CCW

Acknowledgements

In the name of Allah, the Merciful, the Compassionate…

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In the end, we thank our parents who supported us throughout the whole year, and suffered hard times during our sleepless nights and desperate moments. We've worked hard to make their tiredness fruitful, and we hope our success will be the best gift we present to them.

Regards,

CCW Team

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Abstract

Compilers are extremely important programs that have been used since the very beginning of the modern "computing era". Developers have tried writing manual compilers for long. They faced too many problems, but this was their only available option.

In general, compiler writing has always been regarded as a very complex task. In addition to requiring much time, a massive amount of hard and tedious work has to be done. The huge amount of code meant – inevitably – a proportional number of mistakes that normally lead to syntax and even logical errors. In addition, the larger the code gets, the harder the final product can be debugged and maintained. A minor modification in the compiler specification usually resulted in massive changes to the code. The result was usually an inefficient and a harder-to-maintain compiler.

Scientists have observed that much of the effort exerted during compiler writing is redundant as the same principal tasks were repeated excessively. These observations strengthened the belief that some major phases of building compilers can be automated. By *automating* a process it's generally meant that the developer is only to specify what, rather than how, that process is to be done. The developer's mission is much easier – more specifications, less coding; and less errors as well.

Up till now, it's widely acceptable that the phases that are – practically – "fully-automatable" are building the lexical analyzer as well as building the parser. Attempts to automate semantic analysis and code generation were much less successful, although the latter is improving rapidly.

The proposed project is mainly to develop a tool that takes a specification of the lexical analyzer and/or the parser and generates the lexical analyzer and/or the parser code in a specific programming language. This will be introduced to the user through a dedicated IDE that also offers a number of tools to help him/her achieve the mission in minimum time and effort.

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Part I

A General Introduction

1. Basic Concepts

1.1 Definition

A compiler is a program that reads a program written in one language – the *source* language – and translates it into an equivalent program in another language – the *target* language. It can be simply stated alternatively, that a compiler is a program that produces itself as an output if it were fed itself as an input!

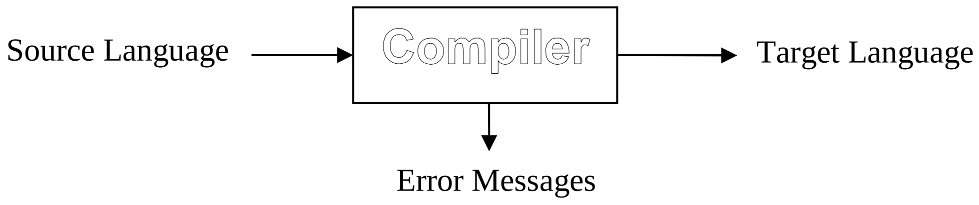


Figure I-1: The Compiler, Abstractly

1.2 Historical Background

Compilers have been used since the very beginning of inventing the computers, and have taken several shapes with varying ranges of complexity. Primarily, they were invented to facilitate writing programs, because the only language that a computer comprehends – the binary language (mere zeroes and ones) – are extremely unreadable by humans, and early programmers exerted tremendous efforts just writing the simplest of programs we run today.

Early computers did not use compilers; because they had just a few opcodes and a confined amount of memory. Users had to enter binary machine code directly by toggling switches on the computer console/front panel.

During the 1940s, programmers found that the tedious machine code could be denoted using some mnemonics (assembly language) and computers could translate those mnemonics into machine code. The primitive compiler, *assembler*, emerged.

During the 1950s, machine-dependent assembly languages were still found not to be that ideal for programmers; and high level, machine-independent programming languages evolved. Subsequently, several experimental compilers were developed (for example, the seminal work by Grace Hopper **[49]** on the A-0 language), but the FORTRAN team led by John Backus at IBM is generally credited as having introduced the first complete compiler in 1957. Three years later, COBOL – an early language to be compiled on multiple architectures – emerged **[39]**.

The idea of compilation quickly caught on, and most of the principles of compiler design were developed during the 1960s.

Programming languages emerged as a compromise between the needs of humans and the needs of machines. With the evolution of programming languages and the increasing power of computers, compilers are becoming more and more complex to bridge the gap between problem-solving modern programming languages and the various computer systems, aiming at getting the highest performance out of the target machines.

Early compilers were written in assembly language. The first *self-hosting compiler* (a compiler capable of compiling its own source code in a high-level language) was created for Lisp by Hart and Levin at MIT in 1962. The use of high-level languages for writing compilers gained added impetus in the early 1970s when Pascal and C compilers were written in their own languages. Building a self-hosting compiler is a bootstrapping problem **[1]** – the first such compiler for a language must be compiled either by a compiler written in a different language, or (as in Hart and Levin's Lisp compiler) compiled by running the compiler on an interpreter.

1.3 Feasibility of Automating the Compiler Construction Process

Compiler writing is a very complex process that spans programming languages, machine architectures, language theory, algorithms and software engineering. Although a few people are likely to build or even maintain a compiler for a major programming language, the ideas and techniques used throughout the compiler writing process (or the compiler construction process – I'll use the two terms interchangeably) are widely applicable to general software design.

May be the first question that may come into the reader's mind is: Do we have a new programming language every day? Programming languages – though numerous – are limited to a few hundreds, most of which are already running and whose compilers have been well-tested and optimized… so why do we need to automate the compiler construction process? And is it worth the effort and time exerted doing that?

The following address these – and other questions – regarding the feasibility of automating the compiler construction process, or at least, some of its phases **[2]**:

(1) The systematic nature of some of its phases.

The variety of compilers may appear overwhelming. There are hundreds of source languages, ranging from traditional programming languages to specialized languages (that have arisen in virtually every area of computer application). Target languages are equally as varied; a target language may be another programming language or the machine language of any computer between a microprocessor and a supercomputer. Despite this apparent complexity, the basic tasks that any compiler must perform are essentially the same. By understanding these tasks, we can construct compilers for a wide variety of source languages and target machines using the same basic techniques, and thus many phases of the compiler construction process are automatable.

(2) The extreme difficulty encountered in implementing a full-fledged compiler.

The first FORTRAN compiler – for example – took 18 staff-years to implement.

(3) The need for compilers in various applications, not only compiler-related issues.

The string matching techniques for building lexical analyzers have also been used in text editors, information retrieval systems, and pattern recognition programs. Context-free grammars and syntax-directed definitions have been used to build many little languages; such as the typesetting and figure drawing systems used in editing books.

In more general terms, the *analysis* portion (described shortly) in each of the following examples is similar to that of a conventional compiler **[2]**:

I. *Text Formatters:* A text formatter takes its input as a stream of characters, most of which is text to be typeset, but some of which include commands to indicate paragraphs, figures or mathematical structures like subscripts and superscripts.

II. *Silicon Compilers:* A silicon compiler has a source language that is similar or identical to a conventional programming language. However, the variables of the language represent not locations in memory, but logical signals (0 or 1) or groups of signals in a switching circuit. The output is a circuit design in an appropriate language.

III. *Query Interpreters:* A query interpreter translates a predicate containing relational and Boolean operators into commands to search a database for records satisfying that predicate.

IV. *XML Parsers:* The role of XML in modern database applications can't be overestimated.

V. *Converting Legacy Data into XML:* For updating legacy systems. This is an extremely important application for large, old corporations with much data that can't be lost when switching to newer systems.

VI. *Internet Browsers:* This is one of the interesting applications that assures the fact that the output of the process is not necessarily "unseen". In internet browsers; the output is drawn to the screen.

VII. *Parsing structured files:* This is the most practical and widely used application of parsers. Virtually any application needs to take its input from a file. Once the structure of such a file is specified, a tool like ours can be used to construct a parser easily (along with any parallel activity, such as loading the contents of the file into memory) in a suitable data structure.

VIII. *Circuit burning applications using HDL specifications:* This is another example from the world of hardware.

IX. *Checking spelling and grammar mistakes in word processing applications:* This is very common in commercial packages, like Microsoft Word®. The importance of such an application stems from saving the great efforts exerted when revising large, formal documents.

2. The Compiler Construction Lifecycle

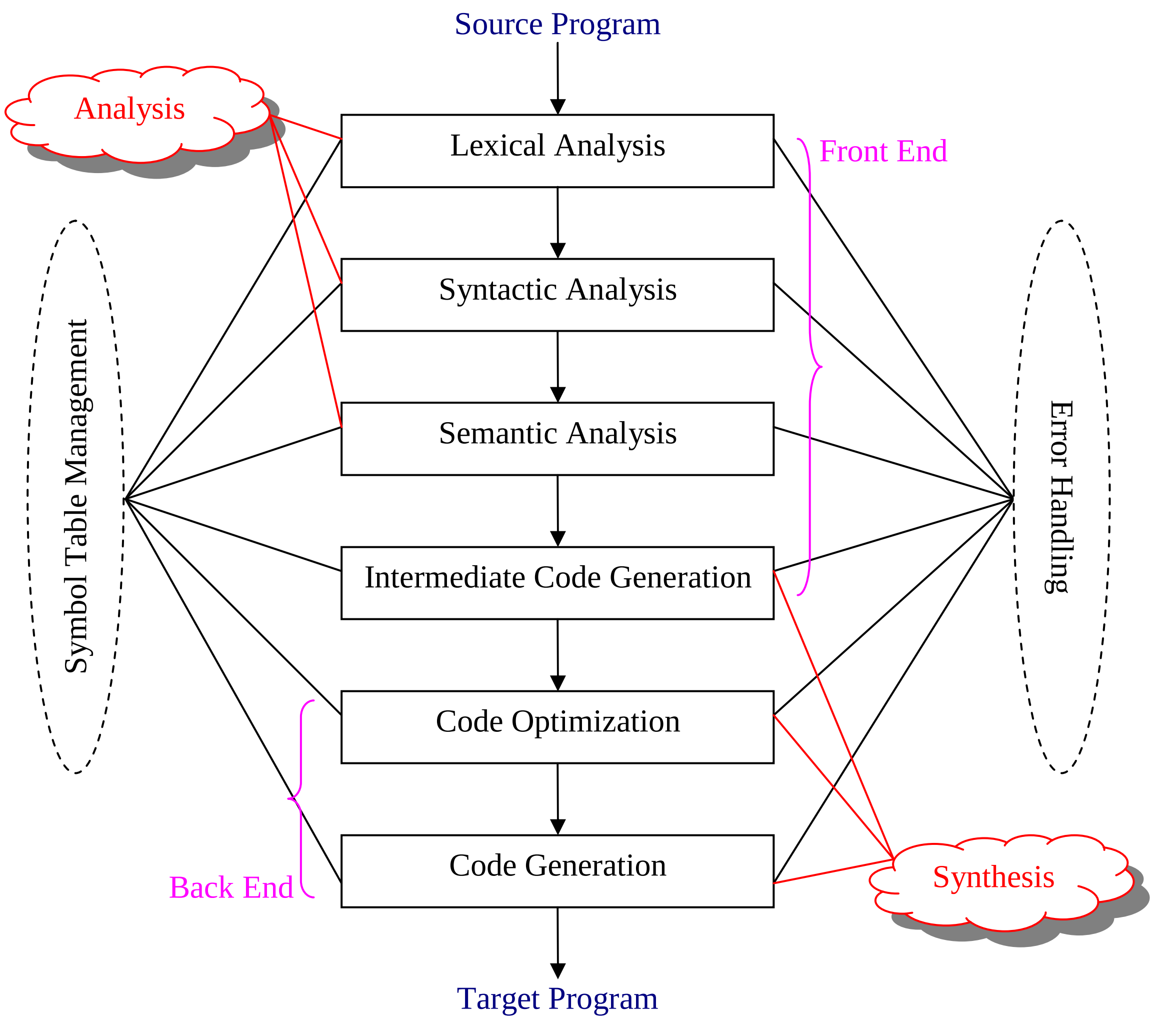


Figure I-2: The Compiler Construction Process

2.1 Front and Back Ends

Often, the phases (described shortly) are collected into a front end and a back end. The front end consists of those phases, or parts of phases, which depend primarily on the source language and are largely independent of the target machine. These normally include lexical and syntactic analysis, the creation of the symbol table, semantic analysis, and the generation of intermediate code. A certain amount of code optimization can be done by the front end as well. The front end also includes the error handling that goes along with each of these phases.

Intermediate Representation: A More-Than-Justified Overhead

It has become fairly routine to take the front end of a compiler and redo its associated back end to produce a compiler for the same source language on a different machine.

If the back end is designed carefully, it may not even be necessary to redesign too much of the back end. It is also tempting to compile several different languages into the same intermediate language and use a common back end for the different front ends, thereby obtaining several compilers for one machine.

Software design experience has mandated that; *"whenever you're in trouble, add an extra layer of abstraction"*. Let's start with an abstract figure that illustrates this concept with no technical details:

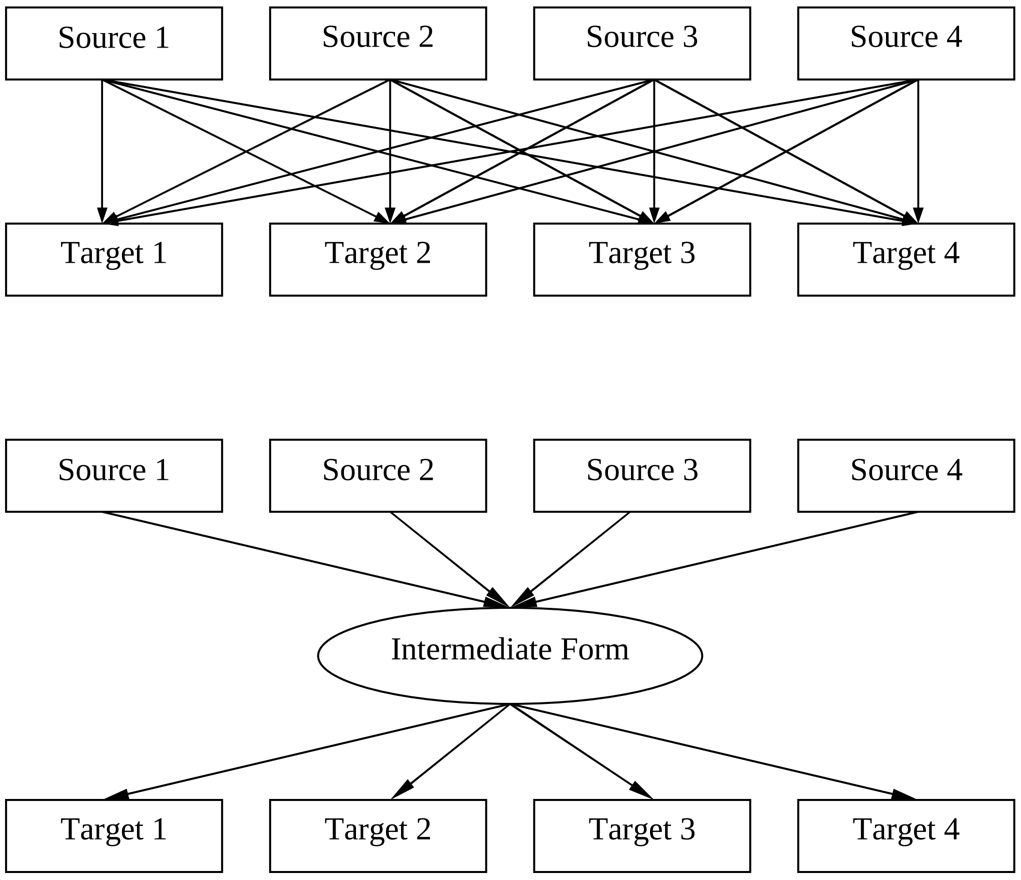


Figure I-3: Intermediate Representation

The figure illustrates the problem we are facing if no intermediate form were used. We have to redesign the back-ends for every front-end and vice versa. In summary, the advantages of using an intermediate form; which more than offsets the extra processing layer – and the performance degradation accordingly – include:

(1) The presence of an intermediate layer reduces the number of "links" in the figure from N^2 to 2*N. Note that each "link" is a complete compiler.

(2) The optimization phase can be dedicated to optimizing the "standard" intermediate format. This raises the efficiency of the optimization phase and reduces its time and effort as the research increases in this area, where certain phases of the optimization phase can be automated as well.

(3) Portability and machine-independence in source languages can be achieved easily, where the back-ends are realized on different platforms.

This approach is widely adopted nowadays; common examples include Java TM and .NET-Compliant languages.

Now it's time to view the situation realistically:

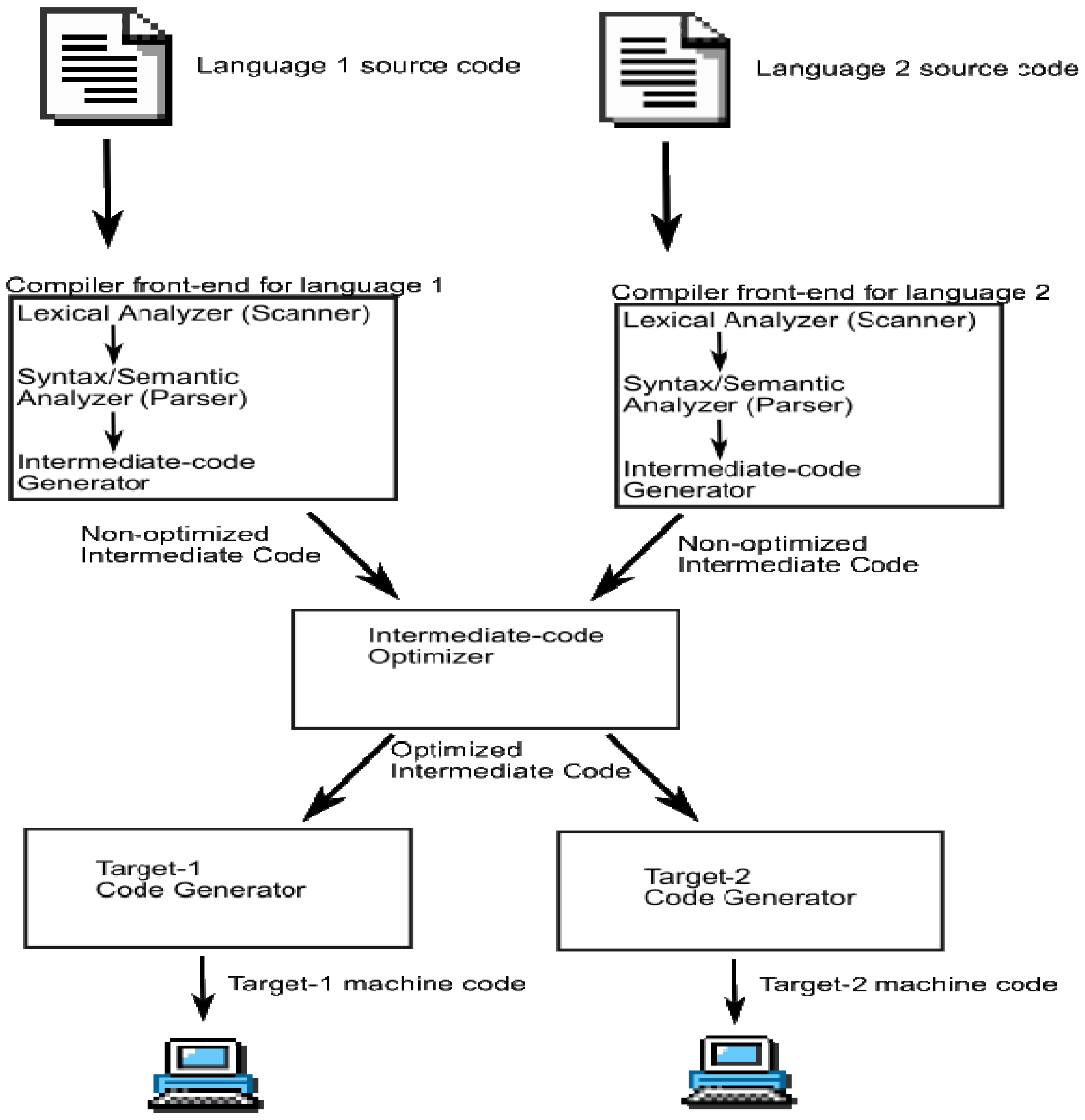

Language 1 source code
Language 2 source code
Compiler front-end for language 1
Lexical Analyzer (Scanner)
Syntax/Semantic Analyzer (Parser)
Intermediate-code Generator
Compiler front-end for language 2
Lexical Analyzer (Scanner)
Syntax/Semantic Analyzer (Parser)
Intermediate-code Generator
Non-optimized Intermediate Code
Non-optimized Intermediate Code
Intermediate-code Optimizer
Optimized Intermediate Code
Target-1 Code Generator
Target-2 Code Generator
Target-1 machine code
Target-2 machine code

Figure I-4: The Whole Picture

2.2 Breaking down the Whole Process into Phases

Conceptually, a compiler operates in *phases*, each of which transforms the source program from one representation to another. There are two main categories of phases: *analysis* and *synthesis*. Another category, which we prefer to name *"meta-phases"*, will be described shortly. The analysis part breaks up the source program into constituent parts and creates an intermediate representation of it. The synthesis part constructs the desired target program from the intermediate representation.

2.2.1 The Analysis Phases

2.2.1.1 Linear (Lexical) Analysis

The stream of characters making up the source program is read in a linear fashion (in one direction, according to the language) and grouped into *tokens* – sequences of characters having a collective meaning **[3]**.

In addition to its role as an "input reader", a lexical analyzer usually handles some "housekeeping chores" that simplify the remaining phases – especially the subsequent phase; parsing **[2]**:

White space elimination:

Many languages allow "whitespace" (blanks, tabs, and newlines) to appear between tokens. Comments can likewise be ignored by the parser as well as the translator, so they may also be treated as white space.

Matching tokens with more than a single character:

The character sequence forming a token is called the *lexeme* for the token. Normally, the lexemes of most tokens will consist of more than a character. For example, anytime a single digit appears in an expression, it seems reasonable to allow an arbitrary integer constant in its place. So the lexical analysis phase can't be simply reading the input character by character (except in very special cases). In other words, *the **character** stream is usually different than the **token** stream.*

Correlating error handling information with the tokens:

The lexical analyzer may keep track of the number of newline characters seen, so that a line number can be associated with an error message.

Efficiency issues:

Since the lexical analyzer is the only phase of the compiler that reads the source program character-by-character, it is possible to spend a considerable amount of time in the lexical analysis phase, even though the later phases are conceptually more complex. Thus, the speed of lexical analysis is a concern in compiler design **[2]**.

Isolating anomalies associated with different encoding formats:

Input alphabet peculiarities and other device-specific anomalies can be restricted to the lexical analyzer. The representation of special or non-standard symbols, such as ↑ in Pascal, can be isolated in the lexical analyzer.

There is much more stuff the lexical analyzer can handle, according to the specific implementation at hand. The lexical analysis phase, together with the parsing phase, is actually our concern. For that we defer a detailed description of both to two dedicated chapters, in part II of this document. Consult section 6 in this part for more information about the document organization.

2.2.1.2 Hierarchical (Syntactic) Analysis

It involves grouping the tokens of the source program into grammatical phrases that are used by the compiler to synthesize output. Characters or tokens are grouped hierarchically into nested collections with collective meaning; these nested collections are what we call *statements*.

For any context-free grammar there is a parser that takes at most $O(n^3)$ time to parse a string of n tokens **[2]**. However, this is very expensive when we engage into practical applications. So, researchers have exerted intensive efforts to find "smarter" techniques for parsing.

Most practical parsing methods fall into one of two classes, called the *top-down* and *bottom-up* methods. These terms refer to the order in which nodes in the parse tree are constructed. In the former, construction starts at the root and proceeds towards the leaves, while in the latter, construction starts at the leaves and proceeds towards the root. *(A parse tree is a visual representation of the hierarchical structure of a language statement, in which the levels in the tree depict the depth and breadth of the hierarchy. We will have more to say about different types of trees later).*

The popularity of top-down parsers is due to the fact that efficient parsers can be constructed more easily by hand using top-down methods. Bottom-up parsing, however, can handle a larger class of grammars and translation schemes.

Lexical Analysis vs. Parsing

I. The Rationale behind Separation

There are several reasons for separating the analysis phase of compiling into lexical analysis and parsing, the most important of which are **[2]**:

1. Simpler design is perhaps the most important consideration. The separation of lexical analysis from syntactic analysis often allows us to simplify one or the other of these phases. For example, a parser embodying the conventions for comments and whitespace is significantly more complex than one that can assume comments and whitespace have already been removed by a lexical analyzer. If we are designing a new language, separating the lexical and syntactic conventions can lead to a cleaner overall language design.

2. Compiler efficiency is improved. A separate lexical analyzer allows us to construct a specialized and potentially a more efficient processor for the task. A huge amount of time is spent reading the source program and partitioning it into tokens. Specialized buffering techniques for reading input characters and processing tokens can significantly speed up the performance of a compiler.

3. Compiler portability is enhanced. Input alphabet peculiarities and other device-specific anomalies can be restricted to the lexical analyzer. The representation of special or non-standard symbols, such as ↑ in Pascal, can be isolated in the lexical analyzer.

4. Specialized tools have been designed to help automate the construction of lexical analyzers and parsers when they are separated. These tools are actually the core of CCW, more about their importance, details and input specifications are presented in the relevant chapters later in the document.

II. A Special Relation?

The division between lexical and syntactic analysis is somewhat arbitrary. One factor in determining the division is whether a source language construct is inherently recursive or not. Lexical constructs do not require recursion, while syntactic constructs often do. The lexical analyzer and the parser form a *producer-consumer* pair. The lexical analyzer produces tokens and the parser consumes them. Produced tokens can be held in a token buffer until they are consumed. The interaction between the two is constrained only by the size of the buffer, because the lexical analyzer cannot proceed when the buffer is full and the parser cannot proceed when the buffer is empty. Commonly, the buffer holds just one token. In this case, the interaction can be implemented simply by making the lexical analyzer be a procedure called by the parser, returning tokens on demand.

2.2.1.3 Semantic Analysis

Certain checks are performed to ensure that the components of a program fit together meaningfully. The semantic analysis phase checks the source program for semantic errors and gathers type information for the subsequent code-generation phase. It uses the hierarchical structure determined by the syntax-analysis phase to identify the operators and operands of expressions and statements.

2.2.2 The Synthesis Phases

2.2.2.1 Intermediate Code Generation

After syntax and semantic analysis, some compilers generate an explicit intermediate representation of the source program. We can think of this intermediate representation as an assembly program for an abstract machine.

2.2.2.2 Code Optimization

The code optimization phase attempts to improve the intermediate code, so that faster-running machine code will result. There is a great variation in the amount of code optimization different compilers perform. In those that do the most – called "optimizing compilers" – a significant fraction of the compilation time is spent on this phase. However, there are simple optimizations that significantly improve the running time of the target program without slowing down the compilation performance noticeably.

2.2.2.3 Final Code Generation

Memory locations are selected for each of the variables used by the program. Then, intermediate instructions are each translated into a sequence of machine instructions that perform the same task. A crucial aspect is the assignment of variables to registers, since the intermediate code is the same for all platforms and machines and should not be dedicated to a specific one.

2.2.3 Meta-Phases

2.2.3.1 Symbol-Table Management

An essential function of a compiler is to record the identifiers used in the source program and collect information about various attributes of each identifier. These attributes may provide information about the storage allocated for an identifier, its type, its scope (where in the program it is valid), and – in the case of procedure names – such things as the number and types of its arguments, the method of passing each argument (e.g. by reference), and the type returned, if any.

A *symbol table* is a data structure containing a record for each identifier, with fields for the attributes of the identifier. The data structure allows us to find the record for each identifier and to store or retrieve data from its record quickly.

2.2.3.2 Error Handling

Each phase can encounter errors. However, after detecting an error, a phase must somehow deal with that error, so that the compilation can proceed, allowing further errors in the source program to be detected. A compiler that stops when it finds the first error is not as helpful as it could be.

The syntax and semantic analysis phases usually handle a large fraction of the errors detectable by the compiler. The lexical phase can detect errors where the characters remaining in the input do not form any token of the language. Errors where the token stream violates the structure rules (syntax) of the language are determined by the syntax analysis phase. During semantic analysis the compiler tries to detect constructs that have the right syntactic structure but no meaning to the operation involved, e.g., if we try to add two identifiers, one of which is the name of an array, and the other the name of a procedure.

3. Problem Definition

3.1 Historical Background

At about the same time that the first compiler was under development, Noam Chomsky **[50]** began his study of the structure of natural languages. His findings eventually made the construction of the compilers considerably easier and even capable of partial automation. Chomsky's studies lead to the classification of languages according to the complexity of their grammars and the power of the algorithms to recognize them. *The Chomsky Hierarchy* (as it's now called) **[51]** consists of four levels of grammars, called the type 0, type 1, type 2 and type 3 grammars; each of which is a specialization of its predecessor. The type 2, or *context-free grammars*, proved to be the most useful for programming languages – and today they are the standard way to represent the structure of programming languages. The study of the *parsing problem* (the determination of efficient algorithms for the recognition of context-free languages) was pursued in the 1960s and 70s, and lead to a fairly complete solution of this problem, which today has become a standard part of compiler theory. Context-free languages and parsing algorithms are discussed in the relevant chapters later in this document.

Closely related to context-free grammars are finite automata and regular expressions, which correspond to Chomsky's type 3 grammars. Their study led to symbolic methods for expressing the structure of words (or *tokens*). Finite automata and regular expressions are discussed in detail in the chapter on lexical analysis.

As the parsing problem became well understood, a great deal of work was devoted to developing programs that will automate this part of compiler development. These programs were originally called *compiler-compilers*, but are more aptly referred to as *parser generators*, since they automate only one part of the compilation process. The best-known of these programs, *Yacc* (Yet Another Compiler-Compiler), was written by Steve Johnson in 1975 for the UNIX system. Similarly, the study of finite automata led to the development of another tool called a *scanner generator*, of which *LEX* (developed for the UNIX system by Mike Lesk about the same time as *Yacc*) is the best known.

During the late 1970s and early 1980s a number of projects focused on automating the generation of other parts of compilers, including code generation. These attempts have been less successful, possibly because of the complex nature of the operations and our less-than-perfect understanding of them. For example, the automatically-generated semantic analyzers have a general performance degradation of 1000%!! (This means that they run ten times slower than manually-written semantic analyzers).

3.2 Compiler Construction Toolkits: Why?

Is it worth automating the compiler writing process? The following – very briefly – discusses the main difficulties a compiler writer encounters when writing a compiler code manually:

- Compiler writing is a complex, error-prone task that needs much time and effort.

- The resulting (manual) code is usually hard to debug and maintain.
- The code walkthrough is hard due to the amount of the written code and the diversity of the available implementations.
- Any small modification in the specification of the compiler results in big changes to the code, and subsequently to severe performance deterioration on the long run as the structure of the code is continuously modified.
- The class of algorithms that suits manual implementation of compilers is generally inefficient.

For these and other problems, tremendous research efforts were exerted in the 1970s and 80s to automate some phases of the compiler writing process. Following the "bulletin board" convention used above; the following are *some* of the advantages that a compiler writer gains when using compiler construction tools:

- The developer is responsible only for providing the specifications. No tedious, repeated work is required; thus avoiding the aforementioned difficulties.
- Adopting the most efficient algorithms in its construction; thus providing the developer with an easy means to generating efficient programs that would otherwise have been too difficult to implement. Manually-written compilers have proven to lack the required efficiency and maintainability.
- Ease of maintenance. Only the specifications are to be modified if a desired amendment is to be introduced.
- Providing developers unfamiliar with the compiler theory with an access to the uncountable benefits of using compiler writing techniques in compiler-unrelated applications.

3.3 Practical Automation of Compiler Writing Phases

The compiler writer, like any programmer, can profitably use software tools such as debuggers, version managers, and profilers … to implement a compiler. These may include:

- **Structure Editors:** A structure editor takes as an input a sequence of commands to build a source program. The structure editor not only performs the text-creation and modification functions of an ordinary text editor, but it also analyzes the program text, putting an appropriate hierarchical structure on the source program. Thus, the structure editor can perform additional tasks such as checking that the input is correctly formed, supplying keywords automatically (such as supplying a closing parenthesis for an opened one, or auto-completing reserved keywords), and highlighting certain keywords. Furthermore, the output of such an editor is often similar to the output of the analysis phase of a compiler; that is – imposing a certain hierarchical structure on the input program.
- **Pretty Printers:** A pretty printer analyzes a program and prints it in such a way that the structure of the program becomes clearly visible. For example, comments may appear in a special font, and statements may appear with an amount of indentation proportional to the depth of their nesting in the hierarchical organization of the statements.

Both of these tools are implemented in CCW 1.0.

In addition to these software-development tools, other more specialized tools have been developed for helping implement various phases of a compiler. I mention them briefly in this section; the tools implemented in CCW are covered in detail in the appropriate chapters.

Shortly after the first compilers were written, systems to help with the compiler-writing process appeared. These systems have often been referred to as *compiler-compilers*, *compiler-generators*, or *translation-writing systems*; as was discussed in the historical background above. Largely, they are oriented around a particular model of languages, and they are most suitable for generating compilers of languages similar to the model.

For example, it is tempting to assume that lexical analyzers for all languages are essentially the same, except for the particular keywords and signs recognized. Many compiler-compilers do in fact produce fixed lexical analysis routines for use in the generated compiler. These routines differ only in the list of keywords recognized, and this list is all that's needed to be supplied by the user.

Some general tools have been created for the automatic design of specific compiler components, these tools use specialized languages for specifying and implementing the component, and many use algorithms that are quite sophisticated. The most successful tools are those that hide the details of the generation algorithm and produce components that can be easily integrated into the remainder of a compiler. The following is a list of some useful compiler-construction tools:

I. Parser Generators. These produce syntax analyzers, normally from input that is based on a context-free grammar. In early compilers, syntax analysis consumed not only a large fraction of the running time of a compiler, but also a large fraction of the intellectual effort of writing it. This phase is now considered one of the easiest to implement. Many "little languages", such as PIC and EQN (used in typesetting books), and any file with a definitive structure; were implemented in a few days using parser generators. Many parser generators utilize powerful parsing algorithms that are too complex to be carried out by hand.

II. Scanner Generators. These automatically generate lexical analyzers, normally from a specification based on regular expressions. The basic organization of the resulting lexical analyzer is in effect a finite automaton – both to be detailed soon.

III. Syntax-Directed Translation Engines. These produce collections of routines that walk the parse tree, generating intermediate code. The basic idea is that one or more "translations" are associated with each node of the parse tree, and each translation is defined in terms of translations at its neighbor nodes in the tree.

IV. Automatic Code Generators. Such a tool takes a collection of rules that define the translation of each operation of the intermediate language into the machine language for the target machine.

3.4 Motivation

Among the aforementioned tools, the first two are the core of our project. There are a number of reasons that restricted us to implementing these two, the most important of which are:

- Not all of these tools have gained wide acceptance due to the lack of efficiency, standardization and practicality. As mentioned before, the semantic analyzers – for example – generated automatically are about ten times slower than their ad-hoc counterparts.
- Practical lexical analyzers and parsers are widely applicable to other fields of application, unrelated to the compiler construction process. Page 8 contains some of the applications a parser (together with its lexical analyzer) can be useful in.
- The available lexical analyzers and parsers – though numerous – share some drawbacks discussed in details in the next chapter on the market survey. We decided to implement a tool that – as much as the time limit permits – avoid these drawbacks.

4. Related Work

We have performed a survey on the currently available compiler construction toolkits. It was found that the most significant tools available are *LEX* and *Yacc*. However, numerous tools exist. Many of the disadvantages of *LEX* and *Yacc* were solved by other tools. However, so far no single tool has solved all of the problems normally encountered in such products. We are going to investigate some of them here:

4.1 Scanner Generators – *LEX*

As previously stated, lexical analyzer generators take as input the lexical specifications of the source language and generate the corresponding lexical analyzers. Different generator programs have different input formats and vary in power and use. We shall describe here *LEX*, which is one of the most powerful and widely used lexical analyzer generators. *LEX* was the first lexical analyzer generator based on regular expressions. It is still widely used. It is the standard lexical analyzer (scanner) generator on UNIX systems, and is included in the POSIX standard.

LEX reads the given input files, or its standard input if no file names are given, for a description of a scanner to be generated. The description is in the form of pairs of regular expressions and C code, called rules. After that, *LEX* generates as output a C source file that implements the lexical analyzer. This file is compiled and linked to produce an executable. When the executable is run, it analyzes its input for occurrences of the regular expressions. Whenever it finds one, it executes the corresponding C code.

Some Disadvantages of *LEX*

We have examined *LEX* from several perspectives and finally we were able to decide the following drawbacks in it:

- The generated code is very complex and completely unreadable. Consequently, its maintainability is low.
- The generated lexical analyzer can be generated only in the C language (Another version of *LEX* has been developed to support object oriented code in C++, but it is still under testing).
- There is only one DFA compression technique utilized.
- There is no clear interface between the scanner module and the application that is going to use the module.
- It doesn't support Unicode, so the only supported language is English.
- Some of the header files used by the generated scanner are restricted to the UNIX OS. Thus, its portability is low.
- It lacks a graphical user interface.

4.2 Parser Generators – *Yacc*

Syntactic analyzer generators take as an input the syntactic specifications of the target language – in the form of grammar rules – and generate the corresponding parsers. It holds for automated parser generation as well that different generator programs have different input formats and vary in power and use. However, the variation here is more acute due to the different types of parsers that might be generated (top-down parsers vs. bottom-up parsers). We shall describe here *Yacc*, which is one of the most powerful and widely used parser generators. Indeed, *LEX* and *Yacc* were designed so that seamless effort is exerted in order to integrate the generated lexical analyzer and the generated parser.

Yacc (*Yet Another Compiler Compiler*) is a general-purpose parser generator that converts a grammar description for an LALR(1) context-free grammar into a C program to parse that grammar. *Yacc* is considered to be the standard parser generator on UNIX systems. It generates a parser based on a grammar written in the BNF notation. *Yacc* generates the code for the parser in the C programming language.

Some Disadvantages of *Yacc*

The disadvantages of *Yacc* are almost the same as the disadvantages of *LEX*. They are repeated here for convenience:

- The generated code is very complex and completely unreadable. Consequently, its maintainability is low.
- The generated parser can be generated only in the C programming language (Another version of *Yacc* has been developed to support object oriented code in C++, but it is still under testing).
- There is only one type of parsers that may be generated which is the LALR(1) bottom-up parser.
- There is no clear interface between the parser module and the application that is going to use the module.
- Some of the header files used by the generated parser are restricted to the UNIX OS. Thus, its portability is low.
- It lacks a graphical user interface.

4.3 Flex and Bison

LEX and *Yacc* have been replaced by Flex and Bison and, more recently, Flex++ and Bison++. Such enhancements have solved the problems of portability and provided the user with a means to generate object oriented compilers in C++ but still the rest of the drawbacks remain.

4.4 Other Tools

Other than *LEX* and *Yacc*, we will make a brief survey on the available tools and packages related to our product together with their drawbacks. The references **[8] – [30]** are used in this section. We preferred not to attach every reference to its program to avoid cluttering this page.

ANTLR

- Only the recursive descent parsing technique is supported.
- It has no graphical user interface.
- It has some problems with Unicode.

Coco/R

- The only parsing technique available is the LL table-based parsing technique.
- It doesn’t support Unicode.
- There is no graphical user interface.

Spirit

- The only output language supported is C++.
- Only the recursive descent parsing technique is supported.
- There is no graphical user interface.
- It doesn't support Unicode.
- It doesn't provide a scanner generation capability.

Elkhound

- The only output languages supported are C++ and Ocaml.
- Only the bottom-up table based parsing technique is supported.
- There is no graphical user interface.
- It doesn't support Unicode.
- It doesn't provide a scanner generation capability.

Grammatica

- The only parsing technique used is the recursive descent parsing technique.
- There is no graphical user interface.
- The scanner produced by its scanner generator is inefficient.

LEMON

- The only output languages available are C and C++.
- The only parsing technique is the LALR(1) table-based parsing technique.
- There is no graphical user interface.
- It doesn't provide a scanner generation capability.
- It doesn't support Unicode.

SYNTAX

- It works only on the UNIX OS.
- There is no graphical user interface.
- The only output language available is C.

- Only the LALR(1) table-based parsing technique is supported.
- It doesn't support Unicode.

GOLD

- Only the LALR(1) table-based parsing technique is supported.
- Doesn't generate the driver programs (only the tables).
- There is no graphical user interface.

AnaGram

- The only output languages allowed are C and C++.
- Only the LALR(1) table-based parsing technique is supported.
- It doesn't support Unicode.

SLK

- Only the LL(k) table-based parsing technique is supported.
- There is no graphical user interface.

Rie

- The only output language available is C.
- Only the LR table-based parsing technique is supported.
- There is graphical user interface.
- It doesn't support Unicode.

Yacc++

- The only output language available is C++.
- Only the ELR(1) table-based parsing technique is supported.
- There is no graphical user interface.
- It doesn’t support Unicode.

ProGrammar

- It uses a separate ActiveX layer which degrades performance.
- It is not clear what type of parsing technique it uses.

YaYacc

- The only output language available is C++.
- The only parsing technique available is LALR(1) table based parsing.
- It works only on FreeBSD.
- It doesn't have a graphical user interface.
- It doesn't support Unicode.
- It doesn’t provide a scanner generation capability.

Styx

- The only output language available is C.
- Only the LALR(1) table-based parsing technique is supported.
- It doesn't have a graphical user interface.

PRECC

- The only output language available is C.
- Only the LL table-based parsing technique is supported.
- There is no graphical user interface.
- It doesn't support Unicode.

YAY

- The only output language available is C.
- Only the LALR(2) table-based parsing technique is supported.
- There is no graphical user interface.
- It doesn't support Unicode.
- There is scanner generation capability.

Depot4

- The only output languages available are Java and Oberon.
- The only parsing technique available is recursive descent parsing.
- There is no graphical user interface.
- There is no scanner generation capability.

LLGen

- The only output language available is C.
- Only the ELL(1) table-based parsing technique is supported.
- There is no scanner generation capability.
- It doesn't support Unicode.
- There is no graphical user interface.

LRgen

- It is designed so that the output is mainly written in C++.
- The only parsing technique is LALR(1) table based parsing.
- It is a commercial application.
- There is no Unicode support.
- There is no graphical user interface.

4.5 Conclusion

Most of the available tools don’t provide the choice among table-based and recursive descent parsing. And it is rare to find a tool with a graphical user interface. Such a tool is usually a commercial one (i.e., it costs a lot of money).

Unicode support is also missing in most of the tools surveyed. Also we can notice that only a few tools support multilingual code generation. That is, other than C and C++, it is not common to find a non-commercial tool that fulfills your needs.

Some tools do provide a scanner generator besides the parser generator, but as we've just seen; this is not always the case.

5. Our Objective

As it's now obvious from the previous section, there are a number of common drawbacks shared by most of the available products. Most of the parser generators implement a single parsing technique, or at most two. Most of them are mere console applications, without a user interface. Unicode is supported in a few of them; even those tools that support Unicode suffer from some shortcomings that make them generally unpractical. Code generation is usually in one or two languages. Scanner generators are sometimes existent, but most often you have to implement them yourself.

So we've decided to develop a tool that overcomes most of these drawbacks. Because of the time limit, we adopted extensibility as a principal paradigm, so that – for example – the LR parsing technique can be introduced in version 2.0 easily, even though version 1.0 currently supports recursive descent and LL(1) parsing techniques only. Unicode is supported in version 1.0, and some demos are available on the companion CD illustrating Arabic applications. Code generation is currently supported in three languages; namely ANSI C++, C# and Java. It's a trivial matter to add a new language, as will be illustrated in details in the chapter on parsing later in the document. *LEXcellent*, our lexical analyzer generator, is available to support its companion, *ParSpring*, the parser generator.

Our interface for integrating the process is CCW (Compiler Construction Workbench), a user friendly interface that supports most of the nice features introduced in IDEs, such as syntax highlighting, line numbers, breakpoints and matching brackets. More advanced features such as auto-completion are included in the future work plan. It's expected that version 2.0 is to eliminate all the drawbacks evident in most commercial applications. Currently, version 1.0 eliminates about 80% of them, given the extensible framework it's based upon.

6. Document Organization

After the field and the problem have been introduced, we turn now to briefly discussing the organization of this document.

Part I – which the reader has probably surveyed before reaching this section – mainly introduces the topic and clarifies the overall picture. Chapters 1 and 2 discuss the basic concepts. The problem is defined precisely in chapter 3. A market survey is carried out in chapter 4, and chapter 5 discusses our objective from implementing our tool.

Part II, which is the bulk of this document, is dedicated essentially to those developers who will use our tool, together with those interested in any implementation details.

Chapter 1 contains mainly a block diagram depicting the overall system architecture, together with a brief discussion of each component.
Chapter 2 is dedicated to the lexical analysis phase. Section 1 is an introduction; augmenting what was presented in the 'Basic Concepts' chapter in Part I. Section 2 introduces *LEXcellent*; our lexical analyzer generator. Section 3 discusses its input stream, and sections 4 and 5 are dedicated to its input file format. Sections 6, 7, 8 and 9 illustrate in full details the algorithms used in our implementation for *LEXcellent*. Section 10 is dedicated to describing the generated lexical analyzer. Section 11 describes the graphical GTG editor; which is a helper tool used to create regular expressions easily via a sophisticated graphical user interface.
Chapter 3 is dedicated to the parsing phase. Sections 1, 2 and 3 are introductory; again augmenting the material presented in Part I. Sections 4 and 5 are dedicated to the input file format of *ParSpring*, the parser generator. Sections 6 and 7 are pure implementation details. Finally, two helper tools are discussed in section 8.

Part III finalizes the document by providing the general conclusion; together with a summary for each tool and its future work plan. Then the tools, technologies and references used in this project are listed. The appendices are attached to the end of the document.

This document may be used by more than one reader. If you are new to the whole issue, the following sections in Part I are recommended for first reading: 1.1, 1.3, 2.1, 2.2, 3.1, 3.2, 3.3, 5, and sections 2.1, 3.1, 3.2 and 3.3 in Part II.

If you know what you want to do, and you prefer to start using the tool directly; read the following in Part II: 2.4, 2.5, 3.4 and 3.5. Section 2.10 will be useful also; though not necessary to get started. Don't forget the user manual in the appendices.

For using the helper tools, consult sections 2.11 and 3.8 in Part II.

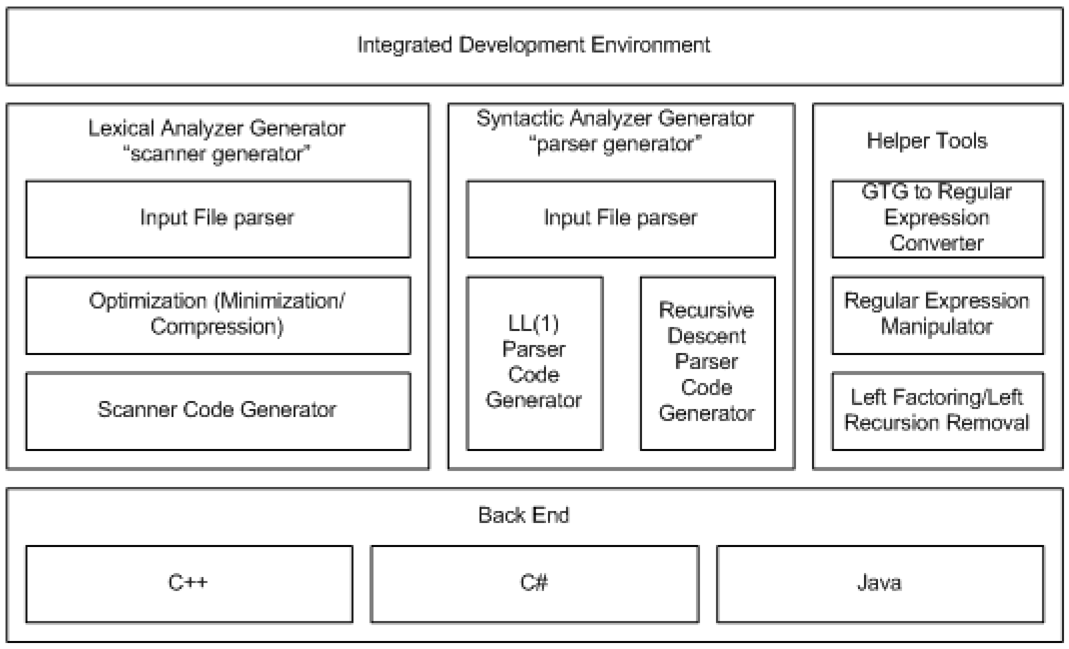
Finally, when you're done using the tool; you may want to take a look at the implementation details – and you're welcome to augment our work. The source code is provided on the companion CD. Sections 2.3, 2.6, 2.7, 2.8 and 2.9 discuss in full details the implementation details for *LEXcellent*. Its companion's details are outlined in sections 3.6 and 3.7.

Part II

Technical Details

1. Architecture and Subsystems

Our Compiler Construction Toolkit consists of several components that interact with each other to facilitate the process of compiler development. The general architecture of the package can be represented in figure II-1:



Integrated Development Environment
Lexical Analyzer Generator "scanner generator"
Input File parser
Optimization (Minimization/ Compression)
Scanner Code Generator
Syntactic Analyzer Generator "parser generator"
Input File parser
LL(1) Parser Code Generator
Recursive Descent Parser Code Generator
Helper Tools
GTG to Regular Expression Converter
Regular Expression Manipulator
Left Factoring/Left Recursion Removal
Back End
C++
C#
Java

Figure II-1: The General Architecture

While the IDE was developed using the .NET platform, almost all the other components of the system were developed in native C++. Such combination allowed us to gain the powerful GUI capabilities of the .NET framework without sacrificing the efficiency and portability of the C++ unmanaged code.

The following is a brief investigation of each component in the system. Each of these components is to be fully detailed in a dedicated chapter later in the document.

- ***Integrated Development Environment:*** It the environment in which the compiler developer creates and maintains projects, edits specification files, uses the utilities and helper tools and invoke the scanner and parser generator tools to generate his compiler.
- ***Lexical Analyzer Generator:*** It is the software component that is responsible for generating the lexical analyzer (scanner), given the user specifications. It consists of the following general modules:
  - ***Input File Parser:*** This module is responsible for parsing the specifications file that contains the regular definitions of the tokens to be returned by the generated scanner. The regular definitions are converted into an NFA then into a DFA. More on both later.
  - ***Optimization (Minimization/Compression):*** This module is responsible for optimizing the produced DFA obtained from the previous phase.

- ***Scanner Code Generator:*** This module is responsible for generating the source code of the required scanner.

- ***Syntactic Analyzer Generator:*** It is the software component that is responsible for generating the syntactic analyzer (parser), given the user specifications. It consists of the following general modules:
  - ***Input File Parser:*** This module is responsible for parsing the specifications file that contains the grammar specifications of the language to be recognized by the generated parser. The grammar rules are converted into a tree inside the program memory.
  - ***LL(1) Parser Code Generator:*** If the user specifies that the generated parser should be an LL(1) parser, then this module should assume responsibility for generating the parser.
  - ***Recursive-Descent Parser Code Generator:*** If the user specifies that the generated parser should be a recursive-descent parser, then this module should assume responsibility for generating the parser.

- ***Helper Tools:*** A set of tools that facilitates the process of writing the specifications of the desired scanner and parser. They are mainly invoked from the IDE.
  - ***GTG to Regular Expression Converter:*** A tool that gives the developer the capability to specify his regular definition in terms of a *Generalized Transition Graph* instead of a regular expression. This may be easier in some cases.
  - ***Regular Expression Manipulator:*** A tool that allows the developer to generate new regular expressions from the union, intersection or negation of input regular expressions.
  - ***Left Factoring/Left Recursion Removal:*** A tool that performs left factoring and left recursion removal on a given CFG, which are two essential operations that must be performed if a recursive-descent parser is to be generated. Such facility frees the developer from doing all that effort manually.

- ***Back End:*** It is the set of classes that generate the required scanners and parsers in any of the supported languages. Currently, only C++, C# and Java are available, but more languages may be supported easily.

Figure II-2 gives a brief illustration of the two main components of the system, the scanner generator *LEXcellent* and the parser generator *ParSpring*. This block diagram is just for reference, more details about both tools are presented in the appropriate chapters later in this part.

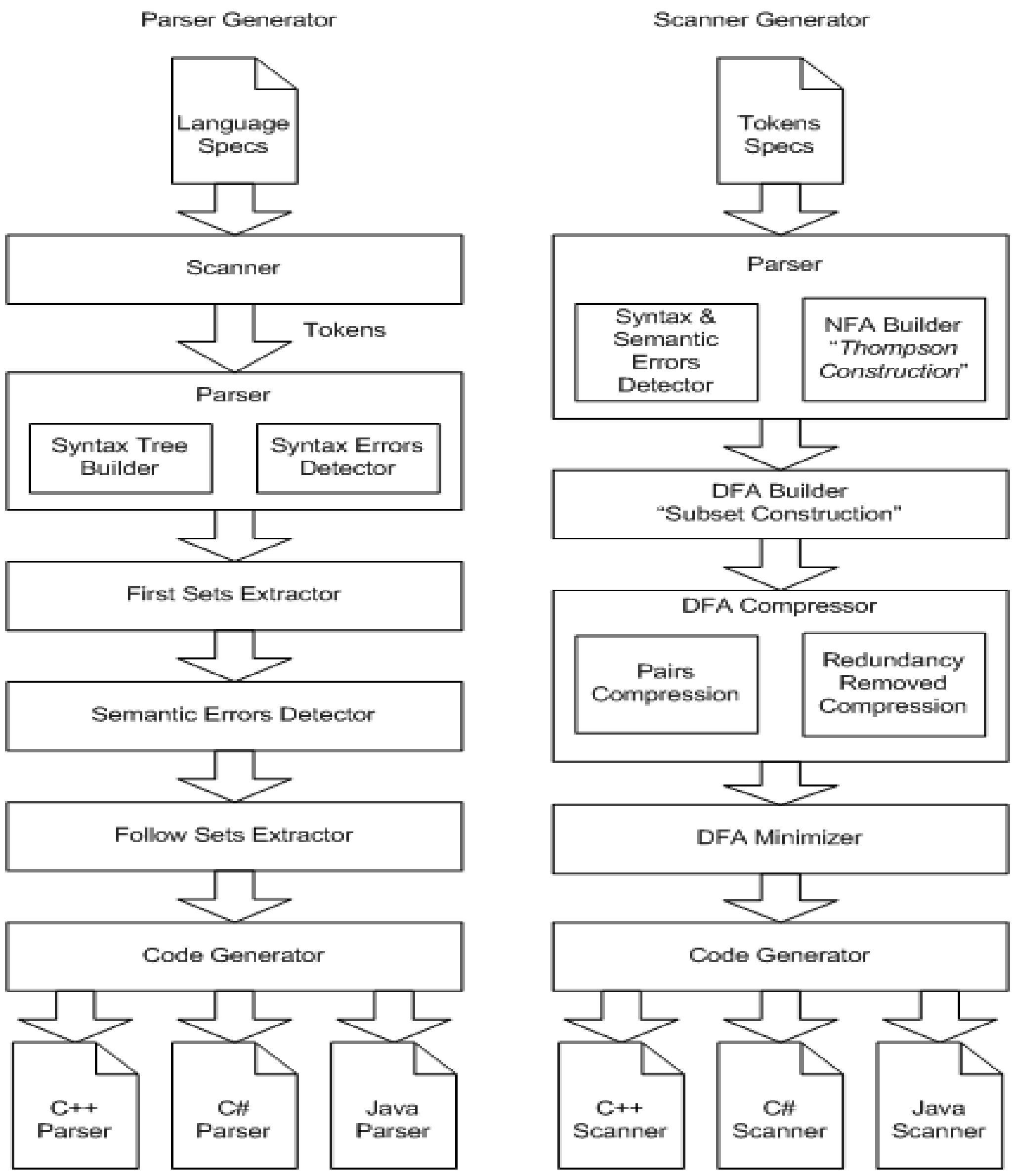


Figure II-2: LEXcellent and ParSpring - The Main Components

The package consists of three main executables: The IDE, the scanner generator and the parser generator. The user runs the IDE to start his development, to create and maintain projects, to edit the specification files in a tailored editor and to utilize the available helper tools.

When it is time to generate code, the IDE invokes the appropriate executable to generate a scanner or a parser, as required by the user. If the operations succeed, the generated code will be released in a code file, otherwise a list of errors will be returned from the code generator to the IDE.

Thus, the process of dealing with the underlying code generators is completely transparent to the user. However, the user has the choice whether to use our IDE to invoke the scanner and parser generators, to use another IDE (such as the Visual Studio IDE) or to invoke the generators directly without an IDE. Our IDE, however, offers a group of functionalities and utilities that makes it the best choice for dealing with the scanner and parser generators.

2. The Lexical Analysis Phase

2.1 More about Lexical Analysis

2.1.1 Definition

Lexical analysis is usually the first phase of the compilation process in which the lexical analyzer takes a stream of characters and produces a stream of names, keywords, and punctuation marks that the parser uses for syntax analysis. In addition, it may discard whitespace and comments between the tokens to simplify the operation of later phases. It would unduly complicate the parser to have to account for possible whitespace and comments at every possible point; this is one of the main reasons for separating lexical analysis from parsing. For example **[2],** in lexical analysis the characters in the assignment statement

```
position := initial + rate * 60
```

would be grouped into the following tokens:

1. The identifier **`position`**.
2. The assignment symbol **`:=`**.
3. The identifier **`initial`**.
4. The plus sign **`+`**.
5. The identifier **`rate`**.
6. The multiplication sign **`*`**.
7. The number ***`60`***.

The blanks separating the characters of these tokens would normally be eliminated during lexical analysis.

2.1.2 Lexical Tokens

A lexical token is a sequence of characters that can be treated as a unit in the grammar of the source language **[3]**. Lexical tokens are usually classified into a finite set of token types. For example, some of the token types of a typical programming language are listed in the table below.

Some tokens have special meaning in programming languages such as IF, VOID and RETURN. These are called reserved *words* and, in most languages, cannot be used as identifiers. Some of these are illustrated in ExTab 2-1 on the next page.

ExTab 2-1: Reserved words and symbols

Type	Examples
ID	`foo n14 last`
IF	`if`
COMMA	`,`
NOTEQ	`!=`
LPAREN	`(`
RPAREN	`)`
NUM	`73 0 00 515 082`
REAL	`66.1 .5 10. 1e67 5.5e-10`

The input file might contain sequences of characters that are either ignored by the lexical analyzer or not tackled by the language grammar. These are called *nontokens*. Examples of nontokens are illustrated in ExTab 2-2.

ExTab 2-2: Examples of nontokens

comment	`/* try again */`
preprocessor directive	`#include<stdio.h>`
preprocessor directive	`#define NUMS 5, 6`
macro	`NUMS`
blanks, tabs, and newlines	

In languages weak enough to require a macro preprocessor, the preprocessor operates on the source character stream, producing another character stream that is then fed to the lexical analyzer. It is also possible to integrate macro processing with lexical analysis.

Given a program such as

```
float match0(char *s) /* find a zero */
{
   if (!strncmp(s, "0.0", 3))
   return 0.;
}
```

the lexical analyzer will return the stream

```
FLOAT   ID(match0)   LPAREN   CHAR   STAR   ID(s)   RPAREN
LBRACE   IF   LPAREN   BANG   ID(strncmp)   LPAREN   ID(s)
COMMA   STRING(0.0)   COMMA   NUM(3)   RPAREN   RPAREN
RETURN   REAL(0.0)   SEMI   RBRACE   EOF
```

where the token-type of each token is reported; some of the tokens, such as identifiers and literals, have *semantic values* attached to them, giving auxiliary information in addition to the token-type. For example, the second identifier is attached the string “match0”.

There many ways to describe the lexical rules of a programming language. For example, we can use English to describe the lexical tokens of a language. A description of identifiers in C or Java is provided on the following paragraph **[1]**:

> An identifier is a sequence of letters and digits; the first character must be a letter. The underscore (_) counts as a letter. Uppercase and lowercase letters are different. If the input stream has been parsed into tokens up to a given character, the next token is taken to include the longest string of characters that could possibly constitute a token. Blanks, tabs, newlines and comments are ignored except as they serve to separate tokens. Some whitespace is required to separate otherwise adjacent identifiers, keywords, and constants.

A more compact, precise, and formal way to specify the lexical tokens of a source language makes use of the formal language of regular expressions. Not only can automated checks be performed on this form of specification, but it can be used to generate efficient lexical analyzers as well.

2.1.3 Regular Expressions

Regular expressions provide a mathematical way to specify patterns. Each pattern matches a set of strings. So, a regular expression will stand for a set of strings. Before providing a definition for regular expressions, we define some of the technical terms that will be used again and again during the discussion of lexical analysis and regular expressions.

The term alphabet or character class denotes any finite set of symbols. Typical examples of symbols are letters and characters. The set {0, 1} is the binary alphabet. ASCII and EBCDIC are two examples of computer alphabets.

A string over some alphabet is a finite sequence of symbols drawn from that alphabet. In language theory, the terms sentence and word are often used as synonyms for the term "string" **[2]**. The length of a string s, usually written as |s|, is the number of occurrences of symbols in s. For example, banana is a string of length six. The empty string, denoted by ε, is a special string of length zero.

The term *language* denotes any set of strings over some fixed alphabet. This definition is very broad. Abstract languages like •, the *empty* set, or $\{\varepsilon\}$, the set containing only the empty string, are languages under this definition. If **A** and **B** are two languages over some fixed alphabet, then we define the concatenation of the two languages **A.B** is a language defined by:

$$\mathbf{A.B} = \{xy:\ x \in \mathbf{A} \text{ and } y \in \mathbf{B}\}$$

$\mathbf{L}^k$ refers to k concatenations of the language **L**. If k = 0, then $\mathbf{L}^0$ contains only the empty word ε. The *Kleene Closure* of a language **L** denoted by **L*** is the language containing all strings that can obtained by forming zero or more concatenations of words from **L**, or mathematically:

$$\mathbf{L^*} = \bigcup_{i=0}^{\infty} \mathbf{L^i}.$$

A *regular expression* describing a given language **L** over some alphabet **Σ** can be any of the following **[1]**:

- If *a* is a symbol in **Σ** ($a \in \Sigma$), then **a** is a regular expression with **L**(**a**) = { *a* }.
- **ε ,** where **L(ε) = {** ε **}** (The empty string)**.**
- If **r** is a regular expression over **Σ**, then **(r)** is a regular expression over **Σ,** with **L((r)) = L(r)**.
- If **r** is a regular expression over **Σ**, then **r*** is a regular expression over **Σ,** with **L(r*) = L*(r)**.
- If **r** and **s** are regular expressions over **Σ**, then their concatenation, **r.s** or simply **r s,** is a regular expression over **Σ,** with **L(r s) = L(r).L(s)**.
- If **r** and **s** are regular expressions over **Σ**, then their union, **r | s** is a regular expression over **Σ,** with **L(r | s) = L(r)** $\bigcup$ **L(s)**.

A language is regular if and only if it can be specified by a regular expression. Some regular expressions and descriptions of the languages they define are listed as examples in ExTab 2-3:

ExTab 2-3: Example regular expressions

(**0** | **1**)* **0**	Binary numbers that are multiples of two.
b* (**a b b***)* (**a** | ϵ)	Strings of a's and b's with no consecutive a's.
(**a** | **b**)* **a a** (**a** | **b**)*	Strings of a's and b's containing consecutive a's.

In writing regular expressions, we will sometimes omit the concatenation symbol, and we will assume that Kleene closure "binds tighter" than concatenation, and concatenation binds tighter than alternation; thus the regular expression a b | c means (a . b) | c, and the regular expression (a | b c *) means a | (b . (c)*).

ExTab 2-4: Operators of regular expressions

a	An ordinary character stands for itself.
ϵ	The empty string. Another way to write it.
M | *N*	Alternation, choosing from *M* or *N*.
M **.** *N*	Concatenation, an *M* followed by an *N*.
MN	Another way to write concatenation.
"a.+"*	Quotation, a string in quotes stands for itself literally.
*M**	Repetition (zero or more times).
M?	Optional, zero or one occurrence of *M*.
M^+	Repetition, one or more times.
[a − zA − Z]	Character set alternation.
.	A period stands for any single character except newline.

Next, we present some of the useful abbreviations that are commonly used to write regular expressions. [**abcd**] means (**a** | **b** | **c** | **d**), [**b**-**g**] means [**bcdefg**], [**b**-**gM**-**Qkr**] means [**bcdefgMNOPQkr**], $\boldsymbol{M}$? means ($\boldsymbol{M} \mid \epsilon$), and $\boldsymbol{M}^+$ means ($\boldsymbol{M} \cdot \boldsymbol{M}^*$). These extensions are convenient, but none of them extend the descriptive power of regular expressions: Any set of strings that can be described using these abbreviations could also be described using the basic set of operators. All the operators are summarized in ExTab 2-4 on the previous page.

Using this language, we can specify the lexical tokens of a programming language as follows:

ExTab 2-5: More examples on regular expressions

`if`	`IF`
`[a-zA-Z_][a-zA-Z_0-9]*`	`ID`
`[0-9]+`	`NUM`
`([0-9]+"."[0-9]*)|([0-9]*"."[0-9]+)`	`REAL`
`("\\"[a-z]*"\n")|(" "|"\n"|"\t")+`	*no token, just white space*
`.`	*error*

The fifth entry of ExTab 2-5 recognizes comments or whitespace but does not report back to the parser. Instead, the white space is discarded and the lexical analysis process is resumed. The comments for this lexical analyzer begin with two slashes, contain only alphabetic characters, and end with a newline.

Finally, a lexical specification should be *complete*, always matching some initial substring of the input; we can always achieve this by having a rule that matches any single character (and in this case, prints an `illegal character` error message and continues).

These rules are a bit ambiguous. For example, `if8` can be matched as a single identifier or as the two tokens `if` and `8`. Moreover, the string `if` can be considered an identifier or a reserved word. There are two important disambiguation rules to resolve such ambiguities that are used by *LEXcellent*:

- **Longest match:** The longest initial substring of the input that can match any regular expression is taken as the next token.
- **Rule priority:** For a particular longest initial substring, the first regular expression that can match determines its token-type. This means that the order of writing down the regular-expression rules has significance.

Thus, `if8` matches as an identifier by the longest-match rule, and `if` matches as a reserved word by rule-priority.

2.1.4 Deterministic Finite Automata

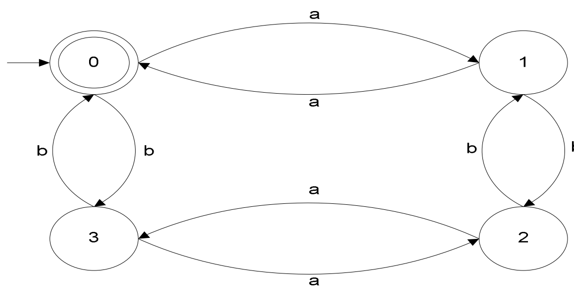
A deterministic finite automaton consists of **[2]**:

1. A finite set of states, often denoted by **Q**.
2. A finite set of input symbols, often denoted by **Σ**.

3. A transition function that takes as arguments a state and an input symbol and returns a state. The transition function will commonly be denoted **δ.**
4. A start state q_0, one of the states in **Q**.
5. A set, of final or accepting states F. The set F is a subset of **Q**. There can be zero or more states in F.

Sometimes, it is comfortable to use informal graph representation of automata, in which states are represented by circles or nodes, and the transition from a give state q_i to state q_j on symbol a is represented by a directed edge from state (node) q_i to state (node) q_j, labeled with a. The start state is marked by an incoming edge, and accepting states are marked by an extra inner circle inside the node.

ExFig 2-1 is a graph representation of a DFA with **Σ** = {a, b}:



ExFig 2-1: An example DFA

A deterministic finite automaton will often be referred to by its acronym: DFA. The most succinct representation of a DFA is a listing of the five components above.

The first thing we need to understand about a DFA is how the DFA decides whether or not to *accept* a sequence of input symbols. The *language* of the DFA is the set of all strings that the DFA accepts. Suppose $a_l\ a_2\ ...\ a_n$ is a sequence of input symbols. We start out with the DFA in its start state, q_0. We consult the transition function **δ**, say $\boldsymbol{\delta}(q_0, a_1) = q_1$ to find the state that the DFA enters after processing the first input symbol a_1.We process the next input symbol, a_2, by evaluating $\boldsymbol{\delta}(q_1, a_2)$; let us suppose this state is q_2. We continue in this manner finding states q_3, q_4 ... q_n where $\boldsymbol{\delta}(q_{i-1}, a_i) = q_i$, for each i. If q_n is a member of F, then the input $a_1, a_2 \ldots a_n$ is accepted, and if not then it is *rejected*. The set of all strings that the DFA accepts is the language of that DFA. For example, the DFA in the figure above accepts the language of all strings over the alphabet {a, b} with even number of a's and even number of b's.

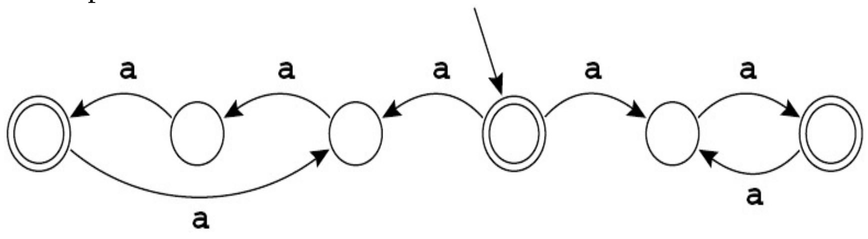
2.1.5 Nondeterministic Finite Automata

A *nondeterministic finite automaton* (*NFA*) has the power to be in several states at once. This ability is often expressed as an ability to "guess" something about its input. It guesses which state to go next such that if there is a sequence of guesses that leads the string to be accepted by the machine, then this sequence of guesses is chosen by the NFA. We introduce the formal notions associated with nondeterministic finite automata. The differences between DFAs and NFAs will be pointed out as we do.

An NFA consists of **[2]**:

1. A finite set of states, often denoted **Q**.
2. A finite set of input symbols, often denoted **Σ**.
3. A start state q_0, one of the states in **Q**.
4. F, a subset of **Q**, is the set of final (or accepting) states.
5. The transition function **δ** is a function that takes a state in **Q** and an input symbol in **Σ** or the empty word **ε** as arguments and returns a subset of **Q**. Notice that the only difference between an NFA and a DFA is in the type of value that **δ** returns: a set of states in the case of an NFA and a single state in the case of a DFA.

Here is an example of an NFA:

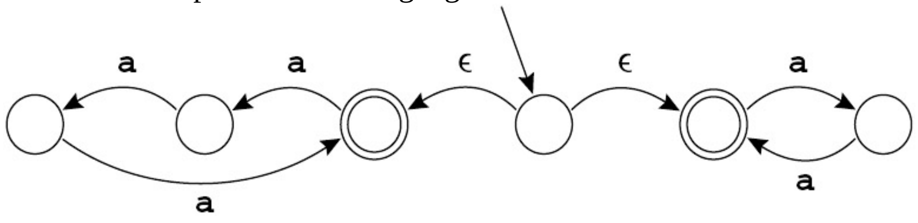


ExFig 2-2: An example NFA

In the start state, on input character a, the automaton can move either right or left. If left is chosen, then strings of a's whose length is a multiple of three will be accepted. If right is chosen, then even-length strings will be accepted. Thus, the language recognized by this NFA is the set of all strings of a's whose length is a multiple of two or three.

On the first transition, the machine in ExFig 2-2 must choose which way to go. It is required to accept the string if there is *any* choice of paths that will lead to acceptance. Thus, it must "guess", and must always guess correctly.

Edges labeled with ϵ may be taken without using up an input symbol. ExFig 2-3 is another NFA that accepts the same language:



ExFig 2-3: An example NFA with ϵ-transitions

Again, the machine must choose which ϵ-edge to take. If there is a state with some ϵ-edges and some edges labeled by symbols, the machine can choose to eat an input symbol (and follow the corresponding symbol-labeled edge), or to follow an ϵ-edge instead.

2.2 *LEXcellent:* An Introduction

LEXcellent is the component responsible for generating the lexical analyzer based on the specifications given in an input file. Since lexical analysis is the only phase in a compiler that deals with input files, special care should be given to dealing with Unicode streams.

The main components of *LEXcellent* are illustrated here. This is just a general overview and a thorough description of each phase of the generation process is provided in the appropriate sections of this chapter.

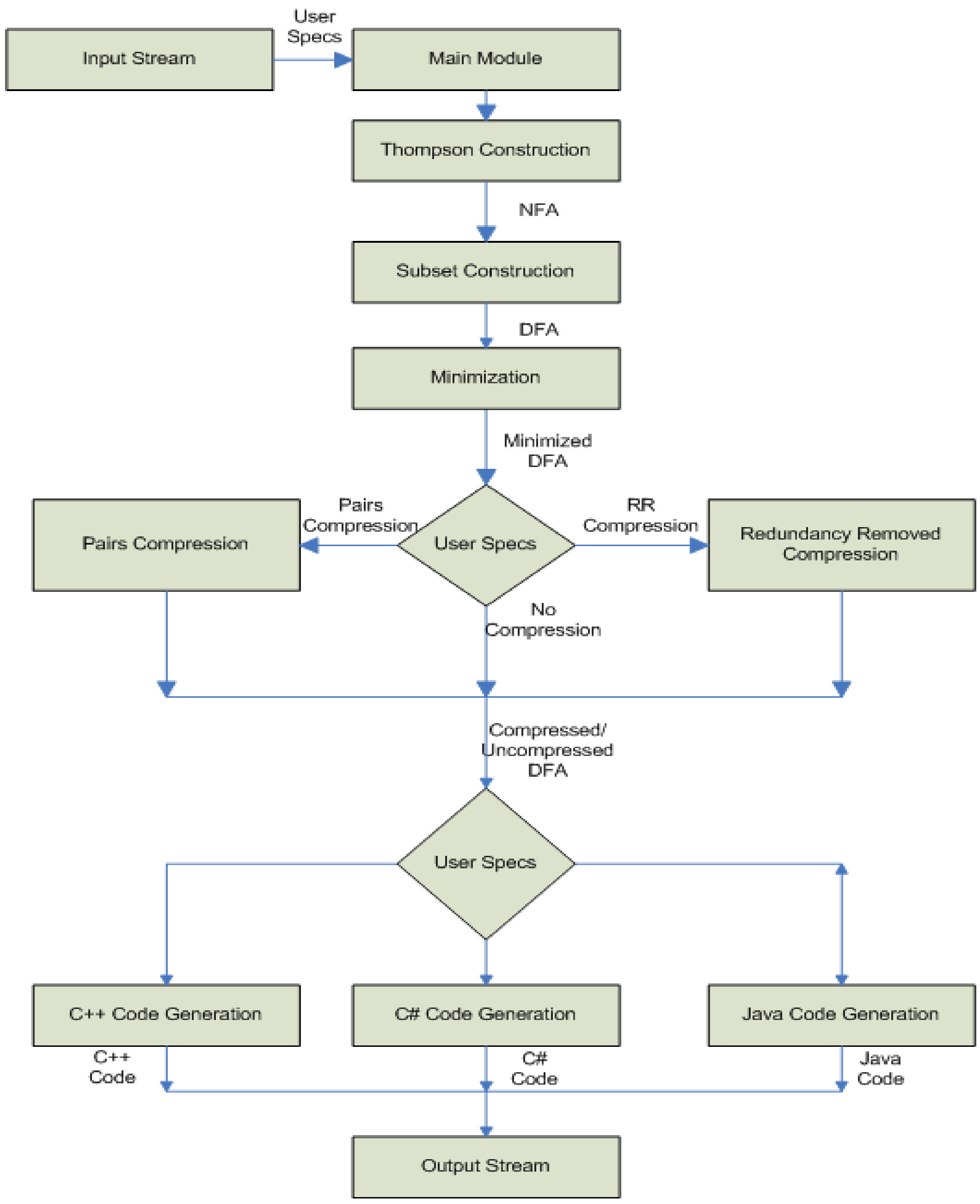


Figure II-3: LEXcellent - The Process

2.3 The Input Stream

The input stream is represented by the class `LexerInputReader`. This class encapsulates all the fields and methods necessary for reading and parsing the input file. The class was designed principally to deal with Unicode files. Its functionalities can be summarized in two main functions:

- Read the user options (such as the output language and the compression technique) and pass it to the following phases to control the scanner generation process.
- Parse the regular definitions and produce the corresponding NFAs. Constructing an NFA from a regular definition should be a straight forward task. The NFAs are then grouped into a single NFA to be passed to the next stage.

2.3.1 Unicode Problems

One of the main features of *LEXcellent* is its ability to deal with the Unicode character set, and to generate lexical analyzers capable of dealing with Unicode. This guarantees that *LEXcellent* will have a widespread use because most systems are now Unicode-enabled and commercial lexical analyzer generators generally lack this feature.

2.3.1.1 What is Unicode?

Unicode **[34]** is an industry standard designed to allow text and symbols from all of the writing systems in the world to be consistently represented and manipulated by computers. Unicode characters can be encoded using any of several schemes termed Unicode Transformation Formats (UTF).

The Unicode Consortium has as its ambitious goal the eventual replacement of existing character encoding schemes with Unicode, as many of the existing schemes are limited in size and scope, and are incompatible with multilingual environments. Its success in unifying character sets has led to its widespread and predominant usage in the internationalization and localization of computer software. The standard has been implemented in many recent technologies, including XML, the Java programming language, and modern operating systems.

2.3.1.2 The Problem

Since we have chosen to use the C++ programming language in the implementation of *LEXcellent*, and to restrict ourselves to the ANSI standards; we have used the *`IOStream`* library to implement the input and the output. The input to *LEXcellent* is the text file containing the description of the lexical analyzer. The output is the generated lexical analyzer, along with errors (if any) and the statistics of the construction process.

Changing the definition of a certain macro converts the program from the *ASCII* build mode to the *Unicode* build mode. This switches the program from using narrow characters and their related character processing functions and *`IOStream`* classes to using wide characters and their related character processing functions and *`IOStream`* classes. Narrow-character programs tend to be faster and smaller. If the user needs are limited to narrow characters, it would be an overhead to use a Unicode program. On the other hand, the user might want to develop a set of programs for the Arabic language or the Chinese language, for instance. So, a Unicode-enabled lexical analyzer generator will be great. Consequently, two builds will be available: an *ASCII* release and a *Unicode* release.

During the development process, the program was compiled and tested under the ASCII build. When the application was complete, it was the time to try the Unicode build. We thought defining the aforementioned macro would get things work as expected. Unicode-encoded test files were prepared and all what remained was to build the application under Unicode. It was true that the application compiled successfully with no problems, but it failed to read the input files of all test cases. The failures ranged from detecting invalid sequence of characters at the beginning of the file to reading spurious null before or after each character. When the input included Arabic letters, nothing related to Arabic was processed. We tried the same files with simple programs developed with C# and faced no problem.

We started to write simple, “Hello World” text files under different Unicode encodings and use binary editors to view the contents of these files. We found that all Unicode files always begin with a fixed sequence of bytes that are independent of the actual text stored in the file. The bytes in that sequence differ according to the encoding under use. We correctly concluded that this was to help the application determine the specific encoding under use in the file. But this was not enough to tell how to solve the problem.

Indeed, this problem exhausted an excessive amount of time from us. Such a problem was never expected. See references **[40]** – **[48]** for more about this problem. We made a research plan for the whole matter. The plan was organized as a set of questions to be answered as follows:

- What are the different encodings used to represent Unicode?
- How does *`IOStream`* internally work and how does it deal with wide characters and different file encodings?
- How did other tools deal with Unicode?

The answer to the first question is quite long and is beyond the scope of this document. The answer of the second question is the topic of many books merely dedicated to the *`IOStream`* library. For the third question, we were not surprised with the number of forums and websites that tackled the topic. However, we shall briefly and collectively illustrate the results of the three questions and the solution of the problem in the following outline **[35]**.

- C++ *`IOStream`* classes use some type of encoder/decoder classes to convert between the internal representation of characters and their external representation. If the characters are externally encoded using some encoding scheme, then an appropriate encoder/decoder object should be ‘imbued’ with the stream object.
- The most famous Unicode encodings are UTF-8, UTF-16 BE, and UTF-16 LE. UTF-32 BE and LE are not as famous. UTF-8 is an 8-bit, variable-width encoding, compatible with *ASCII* that uses one to four bytes per character.

UTF-16 is a 16-bit, variable-width encoding that uses from two to four bytes per character. UTF-16 is available in two flavors: Little-Indian and Big-Indian; which differ in the ordering of bytes in each character. UTF-32 is 32-bit fixed-width encoding that is available either as Little-Indian or Big-Indian. UTF-32 encodings are less commonly used.

- The C++ standard library has not implemented encoder/decoder classes for Unicode encodings. It defines the template, but does not implement it. The C++ standard library implements something like a fake encoder/decoder class for dealing with wide characters. All it has to do is to convert a two-byte character into a single byte when writing to a file (or the opposite if reading from a file). If this is not bad enough, how this conversion is performed is implementation-dependent.
- The number of characters in the Unicode character set exceeds 65,536. Thus, a Unicode character needs more than two bytes for storage. Despite this fact, a wide character variable in Microsoft Visual C++.NET 2003™ takes only two bytes. Thus, some characters took more than two bytes in memory. This means that in-memory characters have variable lengths.
- We were able to find implementations of the encoder/decoder classes for UTF-8 and UTF-16 LE. When it was the time to retry the testing process, we found that it is the responsibility of the developer to determine which encoding scheme is used in the text file, and ‘imbue’ the appropriate encode/decoder object to deal with before opening the file. This means that the file must be opened twice, once to determine its encoding and another to read it.
- Microsoft Visual C++.NET 2003™ implementation of *`IOStream`* library is not that good. It works very well with *`IOStream`* classes based on narrow characters, but it fails miserably to operate with wide characters and different ‘imbued’ encoder/decoder objects. The most predominant failure occurs when trying to reposition the read pointer (seek) although the address sought is given as an absolute address rather than a relative one. The latter feature is crucial for any lexical analyzer to be able to deal with arbitrary lookaheads.

The last observation was extremely painful to us, since it meant that we had to either stop trying to support the Unicode character set or to find an alternative method to process the input. In addition, any alternative method for processing the input should comply with the standards; otherwise our top goal (which is platform independence) is to be sacrificed.

At last, we decided to make our own input classes that wrapped the C file I/O routines included in the C++ standard library. The input classes we have developed support UTF-8, UTF-16 BE and UTF-16 LE. The application was then tested under the Unicode build over Unicode test files and it operated smoothly and without problems. We implemented a successful sample application that deals with the Arabic language. You can view it on the companion CD.

2.4 Input File Format

The input file format of *LEXcellent* is very similar to that of *LEX*. This is because *LEX* is widely used and its input format explained in many compiler books. Thus, anyone familiar with *LEX* should be able to use *LEXcellent* with little trouble.

The *LEXcellent* input file consists of five sections, a line beginning with %% separates each two:

```
Top File Definition
%%
Class Definition – User Code
%%
Rules
%%
Extended Definitions (1) – User Code
%%
Extended Definitions (2) – User Code
```

Figure II-4: LEXcellent – The Format of the Input File

The specializations of these sections differ depending on the programming language used for code generation. For example, the *'Extended Definitions (1)'* section specifies user code to be copied into the generated files. If the lexical analyzer is to be generated in C++, this section will be copied onto the top of the C++ source code file (.cpp file). If the lexical analyzer is to be generated in C#, this section will be copied onto the C# source code file (.cs file) just after the lexical analyzer class definition but inside the same namespace.

Each section is detailed below.

2.4.1 Top File Definition

This section can be used for the following purposes:

- Specifying options related to code generation.
- Declaring macros for latter use in the specification.
- Writing some code that is placed, as-is, at the top of the generated file.

These can be specified in any order, and can be mixed together in the specification. In addition, comments can be freely added anywhere in this section and are copied without changes to the generated code. There are two types of comments:

i) Single-line comments. The line should begin with `//`
ii) Comments delimited by `/*  */`. The delimiters should be placed at the beginning of the line without any indentation. Otherwise, their effect is ignored.

The format of each of the above purposes is detailed below:

Options

Options related to code generation can be specified and configured in the **Top File Definition** section using the following format:

```
%option OptionName = OptionValue
```

For example, the following statement tells the code generator to use the C++ programming language for code generation:

```
%option Language = C++
```

The following statement tells the code generator that the permitted range of Unicode characters is from 0x0000 to 0x007F:

```
%option CharacterSet = [\d0-\d127]
```

Lines describing options should be unindented. Otherwise, it will be considered user-defined code that should be copied as-is into the generated code. This anomaly is found in the LEX input file format, too. That's why we preferred not to modify it.

`OptionName` and `OptionValue` are case insensitive. In addition, each option has a pre-specified default value. If an option is not specified in the specification file, its default value is assumed. Thus, it is possible to write a specification file without explicitly specifying any option.

Table II-1 lists the different configurable options in this section:

Table II-1: Configurable Options in Top File Definition Section

Option Name	*Option Values*	*Default Value*	*Description*
Language	C++ C# Java	C++	The programming language of the generated lexical analyzer.
CharacterSet	Character class (described below)	[d0-d127]	The subset of Unicode character range to use for the input of the lexical analyzer.
Namespace	Identifier	Compiler	The namespace of the generated lexical analyzer class.
ClassName	Identifier	LexicalAnalyzer	The lexical analyzer class name.
FunctionName	Identifier	GetNextToken	The pattern matching function name.
ReturnType	Identifier	int	The Return type of the pattern matching function.
FileName	Name and path of the file	Lex	The path and name of the generated lexical analyzer file(s) – Appropriate file extensions are appended automatically.
CompressionTechnique	None Redundancy Pairs Best	Redundancy	The compression technique to use for compressing the lexical analyzer transition table.
PairsThreshold	A nonnegative integer	8	If pairs compression is used, this specifies the number of items above which, the state is considered dense and is represented by an array rather than a linked list.

InvalidTokenAction	Value to be returned by the function.	-2	If the lexical analyzer faced an invalid token, then the pattern matching function returns by executing: return InvalidTokenAction;
EOFAction	Value to be returned by the function.	-1	If the lexical analyzer reaches the end of file, then the pattern matching function returns by executing: return EOFAction;

Macros

Macros provide a way to give frequently used regular expressions more user-friendly names for later use. They help improve readability as well as maintainability of the specification. Indeed, macros provide a way for centralizing the changes; i.e. if we have a macro used in more than one regular expression and it is required to change the value of this macro, then the change is made only at the macro definition statement. This section contains declarations of simple macro definitions to simplify the scanner specification. Macro definitions have the form:

```
MacroName Definition
```

The `MacroName` is a word beginning with a letter or an underscore ('_') followed by zero or more letters, digits, or '_'. The `Definition` is to begin at the first non-white-space character following the name and continuing to the end of the line. For example,

```
DIGIT     [0-9]
```

The definition can subsequently be referred to using `{MacroName}`, which will expand to `(Definition)`. It is possible to invoke previously defined macros in the definition of the current macro. For example,

```
DIGIT     [0-9]
LETTER    [a-zA-Z]
ID        {LETTER}({LETTER}|{DIGIT})*
```

defines `DIGIT` to be a regular expression which matches a single digit, `LETTER` to be a regular expression which matches an English letter (either in upper-case or lower-case), and `ID` to be a regular expression which matches a letter followed by zero-or-more letters or digits. A subsequent reference to

```
{DIGIT}+"."{DIGIT}*
```

is identical to

```
([0-9])+"."([0-9])*
```

and matches one-or-more digits followed by a '.' followed by zero-or-more digits.

Lines describing macros should be unindented. Otherwise, it will be considered user-defined code that should be copied as-is into the generated code. This anomaly is found in the LEX input file format, too. That's why we preferred not to modify it.

User-Defined Code

This is the code to be copied as-is into the generated file. Indented lines represent user-defined code, which is copied in order into the generated code. An alternative is to delimit a section of code by `%{ %}` (copied as-is into the generated code after removing the delimiters). For example,

```
 #include <iostream>
%{
#include <cmath>
using namespace std;
%}
```

These will be copied to the top of the generated header file as follows:

```
#include <iostream>
#include <cmath>
using namespace std;
```

The delimiters are to be placed at the beginning of the line. Otherwise, they will be ignored. The exact location in the generated code where user-defined code is pasted differs depending on which programming language the code uses. The following table illustrates the location in the generated code where user-defined code is pasted with respect to the used programming language.

Table II-2: Top of Definition - User Defined Code Placement

Programming Language	*Location*
`C++`	At the top of the header file (.h).
`Java`	At the top of the source file (.java).
`C#`	At the top of the source file (.cs).

2.4.2 Class Definition

In this section, the user writes code to be placed inside the lexical analyzer class definition. For a C++ developer, this allows declaring member variables, member functions, static variables and/or static functions. For a C#/Java developer, this allows declaring member/static variables and defining member/static functions. The code is copied as-is into the generated code.

The exact location in the generated code where user-defined code is pasted differs depending on which programming language the code uses. The following table illustrates the location in the generated code where user-defined code is pasted with respect to the used programming language.

Table II-3: Class Definition – User Defined Code Placement

Programming Language	*Location*
`C++`	Inside the lexical analyzer class definition, in the header file (.h).
`Java`	Inside the lexical analyzer class definition, in the source file (.java).
`C#`	Inside the lexical analyzer class definition, in the source file (.cs).

2.4.3 Rules

The rules section contains a series of rules of the form:

```
pattern   action
```

where `pattern` must be unindented and the action must begin on the same line. A detailed discussion of patterns and actions is provided below.

Patterns

The patterns in the input are written using an extended set of regular expressions. These are:

Table II-4: Regular Expression Patterns

Regular Expression	*Description*
`X`	match the character x
`.`	any character except newline (Note that any character means any character from the defined character set in the options)
`[xyz]`	a "character class"; in this case, the pattern matches either an x, a y, or a z
`[abj-oZ]`	a "character class" with a range in it; matches an a, a b, any letter from j through o, or a Z
`[ab[-]`	a "character class"; in this case, the pattern matches either a, b, [, or -.
`[^A-Z]`	a "negated character class", i.e., any character but those in the class. In this case, any character EXCEPT an uppercase letter.
`[^]`	match ^
`[^A-Z\n]`	any character EXCEPT an uppercase letter or a newline
`[]`	an empty word; a[]b matches ab

*r**	zero or more r's, where r is any regular expression
r+	one or more r's
r?	zero or one r's (that is, "an optional r")
{Macro}	the expansion of the "Macro" definition
\x	if x is an a, b, f, n, r, t, or v, then the ANSI-C interpretation of L'\x'. Otherwise, a literal x (used to escape operators such as *)
"[xyz]\"foo"	the literal string: [xyz]"foo
\O12	the Unicode character with octal value 12
\o12	the Unicode character with octal value 12
\x43F	the Unicode character with hexadecimal value 0x043F
\X1212FF	the Unicode character with hexadecimal value 0x1212 followed by two capital F's.
\D48	the Unicode character with decimal value 48
\d434344	the Unicode character with decimal value 43434 followed by the Unicode character L'4'
(*r*)	match an r; parentheses are used to override precedence
rs	the regular expression r followed by the regular expression s; called "concatenation"
R | s	either regular expression r or regular expression s

Note that inside a character class, all regular expression operators lose their special meaning except escape \ and the character class operators, -,], and, at the beginning of the class, ^.

The regular expressions listed above are grouped according to precedence, higher precedence first. Those grouped together have equal precedence. For example,

```
foo | bar*
```

is the same as

```
 (foo) | (ba(r*))
```

since the * operator has higher precedence than concatenation, and concatenation is higher than alternation |. This pattern therefore matches either the string "foo" or the string "ba" followed by zero-or-more r's. To match "foo" or zero-or-more "bar"'s, use:

```
foo | (bar)*
```

and to match zero-or-more "foo"'s-or-"bar"'s:

```
(foo | bar)*
```

Actions

Each pattern in a rule has a corresponding action, which can be any arbitrary C++/C#/Java statement. The pattern ends at the first non-escaped whitespace character; the remainder of the line is its action. If the action is empty, then when the pattern is matched the input token is simply discarded. For example, here is the specification for a regular expression, which deletes all occurrences of the single-line C++ comment from the input:

```
"//".*
```

If the action contains a {, then the action spans until the balancing } is found, and the action may cross multiple lines. *LEXcellent* knows about strings and comments and will not be fooled by braces found within them. Actions are allowed to begin with %{ and will consider the action to be all the text up to the next %} (regardless of ordinary braces, comments, and strings inside the action).

2.4.4 Extended Definitions (1)

This section and the next are optional and the input file may be terminated without specifying them. This section is used to write code that is placed as-is into the generated files. Thus, no syntactic checks are performed on the contents of this section.

For a C++ developer, the code in this section is placed at the top of the generated source (.cpp) file. This can be used to include header files, declare/define external and/or static variables and define macros. For Java and C# developers, the code in this section is placed right after the end of the definition of the lexical analyzer class, but inside the same namespace. This can be used to define other classes, structures, and enumerations under the same namespace. The following table summarizes the placement of the code in the generated files according to the programming language under use.

Table II-5: Extended Definitions (1) - User Defined Code Placement

Programming Language	*Location*
C++	At the top of the generated source file (.cpp).
Java	Right after the end of the lexical analyzer class, but inside the same namespace in the generated source file (.java).
C#	Right after the end of the lexical analyzer class, but inside the same namespace in the generated source file (.cs).

2.4.5 Extended Definitions (2)

This section is also used to write code that is placed without modifications into the generated files. Hence, the tool does not perform syntactic checks on the contents of this section.

For a C++ developer, the code in this section is placed at the end of the generated source (.cpp) file. Thus, it can be used to implement any member functions declared in the *'Class Definition'* section or add any required code. For C# and Java developers, the code is placed at the bottom of the generated source file, after the end of the namespace. This can be used to define other namespaces along with their classes. The following table summarizes the placement of the code in the generated files according to the programming language used.

Table II-6: Extended Definitions (2) – User Defined Code Placement

Programming Language	*Location*
C++	At the bottom of the generated source file (.cpp).
Java	At the bottom of the generated source file, right after the namespace of the lexical analyzer class (.java).
C#	At the bottom of the generated source file, right after the namespace of the lexical analyzer class (.cs).

2.5 Input File Error Handling

In this section, we describe the error messages that *LEXcellent* provides for various types of errors encountered in input files, and indicate some of the situations that cause such errors.

Unexpected End of File.

Causes

The input file terminates before defining the *Rules* section.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++

sin (S|s)(I|i)(N|n)
%%
```

Bad Directive.

Causes

The Top File Definition section contains an invalid directive. The three valid directives are

o %option name = value.

This line specifies modifying the value of an option such as the language to be used for code generation. Although the option name is not case-sensitive, the keyword option is case-sensitive.

o %{

This begins a block of code that will be placed as-is in the generated file. This block is terminated by %}. For further information, see "*LEXcellent* Input File Format".

- o %%

  This terminates the Top File Definition section.

Example

The following sample includes two lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]

/* The following line is valid. */
%option LanGuage = C++

/* The following line is invalid. */
%OPTION ClassName = Lexer

/* The following line is invalid. */
%unknown_directive
```

Invalid Option Specification.

Proper option format:

%option some_thing = some_value.

Causes

The option format is invalid.

Example

The following sample includes three lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]

/* The following line is invalid. */
%option

/* The following line is invalid. */
%optionLanguage = C++

/* The following line is invalid. Missing = */
%option ClassName Lexer
```

The Specified Option is not Supported.

Causes

Although the format of the option is valid, it specifies an unsupported option.

Example

The following sample includes three lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]

/* The following line is invalid. */
%option Lang = C++
/* The following line is invalid. */
%OPTION aBrandNewOption = Lexer

/* The following line is invalid. */
%option Class Name = Lexer
```

Invalid Macro Definition. Eliminate the Trailing Characters.

Causes

The macro definition is followed by spurious characters.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++

Macro1 [a-z]+     /* A valid line. */

/* The following line is invalid. */
InvMacro [0-9]+ spurious characters are the cause of the error
```

The Specified Macro Name is Already Defined.

Causes

The user is trying to redefine a macro.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++

/* The following line is valid. */
Macro1 [a-z]+

/* The following line is invalid. */
Macro1 [0-9]+
```

The Invoked Macro is Undefined.

Causes

The user invokes a macro within a regular expression that has not been defined.

Example

The following sample includes three lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++

/* The following two lines are valid. */
Macro1 [a-z]
Macro2 {Macro1}+

/*The following line is invalid*/
Macro3 {Macro4}+
Macro4 (a|b)*

/*The following line is invalid due to self-reference*/
Macro5 a|{Macro5}

%%
/*Top class definition*/
%%
       /* The following definition is invalid */
[0-9]{UndefinedMacro}      {   cout<<"I   am   invoking   an
undefined macro."<<endl; }

%%
```

Invalid Macro Invocation within the Regular Expression. The Macro Name Contains Invalid Characters.

Causes

The name of the macro invoked by the user is not a valid identifier. The valid format for a macro name is:

[a-zA-Z_][a-zA-Z_0-9]*

Example

The following sample includes two lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++

/* The following two lines are valid. */
GoodMacro [a-z]
BadOrGoodMacro {Macro1}+

/*The following two lines are invalid*/
Macro3 {Good Macro}+
Macro4 {Bad|GoodMacro}+
```

Bad Character Set Definition. Check the Supplied %option Character Set.

Causes

The user specifies an invalid character set. If the user does not specify a character set to use in the input file, then the default character set (ASCII [\x00-

\x7F]) is assumed. Otherwise, the valid format for character sets is the same as that for a valid character class.

Example

The following samples generate the specified error.

```
/* The following line is invalid */
%option CharacterSet = ][

/* The following line is invalid. Unexpected end of character
class*/
%option CharacterSet = [\x00-\x7F
```

Invalid Use of Parentheses within the Regular Expression. Check Balancing.

Causes

The user has put a spurious closing parenthesis ")" inside the regular expression.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++
%%
%%
       /* The following regular definition is invalid. */
(a|b)*)abcd   { cout<<"I am closing something that I did not
open."<<endl; }
```

Unexpected End of the Regular Expression. Check Balance of Parentheses.

Causes

The user has opened one or more parentheses and the regular expression has terminated before balancing them.

Example

The following sample includes two lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++
%%
%%
       /* The following regular definition is invalid. */
((a|b)*       { cout<<"The regex should have terminated with
)"<<endl; }

       /* The following regular definition is valid. */
\((a|b)*      { cout<<"The first ( is escaped is by the
backslash.”<<endl; }
```

Unexpected End of Regular Expression.

Causes

The user has opened double quotes ‟ but has forgotten to close them. It may be the case also that the user has opened a character class [but has forgotten to close it. Finally, the user might have tried to invoke a macro but have forgot the closing brace }.

Example

The following sample includes three lines that generate the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++
%%
%%
       /* The following regular definition is invalid. */
“bad   { cout<<”bad 1”<<endl; }

       /* The following regular definition is invalid. */
{bad2  { cout<<”bad 2”<<endl; }

       /* The following regular definition is invalid. */
[a-z   { cout<<”bad 3”<<endl; }
```

Illegal Spaces within Regular Expression.

Causes

The regular expression contains white spaces. White spaces are not allowed inside a regular expression except after backslashes, inside double quotes, or inside character classes.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++
%%
%%
       /* The following regular definition is invalid. */
((a| b)*      { cout<<”The fifth character is invalid.”<<endl;
}

       /* The following regular definition is valid. */
((a|\ b)*”  “[  ]     {    cout<<”All    spaces    here    are
legal.”<<endl; }
```

Negative Ranges within a Character Class are not Allowed.

Causes

A character class contains one or more range from a later character to an earlier one.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++
%%
%%
          /* The following regular definition is invalid. */
[z-a]  {cout<<"It should have been a-z."<<endl;}
```

One or More Characters within the Regular Expression are Outside the Range of the Defined Character Set.

Causes

Some characters in a regular expression are not covered by the character set defined by the user or by the default character set if the user has not specified a one.

Example

The following sample generates the specified error.

```
%option CharacterSet = [a-z]
%option Language = C++
%%
%%
          /* The following regular definition is invalid. */
A|b     { cout<<"A is outside [a-z]."<<endl; }
```

Unknown Error.

Causes

An error has occurred that is not classified under any of the previous classes of errors.

Example

The following sample generates the specified error.

```
%option CharacterSet = [\x00-\x7F]
%option Language = C++

/* The following line is invalid. */
/

/* The following line is invalid. */
/43
```

2.6 Thompson Construction Algorithm

This phase in the lexical analyzer construction process is that responsible for converting the set of regular expressions specified in the input file into a set of equivalent Nondeterministic Finite Automata (NFAs). Thompson’s Construction is the algorithm we apply to transform a given regular expression into the corresponding NFA. The resulting NFA has a special structure that we exploit so that the remaining phases are performed more efficiently.

Regular Expression Context-Free Grammar

The language of all regular expressions is not regular, i.e., there is no regular expression characterizing the general pattern of any regular expression. This fact is easy to prove by observing that the language

$\{ \ (^n \mathbf{a} \ )^n : n \geq 0 \ \}$

which was proved to be irregular by the pumping-lemma for regular languages, is a mere subset of the language of all legal regular expressions. However, the language of all regular expressions can be expressed by means of a CFG. The production rules of the CFG employed in our application is listed below in EBNF:

```
Regex        → Regex or ConcateRegex | ConcateRegex

ConcateRegex → ConcateRegex Term | Term

Term         → Term plus | Term star |
               Term question_mark | Atom

Atom         → LB Regex RB | quoted_text | symbol |
               any | epsilon | ccl | macro
```

The following are the lexical definitions (the regular definitions of terminals, using regular expressions):

```
or             → ‘|’
plus           → ‘+’
star           → ‘*’
question_mark  → ‘?’
LB             → ‘(‘
RB             → ‘)’
quoted_text    → \“(\\.|[^\”])*\”
symbol         → .
any            → ‘.’
epsilon        → “[]”
```

```
ccl            → “[“([^\]]|\\.)+”]“
identifier     → [a-zA-Z_][a-zA-Z_0-9]*
macro          → “{“identifier”}”
```

The start symbol of this CFG is *Regex*. All nouns beginning with a capital letter are non-terminals. All nouns beginning with small letters are terminals. Since we need to find an NFA that accepts the same language as the parsed regular expression, we add to all non-terminals the attribute *nfa* that provides the NFA equivalent to the regular expression expressed by that nonterminal. The computation of that attribute follows a recursive manner such that the *nfa* of a given nonterminal is constructed recursively from the *nfa*'s of its constituents. The production rules for all non-terminals are written again after augmentation with attribute equations:

Table II-7: Regular Expression Context-Free Grammar

Production	Semantic Rules
Regex$_1$ → Regex$_2$ **or** ConcateRegex	Regex$_1$.nfa = Or(Regex$_2$.nfa, ConcateRegex.nfa)
Regex → ConcateRegex	Regex.nfa = ConcateRegex.nfa
ConcateRegex$_1$ → ConcateRegex$_2$ Term	ConcateRegex$_1$.nfa = Concat(ConcateRegex$_2$.nfa, Term.nfa)
ConcateRegex → Term	ConcateRegex.nfa = Term.nfa
Term$_1$→ Term$_2$ **plus**	Term$_1$.nfa = Closure_plus(Term$_2$.nfa)
Term$_1$ → Term$_2$ **star**	Term$_1$.nfa = Closure_star(Term$_2$.nfa)
Term$_1$ → Term$_2$ **question_mark**	Term$_1$.nfa = Closure_quest(Term$_2$.nfa)
Term → Atom	Term.nfa = Atom.nfa
Atom → **LB** Regex **RB**	Atom.nfa = Regex.nfa
Atom → **symbol**	Atom.nfa = NfaFromSymbol(symbol.value)
Atom → **epsilon**	Atom.nfa = NfaFromEpsilon()
Atom → **quoted_text**	Atom.nfa = NfaFromQuotedText(quoted_text.value)
Atom → **ccl**	Atom.nfa = NfaFromCCL(ccl.value)
Atom → **any**	Atom.nfa = NfaFromCCL(all_symbols)
Atom → **macro**	Atom.nfa = ParseRegex(macro.regex)

The Thompson's Construction algorithm provides a way to construct the NFA of some part from its subparts, such that the resulting NFA accepts the desired language. However, the regular expression grammar we have employed has other features and operations that are not explicitly described in the algorithm. Although these features can be defined in terms of the basic features and operations covered in the algorithm, the definition will be inefficient, as will be seen later as we describe the algorithm.

We begin by describing the basic features and operations covered in the algorithm. In the following illustrations, the states drawn outside boxes are those that have been newly added.

If we have a regular expression consisting of only one symbol **s**, then an NFA that accepts the same language is given by:

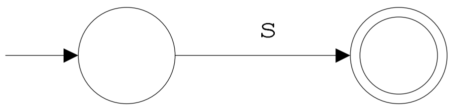


Figure II-5: NFA for a One-Symbol RegEx

This shows how the function `NfaFromSymbol` is implemented.

Now, suppose that we have the regular expression **r | s**, where **r** and **s** represent any two regular expressions. Suppose that we have successfully constructed the NFA of the regular expression **r** and that of the regular expression **s**. We can construct an NFA that accepts the same language of the regular expression **r | s** as follows:

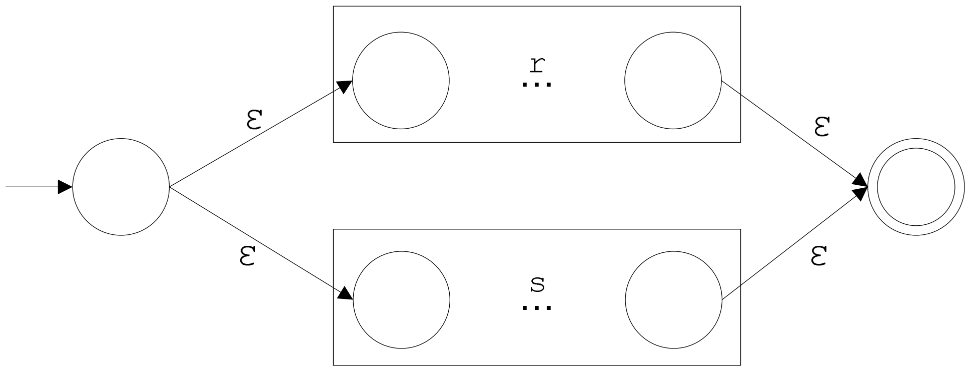


Figure II-6: NFA for Two ORed RegEx's

This shows how the `Or` function used in the first semantic rule is implemented. Assume that we are to construct the NFA equivalent to the regular expression **r s**, and inductively assume that we have available the NFA of **r** and the NFA of **s**. Then, we can construct the NFA of their concatenation by eliminating the start state of **s** after duplicating all its transitions into the final state of **r**, and setting as the final state of the new NFA the final state of **s**. The configuration is shown below:

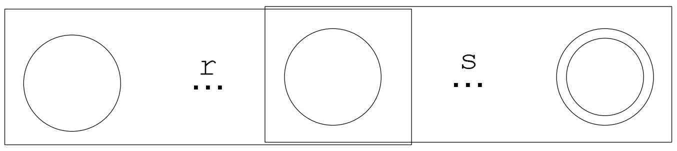


Figure II-7A: NFA for Two Concatenated RegEx's

It could have been alternatively made as follows:

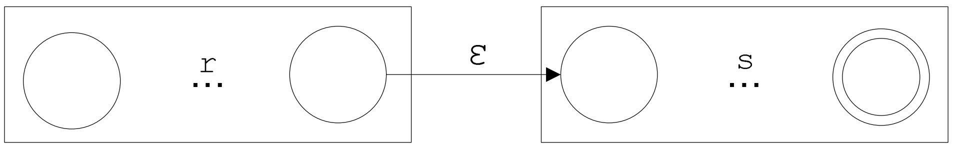


Figure II-7B: NFA for Two Concatenated RegEx's

However, the former configuration takes less storage due to the elimination of one of the states. We have implemented the *Concat* used in the third semantic rule so that it achieves the former configuration.

Assuming that we have the regular expression **r*** and that the NFA of the regular expression **r** is available. Then the final operation described in the method, which is the *Kleene Closure (*)*, is implemented as follows:

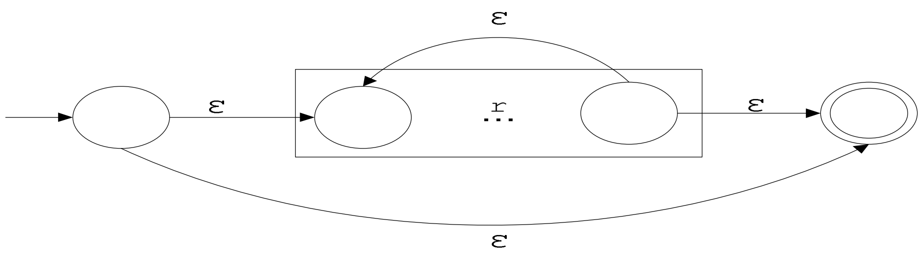


Figure II-8: NFA for a RegEx Closure

The above NFA indeed accepts zero or more occurrences of **r.** This shows how the *Closure_star* is implemented. Next, we describe how the other features and operations are implemented. We begin by constructing the NFA of the empty word (*epsilon* or *[]* in our grammar):

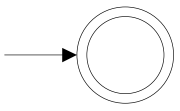


Figure II-9: NFA for the Empty Word (ε)

This is how the function *NfaFromEpsilon* is implemented. The regular expression **r+** means one or more occurrences of **r.** Although this could have been implemented as **r r***; we have used another method to implement it that takes much less space than the former technique. The configuration is shown below:

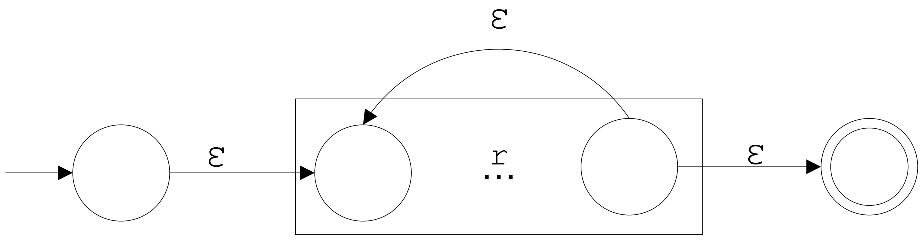


Figure II-10: NFA for a RegEx Positive Closure

If the number of states in the NFA of **r** is M, the number of states in the resulting NFA would be M+2. However, the former technique results in an NFA that has 2M+1 states. This shows how the function `Closure_plus` is implemented. By the regular expression **r?**, we mean at most one occurrence of **r**. Implementing this as **r | []** will result in an NFA that has M+3 states. However, we implemented it so that it takes only M+1 states. The configuration is shown in figure II-11:

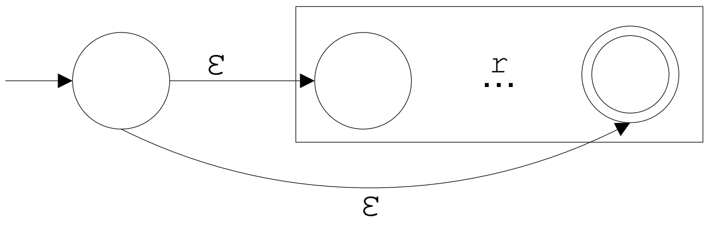
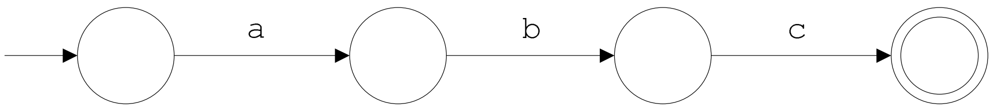


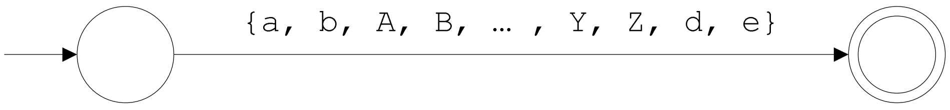
Figure II-11: NFA for an Optional RegEx

This shows how the function `Closure_quest` is implemented. The regular expression **a b c** should be interpreted as **a** followed by **b** followed by **c**. Hence, it is implemented as **a b c**. The NFA of **a b c** is shown in ExFig 2-4:



ExFig 2-4: NFA of the regex (a b c)

This shows how the function `NfaFromQuotedText` is implemented. The reason behind enclosing a string by double quotes rather than writing it directly is that many of the special symbols, having special meaning in the language of all regular expressions, lose that special meaning inside the double quotes. For example, **"|"** means exactly one occurrence of the symbol **|**. The regular expression **[abA-Zde]** is equivalent to the regular expression **a | b | A | B | … | Y | Z | d | e.** However, constructing the NFA of the regular expression using the latter mechanism wastes much space since each "Or" adds new states. We have made an informal technique to implement this as seen in ExFig 2-5:



ExFig 2-5: Example

That is, we represent this transition by an edge labeled with a set of symbols. We move from the start to the final state if we read any of the characters included in that set. We associate with each edge a pointer that is initially set to `null`. If the transition of the edge is based on a character class, then we allocate a portion in the memory to store a representation of that set, and store its address in that pointer. This shows how the function `NfaFromCCL` is implemented. If the regular expression is a mere invocation of a previously defined macro, then we parse the regular expression of that macro. The resulting NFA is the NFA of the macro. Thus, any valid regular expression can be converted into an equivalent NFA using the aforementioned guidelines.

As we previously stated, the NFA resulting from the above procedures has a special structure that allows efficient implementation of the next phase which is the subset construction. The properties of the obtained NFA are:

- The NFA has a unique, non-enterable start state.
- The NFA has a unique, non-exitable final state.
- A given state has exactly one outgoing edge labeled by a symbol, a set of symbols (in case a character class), or at most two edges labeled ε.

2.7 Subset Construction Algorithm

Now we need to convert the NFA obtained from the Thomson Construction phase, into a DFA to be used in the next phases. The basic idea here is that sets of states in the NFA will correspond to just one state in the DFA.

- From the point of view of the input, any two states that are connected by an ε-transition may as well be the same, since we can move from one to the other without consuming any input characters. Thus states which are connected by a ε-transition will be represented using the same states in the DFA.
- If it is possible to have multiple transitions based on the same symbol, then we can regard a transition on a symbol as moving from a state to a set of states (i.e. the union of all those states reachable by a transition on the current symbol). Thus these states will be combined into a single DFA state.

2.7.1 The Basic Idea

To perform this operation, let us define two functions:

- The **ε-closure** function takes a state and returns the set of states reachable from it based on (one or more) ε-transitions. Note that this will always include the state itself. We should be able to get from a state to any state in its ε-closure without consuming any input.
- The function **move** takes a state and a character, and returns the set of states reachable by one transition on this character.

We can generalize both these functions to apply to sets of states by taking the union of the application to individual states. For example, if A, B and C are states;

```
move({A,B,C},‘a’) = move(A, ‘a’) U move(B, ‘a’) U move(C,
‘a’).
```

1) Create the start state of the DFA by taking the ε-closure of the start state of the NFA.

2) Perform the following for the new DFA state: For each possible input symbol:
    a. Apply move to the newly-created state and the input symbol; this will return a set of states.
    b. Apply the ε-closure to this set of states, possibly resulting in a new set. This set of NFA states will be a single state in the DFA.
3) Each time we generate a new DFA state, we must apply step 2 to it. The process is complete when applying step 2 does not yield any new states.
4) The finish states of the DFA are those which contain any of the finish states of the NFA.

2.7.2 The Implementation

`BuildDFA(list_of_states, list_of_actions)`

- *`list_of_states:`* A vector of the states in the NFA to be converted into a corresponding DFA.
- *`list_of_actions:`* A vector of the actions to be performed if the input string terminates while the machine is at the corresponding state. The non-accepting states have a corresponding action of `NULL`.

This procedure takes an NFA as a parameter in the form of two parallel vectors: The vector of states and the vector of corresponding actions.

The procedure is a member function in the DFA class; when the procedure is invoked, the host DFA will be set in such a way that it becomes equivalent to the input NFA.

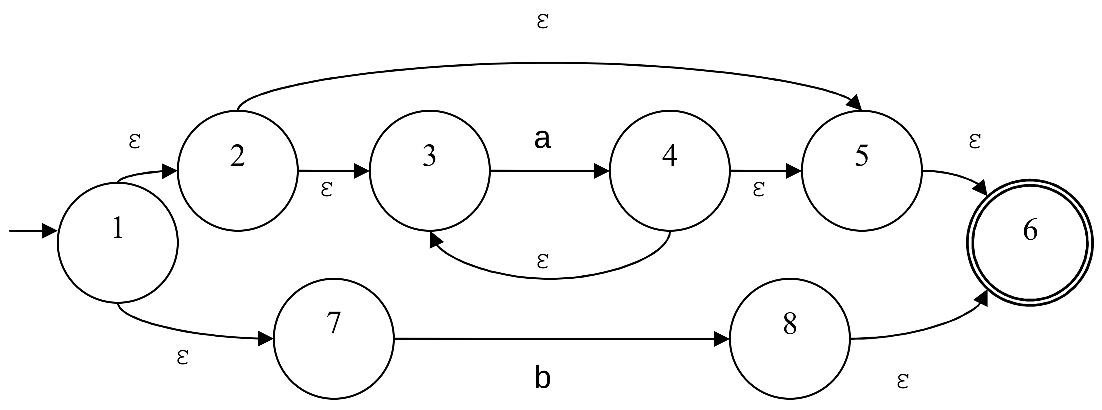
The procedure makes use of the following classes:

- *`IntermediateState:`* This class holds a subset of the states in the input NFA corresponding to one state in the output DFA.
- *`IntermediateStateList:`* A linked list of intermediate states.

Besides using the following helper functions:

- *`eClosure():`* This function takes an NFA state as a parameter and returns the ε-closure of that state.

For example: Given the following NFA which is obviously equivalent to the regular expression (**a* | b**):



ExFig 2-6: NFA for (a * | b)

The procedure starts by constructing a single subset containing the start states of the input NFA, which, in our case, is {1}. It runs the *`eClosure()`* procedure to obtain the ε-Closure of the subset. This will give {1, 2, 3, 5, 6, 7} in our case. Such subset becomes an intermediate state and it should be added to the intermediate states list (the DFA). This will give the following initial value to the DFA State Table:

ExTab 2-6A: DFA state table

DFA State	**NFA Subset**	**Next State (a)**	**Next State (b)**
A	{1, 2, 3, 5, 6, 7}		

The next step is to determine the next state of the DFA if the current state is A and the input character is a or b.

Given the current state is A and input character is a then the next state can be defined as "*the set of all NFA states that can be reached from any of the NFA states in A by following an edge labeled a in the original NFA.*"

Thus, for each NFA state x, where x Є A, run the NFA against (x, a). Then take the closure of the result. That is, **ε-Closure (nxtStat (NFA, x, 'a')), for each x Є A**. This will give the following *Next State* Table:

ExTab 2-7A: DFA next-state table

State	**Next State (a)**	**Closure (Next State(a))**
1	-	-
2	-	-
3	{4}	{3, 4, 5, 6}
5	-	-
6	-	-
7	-	-

Since the subset {3, 4, 5, 6} is not already in the intermediate states list (that is, to the constructed DFA), then we have to add it. And we shall give it a name, say B. Thus, **nxtStat(DFA, A, 'a') = B.**

Repeating the same steps for nxtStat(DFA, A, 'b') we get the following *Next State* Table:

ExTab 2-7B: DFA next-state table

State	Next State (b)	Closure (Next State(b))
1	-	-
2	-	-
3	-	-
5	-	-
6	-	-
7	{8}	{6,8}

Similarly the resulting subset {6, 8} doesn't belong to the DFA, then we have to add a new state, let it be C, to the DFA, such that **nxtStat(DFA, A, 'b') = C**. This will give the following DFA Table:

ExTab 2-6B: DFA state table

DFA State	NFA Subset	Next State (a)	Next State (b)
A	{1, 2, 3, 5, 6, 7}	B	C
B	{3, 4, 5, 6}		
C	{6, 8}		

Now we repeat all the above mentioned steps on the next incomplete row in the DFA State Table. The operations continue until all the intermediate states are fully determined.

The final table configuration will be like ExTab 2-6C:

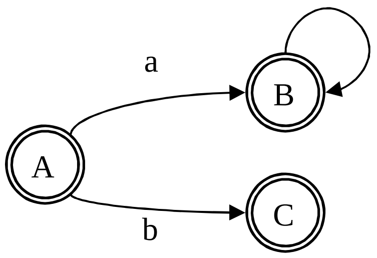
ExTab 2-6C: DFA state table

DFA State	NFA Subset	Next State (a)	Next State (b)
A	{1, 2, 3, 5, 6, 7}	B	C
B	{3, 4, 5, 6}	B	-
C	{6, 8}	-	-

A state (whether deterministic or not) is said to be an *accepting state* if there is an action associated with it. That is, the ith state in the `list_of_states` is an accepting state if the ith action in the `list_of_actions` is not `NULL`.

A DFA state is said to be an *accepting state* if at least one of the NFA states that it contains is an accepting state. In our case, all the DFA states contain NFA accepting states, since the only NFA accepting state available, which is state 6, belongs to all the states in the new DFA. We can say that all the DFA states A, B and C are accepting.

The resulting DFA is shown in the next figure. Obviously it corresponds to the regular language (**a* | b**), which is that same as that of the NFA.

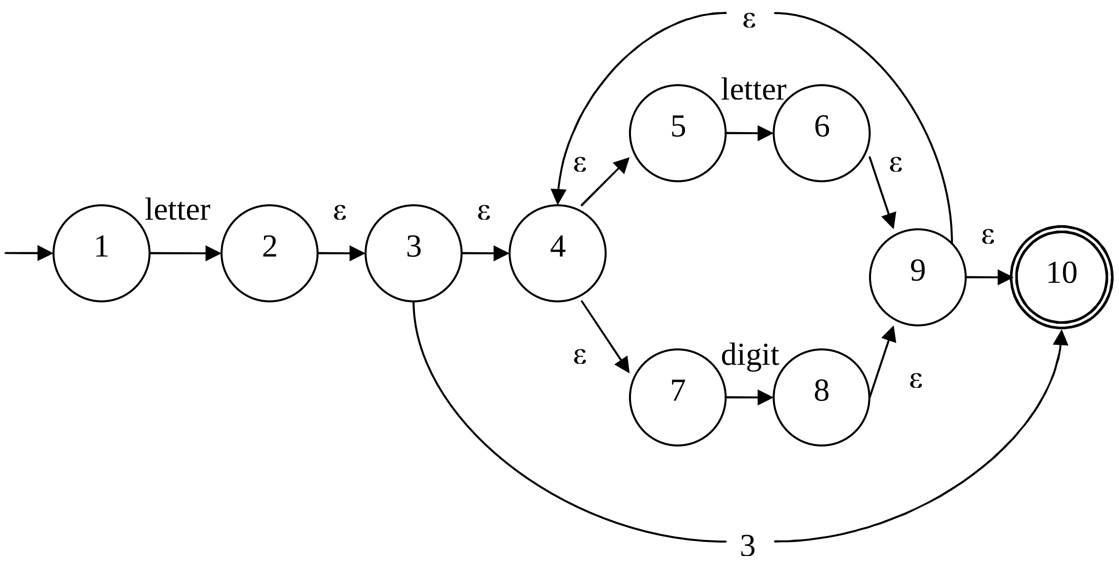


ExFig 2-7: The final DFA

2.7.3 Contribution

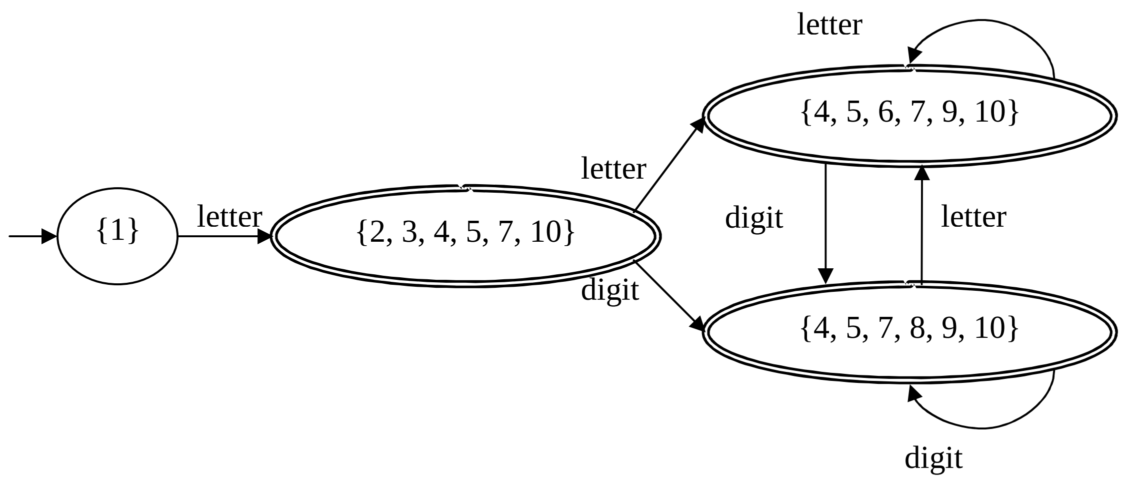
It has been noticed that the traditional subset construction algorithm produces so much intermediate states than needed. We have modified such algorithm to get rid of redundant states.

For example, given the following NFA:



ExFig 2-8: Identifier NFA

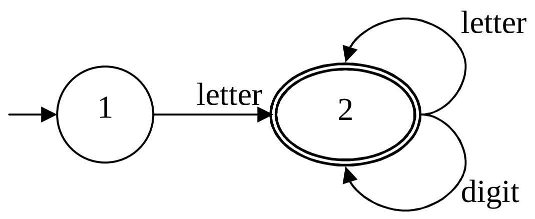
The traditional subset construction should give the following DFA:



ExFig 2-9: Identifier DFA – The traditional algorithm

We noticed that some of the states in the original NFA have no outgoing transitions but the ε-transitions. We have called such states *empty states*; other states that have character-labeled-edges are called *active states*. When comparing intermediate states, two intermediate states are said to be the same if there active states are the same, that is, we don't take empty states in consideration. This contributes to a considerable reduction in the number of resulting intermediate states.

Our algorithm should give the following DFA, as illustrated in ExFig 2-10:



ExFig 2-10: Identifier DFA – The enhanced algorithm

It's noteworthy that this idea was mentioned by Aho in his classical book about compilers **[2]**. Thus it's indeed a previously realized optimization, but we reached it alone before reading it in his book. That's why we listed it under the title "Contribution".

2.8 DFA Minimization

After the regular expression passed Thomson Construction and Subset Construction phases; a DFA resulted. But it's not the optimal one. The role of the DFA minimization algorithm is to produce a new DFA with the minimum number of states.

The algorithm can be illustrated by the following pseudo-logic mentioned below.

```
INITIALLY
Partition the original states into a series of groups. Non-accepting
states comprise a group, and accepting states having the same
```

accepting string are grouped together. A one-element-group containing a single accepting state is permissible. Groups are stored in a Variable called Groups.

```
REPEAT UNTIL NO NEW GROUPS ADDED
BEGIN
   FOREACH (GROUP G in Groups)
   BEGIN
      GROUP new   = Empty.
      STATE first = First state in group G.
      STATE next  = Next state in Group G or NULL if none.
      WHILE (next != NULL)
      BEGIN
         FOREACH (CHARACTER C)
         BEGIN
            STATE goto_first = State reached by making a transition
                               on C out of first.
            STATE goto_next  = State reached by making a transition
                               on C out of next.
            IF(goto_first is not in the same group as goto_next)
            THEN
               Move next from the G into new.
            ENDIF
         END_FOREACH
         next      = The next state in group G or NULL if none.
      END_WHILE
      IF(new is not empty)
      THEN
         Add it to Groups.
      END_IF
   END_FOREACH
ENDREPEAT

// Generate the new DFA
DFA Min_DFA


FOREACH (GROUP G in Groups)
BEGIN
   Min_DFA.CREATE(NEW_STATE)
   FOREACH (CHARACTER CH)
   BEGIN
      ADD transition on NEW_STATE on C to the group in which
      the destination exists.
   END_FOREACH
END_FOREACH
```

For example if we have as an input to the algorithm the following DFA represented in transition matrix of ExTab 2-8A:

ExTab 2-8A: DFA transition matrix

State	**Lookahead**		**Accepting**
	D	**.**	
0	1	2	No
1	4	5	No
2	3	-	No
3	-	-	Yes
4 (The Current State)	4	2	No

5 5 7	6 7 7	- -	Yes Yes Yes

ExTab 2-8B: DFA transition matrix

Initially, the matrix is partitioned into two parts; one for the accepting states (0, 1, 2, 4) and another for the non-accepting states (3, 5, 6, 7). ExTab 2-8B with the illustration.

State	**D**	**.**	**Group**
0 1 2 4	1 4 3 4	2 5 - 2	0
3 5 6 7	- 6 7 7	- - - -	1

ExTab 2-8C: DFA transition matrix

State	D	.	Group
0	1	2	
1	4	5	0
4	4	2	
2	3	-	2
3	-	-	3
5	6	-	
6	7	-	1
7	7	-	

Starting with D column, states 0, 1 and 4 all go to a state in partition 0 on a D, but state 2 goes to partition 1 on a D, and thus state 2 must be removed from partition 0. Continuing in the same manner, state 3 is also distinguished by a D. Changes are illustrated in ExTab 2-8C.

ExTab 2-8D: DFA transition matrix

State	D	.	Group
0	1	2	
4	4	2	0
1	4	5	4
2	3	-	2
3	-	-	3
5	6	-	
6	7	-	1
7	7	-	

Now, going down the dot (**.**) column, the dot distinguishes state 1 from states 0 and 4 because state 1 goes to a state in partition 1 on a dot, but states 0 and 4 go to states in partition 2. The new partitions are on the last column in ExTab 2-8D.

ExTab 2-8E: DFA transition matrix

State	D	.	Group
0	1	2	0
4	4	2	5
1	4	5	4
2	3	-	2
3	-	-	3
5	6	-	
6	7	-	1
7	7	-	

Going through the array a second time, column by column, now D distinguishes state 0 from state 4 because state 0 goes to a state in partition 4 on a D, but state 4 goes to a state in partition 0 on a D, and here no other states can be distinguished from each other, so it's done. So the final partition looks like ExTab 2-8E.

ExTab 2-8F: DFA transition matrix

State	D	.
0	4	2
1	1	-
2	3	-
3	-	-
4	5	1
5	5	2

Finally we build a new transition matrix. Each partition is a single state in the minimized DFA and all next states in the original table are replaced by the partition in which these states are found. Hence, for example, states 5, 6 and 7 are all in partition 1. All references to one of these states in the original table are replaced by a reference to the new state 1. So the new transition table looks like ExTab 2-8F.

2.9 DFA Compression

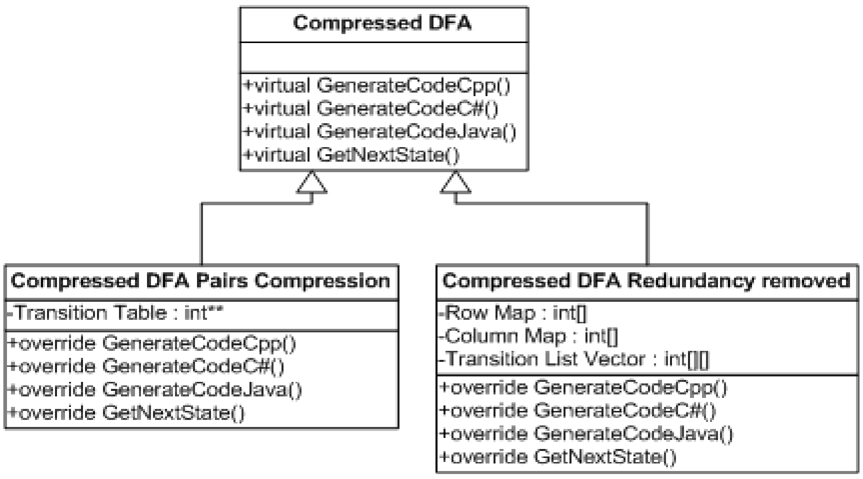

Compressed DFA
+virtual GenerateCodeCpp()
+virtual GenerateCodeC#()
+virtual GenerateCodeJava()
+virtual GetNextState()
Compressed DFA Pairs Compression
-Transition Table : int**
+override GenerateCodeCpp()
+override GenerateCodeC#()
+override GenerateCodeJava()
+override GetNextState()
Compressed DFA Redundancy removed
-Row Map : int[]
-Column Map : int[]
-Transition List Vector : int[][]
+override GenerateCodeCpp()
+override GenerateCodeC#()
+override GenerateCodeJava()
+override GetNextState()

Figure II-12A: Class Diagram for the Compressed DFA

The DFA generated from the scanner generator is always represented in the form of a two dimensional transition matrix with one dimension representing the states and the other representing the input; an element in the matrix indexed as (state, character) merely determines the next state of the DFA if a certain input character has been encountered while the machine is in the given state. It has been noticed that several columns (and perhaps rows) are redundant in the resulting matrix. Such redundancy becomes significant when dealing with Unicode (as in our case) where the DFA transition matrix becomes extremely large.

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

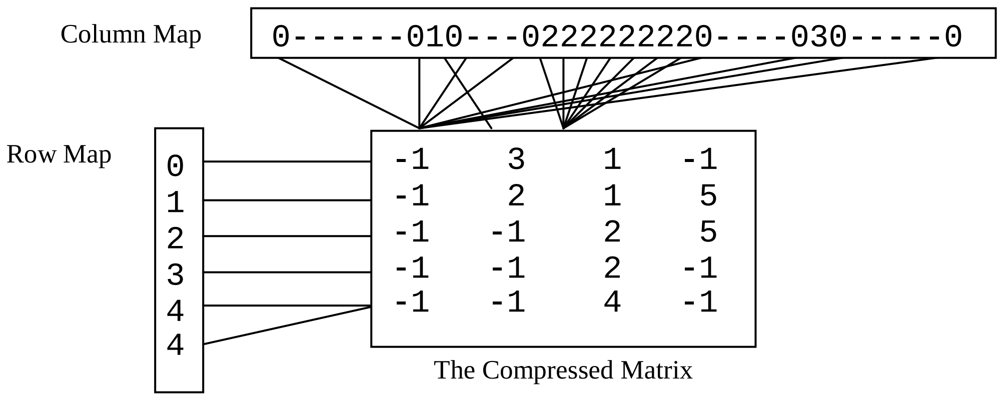
ExFig 2-11: A transition matrix suitable for compression

Several techniques were devised to remove such redundancy, that is, to compress the transition matrix. Amongst the techniques used we use two in our package: **Pairs Compression** (with its two flavors, normal and default) and **Redundancy Removal Compression**.

Another choice given to the user is to let the package choose the **Best Compression** technique in terms of the compression ratio. We shall give more details about the two techniques used in our package in the following two subsections:

2.9.1 Redundancy Removal Compression

The basic idea behind this technique is to create two supplementary arrays to eliminate the redundant rows and columns.



ExFig 2-12: Redundancy removal compression

All the redundant rows are eliminated into one row. The resulting unique rows are grouped together in the compressed matrix. Such matrix cannot be accessed directly using the state number; rather it is accessed using a *"row map"*; that is, a one dimensional array indexed by the state number and holding in each of its elements a pointer to a row in the compressed matrix.

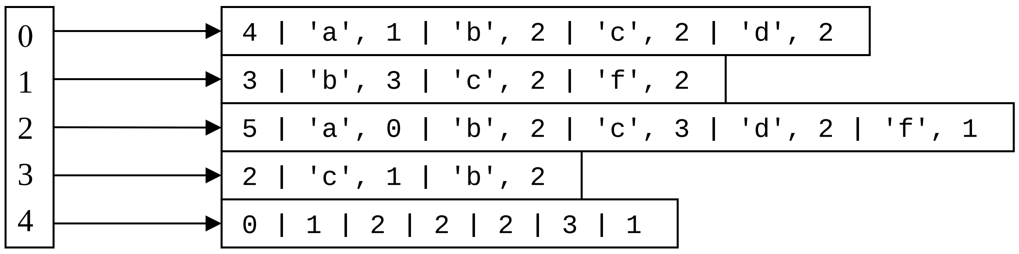
Thus, the transition matrix is now accessed indirectly in two steps. Use the state number to index the row map and to get a pointer to the appropriate row. Then use this pointer to access the appropriate row. A `-1` indicates a "Hell" state.

The same steps are applied to columns to eliminate the redundant ones, using a *"column map"*. The final transition matrix is shown in ExFig 2-12.

2.9.2 Pairs Compression

This technique gives a better compression ratio if the transition matrix is sparse, however, access time is usually longer. The basic idea behind this technique is to convert the rectangular transition matrix to a *jagged* matrix. The new matrix is simply a group of one-dimensional rows of unequal length.

The compressed matrix is represented in memory as an array of pointers; the length of such an array equals the number of rows in the original matrix. Each pointer points to a row, represented as a one-dimensional array, where the different rows are not necessarily the same length. ExFig 2-13 illustrates the logical memory organization.


0
1
2
3
4
4 | 'a', 1 | 'b', 2 | 'c', 2 | 'd', 2
3 | 'b', 3 | 'c', 2 | 'f', 2
5 | 'a', 0 | 'b', 2 | 'c', 3 | 'd', 2 | 'f', 1
2 | 'c', 1 | 'b', 2
0 | 1 | 2 | 2 | 2 | 3 | 1

ExFig 2-13: Pairs compression

Each row begins with an integer that determines the number of character / next state pairs in the row. If the number at the beginning is 0 then the row is not compressed at all, that is, the compressed row is the same as the original one. Such case occurs when the compressed row is more memory extensive than the original row itself. The row is, therefore, accessed normally by using the input character as an index in the one-dimensional array that represents the row.

In the typical case, however, the number at the beginning of the row is a positive integer that determines the number of pairs in the compressed row. The row is then searched pair by pair for the right one. If the search is terminated without a result then the next state is the "Hell" state, or `-1`.

Accessing the transition table this way is apparently ***O(n)***, but its compression ratio is much better if the original transition table is sparse.

2.10 The Generated Scanner

The code generation phase is the last step in the scanner generation process. By then, the regular expressions, which the user provided as an input, have been converted into a NFA, converted into a DFA, minimized, and finally compressed by any of the available compression techniques (or may be not compressed at all).

Each of the compressed DFA classes (or the uncompressed DFA class) has its own code generation functions. Generally speaking, the scanners generated by any of the three possibilities (DFA, Pairs Compression, Redundancy Removal) are essentially the same except for the transition mechanisms, that is, the mechanism by which the machine switches from one state into another.

Every scanner can be divided into three parts: the transition table, the input mechanism and the driver.

- The transition table is a two-dimensional data structure, usually represented as a rectangular matrix or a jagged matrix; it determines the next state of the scanner given the current state and the current input symbol.

- The input mechanism is the mechanism by which the scanner deals with the input data; its functionality includes dealing with the Unicode encoding schemes in a transparent manner, keeping track of the current line number and column number in the input file for buffering and error handling purposes.
- The driver is the software module that invokes the input mechanism to read the input file symbol by symbol. It uses the transition table, together with a data variable that keeps track of the current state, to execute the DFA that represents the regular grammar specified by the compiler developer. When the machine reaches an accepting state, it executes the appropriate action code associated with the given state.

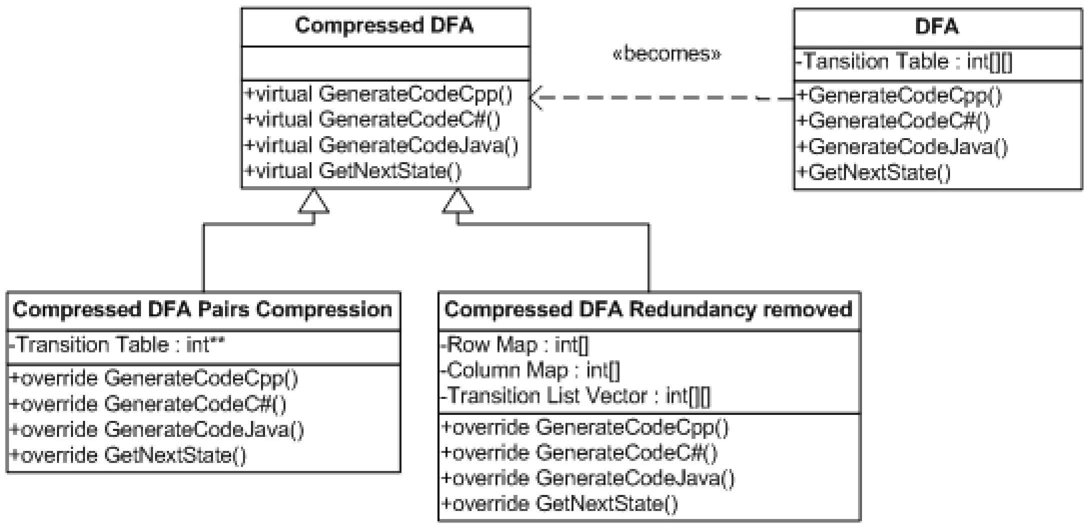

Compressed DFA
+virtual GenerateCodeCpp()
+virtual GenerateCodeC#()
+virtual GenerateCodeJava()
+virtual GetNextState()
«becomes»
DFA
-Tansition Table : int[][]
+GenerateCodeCpp()
+GenerateCodeC#()
+GenerateCodeJava()
+GetNextState()
Compressed DFA Pairs Compression
-Transition Table : int**
+override GenerateCodeCpp()
+override GenerateCodeC#()
+override GenerateCodeJava()
+override GetNextState()
Compressed DFA Redundancy removed
-Row Map : int[]
-Column Map : int[]
-Transition List Vector : int[][]
+override GenerateCodeCpp()
+override GenerateCodeC#()
+override GenerateCodeJava()
+override GetNextState()

Figure II-12B: Class Diagram for the Compressed DFA

We will describe each of these components separately, and then we will provide a complementary explanation of the `Scanner` class itself.

2.10.1 The Transition Table

The structure of the transition table depends on the compression settings specified by the compiler developer in the input file. More details about the compression of transition tables may be found in the "DFA Compression" section (2.9).

2.10.1.1 No Compression

In case no compression is applied to the DFA, the generated transition table is merely a 2-dimensional matrix where the row index represents the state and the column index represents the input symbol. Determining the next state is achieved by substituting the current state and the current input symbol in the row and column indexes respectively; the resulting matrix cell holds the next state of the machine.

For example, in C# the transition table will be defined as follows:

```
private int [,] transitionTable = new int [numberStates, sizeCharSet];
```

Where *numberStates* is the number of states in the DFA representing the regular language specified by the compiler developer, and *sizeCharSet* is the size of the character set to be used by the generated scanner.

Accessing the table will be as follows:

```
currentState = transitionTable[currentState, currentSymbol];
```

2.10.1.2 Redundancy Removal Compression

In case of Redundancy Removal compression, the transition table is compressed into a 2-dimensional array whose size is smaller than or equal to the original matrix size. The new matrix is obtained by removing the redundant rows and columns from the original one. Two linear vectors (1-dimensional arrays) are used to index the new compressed matrix:

- *The Row Map:* Its size equals the number of states in the original matrix. It may be indexed by the state number to determine, for a given current state, which row in the compressed matrix is to be used in next-state lookup.
- *The Column Map:* Its size is equal to the size of the character set of the scanner. It may be indexed by symbols to determine, for a given current symbol, which column in the compressed matrix is to be used in looking up the next-state.

For example, in C# the transition table will be defined as follows:

```
int [] rowMap = new int [numberStates];
int [] columnMap = new int [sizeCharSet];
int [,] transitionTable = new int [newRowsCount, newColumnsCount];
```

Where `numberStates` is the number of states in the DFA representing the regular language specified by the compiler developer, `sizeCharSet` is the size of the character set to be used by the generated scanner, `newRowsCount` is the number of rows in the new compressed matrix, and `newColumnsCount` is the number of columns in the new compressed matrix.

Accessing the table will be as follows:

```
currentState = transitionTable [rowMap[currentState],
                               columnMap[currentSymbol]];
```

2.10.1.3 Pairs Compression

In case of Pairs Compression, the transition table is compressed into a jagged matrix together with a linear vector (1-dimensional array) whose length equals the number of states in the DFA. Each element in the linear vector points to one of the rows in the jagged matrix, that is, it determines which of the rows in the jagged matrix is to be used while looking up the next state.

For example, in C# the transition table will be defined as follows:

```
int [][] transitionTable = new int [numberStates][];
```

where `numberStates` is the number of states in the DFA representing the regular language specified by the compiler developer.

Accessing the transition table is not as easy as the previous two techniques. Since the matrix is jagged, we cannot lookup the next state by simple array indexing. We have to search the appropriate row (the one corresponding to the current state) as if we were searching a linked list. This is done by the driver.

2.10.2 The Input Mechanism

LEXcellent generates an input stream class, called `CodeStream`, to act as an interface between the generated lexical analyzer and its input files. The main tasks performed by `CodeStream` are:

- Decoding the Unicode input files in a transparent manner, that is, the lexical analyzer shouldn't care whether the input file is in the Unicode format or not.
- Keeping track of the current line number and column number so that the lexical analyzer might make use of them is error handling or other purposes.
- Giving the lexical analyzer the capability to bookmark positions within the input file. The lexical analyzer can backup an arbitrary number of positions in a stack to be restored later. This gives the lexical analyzer higher flexibility in looking ahead and backtracking.

Now, we shall give a brief description of the `CodeStream` class, we shall assume – without loss of generality – that the output language, specified by the compiler developer, is C++. However, such claim should never affect our description since all the lexical analyzers generated by *LEXcellent* share essentially the same structure.

2.10.2.1 Constructor

The `CodeStream` class has only one constructor:

```
CodeStream(tifstream& _stream):
      stream(_stream),
      curlineno(1),
      curcolumn(1),
      nextlineno(1),
      nextcolumn(1),
      position(0)
      {}
```

It takes an STL input stream as a parameter and stores it in the local variable `stream`. Besides, it initializes the data members of the class so that the current position is adjusted to the beginning of the input file and the line and column numbers are initialized by 1.

2.10.2.2 Data Members

Table II-8: CodeStream Class Data Members

Data Member	*Description*
`private tifstream& stream`	The STL input stream wrapped by the code stream. It should be obtained through the constructor.
`private stack<int> lines`	A stack that allows the lexical analyzer to backup the current line number. Changes in that stack are always accompanied by changes in other stacks to accomplish the overall task of backup-restore of positions.
`private stack<int> cols`	A stack that allows the lexical analyzer to backup the current column number. Changes in that stack are always accompanied by changes in other stacks to accomplish the overall task of backup-restore of positions.
`private stack<int> positions`	A stack that allows the lexical analyzer to backup the current stream position (in bytes). Changes in this stack are always accompanied by changes in other stacks to accomplish the overall task of backup-restore of positions.
`private int curlineno`	Holds the line number at the beginning of the last consumed token.
`private int curcolumn`	Holds the column number at the beginning of the last consumed token.
`private int nextlineno`	Holds the line number at the end of the last consumed token.
`private int nextcolumn`	Holds the column number at the end of the last consumed token.
`private int position`	The current stream position (in bytes). That is, the number of bytes that have been consumed up till now.

2.10.2.3 Methods

Table II-9: CodeStream Class Methods

Methods	*Description*
`int CurrentLineNo() const`	Returns the line number before the last consumed token. It merely returns the value of the `curlineno` data member.
`int CurrentColumn() const`	Returns the column number before the last consumed token. It merely returns the value of the `curcolumn` data member.
`int NextLineNo() const`	Returns the line number after the last consumed token. It merely returns the value of the `nextlineno` data member.
`int NextColumn() const`	Returns the column number after the last consumed token. It merely returns the value of the `nextcolumn` data member.
`TCHAR Peek()`	Peeks the input stream, that is, returns the next symbol without consuming it. The symbol may be more than one byte depending on the encoding

	scheme. The `position`, `curlineno` and `curcolumn` variables *aren't* affected by this method.
`Void Advance`	Advance the position of the stream to after the next symbol. That is, skip the next symbol. It makes one symbol-size jump in the input file.
`TCHAR ReadChar()`	Read the next symbol and advance your position. The symbol may be more than one byte depending on the encoding scheme. The `position`, `curlineno` and `curcolumn` variables *are* affected by this method.
`Void Backup()`	Save the current position, line number and column number values in the appropriate stacks.
`Void Restore()`	Restore the last saved position, line number and column number values from the appropriate stacks. That is, pop the tops of the stacks.
`Void ReplaceLastBackup()`	Delete the last saved position, line number and column number values from the appropriate stacks. Then save the current position, line number and column number values.
`Void RemoveLastBackup()`	Delete the last saved position, line number and column number values from the appropriate stacks.
`Void SaveCurrentPosition()`	This function should be called by the lexical analyzer before consuming any token. It updates the line and column numbers by making the current column and line numbers equal to the next column and line numbers respectively. That is, set the current line and column numbers to the beginning of the next token.

2.10.3 The Driver

The driver is the component of the lexical analyzer that keeps track of the current state and invokes the input mechanism (the `CodeStream` class) to get the next symbol from the input file. Then, given the current state and input symbol, it looks up the transition table for the next state.

During the process of consuming a token, the driver keeps track of the last accepting state it had encountered. When it eventually crashes into an error state it backtracks to that last accepting state and it executes the code associated with that state. This allows the driver to match the longest possible token given the regular definition. For example, on confronting the input

```
intex
```

it matches the *identifier* `intex` rather than the *keyword* `int`. After executing the action code, the driver will go on consuming the next token unless the action code does make a return statement.

On the other hand, if the driver doesn't encounter any accepting states before entering the error state, it executes the invalid-token action; that is, the action determined by the compiler developer to be executed when an invalid token is consumed. Such action must be either a function to be called or a value to be returned. The driver must return immediately after executing the invalid-token action.

Execution continues until the driver encounters the EOF (End-Of-File) symbol, where it executes the EOF-action and returns immediately. Further invocation of the driver will do nothing but executing the EOF-action again. Similar to the invalid-token action, the EOF-action must be either a function to be called or a value to be returned.

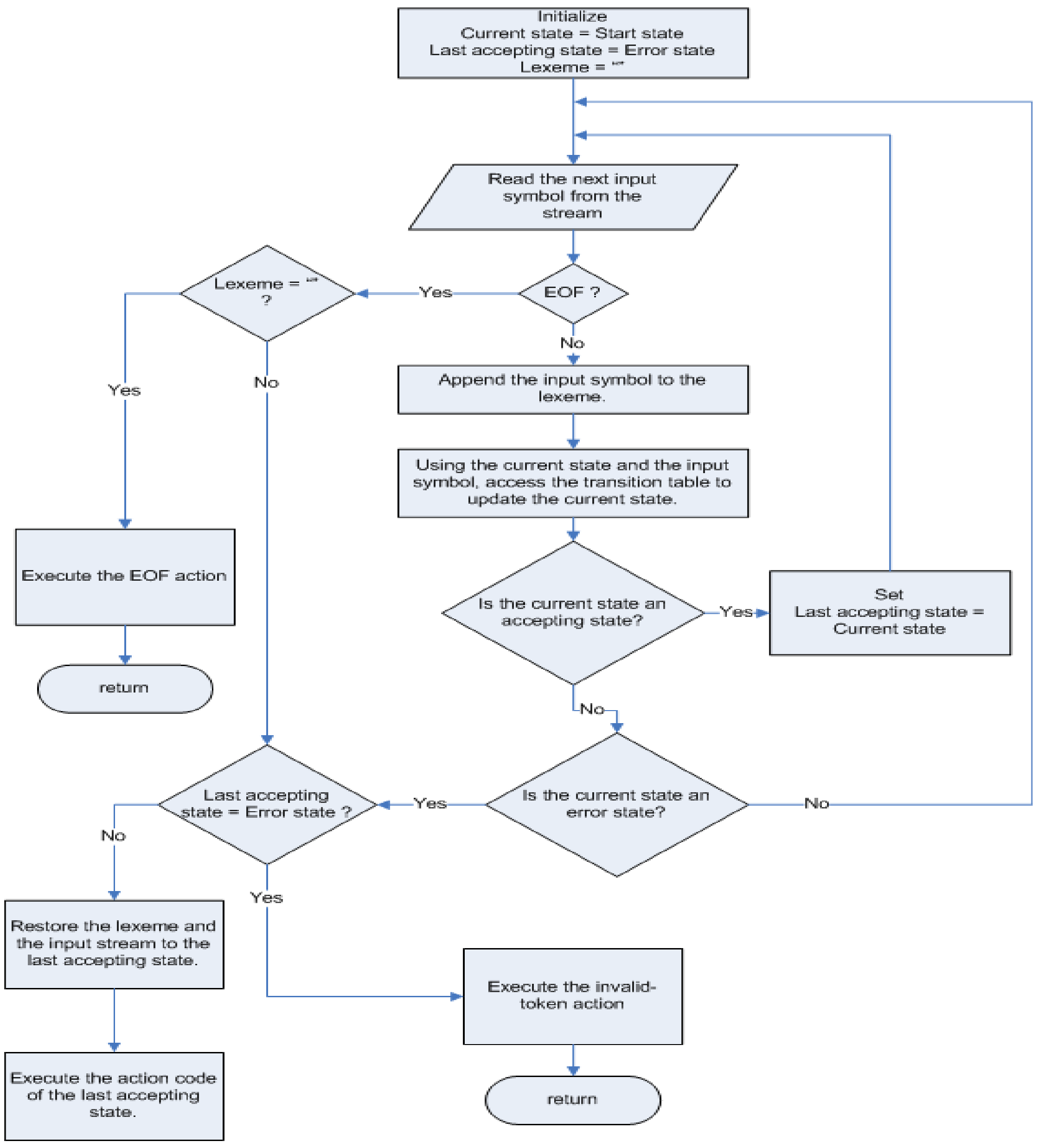

Initialize
Current state = Start state
Last accepting state = Error state
Lexeme = ""
Read the next input symbol from the stream
EOF ?
Yes
No
Lexeme = "" ?
Yes
No
Append the input symbol to the lexeme.
Using the current state and the input symbol, access the transition table to update the current state.
Execute the EOF action
return
Is the current state an accepting state?
Yes
Set Last accepting state = Current state
No
Is the current state an error state?
No
Yes
Last accepting state = Error state ?
No
Yes
Restore the lexeme and the input stream to the last accepting state.
Execute the action code of the last accepting state.
Execute the invalid-token action
return

Figure II-13: Driver Flowchart

Note that if the action code of the last accepting state doesn't return, the driver will not return until an invalid-token or an EOF is encountered.

2.10.4 The Lexical Analyzer Class

Now we will give a brief explanation of the structure of the lexical analyzer class. The name of such a class is provided as an option in the *LEXcellent* input file. The class encapsulates the driver as a member function (whose name is a developer option, too); and encapsulates the transition table as a member variable, besides other helper functions and data members.

2.10.4.1 Constructors

The constructor of the lexical analyzer class performs necessary initializations. It takes, as a parameter, an STL input stream, and then calls the constructor of its `CodeStream` object and passes the former STL stream as a parameter to it.

Other initializations include setting the last accepting state to the error state `-1`, setting the current state to the start state index `0`, setting the backup length to `0` and negating the EOF flag. Such initialization steps will be repeated before reading each token.

```
<LexicalAnalyzerClassName> (tifstream& stream) :
      fin(stream),
      lastAccepting(errorState),
      currentState(startStateIndex),
      backupLength(0),
      endOfFile(FALSE)
      {}
```

2.10.4.2 Constants

The generated lexical analyzer class contains a set of constants whose values are set by *LEXcellent* at generation time. These are listed in table II-10.

Table II-10: Lexical Analyzer Class Constants

Constant	*Description*
`private static const int startStateIndex`	The index of the start state. The default value is 0.
`private static const UTCHAR startSymbol`	The first symbol in the character set of the lexical analyzer, provided as an option in the *LEXcellent* input file.
`private static const UTCHAR finalSymbol`	The last symbol in the character set of the lexical analyzer, provided as an option in the *LEXcellent* input file.
`private static const BOOL accepting[]`	An array whose size is equal to the number of states. It determines, for each possible state, whether it is accepting or not.

Besides, the lexical analyzer class contains the transition map as a constant private member. The data members declared differ according to the compression technique utilized, as mentioned in the *Transition Table* subsection.

2.10.4.3 Data Members

Table II-11: Lexical Analyzer Class Data Members

Data Member	*Description*
`private CodeStream fin`	The code stream that the lexical analyzer deals with.
`private TCHAR currentChar`	The most recently consumed character obtained from the input stream.
`public int lastAccepting`	The last accepting state encountered.
`private int backupLength`	The number of characters consumed since the last accepting character.
`private int currentState`	The current state.
`private tstring lexeme`	The lexeme of the most recently consumed token.
`private BOOL endOfFile`	Determines whether the end of file has been encountered or not.

2.10.4.4 Methods

Table II-12: Lexical Analyzer Class Methods

Function Name	*Description*
`private static int indexOf(UTCHAR c)`	Checks if the given character is in the character set, if so, return its numeric order.
`CodeStream& CodeStream()`	Returns a reference to the code stream used by the lexical analyzer. It merely returns the value of the private data member `fin`.
`tstring Lexeme()`	Returns the lexeme of the most recently consumed token. It merely returns the value of the private data member `lexeme`.

Besides, the lexical analyzer class contains a parameterless function that represents the driver of the lexical analyzer. The name and the return type of the driver function are provided by the compiler developer as options in the *LEXcellent* input file.

2.11 Helper Tools

As was stated in the introductory part of this document, the main goal behind our tool is to facilitate the compiler construction process. For that end we provide – both in the lexical analysis and parsing phases – a set of helper utilities that automate some tasks normally encountered during the process.

2.11.1 Graphical GTG Editor

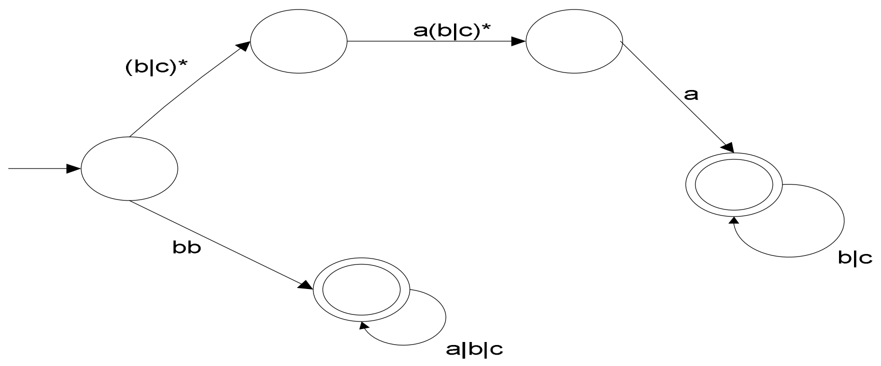
The set of patterns that the lexical analyzer recognizes are specified as regular languages. A *regular language* over a certain character set is the set of all strings over that character set that have the same pattern as a particular regular expression, i.e., a language that can be defined by a regular expression is called a regular language. Relying only on regular expressions to specify the regular patterns of the lexical analyzer can often be cumbersome and error-prone. Indeed, not every regular pattern is best specified by a regular expression. In some situations, it is very hard to deduce the regular expression of a particular regular pattern. In such cases, using an alternative – yet equivalent – method to express the regular pattern can be helpful and straightforward. A generalized transition graph (GTG) is one such alternative.

2.11.1.1 Definition

A generalized transition graph (GTG) is a collection of three items:

1. A finite set of states, with one or more start states and some (may be none) accepting (final) states.
2. An alphabet Σ of input letters (the character set of the input language).
3. Directed edges connecting some pairs of states, each labeled with a regular expression.

For example, we can represent the language of all strings over the alphabet {a, b, c} that begins with bb or have exactly two a's by the GTG in ExFig 2-14:



ExFig 2-14: Example GTG

It is easy to see that every DFA is a GTG and every NFA is a GTG, as well. However, the converse is not true.

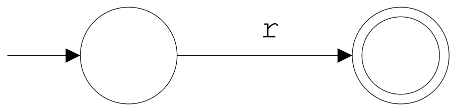


Figure II-14: RegEx as a GTG

It is also straight forward to see that any regular expression can be specified by a GTG with two states, one as a start state, and the other is a final state, and a single edge from the start state to the final state having that regular expression as a label. Figure II-14 illustrates. These observations are the key behind the feasibility of the tool, as will be later illustrated.

In general, automata provide a mathematical way of describing algorithms for recognizing regular patterns. Recall that *Deterministic Finite Automata* (*DFAs*) give the description of the algorithm in a deterministic manner. NFAs, TGs and GTGs are nondeterministic. It was proved that for any language expressible via a regular expression, there exists a DFA that recognizes the same language (and thus a GTG also exists). The basic task of the lexical analyzer generator is to find such a DFA for a set of regular expressions. Finding the regular expression corresponding to a given GTG is the main task of the GTG graphical tool. The algorithm employed in the process is described in a later section, firstly its important to illustrate the need for such a tool.

2.11.1.2 Why GTGs?

Some regular languages are originally specified in a rather procedural manner. Deducing regular expressions for such languages is not often straightforward. The ‘C Comment’ regular language is an example. Any string in that language begins with “/*” and continues until reading the first “*/”. As seen, the description takes the form of a procedure and thus, the associated regular language is more suitably described by means of an automaton rather than a regular expression. A GTG for this language is shown in figure II-15.

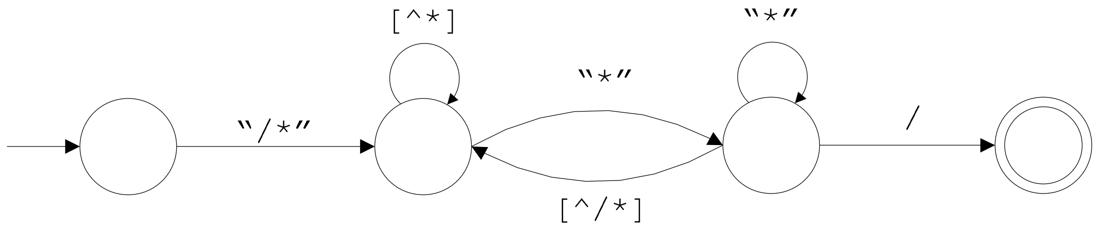


Figure II-15: The "C Comment" Regular Language

Another example is the language ‘EVEN-EVEN’ of all strings over the alphabet {a, b} with even number of a’s and even number of b’s. Specifying an automaton for this language is far easier than deducing the corresponding regular expression. The GTG for ‘EVEN-EVEN’ regular language is shown in figure II-16.

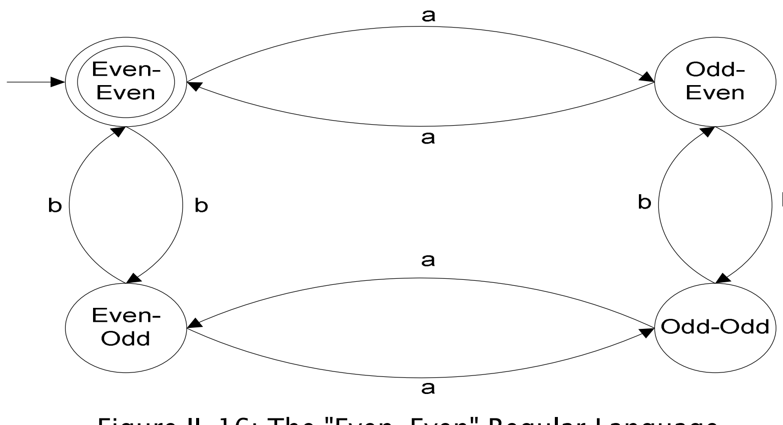


Figure II-16: The "Even-Even" Regular Language

Thus, accepting the specification of regular languages in the form of GTGs, as well as regular expressions, makes the specification process easier and more intuitive. It greatly reduces the errors committed if one tries to deduce the regular expressions of many regular languages.

2.11.1.3 GTG to Regular Expression: The Algorithm

As previously stated, a regular expression **r** can be represented as a GTG (look at figure II-14). Thus, if we can convert any general GTG to an equivalent GTG having the same structure depicted in figure II-14, we can obtain the corresponding regular expression. We can repeatedly reduce the number of states in the given GTG, without changing the language it accepts, until we get the structure depicted in figure. This is illustrated in the following pseudo code:

Given a GTG G = (S, E), where S = {s_1, s_2, …, s_n} is the set of states, and E is the set of edges, with each edge labeled by a regular expression.

Step 1:

Create a non-enterable start state s_0 and for each other start state s_j, add the edge (s_0, s_j), label it as •, and remove the start attribute from s_j. By the end of this step, the GTG will have a unique, non-enterable start state.

Step 2:

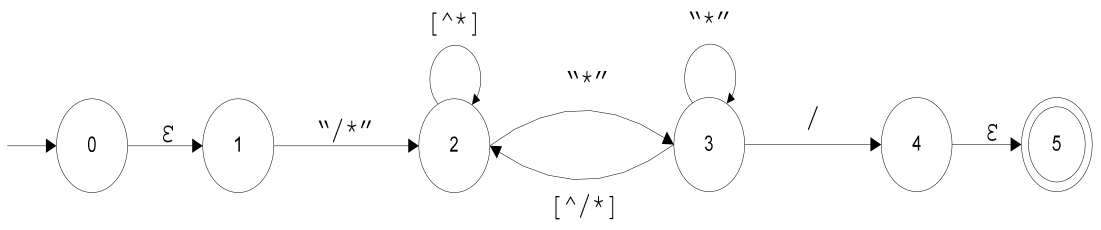
Create a non-exitable final state s_{n+1} and for each other final state s_j, add the edge (s_j, s_{n+1}) and label it as •, then remove the final attribute from s_j. By the end of this step, the GTG will have a unique non-exitable final state.

Step 3: (Elimination)

```
WHILE ( S – {$s_0$, $s_{n+1}$} • • ) do
   Select a state $s_j$ from S.
   IF there is a self-edge on $s_j$ labeled with M,
       THEN set SelfLabel = (M)*
       ELSE set SelfLabel = •
   FOREACH edge ($s_k$, $s_j$) labeled with R, DO
       FOREACH edge ($s_j$, $s_m$) labeled with Q, DO
          Let NewRegex = R.SelfLabel.Q
          IF there is an edge ($s_k$, $s_m$) labeled with OldRegex
             THEN set the label of that edge as OldRegex | NewRegex
             ELSE add the edge ($s_k$, $s_m$) with the label NewRegex
                to the set E
       END_FOREACH
   END_FOREACH
   Remove state $s_j$ from S
END_WHILE
```

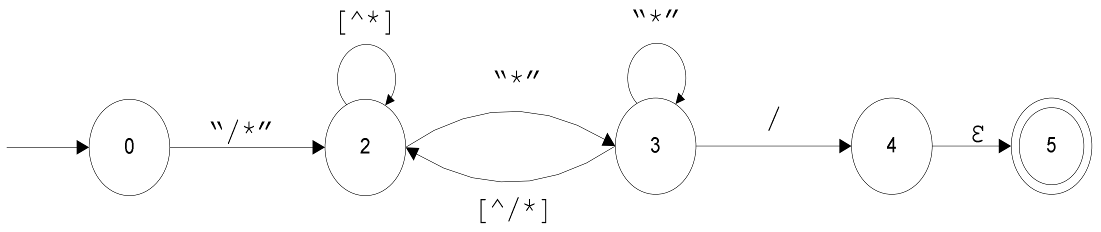
```
IF there is no edge between $s_0$ and $s_{n+1}$, then the language of this GTG
is •.

ELSE the regular expression is the label of that edge.
```

For the sake of illustration, we apply the steps of the algorithm on the “C Comment” GTG. Initially, we add to the original GTG in figure II-15 the non-enterable start state and the non-exitable final state according to steps 1 and 2. We obtain the equivalent GTG shown in ExFig 2-15A. Although these steps seem unnecessary here since the original start and final states have the desired attributes, not every GTG possess this characteristic.



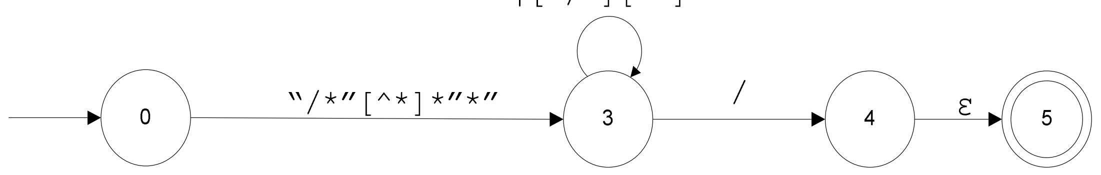
ExFig 2-15A: Converting the "C-Comment" regex to a corresponding GTG

After that, we choose to eliminate state 1 which luckily has a single incoming edge, a single outgoing edge and no cycles. We simply concatenate the regular labels of the two edges. The GTG obtained after this step is shown in ExFig 2-15B. Recall that • represents the empty string and consequently the result of concatenating • with “/*” is “/*”.



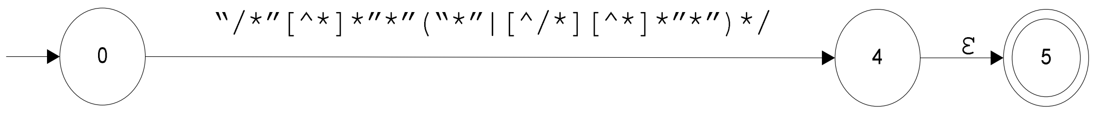
ExFig 2-15B: Converting the "C-Comment" regex to a corresponding GTG

State 2 has one outgoing edge labeled with “*”, a self-edge with label [^*], and two incoming edges labeled “/*” and [^*], respectively. Performing concatenation gives us the labels “/*”[^*]*”*” and [^/*][^*]*”*”. The GTG is shown again in ExFig 2-15C after eliminating state 2.



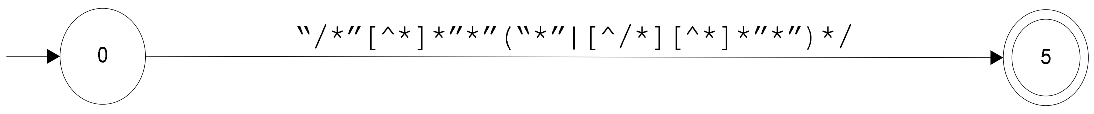
ExFig 2-15C: Converting the "C-Comment" regex to a corresponding GTG

Eliminating state 3 is rather straightforward. ExFig 2-15C shows that the GTG after the elimination of state 3 becomes:



ExFig 2-15D: Converting the "C-Comment" regex to a corresponding GTG

After eliminating state 4, the final GTG results; as illustrated in ExFig 2-15E. The label on the edge (0, 5) is the regular expression for the “C Comment” language.



ExFig 2-15E: Converting the "C-Comment" regex to a corresponding GTG

2.11.1.4 Implementation Details

The GTG is represented as a list of states. Each state contains a list of the edges emanating from that state as well as a list of the edges entering it. There is an additional field for the self-edge of that state. This field is kept NULL if no self-edge exists. Each state contains two Boolean fields to indicate whether the state is a start and/or a final state. Each edge contains pointers to the source and destination states, in addition to a string representing its label. Whether the label is valid or not is checked once and the result of the check is stored along with the edge to help speed up the application. The validity check is made again only when the label is changed or the character set of the GTG is changed.

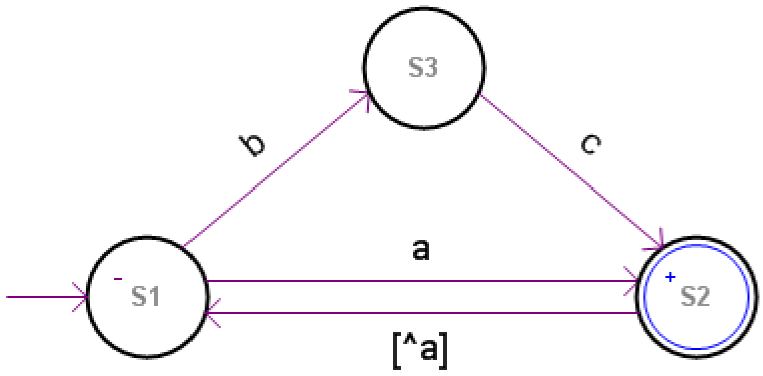
Since this is a visual tool, additional geometric data are kept in the data structure. For example, each state contains a `Point` structure to keep track of the x and y-coordinates of the center of that state. Furthermore, geometric data are cached and maintained along each edge to help speed up the execution of the program.

The GTG-to-Regular Expression algorithm is implemented with minor modifications. For example, we never try to eliminate those states that are not reachable from the unique start state or those that have no paths to the unique final states. This reduces the execution time of the algorithm. Specifically, we perform, as a preprocessing stage, a depth-first search starting from the unique start state to identify those states that are reachable from the start state. Then, we perform a depth-first search starting from the unique final state (the orientation of the edges is reversed in that case) to identify those states that have paths to the unique final state. The result of both searches is kept as an array of Booleans indicating whether a given state can be ignored from elimination or not.

2.11.1.5 Geometric Issues

During the development of the user interface of the graphical GTG tool, we faced certain geometric problems, but we were able to solve them successfully and elegantly. The following subsections contain descriptions of some of these problems and how we solved them, both the idea and the implementation. However, we start by a brief description of the UI of the GTG tool.

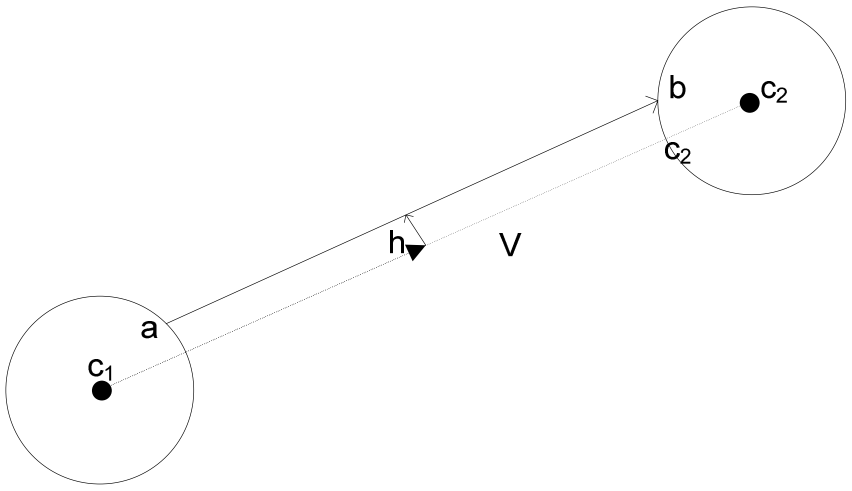
Each state is represented as a circle of a certain constant radius R. Edges are represented by lines connecting the circles of the two states as shown in ExFig 2-16. The label of each edge has the same orientation as that edge.



ExFig 2-16: The GUI of the GTG Editor - States

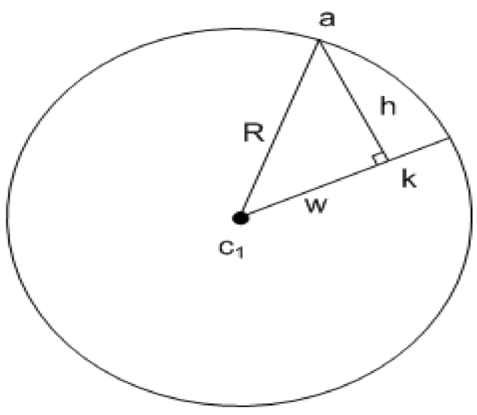
Edges

As seen in the above figure, each edge has the same direction as the vector connecting the start state and the end state. The problem is to find the coordinates of the end-points a, b of a given edge, given the coordinates of the centers c_1, c_2 of the two states the edges connect. As a further constraint, the line segment should have a small offset h on the perpendicular vector of the vector connecting the two centers c_1 and c_2 so that if the edge of the inverse direction is present, the two edges do not cover each other. (For an example, look at the two edges between the states S1 and S2 in the figure above). The end-point a must lie on the circle of radius R around c_1 and the end-point b must lie on the circle of radius R around c_2. The whole issue is illustrated in ExFig 2-17.



ExFig 2-17: The GUI of the GTG Editor - Edges

We now show how to compute the coordinates of the point a. Since a lies on the circle of radius R around c_1, the line segment $\overline{c_1 a}$ has length R (a constant value). The line segment $\overline{ka}$ (which is normal to $\overline{c_1 c_2}$) has length h (a constant value). Let w denote the length of the line segment $\overline{c_1 k}$. Thus, w can be computed by applying Pythagorean Theorem on the triangle c_1 a k. The whole picture becomes:



ExFig 2-18: Finding the endpoints of an edge

The value of w can be computed and fixed at compile time. We reach the point a from c_1 by taking a step w along the direction of the vector $\vec{V}$, followed by a step h along the direction of the perpendicular vector n. The equations are listed below:

$$w = \sqrt{R^2 - h^2}$$

All the remaining computations are performed at runtime.

$$\vec{V} = c_2 - c_1$$

$$\vec{n} = (-y_V, x_V) \quad \text{(normal vector on } \vec{V}\text{)}$$

$$M = \| \vec{n} \| = \| \vec{V} \| \quad \text{(magnitude of both vectors is the same)}$$

$$\vec{u}_{src} = \frac{1}{M}(w.\vec{V} + h.\vec{n})$$

$$a = c_1 + \vec{u}_{src}$$

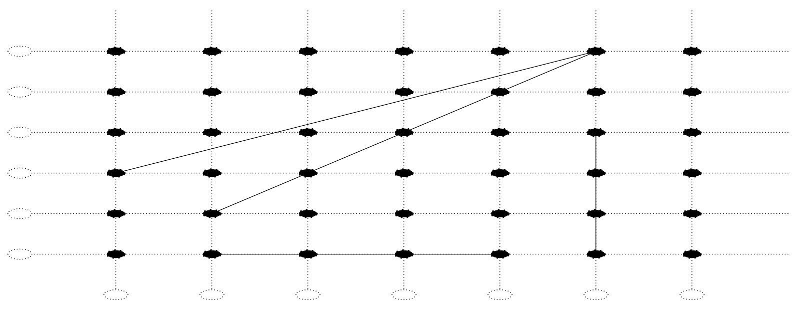
$$\vec{u}_{dst} = \frac{1}{M}(-w.\vec{V} + h.\vec{n})$$

$$b = c_2 + \vec{u}_{dst}$$

The above computations guarantee that the edge of the reverse direction (the edge from state c_2 to state c_1) takes the small offset h on the reverse direction of the perpendicular vector $\vec{n}$, computed above. This is because the vector from c_2 to c_1 is the inverse of $\vec{V}$. Thus, the new normal will be the inverse of $\vec{n}$.

Selection of States and Edges

When the user clicks the button of the mouse, the operating system informs the application that the user pressed the button of the mouse and supplies the coordinates of the mouse pointer at that time instance. The problem here is to determine whether that event occurred when the mouse pointer was inside the circle of a given state or near an edge. In addition, we need to determine that specific state or that edge that contained the mouse pointer. This is needed because the user might want to change the label of the state, change the start/final attributes of the state, change the position of the state on the screen, remove that state, change the label of the edge, or remove that edge. The solution of the problem seems pretty easy. We just loop through each state and check whether that state contains the mouse pointer (the state contains the mouse pointer if and only if the distance between the center of the state and the mouse pointer is less than or equal to R). If no state contains the mouse pointer, we just loop through the edges and check whether the mouse pointer lies on the line segment defined by that edge or not. The routine was implemented using these ideas, and was thoroughly tested, but matters did not go as were intended. There was no problem selecting a state. However, edges were never selected except when the direction of the edge was strictly vertical, strictly horizontal or making a 45° angle with the horizontal. After further analysis of the situation, we discovered that although the pointer of the mouse visually lies very near to (or even lies exactly on) the line segment of the edge, the coordinates of the mouse are integral and would rarely represent a point on the line at the specified x-coordinate of the mouse pointer. The situation is illustrated in the following figure:

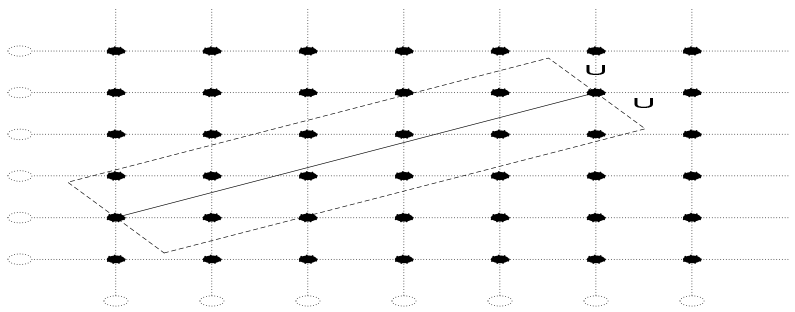


ExFig 2-19A: The edge-clicking problem

To solve this problem, we enclosed each edge in an imaginary rectangle having one side parallel and equal in length to the edge, and the other perpendicular side has a predefined, fixed length 2U. The situation is illustrated again on the next page. An edge is selected if no state is selected and the mouse pointer lies within the enclosing rectangle. It is worth noting that setting U = 0 will be the same as testing whether the mouse pointer lies on the edge defined by that line segment. U is chosen large enough so that the area sensitive to mouse clicks around the edge has a suitable value.

The line segment passes through these points only when the line segment is vertical, horizontal or making a 45° angle with the horizontal.

But how can we determine if a given point Z lies near the edge defined by the two points P and Q?

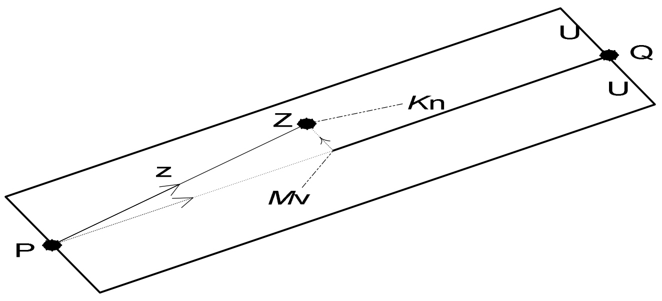


ExFig 2-19B: The edge-clicking problem

Let z denote the vector from the point P to the point Z. Let v be the vector from the point P to the point Q, and n be the vector perpendicular to v. We resolve z into its components along v and n. This is illustrated in the figure below. Thus, we can write z as a linear combination of both vectors v and n as follows:

$$z = M \cdot v + K \cdot n$$

If $||Kn|| \leq$ U and $0 \leq M \leq 1$, then z lies inside the enclosing rectangle. Otherwise, it is outside.



ExFig 2-19C: The edge-clicking problem

M can be found by forming the dot product of both sides by v:

$$z \cdot v = Mv \cdot v$$

Dividing both sides by *v.v* gives us *M*:

$$M = \frac{z.v}{v.v}$$

Of course, we must check that P and Q are not coincident so that *v.v* is nonzero. Similarly, $||Kn||$ can be found by forming the dot product of both sides by n:

$$z \cdot n = Kn \cdot n$$

Dividing both sides by *n.n* gives us *K*:

$$K = \frac{z.n}{n.n}$$

Hence;

$$\|Kn\| = |K| \cdot \|n\|$$

3. The Parsing Phase

The bulk of this part is devoted to parsing methods that are typically used in compilers. We first present the basic concepts, then the techniques we used in our tool. Since programs may contain syntactic errors, we extend the parsing methods so they recover from commonly occurring errors. We also present the input file specifications as a guide to the user to build a parser using our tool, as well as the helper tools we provide to aid the user adjust the input grammar to suit the parsing methods we provide.

3.1 More about Parsing

3.1.1 A General Introduction

Every programming language has rules that prescribe the syntactic structure of well-formed programs. In Pascal, for example, a program is made out of blocks, a block out of statements, a statement out of expressions, an expression out of tokens, and so on. The syntax of programming language constructs can be described by context-free grammars or BNF (Backus-Naur Form) notation.

A **context-free grammar** (grammar, for short), also known as **BNF (Backus-Naur Form)** notation, is a notation for specifying the syntax of a language. A grammar naturally describes the hierarchical structure of many programming language constructs. For example, an if-else statement in C has the form

if (expression **)** statement **else** statement

That is, the statement is the concatenation of the keyword **if**, an opening parenthesis, an expression, a closing parenthesis, a statement, the keyword **else**, and another statement. (In C, there is no keyword then.) Using the variable *expr* to denote an expression and the variable *stmt* to denote a statement, this structuring rule can be expressed as:

stmt → **if (** *expr* **)** *stmt* **else** *stmt*

in which the arrow may be read as "can have the form". Such a rule is called a **production**. In a production, lexical elements like the keyword *if* and the parentheses are called **terminals**, variables like *expr* and *stmt* represent sequences of tokens and are called **non-terminals [2]**.

A *context-free grammar* has four components:

1) A set of tokens, known as *terminal* symbols.
2) A set of *non-terminals*.
3) A set of *productions* where each production consists of a non-terminal, called the left side of the production, an arrow, and a sequence of tokens and/or non-terminals, called the right side of the production.

4) A designation of one of the non-terminals as the start symbol.

We follow the convention of specifying grammars by listing their productions, with the productions for the start symbol listed first. We assume that digits, signs such as <=, and boldface strings such as **while** are terminals. An italicized name is a non-terminal and any non-italicized name or symbol may be assumed to be a token. For notational convenience, productions with the same non-terminal on the left can have their right sides grouped, with the alternative right sides separated by the symbol |, which we read as "or".

3.1.2 Advantages of using Grammars

Grammars offer significant advantages to both language designers and compiler writers **[2]**.

- A grammar gives a precise, yet easy-to-understand, syntactic specification of a programming language.
- From certain classes of grammars we can automatically construct an efficient parser that determines if a source program is syntactically well-formed. As an additional benefit, the parser construction process can reveal syntactic ambiguities and other difficult-to-parse constructs that might otherwise go undetected in the initial design phase of a language and its compiler.
- A properly designed grammar imparts a structure to a programming language that is useful for the translation of source programs into correct object code and for the detection of errors. Tools are available for converting grammar-based descriptions of translations into working programs.
- Languages evolve over a period of time, acquiring new constructs and performing additional tasks. These new constructs can be added to a language more easily when there is an existing implementation based on a grammatical description of the language.

In our compiler model, the parser obtains a string of tokens from the lexical analyzer, as shown in figure III-1 **[2]**, and verifies that the string can be generated by the grammar for the source language.

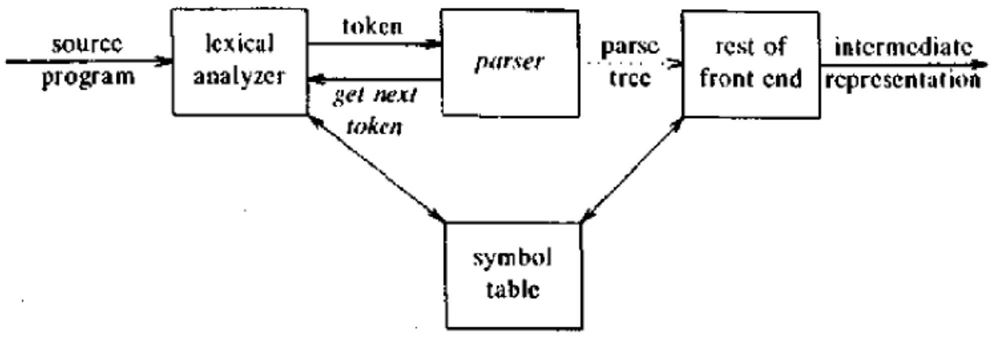


Figure III-1: Parser-Lexical Analyser Interaction

We expect the parser to report any syntax errors in an intelligible fashion. It should also recover from commonly occurring errors so that it can continue parsing the remainder of its input.

There are three general types of parsers for grammars **[1]**. *Universal parsing methods* such as the Couke-Younger-Kasami algorithm and Earley's algorithm can parse any grammar. These methods, however, are too inefficient to use in production compilers. The methods commonly used in compilers are classified as being either top-down or bottom-up.

As indicated by their names, *top-down parsers* build parse trees from the top (root) to the bottom (leaves), while *bottom-up parsers* start from the leaves and work up to the root. In both cases, the input to the parser is scanned in one direction (according to the language), one symbol at a time. Our tool implements two top-down parsers, the details of which are covered in the next two sections.

The last concept to present in this brief introduction is that of a parse-tree and a syntax-tree.

3.1.3 Syntax Trees *vs.* Parse Trees

During analysis, the operations implied by the source program are determined and recorded in a hierarchical structure called a tree. A *parse-tree* pictorially shows how the start symbol (or a grammar) derives a string in the language. Each node in the parse-tree is labeled by a grammar symbol. An interior node and its children correspond to a production; the interior node corresponds to the left side of the production, the children to the right side.

Abstract syntax trees, or simply syntax trees, differ from parse trees because superficial distinctions of form – unimportant for translation – do not appear in syntax trees.

Formally, given a context-free grammar, a parse-tree is a tree with the following properties:

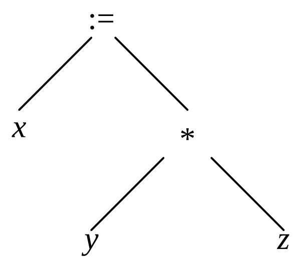
1) The root is labeled by the start symbol.
2) Each leaf is labeled by a token or by ε (the *empty* string).
3) Each interior node is labeled by a non-terminal.
4) If A is the non-terminal labeling some interior node and X_I, X_2 … X_n are the labels of the children of that node from left to right, then $A \rightarrow X_1\ X_2 \ldots X_n$ is a production. Here, X_I, X_2 … X_n stand for a symbol that is either a terminal or a non-terminal. As a special case, if $A \rightarrow \varepsilon$ then a node labeled A may have a single child labeled ε.

The leaves of a parse tree read from left to right form the *yield* of the tree, which is the string *generated* or *derived* from the non-terminal at the root of the parse tree.

Another definition of the *language* generated by a grammar is as the set of strings that can be generated by some parse tree. The process of finding a parse tree for a given string of tokens is called *parsing* that string.

Often, a special kind of trees called a *syntax-tree* is used, in which each node represents an operation and the children of a node represent the arguments of the operation **[2]**. Thus, a *syntax-tree* is a compressed representation of the parse tree in which the operators appear as the interior nodes, and the operands of an operator are the children of the node for that operator.

For example, a syntax tree for the assignment statement (*x* := *y* * *z*) may be as illustrated in ExFig 3-1:



ExFig 3-1: Syntax tree

3.2 Recursive Descent Parsers

A *recursive descent parser* is a top-down parser built from a set of mutually-recursive procedures (or a non-recursive equivalent) where each such procedure usually implements one of the production rules of the grammar. Thus the structure of the resulting program closely mirrors that of the grammar it recognizes **[1]**.

A *predictive parser* is a recursive descent parser with no backup. Predictive parsing is possible only for the class of *LL(k) grammars*, which are the class of context-free grammars for which there exists some positive integer k that allows a recursive descent parser to decide which production to use by examining only the next k tokens of input. (The LL(k) grammars therefore exclude all ambiguous grammars, as well as all grammars that contain left recursion. Any context-free grammar can be transformed into an equivalent grammar that has no left recursion, but removal of left recursion does not always yield an LL(k) grammar.) A predictive parser runs in linear time, and that's why it's preferred on an equivalent backtracking parser, whose running time is cubic in the input size, although the latter can parse any input grammar.

Recursive descent with backup is a technique that determines which production to use by trying each production in turn. Recursive descent with backup is not limited to LL(k) grammars, but is not guaranteed to terminate unless the grammar is LL(k). Even when they terminate, parsers that use recursive descent with backup may require exponential time.

A *packrat parser* is a modification of recursive descent with backup that avoids non-termination by remembering its choices, so as not to make exactly the same choice twice. A packrat parser runs in linear time, but usually requires more space than a predictive parser.

Our project generates recursive descent predictive parsers; the parser generator expects left-factored and left-recursion-free grammar. Thus we implemented two tools for this purpose. More on both of them later in this part.

To explain the concept of recursive descent parsers, we will take a complete example which will run on our tool to produce the parser code which is going to be explained. First of all, we are going to list the parser description file which acts as the input to our parser generator tool and we will explain it briefly. The grammar contained in the file describes variable declaration statements in a C-language-like format. For simplicity we work with two data types only: *int* and *float*.

```
Options
        NameSpace = "MyLangCompiler" ClassName="Parser" Language = CSharp

Tokens
        int float identifier comma

Grammar
        Declaration    → DataType VarList.
        VarList        → identifier Var.
        Var            → comma identifier Var | Eps.
        DataType       → int | float.
```

In the *Options* section we specify the name of the generated parser class; in this case it is *Parser*. The namespace in which the parser class will be contained is *MyLangCompiler* in this example. Also, we specify *CSharp* as the language in which the generated parser is written in.

Next, we specify the *Tokens* section, which is the interface between the generated parser and the scanner used by that parser. In this section we specify the terminals which will be used in our grammar productions. These tokens will be translated into enumerated members where *int* will take the value 3, "float" will take the value 4, "identifier" will take the value 5 and "comma" will take the value 6.

Last but not least, we specify our productions rules in the *Grammar* section. A grammar production is specified in this format:

A → B

where A denotes a non-terminal, and B is a set of terminals and non-terminals. Each production is terminated by a dot. We use the bar symbol "|" to denote the ORing operation. Also, we use *Eps* which is a reserved keyword to denote *epsilon "ε"*, the empty string.

Before discussing the generated code we list the first sets and the follow sets of our terminals and non-terminals:

```
first set of [DataType] is {   int , float   }
first set of [Declaration] is {   int , float   }
first set of [Var] is {   Eps , comma   }
first set of [VarList] is {   identifier   }

follow set of [DataType] is {   identifier   }
follow set of [Declaration] is {   EOF   }
follow set of [Var] is {   EOF   }
```

follow set of [VarList] is {   EOF   }

We could run our tool (ParserGenerator) as follows from the command prompt passing "MyParser.cs" as the filename for the generated code.

```
C:\ParserGenerator MyParser.cs
```

Now, it is time to list the generated code, the "MyParser.cs" file:

```
namespace MyLangCompiler
{
   public class Parser
   {
      public Parser( IScanner lexicalAnalyzer )
      {
         scanner = lexicalAnalyzer;
      }

      public void Declaration()
      {
         DataType();
         VarList();
      }

      public void VarList()
      {
         match( _TokenType._identifier );
         Var();
      }

      public void Var()
      {
         if ( currentToken.TokenType == _TokenType._comma )
         {
            match( _TokenType._comma );
            match( _TokenType._identifier );
            Var();
         }
      }

      public void DataType()
      {
         if ( currentToken.TokenType == _TokenType._int )
         {
            match( _TokenType._int );
         }
         else if ( currentToken.TokenType == _TokenType._float )
         {
            match( _TokenType._float );
         }
         else
            SyntaxError(currentToken);
      }
      public void Parse()
      {
         currentToken = scanner.GetNextToken();
         Declaration();
         if ( currentToken.TokenType != _TokenType._EOF )
            SyntaxError(currentToken);
```

```
        }

        protected void match( _TokenType expected )
        {
           if ( currentToken.TokenType == expected )
              currentToken = scanner.GetNextToken();
           else
              ErrorHandler( expected, currentToken );
        }

        protected void ErrorHandler(_TokenType expected, Token  found)
        {
           // Write your own error handling here
        }

        protected void SyntaxError( Token errorAtToken )
        {
           // Write your own error handling here
        }

        Token currentToken;
        IScanner scanner;
     }

     public enum _TokenType
     {
        _EOF, _Char, _String, _int, _float, _identifier, _comma
     }

     public interface IScanner
     {
        Token GetNextToken();
     }

     public class Token
     {
        public _TokenType TokenType;
     }
  }
```

Note that our tokens specified in the "Tokens" section is mapped to the following _TokenType enum:

```
     public enum _TokenType
     {
        _EOF, _Char, _String, _int, _float, _identifier, _comma
     }
```

The used scanner must return a `_TokenType` value that is equivalent to the token it sees.

To understand the generated code we have to clarify some concepts first, then we are going to investigate each grammar production and see its effect on the generated code. First of all, to use our generated parser we have to pass an object from a class which implements the `IScanner` interface. This object is going to be the scanner used by the generated parser. To implement the `IScanner` interface, you have to implement the following function, `GetNextToken()`

```
Token GetNextToken();
```

This function returns an object of type `Token` which contains the `TokenType` member of type `_TokenType` enum which tells the parser the type of the token it is currently working with.

Recursive descent parsers use one lookahead token, we call it `currentToken` to predict what path to production to produce starting from the start symbol (`Declaration` in this example). Every time the grammar tells us that a specific token is expected we call the `match` function:

```
protected void match( _TokenType expected )
{
   if ( currentToken.TokenType == expected )
      currentToken = scanner.GetNextToken();
   else
      ErrorHandler( expected, currentToken );
}
```

The `match` function works as follows, if the `currentToken` is the expected one, then the next lookahead token is requested from the scanner and we continue parsing. If not, then an error is present so we call the `ErrorHandler` function passing the expected and the found tokens for the user to handle the error as the application requires.

In recursive descent parsers, every non-terminal corresponds to a function which is called every time this non-terminal is seen in any production. To grasp the idea, we are going to take every production and see its corresponding fuction, as each production yields a function in the produced code.

Declaration → DataType VarList.

```
public void Declaration()
{
   DataType();
   VarList();
}
```

Since the righthand side of this production consists of only non-terminals, the corresponding fuctions to these non-terminals are called.

VarList → identifier Var.

```
public void VarList()
{
   match( _TokenType._identifier );
   Var();
}
```

Here the identifier is matched as it is a terminal and the function `Var()` is called for the *Var* terminal.

```
Var → comma identifier Var            //Production1
        | Eps.                        //Production2
```

```
public void Var()
{
   if ( currentToken.TokenType == _TokenType._comma )
   {
      match( _TokenType._comma );
      match( _TokenType._identifier );
      Var();
   }
}
```

Because *Var* is optional, as one of its right-hand-side is ε, the lookahead is checked. If it is a comma, then we work with the *Production1* else we return from the `Var()` function adhering to *Production2*.

DataType → int | float.

```
public void DataType()
{
   if ( currentToken.TokenType == _TokenType._int )
   {
      match( _TokenType._int );
   }
   else if ( currentToken.TokenType = _TokenType._float )
   {
      match( _TokenType._float );
   }
   else
      SyntaxError(currentToken);
}
```

Because this production is really composed of two productions ORed together, we use the look ahead token to decide which one we are going to follow. Note that if the current token is not one of the types _TokenType._int or _TokenType.float we call the SyntaxError function because the Data Type production is not an optional one. The implementation of the SyntaxError is left to the user.

Finally, we have to see how this process begins. The user initiates the parsing process by calling the `Parse()` function:

```
public void Parse()
{
   currentToken = scanner.GetNextToken();
   Declaration();
   if ( currentToken.TokenType != _TokenType._EOF )
      SyntaxError(currentToken);
}
```

which simply initialized the lookahead token, `currentToken`. Then, it calls the first production rule (*Declaration*) which is the start symbol of our grammar. Finally, it makes sure that at the end of the parsing process the file has reached an end and that no tokens appear after accepting the processed input.

3.3 LL(1) Parsers

3.3.1 Definition

An LL parser is a table-based top-down parser for a subset of context-free grammars. It parses the input from **L**eft to right, and constructs a **L**eftmost derivation of the sentence (Hence **LL**). The class of grammars parsable this way is known as the LL grammars. Older programming languages sometimes use LL grammars because it is simple to create parsers for them by hand – using either the table-based method (described shortly), or a recursive-descent parser as we've just seen.

An LL parser is called an LL(*k*) parser if it uses *k* tokens of lookahead when parsing a sentence. If such a parser exists for a certain grammar and it can parse sentences of this grammar without backtracking then it is called an LL(*k*) grammar. Of these grammars, LL(1) grammars, although fairly restrictive, are very popular because the corresponding LL parsers only need to look at the next token to make their parsing decisions.

3.3.2 Architecture of an LL Parser

```
       +---+---+---+---+---+---+
Input: | ( | 1 | + | 1 | ) | $ |
       +---+---+---+---+---+---+
                         ^
Stack:                   |
            +-------+--------+
+---+       |                |
| + |<------+    Parser      +-----> Output
+---+       |                |
| F |       +------+---------+
+---+              |  ^
| ) |              |  |
+---+       +------+---------+
| $ |       |    Parsing     |
+---+       |    table       |
            +----------------+
```

Figure III-2: Architecture of a Table-Based Top-Down Parser

A table-based top-down parser can be schematically presented as in figure III-3. The parser has an *input buffer*, a *stack* on which it keeps symbols from the grammar, a *parsing table* which tells it what grammar rule to use given the symbols on top of its stack, and its *input tape*. To explain its working we will use the following small grammar:

```
(1) S → F
(2) S → ( S + F )
(3) F → 1
```

The parsing table for this grammar looks as follows:

	(	)	1	+	$

S	2	-	1	-	-
F	-	-	3	-	-

(Note that there is also a column for the special terminal $ that is used to indicate the end of the input stream). Depending on the top-most symbol on the stack and the current symbol in the input stream, the parser applies the rule stated in the matching row and column of the parsing table (e.g., if there is an 'S' on the top of the parser stack and a '1' in the front-most position of the input stream, the parser executes rule number 1, i.e., it replaces the 'S' on its stack by 'F').

When the parser starts it always starts on its stack with

```
[ S, $ ]
```

where $ is a special terminal to indicate the bottom of the stack (and the end of the input stream), and S is the start symbol of the grammar. The parser will attempt to rewrite the contents of this stack to what it sees on the input stream. However, it only keeps on the stack what still needs to be rewritten. For example, let's assume that the input is "(1 + 1)". When the parser reads the first "(" it knows that it has to rewrite S to `( S + F )` and writes the number of this rule to the output. The stack then becomes:

```
[ (, S, +, F, ), $ ]
```

In the next step it removes the '(' from its input stream and from its stack:

```
[ S, +, F, ), $ ]
```

Now the parser sees a '1' on its input stream so it knows that it has to apply rule (1) and then rule (3) from the grammar and write their number to the output stream. This results in the following stacks:

```
[ F, +, F, ), $ ]
[ 1, +, F, ), $ ]
```

In the next two steps the parser reads the '1' and '+' from the input stream and also removes them from the stack, resulting in:

```
[ F, ), $ ]
```

In the next three steps the 'F' will be replaced on the stack with '1', the number 3 will be written to the output stream and then the '1' and ')' will be removed from the stack and the input stream. So the parser ends with both '$' on its stack and on its input stream. In this case it will report that it has accepted the input string and on the output stream it has written the list of numbers [2, 1, 3, 3] which is indeed a leftmost derivation of the input string. Therefore, the derivation goes like this:

```
S → ( S + F ) → ( F + F ) → ( 1 + F ) → ( 1 + 1 )).
```

As can be seen from the example the parser performs three types of steps depending on whether the top of the stack is a non-terminal, a terminal or the special symbol $:

- If the top is a non-terminal then it looks up the parsing table (on the basis of this non-terminal and the symbol on the input stream) which rule of the grammar it should use to replace the one on the stack. The number of the rule is written to the output stream. If the parsing table indicates that there is no such rule then it reports an error and stops.
- If the top is a terminal then it compares it to the symbol on the input stream. If they are equal, they are both removed. Otherwise the parser reports an error and stops.
- If the top is $ and on the input stream there is also a $ then the parser reports that it has successfully parsed the input, otherwise it reports an error. In both cases the parser will stop.

These steps are repeated until the parser stops, and then it will have either completely parsed the input and written a leftmost derivation to the output stream, or it will have reported an error.

3.3.3 Constructing an LL(1) Parsing Table

In order to fill the parsing table, we have to establish what grammar rule the parser should choose if it sees a non-terminal A on the top of its stack and a symbol a on its input stream. It is easy to see that such a rule should be of the form $A \rightarrow w$ and that the language corresponding to w should have at least one string starting with a. For this purpose we define the **First-Set** of w, written here as $\mathbf{Fi}(w)$, as the set of terminals that can be found at the start of any string in w, plus ε if the empty string also belongs to w. Given a grammar with the rules $A_1 \rightarrow w_1, \ldots, A_n \rightarrow w_n$, we can compute the $\mathbf{Fi}(w_i)$ and $\mathbf{Fi}(A_i)$ for every rule as follows:

- Initialize every $\mathbf{Fi}(w_i)$ and $\mathbf{Fi}(A_i)$ with the empty set
- Add $Fi(w_i)$ to $\mathbf{Fi}(w_i)$ for every rule $A_i \rightarrow w_\mathrm{i}$, where Fi is defined as follows:
    - $Fi(a\ w') = \{\ a\ \}$ for every terminal a
    - $Fi(A\ w') = \mathbf{Fi}(A)$ for every non-terminal A with ε not in $\mathbf{Fi}(A)$
    - $Fi(A\ w') = \mathbf{Fi}(A) \mid \{\ \varepsilon\ \}$ □ $Fi(w')$ for every non-terminal A with ε in $\mathbf{Fi}(A)$
    - $Fi(\varepsilon) = \{\ \varepsilon\ \}$
- Add $\mathbf{Fi}(w_i)$ to $\mathbf{Fi}(Ai)$ for every rule $A_i \rightarrow w_i$
- Do steps 2 and 3 until all **Fi** sets stay the same.

Unfortunately, the First-Sets are not sufficient to compute the parsing table. This is because a right-hand-side w of a rule might ultimately be rewritten to the empty string. So the parser should also use the rule $A \rightarrow w$ if ε is in $\mathbf{Fi}(w)$ and it sees on the input stream a symbol that could follow A. Therefore we also need the **Follow-Set** of A, written as $\mathbf{Fo}(A)$ here, which is defined as the set of terminals x such that there is a string of symbols $\alpha Ax\beta$ that can be derived from the start symbol. Computing the Follow-Sets for the non-terminals in a grammar can be done as follows:

- Initialize every $\mathbf{Fo}(A_i)$ with the empty set
- If there is a rule of the form $A_j \rightarrow wA_iw'$, then
    - if the terminal a is in $Fi(w')$, then add a to $\mathbf{Fo}(A_i)$

    - if ε is in *Fi*(*w'*), then add **Fo**(A_j) to **Fo**(A_i)
- Repeat step 2 until all *Fo* sets stay the same.

Now we can define exactly which rules will be contained where in the parsing table. If *T*[*A*, *a*] denotes the entry in the table for non-terminal *A* and terminal *a*, then

- *T*[*A*, *a*] contains the rule $A \rightarrow w$ if one of the following is true.
    - *a* is in **Fi**(*w*)
    - ε is in **Fi**(*w*) and *a* is in **Fo**(*A*).

If the table contains at most one rule in every one of its cells, then the parser will always know which rule it has to use and can therefore parse strings without backtracking. Precisely is this case that the grammar is called an *LL(1) grammar*.

3.4 Input File Format

In this chapter we present the syntax of the recursive descent parser generator input file (grammar file) and then we present the slight differences in the LL(1) parser generator input file from the recursive descent one.

It is important to note that the recursive descent parser accepts grammar in the EBNF (Extended Backus-Naur Format) while the LL(1) parser generator accepts grammar in the BNF (Backus-Naur Format).

The input file consists of labeled sections, in what follows; we present each section with its syntax and meaning. The next two subsections introduce the overall picture and the detailed explanation of the input file.

3.4.1 Input File Syntax: The Overall Picture

Options
NameSpace = *namespace* ClassName = *classname* Language = *language*

Tokens
token1 token2 ……… *tokenN*

TopOfDeclaration
%%
anystring
%%

BottomOfDeclaration
%%
anystring
%%

TopOfDefinition
%%
anystring
%%

BottomOfDefinition
%%
anystring
%%

Grammar
NonTerminal → *terminalsAndNonTerminals*.
…..
…..
ProductionN

Figure III-3: ParSpring - The Syntax of the Input File

3.4.2 Input File Syntax: The Details

Options: Denotes the beginning of the *Options* sections

namespace is a string representing the name of the namespace where the generated class will be enclosed in.

classname is a string representing the name of the generated parser class.

language is an identifier that specifies the language in which the generated parser will be written in. The following values are currently supported:

CSharp	For generation in the C# language
JAVA	For generation in the Java language
CPlusPlus	For generation in the C++ language

Tokens: Denotes the beginning of the tokens section which is the interface between the generated parser and the scanner used by that parser. In this section, specify the terminals which will be used in the grammar productions. These tokens will be translated into enumerated members beginning at the value 3.

token1 token2 … tokenN are a set of identifiers separated by spaces which represents the terminals used in the grammar productions.

TopOfDeclaration: Denotes the beginning of the *TopOfDeclaration* section where %% delimits the beginning and the end of a block of code which will be pasted as-is in the generated file. Depending on the target language, the *TopOfDeclaration* block of code will be pasted as follows:

> **C#:** At the very beginning of the generated file; before opening the namespace.
>
> **Java:** At the very beginning of the generated file; before opening the class.
>
> **C++:** At the top of the .h declaration file.

BottomOfDeclaration: Denotes the beginning of the *BottomOfDeclaration* section where %% delimits the beginning and the end of a block of code which will be pasted as-is in the generated file. Depending on the target language, the *BottomOfDeclaration* block of code will be pasted as follows:

> **C#:** At the end of the generated file; after closing the namespace.
>
> **Java:** At the end of the generated file; after closing the class.
>
> **C++:** At the bottom of the .h declaration file.

TopOfDefinition: Denotes the beginning of the *TopOfDefinition* section where %% delimits the beginning and the end of a block of code which will be pasted as-is in the generated file. Depending on the target language, the *TopOfDefinition* block of code will be pasted as follows:

> **C#:** At the top of the generated file; after opening the namespace but before opening the class.
>
> **Java:** At the top of the generated class.
>
> **C++:** At the top of the .cpp definition file.

BottomOfDefinition: Denotes the beginning of the *BottomOfDefinition* section where %% delimits the beginning and the end of a block of code which will be pasted as-is in the generated file. Depending on the target language, the *BottomOfDefinition* block of code will be pasted as follows:

> **C#:** At the bottom of the generated file; before closing the class.
>
> **Java:** At the end of the class before closing it.

C++: At the bottom of the .cpp definition file.

Grammar: Denotes the beginning of the grammar productions section. It consists of an identifier representing a non-terminal at the left hand side of the "->" mark where its right-hand-side is the production itself consisting of terminal and non-terminals. Every production is terminated by a dot. The following lines are going to give the syntax of writing productions, let S1 and S2 denotes any two terminals or non-terminals or a mixture, then:

`S1 | S2`	S1 or S2
`S1 S2`	S2 is concatenated after S1
`{S1}`	S1 closure
`[S1]`	S1 is optional

<. .> delimits a semantic action which is a piece of code which is guaranteed to be executed after evaluating S1 and before evaluating S2.

```
S1 <. semAction .> S2
```

Every non-terminal produces a void function in the generated code. By default this function takes no parameters, to make it take parameters; in the left hand side of the production write the parameters enclosed between (. .), for example:

```
S1 (. TreeNode node, int level .) →
     S2 S1 (. node.Left, level+1 .).
```

Note that when S1 is called in the right hand side, you have to pass the parameters it is expecting as shown above.

3.4.3 Resolvers

Consider the following production:

```
S1 -> S2 | S3.
```

If the S2 and S3 first sets are intersecting; we can remove this ambiguity by using resolvers. We can write a Boolean expression which will be checked and the associated symbol will be evaluated if it evaluates to true. For example:

```
S1 -> IF (. BoolExpression .) S2 | S3.
```

So if there is an ambiguity S2 will be chosen if BoolExpression evaluates to true, otherwise S3 way will be chosen.

3.4.4 Comments

We can use the one line comments // and the multiline ones /* */ in the input file and the comments will be ignored totally by the generator.

3.4.5 The LL(1) Input File Differences

The LL(1) input file is the same as the recursive decent one except that the LL(1) input file doesn't support the following:

- Specifying parameters to non-terminals.
- Specifying resolvers.

3.5 Input File Error Handling

Our parser generator tool *ParSpring* besides generating the parser, it also detects various types of errors and warnings whether syntactic or semantic ones. Error handling is one of the most important aspects for achieving the practicality of any parser. That's why we discuss this vital capability in this separate chapter.

3.5.1 Semantic Errors and Warnings

The semantic error handler embedded in our tool detects various types of semantic errors and warnings. The following describes each of them in detail.

3.5.1.1 Warnings

Terminal defined but not used

This is just a warning that occurs when a terminal defined in the *Tokens* section is not used within the *Grammar* section.

For example, if the terminal

Addop

is defined in the *Tokens* section but not used the error handler displays the message

Warning: Terminal *Addop* defined but not used.

Unreachable production

A warning occurs when a production is not reachable from the start symbol. This is equivalent in programming to writing code after a `return`, `break` or `continue` statement.

For example, if

```
S → a S | b B | Eps.
B → b.
C → c C | Eps.
```

It's clear that production C is not reachable from the start symbol `S` and the error handler displays the message

Warning: Unreachable Production for *C*.

Contents of {…} or […] must not be deletable

This is an LL(1) grammar warning that occurs when the contents of a closure or an option are deletable.

For example, if there exists a rule such as

```
A → {[a]}.
```

The error handler displays the message

Warning: LL(1) Conflict in *A*: Contents of {...} must not be deletable.

Several alternatives start with …

This is another LL(1) warning that occurs when more than one alternative overlap in the first set.

For example if we have a rule

```
A → b [ a ] [ a B ].
A → a b | a c.
```

The error handler displays the message

LL(1) Warning in *A*: Several alternatives start with a.

3.5.1.2 Errors

Non-terminal undefined

This is an error that occurs when a given non-terminal was used in a rule but has no definition, i.e. it doesn't occur on the left-hand-side of a production.

For example, if we have the rule

```
S → b B | a A | Eps.
B → b.
```

The error handler displays the message

Error: Non-terminal *A* undefined.

Using a reserved keyword as a terminal or a non-terminal name

This is an error caused by using a reserved keyword (i.e. without being within double quotes) as a name of a terminal or a non-terminal.

For example, if the keyword *ClassName* is used within the *Tokens* section, the error handler displays the message

Error: *ClassName* is a reserved keyword and can not be used as a token.
You can use "*ClassName*" instead.

However, as the message clarifies, we allow the user to use reserved keywords as tokens after surrounding them with double quotes.

Non-terminal … does not lead to a terminal

This is an error that occurs when given a non-terminal X, there's no derivation of X that leads to a terminal.

For example, if we have a rule

A->b A| a A.

The error handler displays the message

Error: Non-terminal *A* does not lead to a terminal.

3.5.2 Syntactic Errors

The error handler also tool detects various types of syntactic errors mentioned below.

Missing keyword Grammar

Occurs when the keyword *Grammar* is missing.

Unbalanced () or [] or {}

Occurs on detecting unbalances in any bracket type: () or [] or {}.

Missing non-terminal in the left-hand-side

Missing production operator "→"

Missing "." to terminate a grammar rule

3.6 Syntactic Analyzer Generator Front-End (SAG-FE)

This chapter discusses the design and some implementation details for the parser generator tool such as scanning, parsing and tree node functions and algorithms.

The following figure illustrates the skeleton of the parser generator front end.

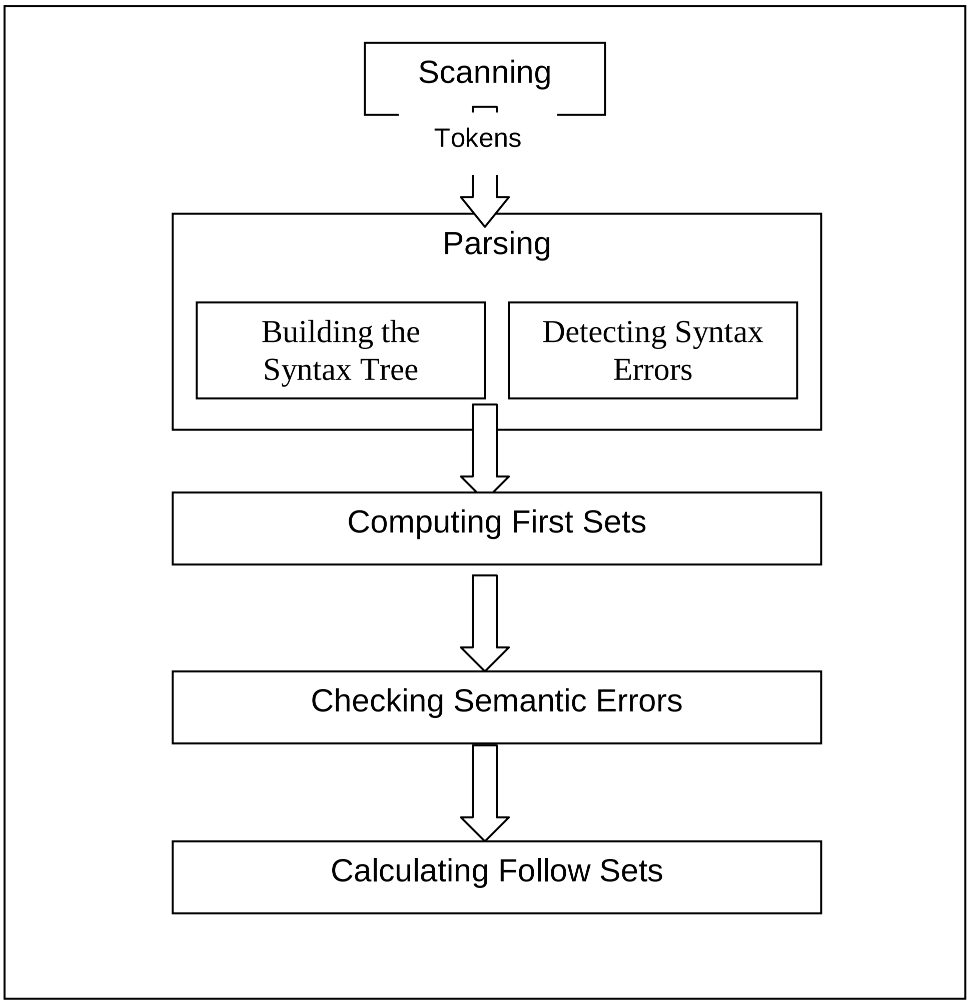


Figure III-4: The Parser Generator Front-End

3.6.1 Scanning the Input File

In this phase, the input file is scanned by reading characters and assembling them into logical units (*tokens*) to be dealt with in the parsing process.

3.6.1.1 Reserved Keywords

`"Tokens", "Options", "NameSpace", "ClassName", "Language", "TopOfDeclaration", "TopOfDefinition", "BottomOfDeclaration", "BottomOfDefinition", "CPlusPlus", "CSharp", "Java", "Grammar", "Eps", "Sync", "IF".`

3.6.1.2 Macro Representation of Other Tokens

Table III-1: Macro Representation of Tokens

Token	*Representation*
`BulkOfCode`	`%% {ANY} %%`

Identifier	(_a-zA-Z){_0-9a-zA-Z}.
String	"{ANY}"
Character	'ANY'
Production	->
Or	|
Dot	.
Equal	=
OpenBracket	(
CloseBracket	)
OpenSquareBracket	[
CloseSquareBracket	]
OpenCurly	{
CloseCurly	}
Attributes	(. {ANY} .)
SemAction	<. {ANY} .>
EndOfFile	EOF Char
Error	Otherwise

3.6.1.3 Data Structure for Scanning

The following is the code of the data structures used during scanning. The comments in the code are useful to understand the whole topic in a glance.

TokenType Enumerator

```
enum TokenType
{
   Tokens, Options, NameSpace, ClassName, Language, DeclTop,
DeclBottom, DefTop, DefBottom, CPlusPlus, CSharp, Java, Grammar,
Weak, Eps, Any, Sync, If, BulkOfCode, Identifier, String, Character,
Production, Or, Dot, Equal, OpenBracket, CloseBracket,
OpenSquareBracket, CloseSquareBracket, OpenCurly, CloseCurly,
Attributes, SemAction, Error, EndOfFile
}
```

Token Structure

```
struct Token
{
public:
   tstring Lexeme;       // String containing the lexeme
   TokenType Type;       // Type of matched token
   unsigned int LineNo;  // Line number (useful for error handling)
   unsigned int ColNo;   // Column number (useful for error handling)
};
```

States Enumerator

```
enum States // Holds the current state of scanner DFA
{
   Start, InIdent, InString, InChar, InProduction,
   InDot, InOpenBracket, InSemAction, Done, ErrorState,
   InBulkCode, AttributesState
};
```

Scanner Class

```
class Scanner
```

```
{
public:
  Scanner(string fileName, unsigned int numberOfCharsPerRead = 1024);
  Token GetToken(); // Get next token from the input file
  ~Scanner();
  unsigned char TabSize;

protected:
  TCHAR getNextCharachter(); // TCHAR is the Unicode character
  void ungetCharachter();
  void initializeReservedKeywords();
  TokenType reservedLookUp(tstring lexeme);
  InputFile* file;
  unsigned int currentLineNum,
               bufferSize,
               currentColNo,
               maxCharsToRead, // Number of characters to read per
                               // journey to the hard disk
               currentCharPosition; // A pointer in the buffer
  TCHAR* buffer;
  map<tstring, TokenType> reservedWords;
};
```

3.6.2 Parsing the Input File

This section introduces a detailed explanation of the `ParserGenerator` and `Node` classes and supported functionalities. The CFGs for LL(1) and recursive descent parsers are listed, along with nodes' functionalities, the process of building the tree and syntax error detection.

3.6.2.1 Recursive Descent Parser Generator CFG

```
Start     → [ OptionSet ] TokenSet { TDec | TDef | BDec | BDef }
             MyGrammar.

OptionSet → "Options" [ "NameSpace" Equal String ] [ "ClassName"
             Equal String ] [ "Language" Equal ID ].

TokenSet  → "Tokens" { ID | String }.

TDec      → "TopOfDeclaration" { "ANY" }.

TDef      → "TopOfDefinition" { "ANY" }.

BDec      → "BottomOfDeclaration" { "ANY" }.

BDef      → "BottomOfDefinition" { "ANY" }.

MyGrammar → "Grammar" { ( ID | String [ Attributes ] ) Production
             Expression Dot }.

Expression (. int x, int y .) →
             Term { Or Term } <. string s = ""; .>.

Term      → [ Resolver ] Factor { Factor }.

Factor    → IF (..) Symbol [ Attributes ]
            | OpenBracket Expression CloseBracket
            | OpenOption Expression CloseOption
            | OpenClosure Expression CloseClosure
            | "SYNC" | SemAction.
```

```
Attributes → OpenAttr { "ANY" } CloseAttr.
SemAction  → OpenAction { "ANY" } CloseAction .
Resolver   → "IF" OpenBracket { "ANY" } CloseBracket.
```

[**Hint:** Words without rules in the previous grammar represent the tokens previously discussed ("Options", "Namespace" …)].

3.6.2.2 LL(1) Parser Generator CFG

```
Start      → [ OptionSet ] TokenSet { TDec | TDef | BDec | BDef }
             MyGrammar.
OptionSet  → "Options" [ "NameSpace" Equal String ] [ "ClassName"
             Equal String ] [ "Language" Equal ID ].
TokenSet   → "Tokens" { ID | String }.
TDec       → "TopOfDeclaration" { "ANY" }.
TDef       → "TopOfDefinition" { "ANY" }.
BDec       → "BottomOfDeclaration" { "ANY" }.
BDef       → "BottomOfDefinition" { "ANY" }.
MyGrammar  → "Grammar" { ( ID | String ) [ Attributes ] Production
             Expression Dot }.
Expression(. int x, int y .) →
             Term { Or Term } <. string s = ""; .>.
Term       → [ Resolver ] Factor { Factor }.
Factor     → IF(..) Symbol [ Attributes ] | "SYNC" | SemAction.
Attributes → OpenAttr {"ANY"} CloseAttr.
SemAction  → OpenAction {"ANY"} CloseAction.
Resolver   → "IF" OpenBracket { "ANY" } CloseBracket.
```

[**Hint:** The CFG for the LL(1) parser generator does not include closure, option or bracket (for BNF notation restrictions) rather than EBNF notation for recursive descent parser generator specification].

According to the previous CFGs (i.e. separate parser for each supported type) a recursive-descent parser is built for analyzing the input file, the parser generator class has a member function for this purpose.

```
void ParserGenerator::Parse() // Maps Start in the CFG
void ParserGenerator::OptionsSet() // Maps OptionSet
void ParserGenerator::TokensSet() // Maps TokenSet
void ParserGenerator::TopOfDeclaration() // Maps TDec
void ParserGenerator::TopOfDefinition() // Maps TDef
void ParserGenerator::BottomOfDeclaration() // Maps BDec
void ParserGenerator::BottomOfDefinition() // Maps BDef
void ParserGenerator::Productions()
void ParserGenerator::Expression(GenericCFGNode** node, bool
      reachable)
void  ParserGenerator::Term(GenericCFGNode**  node,  bool  reachable)
void ParserGenerator::Factor(GenericCFGNode** node, bool reachable)
void ParserGenerator::match(TokenType expected, string ErrorMsg="",
      bool Resume=true)
void ParserGenerator::onError(tstring errorMsg)
```

The mentioned functions implement parsing the input files, building the syntax tree and detecting syntax errors, the following is a detailed description of the three processes.

The tree data structure is used to represent the RHS of a rule. The following section describes how the optimized syntax tree is generated and how syntax errors are detected during parsing.

3.6.2.3 The Tree Data Structure

Firstly it's better to mention why to represent the LHS of a rule by a node rather than a closure of terminals and non-terminals {N U T} (i.e. rules in the form

```
A → BCD...
```

only is accepted). This is to accept productions in a flexible form and to facilitate dealing with the left factored form of a rule. For example, a rule in the form

```
A → BC ( A [F] | YU (IO <. int x = 7; int y = x*x + 3*x; .> | {PU} Y).
```

is accepted.

As mentioned in the previous example, the LHS can be an *Or*, an *And*, an *Option*, a *Closure*, a *Terminal*, a *Non-terminal*, or a *Semantic Action*. So the LHS must be a generic node that can be an OredNode, an AndedNode, a ClosureNode… so the data structure is represented as follows:

NodeType Enumerator

```
enum NodeType // various types of nodes Ored,Anded,closure,….,etc.
{
      _Anded, _Ored, _Closure, _Brackets, _Optional, _Terminal,
      _NonTerminal, _SyncNode, _SemAction
};
```

GenericCFGNode Class

```
class GenericCFGNode
{
public:
   NodeType NType; // Store the type of this node
   virtual BitSet_Min FirstSet(ParserGenerator* P);
   virtual bool FollowSet(ParserGenerator* P);
   virtual BitSet_Min GetNonTerminals(ParserGenerator* P);
   void virtual Print(ParserGenerator* P)=0; // Print this node
   tstring virtual check_LL1(ParserGenerator* P)=0;
   virtual GenericCFGNode*   Copy()=0;
      // Returns a copy of this node
   void virtual Remove()=0;
      // remove all descendents the this node
   virtual bool LeadToTerminal(ParserGenerator* P,
                              unsigned int LHS)=0;
};
```

Functions that are in not bold will be discussed later.

The `GenericCFGNode` class mentioned above is just the interface; thus all types of nodes inherit from it. The children are as follows:

OredNode Class

```
class OredNode : public GenericCFGNode
{
public:
   list<GenericCFGNode*> Children; // A list of Ored children
   OredNode();
};
```

AndedNode Class

```
class AndedNode : public OredNode
{
public:
   tstring ResolverString; // Used if there is an LL(1) conflict
                           // Contains the decision logic to
                           // determine which production to go
                          // through.
   AndedNode();
};
```

ClosureNode Class

```
// Semantically having zero or more occurrences of the child node
// A ClosureNode can have only one child that can be Ored, Anded, ...
```

```
class ClosureNode : public OredNode
{
public
   ClosureNode();
};
```

OptionNode Class

```
// Semantically having zero or more occurrences of the child node
class OptionNode : public OredNode
{
public:
   OptionNode();
};
```

SemActionNode Class

```
// Actions to be executed
class SemActionNode : public GenericCFGNode
{
public:
   tstring SemAction; // The string containing the action.
   SemActionNode();
};
```

TerminalNode Class

```
class TerminalNode : public GenericCFGNode
{
public:
   int NameIndex; // Index of the terminal
   tstring Attributes; // Attributes for this node
   RDParserGenerator::TokenType TerminalType;
   bool IsWeak;
   TerminalNode();
};
```

NonTerminalNode Class

```
// Here the inherited NameIndex and attributes refer to a non-
// terminal one rather than terminal
class NonTerminalNode : public TerminalNode
{
public:
   NonTerminalNode();
};
```

The last declarations are shortened by ignoring the repeated code for overriding functions (e.g. Copy(), Remove(), Print(), …) in the interface (i.e. the `GenericCFGNode` class).

3.6.2.4 Building an Optimized Syntax-Tree

The tree building process in the `ParserGenerator` class deals with data members that comprise a number of data structures described here.

ParserGenerator Class Members

```
// Terminals used in the specifications.
// Terminals are loaded from values in the Tokens section.
map<tstring,TerminalEntry> Terminals;

// Non-Terminals used in the specifications.
// Non-Terminals are loaded during the parsing phase.
map<tstring,NonTerminalEntry> NonTerminals;

// Index of the next terminal
// [initialized using a TerminalBase]
unsigned int nextTerminalIndex;

// Index of the next non-terminal
// [initialized using a NonTerminalBase]
unsigned int nextNonTerminalIndex;
```

The goal of representing terminals as an index is to only store the index in the node rather than storing a string representing the non-terminal; as it's faster to compare integers rather than strings. To avoid ambiguities for a given node each type has a range of indices. Terminals start from `TerminalBase`, non-terminals starts from `NonTerminalBase` [in case of LL(1) parser generator a code index starts from `CodeBase`]. These bases are defined in a `#define` directive which can be easily changed, there is no intersection among any of these ranges (i.e. terminals' range, non-terminals' range and codes' range).

Grammar Items Data Structures

TerminalEntry Class

```
class TerminalEntry
{
public:
   unsigned int NameIndex; // The index given to the terminal
   BitSet_Min* FirstSet; // The First Set of this Terminal
   TokenType Type; // The type of this token
   vector<location> locations ; // Locations at which this
                                 // terminal exist
   bool used; //Is this terminal used so far or not?

   TerminalEntry();
   TerminalEntry(unsigned int NI, TokenType T, bool used = false);
};
```

TerminalEntry Class

```
class NonTerminalEntry
{
```

```
public:
   unsigned int NameIndex; // The index given to the non-terminal
   BitSet_Min* FirstSet; // The First Set of this non-terminal
   BitSet_Min* FollowSet; // The Follow Set of this terminal
   bool Defined; // This non-terminal has a rule?
   bool reachable; // Is this non-terminal reachable?
   ProductionRule* Rule; // The rule of this non-terminal
   vector<location> locations; // Locations at which this
                               // non-terminal exists
   NonTerminalEntry();
   NonTerminalEntry(unsigned int NI, bool defined = false);
};
```

Grammar Data Structure

Simply, the grammar is a list of production rules in the `ParserGenerator` class.

```
list<ProductionRule*> Grammer;      //ParserGeneratormember
```

Firstly, we want to know how a rule is represented, and so this is the rule declaration containing overall attributes required for the rule like LHS, attributes, SemAction,…,etc.

ProductionRule Class

```
class ProductionRule
{
public:
   ProductionRule(void);
   ~ProductionRule(void);

   unsigned int LHS; //The index of the non-terminal in the LHS
   tstring Attributes; // Attributes for LHS
   tstring SemAction; // Semantic action "string of code"
   GenericCFGNode* RHS; // Root node for RHS
   bool reachable; // Is this rule reachable?
   list<location> locations;
};
```

Tree Construction

During building the tree two types of operation are done, these operations are optimization and gathering.

Tree Optimization

The tree is built in the minimum number of levels and nodes. For example, a tree for the production

```
A → B C D.
```

is the same as the tree for the production

```
A → (B)(C D).
```

is the same as the tree for the production

```
A → ((B)C)D.
```

To illustrate the difference between an optimized tree and non-optimized tree the following is the representation of the tree of each rule in a non-optimized form:

```
ORed(ANDed(B, C, D)).
ORed(ANDed(ORed(ANDed(B)), ORed(ANDed(ORed(ANDed(C, D)))))).
ORed(ANDed(ORed(ANDed(ORed(ANDed(B)), C)), D)).
```

But the optimized tree is the simplest of the three for all of them.

```
A → B C D      … ANDed(B, C, D).
A → (B)(C D)   … ANDed(B, C, D).
A → ((B)C)D    … ANDed(B, C, D).
```

Optimization is achieved in the implementation as the called process assigns the children pointer. And that's why `Expression`, `Term` and `Factor` functions each has a pointer to the node pointer as a parameter.

```
void ParserGenerator::Expression(GenericCFGNode** node,
                                 bool reachable)
void ParserGenerator::Term(GenericCFGNode** node, bool reachable)
void ParserGenerator::Factor(GenericCFGNode** node, bool reachable)
```

The reachable parameters are used to assign the `reachable` property of the non-terminal (if it exists) in the node's children.

Optimization While Traversing

The following listing illustrates how the optimization is carried out while traversing the tree. We adopted a convention of "mixing" C++ and structured English to clarify the overall situation.

```
FUNCTION ParserGenerator::Expression
         (
            GenericCFGNode** node, // A passed node, to be assigned
            bool reachable
         )
BEGIN
   IF(Token in first Set of Term)
   THEN
      GenericCFGNode* ChildNode;
      Term(&ChildNode, reachable);
   // If this is the only child of the ORed node,
   // assign it to a referenced node.
   IF(token.Type != Or)
      THEN
         *node = ChildNode;
         return;
      END
   *node = new OredNode();
   ((OredNode*)*node) -> Children.push_back(ChildNode);
   END
   ...
   The remaining logic is here
   ...
END



FUNCTION ParserGenerator::Term
        (GenericCFGNode** node, bool reachable)
BEGIN
   *node=NULL;
   IF(token.Type == Eps)
   THEN
   ...
   Eps logic is here
   ...
   ELSE
      bool ResolverExists = false;
      IF(token.Type == If)
      THEN
         ...
         Resolver logic is here
         ...
      END
   END

   IF(Token is in the First Set of factor)
   THEN
      GenericCFGNode* child;
      Factor(&child, reachable);
      IF(!ResolverExists)
      THEN
         IF(Token is not in the First Set of factor)
         // If the only child of anded node,
         // assign it to a referenced node
         THEN
            *node = child;  // Assign referenced node
            return;
         END
         *node = new AndedNode();
      END
      if(child != NULL)
         ((AndedNode*)*node) -> Children.push_back(child);
   END
   ...
   Remaining logic is here
   ...
END




FUNCTION ParserGenerator::Factor
         (GenericCFGNode** node, bool reachable)
BEGIN
   ...
   Factor logic is here
   ...
END
```

This function assigns a node directly for terminals, non-terminals, semantic actions, but continues the recursion process on the expression in case of closures, options or parentheses and does not have a clear optimization code.

Gathering

Rules are gathered using the non-terminal on the left-hand-side of the rule. For example, the rules

```
A → B.
A → C.
A → D.
```

are gathered to a single rule with a right-hand-side having a prefix notation of ORed(B, C, D) for the non-terminal A.

The gathering logic is described in the following listing.

```
IF(It's the first rule for the given non-terminal)
BEGIN
   // Add the grammar rule and assign it to the non-terminal
   Expression(&Rule->RHS, reachable);
   Rule -> locations.push_back(loc);
   Grammer.push_back(Rule);
END
ELSE
      GenericCFGNode* RuleNode;
      Expression(&RuleNode, reachable);
      ...
      Code for ORing the current node with the current rule of the
      LHS non-terminal and assigning the result to the rule of this
      non-terminal
      ...
END
```

Building the Tree

The tree is built using the *Expression*, *Term* and *Factor* functions. *Expression* makes an *OredNode* if there exists OR(s) between at least two terms. *Term* function makes an *AndedNode* if there exists two or more ANDed factors. *Factor* function has no more than one child adding just one node in this process.

Expression Function

```
void ParserGenerator::Expression
    (GenericCFGNode** node, bool reachable)
BEGIN
   IF(token is in the First Set of Term)
   THEN
      GenericCFGNode* ChildNode;
      Term(&ChildNode, reachable);
      IF(token.Type != Or) // If a single child exists
      THEN
         *node = ChildNode;
         return;
      END
      *node = new OredNode();
      ((OredNode*)*node) -> Children.push_back(ChildNode);
   END
   while(token.Type == Or) // If more than one child exist,
   BEGIN                   // add children to the Ored Node
      match(Or);
      GenericCFGNode* Child;
      Term(&Child, reachable);
      ((OredNode*)*node) -> Children.push_back(Child);
   END
END
```

Term Function

```
*node = NULL;
IF(token.Type == Eps)
   ...
   Eps logic code
   ...
ELSE
   bool ResolverExists = false;
   IF(token.Type == If) // If there is a resolver
   THEN                 // It must be an ANDed node
      match(If); // Even if a single child exists
      *node = new AndedNode();
      IF(token.Type == Attributes)
      BEGIN
         ((AndedNode*)*node) -> ResolverString = token.Lexeme;
         match(Attributes,
               "Error: Resolver attributes are missing,
                  the valid form is IF(. {ANY} .)",
               false);
         ResolverExists = true;
      END
      IF(token is in the First Set of Factor)
      THEN
         GenericCFGNode* child;
         Factor(&child, reachable);
         IF(!ResolverExist)
         THEN
            IF(Token is not in the First Set of factor)
            THEN  // If one child
               *node = child;
               return;
            END
         *node = new AndedNode();
      END
      IF(child != NULL)
         ((AndedNode*)*node) -> Children.push_back(child);
   END

   // More than one child
   WHILE(token in the First Set of Factor)
   BEGIN
      GenericCFGNode* child; // Add a new child
      Factor(&child,reachable); // To given Anded node
      // This check is just for error handling purposes
      IF(child != NULL)
         ((AndedNode*)*node) -> Children.push_back(child);
   END
END
```

3.6.2.5 Syntax Error Detection

This is supported by the `match` function that deals with many variables as number of braces, brackets and square-brackets to detect any non-balancing, if exists.

```
void ParserGenerator::match(
   TokenType expected, // Type of expected token
   tstring ErrorMsg, // Error message to store if there exists a type
                     // mismatch
   bool Resume) // In case that an error exists,
                // is an advance to the next token needed?
{
   ...
   Logic for balancing braces, brackets and square-brackets
   ...

   // If the current token type is as expected advance to the
   // next token, where token is the current token
   if (token.Type == expected)
   {
      token = la1; // la1 is the first lookahead
      la1 = la2;   // la2 is the second lookahead
      la2 = scanner -> GetToken();
   }
   else // An error exists, perform the error action
   {
      onError(ErrorMsg); // Store error message
      HasErrors = TRUE;  // Mark grammar as has errors
      if (Resume)        // If advancing on errors is allowed
      {
         token = la1; // Advance to the next token
         la1 = la2;
         la2 = scanner -> GetToken();
      }
   }
}
```

As described in the previous code, when the `match()` function detects an error it marks the error using `OnError()` function that stores the error in an internal data structure with the associated location (i.e. row number, column number…).

```
void ParserGenerator::onError(tstring errorMsg)
{
   // Store the error
   FileErrors[token.LineNo][token.ColNo].push_back(errorMsg);
   NumberOfErrors++; // Increment the errors counter

   // If the number of errors exceeds a certain threshold
   if(NumberOfErrors >= 1000)
   {
      cout<<"Error: Too many errors!"<<endl;
      exit(1); // Exit unsuccessfully
   }
}
```

In the previous code, the `FileErrors` (a `ParserGenerator` data member) is defined as

```
map<int, map<int, list<tstring> > > FileErrors;
```

where the first integer is the line number, the second is the column number, and `list<string>` is used to store the errors with their corresponding line number and column number.

On the call of the `match` function, only the expected token, "message if error" and "advance on errors" parameters are passed. For example,

```
match(Equal, "Error: Equal Sign Missing", false);
```

is used to match the *equal* token, store passed message if mismatch exists, and not to advance on mismatch.

3.7 Syntactic Analyzer Generator Back-End (SAG-BE)

3.7.1 Code Generation Internals - RD Parser Generator

The code generation part in the parser generator (either the LL(1) or Recursive-Descent) is designed and implemented in a way that permits extensibility. It is very easy to extend the parser to generate in a new language by only implementing a well-defined interface called `ICodeGenerator` which abstracts the core of the parser generator from code generation.

The `ICodeGenerator` interface for the recursive-descent parser generator is defined as follows:

```
class ICodeGenerator
{
public:
   void virtual GenerateCode( ParserGenerator* parser ) = 0;
   void virtual OrGenerator( OredNode* node ) = 0;
   void virtual ClosureGenerator( ClosureNode* node ) = 0;
   void virtual OptionalGenerator( OptionNode* node ) = 0;
   void virtual AndGenerator( AndedNode* node ) = 0;
   void virtual SemActionGenerator( SemActionNode* node ) = 0;
   void virtual TerminalGenerator( TerminalNode* node ) = 0;
   void virtual NonTerminalGenerator( NonTerminalNode* node ) = 0;
protected:
    ofstream DefinitionFile;
    ParserGenerator* Parser;
};
```

In the current version, three classes implement the `ICodeGenerator` interface: `CPlusPlusGenerator`, `CSharpGenerator` and `JavaGenerator`. These classes generate code in C++, C# and Java respectively.

We will discuss the `ICodeGenerator` protected members first:

- ***DefinitionFile:*** Every code generator must write to at least one file. This member represents the output file stream through which the generated parser is written to the disk. The `DefinitionFile` member for example creates the .cs file in the `CSharpGenerator` class. Also, in the `JavaGenerator` class, it creates the .java file. For languages that needs more than one file to be generated, the derived class representing the code generator for this language must define these files. For example, the `CPlusPlusGenerator` generates two files (.cpp and .h files). Here, the definition file (.cpp file) is written through the `DefinitionFile` member inherited from the parent abstract class `ICodeGenerator` while the declaration file (.h file) is written to disk through the `CPlusPlusGenerator` class member `DeclarationFile`.
- ***Parser:*** This is a pointer to a parser object for which code is to be generated. This pointer is used by the generator class to access the syntax tree from which code is generated.

The public members of the `ICodeGenerator` are as follows:

- ***`OrGenerator( OredNode* node ):`*** takes an `OredNode` pointer and writes its contents to the stream used in code generation.
- ***`ClosureGenerator( ClosureNode* node ):`*** takes a `ClosureNode` pointer and writes its contents to the stream used in code generation.
- ***`OptionalGenerator(OptionalNode* node ):`*** takes an `OptionalNode` pointer and writes its contents to the stream used in code generation.
- ***`AndGenerator( AndedNode* node ):`*** takes an `AndedNode` pointer and writes its contents to the stream used in code generation.
- ***`SemActionGenerator( SemActionNode* node ):`*** takes a `SemActionNode` pointer and writes its contents to the stream used in code generation.
- ***`TerminalGenerator( TerminalNode* node ):`*** takes a `TerminalNode` pointer and writes its contents to the stream used in code generation.
- ***`NonTerminalGenerator( NonTerminalNode* node ):`*** takes a `NonTerminalNode` pointer and writes its contents to the stream used in code generation.
- ***`GenerateCode( ParserGenerator* parser ):`*** this is the most important function which is called firstly to begin code generation. This function takes a pointer to a parser. By passing a pointer to a parser, the code generation class will have access to all the sections found in the grammer input file besides the most

important member, *Grammer*, which is a list of the production rules each of which consists of an object of a derived class from *GenericCFGNode*. Objects of classes inherited from the *GenericCFGNode* class contain a fuction called *GenerateCode()* which overrides the virtual function *GenerateCode()* of the *GenericCFGNode* base class. This virtual function is to be called from *ICodeGenerator.GenerateCode()* function. Depending on the type of the node, a specific function is called which calls the suitable function in *ICodeGenerator*. For example, if *ICodeGenerator* is now processing a *GenericCFGNode* object which is a *NonTerminalNode* object, then on calling *node.GenerateCode(this)* (where *this* is the pointer of the calling *ICodeGenerator*) then the *NonTerminalNode.GenerateCode()* function will be called due to the rules of virtual functions. Finally, the *NonTerminalNode.GenerateCode()* function will call *ICodeGenerator.NonTerminalGenerator()* passing the *NonTeminalNode* object to be used in generating the code corresponding to this *NonTeminalNode*. This is a very elegant usage which illustrates the beauty of virtual functions.

In what follows, we show the class diagram of the code generation part of the recursive descent parser generator targeting the languages C++, C# and Java:

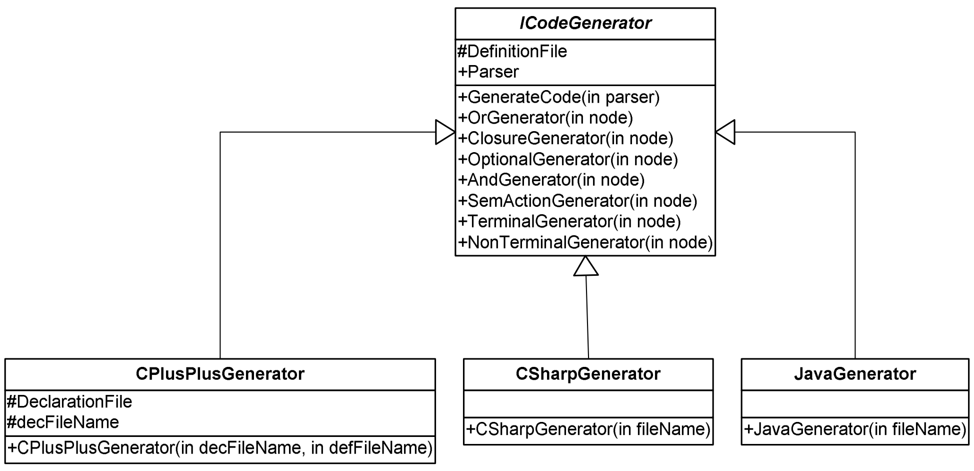

ICodeGenerator
#DefinitionFile
+Parser
+GenerateCode(in parser)
+OrGenerator(in node)
+ClosureGenerator(in node)
+OptionalGenerator(in node)
+AndGenerator(in node)
+SemActionGenerator(in node)
+TerminalGenerator(in node)
+NonTerminalGenerator(in node)
CPlusPlusGenerator
#DeclarationFile
#decFileName
+CPlusPlusGenerator(in decFileName, in defFileName)
CSharpGenerator
+CSharpGenerator(in fileName)
JavaGenerator
+JavaGenerator(in fileName)

Figure III-5: RD Parser Generator
Code Generation Class Diagram

3.7.2 Code Generation Internals – LL(1) Parser Generator

The code generation of the LL(1) parser generator is simpler than the code generation of the recursive-descent parser generator. This is due to the fact that in the LL(1) code generation we use the LL(1) table (whose details were demonstrated in the LL(1) parser section) which is contained in the parser object. So, instead of traversing the simple trees as in recursive-descent code generation; we only translate the LL(1) table into a data structure in the output code of the generated parser with the implementation of the LL(1) parsing algorithm in the target language (C++, C#, Java).

The *ICodeGenerator* interface for the LL(1) parser generator is defined as follows:

```
class ICodeGenerator
{
public:
   void virtual GenerateCode( ParserGenerator* parser ) = 0;

protected:
   ofstream DefinitionFile;
   ParserGenerator* Parser;
};
```

We will discuss the *ICodeGenerator* protected members first:

- ***DefinitionFile:*** Every code generator must write to at least one file. This member represents the output file stream through which the generated parser is written to the disk. The *DefinitionFile* member for example creates the .cs file in the *CSharpGenerator* class. Also, in the *JavaGenerator* class, it creates the .java file. For languages that needs more than one file to be generated, the derived class representing the code generator for this language must define these files. For example, the *CPlusPlusGenerator* generates two files (.cpp and .h files). Here, the definition file (.cpp file) is written through the *DefinitionFile* member inherited from the parent abstract class *ICodeGenerator* while the declaration file (.h file) is written to disk through the *CPlusPlusGenerator* class member *DeclarationFile*.
- ***Parser:*** This is a pointer to a parser object for which code is to be generated. This pointer is used by the generator class to access the syntax tree from which code is generated.

The public members of the *ICodeGenerator* are as follows:

- ***GenerateCode(ParserGenerator* parser):*** This function is called to generate the LL(1) table as a data structure using the LL(1) parsing algorithm (referred to as the LL(1) driver).

The *ICodeGenerator* is the interface that should be implemented by developers extending our parser generator tool to generate code. Currently, three languages are supported for code generation: C++, C# and Java. Specific to our implementation for the generators of these three languages; the classes *CPlusPlusGenerator*, *CSharpGenerator* and *JavaGenerator* inherit also from a class called *ISpecificGenerator* as these three classes share three functions that are used internally in code generation. Here is the declaration of the *ISpecificGenerator* and a description for its three members:

```
class ISpecificGenerator
{
public:
   void generateUserFunctions();
   void initializeParser(); //Initialize the LL(1) table and the delegates
   void generateLL1Controller();
};
```

- ***`generateUserFunctions:`*** Every block of code embedded in the grammar is generated as a fuction by the *`generateUserFunctions()`* where each generated fuction is called in its correct time while parsing.
- ***`initializeParser:`*** This function initializes the LL(1) table to that of the parser and initializes pointers (for C++) or delegates (for C#) to the generated user functions to be called while parsing (to run the user code embedded in the grammar). In the Java generated parsers, we give a unique number to each function and when it is time for function *`X`* to be called *(`X` is an integer representing the id of the function)*, a switch statement is made on this number to call the corresponding function.
- ***`generateLL1Controller:`*** This function generates the implementation of the LL(1) parsing algorithm in the target language.

This is the class diagram of the code generation part of the LL(1) parser generator targeting the languages *ParSpring* supports in its current version; C++, C# and Java:

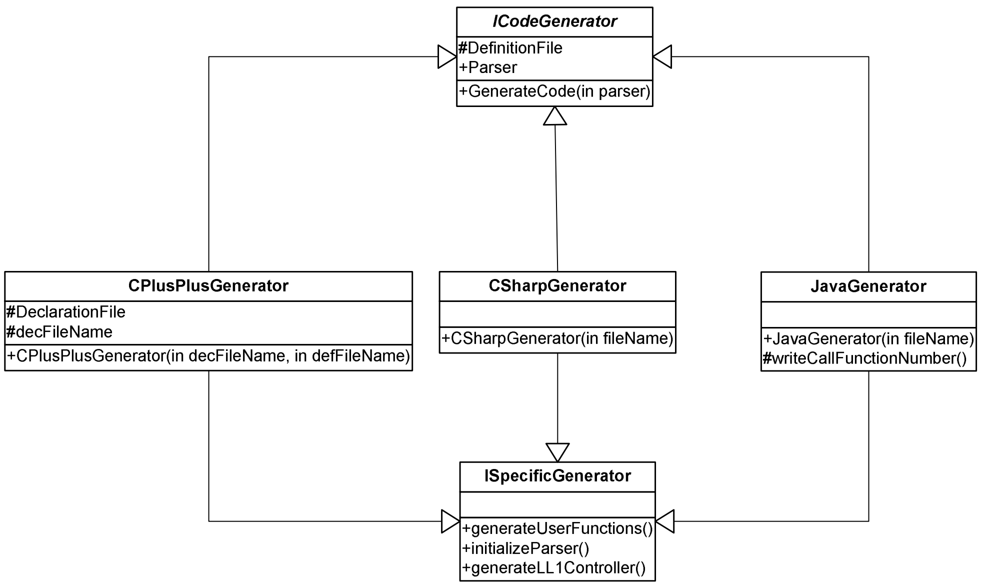


Figure III-6: LL(1) Parser Generator Code Generation Class Diagram

3.8 Helper Tools

Sometimes developers write grammars that contain LL(1) conflicts and it's such a tedious mission to convert them manually into grammars without conflicts by using algorithms like left recursion removal and left factoring that it's worth automating the process. In this chapter we discuss both tools in full detail.

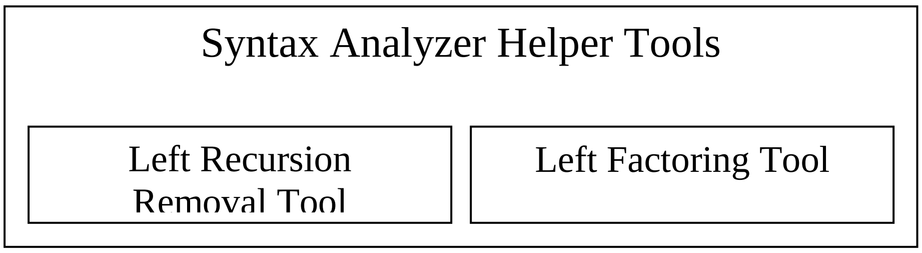


Figure III-7: Syntax Analyzer Helper Tools

3.8.1 Left Recursion Removal

Left recursion removal is an algorithm commonly used to make operators left associative and to eliminate LL(1) conflicts emerging due to left recursive rules. Taking the simple expression CFG

```
exp → exp addop term | term
```

as a simple example of left recursion removal, the rule is split into two rules:

```
exp  → term exp1
exp1 → addop term exp1 | Eps.
```

It's noteworthy that these tools are more important in the case of LL(1) parsers than in their recursive-descent counterparts; this is because the recursive-descent parser generator accepts its input grammar in the EBNF notation that solves repetition and choice problems, however the LL(1) parser generator accepts its input grammar in the BNF notation.

3.8.1.1 The Input

The input of this tool is considered to be a valid LL(1) parser specification file, if the file contains errors the tool will inform the developer that the file contains errors and will exit.

3.8.1.2 The Output

The output is a new specification file containing the left-recursion-free grammar, which may be the same as the input grammar if no left-recursion originally existed. The figure above illustrates the skeleton of the left recursion removal tool.

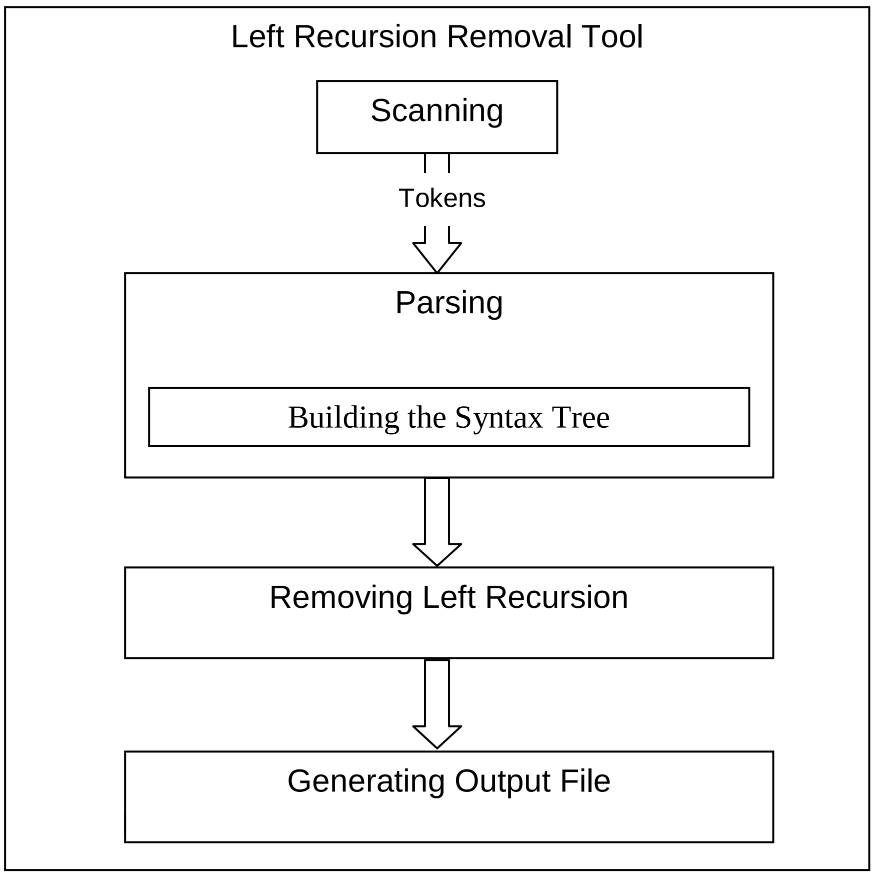


Figure III-8: Left Recursion Removal Tools

Some phases (such as the scanning and the parsing phase) illustrated above have been already explained, so we will skip these two phases and we will focus on the "Removing Left Recursion" and "Generating Output File" phases.

3.8.1.3 The Process

This process performs left recursion removal on the current grammar (represented as nodes in memory) and generates a new grammar after eliminating left recursion from the old one. The logic of the operations to be performed is illustrated in the following pseudo code.

```
RemoveLeftRecursion(Non-Terminal LHS) returns
BEGIN
      // Temp_NonTerminals store new generated non-terminals
      Map<tstring, NonTerminalEntry> Temp_NonTerminals

      FOREACH(NonTerminal NT in NonTerminals)
      BEGIN
            FOREACH(NonTerminal NTi in NonTerminals from the
                    beginning to NT) // Not including NT
            BEGIN
                  NT.Rule.RHS = NT.Rule.RHS.ReplaceIfPosible(NTi)
            END_FOREACH

            NT.Rule = ILRemoval(NT.Rule, &Temp_nonTerminals);
            // ILRemoval function makes an immediate left recursion
            // Removal adding rules to the new grammar
      END_FOREACH

      FOREACH(NonTerminal NT1 in Temp_nonTerminals)
      BEGIN
            Add NT1 to NonTerminals Map
      END_FOREACH

      RETURN LeadToTerminal
END
```

As exposed in the previous logic, the node has added functionality – the `ReplaceIfPossible()` function; which is implemented for all node types, besides the `ILRemoval()` function.

ReplaceIfPossible() Function

1) OredNode

The returned node in the case of an OredNode is a big Or Node between children `ReplaceIfPossible()` call, if the `Child` call returned an OredNode just children are added not the OredNode.

```
OredNode::ReplaceIfPossible(non-terminal NTi) returns node
BEGIN
      OredNode ReturnedNode = New OredNode

      FOREACH(Child Ch in Children)
      BEGIN
            Node N = Ch.ReplaceIfPossible(NTi)
            IF (N.Type = OredNode)
            THEN
                  Add each child in N to ReturnedNode children
            ELSE
                  Add Node N to ReturnedNode Children
            END_IF
      END_FOREACH

      RETURN ReturnedNode;
END
```

2) Anded Node

Replacement is done if left recursion exists, each existence of a node referring to `NTi` is replaced with mapped Rule Right Hand Side node and then formatting them in BNF notation, as illustrated in the logic below.

```
AndedNode::ReplaceIfPossible(non-terminal NTi) returns node
BEGIN
      AndedNode ReturnedNode = New AndedNode
      SELECT(Child Ch in Children;
              Ch is the Left Recursive and Equal NTi)
      BEGIN
            Replace Ch Node with the definition of its Rule.
            Formatting it and store it into ReturnedNode
      END_SELECT

      RETURN ReturnedNode
END
```

The following is an example to illustrate this functionality:

```
Production   : A → B a A1 | c A1
Current Rule : B → B b | A b | d
Replacement  : B → B b | (B a A1 | c A1) b | d
Formatting   : B → B b | B a A1 b | C A1 b | d
```

3) Terminal Node & SemAction

No replacement of these nodes is done; they just return a copy of themselves.

```
ReplaceIfPossible(non-terminal NTi) returns node
BEGIN
      RETURN this.Clone()
END
```

4) NonTerminal Node

A non-terminal node returns a copy of itself except when it refers to the passed non-terminal; in which case the RHS of the passed non-terminal rule is returned.

```
NonTerminalNode::ReplaceIfPossible(non-terminal NTi) returns node
BEGIN
      IF (this refers to NTi)
      THEN
            NTi.Rule.RHS.Clone()
      ELSE
            RETURN this.Clone()
      END_IF
END
```

ILRemoval() Function

This procedure makes **I**mmediate **L**eft (**IL**) recursion for a non-terminal if necessary.

```
ILRemoval(Rule r, Map* Temp-NonTerminals) returns rule
BEGIN
      Split r.RHS into two types
            (one left-recursive and one non-left-recursive)

      OredNode N1 = r.RHS.LeftRecursiveNode
                        (without recursive non-terminal)
      OredNode N2 = r.RHS.Non-LeftRecursive Node

      Let NT be a new non-terminal
      Let R1 new rule with r1.LHS
      Let R2 new rule with NT as LHS

      IF (N2.ChildrenCount = 0)//No possible immediate left recursion
      THEN
            Add r.Clone() To New_Grammar
            RETURN r.RHS
      ELSE
            Add NT to Temp-NonTerminals
            R1.RHS = N1.Children && NT
            R2.RHS = N2.Children && ( NT | Eps )
            Add R1, R2 to New_Grammar
      END
END
```

3.8.1.4 Generating the Output File

This function generates the new file containing the specification of the grammar after eliminating left recursion.

```
OutputFile()
BEGIN
      Output Options, Terminals, TopOfDeclaration, TopOfDefinition,
            ButtomOfDeclaration, BottomOfDefinition sections as-is
            into the new file
      Output The Word "Grammar"

      Rule R = Start Symbol Rule
      R.RHS.Output() //Node function that prints to the file

      FOREACH(Rule R in New_Grammar)
      BEGIN
            IF(R.LHS does not refer to start symbol)
            THEN
                  Output R.LHS
                  Output "->"
                  R.RHS.Output()
                  Output "."
                  Output "\n"
            END
      END
END
```

As mentioned in the logic above, a function is implemented in each node to output its contents to the file.

1) Ored Node

```
OredNode::Output()
BEGIN
      FOREACH(Child Ch in Children)
      BEGIN
            Ch.Output()
            IF(Ch is not the last child)
            THEN
                  Output " |"
            END_IF
      END_FOREACH

      RETURN FS;
END
```

2) Anded Node

```
AndedNode::Output()
BEGIN
      IF(Resolver)
      THEN
            Output Resolver
      END_IF

      FOREACH(Child Ch in Children)
      BEGIN
            Ch.Output()

            IF(Ch is not the last child)
            THEN
                  Output " "
            END
      END_FOREACH

      RETURN FS;
END
```

3) Terminal Node

```
TerminalNode::Output()
BEGIN
      Output TerminalNode.Name
END
```

4) NonTerminal Node

```
NonTerminalNode::Output()
BEGIN
      Output NonTerminalNode.Name

      IF(Attributes)
      THEN
            Output Attributes between (.  .)
      END_IF
END
```

5) SemAction Node

```
SemActionNode::FirstSet() returns BitSet
BEGIN
      Output semantic action string between <.  .> terminal Name
END
```

3.8.2 Left Factoring Tool

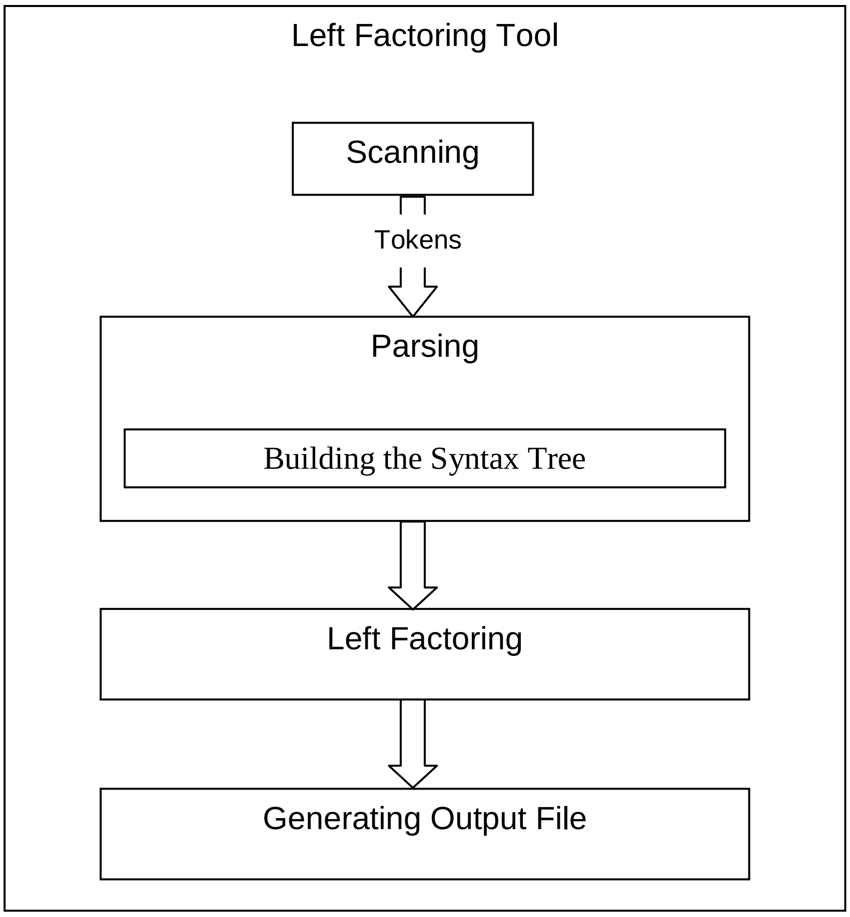


Figure III-9: Left Factoring Tool

Left factoring is an algorithm required when two or more grammar rule choices (productions) share a common prefix string. For example;

```
Before Left-Factoring : A  → B C | B D
After  Left-Factoring : A  → B A1
                        A1 → C | D
```

3.8.2.1 The Input

The input of this tool is considered to be a valid LL(1) parser specification file. If the file contains errors the tool will inform the developer that the file contains errors and will exit.

3.8.2.2 The Output

The output is a new specification file containing the left-factored grammar, which may be the same as the input grammar if no common prefixes exist.

Some phases (such as the scanning and the parsing phase) illustrated above have been already explained, so we will skip these two phases and we will focus on the "Left Factoring" and "Generating Output File" phases.

3.8.2.3 The Process

This process performs left factoring on the current grammar (represented as nodes in memory) and generates a new grammar after left factoring the old one. The logic of the operations to be performed is illustrated in the following pseudo code.

```
Left Factoring ()
BEGIN
      BOOL Changed = TRUE
      WHILE (Changed)
      BEGIN
            Changed = FALSE

            FOREACH(NonTerminal A in NonTerminals)
            BEGIN
                  Let F be a prefix of maximal length shared by
                        two or more production choices for A

                  IF(F != Eps)
                  THEN
                        Let A → F₁ | F₂ | F₃ ... | Fₙ.
                              be all production choices for A
                        Suppose F₁, F₂, ..., Fₖ share F so that
                           A → F B₁|F B₂|...|F Bₖ|Fₖ₊₁|...|Fₙ.
                           The Bⱼ's share no common prefix, and the
                           Fₖ₊₁ | ... | Fₙ do not share F.
                        Replace rule A → F₁ | F₂ | F₃ | ... | Fₙ.
                           by adding two new rules in New_Grammar
                           Map:
                              A  → F A₁ | Fₖ₊₁ | ... | Fₙ.
                              A₁ → B₁ | B₂ | ... | Bₖ.
                  END_IF
            END_FOREACH
      END
END
```

As exhibited in the above logic, the algorithm just extracts common factors in the given production choices and perform the factorization process for each non-terminal rule if possible. For example, consider the grammar:

A → a b d c **A** | a b d c **B D** | a b c d **C D** | a b c d **A B**.
B → b **B** | Eps.
C → c **C** | Eps.
D → d **D** | Eps.

Considering symbols in bold as non-terminals and non-bold symbols as terminals (i.e. defined in the *Tokens* section), if this grammar is applied as an input to the algorithm, in the first loop *a b d c* is detected as the prefix with maximal length shared in the first rule, while other rules has no common prefixes, and the changes the happen to the first rule are:

A → a b d c **A_1** | a b c d **C D** | a b c d **A B**.
A_1 → **A** | **B D**.

In the second loop, the prefix with maximal length detected is *a b c d* for the first rule while other rules have no common prefixes, and the rule changes to:

$\mathbf{A} \rightarrow$ a b d c $\mathbf{A_1}$ | a b c d $\mathbf{A_2}$.
$\mathbf{A_2} \rightarrow$ **C D** | **A B**.

In the last loop, *a b* is detected as the prefix with maximal length, so it becomes:

$\mathbf{A} \rightarrow$ a b $\mathbf{A_3}$.
$\mathbf{A_3} \rightarrow$ d c $\mathbf{A_1}$ | c d $\mathbf{A_2}$.

The left-factored grammar after all changes take effect is listed below.

$\mathbf{A} \rightarrow$ a b $\mathbf{A_3}$.
$\mathbf{A_3} \rightarrow$ d c $\mathbf{A_1}$ | c d $\mathbf{A_2}$.
$\mathbf{A_2} \rightarrow$ **C D** | **A B**.
$\mathbf{A_1} \rightarrow$ **A** | **B D**.

Part III

Conclusion and Future Work

1. LEXcellent

1.1 Summary

We can summarize the features and the capabilities offered by *LEXcellent* as follows:

- The developer interacts with *LEXcellent* via providing the specification of his tokens in a text file, together with the actions to be performed by the scanner when a given token is encountered.
- The format of the input file provides the developer with the capability to declare macros, so as to simplify his regular definitions. It allows him to define specific pieces of code to be inserted in the generated code files in the positions needed.
- The format of the *LEXcellent* input file is closely similar to the format of the *LEX* input file. Such a similarity makes it easier for the developers to learn the *LEXcellent* format since *LEX* is a well known tool by most compiler developers.
- *LEXcellent* converts the regular definitions stated in the input file into an NFA through a very efficient process. The Thompson construction of *LEXcellent* is characterized by a special memory management system that was developed specifically for that purpose.
- The NFA is converted into a DFA through the well known Subset Construction algorithm. However, we have made a contribution to the Subset Construction algorithm making it more efficient than the generic one published in most of the classic compiler texts. After such modifications have been made, the resulting DFA is almost ideally optimized to the extent that only a small effort is needed in the forthcoming optimization phase.
- The DFA is then minimized to optimize its memory size.
- The optimized DFA then undergoes a compression process to further optimize the memory size. *LEXcellent* gives the developer two compression techniques to choose from (besides one of them – the *Pairs* compression technique – has two variations, which makes them effectively three), besides the choice not to compress at all. Another choice, and possibly the most useful one, is to let *LEXcellent* choose the best compression technique for you, based on the compression ratio criterion.
- *LEXcellent* can generate the lexical analyzer using any of the three languages supported in its current version: C++, C# and Java. Such languages where chosen from among all available languages since they are the most widely used. *LEXcellent*, however, can be easily extended to support more languages with a little maintenance cost.
- The lexical analyzer generated by *LEXcellent* supports the Unicode **[34]** encoding system, thus, it supports an uncountable number of languages, including Arabic. This feature is missing in many other similar tools.

1.2 Future Work

As a future work, *LEXcellent* is expected to undergo the following enhancements:

- Supporting more output languages. Besides C++, C# and Java we can support other languages easily.
- Supporting other input file formats so as not to restrict the compiler developer to the *LEX* input file format.
- Providing more compression techniques besides the Pairs and the Redundancy Removal techniques currently available.
- Adding more error and warning messages as reported by the prospective users of *LEXcellent*.

2. ParSpring

2.1 Summary

We can summarize the features and the capabilities offered by *ParSpring* as follows:

- *ParSpring* takes as an input a text file describing the parser to be generated. The main section in the input file is the *Grammar* section which contains the CFG of the desired parser. The grammar mainly consists of terminals and non-terminals. The terminals are declared firstly in the *Tokens* section. The generated parser expects from the used scanner to pass it a number corresponding to a token declared in the *Tokens* section of the input specification file.
- The input grammar must be left-factored and left-recursion free.
- *ParSpring* provides warnings and errors reporting problems in the input file, if any.
- We provide tools to left factor CFGs and remove left recursion from them.
- The user is able to embed code within the grammar productions. These lines of code are guaranteed to be executed in the right time specified by its position within the production.
- The user is able to use predetermined sections by writing code in them which is guaranteed to be generated in the output parser code file according to the description of these sections (*TopOfDeclaration*, *TopOfDefinition*, *BottomOfDeclaration*, *BottomOfDefinition*) in the input file specification section.
- *ParSpring* generates parsers of two types: recursive-descent and LL(1) parsers.
- The generated parser could be generated in any one of three famous languages supported in version 1.0: C++, C# and Java.

2.2 Future Work

Generally speaking, the way of making parser generators more powerful is to make them capable of accepting less-restricted grammars as well as generating parsers in many languages (Python, Delphi, …) as well as of different types(LALR, LR(1), …).

So, in the future, it's expected that *ParSpring* will be enhanced to support:

- Generating LALR(1) parsers.
- Generating LR(1) parsers.
- Generating LR(n) parsers, which is the Nirvana of any parser generator.
- Generating parsers in more languages (like Delphi and Python).
- Enhancing error handling in the generated parser.

3. The General Conclusion

A compiler writer's mission becomes a nightmare once manual implementation is decided. Developers get bored repeating the same tedious work writing scanners and parsers; essentially "reinventing the wheel" every time a new product is to be coded. The manual process is extremely time consuming and highly error-prone. Nowadays, manual compilers are only written in compiler undergraduate courses as a kind of training, but as long as "real" applications are regarded, tools must be used to facilitate the process.

Using CCW, *LEXcellent* and *ParSpring* provides the developer with numerous advantages, including the ability of generating parsers using more than one technique, using different programming languages, and parsing endless languages via the Unicode **[34]** support feature. The graphical user interface provided simulates actual IDEs intended for developing complete applications. By integrating the previous advantages, our tool has virtually overcome all the difficulties encountered in the compiler writing process and the drawbacks found in the available tools, given its extensible architecture.

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URLs

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[9] http://parsetec.com/lrgen
[10] http://www.gnu.org/software/bison/
[11] http://www.gnu.org/software/flex/
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[32] http://www.gca.org/papers/xmleurope2001/papers/html/s07-3.html
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[34] http://www.unicode.org/
[35] http://www.codeproject.com/vcpp/stl/upgradingstlappstounicode.asp
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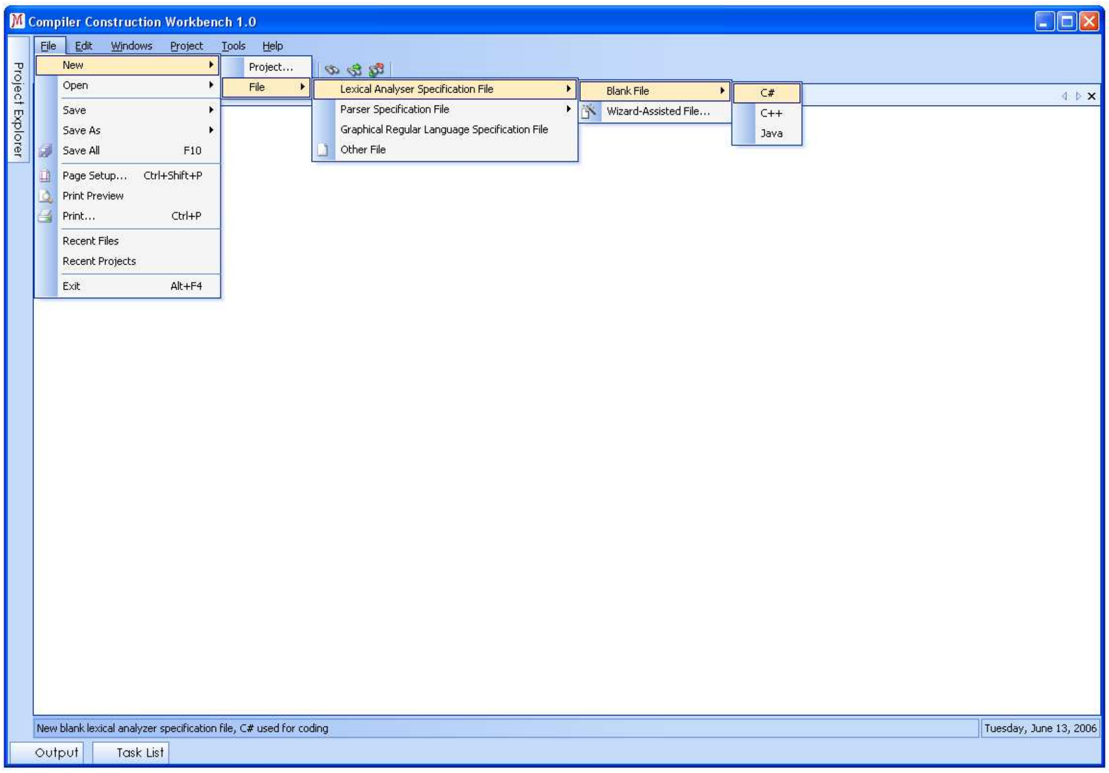
Appendices

A. User's Manual

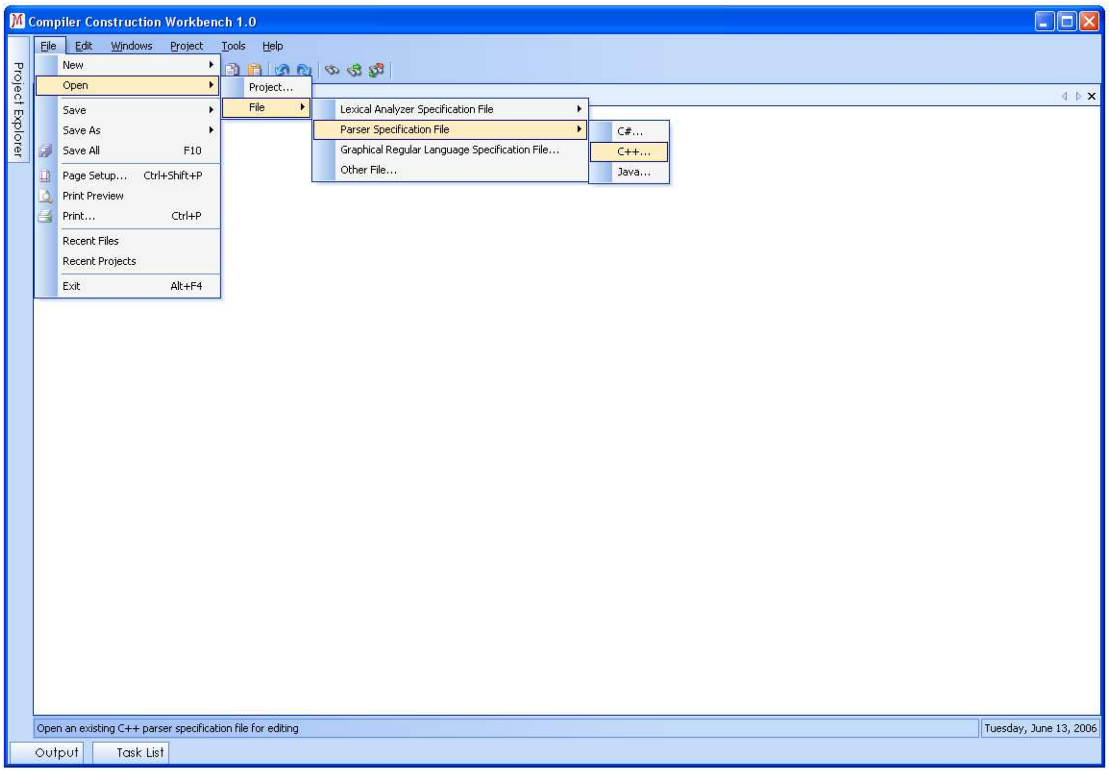
This user manual is mainly dedicated to the prospective users of CCW (Compiler Construction Workbench) in its first version. We list the functionalities of the menus, together with their hierarchical arrangement. Then the tool bar is depicted in an independent figure. The dockable windows are illustrated.

We depend heavily on the user viewing the accompanying tutorials, and that's why the manual here is relatively simple. We believe that "an image is worth a thousand words.



New blank lexical analyzer specification file, C# used for coding

Tuesday, June 13, 2006



Open an existing C++ parser specification file for editing

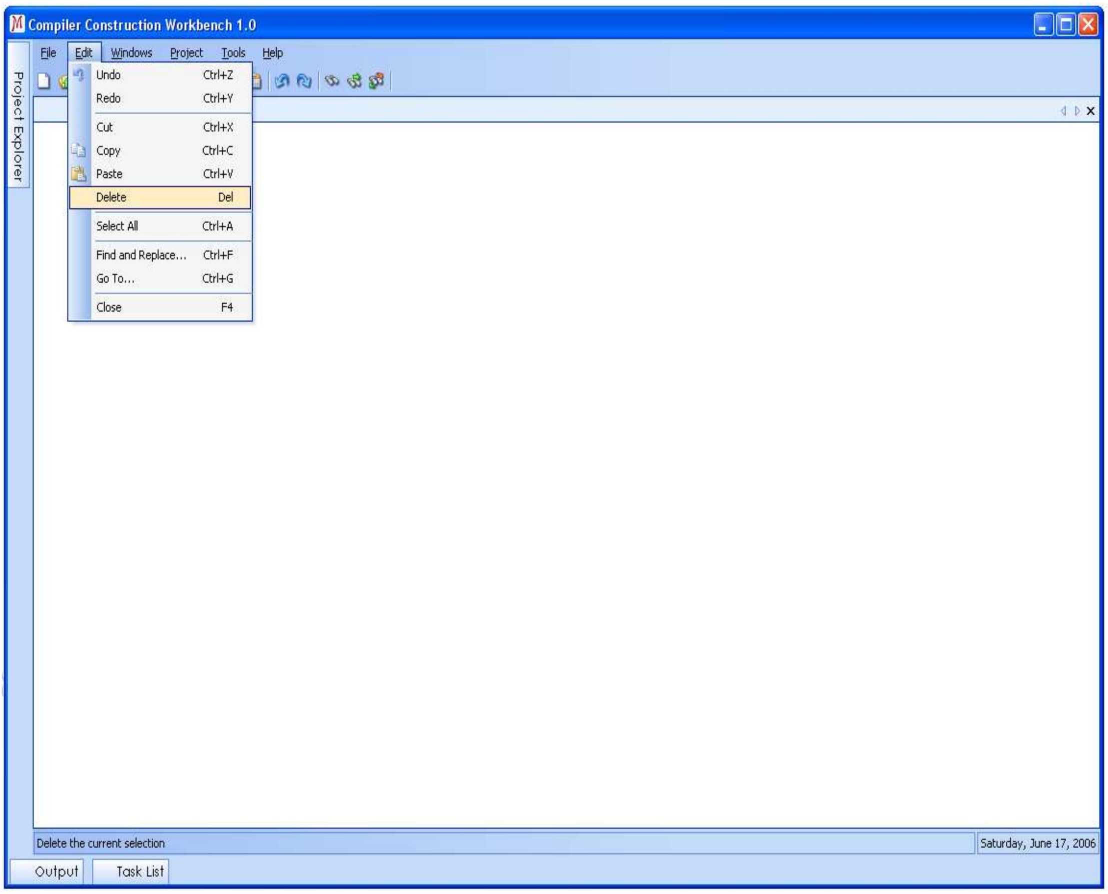
Tuesday, June 13, 2006

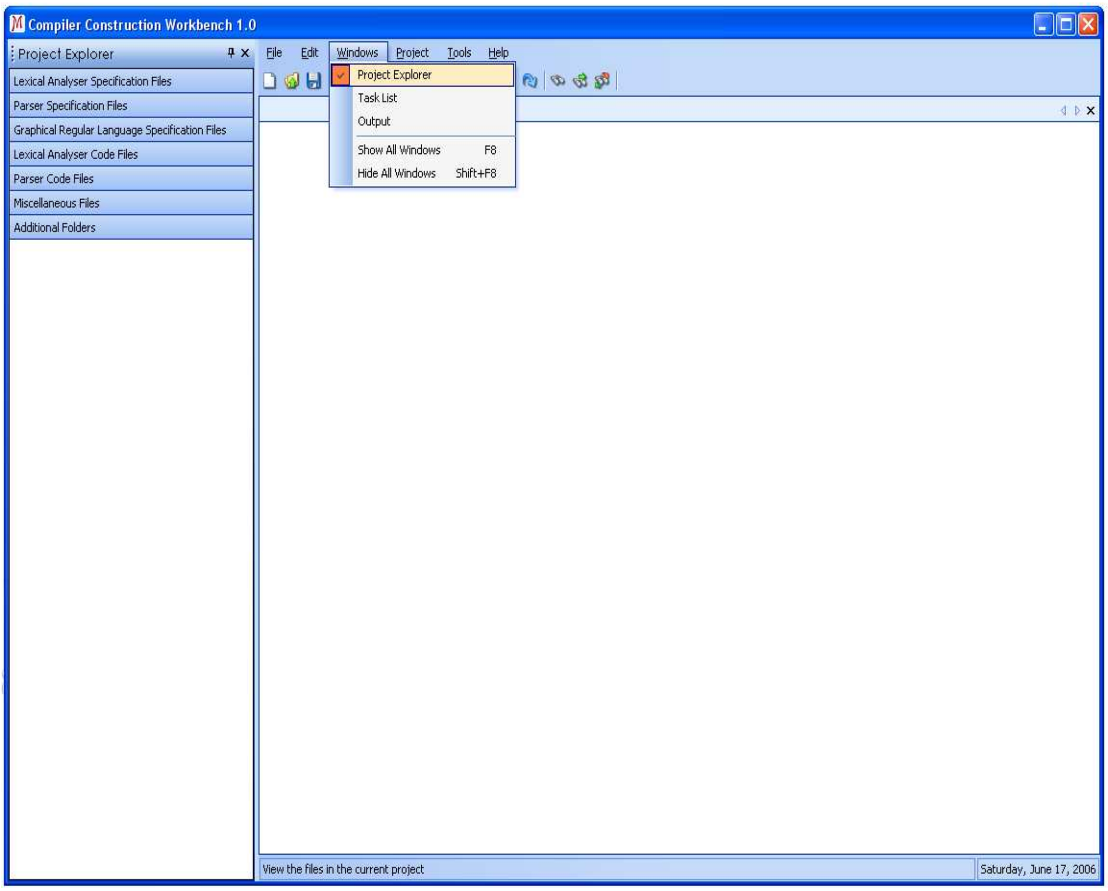
[File] Menu Details

File
Common file operations

- **New**
  Common operations for dealing with new items
  - **Project**
    Create a new project
  - **File**
    Create a new file
    - **Lexical Analyzer Specification File**
      New lexical analyzer specification file
      - **Blank File**
        New blank lexical analyzer specification file
        - **C#**
          New blank C# lexical analyzer specification file
        - **C++**
          New blank C# lexical analyzer specification file
        - **Java**
          New blank C# lexical analyzer specification file
      - **Wizard-Assisted File**
        Use the RegEx builder to create a set of regular expressions
    - **Parser Specification File**
      New parser specification file
      - **Blank File**
        - **C#**
          New blank C# lexical analyzer specification file
        - **C++**
          New blank C++ lexical analyzer specification file
        - **Java**
          New blank Java lexical analyzer specification file
      - **Wizard-Assisted File**
        Use the CFG builder to create a CFG
    - **Graphical Regular Language Specification File**
      New graphical regular language specification file
    - **Other File**
      New file of any type
- **Open**
  Common operations for dealing with existing items
  - **Project**
    Open an existing project
  - **File**
    Open an existing file
    - **Lexical Analyzer Specification File**
      Open an existing lexical analyzer specification file for editing
      - **C#**
        Open an existing C# lexical analyzer specification file for editing
      - **C++**
        Open an existing C++ lexical analyzer specification file for editing
      - **Java**
        Open an existing Java lexical analyzer specification file for editing
    - **Parser Specification File**
      Open an existing parser specification file for editing
      - **C#**

        Open an existing C# parser specification file for editing
    - **C++**
      Open an existing C++ parser specification file for editing
    - **Java**
      Open an existing Java parser specification file for editing
  - **Graphical Regular Language Specification File**
    Open an existing graphical regular language specification file for editing
  - **Other File**
    Open an existing file of any type for editing
- **Save**
  Common operations for saving modified documents
  - **Project**
    Save changes in the current project
  - **File**
    Save changes in the current file
- **Save As**
  Save changes in the current project as a new project without altering the current one
  - **Project**
    Creates a new project as a copy of the current project
  - **File**
    Creates a new file as a copy of the current file
- **Save All**
  Save changes in all open files
- **Page Setup**
  Adjustments before printing
- **Print Preview**
  Preview for WYSIWYG printing
- **Print**
  Print the current document
- **Recent Files**
  A list of the most recently used files
- **Recent Projects**
  A list of the most recently used projects
- **Exit**
  Exit the application


Compiler Construction Workbench 1.0
File
Edit
Windows
Project
Tools
Help
Undo Ctrl+Z
Redo Ctrl+Y
Cut Ctrl+X
Copy Ctrl+C
Paste Ctrl+V
Delete Del
Select All Ctrl+A
Find and Replace... Ctrl+F
Go To... Ctrl+G
Close F4
Project Explorer
Delete the current selection
Saturday, June 17, 2006
Output
Task List


Compiler Construction Workbench 1.0
Project Explorer
Lexical Analyser Specification Files
Parser Specification Files
Graphical Regular Language Specification Files
Lexical Analyser Code Files
Parser Code Files
Miscellaneous Files
Additional Folders
File
Edit
Windows
Project
Tools
Help
Project Explorer
Task List
Output
Show All Windows F8
Hide All Windows Shift+F8
View the files in the current project
Saturday, June 17, 2006

[Edit] Menu Details

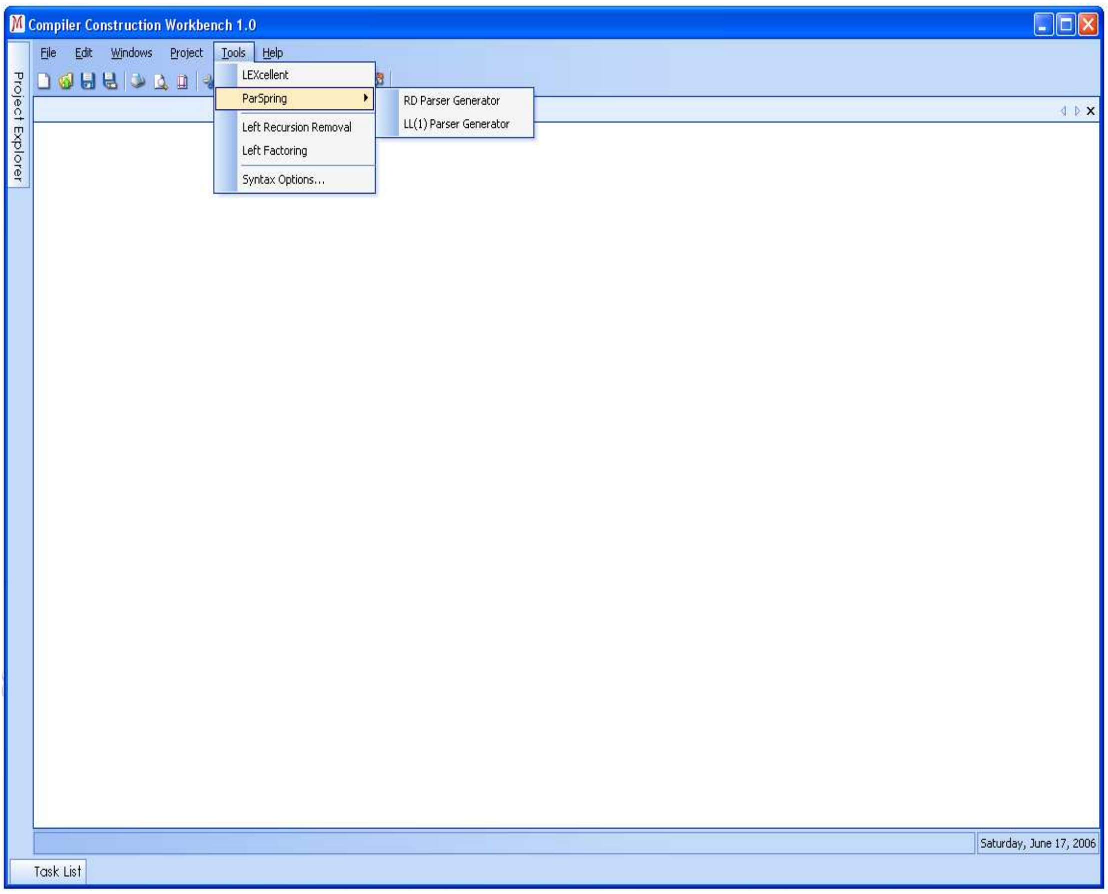
Edit
Common operations for editing in the current file

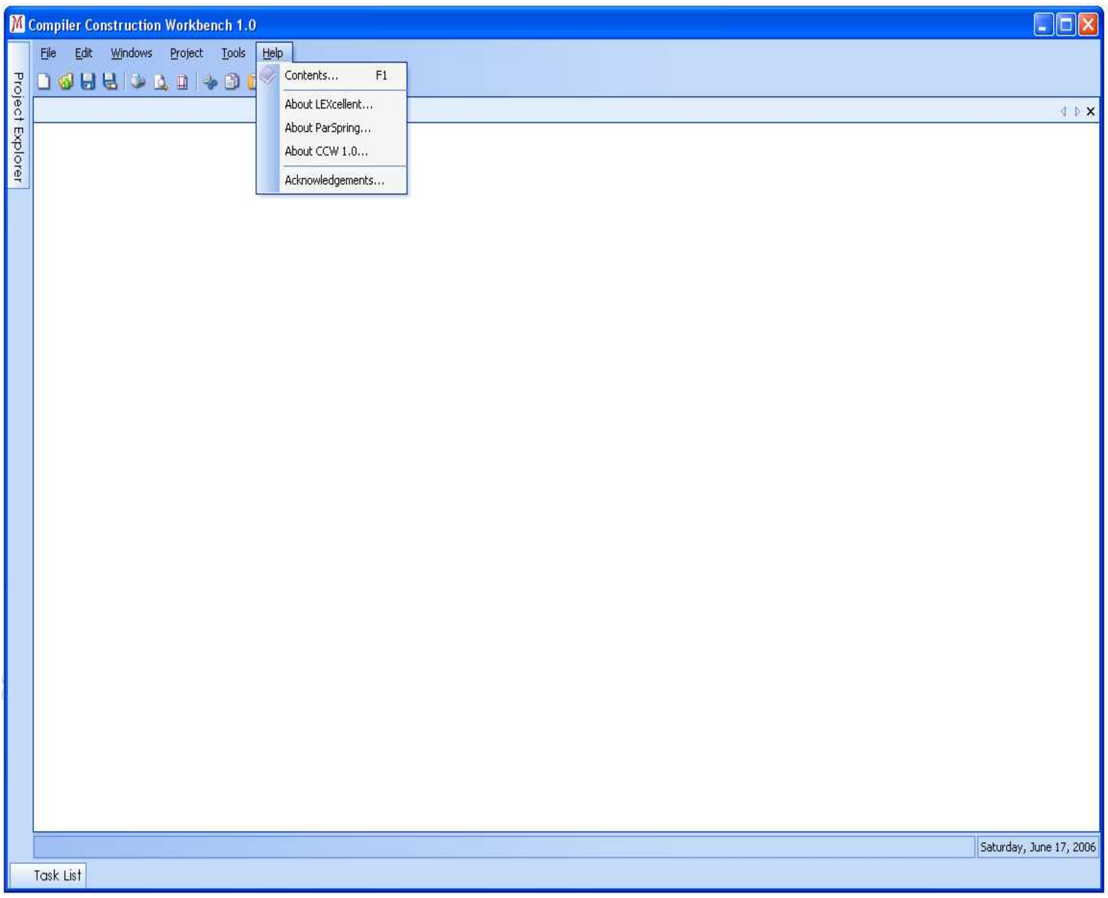
- **Undo**
  Undo the last operation
- **Redo**
  Redo the last operation
- **Cut**
  Cut the current selection into the clipboard
- **Copy**
  Copy the current selection into the clipboard
- **Paste**
  Paste the current contents of the clipboard into the current file, at the position of the caret
- **Delete**
  Delete the current selection
- **Select All**
  Select all the contents of the current file
- **Find and Replace**
  Find and replace strings in the current file
- **Go To**
  Go to a certain line in the current file
- **Close**
  Close the current file

[Windows] Menu Details

Windows
Common windows

- **Project Explorer**
  View the files in the current project
- **Output**
  View the tasks in the current build
- **Task List**
  View the output of the current build
- **Show All Windows**
  Show all dockable windows
- **Hide All Windows**
  Hide all dockable windows


Compiler Construction Workbench 1.0
File
Edit
Windows
Project
Tools
Help
LEXcellent
ParSpring
Left Recursion Removal
Left Factoring
Syntax Options...
RD Parser Generator
LL(1) Parser Generator
Project Explorer
Saturday, June 17, 2006
Task List


Compiler Construction Workbench 1.0
File
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Windows
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Tools
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Contents... F1
About LEXcellent...
About ParSpring...
About CCW 1.0...
Acknowledgements...
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Task List

[Tools] Menu Details

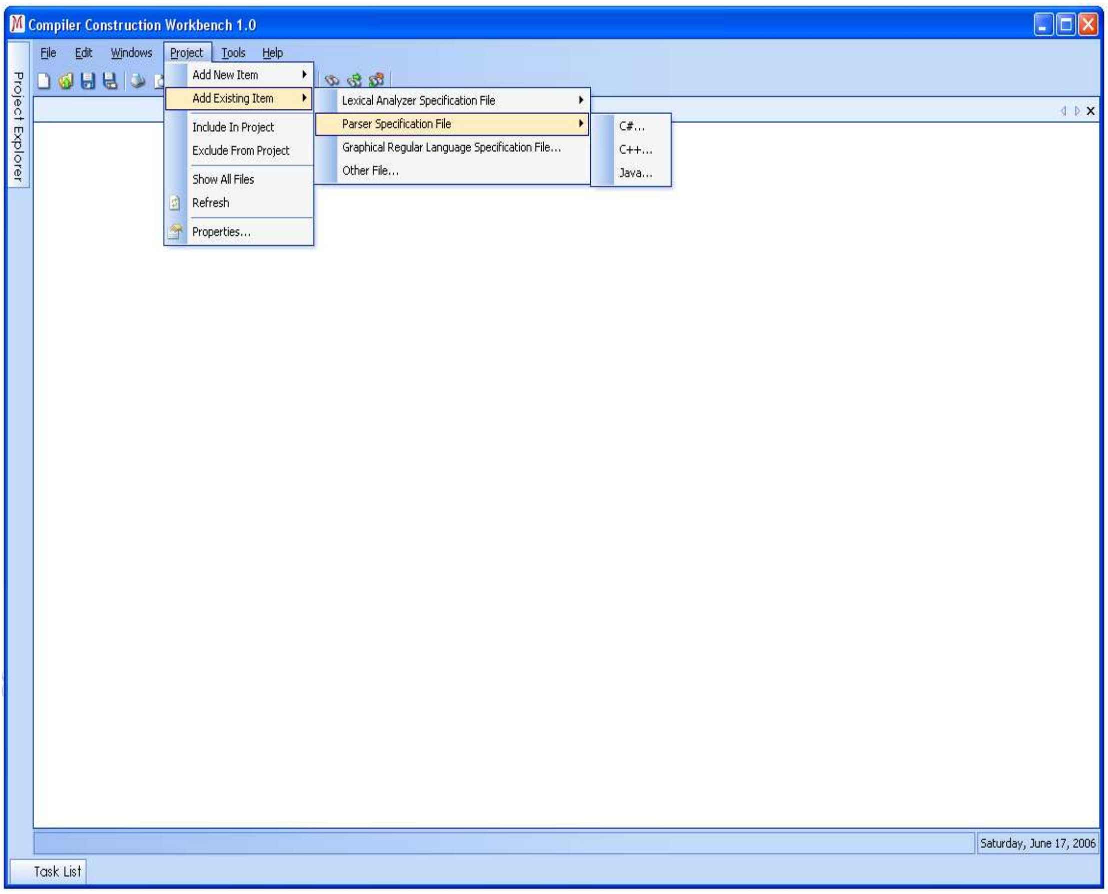
Tools
Helper tools

- **LEXcellent**
  Generate a lexical analyzer
- **ParSpring**
  Generate a parser
  - **LL(1) Parser Generator**
    Generate an LL(1) Parser
  - **RD Parser Generator**
    Generate an RD Parser
- **Left Recursion Removal**
  Remove the left recursion - if exists - from a context-free grammar
- **Left Factoring**
  Left-factor a context-free grammar
- **Syntax Options**
  Options for customizing text appearances in files

[Help] Menu Details

Help
Help and support information

- **Contents**
  Help contents
- **About LEXcellent**
  Technical support for LEXcellent
- **About ParSpring**
  Technical support for ParSpring
- **About CCW 1.0**
  Technical support for CCW 1.0
- **Acknowledgements**
  Acknowledgements



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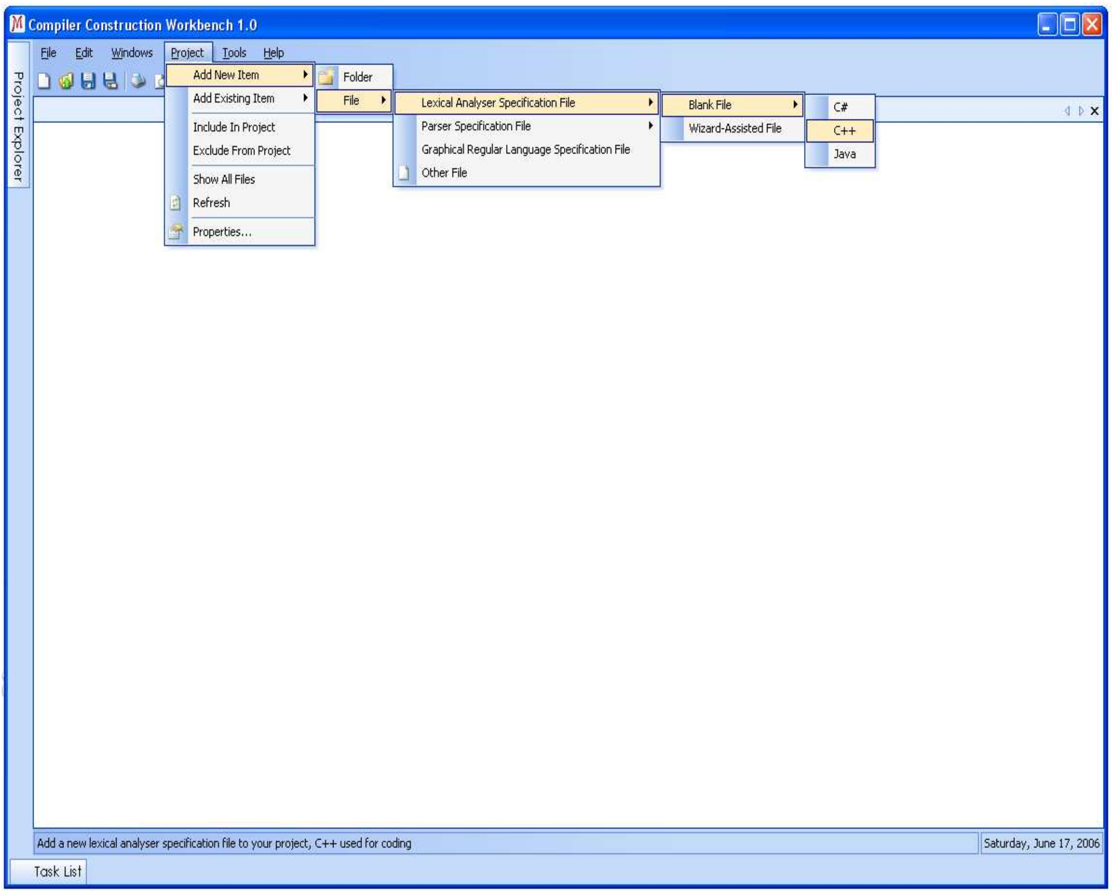


Add a new lexical analyser specification file to your project, C++ used for coding

Saturday, June 17, 2006

[Project] Menu Details

Project

- **Add New Item**
  Add a new item to the project
  - **Folder**
    Add a new folder to your project
  - **File**
    Add a new file to your project
    - **Lexical Analyzer Specification File**
      Add a new lexical analyser specification file to your project
      - **Blank File**
        Add a new blank lexical analyser specification file to your project
        - **C#**
          Add a new lexical analyser specification file to your project,
          C# used for coding
        - **C++**
          Add a new lexical analyser specification file to your project,
          C++ used for coding
        - **Java**
          Add a new lexical analyser specification file to your project,
          Java used for coding
      - **Wizard-Assisted File**
        Use the RegEx builder to add a set of regular expressions
        to your project
    - **Parser Specification File**
      Add a new parser specification file to your project
      - **Blank File**
        Add a new blank parser specification file to your project
        - **C#**
          Add a new parser specification file to your project,
          C# used for coding
        - **C++**
          Add a new parser specification file to your project,
          C++ used for coding
        - **Java**
          Add a new parser specification file to your project,
          Java used for coding
      - **Wizard-Assisted File**
        Use the CFG builder to add a context-free grammar to your project
    - **Graphical Regular Language Specification File**
      Add a new graphical regular language specification file to your project
    - **Other File**
      Add a new file of any type you want to associate with your project
- **Add Existing Item**
  Add an existing item to your project
  - **Lexical Analyzer Specification File**
    Add an existing lexical analyzer specification file to your project
    - **C#**
      Add an existing lexical analyzer specification file to your project,
      C# used for coding
    - **C++**
      Add an existing lexical analyzer specification file to your project,
      C++ used for coding
    - **Java**
      Add an existing lexical analyzer specification file to your project,
      Java used for coding

- **Parser Specification File**
  Add an existing parser specification file to your project
  - **C#**
    Add an existing parser specification file to your project, C# used for coding
  - **C++**
    Add an existing parser specification file to your project, C++ used for coding
  - **Java**
    Add an existing parser specification file to your project, Java used for coding
- **Graphical Regular Language Specification File**
  Add an existing graphical regular language specification file to your project
- **Other File**
  Add an existing file of any type to your project

Include In Project
Include the selected item in the project

Exclude From Project
Exclude the selected item from the project

Show All Files
Show all the available files in the selected folder.
Some of these files may NOT be related to the project

Refresh
Reload the file list

Properties
View the properties of the current project

Main ToolBar Details

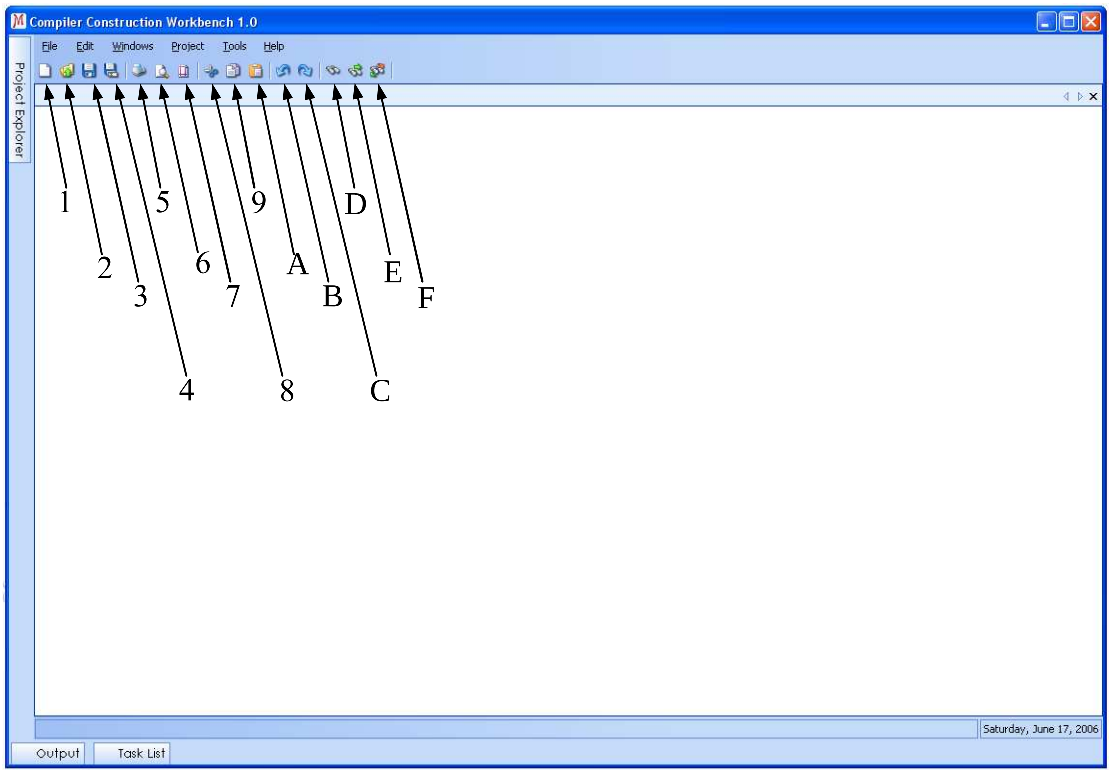
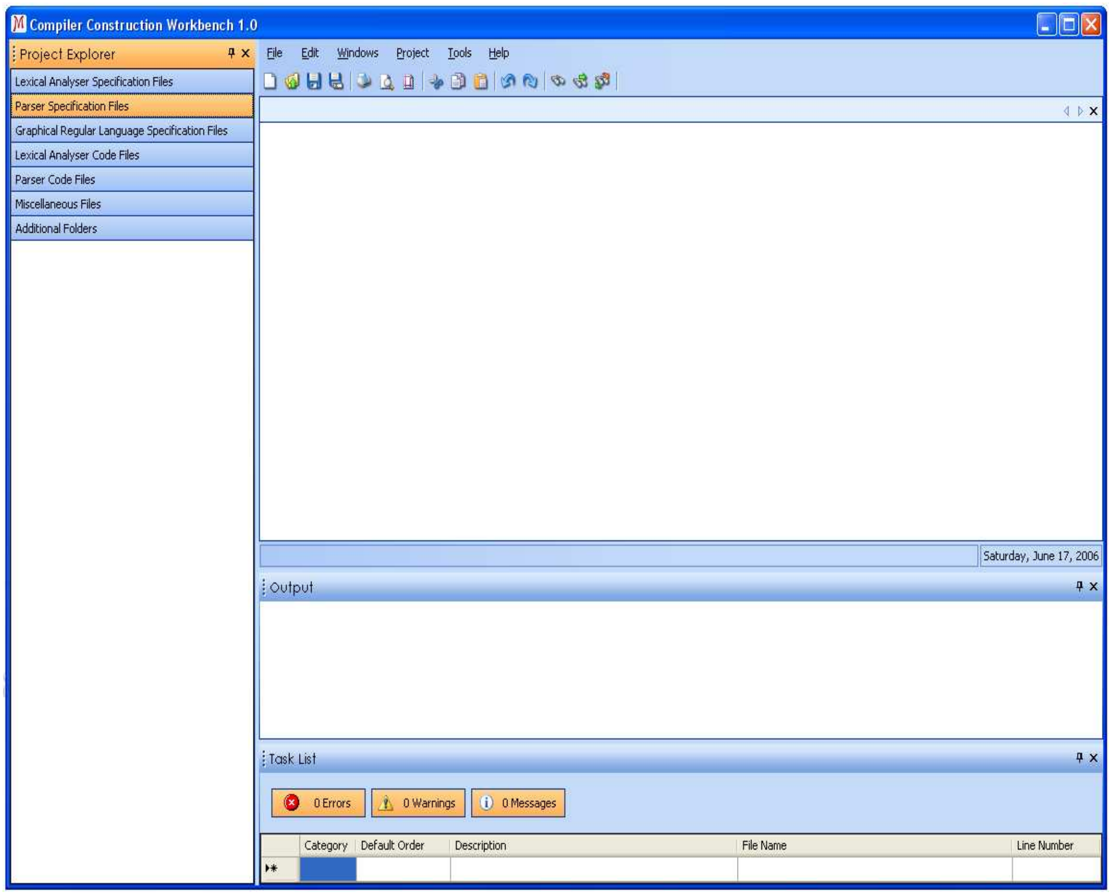


Table A-1: Main ToolBar Details

Number	Button Name	Icon	Description
1	**New Button**		Common operations for dealing with new items
2	**Open Button**		Common operations for dealing with existing items
3	**Save Button**		Save changes in the current file
4	**Save As Button**		Save changes in the current file as a new file without altering the current one
5	**Print Button**		Print the current document
6	**Print Preview Button**		Preview for WYSIWYG printing
7	**Page Setup Button**		Adjustments before printing
8	**Undo Button**		Undo the last operation
9	**Redo Button**		Redo the last undone operation
A	**Cut Button**		Cut the current selection into the clipboard
B	**Copy Button**		Copy the current selection into the clipboard
C	**Paste Button**		Paste the current contents of the clipboard into the current file, at the position of the caret
D	**Find Button**		Find strings in the current file
E	**Find Next Button**		Find the next currently searched string
F	**Replace Button**		Replace strings in the current file

Docking Windows



Project Explorer Window

Shows the files in the current project directory, either those registered in the project or all files. Double-clicking a file name opens it for editing. Clicking a tab collapses/uncollapses it. This window is dockable, i.e. you can show it, hide it or make it invisible, via the appropriate commands in the **Windows** menu or using the two small buttons on the right side of the title bar.

Task List Window

Shows the tasks in the current build if there were errors. Double-clicking an error opens its file for editing, and highlights the line number that contains the error. You can select what types of output are shown (errors, warnings or messages) by toggling the appropriate push button. This window is dockable, i.e. you can show it, hide it or make it invisible, via the appropriate commands in the **Windows** menu or using the two small buttons on the right side of the title bar.

Output Window

Shows a summary of the output of the current build. This window is dockable, i.e. you can show it, hide it or make it invisible, via the appropriate commands in the **Windows** menu or using the two small buttons on the right side of the title bar.

B. Tools and Technologies

- Visual C++ 6.0, Enterprise Edition
- Standard Template Library (STL)
- Component Object Model (COM)
- Visual Studio .NET 2003
- Visual Studio .NET 2005
- DotNetMagic Library (Ver 3.0.2)
- Fireball Text Editor
- Microsoft Office Visio 2003

C. Glossary

Deterministic Finite Automaton: A state transition function implementation. It consists of:

1. A finite set of states, often denoted by Q.
2. A finite set of input symbols, often denoted by Σ.
3. A transition function that takes as arguments a state and an input symbol and returns a state. The transition function will commonly be denoted δ.
4. A start state q_0, one of the states in Q.
5. A set, of final or accepting states F. The set F is a subset of Q. There can be zero or more states in F.

Compiler: A program that reads a program written in one language – the source language – and translates it into an equivalent program in another language – the target language.

Front End of a Compiler: Consists of those phases, or parts of phases, which depend primarily on the source language and are largely independent of the target machine. These normally include lexical and syntactic analysis, the creation of the symbol table, semantic analysis, and the generation of intermediate code.

Lexical Analysis: The stream of characters making up the source program is read in a linear fashion (in one direction, according to the language) and grouped into tokens – sequences of characters having a collective meaning.

Parser Generator: A program that produce syntax analyzers, normally from an input that is based on a context-free grammar.

Scanner Generator: A program that automatically generates lexical analyzers, normally from a specification based on regular expressions. The basic organization of the resulting lexical analyzer is in effect a finite automaton.

Syntax-Directed Translation Engine: A program that produce collections of routines that walk the parse tree, generating intermediate code. The basic idea is that one or more "translations" are associated with each node of the parse tree, and each translation is defined in terms of translations at its neighbor nodes in the tree.

Automatic Code Generator: A program that takes a collection of rules that define the translation of each operation of the intermediate language into the machine language for the target machine.

Lexical Token: A sequence of characters that can be treated as a unit in the grammar of the source language

Regular Language: A language is regular if and only if it can be specified by a regular expression.

Unicode: is an industry standard designed to allow text and symbols from all of the writing systems in the world to be consistently represented and manipulated by computers. Unicode characters can be encoded using any of several schemes termed Unicode Transformation Formats (UTF).

Thompson's Construction Algorithm: This phase in the lexical analyzer construction process is responsible for converting the set of regular expressions specified in the input file into a set of equivalent Nondeterministic Finite Automata (NFAs).

Nondeterministic Finite Automaton: An NFA consists of:

1. A finite set of states, often denoted **Q**.
2. A finite set of input symbols, often denoted **Σ**.
3. A start state q_0, one of the states in **Q**.
4. F, a subset of **Q**, is the set of final (or accepting) states.
5. The transition function **δ** is a function that takes a state in **Q** and an input symbol in **Σ** or the empty word **ε** as arguments and returns a subset of **Q**. Notice that the only difference between an NFA and a DFA is in the type of value that **δ** returns: a set of states in the case of an NFA and a single state in the case of a DFA.

Subset Construction Algorithm: This phase in the lexical analyzer construction process is responsible for converting the nondeterministic finite automata (NFAs) resulting from the Thompson's construction algorithm into their corresponding DFA's.

Context-Free Grammar: (Grammar, for short), also known as **BNF (Backus-Naur Form)** notation, is a notation for specifying the syntax of a language. A grammar naturally describes the hierarchical structure of many programming language constructs. It mainly consists of four components:

1. A set of tokens, known as *terminal* symbols.
2. A set of *non-terminals*.
3. A set of *productions* where each production consists of a non-terminal, called the left side of the production, an arrow, and a sequence of tokens and/or non-terminals, called the right side of the production.
4. A designation of one of the non-terminals as the start symbol.

Parse Tree: A structure that shows pictorially how the start symbol (or a grammar) derives a string in the language. Each node in the parse-tree is labeled by a grammar symbol. An interior node and its children correspond to a production; the interior node corresponds to the left side of the production, the children to the right side.
Formally, given a context-free grammar, a parse-tree is a tree with the following properties:

1. The root is labeled by the start symbol.
2. Each leaf is labeled by a token or by ε (the *empty* string).
3. Each interior node is labeled by a non-terminal.

4. If A is the non-terminal labeling some interior node and X_I, X_2 … X_n are the labels of the children of that node from left to right, then $A \rightarrow X_1\ X_2 \ldots X_n$ is a production. Here, X_I, X_2 … X_n stand for a symbol that is either a terminal or a non-terminal. As a special case, if $A \rightarrow \varepsilon$ then a node labeled A may have a single child labeled ε.

Syntax Tree: A compressed representation of the parse tree in which the operators appear as the interior nodes, and the operands of an operator are the children of the node for that operator.

Recursive-Descent Parser: A top-down parser built from a set of mutually-recursive procedures (or a non-recursive equivalent) where each such procedure usually implements one of the production rules of the grammar. Thus the structure of the resulting program closely mirrors that of the grammar it recognizes.

Predictive Parser: A recursive-descent parser with no backup.

Packrat Parser: A modification of recursive descent with backup that avoids non-termination by remembering its choices, so as not to make exactly the same choice twice.

CCW