found in the output of an immediate is stored for later execution, while immediates found in the output of immediates are recursively executed.

The output of recursive execution of immediates is recursively interpolated into the input stream. Recursive interpolation makes it possible to `@Include` files that `@Import` other files that `@Splice` the output of a system command which prints some more Lola directives, and it makes it possible to write if Lola, the equivalent of this C preprocessor programming idiom:

```
#if 0
#define A 1
#else
#define A 2
#endif
```

The *pruned text* is obtained by removing all directives, and recursively executing immediate. Ignoring trivia for now, the pruned text is tokenized, and converted into a *string* of n tokens $\tau_0 \cdots \tau_{n-1}$ stored in an appropriate *buffer*, on which Lola employs a fixed point (work-list) computation, applying substitutions defined by lexies, until no more apply.

More concretely, LOLA steps through this buffer, and after reading each token in it, checks to see when, where and which of the stored lexies concludes in a *match*. Think of match M as having two properties: the lexi (and the reifying object), and the substring of $\tau_0 \cdots \tau_{n-1}$ with which the match occurred. Notice that a lexi may be involved in several matches that conclude at the same token, but have started at different locations.

Under certain conditions, a matching lexi triggers, in which case it conducts a replacement. In the general case, the substituted text could have been generated by PYTHON (e.g., by using the PYTHON escape keyword `@`) and needs to re-tokenized. However, unlike immediates, the output of lexies may not contain other LOLA directives: LOLA is willing to process directives only at the initial phase, when immediates are executed and expanded recursively to produce the pruned text.

7.2 The Match of the Matches

LOLA must run a match among the all possible matches, to determine the winning match. The winning match then proceeds to trigger its lexi. A triggered lexi typically changes the text it matched; the matched tokens are removed, and is replaced by the substitution text (which may occasionally be identical to the matched tokens).

A total ordering of matches is required in this match of matches. Without it, LOLA programs cannot be guaranteed to exhibit deterministic behavior.

Clearly, least, `@run` sections must be executed in a deterministic, predictable order. But, even without `@run` sections, the order of application of `@replace` sections of different lexies matters.

For examples, here are two lexies that do not commute:

- First is

```
@Find +- @replace -
```
(7.1)

- Second is

```
@Find -+ @replace +.
```
(7.2)

If the lexies are applied to the input

‘‘`+-+`″,

the first and only then the second, the final output is

‘‘`+`″.

(The first lexi yields “`-+`” which is then converted by the second lexi to “`+`”.)

However, the application of the second lexi and then the first, to the same input, yields the final output

‘‘`++`″.

(The second lexi, which is applied first, converts input “`+-+`” to “`++`”, which does not trigger the first lexi that is applied only second.)

7.3 Multiple Matches of the Same Lexi

The action of a lexi can interfere with itself, since the match may span overlapping and contained substrings of the buffer.

Take for example pattern `@Expressions` that matches a sequence of one or more comma separated matches of `@Expression` (both defined in Listing 1.4 above), where `@Expression` is a valid C (say) expression that does *not* match pattern `@Expressions`. (Patterns `@Expression` and `@Expressions` are mutually recursive: Each may directly contain the other, but not itself.)

Consider now a lexi intended to parenthesizes a comma separated list of expressions.

```
@Find @Expressions @prepend( @append)
```

A definition of an execution order must be able to deal with the application of this lexi to (pruned) input such as

```
1,2,(3,4,5)
```

As it turns out, `@Expressions` matches the above input a dozen times:

- There are 6 distinct matches in the outer comma separated list:
  - 3 matches in which the list has only one `@Expression`: “`1`”, “`2`”, and “`(3,4,5)`”;
  - 2 matches in which the list is made by two matches of `@Expression` separated by a match with a comma: “`1,2`” and “`2,(3,4,5)`”; and,
  - 1 match of list of three elements: “`1,2,(3,4,5)`”.
- Similarly, there are 6 additional matches in the inner list:
  - 3 with list of size one: `3`”, “`4`”, and “`5`”;
  - 2 with list of size two: “`3,4`”, “`4,5`”; and,
  - 1 with list of size three: and, “`3,4,5`”.

The canonical Perl “*regexen*” and many other regular expression subsystems exercise *greedy* matching policy in which only the longest possible match is used. There is often also a *lazy* version of the Kleene star regular expression constructor and of the “optional” element constructor.

In contrast, Lola uses the full range of semantics between *lazy* to *greedy*: the matching engine is generating, at least conceptually, *all* possible matches.

Not all matches trigger the lexi. In fact, at each iteration of Lola’s main loop, only one match triggers: this is single match that “*overrules*” all other candidate matches. The effect of triggering this *overruling match* is a replacement of the *matched substring* of the input by a *substitution string* that might be longer, short, of the same length, and even identical to the matched string.

To guard against accidental infinite recursion, the overruling match is earmarked as have been applied to the substitution string.

At the next iteration Lola regenerates (conceptually) the set of all matches making sure to ignore earmarked matches. This set is typically different than the set of matches in the previous iteration, since the input string has changed. But, again, the overruling match is determined, earmarked, triggers its lexi.

7.4 Lola's Iterative Fixed Point Behavior

The triggering of lexies in LOLA follows an iterative and stops only when a fixed-point is reached. At each step, LOLA examines *all* matches of *all* of lexies, selecting only one of them, triggering it (possibly changing the text), and reiterates. Iteration stops when no more matches can be found.

More formally, the *conceptual* iterative procedure that LOLA uses to exhaustively apply lexies to the pruned input is presented in Algorithm 7.1.

Algorithm 7.1 Function $\mathsf{fixedPoint}(\mathcal{L}, S)$ receiving a set of lexies $\mathcal{L}$ and pruned text S, and returning S after all lexies in $\mathcal{L}$ were exhaustively applies to it.

```
1:  Repeat                                              // find winner of match of matches and trigger it
2:    $\mathcal{M} \leftarrow \emptyset$                // set of potential matches is initially empty
3:    For $L \in \mathcal{L}$ do                        // examine all lexies
4:      For all $f, t$, s.t. $0 \le f \le t \le \mathsf{length}(S)$ do   // examine all substrings $S_{f,t}$ of $S$
5:        If $f \le \mathsf{offset}(L)$ then            // lexi $L$ was defined before $S_{f,t}$
6:          continue                                    // $L$ not applicable to a substring starting before $L$ was defined
7:        Let $M \leftarrow \langle L, S_{f,t} \rangle$  // create a "match" record
8:        If $\mathsf{earmarked}(M)$ then               // $L$ previously applied $S_{f,t}$ or to $S_{f',t'}$ $S$ containing it
9:          continue                                    // don't apply $L$ to its own output
10:       $\mathcal{M} \leftarrow \mathcal{M} \cup \{M(S_{f,t}, L)\}$   // record a match candidate
11:   If $\mathcal{M} = \emptyset$ then                 // no more applicable lexies
12:     Return $S$                                      // we are done
13:   $M \leftarrow \mathsf{first}(\mathcal{M})$       // pick some arbitrary $M \in \mathcal{M}$
14:   For $M' \in \mathcal{M}$ do                       // search for the smallest $M \in \mathcal{M}$
15:     If $M'.\mathsf{overrules}(M)$ then              // is $M'$ smaller than $M$
16:       $M \leftarrow M'$                             // better match found
17:   $M.\mathsf{trigger}()$                            // trigger the lexi, possibly changing $S$
18:   $M.\mathsf{earmark}()$                            // prevent further triggering with $M$
19: until done
```

Lines 2–10 creates the list of all matches, by examining all substrings and all lexies.[1] Two exceptions are made though: a lexi is not allowed to match substring that started before the lexi was defined (lines 5–6), and a match which was earmarked for having been triggered before is not considered (lines 8–9).

Lines 11–12 stop execution when the fixed point was reached, i.e., no more valid non-earmarked matches were found. Lines 13–16 selects the winning match, i.e., match M that overrules all $M' \in \mathcal{M}$, $M' \neq M$. Match M is then triggered at line 17.

Earmarking, done at line 18, means that the lexi of M will never be triggered again, neither for the concrete substring it matched nor for any substring of it, however these substrings are transformed by later applications.

The four rules that determine the total order of overruling among matches are listed in Figure 7.1.

[1]The actual implementation is of course much more efficient. LOLA never produces a match if it is guaranteed to be overruled.

Figure 7.1 The four rules that impose a total order on candidate matches, whereby ensuring existence of a single overruling match

1. *Inner to Outer:* If match M_1 is strictly contained in match M_2, i.e., $M_1 \subset M_2$ then M_1 overrules M_2.
2. *Left to Right:* If neither $M_1 \subset M_2$ nor $M_2 \subset M_1$, then M_1 overrules M_2 if M_1 begins before M_2 does.
3. *Single Chance:*
   (a) no match can trigger more than once, *moreover*,
   (b) a match can never be triggered on its own output, and, *even more yet*,
   (c) a lexi is never applied to a substring of its own output.
4. *Latest Overrules:* Otherwise, the substrings associated with match M_1 and match M_2 must be equal, i.e., M_1 and M_2 matched simultaneously.

   In this case, M_1 overrules M_2 if the lexi of M_1 was defined at a location that occurs later in the code in the lexi of M_2.

The first rule is that lexies work their way bottom-up, preferring matches to longer ones. The second is that in the absence of containment relationship, matches are executed left to right, i.e., in the order of their beginning point.

The third rule is to guard against accidental recursive definition, and to make it possible for a lexi to `@append` or `@prepend` code, without going into an infinite series of applications. The rule does not provide absolute production. A stubborn program can write two lexies whose fixed computation will inflate the code for ever.

The fourth rule, giving higher priority to lexies defined later, is to make it easier for clients to override lexies imported from an external library.

In what follows we formulate these rules more precisely, and try to make them more intuitive.

7.5 Locations and Substrings

7.5.1 Locations

A *location* in the string of n tokens $\tau_0 \cdots \tau_{n-1}$ might be either the point *just before the first* token, the point *just after the last* token, or, any point *between two consecutive tokens*. For i in the range $0 \ldots n$, integer, ℓ_i is the $(i+1)^{th}$ location.

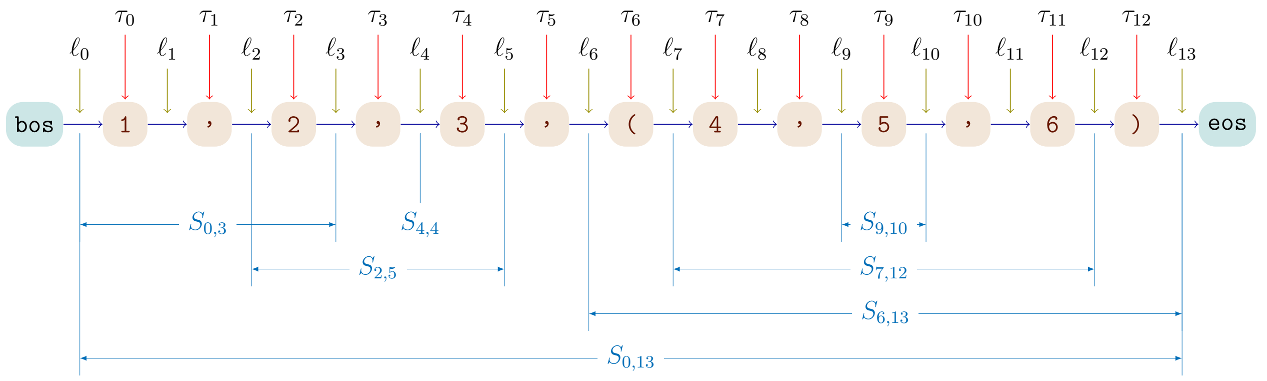
As depicted in Figure 7.2 the input string of 13 tokens

```
1,2,3,(4,5,6)
```

has $13+1$ locations, denoted

$$\ell_0, \ell_1, \ldots, \ell_{12}, \ell_{13}.$$

Figure 7.2 Tokens, locations and substrings for the tokens string `1,2,3,(4,5,6)`



τ_0 τ_1 τ_2 τ_3 τ_4 τ_5 τ_6 τ_7 τ_8 τ_9 τ_{10} τ_{11} τ_{12}
ℓ_0 ℓ_1 ℓ_2 ℓ_3 ℓ_4 ℓ_5 ℓ_6 ℓ_7 ℓ_8 ℓ_9 ℓ_{10} ℓ_{11} ℓ_{12} ℓ_{13}
bos 1 , 2 , 3 , (4 , 5 , 6) eos
$S_{0,3}$
$S_{4,4}$
$S_{9,10}$
$S_{2,5}$
$S_{7,12}$
$S_{6,13}$
$S_{0,13}$

These 14 locations are placed in the string "`1,2,3,(4,5,6)`": *just before the first token* (ℓ_0), *between two consecutive tokens* ($\ell_1, \ldots, \ell_{12}$), or, *just after the last token* (ℓ_{13}).

7.5.2 Substrings

Let ℓ_f be some location, and let ℓ_t, $f \leq t$ be some other location. Together, ℓ_f and ℓ_t define a *substring*

$$S_{f,t} = \tau_f \cdots \tau_t,$$

i.e., the zero-or-more tokens (precisely $f - t$) between ℓ_f and ℓ_t.

In the figure we see that $S_{4,4}$ is empty, that $S_{0,13}$ contains all tokens, that $S_{9,10}$ is made by the single token $\tau_9 =$ `5`, and that $S_{2,5}$ contains three tokens numbered 2 up until (but not including) 5: $\tau_2 =$ `2`, $\tau_3 =$ `v`, and, $\tau_4 =$ `3`.

Any pair of two substrings is either

1. *Disjoint.* Figure 7.2 visualizes e.g., $S_{2,5}$ being disjoint of $S_{6,12}$ and $S_{0,3}$ being disjoint of $S_{4,4}$.

2. *Overlapping.* The only two overlapping substrings in the figure are $S_{0,3}$ and $S_{2,5}$.

3. *Strictly Contained.* In the figure we see e.g., $S_{9,10}$, contained in turn in $S_{7,12}$, contained in turn in $S_{6,13}$, contained in turn in $S_{0,13}$.

4. *Equal.* If two substrings are not disjoint, neither contained in each other, nor overlapping, then they must be equal.

Let

$$\mathbb{S} = \mathbb{S}(n) = \{S_{f,t} \mid 0 \leq f \leq t \leq n\}. \tag{7.3}$$

be the set of all such substrings. Now the evaluation order question is firstly a matter of imposing a total order on set $\mathbb{S}$.

7.6 Total Order of Overruling

We say that a substring $s = S_{f_1,t_1}$ *overrules* another substring $s' = S_{f_2,t_2}$ if either one of the following two holds:

- it is strictly contained in it, $S \subset S'$, i.e.,

$$\big(f_2 < f_1 \leq t_1 \leq t_2\big) \vee \big(f_2 \leq f_1 \leq t_1 < t_2\big) \Rightarrow S'.\mathsf{overrules}(S) \tag{7.4}$$

  or,

- if S' does not (strictly) contain S, i.e., $S' \not\supset S$, *and* S begins before S', formally,

$$\neg\Big(\big(f_1 < f_2 \leq t_2 \leq t_1\big) \vee \big(f_1 \leq f_2 \leq t_2 < t_1\big)\Big) \wedge \big(f_1 < f_2\big) \Rightarrow S'.\mathsf{overrules}(S). \tag{7.5}$$

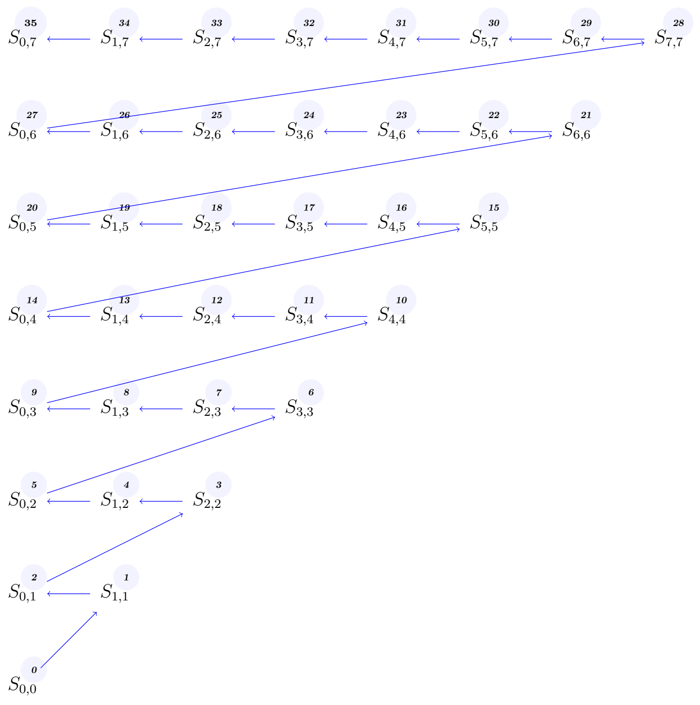
More generally, the overruling relationship is the order relationship generated as the transitive closure of the above two conditions.

We now show that overruling is well defined, i.e., that no cycles are do not lead to a cycle, and that it is a total order, i.e., that it is defined over all substrings. To do so, define a ranking function $r : \mathbb{S} \to \mathbb{N}$,

$$r\big(S_{f,t}\big) = \frac{t(t+1)}{2} + t - f. \tag{7.6}$$

Figure 7.3 demonstrates that r defines a total order on $\mathbb{S}(7)$; the formal proof follows.

Figure 7.3 The total order imposed by overruling on $\mathbb{S}(7)$, the set of substrings of a string of length 7


35 $S_{0,7}$ 34 $S_{1,7}$ 33 $S_{2,7}$ 32 $S_{3,7}$ 31 $S_{4,7}$ 30 $S_{5,7}$ 29 $S_{6,7}$ 28 $S_{7,7}$
27 $S_{0,6}$ 26 $S_{1,6}$ 25 $S_{2,6}$ 24 $S_{3,6}$ 23 $S_{4,6}$ 22 $S_{5,6}$ 21 $S_{6,6}$
20 $S_{0,5}$ 19 $S_{1,5}$ 18 $S_{2,5}$ 17 $S_{3,5}$ 16 $S_{4,5}$ 15 $S_{5,5}$
14 $S_{0,4}$ 13 $S_{1,4}$ 12 $S_{2,4}$ 11 $S_{3,4}$ 10 $S_{4,4}$
9 $S_{0,3}$ 8 $S_{1,3}$ 7 $S_{2,3}$ 6 $S_{3,3}$
5 $S_{0,2}$ 4 $S_{1,2}$ 3 $S_{2,2}$
2 $S_{0,1}$ 1 $S_{1,1}$
0 $S_{0,0}$

The following technical lemma is pertinent:

Lemma 7.1. *Let $S_{f_1,t_1}, S_{f_2,t_2} \in \mathbb{S}$, $t_1 < t_2$. Then $r(S_{f_1,t_1}) < r(S_{f_2,t_2})$.*

Proof.

$$\begin{aligned} r(S_{f_2,t_2}) &\overset{1}{=} \frac{t_2(t_2+1)}{2} + t_2 - f_2 \\ &\overset{2}{\geq} \frac{(t_1+1)(t_1+2)}{2} + t_2 - f_2 \\ &\overset{3}{=} \frac{t_1(t_1+1)}{2} + t_1 + 1 + t_2 - f_2 \\ &\overset{4}{>} \frac{t_1(t_1+1)}{2} + t_1 - f_1 \\ &\overset{5}{=} r(S_{f_1,t_1}) \end{aligned} \tag{7.7}$$

(1) By definition.

(2) Since $t_2 > t_1$, it must be that $t_2 \geq t_1 + 1$. The substituted expression is an increasing function.

(3) Simplifying the first expression.

(4)

$$\frac{t_1(t_1+1)}{2} + t_1 + 1 + t_2 - f_2 > \frac{t_1(t_1+1)}{2} + t_1 - f_1$$

iff

$$t_1 + 1 + t_2 - f_2 > t_1 - f_1$$

iff

$$1 + t_2 - f_2 > -f_1.$$

The last equation holds because $t_2 - f_2 \geq 0$ (since, by the definition of a substring we have $0 \leq f \leq t$).

(5) By definition.

□

Lemma 7.2. *Function r is a mapping (a one-to-one function).*

Proof. Let $S_{f_1,t_1}, S_{f_2,t_2} \in \mathbb{S}$. If $t_1 < t_2$ then Lemma 7.1 implies that $r(S_{f_1,t_1}) \neq r(S_{f_2,t_2})$. Similarly for the case that $t_1 > t_2$. If $f_1 \neq f_2$, $t_1 = t_2$ then

$$\frac{t_1(t_1+1)}{2} + t_1 - f_1 \neq \frac{t_2(t_2+1)}{2} + t_2 - f_2$$

if and only if,

$$\frac{t_1(t_1+1)}{2} + t_1 - f_1 \neq \frac{t_1(t_1+1)}{2} + t_1 - f_2$$

if and only if,

$$-f_1 \neq -f_2$$

if and only if,

$$f_1 \neq f_2.$$

□

Lemma 7.3. *Function $r(\cdot)$ follows the* precedes *desiderata eq. (7.5).*

Proof. Equation (7.5) implies $t_1 < t_2$, and therefore, by Lemma 7.1 we have

$$r(S_{f_1,t_1}) < r(S_{f_2,t_2}).$$

□

Lemma 7.4. *Function $r(\cdot)$ follows the* containment *desiderata eq. (7.4).*

Proof. The equation $r(S_{f_1,t_1}) < r(S_{f_2,t_2})$, which translates to

$$\frac{t_1(t_1+1)}{2} + t_1 - f_1 < \frac{t_2(t_2+1)}{2} + t_2 - f_2 \tag{7.8}$$

holds since

$$t_1 - f_1 < t_2 - f_2 \tag{7.9}$$

and

$$\frac{t_1(t_1+1)}{2} < \frac{t_2(t_2+1)}{2}. \tag{7.10}$$

(because $t_1 < t_2$). □

Lemma 7.5. *The desiderata describes a total ordering.*

Proof. Since $\leq$ is a total ordering over $\mathbb{N}$, and r preserves the order of substrings, a total ordering that conforms to the described desiderata exists. □

7.7 Understanding Overruling

To understand the rationale of overruling, eqs. (7.4) and (7.5), and the figure examine the four cases in which s overrules s':

- the substrings s and s' are *disjoint*, and S_{f_1,t_1} begins and ends before S_{f_2,t_2} begins, or,
- the substrings s and s' *overlap* and S_{f_1,t_1} begins before S_{f_2,t_2} begins, or,
- substring S_{f_1,t_1} is *strictly contained* in S_{f_2,t_2}, or,
- substrings S_{f_1,t_1} and S_{f_2,t_2} are *equal*, and the definition of the lexi of M_1 took place after the definition of the lexi of M_2.

Let us consider these four cases in order:

1. *M_1 precedes M_2*, that is to say,

   $$f_1 < f_2 \text{ and } t_1 < t_2. \tag{7.11}$$

   The rationale is that if a certain substring both begins before another substring and ends before that substring, then a match against the first substring must be processed before a match with the second. Consider an enumeration that starts with the `Enum` word, and ends with a `Mune`:

   ```
   Enum
     ONE = iota
     TWO = iota
     NUM = iota
   Mune
   ```

   As in the Go [11] programming language, the user may use the word `iota` to indicate a literal whose value is incremented by one any time it is used (in Go, the value is incremented in a slightly different way).

   The structure is created using the lexies

   ```
   @Find(Enum) Enum @run {global i; i = 1}
   @Find(Iota) iota @replace @(i) @{i+=1}
   @Find(Mune) Mune @log ('enum is over')
   ```

   The order of matches, as probably expected, is `Enum`, `Iota` and then `Mune`.

2. *M_1 is a prefix of M_1*, or, in other words,

   $$f_1 = f_2 \text{ and } t_1 < t_2. \tag{7.12}$$

   Continuing the previous example, and assuming the lexi

   ```
   @Find(Whole) Enum @Any(body) Mune
   @replace enum { @(body) }
   ```

   we see that the lexi `Enum` is matched before lexi `Whole`.

   The presented lexi is used to convert the special `Enum` to a C `enum`. Note that this lexi is not aware of the `Iota` lexi. A longer pattern should "understand" what it sees, i.e., what it contains. Its contents, or the contents of the `body` variable, should be based on the host language, rather than some macros that will be expanded later.

   This rule, and the two following ones, are the reason that this pattern matches over the code after the rewriting.

3. *M_1 is contained in M_2*, that is to say,

   $$f_1 > f_2 \text{ and } t_1 < t_2. \tag{7.13}$$

   According to this rule, the `Iota` lexi is matched before the `Whole` lexi.

   Another interesting case that belongs to this category is the case of nested classes. In this case, it means that the inner class will match first.

4. *M_1 is suffix of M_2*, or, more formally,

$$f_1 > f_2 \text{ and } t_1 = t_2. \tag{7.14}$$

   The reasoning is similar to previous rules, and is demonstrated in that the **`Mune`** lexi is matched before **`Whole`**.

5. *M_1 and M_2 are equal*, i.e.,

$$f_1 = f_2 \text{ and } t_1 = t_2, \tag{7.15}$$

   and M_1's lexi was defined after M_2's lexi. We would like to enable the overriding of a previously defined lexi with a new lexi, since it is assumed that the latter is aware of the former.

   For example, a definition of the lexi

```
@Find iota @replace @(1 << i) @{i+=1}
```

   after the **`Iota`** lexi, and before the usage, will override the previous definition (the **`Iota`** lexi), resulting in an **`iota`** that yields a power of 2 each time it is accessed.

7.8 The Single Chance Principle and Earmarking

The representation of substrings and locations is such that the replacement of content of substring by another content, does not invalidate the substring data structure. A substring is invalidated only if one of its end points was substituted, being contained in another substring, disappeared when this containing substring was substituted itself.

As per the *Single Chance* principle, a triggered lexi tracks (as long as possible) the range of tokens in the buffer string which it processed, regardless of how this range shrinks or enlarges, and will never match this range again. We say that the lexi is earmarked with this substring it manipulated, and will not reprocess it again.

In particular, this means that if lexi a was triggered on substring s, and lexi b was triggered on a substring s, $s' \subseteq s$, then a will not be triggered for the s even though it was partly or even fully modified.

Here is an example: When the two lexies

```
@Find Hello @replace Hi
@Find Hi @replace Hello Hello
```

are applied to

```
Hello
```

After the first triggering the string of tokens will be

```
Hi
```

and after the second triggering

```
Hello Hello
```

There will be no third triggering.

This earmarking technique works nicely with these two lexies, which seem to be mutually recursive:

```
@Find Hello @replace Hi
@Find Hi @replace Hello
```

When applied to **`Hello`** the buffer changes to **`Hi`** after the first triggering, and back to **`Hello`** in the second, and final, triggering.

7.9 The Inner Out Principle and Backtracking

At each input token Lola scans in the buffer, it starts one *listener* for every lexi it stores. This listener tries to match the pattern starting at this token. Also, as tokens are read, all active listeners are notified. This notification can be replied by the listener, telling Lola that a match was found. If the listener also detects that other, longer matches can be found as well, it forks, and the forked listened proceeds with the search for matches. The matched listener however creates a match data structure, which is then send to the grand match of matches.

Lola maintains a concept of a *current token* in processing its buffer. Often this token is read and copied as is to the output stream. However, if one or more listeners mature at the current token, a lexi is triggered, changing the current buffer, the matched substring is removed and replaced with the output of this lexi.

After the substitution Lola backtracks the current-token to the beginning of the replaced substrings, restoring the state of all pattern matchers as they were at that point. Lexies therefore get a chance to further transform the output of other lexies.

Nested matches of the same pattern are shown in Listing 7.1. The *Inner to Outer* principle says that triggering is on the matches the inner **`squared`**. The second triggering, only after the restart the second one will also match.

Listing 7.1 An example of how nesting of rewrites works

```
@Find squared @Literal(f)
@replace @(f * f)
@example double sixteen = squared squared 2.0;
@resultsIn double sixteen = 16.0;
```

Chapter 8

Conclusions and Future Work

In a world where new programming languages are introduced frequently but change slowly, in a world where the M4 preprocessor is a string substitution tool collecting dust, C preprocessor dying, and TEX is baffling, LOLA, comes in to offer a new perspective on pre-processing.

LOLA maintains the usual pre-processing principles: non-intrusive extension to the programming language, and not any runtime impact, while supporting high-level programming language structure. LOLA's should be useful for identifying structures in source files, and it has some capacity for reflection. LOLA suggests a flexible syntax for macro calls, for adding constructs that are more intuitive to the individual programmer, and that fit better in the specific programming domain.

My work was intended to make LOLA terse, elegant, readable, writable and language independent. Towards the end of readability, LOLA's statements try to follow English like sentence structure, including capitalization conventions to make reading smoother: `@CamelCase` convention for constructors,@camelCasĕ convention for for elaborators, and absolutely no abbreviations or acronyms, not even for familiar terms such as EOF. (The rationale is this: Obviate the need to remember these times when acronyms and common abbreviations are used. This never happens). Elegance and brevity are achieved through a powerful model of pattern matching and code generation.

I hope that the fruits of my work can be appreciated by readers of this essay and that the resulting LOLA bears the potential of evolving into a tool that would be used by many programmers.

In many ways, LOLA supersedes everyday tools such as "grep", "sed", AWK, PERL, PYTHON and others, in the context of applying of their application to software. In this sense, LOLA is a software engineering tool: When put in the hands of able programmers it makes it possible to "engineer" the software itself, modify it, enhance it, measure it, and reason about it.

A combination of external scripts and other software tools can, and are, used, to, e.g., compute the Halstead metrics, or enforce the style rule (practiced mercilessly in Google) that C++ classes should never inherit from more than one class. With LOLA, the same deeds are carried out in a tongue that programs already speak: the host programming language itself, albeit augmented with LOLA's syntax. And, it makes it possible to do all that in a reproducible, concise and modular fashion.

The work on LOLA turned out to be much larger than planned. The major challenges encountered on course were:

- Maintaining expressive power, elegance and brevity. Achievements toward meeting this challenge can be seen in the examples gallery (Chapter 3).

- A simple theoretical model unifying the major language concepts including constructors, elaborators, lexies, generating expressions etc. (Chapter 4).
- The design of the configuration file so that it can adapt LOLA to many programming languages (Chapter 5).
- The unique use of indentation in the language, and the algorithm for parsing in presence of the three kinds of children: PYTHON snippets, the list, and the elaborators (Chapter 6).
- The exact semantics and ordering of evaluation of immediates and lexies (Chapter 7).

8.1 Future Research

Here are some directions for future research of major enhancements to LOLA.

- Currently, LOLA support for patterns that explore the contents of a trivia is limited to atomic patterns such as **`@NewLine`** and **`@EndOfFile`** and the **`@Unbalanced`** modifier.

  A future extension is to support finer grained pattern matching that makes it possible to further examine the contents of trivia. The need for such an extension may arise if LOLA is employed to process comments' text, as may be necessary for the processing of JAVADOC.

- Similarly, the need for matching patterns against the contents of the string literals may arise. LOLA must be extended to be able to do this.

- More generally, it should be also possible change the host programming language on the fly, so that LOLA can handle XML structure embedded in JAVA, SQL embedded in AWK, etc.

  Such a generalization should supersede LOLA enhancements for processing strings and comments.

- Since LOLA is a language for extending languages, it is only natural to ask whether LOLA can be used for extending LOLA itself. Currently such a recursive application is not possible, mostly because LOLA directives are removed from the input immediately. But, just like many recursive questions of this sort, this research direction is likely to be fun more than useful.

- Keywords in LOLA are implemented using an API is intended to be accessible by mortal programmers. The implementation of a new keyword should be a matter of defining a simple and short PYTHON class. We wish to make it possible to define new LOLA keywords from within LOLA itself.

8.2 Lola's Past and Planned Evolution

Candidly speaking, premature optimization concerns and the sheer challenge of implementing a **D**eterministic **F**inite **A**utomaton (DFA) for conjunction and negation constructors of regular expressions, were the reasons why "Lola 0.032" was implemented with a DFA engine.

Lola steps its versions in multiples of two, with this current short past and future grand plan:

Lola 0.032 *First experimental implementation.* This was my initial, DFA based implementation. Examples in this thesis are based on experience gained while experimenting with this version. Available for demonstration purpose, but otherwise defunct.

Lola 0.064 Lola as specified in this document (LaTeX*ed* on May 16, 2016), revising Lola 0.032 with cleaner and tighter design, but still based on a DFA engine. *In preparation, might be canceled.*

Lola 0.128 *Planned first public release.*

Lola 0.256 *Cisco deployment.*

Revising the language design and implementation to use the less efficient recursive-descent pattern recognizer, with the advantage of clearer semantics. Based on ideas drawn from Snobol [23], the hypothesis is that the AST of the lexi compound objects is interpreted to be just an elegant way of writing a recursive descent parser for the pattern.

This addition should make it possible to evaluate a general Python expression, a *predicate.* A pattern will match only if the predicate evaluates to `True`, and backtrack otherwise.

Lola 0.512 *Interim version.*

Introducing lexies that analyze spacing, strings and comments. Modifier for lexies to allow greedy and lazy semantics.

Lola 1.024 *First industrial strength release.*

8.3 Reflection

I learned the hard way that relying on cryptic, above all, existing language paradigms is not the way to go. I believe that Lola invents its own little paradigm made of by assembling concepts such as patterns, generating expressions, lexies, etc.

Concepts such as regular expressions and language embedding are more familiar, other, such as generating expressions are less, and others, such as elaborators, "match all possible" (rather than lazy or eager) semantics of regular expressions, or fixed point semantics of search and replace, are quite novel. The particular way in which Lola puts all of these together is what makes it special.

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תקציר

לולה, שפת תכנות להעשרת שפות תכנות, היא הנושא של חיבור על מחקר זה לתואר מגיסטר במדעים במדעי המחשב. לולה היא קדם מעבד מודרני ובלתי-תלוי שפה להעשרת שפות תכנות. בהשראת מגמת דקדוקי-אי, לולה הופכת הרחבות שפה לא טריוואליות רבות לנגישות ואפשריות, וזאת בעזרת לא יותר מאשר כמה שורות קוד.

בעבודת המגיסטר המוגשת נעשה שימוש בלולה לצורך משימות כמו העשרת ג'אווה במילות מפתח כגון This (מקושר לשם המחלקה הנוכחית) וגם Super (קריאה לשיטה הנדרסת עם הפרמטרים אשר הועברו לשיטה הדורסת), גישת בעזרת אינדקס מיקום לפרמטרים, להוספת לולאת for מבוססת טווח לשפת C, להגדרת מבנה max (לחישוב המקסימום על פני מספר לא מוגבל של פרמטרים), להוספת תכונות דמויות תכנות-מונחה-היבטים, ואפילו לחישוב מטריקות קוד. למעשה, לולה היא בעלת כושר ביטוי עשיר מספיק המאפשר למשתמשים להגדיר גרסה משלהם של קדם המעבד של C וקדם מעבדים אחרים, ובתוכם הסמנטיקה המיידית והדחוייה של קדם המעבד make מסביבת Unix.

קובץ הגדרות מונגש למשתמש מגדיר את האסימונים של השפה המארחת. לולה מנתחת את זרם האסימונים (ולא את זרם התווים הגולמי) עם ביטויים רגולריים מורחבים ומפעילה ביטויים מחוללים כדי להחליף, למחוק או לשנות בצורה אחרת חלקים מהקלט אליה. העשרת שפה מתבצעת על ידי שימוש מתאים בלקסים, כאשר כל לקסי היא יחידת תפקוד הצהרתית בחלקה המתארת התמרת קוד מסויימת ופעולות עיבוד שונות המביאות להתמרה זו.

ביסודה של לולה נמצא מנוע פייתון, ולמתכנתי לולה ניתנת גישה מלאה לתכונות שפת פייתון. היבט זה מאפשר את השארת הגדרת שפת לולה קצרה ותמציתית, תוך התמקדות בשזירת מילות המפתח של לולה, זרם האסימונים מהשפה המועשרת וקוד פייתון, בהם המתכנת בוחר להשתמש באופן רציף.

בעיית החסר בשפות תכנות הינה בעייה אינהרנטית בתכנון שפות תכנות, שכן הוספת תכונה עלולה להשפיע על היבטים לא צפויים. בנוסף, שפה המשתנה באופן בלתי שקול אינה אמינה דיה לפיתוח מתמשך. המחשה לכך שבעיית חסר זו קיימת היא שבשפת ג'אווה לקח כעשרים שנים מהתחלת הצטברות התלונות ועד להוספת המבנה המבוקש של switch על מחרוזות.

חיבור זה מקדם רעיון הגורס כי בעזרת כלי קדם עיבוד רב עוצמה, מתכנתים יוכלו להוסיף אבסטרקציות חדשות לשפת התכנות בה הם משתמשים מבלי להזדקק (ולהמתין) להרחבת שפת התכנות עצמה. כדי לתקף טענה זו מוצגת בזה שפת התכנות לולה המאפשרת את הוספת האבסטרקציות המדוברות מבלי לשנות את ליבת השפה המארחת. כדוגמה אף מוצג לקסי אשר מוסיף מבנה זה לשפה.

כמושא עיקרי למטרה זו אנו בוחנים את שפת C כשפה המארחת. אנו מעוניינים שלא לפגוע בעיקרון העדר העלות החבויה ואף על פי כן לאפשר מטא-תכנות. כל זאת תוך שימוש במושג המוכר של קדם עיבוד. אכן, קדם המעבד המוכר ביותר, קרוב לוודאי, הינו זה של שפת C. עם זאת, קדם מעבד זה חסר את יכולת הביטוי של שפות תכנות למטרה כללית. בניגוד לכך, לולה מתפקדת כשפת תכנות מלאה.

אחת המטרות החשובות בפיתוח שפת לולה היא לפשט את פעולת זיהוי מבני קוד בקבצי המקור. לולה מציעה תחביר גמיש המשמש לביצוע לקסים. בעזרת לולה מתאפשרת יצירת תחביר אשר יתאים לשפת תכנות בתחום מסויים.

לולה עושה שימוש בתחביר דמוי אנגלית ובמילים בשפה האנגלית, אשר מהווים בסיס לשפה אסוציאטיבית וקריאה לכתיבת לקסים, וזאת בניגוד לשימוש בסימנים שונים המקובלים בשפות רגולריות כגון * (כוכבית לסימון חזרה), ? (סימן שאלה לסימון אופציונליות) וכדומה. מעבר לשימוש בתחביר זה לצורך הגדרת תבניות, כמתואר לעיל, תחביר זה מהווה בסיס אינטגרטיבי ועקבי להגדרה אוניברסלית של השפה.

הבעות תודה

המחקר נעשה בהנחיית פרופ' יוסף גיל בפקולטה למדעי המחשב

אני מודה לטכניון על התמיכה הכספית הנדיבה בהשתלמותי

לולה

שפת תכנות

להעשרת שפות תכנות

חיבור על מחקר

לשם מילוי חלקי של הדרישות לקבלת התואר

מגיסטר למדעים במדעי המחשב

עידו א. זמירי

הוגש לסנט הטכניון - מכון טכנולוגי לישראל

ניסן תשס"ו,   חיפה,   אפריל 2016