UNIVERSITÀ DEGLI STUDI DI PADOVA

Facoltà di Ingegneria Informatica, DEI

Degree Thesis

Designing a flexible compilation framework for CAL language

Laureando
Fabio Rampazzo

Relatore
Prof. **Sergio Congiu**

Correlatore
Prof. **Per Andersson**

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I

. . . io so che Miché
ha voluto morire perché
ti restasse il ricordo del bene profondo
che aveva per te. . .

Abstract

The CAL, created as a part of the Ptolemy II project [1], is an open source actor-based data-flow language. Some of its contributors are Xilinx, Ericsson research, and the MPEG-consortium. More information about CAL can be found at opendf.org.

Today there exist several back ends for CAL, all share a common front end, which translates the CAL language to an intermediate format called XLIM. The back end then translates XLIM to the target language, i.e., VHDL, C, and ARM (C code and run-time environment). The existing tool chains are based on XML and XML-transformations (XSLT), but the expressiveness of the XSLT language limits which transformations can be carried out. Furthermore, some parts of the existing front end are not efficient implemented and for larger designs the compilation time can be very long.

In the existing tool chains some mapping decisions are taken very early, for example, action schedulers, for managing the firing of actions in an actor, are generated as one of the first steps in the front end. This is done before the intermediate format is generated. The main consequence, of this fact, is that it is hard for the back end to extract the firing rules of the actors which is needed to implement other scheduling policies or distributing the scheduling on several computational nodes.

In this project work I implemented a new front end for CAL using JastAdd. The new front end parses actor descriptions (.cal files) and network descriptions (.nl files) and generates the intermediate format XLIM. The new front end implementation is combinable with the existing back ends.

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Chapter 1

Introduction

This project is based on a five months Erasmus experience at the LTH department of Lund University. I worked in a start up phase of the project which is looking into compiling the data flow language CAL to coarse grained configurable arrays.

Today a CAL compiler is available thanks to a tool chain created by the openDF community. It is composed by two main parts: the front end parses the CAL program, applies some transformations and generates an intermediate representation called XLIM. The back end then translates XLIM to the target language, i.e., VHDL, C, and ARM (C code and run-time environment) At the moment the problem is that some parts of the front end are not efficient implemented, so it is currently a bottleneck. Thus, the translation process is slow, almost half an hour for larger programs, although the computations involved in this step should only take a few seconds.

My thesis project implements the CAL front end, using JastAdd, a compiler generator developed at the department. It parses actor descriptions (.cal files) and network descriptions (.nl files) and generates the intermediate format XLIM.

This report is structured in three chapter:

Chapter 2 contains the background knowledges that allowed me to realize this project:

- the dataflow programming paradigm, whose CAL is an instance of this class;
- the compiler construction phases and the tools that realized them.

Chapter 3 gives a description of each element that I realized in order to build the front end, they are:

- two lexical analyzers (one for CAL and one for NL), using jFlex tool;
- two syntax analyzers, using Beaver for the parser specification and JastAdd for the abstract syntax tree construction;
- a set of modules that allow the semantic analysis and the translation to the intermediate representation.

Chapter 3 treats about final considerations, as conclusions and future works.

1.1 Problem statement

In this project I was assigned to design a flexible compilation framework for CAL language in JastAdd. The aim of this work is to realize a front end that parses actor descriptions (.cal files) and network descriptions (.nl files) and generates the intermediate format XLIM. It should be possible to combine with the existing back ends.

The assignment of a front end designing is a multi-step job. Firstly, a scanner needs to be developed, for the lexical analysis, secondly, a parser, for the syntax analysis and the abstract syntax tree construction. After that, a set of elements are required for the semantic analysis and for the intermediate code generation. Even though each step works and produces informations for the next one, it is been realized as an independent module. This was possible through the use of JFlex, Beaver and JastAdd tools, which can be interfaced to work together. However, the modification of a module may lead to the rewriting of the high-level modules.

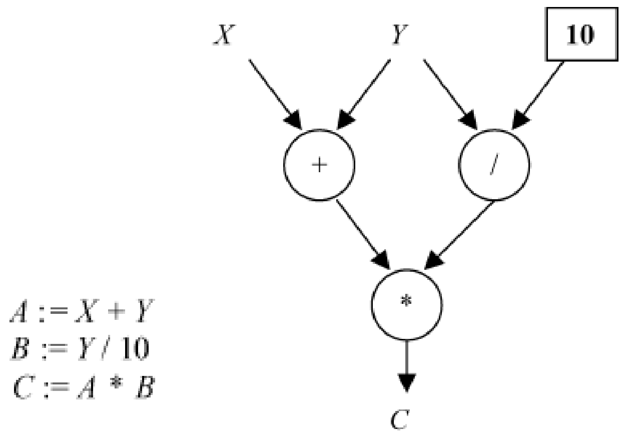
Chapter 2

Background knowledge

2.1 Dataflow Programming

In dataflow programming paradigm a program is modeled as a direct graph whose nodes are operators and whose arcs are data paths. An operation has one or more incoming/outgoing paths and we say that it “fires” when its required inputs are available on its incoming paths and it sends the results on its outgoing paths. Therefore operators implicitly work in parallel, since if two or more operations have the possibility to “fire” at the same time they may do it!
The key advantage to choose dataflow programming is that concurrency and parallelism are easy implemented, while this would be difficult using sequential programming language.
Figure 2.1.a shows a fragment of program code and Figure 2.1.b shows how this is represented as a dataflow graph: circles represent instruction nodes, square represents a constant value and letters are variables.
Under the Von Neumann execution model, the program in Figure 2.1.a would execute sequentially in three steps. Whereas, under the dataflow execution model the addition and the division are both immediately fireable, as all of their data is initially present. The results are placed on the output arcs, that represent `A` and `B` variables. Then the multiplication node becomes fireable and is executed. The result is placed on the arc representing the variable `C`. In this scenario, a parallel execution requires fewer steps than sequentially one.

Dataflow paradigm offers the potential to provide a speed improvement. Furthermore, if `X` and `Y` represent sets of data, the computation on the second series of values can be started before those on the first series have been completed. This is known as *pipelined* dataflow.



(a) (b)

Figure 2.1: sequential vs dataflow program.

It's interesting to underline, also, some disadvantages of using dataflow programming:

- the mindset of dataflow programming is unfamiliar to most professional programmers;
- if you need to convert an existent traditional program into data flow program then this could be very difficult especially for the fact that in data flow paradigm there is not the concept of shared data structures.

The intent of this chapter is to provide a short introduction, by constructing a simple example, to the most important features of the actor-based dataflow programming paradigm using CAL and NL languages, for a more detailed description of the syntax of these two languages see [2],[3].

2.1.1 CAL: the Caltrop Actor Language

In CAL an *actor* is a computational entity with input ports, output ports, state and parameters. It communicates with other actors by sending and receiving *tokens* along unidirectional connections. A model, or application, then consists of a network of interconnected actors. When an actor is executed it is said to be *fired* [5]. During a firing:

1. the actor may consume tokens from its input ports;

2. it may modify its internal state;

3. it may produce tokens at its output ports.

One way of thinking about an actor is as an operator on streams of data sequences of tokens enter it on its input ports, and sequences of tokens leave it on its output ports.

In order to underline the main features of the dataflow programming and CAL language we build a simple example that consists of a network of actors which computes the list of Fibonacci numbers. This network, shown in Figure 2.4, is composed of three actors: one that adds two numbers (`AddUntilOverflow`) and two delay blocks (`SingleDelay`). Since the adder block is more interesting than the delay blocks we look inside of it. The first line of the Listing 2.1 declares an actor, called `AddUntilOverflow`, followed by a list of parameters (empty in this case) and the declaration of the input ports, called `X` and `Y`, and output ports, called `Sum`, all of type `int`[1]. The graphical representation of the actor `AddUntilOverflow` is shown in Figure 2.2.

```
actor AddUntilOverflow() int X, int Y ==> int Sum :
    ...
end
```

Listing 2.1: simple actor.

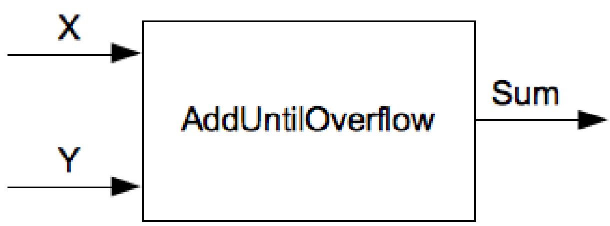


Figure 2.2: graphical representation of the `AddUntilOverflow` actor.

The behavior of an actor is defined by its set of *actions*, in fact, a firing consists of the execution of an action. An actor execution alternate the selection of the next action to fire and the execution/firing of that action. An action declaration is optionally preceded by an *action tag* in front of the keyword `action`. This label is used to refer to the action, or to a set of actions, in fact this tag need not to be unique. At this point the declaration is divided in two parts: the first one, in

[1]CAL is optionally typed: the type declaration of a variable might be not present.

front of the $\Longrightarrow$ symbol, is a list of *input patterns* that defines how many tokens to consume, from which incoming ports, and what to call those tokens in the rest of the action. While the second one, in the right side of the $\Longrightarrow$ symbol, is a list of *output expression* that specifies the number of and the values of the output tokens that will be produced on each output port by each firing of the action. As shown in Listing 2.2, the actor `AddUntilOverflow` has three actions called `run`, `drain` and `terminate`. The first two take one token from each incoming port of the actor, but only `run` produces a token on the outgoing port `Sum`, while the third action takes one token from the `Y` input port, but, as `drain` action, doesn't produce any token. The idea behind the functionality of this actor is clearly suggested by its name and by the design of the network: this actor adds two numbers until the arithmetic overflow occurs (action `run`). When this happens the actor still has tokens at its input ports (which are the products of previous addition). It consumes them without producing other tokens (action `drain`), until it only have one token at one input port (action `terminate`).

```
actor AddUntilOverflow() int X, int Y ==> int Sum :
   run: action X:[x], Y:[y] ==> Sum:[sum]
      ...
      var
         int sum=x+y
   end
   drain: action X:[x], Y:[y] ==>
   end
   terminate: action Y:[lastToken] ==>
   end
   ...
end
```

Listing 2.2: simple actor with actions.

The only condition for an action to be *fireable*, so far, is that there are enough tokens for it to consume as defined on its input patterns. There exist a *nondeterministic* behavior when two or more actions have sufficient input tokens to fire, and the output will be different in agreement on which action it is chosen to fire. It's important to clarify that there aren't rules to determine which action will be fired, so, it's possible to implement a nondeterministic actor, and it can be very powerful when it is used responsibly!

CAL provides a set of additional criteria that need to be satisfied for an action to be fired:

Guard contains a set of expressions that all need to be evaluate to true in order for the action to be fireable. The guard conditions should be exhaustive, otherwise that actor may reach a deadlock. While if they are disjoint we will obtain a deterministic actor, otherwise a nondeterministic one;

Priority is a set of inequality that defines a *partial order* between actions, and this order determines their firing precedence;

Schedule specifies a list of possible state transitions, each state transition consists of the original state, a list of valid action and the target state. So a schedule is a textual representation of a finite state machine.

```
actor AddUntilOverflow() int X, int Y ==> int Sum :
   run: action X:[x], Y:[y] ==> Sum:[sum]
      guard
         sum >= 0
      var
         int sum = x+y
   end
   drain: action X:[x], Y:[y] ==>
   end
   terminate: action Y:[lastToken] ==>
   end
   priority
      run > drain;
   end
   schedule fsm run:
      run (run) --> run;
      run (drain) --> drain;
      drain (terminate) --> drain;
end
```

Listing 2.3: actor `AddUntilOverflow`.

In Listing 2.3 is shown a simple use of the three criteria presented above: in the `run` action there is the guard `sum` ≥ 0. Note that the variable `sum` is what we want to produce in the output, so, a guard conditions, in order to be evaluated, can peek at the incoming tokens without actually consuming them. If it happens to be false or the action is not fired for some other reason, and if the tokens aren't consumed by another action, then they remain where they are, and will be available for the next firing. In relation to the meaning of behavior of this action, the aim of this guard is to check when the arithmetic overflow event occurs. Indeed when this event happens `sum` becomes < 0 and action `run` can't fire.
Listing 2.4 illustrates the behavior of two actors which have non exhaustive and non disjoint guard conditions:

```
actor A() In ==> Out:
   action In:[in] ==> Out:[out]
      guard
         in > 0
```

```
    end
    action In:[in] ==> Out:[out]
        guard
            in < 0
    end
end
actor B() In ==> Out:
    action In:[in] ==> Out:[out]
        guard
            in >= 0
    end
    action In:[in] ==> Out:[out]
        guard
            in <= 0
    end
end
```

Listing 2.4: actor `A` with non exhaustive guards and actor `B` with non disjoint guards.

The actor `A` will be in deadlock if it meets a zero token on its input port (guard conditions not exhaustive), while the actor `B` will run in a nondeterministic way if it meets a zero token on its input port (guard conditions not disjoint). In the case of the `AddUntilOverflow` actor the exhaustivity clause is met and the disjoint clause not, but this problem is resolved by the presence of a list of priority inequalities, in this case by the only inequality `run` > `drain`. This means that the `run` action has higher priority than the `drain` action, so if both are fireable the actor behavior will be deterministic since it will fire the action with the highest priority.
In the end of the `AddUntilOverflow` actor, there's a schedule declaration: a simple way to understand it is to think of the finite state machine that it generates (Figure 2.3). The way to read this is that if the schedule is in `run` state (initial state) and

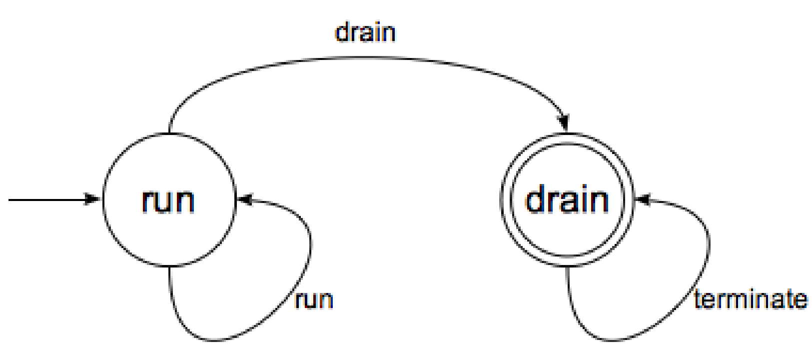


Figure 2.3: finite state machine for the `AddUntilOverflow` actor.

an action tagged with `run` occurs, then the schedule will stay in `run` state, while if the schedule is in the same state and an action tagged with `drain` occurs, then the schedule will changes its state to `drain`. Finally if the schedule is in `drain` state and an action tagged with `terminate` occurs, then the schedule will remain in its final state `drain`.

Now it's possible to define the actor strategy to select the action to fire:

1. determine the set of suitable actions. Suitable actions are those that can possibly be fired according to the schedule. If there is no schedule, then all actions are suitable;
2. from those suitable actions, determine the subset of activated actions. An action is activated if and only if it is suitable and the following conditions are met:
   (a) there are enough tokens available on the input ports to satisfy the input patterns;
   (b) all the guard expressions evaluate to true;
3. from the activated actions, determine the subset of fireable actions. An action is fireable if and only if it is activated and there is no other activated action with a higher priority.

Whereas there isn't any policy for selecting the next action to execute among the set of fireable actions any fireable action may be picked to be fired.

In Listing 2.5 there is the code of the other two components of the `Fibonacci` network which we want to build, but it adds nothing to the discussion except for the fact that here we can see the use of a parametric actor: `SingleDelay` actor has an input parameter, called `initialToken`, whose meaning is to initialize the actor, so in the case of `Fibonacci` network they will be initialized with the first two numbers of the succession.

```
actor SingleDelay(int initialToken) int In ==> int Out :
   init: action ==> Out:[initialToken]
   end
   run: action In:[x] ==> Out:[x]
   end
   schedule fsm init:
      init (init) --> run;
      run  (run)  --> run;
   end
end
```

Listing 2.5: actor `SingleDelay`.

2.1.2 NL: the Network Language

NL is a language for expressing algorithms that compute directed graph among *entities* with *ports*, as expressed in [3]. A use of this language is the description of dataflow system, that consist of several actors (the entities) connected by FIFO channels, from an output port of an actor to an input port of another, along which they pass tokens to each other. NL is designed in respect of three key features:

generality allows the description of arbitrary structures and algorithms computing graph structures;

expressiveness: structures description is kept as simple as possible, but structures representation may be complex;

target independence: NL is a general way to describe structures of the same kind, such as dataflow networks or circuits.

To build a network of actors two main things needs to be done:

1. instantiate the number of actors required;
2. create the connections between them.

In addition, a network of actors can itself have input and output ports, which may be connected to the ports of actors inside it.

The definition of a network, shown in Listing 2.6 is an example, starts similar to that of an actor, with its name (`Fibonacci`), parameters (none in this case), as well as input and output ports (none in this case). This is followed by a section, introduced by the keyword `entities`, that instantiates the actors of the network (actor instances are referred to by their instance names.): one `AddUntilOverflow` actor and two `SingleDelay` actors (with parameter 1 and 0 respectively). In the following section, introduced by the keyword `structure`, contains the definitions of connections between actors. The representation of this declaration is shown in Figure 2.4.

```
network Fibonacci () ==> :
  entities
    d1   = SingleDelay(initialToken=1);
    d2   = SingleDelay(initialToken=0);
    add  = AddUntilOverflow();
  structure
    add.Sum --> d1.In;
    d1.Out -->  d2.In;
    d1.Out -->  add.X;
```

```
        d2.Out  -->  add.Y;
end
```

Listing 2.6: simple `Fibonacci` network.

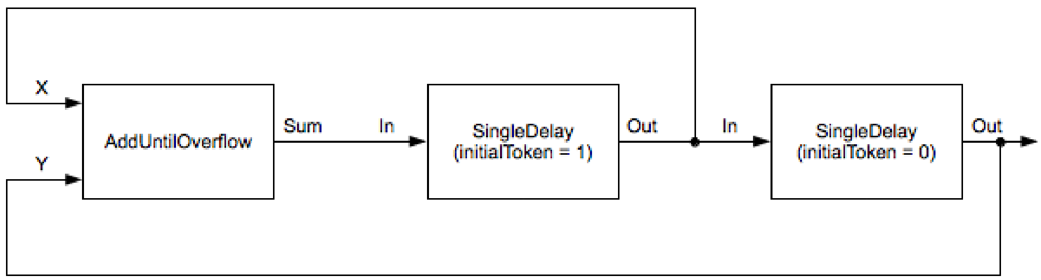


Figure 2.4: `Fibonacci` network.

It would of course be much more convenient to write a NL program for one entire family of generalized network, for example the generalized Fibonacci number generators network. In fact the network language provides a number of constructs that allow the construction of parametric network structures. They are fully described in [3].

2.2 Compiler design

Modern compilers divide the compiling operation in two steps: *front end* and *back end*. In the first step the compiler analyzes and translates the source code written in a computer language (called source language) into an intermediate code. The second step optimizes and translates the intermediate code into a executable binary code. In some cases the compiler generates code in another computer language (called target language) in order to create an executable program. The front end step is divided in more phases:

- lexical analysis;
- syntactic analysis;
- semantic analysis;
- intermediate code generation.

Also the back end step is divided in more phases:

- data and control flow analysis;
- optimization;
- code generation.

The operation flow of a compiler is shown in Figure 2.5.
In this chapter techniques for designing a compiler front end are presented.

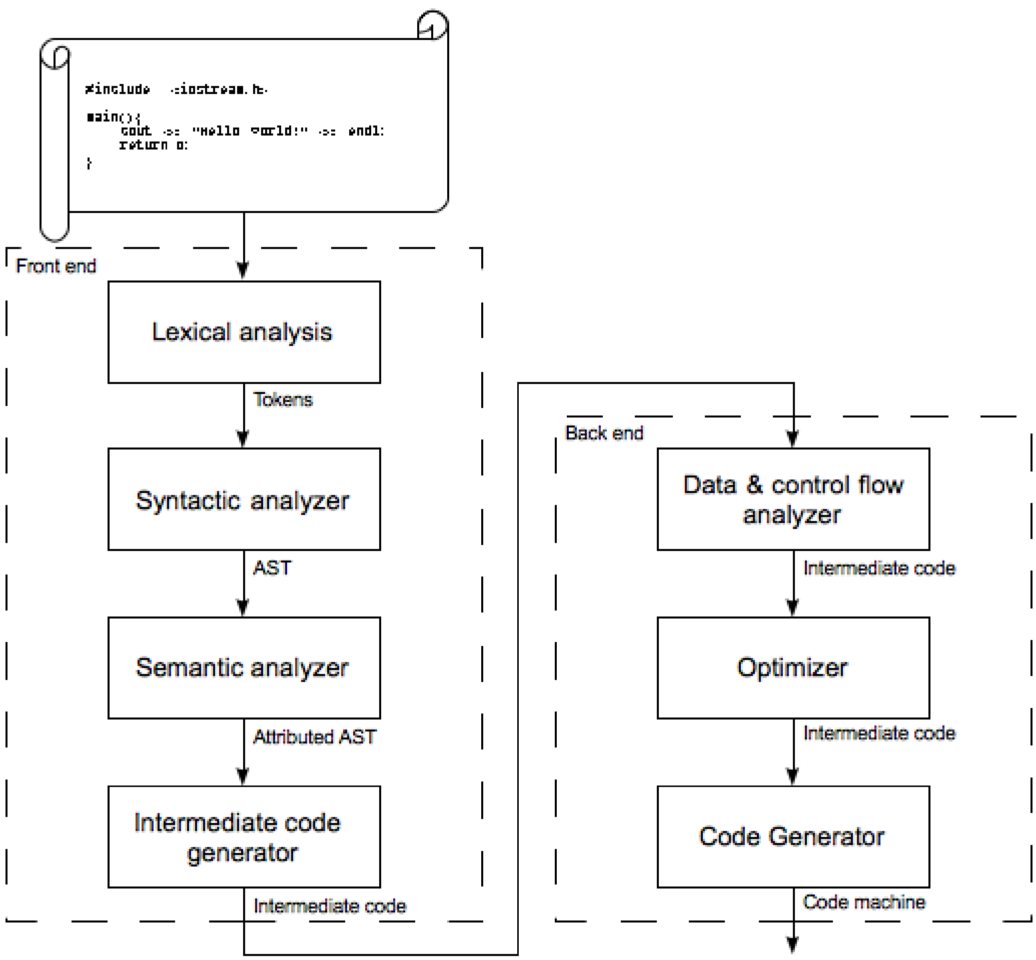


Figure 2.5: compiler design flow.

2.2.1 Lexical analysis

In a compiler front end, the lexical analyzer, also called scanner, reads the source code characters and it assembles them into expressive words, called lexemes. To each of these lexemes coincide a *token* which consists of two components: a type and a value (the lexeme). Therefore, a lexical analyzer takes a stream of characters and produces a stream of tokens, that will be the input of the syntactic analyzer.

Figure 2.6 shows a possible execution of a scanner: the input is a code fragment and the output is the produced stream of tokens. This example shows the most

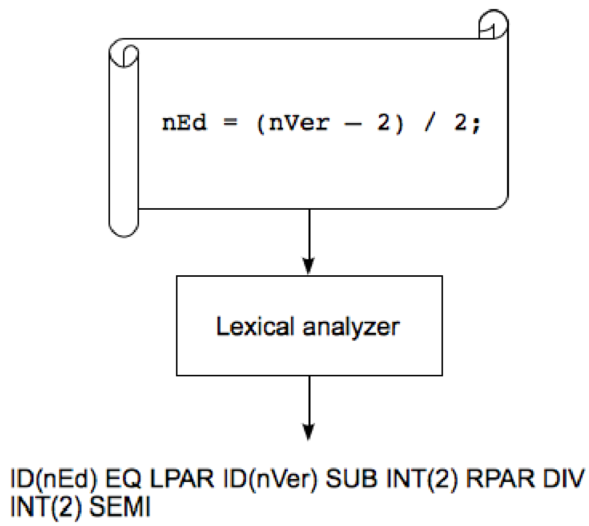


Figure 2.6: tokens generation.

important tokens for a programming language like identifiers, separators, operators and literals, as it's shown in Table 2.1.

Type	**Names**	**Lexemes**
Identifier	ID	nEd nVer
Literal	INT	2
Operator	EQ SUB DIV	= - /
Separator	LPAR RPAR SEMI	( ) ;

Table 2.1: typical token.

For any programming language it is possible to implement an ad hoc lexer, this

is done in a simple and readable way using a lexical analyzer generator. It specifies lexical tokens using the formal language of regular expressions, implements lexers using deterministic finite automata and use mathematics to connect the two.
Using regular expression it is possible to represent a regular language, that is set of finite sequence of *symbols* (each sequence is called *string*) chosen from a non empty set called *alphabet*. Table 2.2 shows the regular language L(R) generated by the regular expression R, where ϵ is the empty string, | is the union operand, $\cdot$ is the concatenation operand and * is the Kleene closure.

Suppose, for example, that we want to recognize the language of identifiers and

R	**L(R)**
ϵ	$\emptyset$
a	{"a"}
R | S	L(R) $\cup$ L(S)
R $\cdot$ S	L(R) L(S)
R*	$\emptyset\cup$ L(R) $\cup$ L(R $\cdot$ R) $\cup \ldots$
(R)	L(R)

Table 2.2: language $\mathcal{L}$ described by the regular expression $\mathcal{R}$.

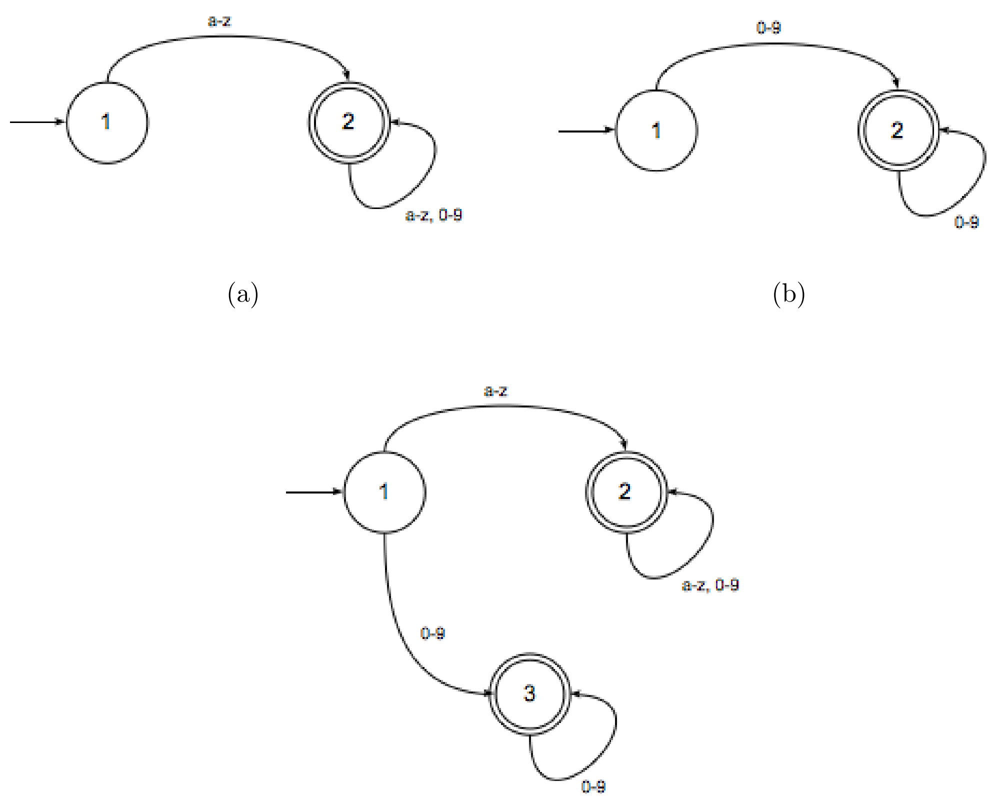
integer numbers, so we can write this two regular expressions:
ID $= [a-z][a-z0-9]^\star$
NUM $= [0-9][0-9]^\star$
This means that an identifier, ID, is a letter (between "a" and "z") followed by a sequence (empty, finite or infinite) of letters and digits (between "0" and "9"). An integer, NUM, is a digit followed by a sequence of digits[2].
It is possible to see that this rules are ambiguous, for example is `max0` a single identifier or an identifier followed by an integer number?
In order to answer to this question the common scanners use the following two disambiguations rules:

longest match: the next token is the longest substring of the input that can match a definition of a regular expression;

rule priority: the order of writing down the regular expression has significance, in fact if two rules match the same input substring the next token is the regular expression that is written first. So in this case `max0` is an identifier by the longest match rule.

[2]note that in this way $0\ldots$ are valid integer numbers

Regular expressions are common way to specify lexical tokens, but to understand how a scanner works we need a formalism that can be implemented by a computer program. To do this it is possible to translate a regular expression to a finite state automaton which recognize the tokens that we want. Below an automaton for recognizing identifiers is shown(Figure 2.7.a) and an automaton for recognizing integer numbers (Figure 2.7.b) defined above like a regular expression. In Figure 2.7.c we can see the merging of this two automata into a new automaton that recognize both identifiers and numbers.



(a) (b)

(c)

Figure 2.7: automata for the regular expressions recognition.

The implementation of an automaton is a mechanical task easily performed by a computer, so it makes sense to have an automatic lexical-analyzer generator to translate regular expressions into an automaton. JFlex is an example of this kind of generators.

2.2.1.1 JFlex a scanner generator

JFlex is a lexical analyzer generator for Java written in Java, as expressed in [9]. It permits a fast scanner generation and the design of fast generated scanners.
A JFlex specification file (`.flex`) generates a `.java` file that implements a scanner class. It consists of three parts where is possible to declare user code, options and declarations, and the lexical rules, divided by %%:

user code: consists of `package` declarations and `import` statements. It is copied verbatim at the beginning of the scanner class.

%%

options: contains the directives and the java code to include in the generated lexer. Each directive is situated at the beginning of the line and is preceded by the % character. There are a lot of types of directives, for example this piece of code
...
%public
%final
%class "classname"
%extends "classname"
...
tells JFlex to give the generated class the signature
`public final class "classname" extends "classname"`.
These are some of the class options allowed by JFlex. Other important types of options are the scanning method, the management of the end of file, the CUP[3] compatibility etc...

declarations: contains the specifications of lexical states and macros useful for the last section of the `.flex` file. This section can define, thanks to the macros, the regular expressions that will be recognized by the scanner. The way to declare a macro is:

`macro_id = reg_exp`

A `macro_id` is only a shortcut to refer to a regular expression in the lexical rules section. For example with
...
`Integer` $= [1-9][0-9]^{\star}$
`Identifier` $= [a-zA-Z][a-zA-Z0-9]^{\star}$

[3] a free parser generator.

...
we tell JFlex that `Integer` is a non negative and non zero decimal number, while `Identifier` is a letter in upper or lower case style followed by a sequence of zero or more letters or digits. The operations allowed by JFlex are most common operations between regular expressions like: union (|), concatenation, Kleene closure (*), iteration (+), option (?) etc...

%%

lexical rules: consist of a set of regular expression followed by an action (expressed in Java code). During the running, the scanner consumes its input and determines the regular expressions that match the longest portion of the input (longest match rule). If there are more than one, the generated scanner chooses the expression that appears first in this section of the specification (priority rule). After that it executes the associated action. If there is no matching regular expression, the scanner terminates the program with an error message. For example the following declaration

```
...
 "while"       {"code_action"}
 "for"         {"code_action"}
 {Integer}     {"code_action"}
 {Identifier}  {"code_action"}
...
```

tells the generated scanner that when the input matches with the string `"while"` the related action will execute. This example shows, also, the use of macros: input matches with an `Integer` if and only if it is generated by the regular expression defined in the related macro.

JFlex generates exactly one file containing the scanner class in agreement to the specification file. This class contains the Deterministic Finite Automaton tables, an input buffer, the lexical states of the specification, a constructor, and the scanning method with the user defined actions. The input buffer of the lexer is connected with an input stream over the `java.io.Reader` object which is passed to the lexer in the generated constructor. When it is called, it will consume input until either an error occurs or the end of file is reached. In the later case the scanner executes the EOF action, and returns the specified EOF value.

2.2.2 Syntactic analysis

The syntactic analysis phase is the process of analyzing a continuous stream of tokens to determine its grammatical structure due to a given formal grammar. As shown in Figure 2.8 the task of this step is executed by two important components:

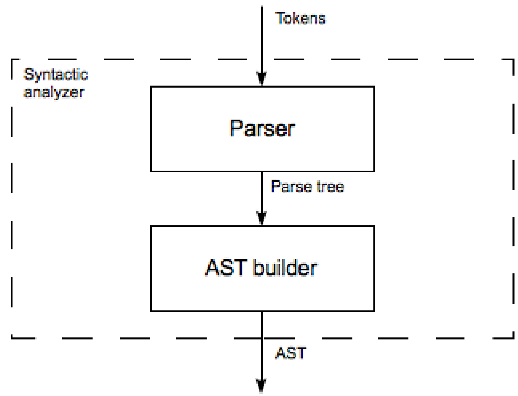


Figure 2.8: syntactic analysis steps.

Parser: checks for the correct syntax and builds a data structure, called *parse tree*;

Abstract Syntax Tree builder: builds a simplified structure[4], called *Abstract Syntax Tree* or *AST*, from the parse tree.

The leaves of the parse tree are the tokens found by the scanner, thus, what is important in this kind of tree is how these leaves are combined to form the structure of the tree and how the internal nodes are labeled.
In this context, the parser obtains a series of tokens from the scanner and verifies that the series can be generated by the grammar of the source language. There are two types of parsers which use a top-down (LL parser) or a bottom-up (LR parser) approach. In either case, the string of tokens in the input of the parser is scanned from left to right, one symbol at time. The syntax of programming language, like expressions and statements, can be expressed by a context-free grammar. For example, using a syntactic variable `stmt` to denote statements and the variable `expr` to denote expression, the production

$$stmt \rightarrow \textbf{while} \ (\ expr \ ) \ \{ \ stmt \ \} \tag{2.1}$$

indicates the structure of this type of control flow statement. Moreover, other productions must define what an `expr` is and what else a `stmt` can be.

In the formal definition, a context-free grammar consists of four components, $G = (N, T, P, S)$:

[4]Simplified in the sense that it does not represent every detail that appears in the real syntax (for example the parenthesis of an expression are not needed at this level).

N: is the finite set of nonterminals symbols. A nonterminal symbol is a syntactic variable that represents a phrase or a clause in a sentence (`stmt` and `expr` are nonterminals);

T: is the finite set of terminals symbols. It specifies the alphabet of the language definite by the grammar;

P: is the set of productions (or rules). A production specifies in which manner the terminals and nonterminals symbols can combined to form strings. Each production is composed of:

1. a nonterminal, called the *head* or *left side* of the production;
2. zero or more terminals and nonterminals, called *body* or *right side* of the production. It describes how to is possible to construct the head of the production;

S: is the start symbol that generates the grammar.

There are three operations to combine the terminal and nonterminal symbols: alternation (|), concatenation and repetition or Kleene closure (*).

The construction of a parse tree can be made thanks to the derivation: beginning with the start symbol, each rewrite step replaces a nonterminal with the body of one of its productions. There are two types of derivations: the first, called *leftmost* derivation, the first leftmost nonterminal in each production is replaced with the body of one of its productions, in this case we talk about a LL parser, while, in the *rightmost* derivation, the first rightmost nonterminal is chosen for the replacing, so we talk about a LR parser.

A parse tree is a graphical representation of a derivation. Each internal node of a parse tree represents the application of a production, in fact the internal nodes are labeled with the nonterminal in the head of the production.
Suppose, for example, we have these productions

$$
\begin{array}{lll}
\text{assign} & \rightarrow & \text{ID EQ exp SEMI} \\
\text{exp} & \rightarrow & \text{exp DIV exp} \\
 & | & \text{exp SUB exp} \\
 & | & \text{LPAR exp RPAR} \\
 & | & \text{ID} \\
 & | & \text{INT}
\end{array}
$$

so, in Figure 2.9 it's shown a representation of a parse tree obtained from these (leftmost) derivations:

assign ⇒ ID(nEd) EQ exp SEMI ⇒
ID(nEd) EQ exp DIV exp SEMI ⇒
ID(nEd) EQ LPAR exp RPAR DIV exp SEMI ⇒
ID(nEd) EQ LPAR exp SUB exp RPAR DIV exp SEMI ⇒
ID(nEd) EQ LPAR ID(nVer) SUB exp RPAR DIV exp SEMI ⇒
ID(nEd) EQ LPAR ID(nVer) SUB INT(2) RPAR DIV exp SEMI ⇒
ID(nEd) EQ LPAR ID(nVer) SUB INT(2) RPAR DIV INT(2) SEMI

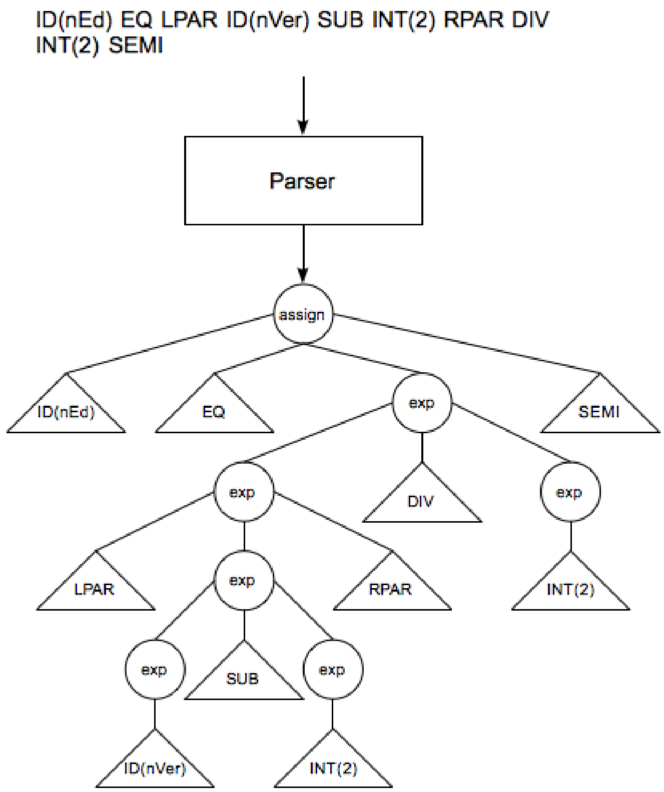


Figure 2.9: representation of a parse tree: circular nodes are the nonterminal symbols, while triangular nodes are terminal symbols.

In general, we say that a string belongs to a language $L(G)$, generated by grammar G, if it can be derived from the start symbol. Using mathematical formalism:

$$L(G) = \{w \in T^{\star} | S \Rightarrow^{\star} w\}$$

where $\Rightarrow^{\star}$ is the relation that represents the list of derivations that carry from a nonterminal symbol to a string of terminal symbols.

The parse trees aren't optimally appropriate for compilation. They contain a lot of redundant information, as parentheses, keywords, and so on. Hence, abstract syntax trees are generally used. Abstract syntax tree omits the irrelevant details, but keeps the essence of the structure of the text. It is a tree structure where each node corresponds to one or more nodes in the parse tree. For example, the parse tree shown in Figure 2.9 may be replaced by the abstract syntax tree shown in Figure 2.10:

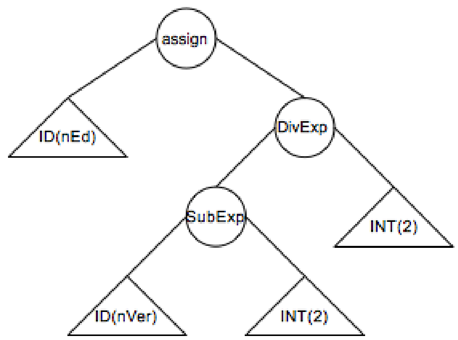


Figure 2.10: abstract syntax tree.

Exactly how the abstract syntax tree is represented and built depends on the parser generator used.

2.2.2.1 Beaver: a parser generator

Beaver is a Look-Ahead LR parser generator [10]. LR parsers give the fastest parsing speed, but they are considered impracticable because the automaton that they implement require huge number of states. LALR parsers offer the same high performance as LR parsers, but are much smaller in size, since they reduce the number of states in an LR parser by merging similar states. For this reason, LALR parsers are most often generated by compiler generators.

Beaver takes a context-free grammar and converts it into a Java class that implements a parser for the language described by the grammar. This parser will perform a syntactic analysis and assemble input tokens (supplied by a scanner) into structures as described by the production rules of the language specification.

Like JFlex, Beaver also allows the programmer to declare directives that are used to customize the generated parser or declare how some symbols will be used in the grammar. This part must be specified before production rules, in the followings are some examples of these directives:

`%package "package.name";` declares the parser package name.

`%import "package_or_Type"[,"package_or_Type" ...];` declares which Java packages and types should be imported.

`%class "ClassName";` declares the name of the Java class for the generated parser.

The parser main aim is to match symbols to their definition. Therefore the bulk of a specification usually is represented by production rules that combined represent the grammar of a language that the generated parser will recognize. Each rule declares a nonterminal symbol (on the left-hand side) and a sequence of other symbols (on the right-hand side of =) that will produce the nonterminal:

```
symbol = symbol_a symbol_b ...{: action routine code :};
```

Beaver allows the altering of the meaning of right-hand side symbols by marking them with the following special characters:

? the symbol is optional;

+ the symbol represents a nonempty list of symbols;

∗ the symbol represents a possibly empty list of symbols.

The "action routines" will be called when all the symbols on the right-hand side are matched and are ready to be reduced to a single nonterminal from the left-hand side of the rule. Action routine creates and returns the symbol node that will become accessible as a symbol of some other production's right-hand side. To exemplify the AST building process consider the following grammar:

```
Exp =  Exp.a MUL Exp.b   {: return new MulExp(a,b); :}
|      Exp.a ADD Exp.b   {: return new AddExp(a,b); :}
|      INT.i             {: return new IntExp(i); :}
;
```

Figure 2.11 shows the AST for the expression $5 + 7 * 60$. When `return new AddExp(a,b);` is executed, it means that the expressions `a` and `b` were available as symbol nodes, a new `AddExp` node is created (with two child: `a` and `b`) and its reference is now open for the right-hand side production that contains it.

Beaver defines a simple interface that it expect scanners will follow in order to feed it with tokens. Scanner returns the next token it finds in the input when

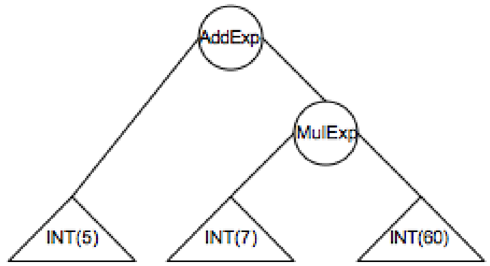


Figure 2.11: abstract syntax tree for the expression $5 + 7 * 60$.

parser calls `nextToken` method.
Moreover the Beaver's parsing engine uses simple token stream repairs and a phrase-level error recovery in order to recover from a syntax error. Parse grammars are specified in `.parser` files.

2.2.2.2 JastAdd: a compiler compiler system

JastAdd is an open source Java-based compiler compiler system [12]. The main design idea behind JastAdd is to make a specification formalism, called Rewritable Circular Reference Attributed Grammars(ReCRAGs) easily accessible to Java programmers. For this reason, JastAdd uses a syntax very close to Java. It is designed to work with any Java-based parser generator that supports user-defined semantic action, as JavaCC, CUP, and Beaver. AST is specified in `.ast` file and represents a set of Java class hierarchy, thus it allows behavior to be defined in classes and specialized in subclasses. In a JastAdd class hierarchy there are three predefined java classes as shown in Table 2.3. Furthermore, in order to create a class hierarchy,

Class	**Use**	**Sintax**
ASTNode	topmost node in the hierarchy, each other class extends it	
List	implement lists	$className*$
Opt	implement optionals	$[className]$

Table 2.3: JastAdd predefined Java classes.

JastAdd provides some basic syntax constructs, as:

abstract A; ⇒ produces an abstract class A, that corresponds to a nonterminal;

B : A ::= A [**B**] **C**∗ <**D**>**;** ⇒ produces a class B, that is an extension of A, thus B is a production of A. Moreover, B has four children of types A, an optional child of type B, a list of children of type C and a token child of type D.

JastAdd is used for doing computations on an AST. In a traditional compiler, you create external data structures like symbol tables and alternative program representations like flow graphs. In JastAdd, you represent all those things directly in the AST using attributes. These and other JastAdd features is presented in Section 2.2.3.1.

2.2.3 Semantic analysis

In the semantic analysis phase the compiler adds semantic information to the AST. At this point the analysis can be divided in the following two main analysis steps:

Name Analysis: in a programming language, each object (as variables and functions) has a *declaration*, that is a name used to refer to the object. Moreover, each name also have a number of *uses*, inside the source code, each of which is a reference to the named object in order to compute the goal task. Associating use and declaration is called **name binding** and it is shown in Figure 2.12.
If a declaration of a name is not visible in the entire program it has a restricted *scope* then that declaration is called *local*. On the contrary, if it is is visible in the entire program code than the declaration is called *global*.
To do name binding *symbol tables* are used. They are useful to bind the identifiers uses to their declarations. In some languages (as CAL) a variable and a

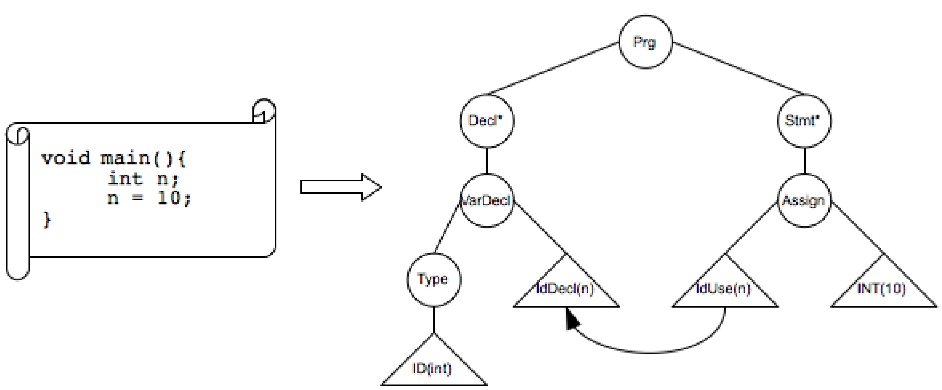


Figure 2.12: name binding example.

function in the same scope may have the same name, as the context of use will make it clear whether a variable or a function is used. In order to discriminate which are variables and which are functions we say that they have separate name spaces, which means that their name sets are disjoint. Usually each name space corresponds a symbol table, but nothing prevents us from sharing name spaces using just one symbol table, but this case needs additional information in order to avoid confusion between different name spaces.

Type Analysis: in this step a compiler must compute the type for each expression in the source code in order to check if it has the correct type in the context where it is located. For example a possible way to do this task may be the following:

$Exp_1 + Exp_2$	$\Rightarrow$	t_1=checkExp(Exp_1) t_2=checkExp(Exp_2) if t_1=int and t_2=int then int else error()
$Exp_1 = Exp_2$	$\Rightarrow$	t_1=checkExp(Exp_1) t_2=checkExp(Exp_2) if t_1=t_2 then bool else error()
...	$\Rightarrow$	...

As seen in the example above, at this point it is necessary to have, at least, a representation of predefined types available in the language. Thus, we can create a constant object for each type as:

```
interface PredType{
   public static final PredType intType=...;
   public static final PredType boolType=...;
   ...
}
```

This interface is useful, thanks to the object-oriented nested class, to create the type conversion rules. For example, in Figure 2.13 is shown the Java conversion rule, that is a widening conversions, which are intended to preserve information. The widening rules are given by a hierarchy of class: any type lower in the hierarchy can be widened to a higher type. Thus, a char can be widened to an int or to a float, but a char cannot be widened to a short.
Essentially, the compiler, in this step, must determine that these type expressions conform to a collection of logical rules that is called the *type system* for the source language.

During the semantic analysis the analyzer may discover some types of errors:

- names uses without declaration;

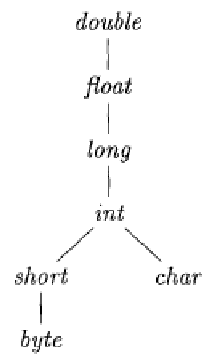


Figure 2.13: Java widening conversion rule.

- multiple declaration of the same name in the same block;
- type expression errors.

2.2.3.1 JastAdd aspects

Usually, semantic analysis is performed by adding aspects to the AST. JastAdd aspects support declarations that are written in an aspect file, but that actually belongs to an AST class, these declarations are called **intertype**. The JastAdd system reads the aspect files and weaves the intertype declarations into the appropriate AST classes, as shown in Figure 2.14. The aspect files contain ordinary Java methods and fields, and attribute grammar constructs like attributes, equations, and rewrites. An aspect file can have the suffix `.jadd` or `.jrag`. There is not difference between this two types of files but it is recommended for the following use:

- in a `.jrag` file we add attributes, equations, and rewrites to the AST classes, thus for declarative aspects;
- in a `.jadd` file we add ordinary fields and methods to the AST classes, thus for imperative aspects.

As in attribute grammars, attributes are declared in AST classes, and their values are defined by equations. An attribute is either synthesized, if it is used for propagating information upwards in the AST, or inherited, otherwise.
A synthesized attribute is analogous to an ordinary virtual method: the attribute declaration corresponds to the method declaration, and the equations to the method implementations.
Inherited attributes are used for passing information downwards in an AST, giving

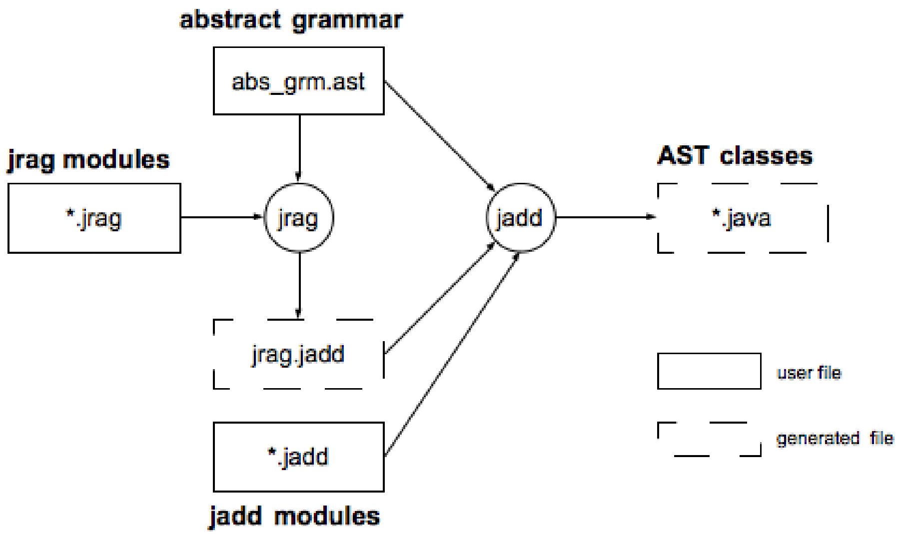
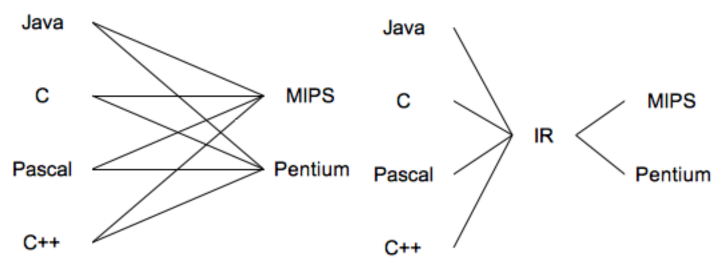


Figure 2.14: Architecture of the JastAdd system.

child nodes information about their context.
A typical example is that information about visible declarations, usually called the environment is passed down to each statement, which in turn passes down this information to the variables inside it. A variable can use this environment information to find its declaration and type.

2.2.4 Intermediate code generation

The final goal of a compiler is to allow programs written in a high-level language to run on a computer. Thus, compilers perform the translation from a high-level to a machine code language.
Suppose, for example, we want compilers for N source languages and we have M target machine, then we should implement $N \cdot M$ compilers (Figure 2.15.a). Many compilers use a medium-level language, called *intermediate code* or *intermediate representation* (IR), between the high-level language and the very low-level machine code. In this solution we have to implement only $N + M$ compilers (Figure 2.15.b), in fact N front ends of the compiler do lexical analysis, parsing, semantic analysis, and translation to intermediate representation, while M back ends do optimization of the intermediate representation and translation to machine language.
However, this solution produces an increasing of the information overhead that in some cases reduces the translation speed.



(a) without IR (b) with IR

Figure 2.15: compilers for four source languages and two target machine.

An intermediate language should, ideally, have the following properties:

- it should be easy to translate from a high-level language to the intermediate language;
- it should be easy to translate from the intermediate language to machine code.
- the intermediate format should be suitable for optimizations.

The first two of these properties can be somewhat hard to reconcile, so a language that is intended as target for translation from a high-level language should be fairly close to this.

2.2.4.1 XLIM: a XML Language-Independent Model

XLIM is a XML format for representing a language independent model of imperative programs. It is essentially equivalent to a program in static single assignment (SSA) form, in which each variable is assigned to in only one place of the source [6].
The root level of a XLIM document is the `design` element (there must be only one per document) and it consists of three main types of elements:

1. a list of `port` elements that define how data travel to and from the functionality block represented;
2. a list of program states (called `state variables`) that represent persistent storage for the design and they are accessible from any portion of the design;
3. a collection of `modules` and `operations`. Modules can contain operations and/or other modules in order to create a hierarchy of arbitrary depth. They

are used to define control flow within the design. Whereas, operations are the atomic unit of functionality, their execution depend on availability of data.

To show a simple example of intermediate code generated for the actor in the Listing 2.1 we quote the following little piece of code, that declares a XLIM design called `AddUntilOverflow` with three actor ports:

```
<design name=AddUntilOverflow>
   <actor-port dir="in" name="X" size="32" typeName="int"/>
   <actor-port dir="in" name="Y" size="32" typeName="int"/>
   <actor-port dir="out" name="Sum" size="32" typeName="int"/>
    ...
</design>
```

Listing 2.7: intermediate code generated for `AddUntilOverflow`.

When we declare an actor-port we define an element of the interface to the design. An actor-port is a conceptual port, it is implemented as simple I/O, or a complex port that requires a protocol. Accesses to the port are achieved by pinRead and pinWrite operations. For a more detailed specification of these and other XLIM features [6] is a recommended reading.

Chapter 3

Developed work

3.1 Scanning

As seen in section 2.2.1.1 a scanner is defined by a list of regular expressions that will recognize significative strings of characters. CAL and NL, as most of the common languages, have the following kinds of lexical tokens: keywords, identifiers, operators, delimiters, comments and numeric literals. For example, the following regular expression defines the identifier token class using JFlex syntax:

```
Alpha         =  [$A-Z_a-z]
DecimalDigit  =  [0-9]
Identifier    =  {Alpha}({Alpha}|{DecimalDigit})*
```

When the scanner matches a regular expression it returns the related symbol defined by the parser in the context-free grammar. For example, when an identifier is matched the scanner executes:

return sym(Terminals.IDENTIFIER);

which creates and returns an object `Symbol` that represents the token.
`Terminals.IDENTIFIER` is declared in the concrete grammar.

3.2 Parsing

In order to build the parse trees for CAL and NL you must specify their context-free grammars. Thus, this step involves a study of the syntax of the two languages. CAL syntax is specified in the Appendix A of [2] by a list of productions divided into five class rules:

1. **Actor:** specifies the rules to declare an actor, imports, variables and functions;
2. **Expressions:** specifies how to build expressions and special CAL constructs;
3. **Statements:** describes the syntax for the use of CAL statement constructs;
4. **Actions:** describes the rules to declare actions;
5. **Action control:** specifies the CAL constructs for the action control flow.

NL syntax is expressed in [3] and it is divided into three class rules:

1. **Network:** specifies the rules to declare a network;
2. **Entities:** describes how to define the entities that make up the network nodes;
3. **Building structure:** specifies the rule to define the structure of the network.

Moreover, NL uses some elements of CAL, for example Expressions and Statements.

I have developed two Beaver context-free grammars by the translation of these rules in agreement to the Beaver syntax. For example this CAL production

PortDecl → [**multi**] [Type] ID

specifies that a port is an optionally terminal symbol `multi` followed by an optionally nonterminal symbol `Type` followed by an identifier declaration, represented by the nonterminal symbol `ID`. It is translated into this Beaver production:

```
PortDecl port_decl = multi? type? id_decl
                     {: return new PortDecl(multi,type,id_decl); :};
```

that allows the parser to build a new `PortDecl` node when the input stream of tokens match to the right-hand side of the production.

3.3 Abstract Syntax Tree

The `.ast` files that contain the abstract grammar descriptions are very similar to a list of productions, as in the case of a context-free grammars, specified in the

`.parser` files. But the abstract grammar has the power to "prune" the parse tree[1] by all those nodes that are unnecessary, and to specialize other nodes.
A classical example of these aspects are the specialization of expression nodes with the consequent omission of operation terminal symbols from the tree. The following Beaver productions

Expression	expression=	
	binary_exp;	
Expression	binary_exp=	
	and_exp	
|	expression.e1 OR and_exp.e2	{:return new OrExp(e1,e2);:};
Expression	and_exp=	
	equal_exp	
|	and_exp.e1 AND equal_exp.e2	{:return new AndExp(e1,e2);:};
...		

use nonterminal symbols that are defined in the following abstract grammar:

abstract Expression;
abstract ExpressionBinary : Expression ::= LOp:Expression ROp:Expression;
abstract BooleanExp : ExpressionBinary;
AndExp : BooleanExp;
OrExp : BooleanExp;
...

JastAdd creates three abstract classes and two concrete classes with this relation between them:

Expression
↑
ExpressionBinary
↑
BooleanExp
↗↖
AndExp OrExp

where the arrow represent the function "is a".

[1] the parse tree is not created: when the parser parses a stream of tokens it directly build the AST. The pruning is referred only to the fact that unnecessary tokens are not used in the AST, so they are pruned.

An abstract grammar makes a clean interface between the parser and the later phases of a front end. It keeps the essence of the structure of the text but omits the irrelevant details. In an abstract syntax tree, interior nodes represent programming constructs, while in a parse tree, interior nodes represent nonterminals. A designer of a front end has much freedom in the choice of abstract grammar. As expressed in [8], some use an abstract syntax that retains all of the structure of the concrete syntax tree plus additional positioning information used for error reporting. Others prefer abstract syntax that contains only the information necessary for compilation, skipping parentheses and other irrelevant structure. Based on the semantic meaning of each CAL construct, my abstract grammar separators, operators and almost all keywords are dropped. To exemplify this choice, consider the port declaration construct which syntax is:

$$\text{PortDecl} \rightarrow [\textbf{multi}]\ [\text{Type}]\ \text{ID}$$

If, in the source code, the keyword `multi` is not specified then it means that that port is single. A single port represents exactly one sequence of input or output tokens. Otherwise it specifies a multi port, that represents any number of those sequences. Thus, this is an example of a keyword that must not be omitted in the abstract grammar since it has an important semantic meaning. The previous production is equivalently translated in the following one contained in the abstract grammar, in agreement with the JastAdd syntax:

abstract PortDecl	::=	[Type] IdDecl;
PortDeclSingle	:	PortDecl;
PortDeclMulti	:	PortDecl;

or alternatively:

PortDecl ::= [<MULTI:String>] [Type] IdDecl;

In the first case, when the parser matches the right hand side of the production with the `multi` keyword it creates and returns a `PortDeclMulti` node, otherwise a `PortDeclSingle` node. In this case JastAdd generates one abstract class for `PortDecl` and two subclasses: one for `PortDeclSingle` and one for `PortDeclMulti` nonterminal symbol. Whereas, in the second case it generates a java class for `PortDecl` nonterminal symbol that has, as child, the token which represents the `multi` keyword. First solution is probably better than second one because it reduces the number of nodes in the tree, but, as first implementation, I chose the second way in order to keep the class hierarchy as smaller as possible. Using this procedure, based on the semantic meaning of each symbol of the concrete grammar, I wrote the complete abstract grammar for CAL and NL language.

3.4 Semantic analysis

This section describes how I implemented name analysis and type checking for the CAL language main constructs.
First I want to clarify that, in my implementation, these two phases are not realized by two aspects which traverse the abstract syntax tree in two different moments, but checking is launched by name analysis at the when needed, this will become clear in subsection 3.4.5.

Name analysis is realized by `CalNameBinding.jrag` aspect and it uses other aspects to do its task. In order to bind identifier uses to its declaration this aspect adds this attribute:

public IdDecl IdUse.decl;

JastAdd will add the attribute `decl`, of type `IdDecl`, in the `IdUse` class. This new attribute will represent the reference to the identifier declaration (as shown in Figure 2.12).

Name analysis and type checking start their execution when `nameBinding()` method in `Actor` main class is called, from then running proceeds by the execution of eight steps described in the next subsections.

3.4.1 Namespaces creation

Using an auxiliary structure, called *symbol table*, I defined five different namespaces for input ports, output ports, functions, variables and actions names. The symbol tables are implemented as a stack of hash maps, as explained in [7], where a new hash map is pushed on the stack when the analyzer enters a block and is popped when it leaves the block. A symbol table supports seven main operations:

- void add(String symbol, Object meaning): adds the symbol and its associated meaning to the top symbol table;
- boolean alreadyDeclared(String symbol): returns true if the symbol is already in the symbol table;
- int blockLevel(): returns the numbers of hash maps in the stack;
- void enterBlock(): pushs a new hash map to the stack;
- void exitBlock(): pops the top hash map from the stack;

- Object lookup(String symbol): returns the meaning of symbol if it is in the table null otherwise;
- Set<String> keySet(): returns all the symbols in the table.

In particularly, in this case, the meaning is represented by `IdDecl` node of the AST. Thus to perform the name analysis an analyzer must, first, traverse the tree to look for each identifier declaration and put in the symbol table. Secondly it makes the binding between uses and declaration of an identifier. At the end the symbol tables are empty.

3.4.2 Port name setting

This phases, realized by `CalPortName`, is necessary to allow the analyzer to bind the ports in actions to the ports in the actor signature. The following is a piece of AST declaration present in `.ast` file:

ActorHead	::=	Import* Identifier TypePar* DeclPar* Input:PortDecl* Output:PortDecl* [Time];
PortDecl	::=	[Multi] [Type] IdDecl;
Action	::=	[QualIdDecl] Input* Output* [Guards] [Delay] DeclVariable* Statement*;
Input	::=	[IdUse] IdDecl* [Repeat] [Channel];
Output	::=	[IdUse] Expression* [Repeat] [Channel];

in the `Input` and `Output` productions `IdUse` represents the name of an actor ports. Thus, the aim of this step is to create an `IdUse` child, if not yet present, in `Input` and `Output` nodes in order to be able to bind that use to the related declaration contained in `PortDecl`. The binding is either by name, if `IdUse` child is present, or by position, otherwise. For example, the `Run` action in the `Cell` actor declared in the Listing 3.1 has a list of tokens, but it is not specified from which ports they come from. After this step the first token (`nw`) will be associated to the first port (`NW`), and so on...

3.4.3 Declarations adding

This is really the first phase of name analysis. Here, the analyzer scan the entire abstract syntax tree in order to find global name declarations and adds them in the correct symbol table. In a CAL program the global names are: state variables, functions, procedures, ports name and action tags. Consider Listing 3.1:

```
actor Cell (init) NW, N, NE, W, E, SW, S, SE ==> Out:
   state := null;
   Init: action ==> Out: [state]
   do
      state := init;
   end
   Run:action [nw],[n],[ne],[w],[e],[sw],[s],[se] ==> [state]
   var
      count = sum([nw, n, ne, w, e, sw, s, se])
   do
      if state = 0 then
         if count = 3 then
            state := 1;
         end
      else
         if count < 2 or count > 3 then
            state := 0;
         end
      end
   end
   schedule fsm s0:
      s0 (Init) --> s1;
      s1 (Run) --> s1;
   end
   function sum (L) :
      accumulate(lambda (x, y) : x + y end, 0, L)
   end
end
```

Listing 3.1: adding global declarations.

The global declarations and the related namespaces are shown in Table 3.1. Note that the name declaration `init` will be inserted in two different symbol tables, since it is not possible (at this point) to discriminate if it is a variable declaration or a function declaration. Local declarations will be added to the related symbol table during the name binding phase.

3.4.4 FSM transformation

When syntactic analyzer parses a CAL schedule construct it builds a tree unsuitable for the name analysis. For example look at the schedule declaration in the Listing 3.2. The abstract syntax tree built by the parser is very similar to that one shown in Figure 3.1.a, where it is possible to see that a transition is an initial state followed by one or more action tags followed by a target state. we can raise the following two question: which of those names are declarations and which of those names are

Decl	Line	Table
init	1	variable, function
NW	1	input
N	1	input
NE	1	input
W	1	input
E	1	input
SW	1	input
S	1	input
SE	1	input
Out	1	output
state	2	variable
Init	3	action
Run	7	action
sum	25	function

Table 3.1: name declarations and their related symbol table.

uses? And, what action or actions the name `do` refers?

```
actor A () IN ==> OUT :
   start: action ==> ...
   do.down: action ==> ...
   do.up: action ==> ...
   done: action ==> ...
   ...
   schedule fsm init:
      init (start) --> run;
      run (do) --> run;
      run (done) --> init;
   end
end
```

Listing 3.2: schedule declaration example.

As seen, using this schedule declaration syntax an action tag may refers to a set of actions. Thus, the previous schedule declaration is equivalent to that shown in Listing 3.3.

```
schedule fsm init:
   init (start) --> run;
   run (do.down,do.up) --> run;
   run (done) --> init;
end
```

Listing 3.3: equivalent schedule declaration.

For a name analyzer is easy to directly bind the action tags used to their declarations in the action signatures with the second schedule declaration, but it's impossible with the first one. Moreover states are implicitly declared states and also they are used to define a finite state machine. To avoid these problems the code in `CalFSMTransf` aspect operates a rewriting of this subtree.
In this new representation a finite state machine is a list of state transitions, each transition declares its initial state, as a left child, and a list of transition bodies. A transition body is a list of action tags followed by a name of a target state (now a name analyzer is able to bind state uses to their declarations). Each action tag contain a vector of references to the related action tag declaration in the action signature. Moreover, the name declaration as left child of the first transition represents the initial state of the finite state machine.
References vector filling is an assignment of the name binder. A reference is added into the vector whenever an action tag use matches to a declaration contained in the action names symbol table. If an action tag use is a prefix of an action tag declaration then there is a matching.

In Figure 3.1.b is shown the result of this transformation. This new subtree will replace the old one.

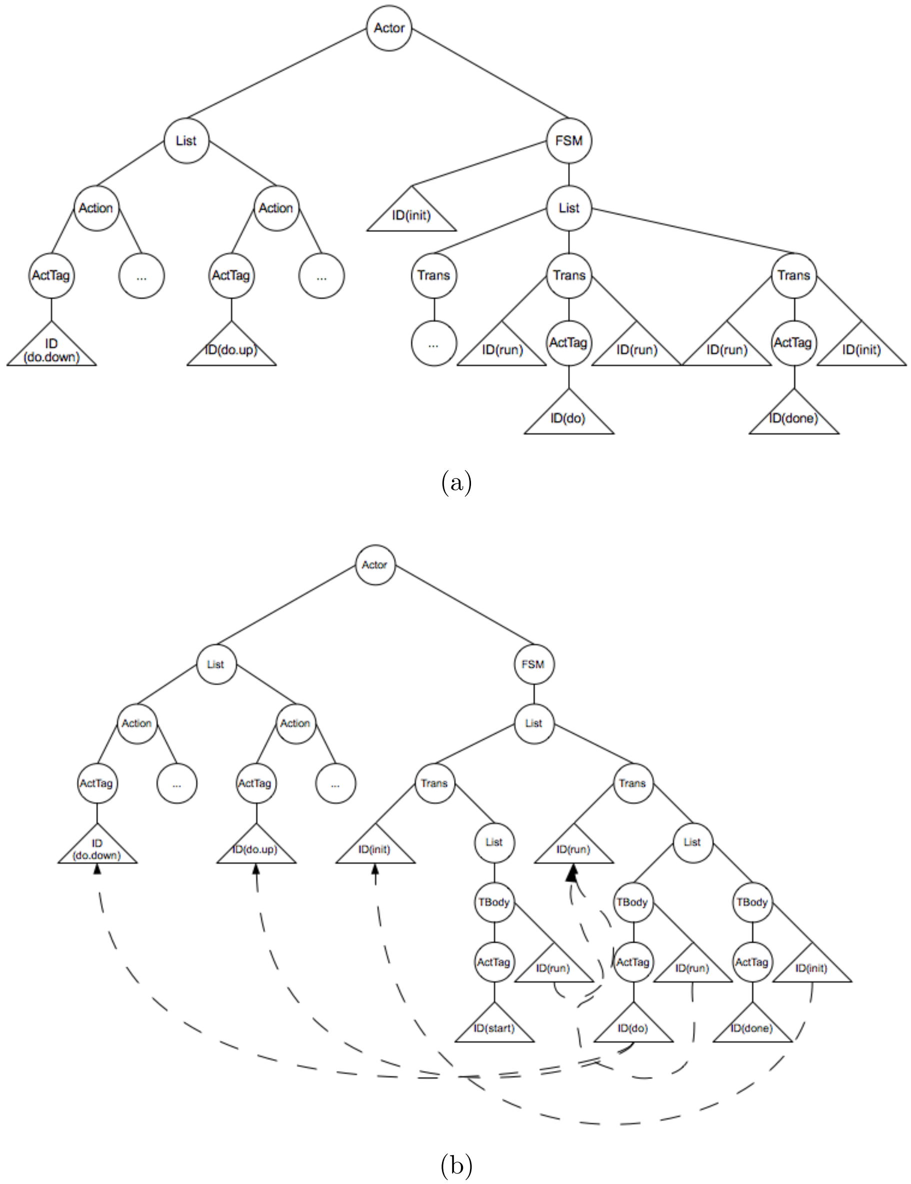


Figure 3.1: Finite State Machine subtree.

3.4.5 Name binding

This is the core of name analysis and the code is contained in `CalNameBinding` aspect. By recursive traversal among the AST the analyzer should, firstly, look for any local declarations, that adds to the correct symbol table, secondly, look for any `IdUse` node and, thirdly, call the routine dedicated to the type checking when necessary. When a `IdUse` node is found this piece of code is executed:

```
decl=(IdDecl)table.lookup(getIdentifier().getID());
```

thus, the analyzer looks for the current identifier use in the table that represent the namespace of the declared identifiers. If it find the related declaration set the `IdUse` binding attribute to the value of the `IdDecl` node that contains the name declaration, otherwise it reports a "MISSING DECLARATION" error message. The analyzer behavior described above is not the same for each node in the AST, in fact we can distinguish four types of nodes:

- **class A:** all nodes that contain local variable or function declarations and that require a name binding analysis for each child. For example, actions are instances of this class;
- **class B:** all nodes of class A that needs type checking. An example of an element of this class is the `while` statement construct, i.e. the local variable declarations must be added and the condition must be boolean;
- **class C:** all nodes that require name binding analysis for each child and type checking, but they have not local declarations. For example, `if` statement constructs represent an element to this class;
- **class D:** schedule and priority declarations.

Summarizing:

Class	Add Declarations	Name binding	Type checking
A	yes	yes	no
B	yes	yes	yes
C	no	yes	yes
D	no	yes	no

Whenever the analyzer meet a class A or B node it pushes a new dictionary in the symbol table, this means that those declarations have a limited scope. So they are visible only for the uses that the analyzer meets in the next name binding analysis. After that the analyzer pops the top dictionary from the symbol table and its declarations are no longer available to be binded.

3.4.6 Type assignment

This step is integrated with name binding and declarations adding steps. When the analyzer finds an `IdDecl` node and pushes it in the correct symbol table, it also, tries to assign it a type. The type hierarchy is defined in an auxiliary class structure. It is specified in `ObjectType.java` class contained in semanticlib directory and its graphical representation is shown in Figure 3.2. An arrow, that connects two

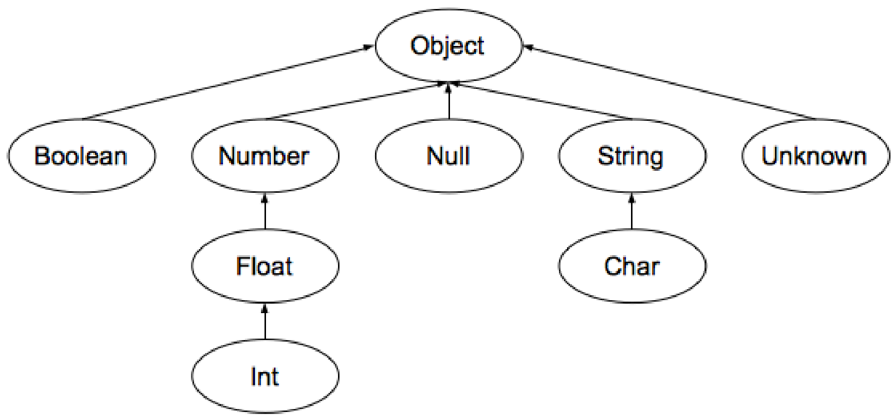


Figure 3.2: hierarchy types representation.

different type classes, represents the function "is a". Thus, for example a `Char` is a `String` that is an `Object`.
To perform the type assignment task I added an attribute to the `IdDecl` class in this way:

public ObjectType IdDecl.type;

The attribute will contain the type of the current declaration. To assign a type the analyzer simply tries to find a string that matches a type declaration, for example *int i* is a `Int` object. CAL is a optional typed language, so a type declaration may be omitted, in this case, that declaration has type unknown.

3.4.7 Type checking

When the analyzer meets a node that needs a type checking, it executes the code that is specified in the `CalTypeChecking` aspect.
During the name binding step, when the analyzer requires a type checking for a

node then this means that it has met a particular CAL construct that requires a particular type, as a `guard` or a `repeat` construct, or the current node has a class `IdUse` as child.
The following table shows the operations that the analyzer executes when it met a `Repeat` node:

Node	**Operation**
Repeat	t=getExpression().getExpressionType(); if(!t.isIntType()) then error();

Note that operations between types, as `isSubtype()` or `isBoolType()`, are implemented in the `ObjectType.java` class.
An objects t_1 of type `ObjectType` may check if it is a same type of another object t_2, of type `ObjectType`, calling `isSameType(`t_2`)` method, and, also, t_1 may check if it is a subtype of t_2 by calling the `isSubtype(`t_2`)` method. Moreover, t_1 may check if it is of a certain type calling the `is<type_name>Type()` method or if it is of a certain subtype calling the `is<type_name>Subtype()` method.

Errors launched by the analyzer, at this computation step, are represented by strings printed in a XML form. For example this error message

```
<Check Type Repeat>
  <ERROR type= CAL.Object.Unknown line= (50,20;50,27)/>
</Check Type Repeat>
```

tells that in the repeat clause at line (50,20;50,27) the analyzer found a unknown object instead of an integer. Line informations are printed by the `lineCol()` method, implemented in the `SourceLine` aspect, which is available for each class in the hierarchy defined by AST.

3.4.8 Expression type computation

This is the last step of the name and type checking analysis and it performs the task of returning a type of an expression.
CAL provides four main expression constructs that in the AST are represented by particular nodes:

- **binary expressions** consist of a left expression and a right expression child. The analyzer must evaluate their type and checks if the operation has the correct operand. At the end it returns the expression type.To exemplify look at this table:

Binary Exp	Op1	Op2	Return
BooleanExp	bool	bool	bool
	bool	unknown	unknown
	unknown	bool	unknown
	unknown	unknown	unknown

It shows the accepted operand types for a boolean operation (as `and`), and the returned type;

- **unary expressions** consist of a only one expression child. Thus, analyzer behavior is fairly near to the previous one;
- **expression literals** represent the constant value of an expression. Thus their type is implicitly defined in what they are. For example an integer literal belongs trivially to the `Int` class;
- **other constructs** are provided by the CAL language, as if-expression, let-expression, lambda-expression, etc...
  They should be treated case by case but the basic idea remains the same: analyze expressions child, check if they have the correct type and return the expression type. The following table exemplify this concept for if-expressions:

Expression	Operations
IfExp	1) checks if 'if' expression is boolean 2) checks if 'then' expression is a subtype of the 'else' expression or vice versa 3) launch an error or return the higher type class found

3.5 Intermediate code generation

In this section, I illustrate a scheme for generating intermediate code. The source code used to generate an intermediate representation is contained in the `CalToXLIM` aspect.

This intermediate code generation step is done after the previous analysis. This process starts when the `writeXLIM(String filename)` function, in the `Actor` class, is called. The process traverse the AST in order to translate the attributed AST into a XLIM intermediate representation. This task is summarized by the following list of step:

1. open a new design block;

2. add actor-port declarations blocks;
3. add action declarations blocks:
   (a) add a `pinRead` operation block for each incoming port;
   (b) add operation blocks to compute the outputs tokens;
   (c) add a `pinWrite` operation block for each outgoing port.
4. add finite state machine declaration blocks in order to specifies action firing rules:
   (a) add a `stateVar` block that represents the current state of the state machine;
   (b) add operation blocks to represent the finite machine states;
   (c) add an infinite loop module that represents the finite machine running. In the body of this loop for each action:
      i. add a `pinAvailable` operation block for each incoming port
      ii. if the action is guarded add a `pinPeek` operation block for each incoming port, then add the operation blocks necessary to evaluate all the guards;
      iii. add an `and` operation between the exits of `pinAvailable` and guard blocks;
      iv. add a `pinAvailable` operation block for each outgoing port;
   (d) add a series of module and operation that implement the schedule defined by the finite state machine.

3.6 Testing

In order to test my work I created, using JUnit, a test framework class, named `TestAll.java` contained in `testframework` directory. It looks for all the classes in the project that extend the `TestCase` class and it run them. Thus, it is easy to add new test classes. At the moment the only available test class is contained in `test` directory and it is named `ParserTest.java`. The functionality of this class is to parse and execute name binding (and type checking) for all `.cal` files in the `data` directory, while for all `.nl` files in that directory this class execute the parsing. At the end of the execution two log files are produced in the `output` directory: `out_test.log` and `err_test.log`. Both are written in a XML mode, and both show the computational results during all the analysis phases. The first one shows the successful executed operations and the second one shows the errors launched by the analyzer. The following is an example of successful operation:

```
<Bind idUse= a idDecl= a lines= (52,16;52,16), (50,17;50,17)/>
```

which inform us that the use of name a in line (52,16; 52,16) is successfully binded to the name declaration in line (50,17; 50,17). Whereas an example of error is:

```
<Check Type Repeat>
  <ERROR type= CAL.Object.Unknown line= (50,20;50,27)/>
</Check Type Repeat>
```

which informs us that during the type checking the type of the expression in a repeat clause is evaluated unknown instead of int. Another type of error is shown in this way:

```
<MISSING DECLARATION idUse= complex line= (61,9;61,15)/>
```

which informs us that the use of the name `complex` does not have declaration in the `.cal` file.

In the `test` folder there is another class file, called `Cal2XLIM.java`. This is the main class of the project. It receives a CAL project as input and parses all files and generates, from `.cal` files, a folder, called `compiled`, that contains all the intermediate representations (`.xlim` files).

Chapter 4

Final remarks

4.1 Conclusion

At the beginning of this thesis I did not have much knowledge about compiler design, CAL, or Network language. Therefore, after an initial period of familiarization with these two languages and compiler structures I have realized this work. It covers the design and implementation of an intermediate code generator for the actor-based CAL language. To achieve this result I had to implement:

1. a scanner for the lexical analysis, for CAL and NL, using JFlex scanner generator;
2. a parser for the syntactical analysis, for CAL and NL, using Beaver parser generator;
3. a set of aspects for the semantic analysis and the intermediate code generation using JastAdd compiler generator.

During the realization of this work I met many difficulties due to my inexperience with this type of requirement. For example, I spent a lot of time to understand how to create an abstract syntax tree that stores only important semantic information for each language. Sometimes, during the semantic analysis, I realized that my abstract tree had a "hole" or a redundant information so I had to rewrite my AST specification many times.

The project correctness is checkable by reading the two log files, in the `output` folder that keep trace of all the operations performed by the front end.

In the next section I present some improvement for the project continuation, because this work represents the foundations for an complete CAL compiler.

4.2 Future works

The generated front end produces intermediate code only for simple actors, thus there are still a number of opportunities for improving it:

- integrate name binding and type checking for CAL structures, as lists and maps;
- integrate intermediate code generation for:
  - structures, for example lists and maps;
  - statements, for example chooses and generators;
  - priority clauses.
- implement semantic analysis for NL;
- complete the main class, so that the front end can generate the intermediate representation for each actor that is instantiated in the `.nl` file.

Appendix A

Implementation structure

This appendix presents, in detail, the structure of my developed work for the implementation of a CAL front-end.

The main folder of my project is composed by the following list of files and subfolders:

CalScanner.flex, NlScanner.flex are the JFlex files for the implementation of the lexical analyzer for CAL and for NL respectively;

CalParser.parser, NlParser.parser are the Beaver files for the specification of the context-free grammar for CAL and for NL respectively;

CalAST.ast, NlAST.ast are the JastAdd files for the declaration of the abstract syntax tree for CAL and for NL respectively;

build.xml is the build file used by ant[1]. If you want to build the project you have to use `ant` command followed by one of these targets:

- <`none`>: see build target;
- `scanner`: runs JFlex to generate CAL and NL scanners;
- `parser`: runs Beaver to generate CAL and NL parsers;
- `gen`: depends on `scanner` and `parser` targets, runs JastAdd to generate CAL and NL abstract syntax trees;
- `build`: depends on `gen` target, compiles all the java classes in the project;
- `test`: depends on `build` target, compiles and runs some testing classes;
- `clean`: deletes all generated files.

[1]Apache Ant is a Java-based build tool, more detail in [13]

tools/ contains the third-party tools used for the implementation of this front-end;

beaver/ contains some classes of the Beaver parser generator;

data/ contains some CAL example files useful for the testing phase;

output/ will contain results of the testing phase;

testframework/ contains a program that searches the project's folder for JUnit[2] tests and executes them.

test/ contains one test and the main program;

AST_CAL/, AST_NL/ are the two generated folders that will contain, after the compilation phase, the scanners, the parsers and all the java classes, that represent the hierarchy for the abstract syntax tree classes, for CAL and NL respectively. These folders are removed when the project is "clean";

semanticlib/ contains the implementations of auxiliary structures, as symbol table and predefined CAL types hierarchy.

[2]JUnit is a unit testing framework for the Java programming language, more details at [14]

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