Grammars and Parsing

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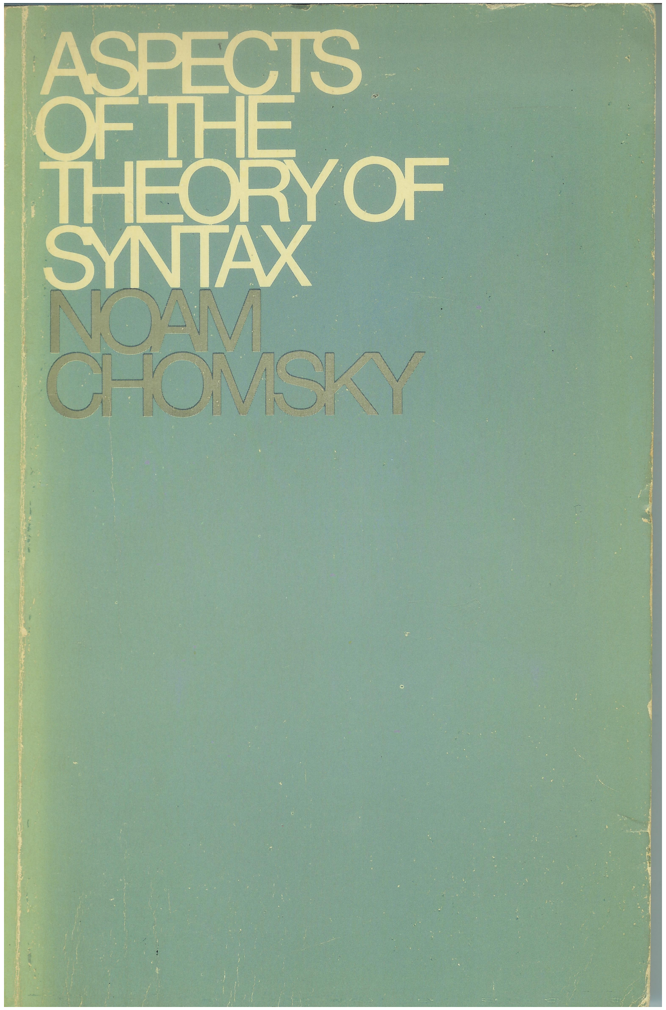
Grammars and Languages are one of the most established areas of Natural Language Processing and Computer Science



N. Chomsky,
Aspects of the theory of syntax,
1965

A Language ...

- ... is a (possibly infinite) set of sentences
- Exercise:
  - Give examples of finite languages
  - Give examples of infinite languages

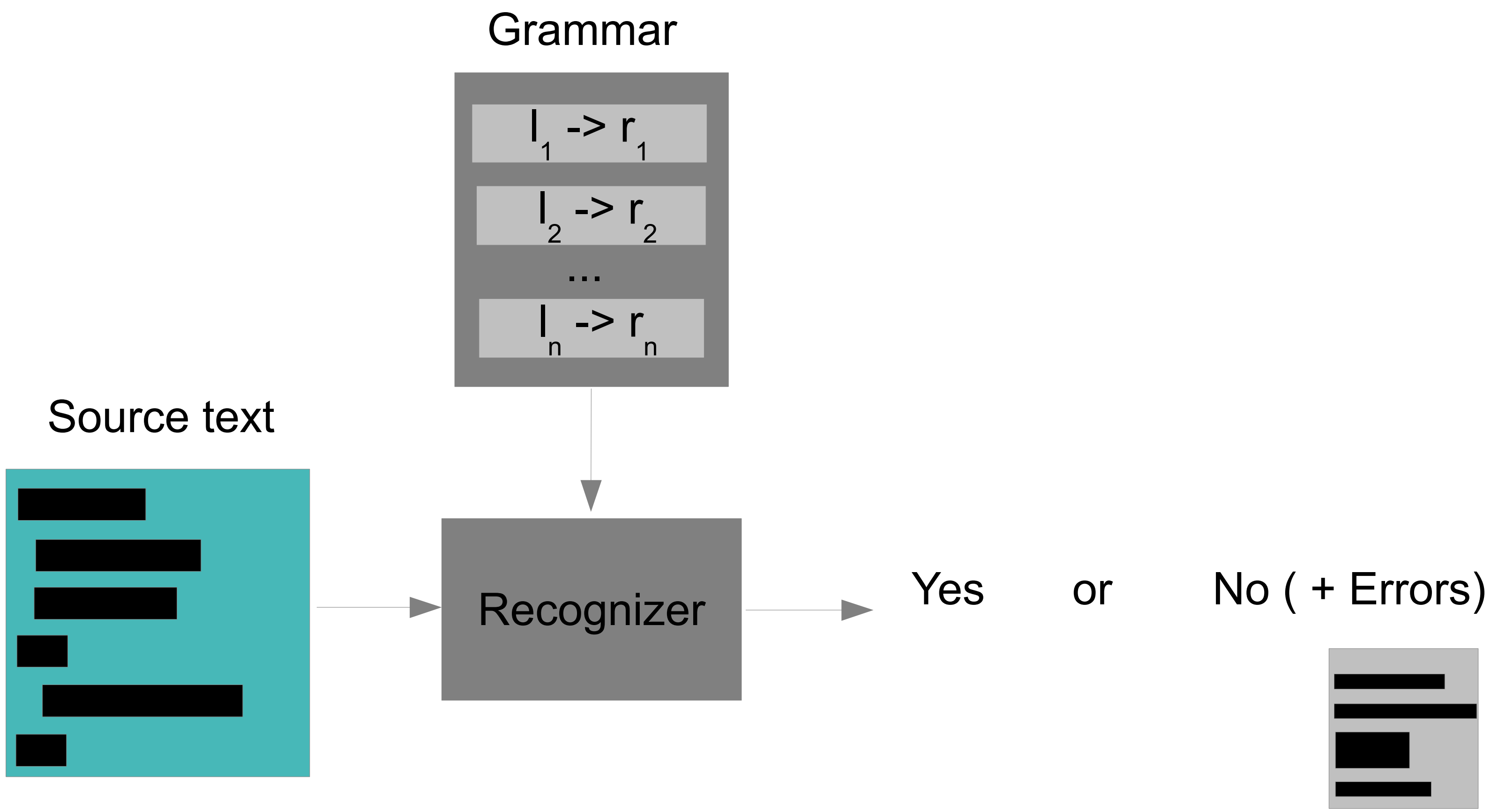
A Grammar ...

- ... is a set of formation rules to describe the sentences in a language
- The Chomsky hierarchy:
  - Context-sensitive languages
    - Natural language processing
  - Context-free languages
    - Syntax of programming languages
  - Regular languages
    - Regular expressions, grep, lexical syntax

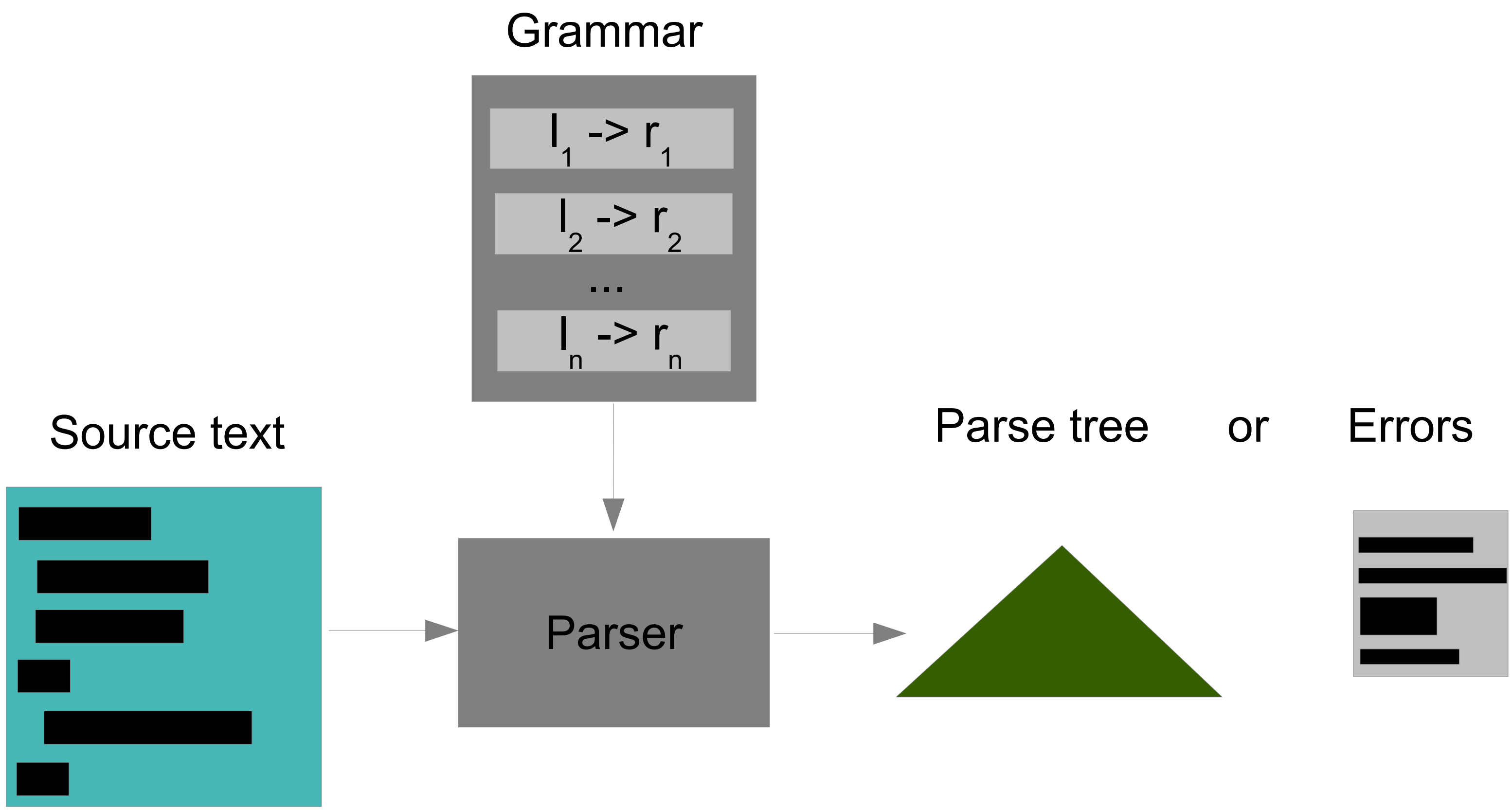
Syntax Analysis (aka Parsing) ...

- ... is the process of analyzing the syntactic structure of a sentence.
- A recognizer only says Yes or No (+ messages) to the question:
  - Does this sentence belong to language L?
- A parser also builds a structured representation when the text is syntactically correct.
  - Such a “syntax tree” or “parse trees” is a proof how the grammar rules can be sued to derive the sentence.

A Recognizer

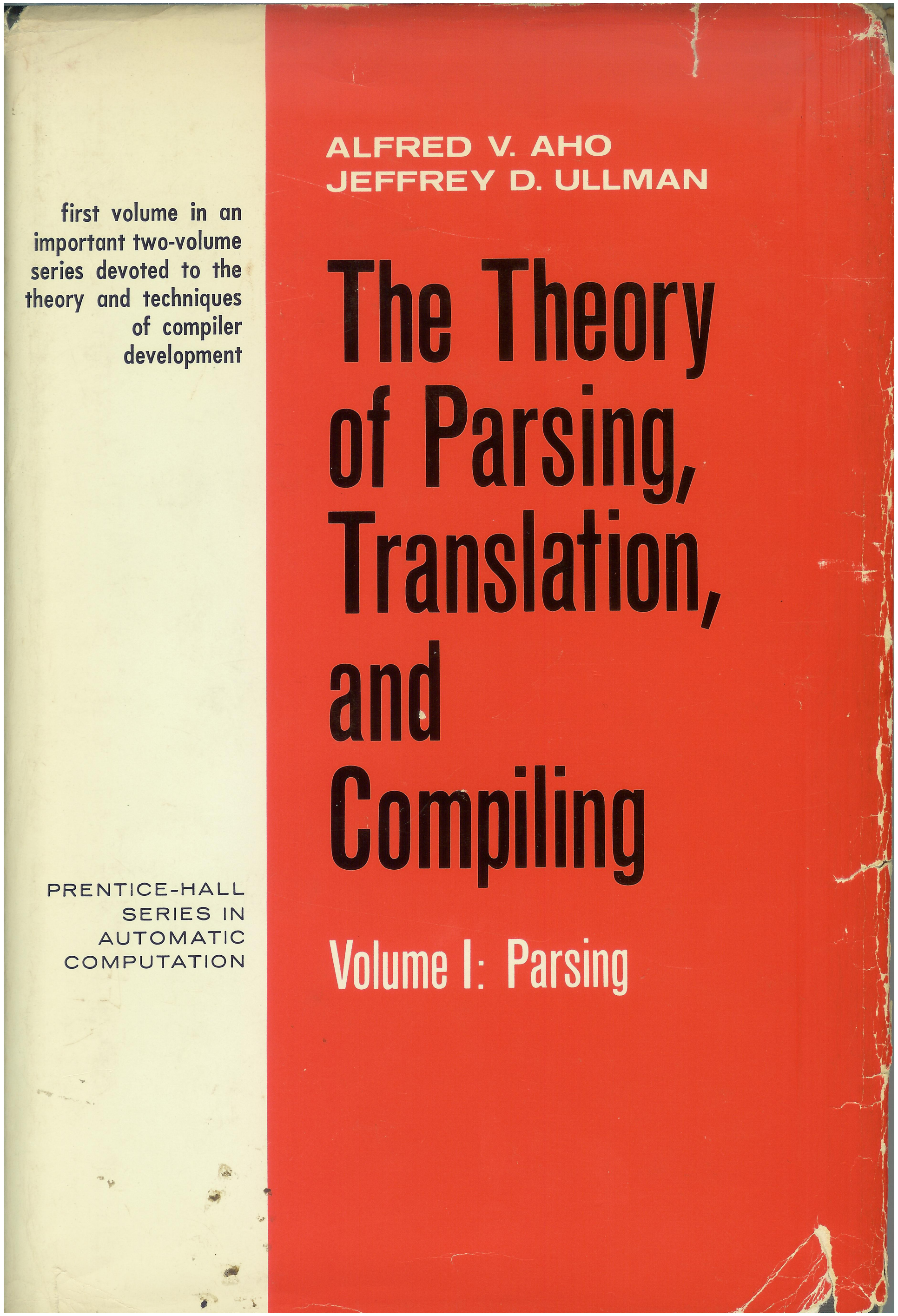


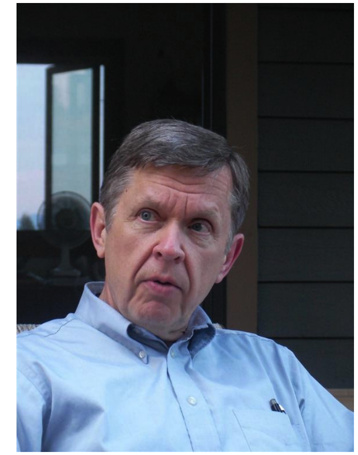
A Parser

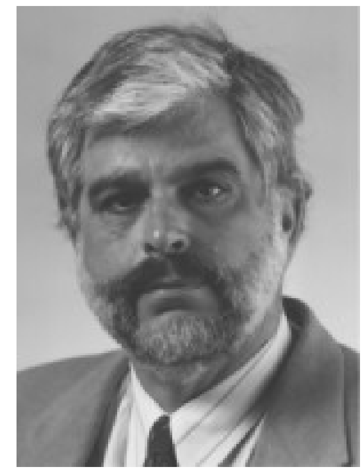

Grammar
l_1 -> r_1
l_2 -> r_2
...
l_n -> r_n
Source text
Parser
Parse tree
or
Errors

Why are Grammars and Parsing Techniques relevant?

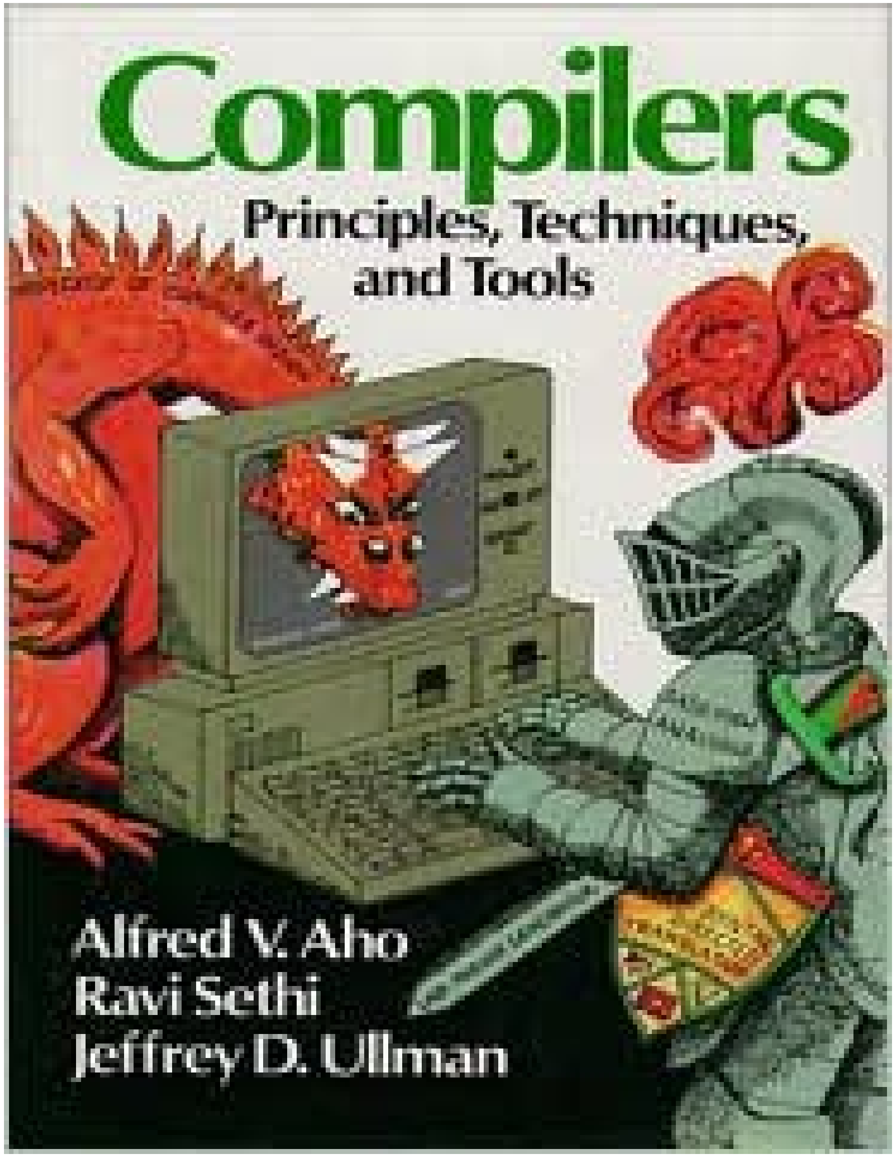
- A *grammar* is a formal method to describe a (textual) *language*
  - Programming languages: C, Java, C#, JavaScript
  - Domain-specific languages: BibTex, Mathematica
  - Data formats: log files, protocol data
- *Parsing*:
  - Tests whether a text conforms to a grammar
  - Turns a correct text into a parse tree



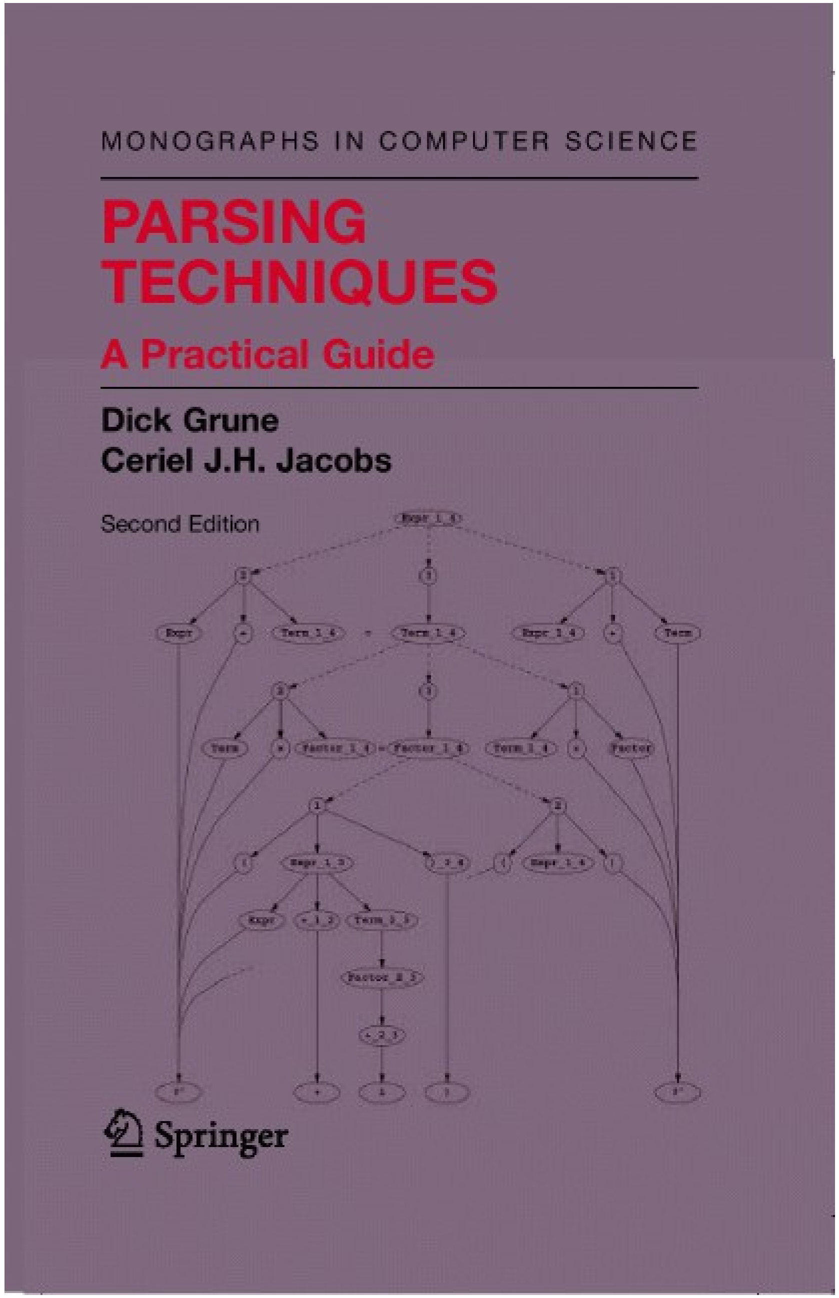




A.V. Aho & J.D. Ullman,
The Theory of Parsing,
Translation and
Compiling,
Parts I + II, 1972



A.V. Aho, R. Sethi, J.D. Ullman, Compiler, Principles, Techniques and Tools, 1986



D. Grune, C. Jacobs,
Parsing Techniques,
A Practical Guide,
2008

What is Syntax Analysis about?

- Syntax analysis (or parsing) is about recognizing structure in text (or the lack thereof)
- The question “Is this a textually correct Java program?” can be answered by syntax analysis.
- Note: other correctness aspects are outside the scope of parsing:
  - Has this variable been declared?
  - Is this expression type correct?
  - Is this method called with the right parameters?

When is Syntax Analysis Used?

- Compilers
- IDEs
- Software analysis
- Software transformation
- DSL implementations
- Natural Language processing
- Genomics (parsing of DNA fragments)

How to define a grammar?

- Simplistic solution: finite set of acceptable sentences
  - Problem: what to do with infinite languages?
- Realistic solution: finite recipe that describes all acceptable sentences
- A grammar is a finite description of a possibly infinite set of acceptable sentences

Example: Tom, Dick and Harry

- Suppose we want describe a language that contains the following legal sentences:
  - Tom
  - Tom and Dick
  - Tom, Dick and Harry
  - Tom, Harry, Tom and Dick
  - ...
- How do we find a finite recipe for this?

The Tom, Dick and Harry Grammar

- Name -> **tom**
- Name -> **dick**
- Name -> **harry**
- Sentence -> Name
- Sentence -> List End
- List -> Name
- List -> List **,** Name
- **,** Name End -> **and** Name

Non-terminals:
Name, Sentence, List, End

Terminals:
tom, **dick**, **harry**, **and**, **,**

Start Symbol:
Sentence

Example

- Name -> **tom**
- Name -> **dick**
- Name -> **harry**
- Sentence -> Name
- Sentence -> List End
- List -> Name
- List -> List , Name
- , Name End -> and Name

- Sentence ->
  - Name ->
  - tom
- Sentence ->
  - List End ->
  - List , Name End ->
  - Name , Name End ->
  - tom, Name End -> tom, dick End ->
  - tom and dick

Variations in Notation

- Name -> **tom | dick | harry**
- <Name> ::= "tom" | "dick" | "harry"
- "tom" | "dick" | "harry" -> Name
- In Rascal:
  - syntax Name = "tom" | "dick" | "harry";

Chomsky's Grammar Hierarchy

- Type-0: Recursively Enumerable
  - Rules: $\alpha \rightarrow \beta$ (unrestricted)
- Type-1: Context-sensitive
  - Rules: $\alpha A\beta \rightarrow \alpha\gamma\beta$
- Type-2: Context-free
  - Rules: $A \rightarrow \gamma$
- Type-3: Regular
  - Rules: $A \rightarrow a$ and $A \rightarrow aB$

Context-free Grammar for TDH

- Name -> **tom** | **dick** | **harry**
- Sentence -> Name | List and Name
- List -> Name **,** List | Name

Exercise: What changed and Why?

- Name -> **tom**
- Name -> **dick**
- Name -> **harry**
- Sentence -> Name
- Sentence -> List End
- List -> Name
- List -> List , Name
- , Name End -> and Name

- Name -> **tom**
- Name -> **dick**
- Name -> **harry**
- Sentence -> Name
- Sentence -> List and Name
- List -> Name
- List -> Name , List

In practice ...

- Regular grammars used for lexical syntax:
  - Keywords: if, then, while
  - Constants: 123, 3.14, “a string”
  - Comments: /* a comment */
- Context-free grammars used for structured and nested concepts:
  - Class declaration
  - If statement

We start with text

Consider the assignment statement:

Position := initial + rate * 60

First approximation, this is a string of characters:

p	o	s	i	t	i	o	n		:	=		i	n	i	t	i	a	l		+		r	a	t	e		*		6	0

From text to tokens

p	o	s	i	t	i	o	n		:	=		i	n	i	t	i	a	l		+		r	a	t	e		*		6	0

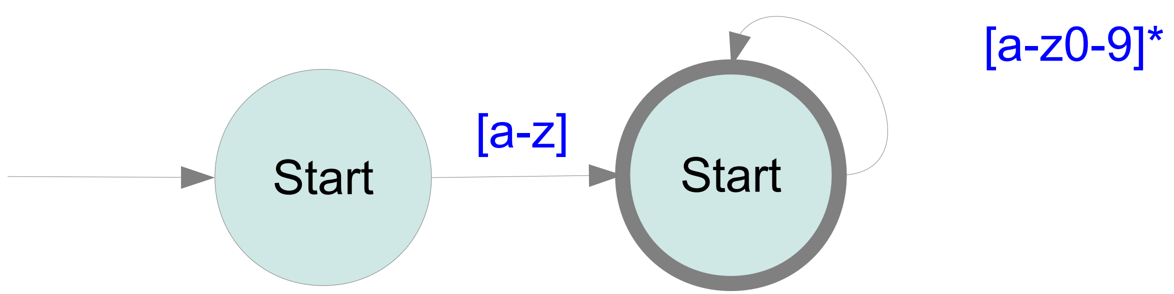
- The identifier position
- The assignment symbol :=
- The identifier initial
- The addition operator +
- The identifier rate
- The multiplication operator *
- The number 60

Lexical syntax

- Regular expressions define lexical syntax:
  - Literal characters: a,b,c,1,2,3
  - Character classes: [a-z], [0-9]
  - Operators: sequence (space), repetition (* or +), option (?)
- Examples:
  - Identifier: [a-z][a-z0-9]*
  - Number: [0-9]+
  - Floating constant: [0-9]*.[0-9]*(e-[0-9]+)

Lexical syntax

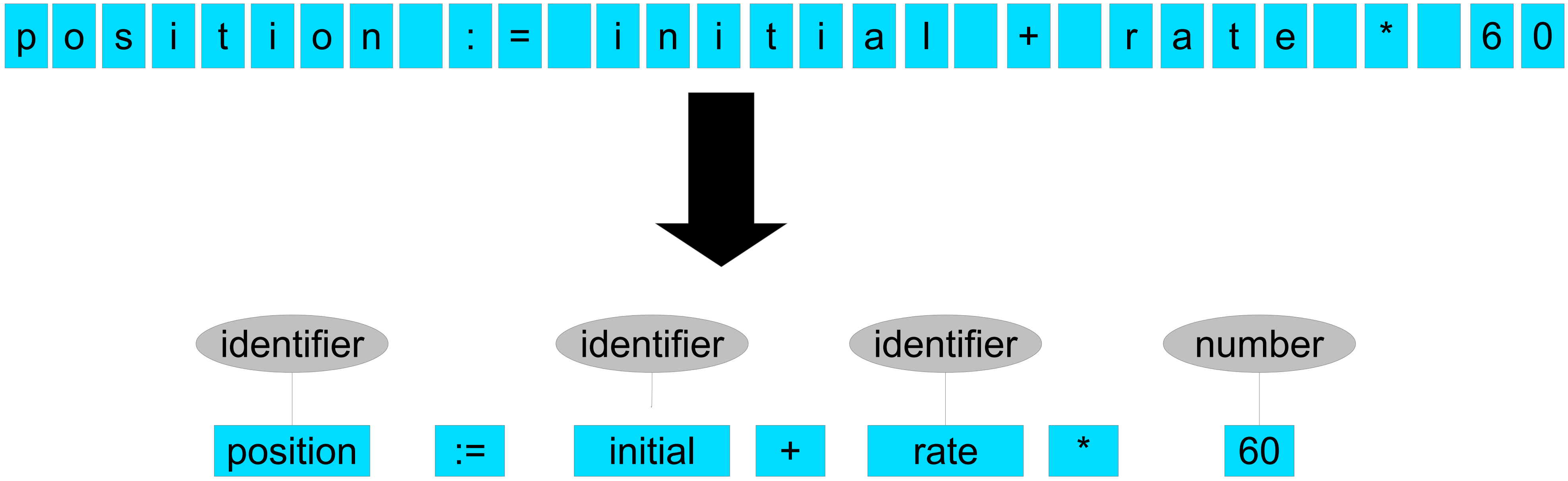
- Regular expressions can be implemented with a finite automaton
- Consider [a-z][a-z0-9]*



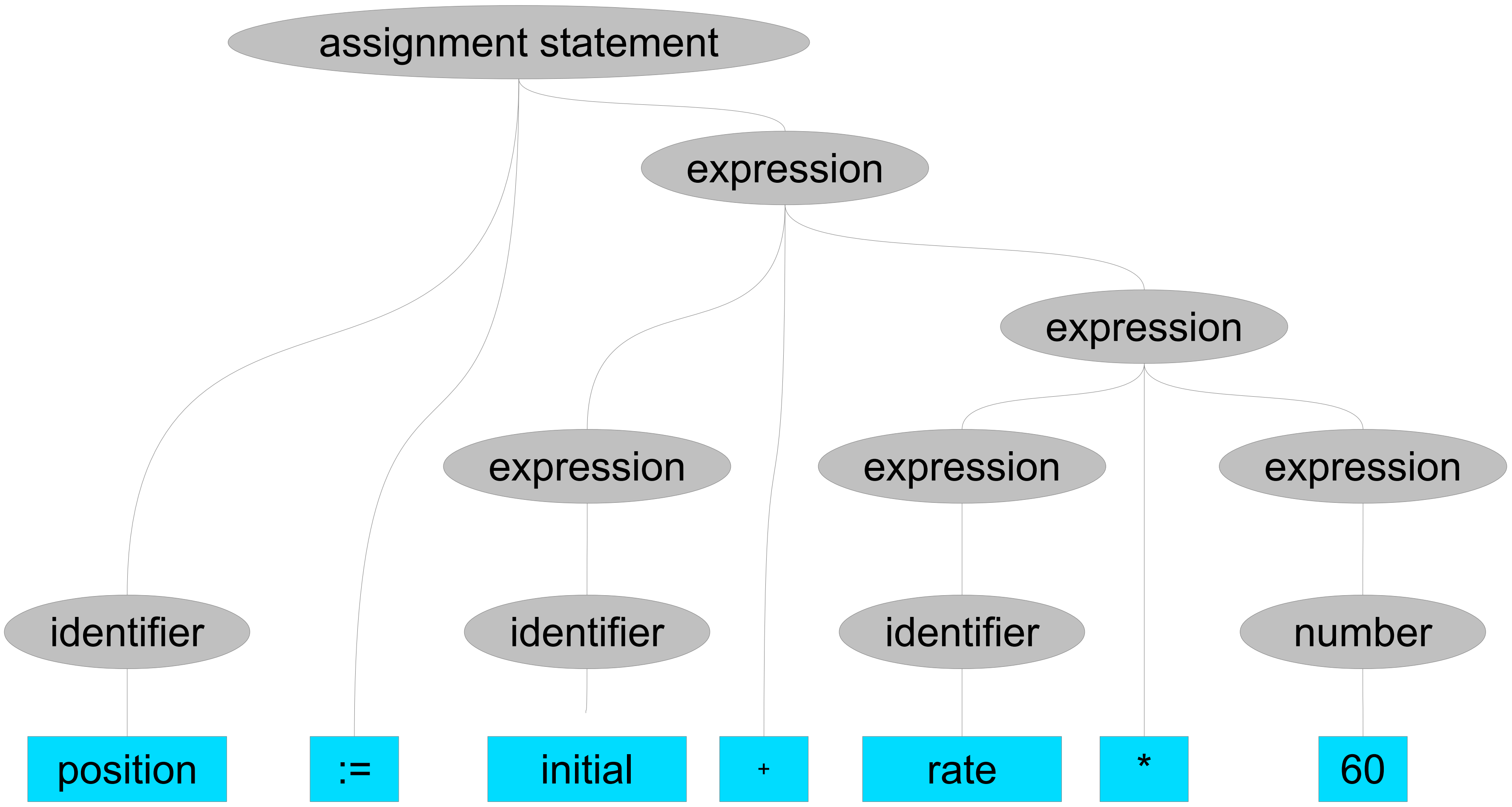
From text to tokens

Classify characters by lexical category:

- Tokenization
- Lexical analysis
- Lexical scanning



From Tokens to Parse Tree



Expression Grammar

The hierarchical structure of expressions can be described by recursive rules:

1. Any Identifier is an *expression*
2. Any Number is an *expression*
3. If Expression_1 and Expression_2 are *expressions* then so are:
   - Expression_1 + Expression_2
   - Expression_1 * Expression_2
   - (Expression_1)

Statement Grammar

1. If $Identifier_1$ is an identifier and $Expression_1$ is an expression then the following is a statement:
    - $Identifier_1$:= $Expression_1$
2. If $Expression_1$ is an expression and $Statement_1$ is an statement then the following are statements:
    - while ($Expression_1$) $Statement_1$
    - if ($Expression_1$) then $Statement_1$

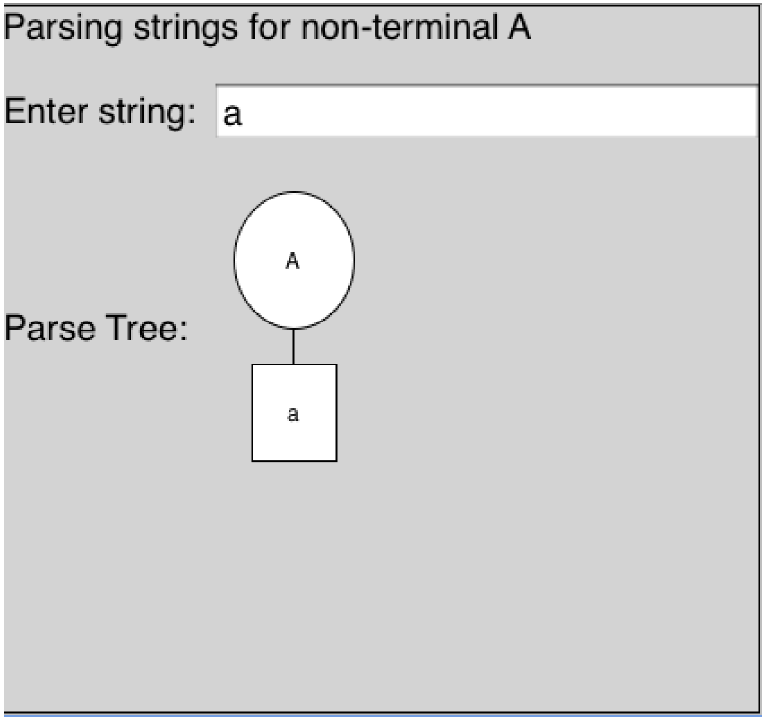
How do we get a parser?

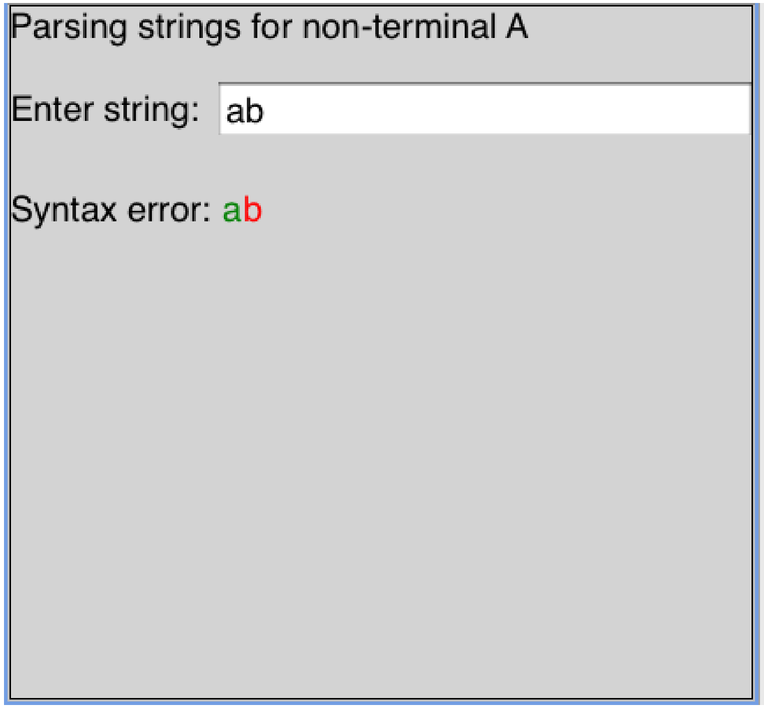
Use a parser generator

- Pro: regenerate when grammar changes
- Pro; recognized language is exactly known
- Pro: less effort
- Con: Grammar has to fit in the grammar class accepted by the parser generator (this may be very hard!)
- Con: mixing of parsing and other actions somewhat restricted
- Con: limited error recovery

Language A

```
start syntax A = "a";
```

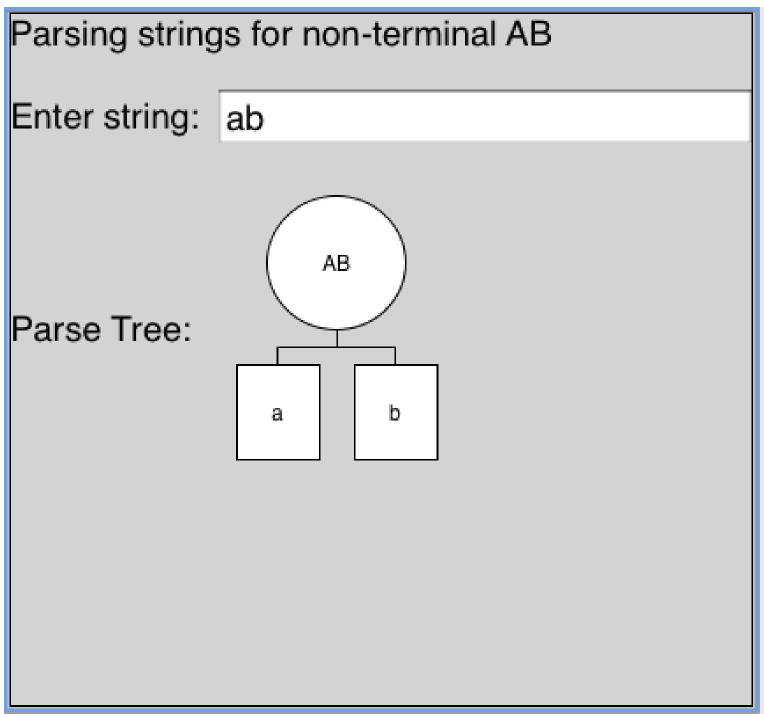




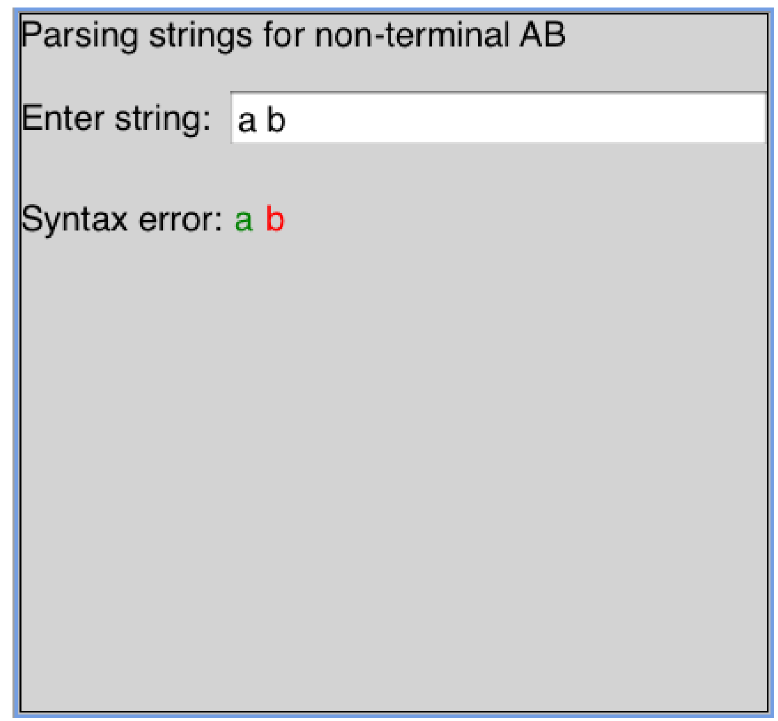

```
parseTreeViewer(#start[A])
```

Language AB

```
start syntax AB = "a" "b";
```

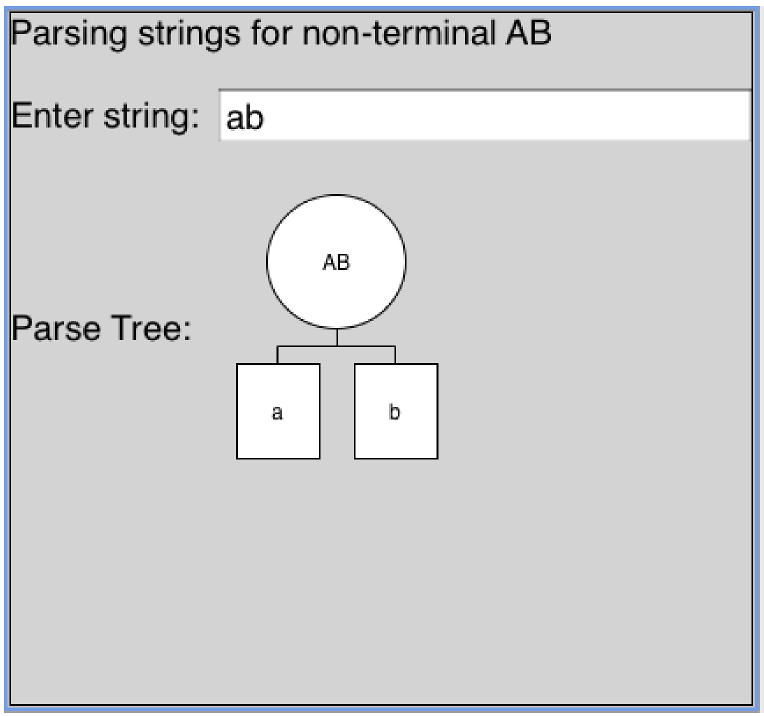


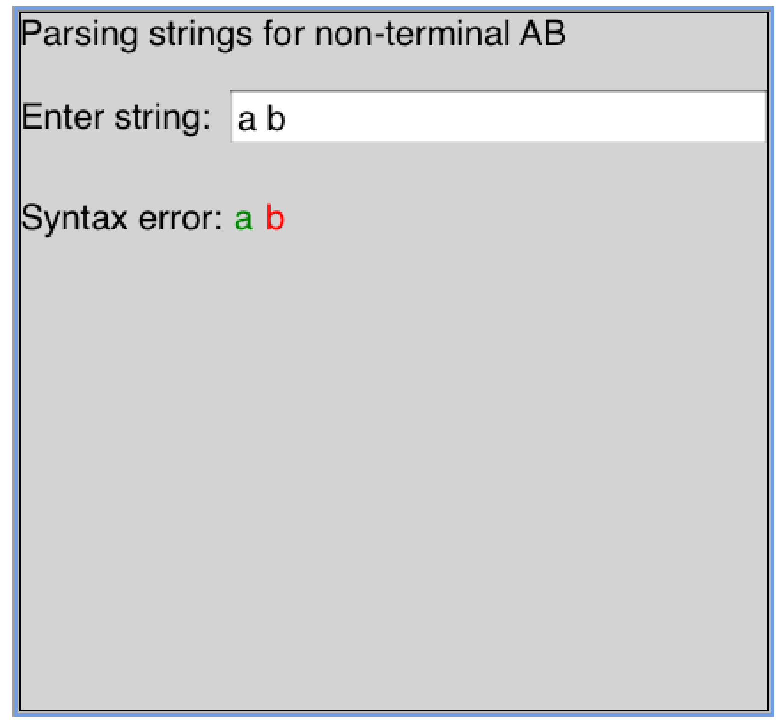

```
parseTreeViewer(#start[AB])
```



Language AB

```
start syntax AB = "a" "b";
```

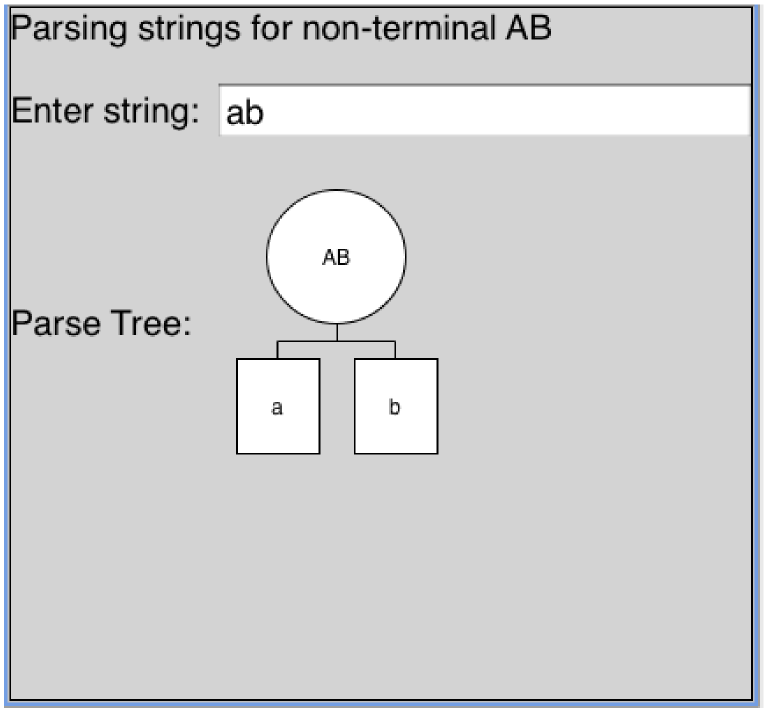


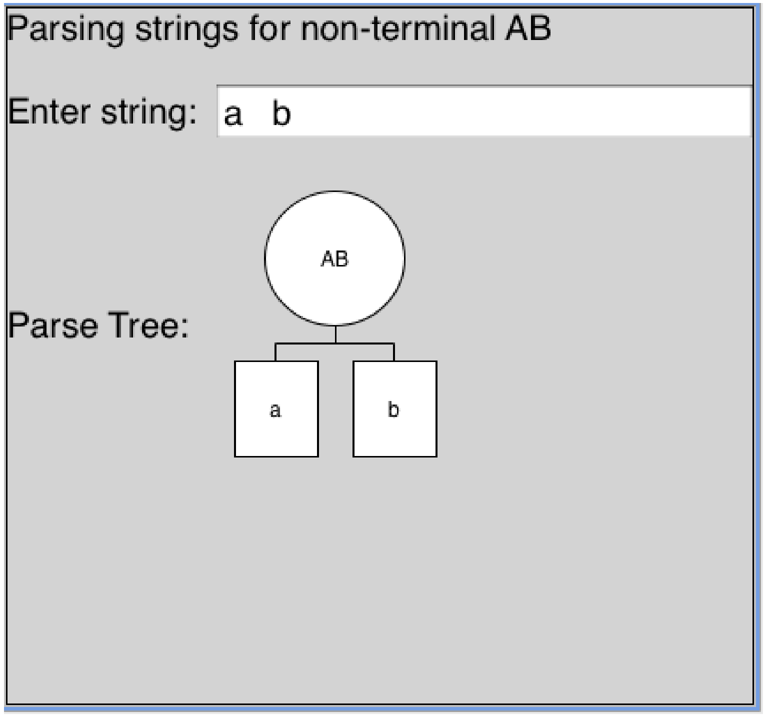



```
parseTreeViewer(#start[AB])
```

Language AB (with layout)

```
layout Whitespace = [\ \t\n]*;
start syntax AB = "a" "b";
```

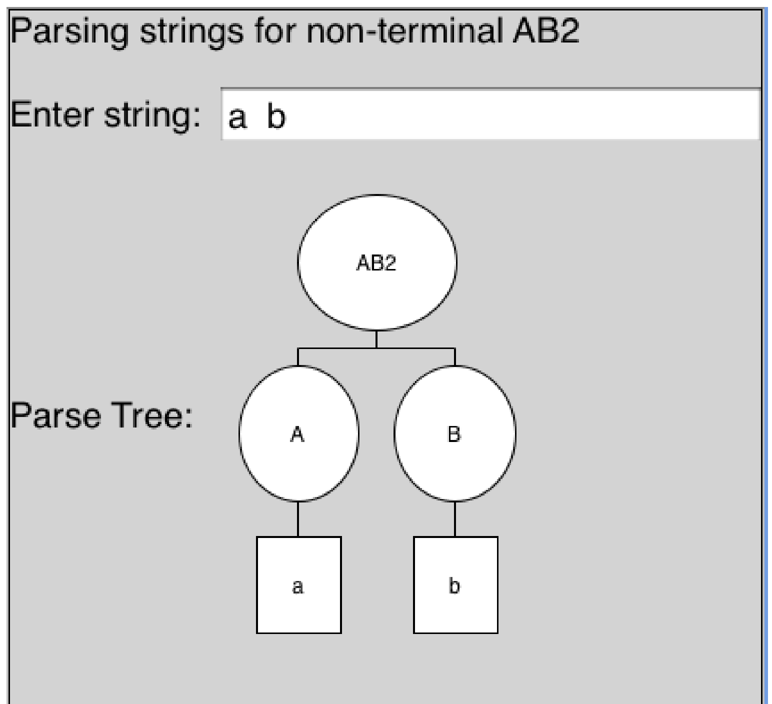





```
parseTreeViewer(#start[AB])
```

Language AB2

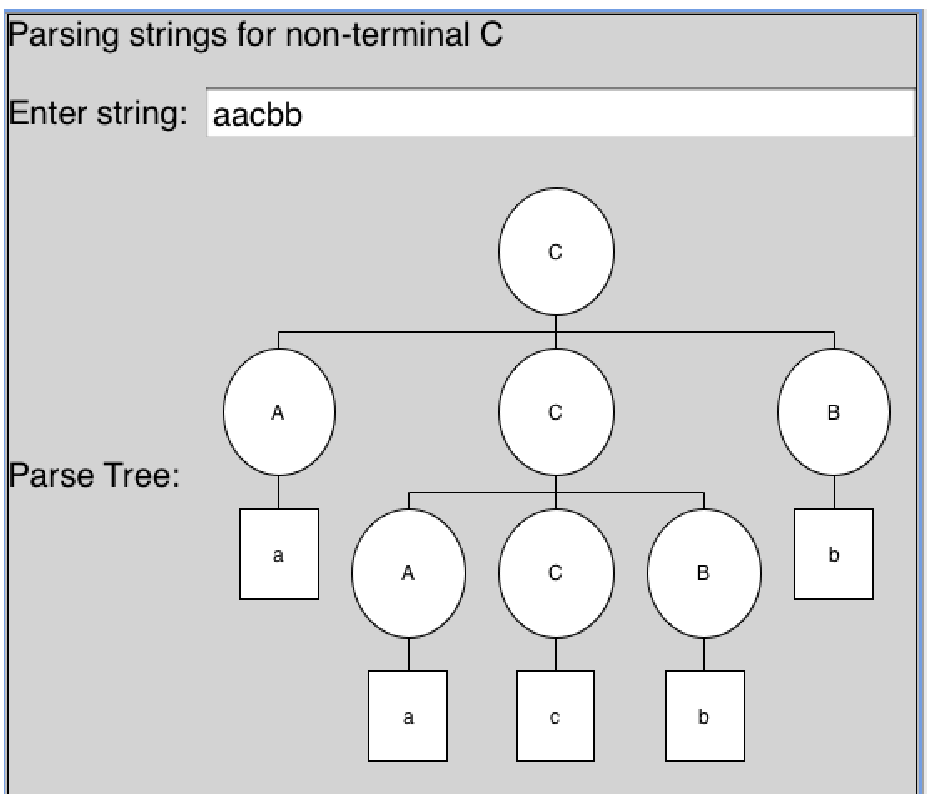
```
layout Whitespace = [\ \t\n]*;
syntax A = "a";
syntax B = "b";
start syntax AB2 = A B;
```

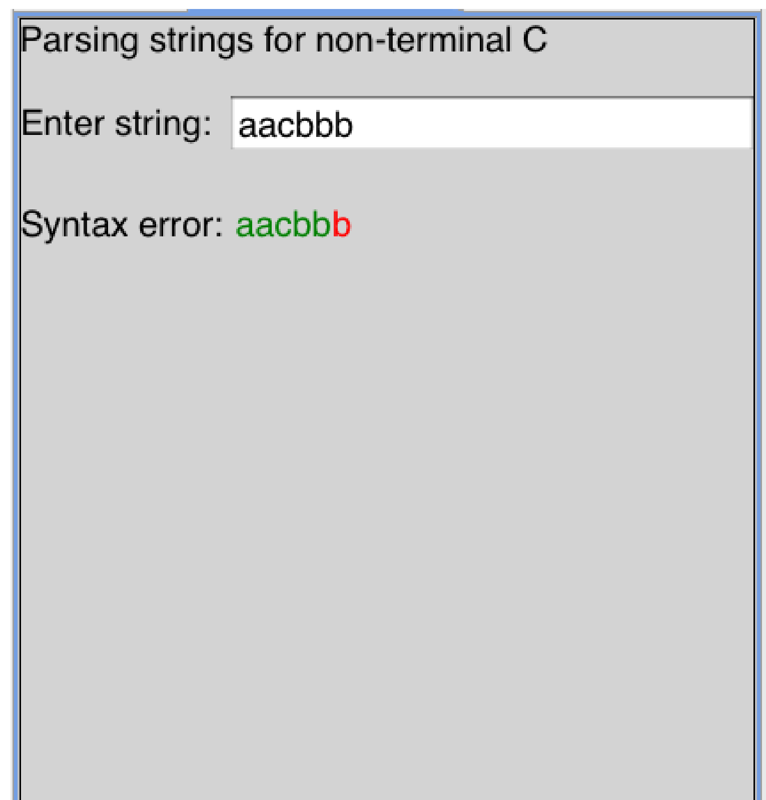



```
parseTreeViewer(#start[AB2])
```

Language C

```
layout Whitespace = [\ \t\n]*;
syntax A = "a";
syntax B = "b";
start syntax C = "c" | A C B;
```

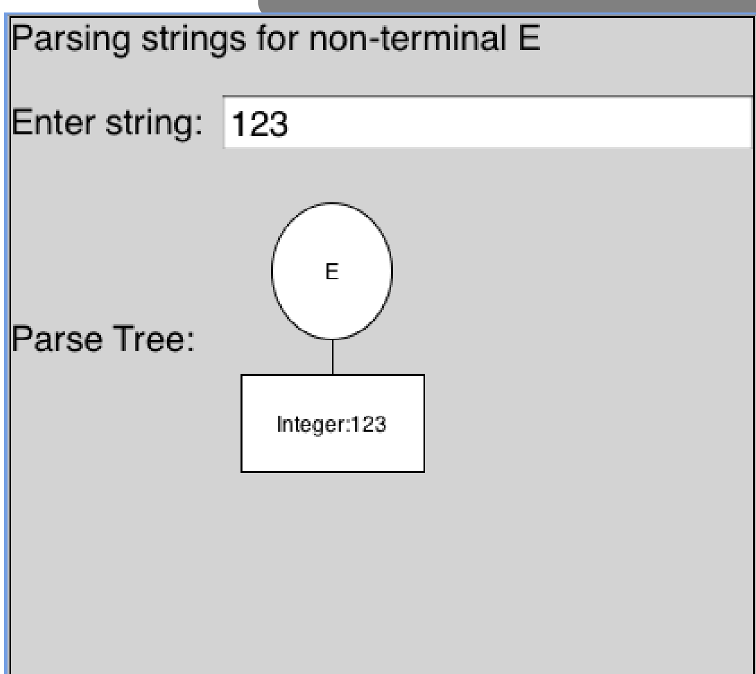


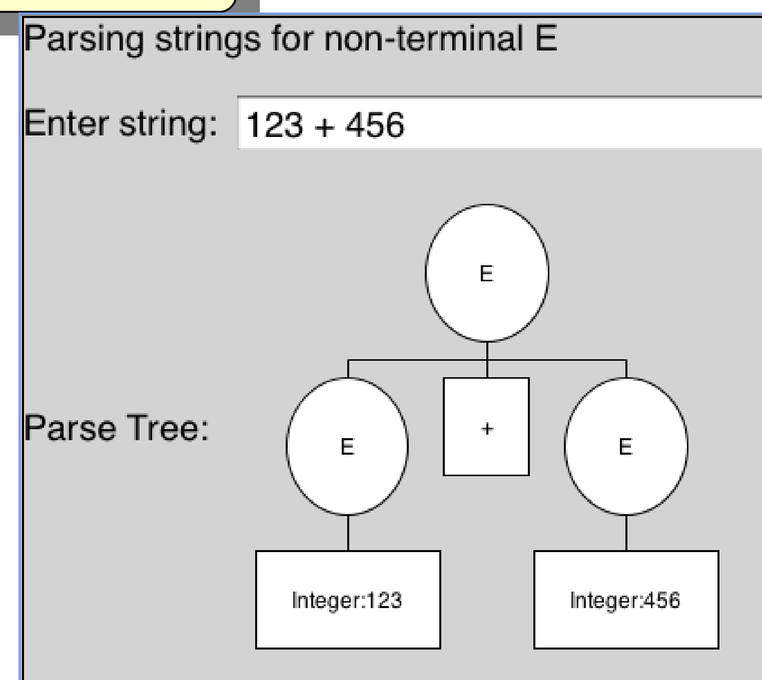



```
parseTreeViewer(#start[C])
```

Language E

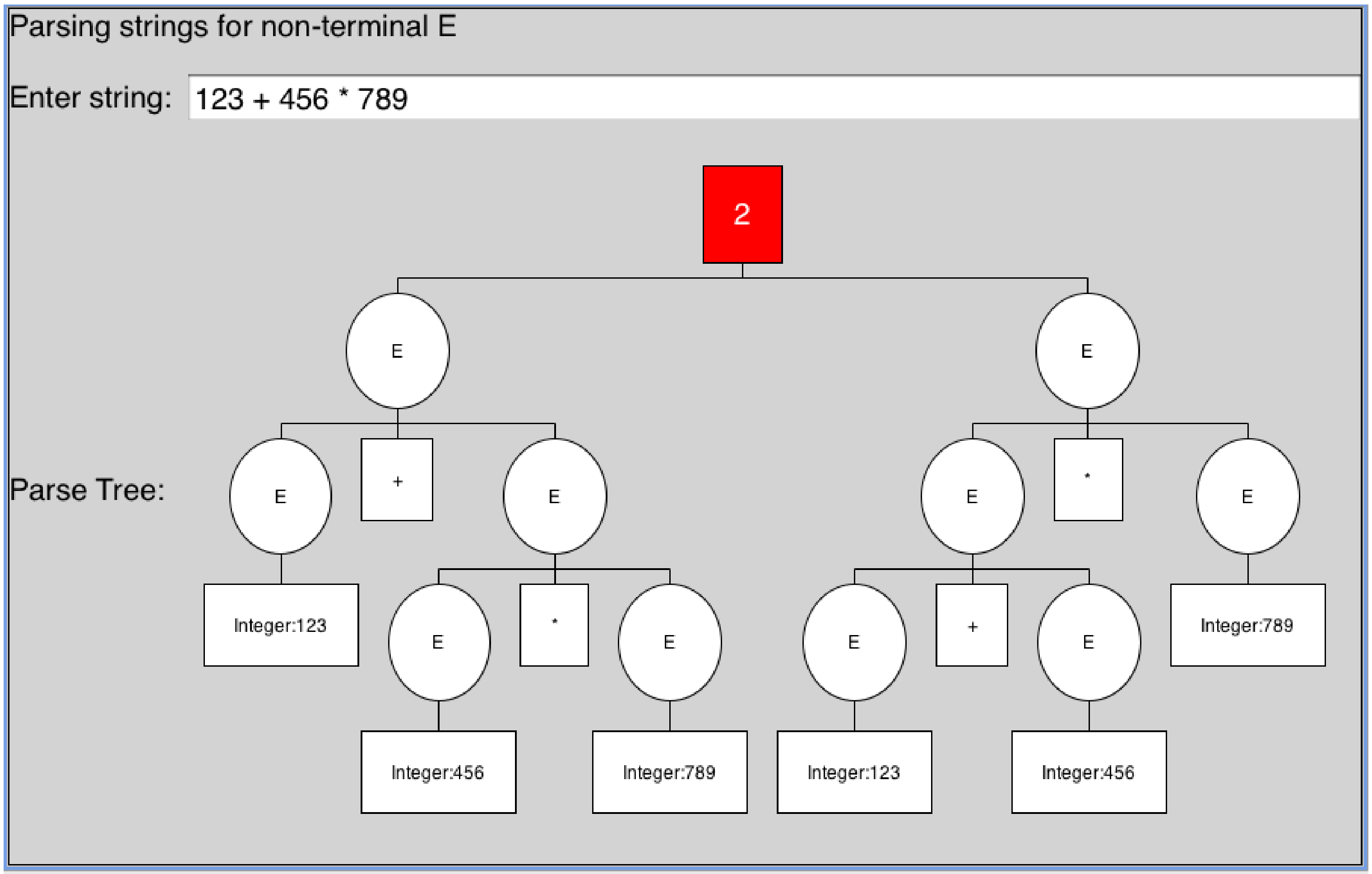
```
layout Whitespace = [\ \t\n]*;
lexical Integer = [0-9]+;
start syntax E = Integer
               | E "*" E
               | E "+" E
               | "(" E ")"
               ;
```





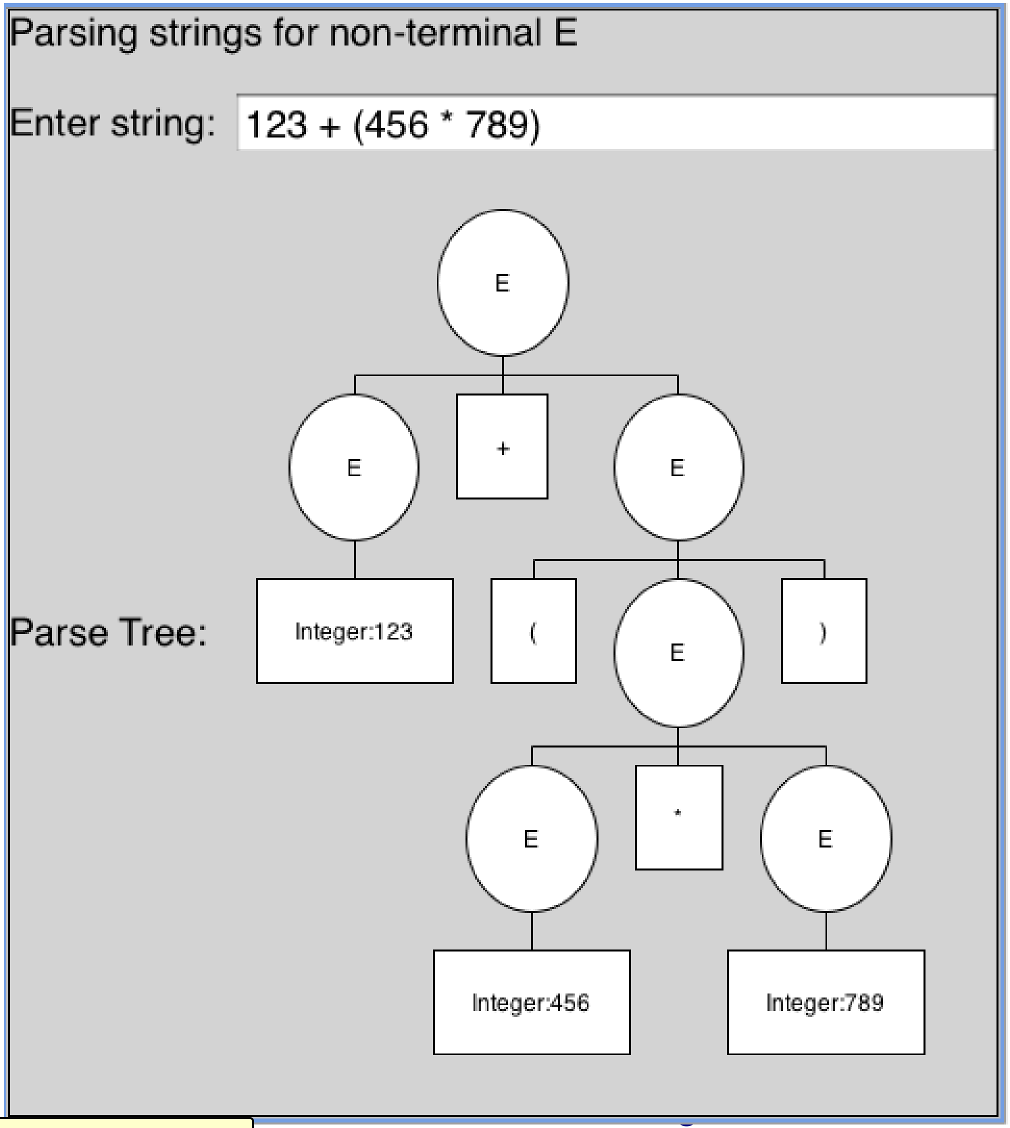

```
parseTreeViewer(#start[E])
```

Language E: ambiguity




```
parseTreeViewer(#start[E])
```

Language E: Using Parentheses

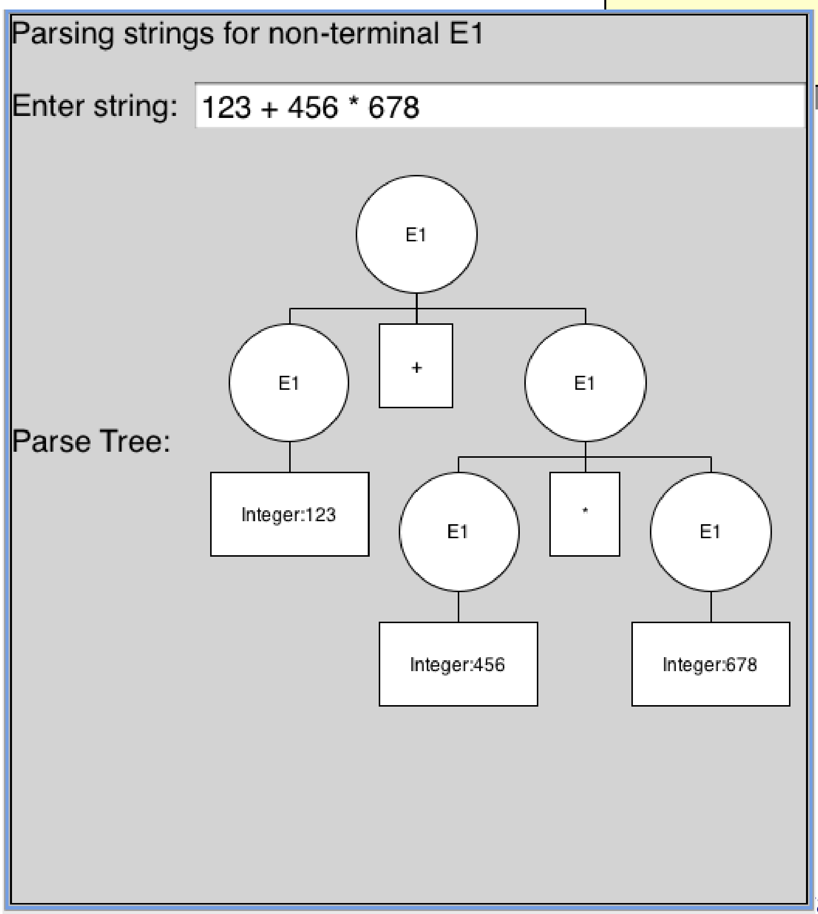



```
parseTreeViewer(#start[E])
```

Language E1: Define Priority

```
layout Whitespace = [\ \t\n]*;
lexical Integer = [0-9]+;
start syntax E1 = Integer
               | E1 "*" E1
               > E1 "+" E1
               | "(" E1 ")"
               ;
```

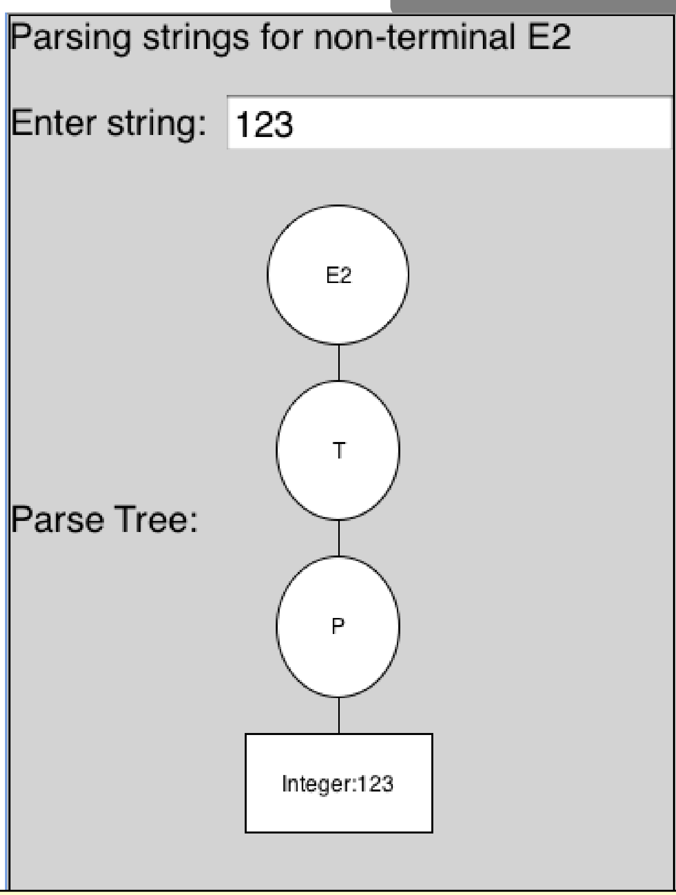
> defines that E1 “*” E1 has higher priority than E1 “+” E1



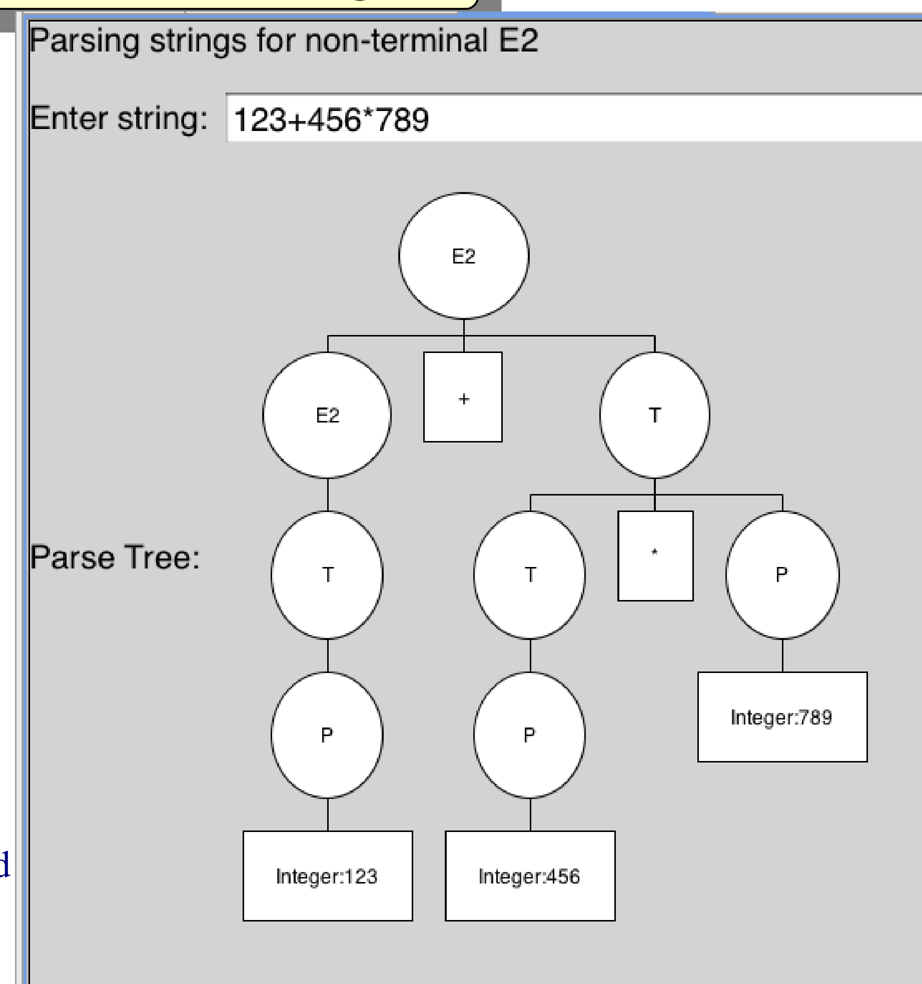

```
parseTreeViewer(#start[E1])
```

Language E2: Extra non-terminals

```
layout Whitespace = [\ \t\n]*;
lexical Integer = [0-9]+;
start syntax E2 = E2 "+" T | T;
syntax T = T "*" P | P;
syntax P = "(" E2 ")" | Integer;
```

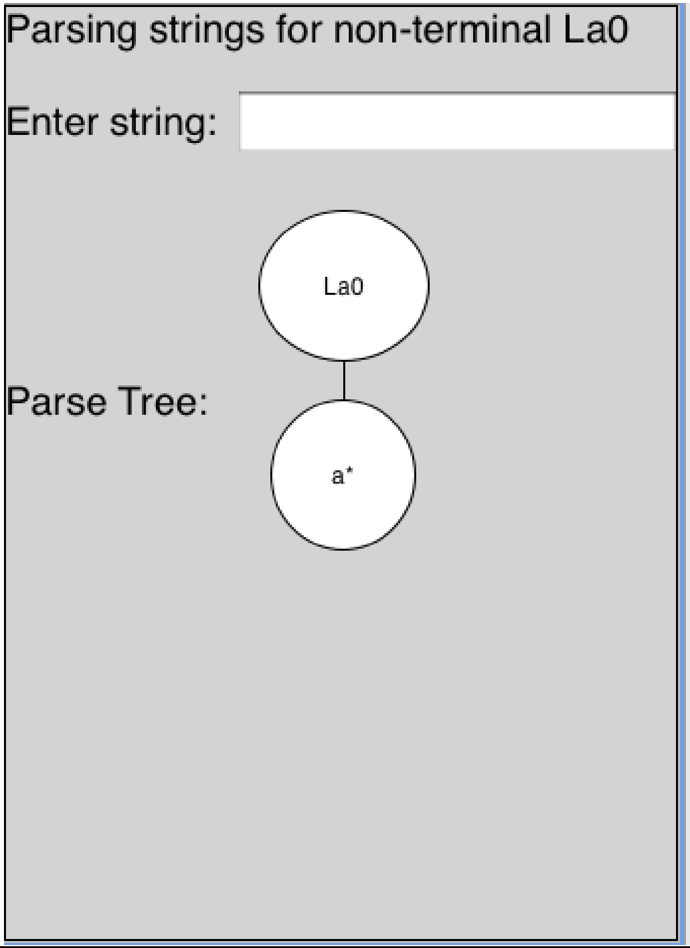


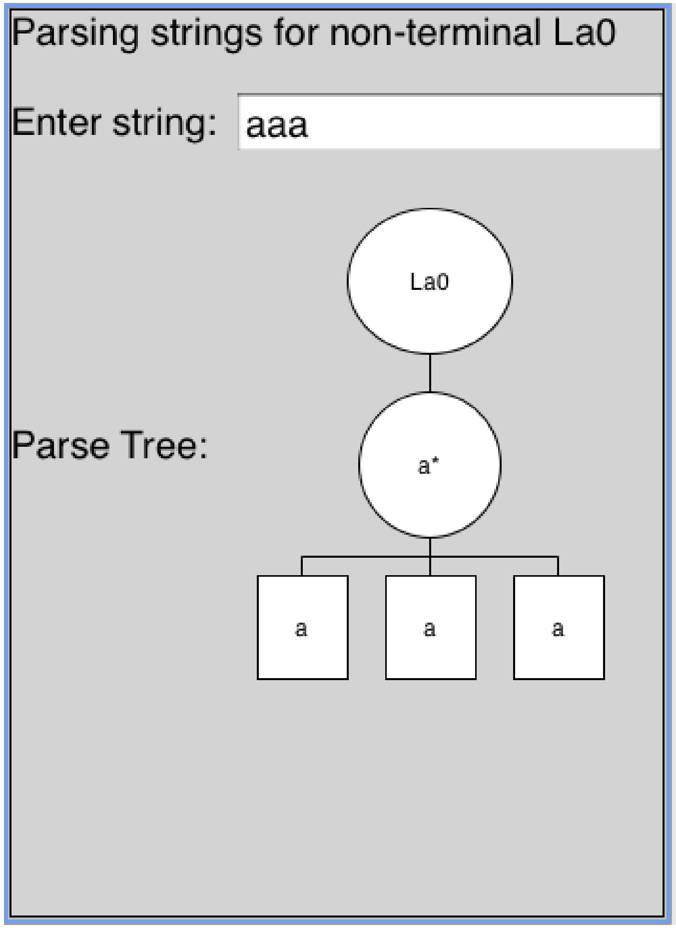

```
parseTreeViewer(#start[E2])
```



Language La0: List of zero or more a's

```
start syntax La0 = "a"*;
```

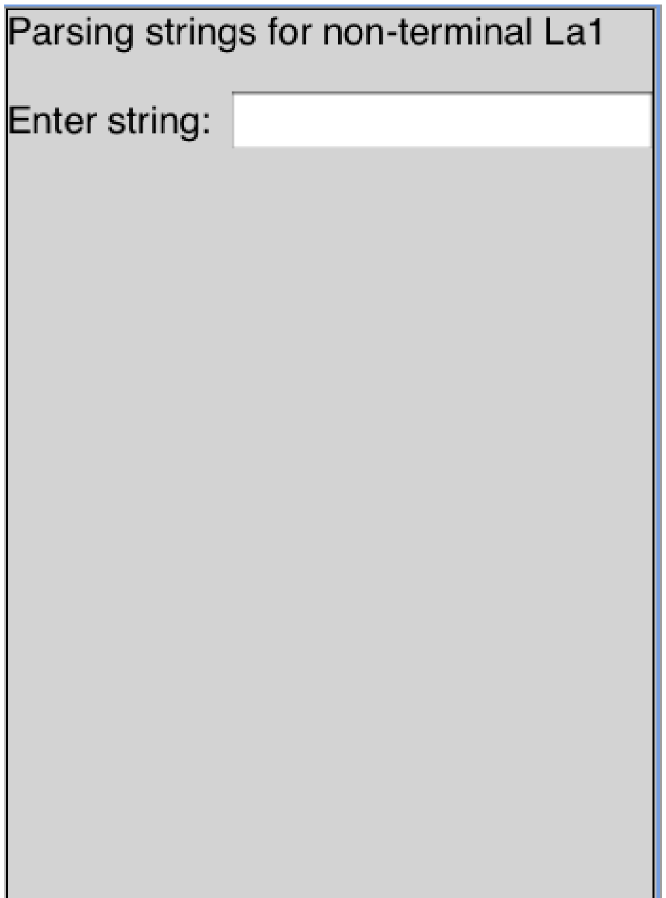


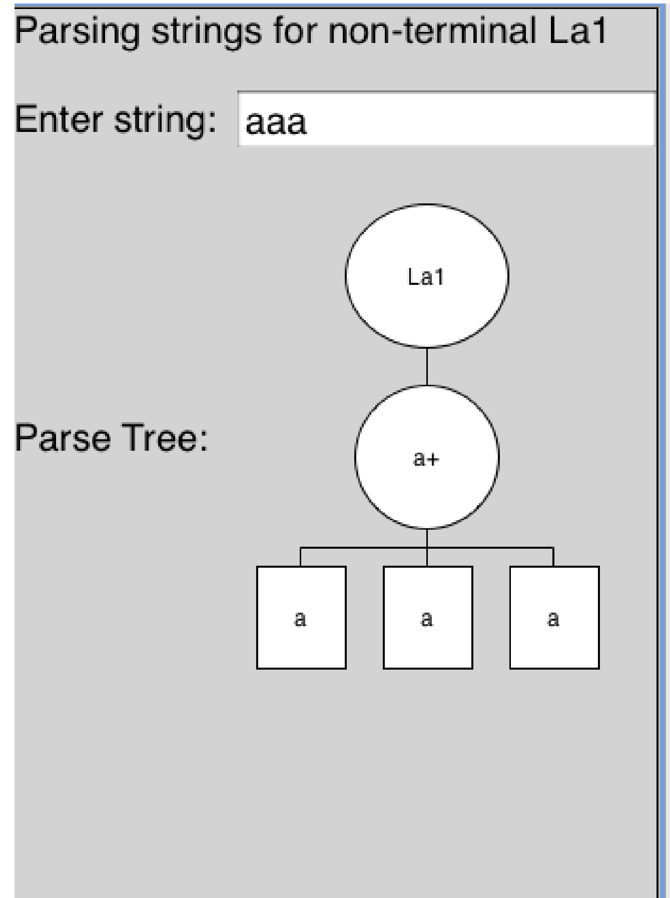



```
parseTreeViewer(#start[La0])
```

Language La0: List of one or more a's

```
start syntax La1 = "a"+;
```

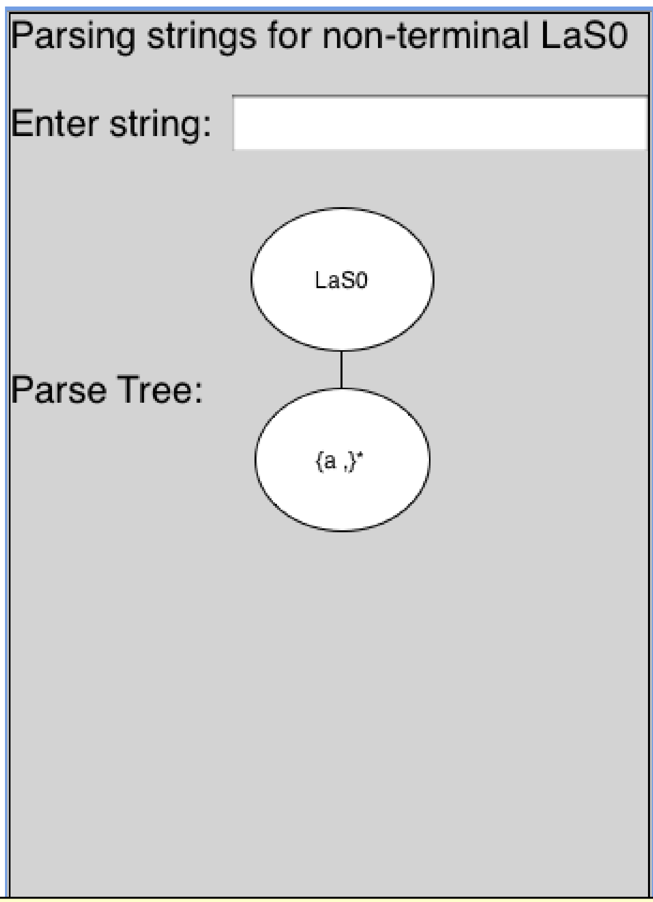


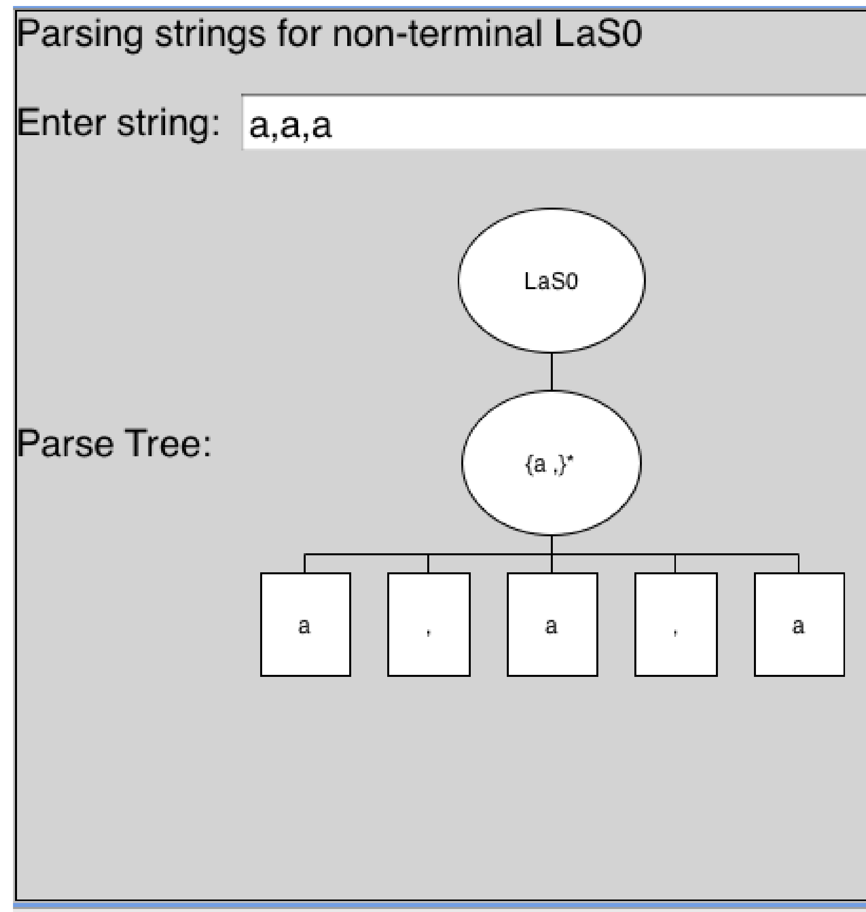



```
parseTreeViewer(#start[La1])
```

Language LaS0: List of zero or more a's separated by comma's

```
start syntax LaS0 = {"a" ","}*;
```

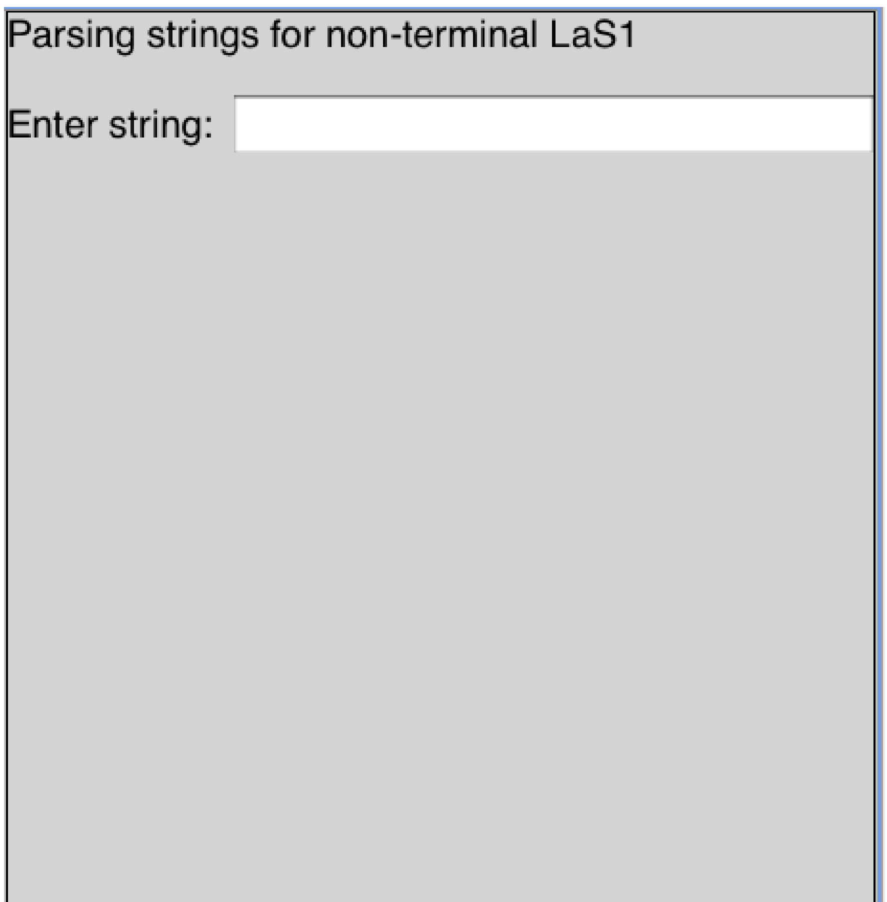


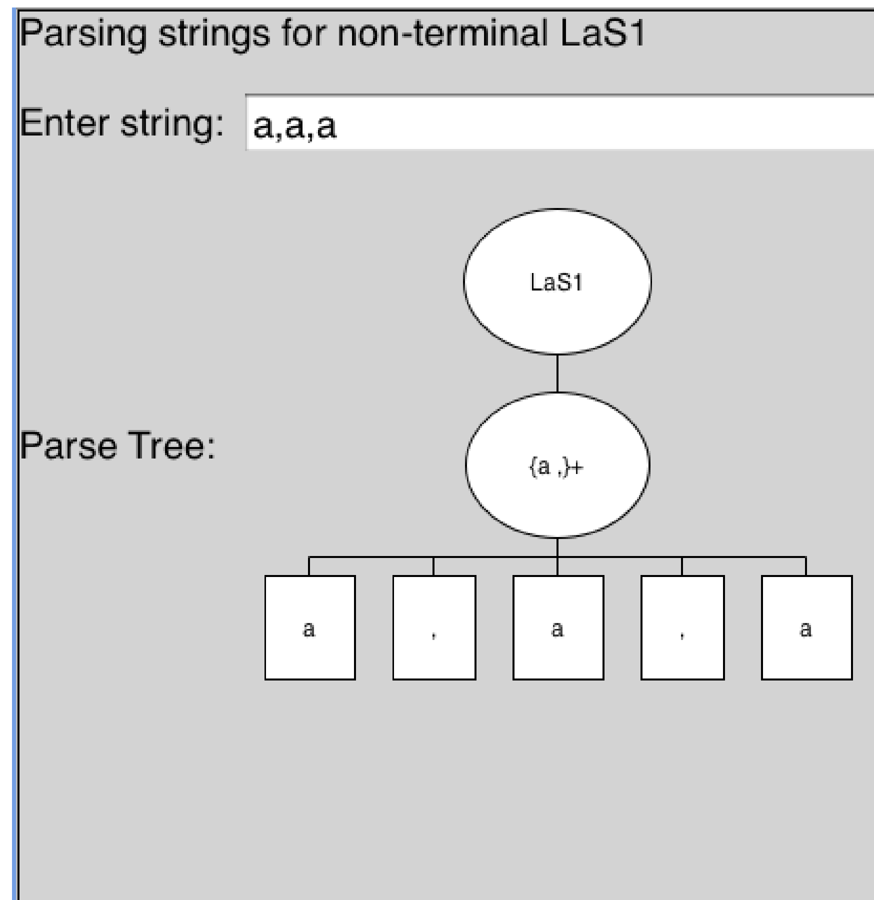



```
parseTreeViewer(#start[LaS0])
```

Language LaS1: List of one or more a's separated by comma's

```
start syntax LaS1 = {"a" ","}+;
```

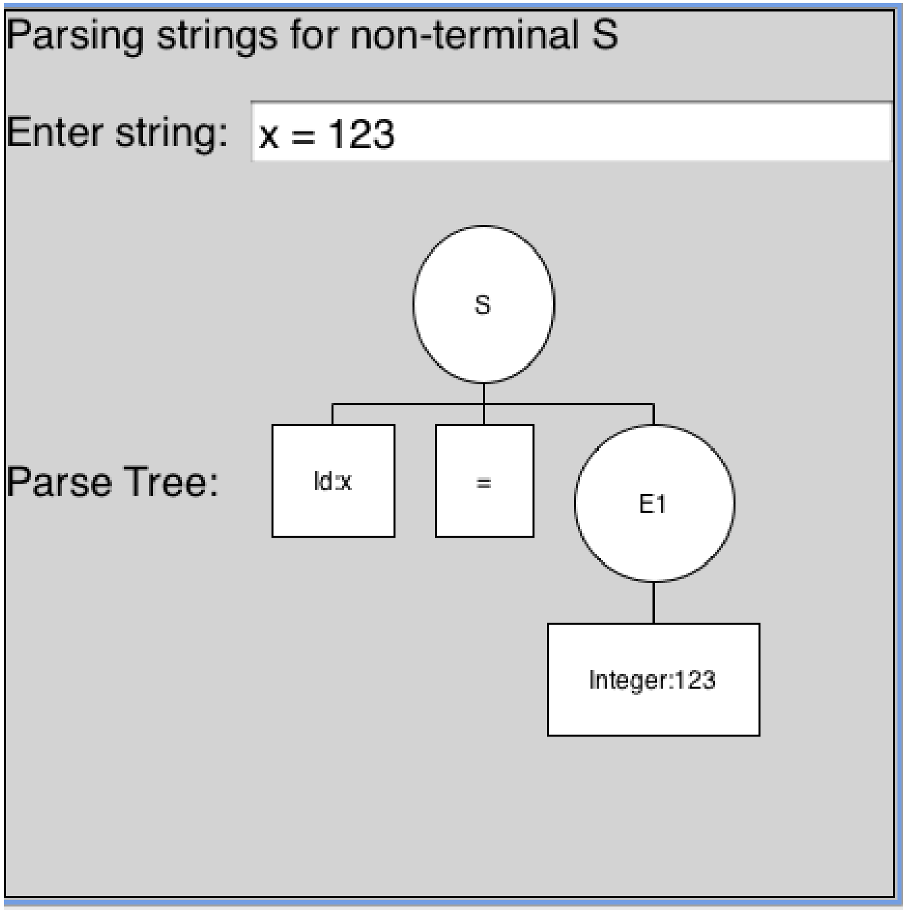





```
parseTreeViewer(#start[LaS1])
```

Language S: Statement-like

```
layout Whitespace = [\ \t\n]*;

lexical Integer = [0-9]+;
syntax E1 = Integer
          | E1 "*" E1
          > E1 "+" E1
          | "(" E1 ")"
          ;
lexical Id = [a-z][a-z0-9]*;

start syntax S =
     Id "=" E1
   | "while" E1 "do" {S ";"}+ "od"
   ;
```




```
parseTreeViewer(#start[S])
```

What is a grammar?

- A context-free grammar is 4-tuple G=(N,Σ,P,S)
- N is a set of nonterminals
- Σ is a set of terminals (literal symbols, disjoint from N)
- P is a set of production rules of the form (A, α) with A a nonterminal, and α a list of zero or more terminals or nonterminals. Notation:
  - A ::= α (in BNF)
  - `syntax A = α;` (in Rascal)
- S ε N, is the start symbol.

Derivations

- A grammar is a formal system with one proof rule:
  - $\alpha A \beta \Rightarrow \alpha \gamma \beta$ if A ::= γ is a production
  - A is a nonterminal, α, β, γ possibly empty lists of (non)terminals

Example

- N = {E}
- Σ = { +, *, (,), -, a}
- S = E
- P = {E::=E+E, E::=E*E, E::=(E), E::=-E, E::= a}
- A derivation:
  - E => - E => - (E) => - (E + E) => - (a + E) => - (a + a)
- A derivation generates a sentence from the start symbol

Exercise

- Give a derivation for a + a * a

Language defined by a Grammar

- Extend the one step derivation $\Rightarrow$ to
  - $\Rightarrow^*$ derive in *zero* or more steps
  - $\Rightarrow^+$ derive in *one* or more steps
- The language defined by a grammar
  $G = (N,\Sigma,P,S)$ is:
  - $L(G) = \{ w \in \Sigma^* \mid S \Rightarrow^+ w \}$
- A sentence $w \in L(G)$ only contains terminals

Derivations

- At each derivation step there are choices:
  - Which nonterminal will we replace?
  - Which alternative of the selected nonterminal will we apply?
- Two choices:
  - Leftmost: always select leftmost nonterminal
  - Rightmost: always select leftmost nonterminal

Examples

- Recall our -(a+a) example
- Leftmost derivation of -(a+a):
  - E => - E => - (E) => - (E + E) => - (a + E) => - (a + a)
- Rightmost derivation of -(a+a):
  - E => - E => - (E) => - (E + E) => - (E + a) => - (a + a)

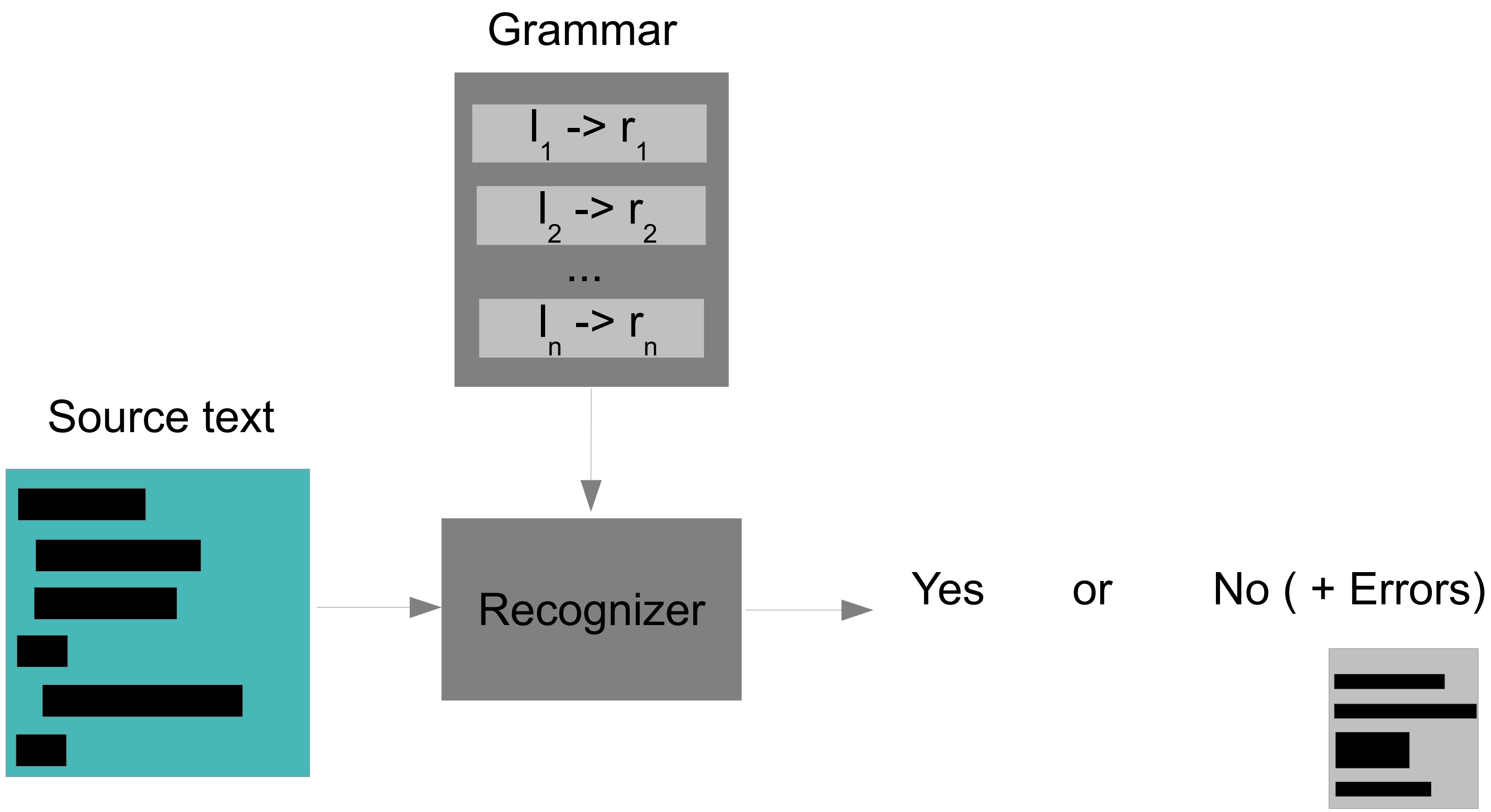
Derivation versus parsing

- A derivation generates a sentence from the start symbol
- A recognizer does the inverse: it deduces the start symbol from the sentence
- Leftmost derivation leads to a topdown recognizer (LL parser)
- Rightmost derivation leads to a bottom-up recognizer (LR parser)

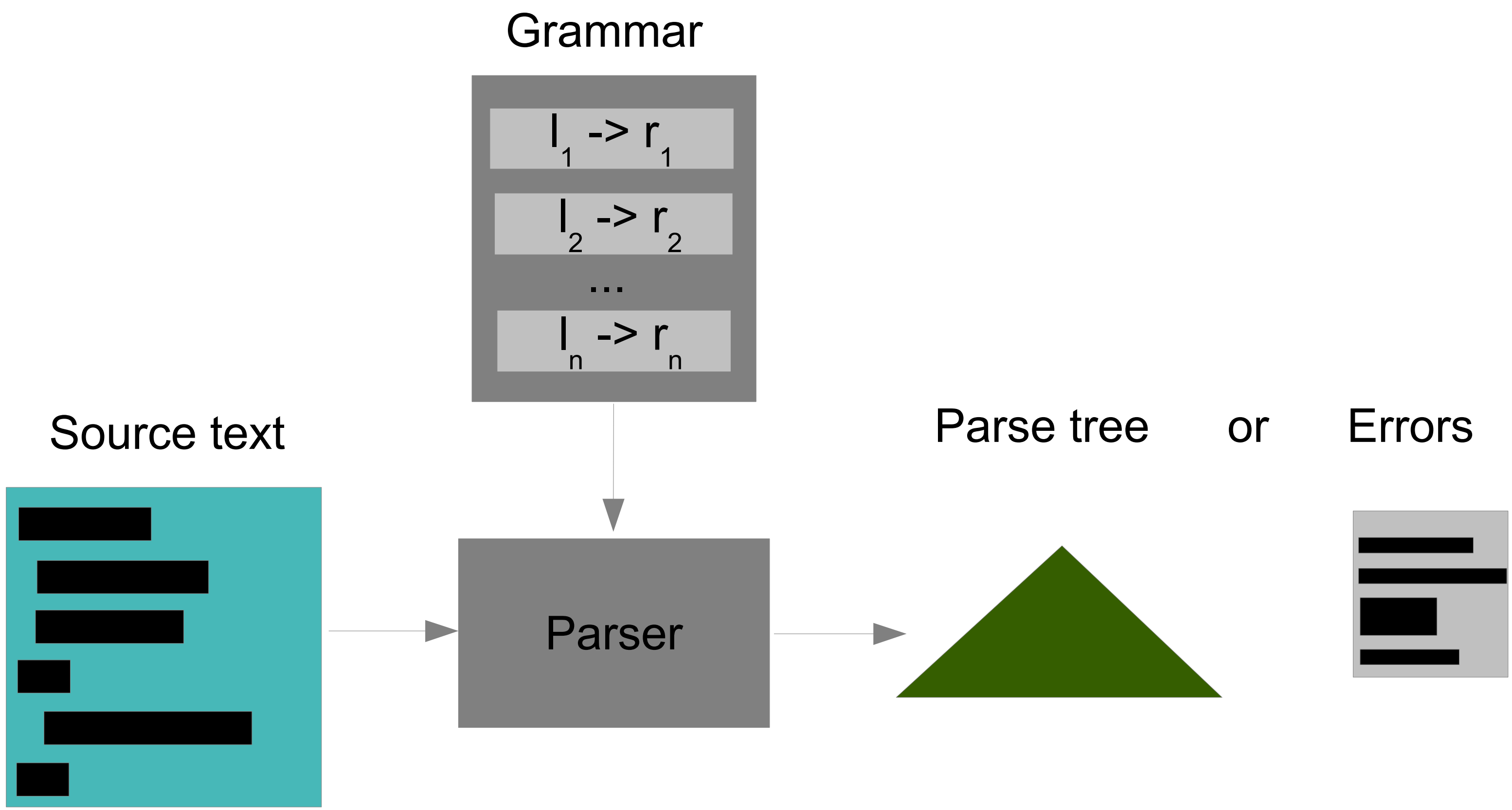
Recognizing versus Parsing

- Recognizer:
  - Is this string in the language?
- Parser:
  - Is this string in the language?
  - If so, return a syntax tree
- Generalized Parser:
  - Idem, but may return more than one tree
  - Accepts larger class of grammars

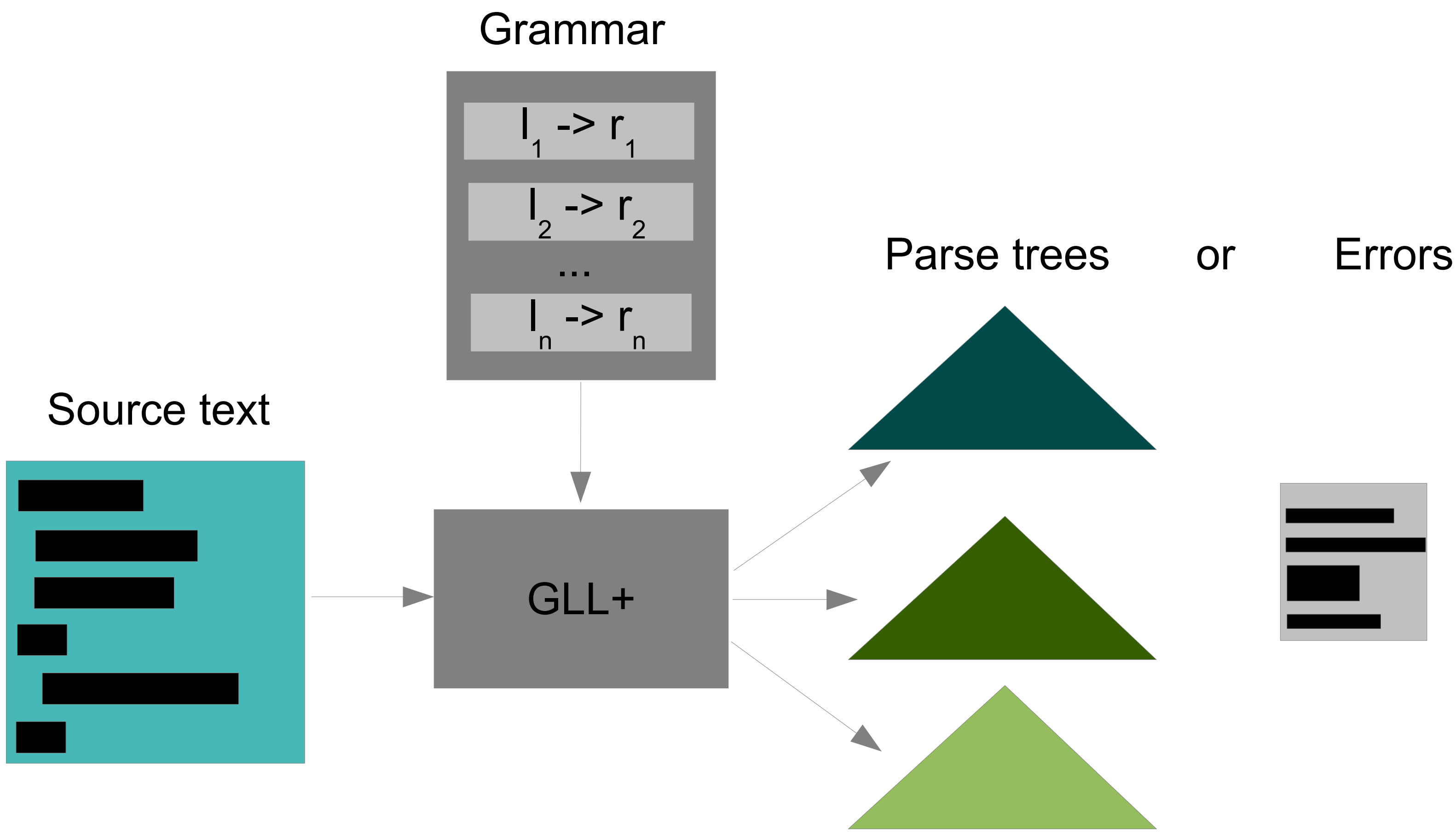
A Recognizer



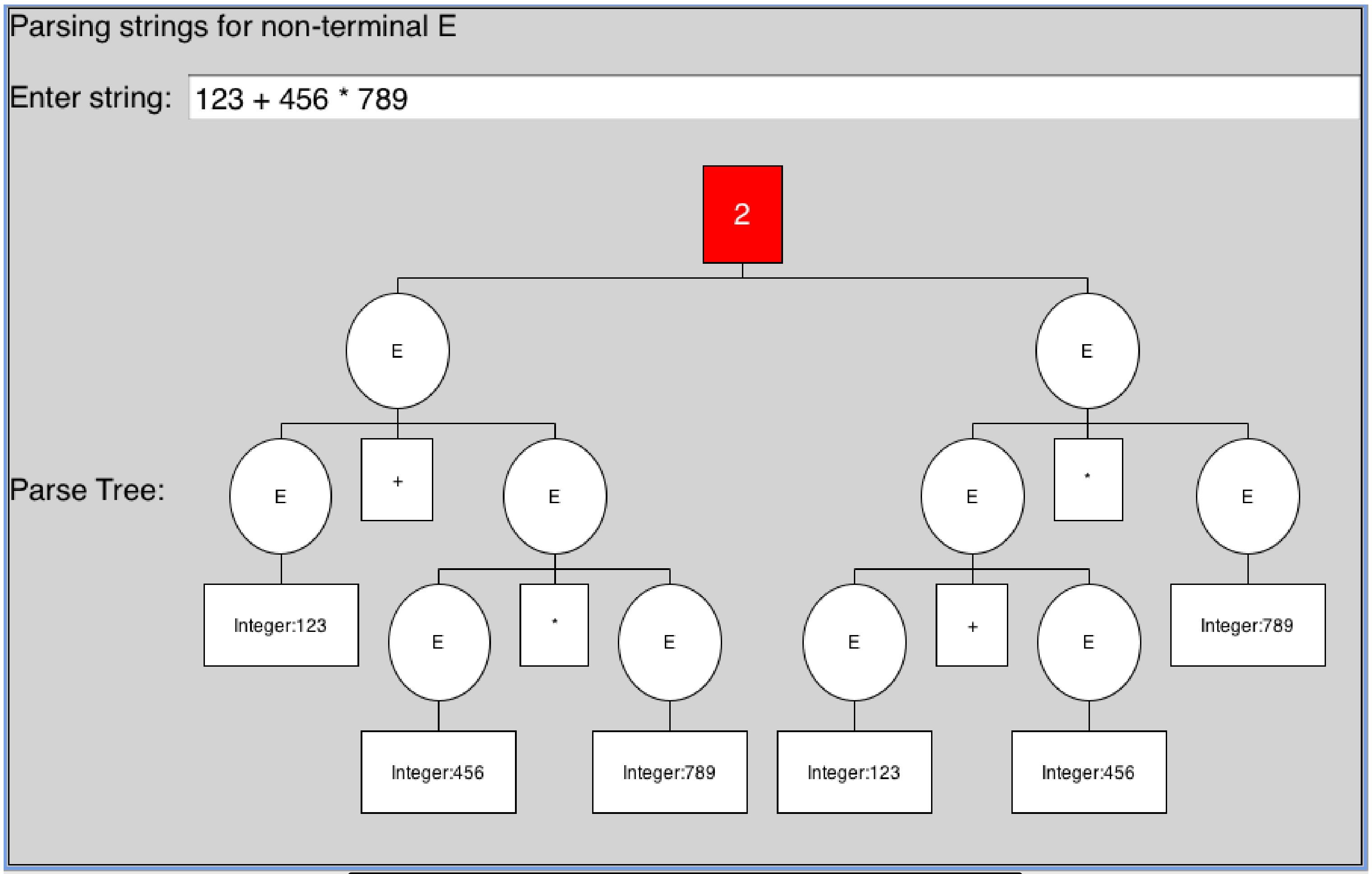
A Parser


Grammar
l1 -> r1
l2 -> r2
...
ln -> rn
Source text
Parser
Parse tree
or
Errors

Generalized Parser (as used in Rascal)



Recall Language E



`parseTreeViewer(#start[E])`

General Parsing Approaches

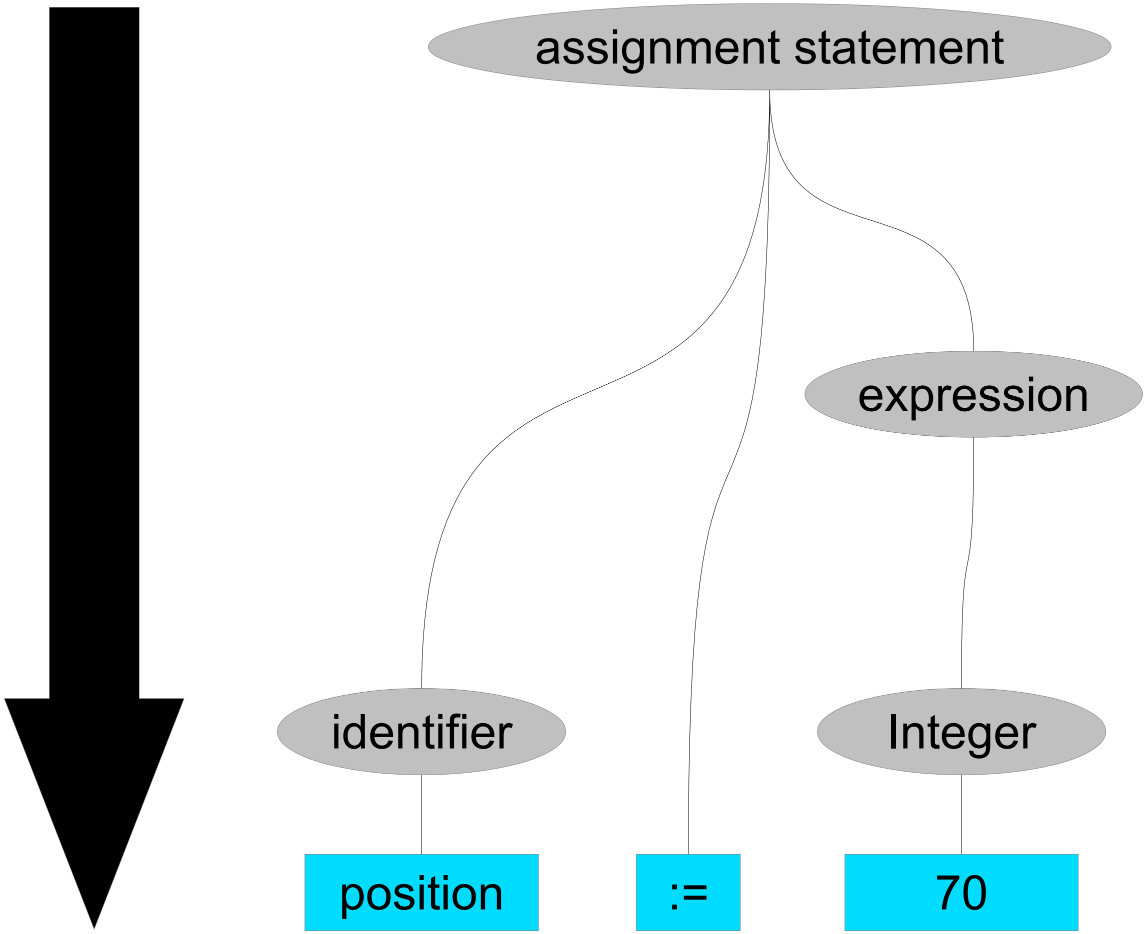
- Top-Down (predictive)
  - Predict what you want to parse, and verify the input
  - Leftmost derivation
- Bottom-Up
  - Recognize token by token and infer what you are recognizing by combining these tokens.
  - Rightmost derivation
- The type of grammar determines the parsing techniques that can be used

Parsing techniques

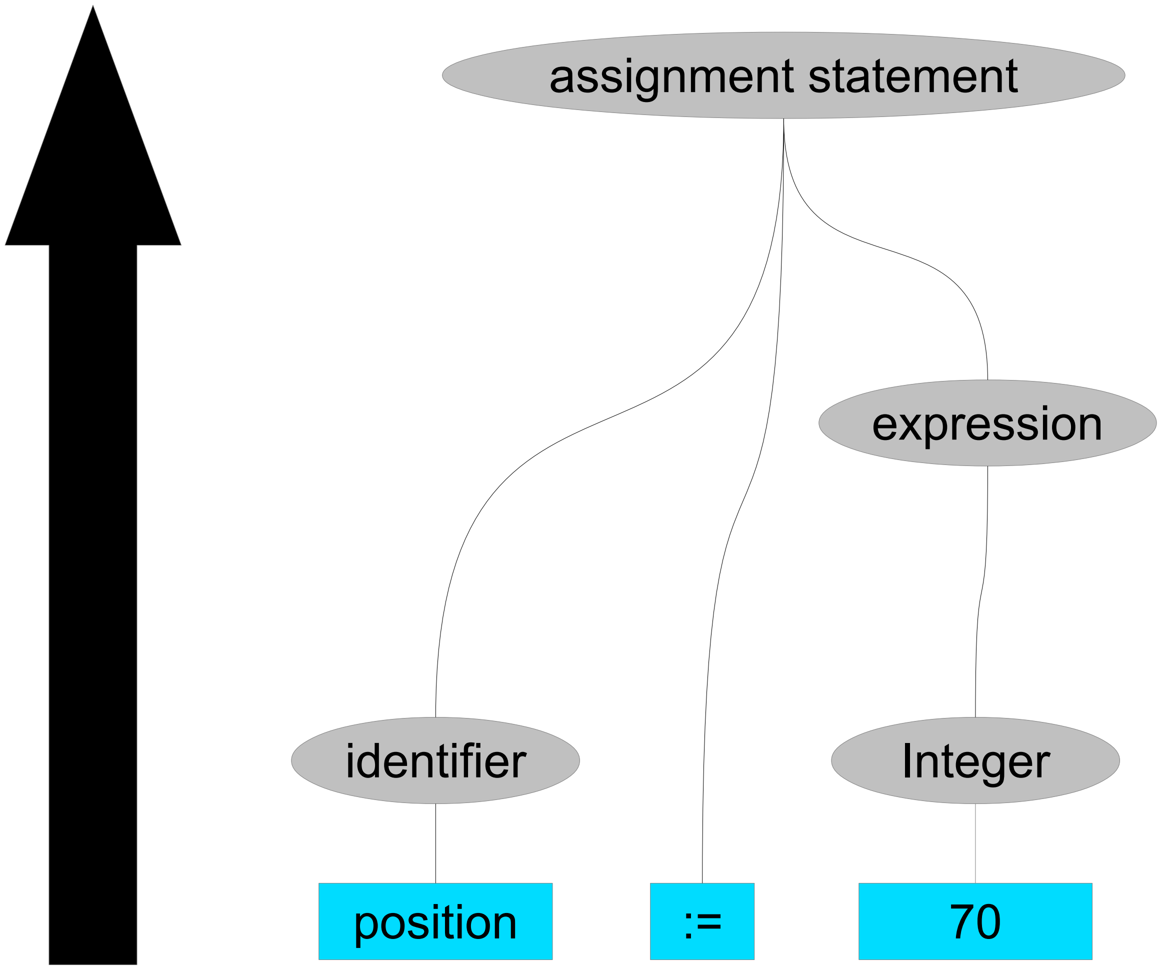
- Top-Down
- **LL**(**1**): **L**eft-to-right, **L**eftmost derivation, 1 symbol lookahead
- LL(k), k symbols lookahead
- ...

- Bottom-Up
- **LR**(1): **L**eft-to-right, **R**ightmost, 1 symbol lookahead
- LR(k)
- LALR(k)
- SLR(k)
- ...

Top-Down Parser



Bottom-Up Parser



How do we get a parser?

Write it by hand

- Pro: large flexibility
- Pro: each mixing of parsing with other actions
  - Type checking
  - Tree building
- Pro: specialized error messages/error recovery
- Con: more effort
- Con: reprogramming needed when grammar changes
- Con: unclear which language is recognized

Example: Writing a Parser

```
syntax A = "a";
syntax B = "b";
start syntax C = "c" | A C B;
```

Idea: implement three functions

bool parseA()

bool parseB()

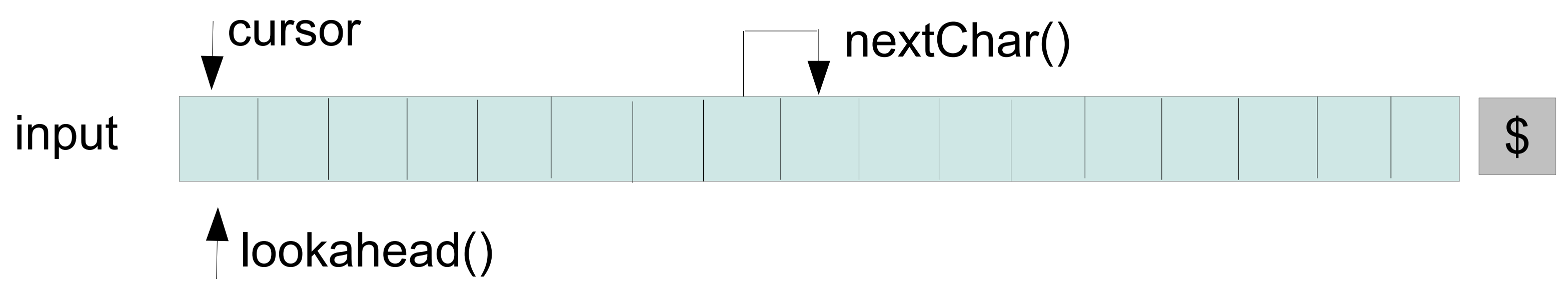
bool parseC()

that parse the corresponding non-terminal

Infrastructure

```
syntax A = "a";
syntax B = "b";
start syntax C = "c" | A C B;
```

```
str input = "";
int cursor = -1;

private void initParse(str s) { input = s; cursor = 0; }

private str lookahead() = cursor < size(input) ? input[cursor] : "$";

private void nextChar(){
     cursor += 1;
}

public bool endOfString() = lookahead() == "$";

public bool parseC(str s){
  initParse(s);
  return parseC() && endOfString();
}
```



Parser

```
syntax A = "a";
syntax B = "b";
start syntax C = "c" | A C B;
```

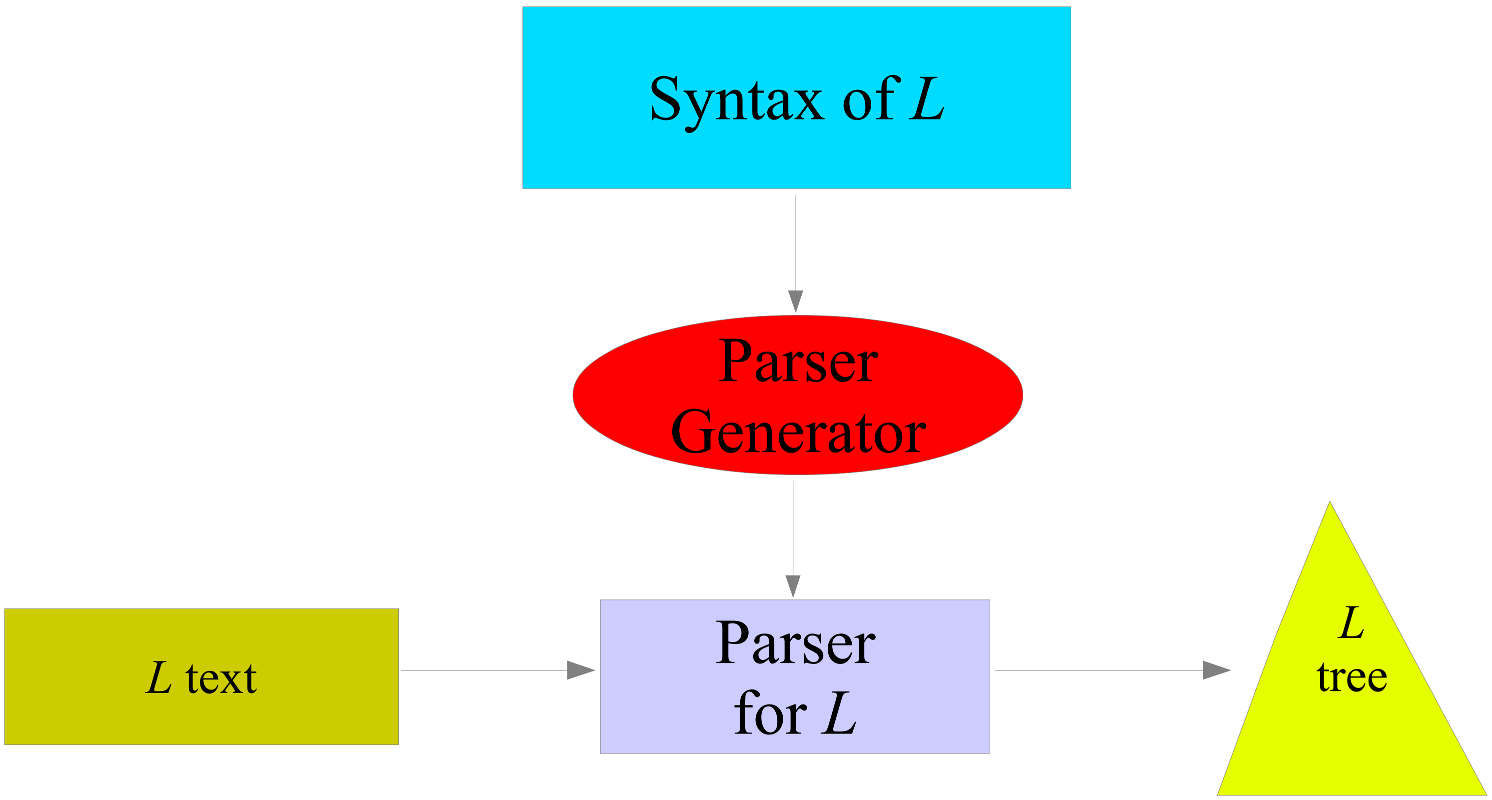
```
public bool parseTerm(str term){
  if(lookahead() == term){
     nextChar();
     return true;
  }
  return false;
}

public bool parseA() = parseTerm("a");

public bool parseB() = parseTerm("b");

public bool parseC(){
   if(lookahead() == "c")
      return parseTerm("c");
   if(lookahead() == "a"){
      parseA();
      if(parseC()){
         if(lookahead() == "b"){
            return parseB();
         }
      }
   }
   return false;
}
```

```
rascal>parseC("aaacbbb")
bool: true

rascal>parseC("aaacbb")
bool: false
```

Trickier Cases

- Fixed lookahead > 1 characters
- No fixed lookahead
- Alternatives overlap partially:
  - Naive approach tries first alternative and then fails but another alternative may match.
  - A backtracking approach tries each alternative and if it fails it restores the input position and tries other alternatives.
- Generalized parsing approach: try alternatives in parallel

Automatic Parser Generation



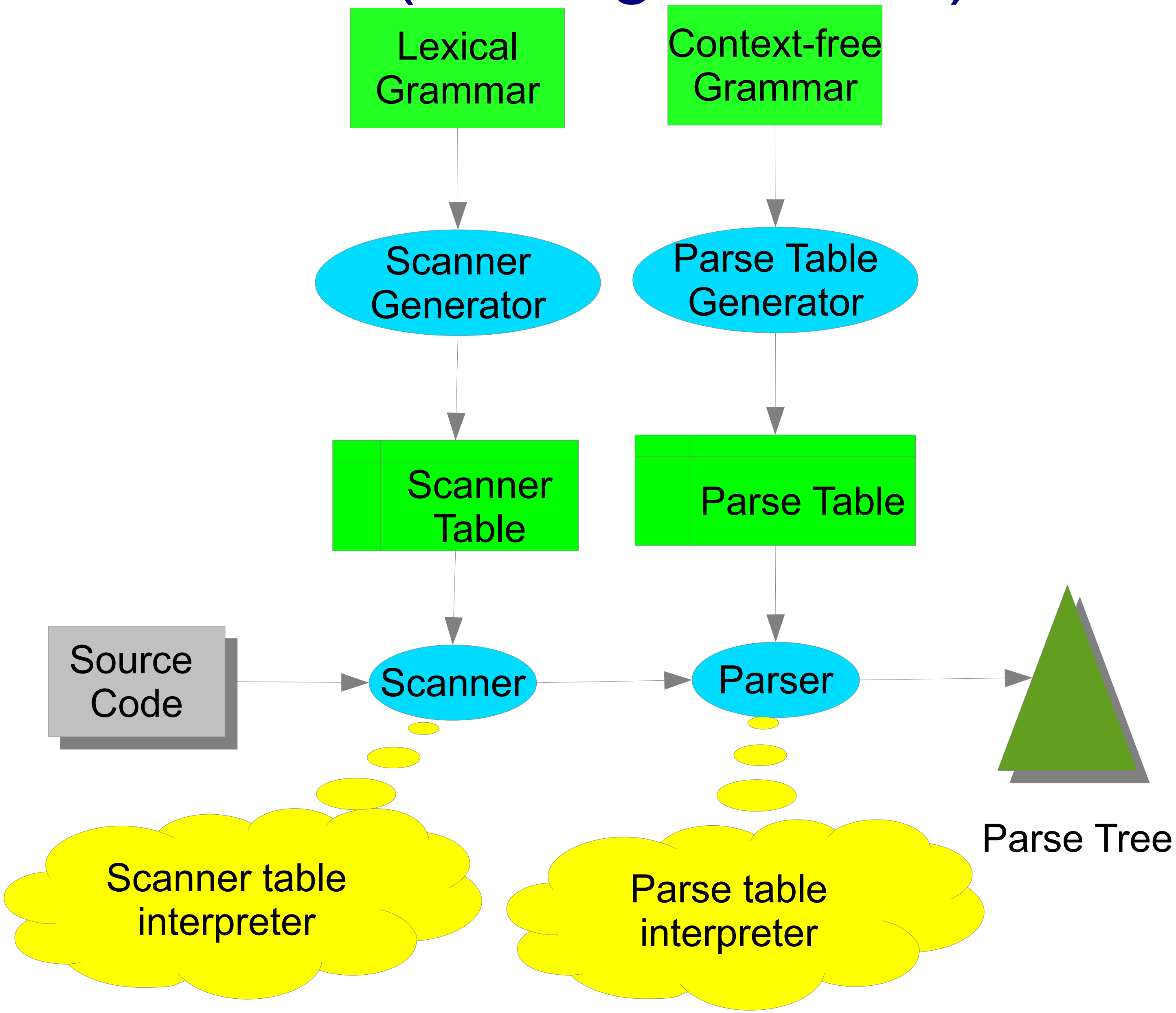
Some Parser Generators

- Bottom-up
  - Yacc/Bison, LALR(1)
  - CUP, LALR(1)
  - SDF, SGLR
- Top-down:
  - ANTLR, LL(k)
  - JavaCC, LL(k)
  - Rascal, GLL+
- Except SDF and Rascal, all depend on a scanner generator

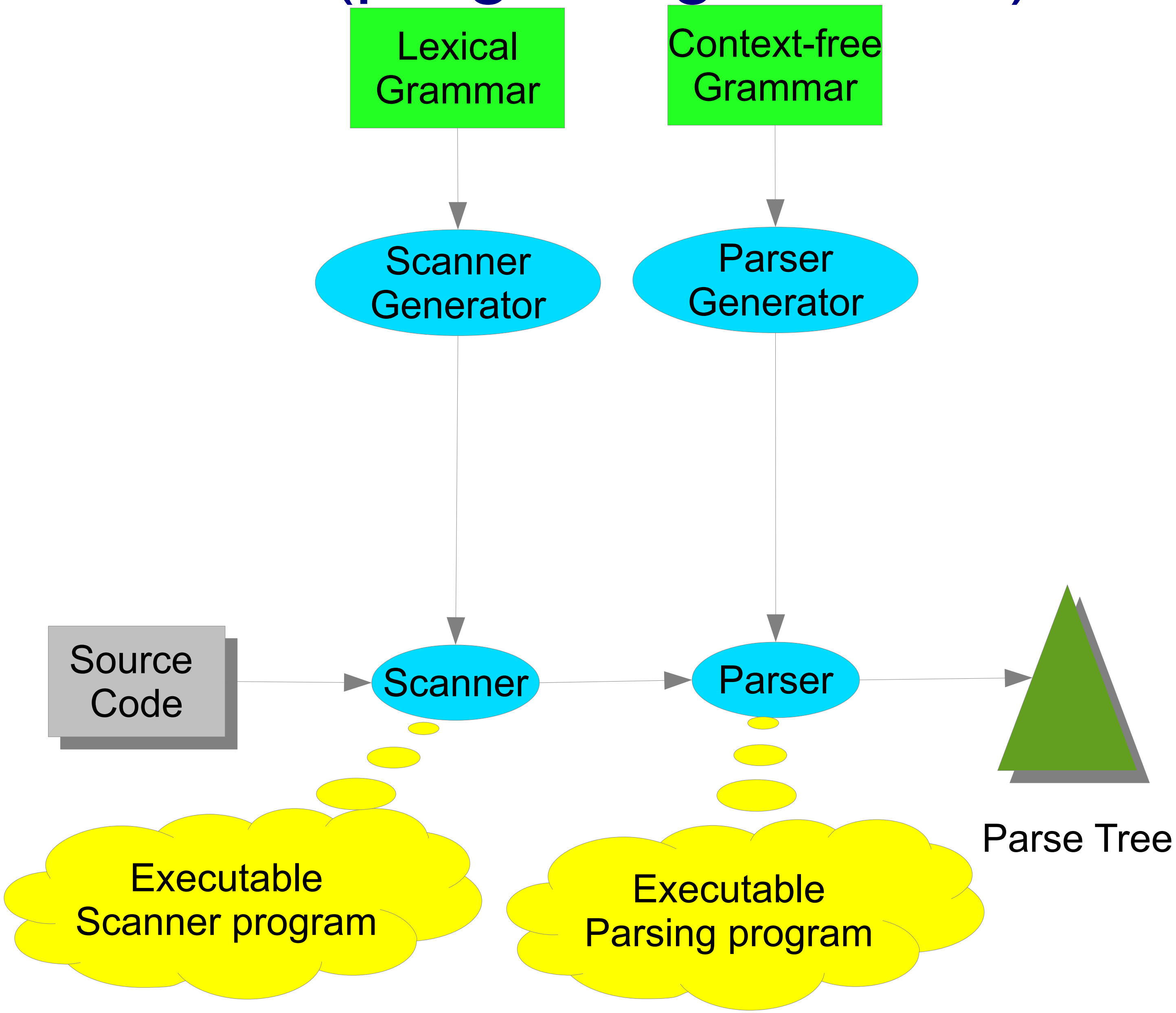
Assessment parser implementation

- Manual parser construction
  - \+ Good error recovery
  - \+ Flexible combination of parsing and actions
  - \- A lot of work
- Parser generators
  - \+ *May* save a lot of work
  - \- Complex and rigid frameworks
  - \- Rigid actions
  - \- Error recovery more difficult

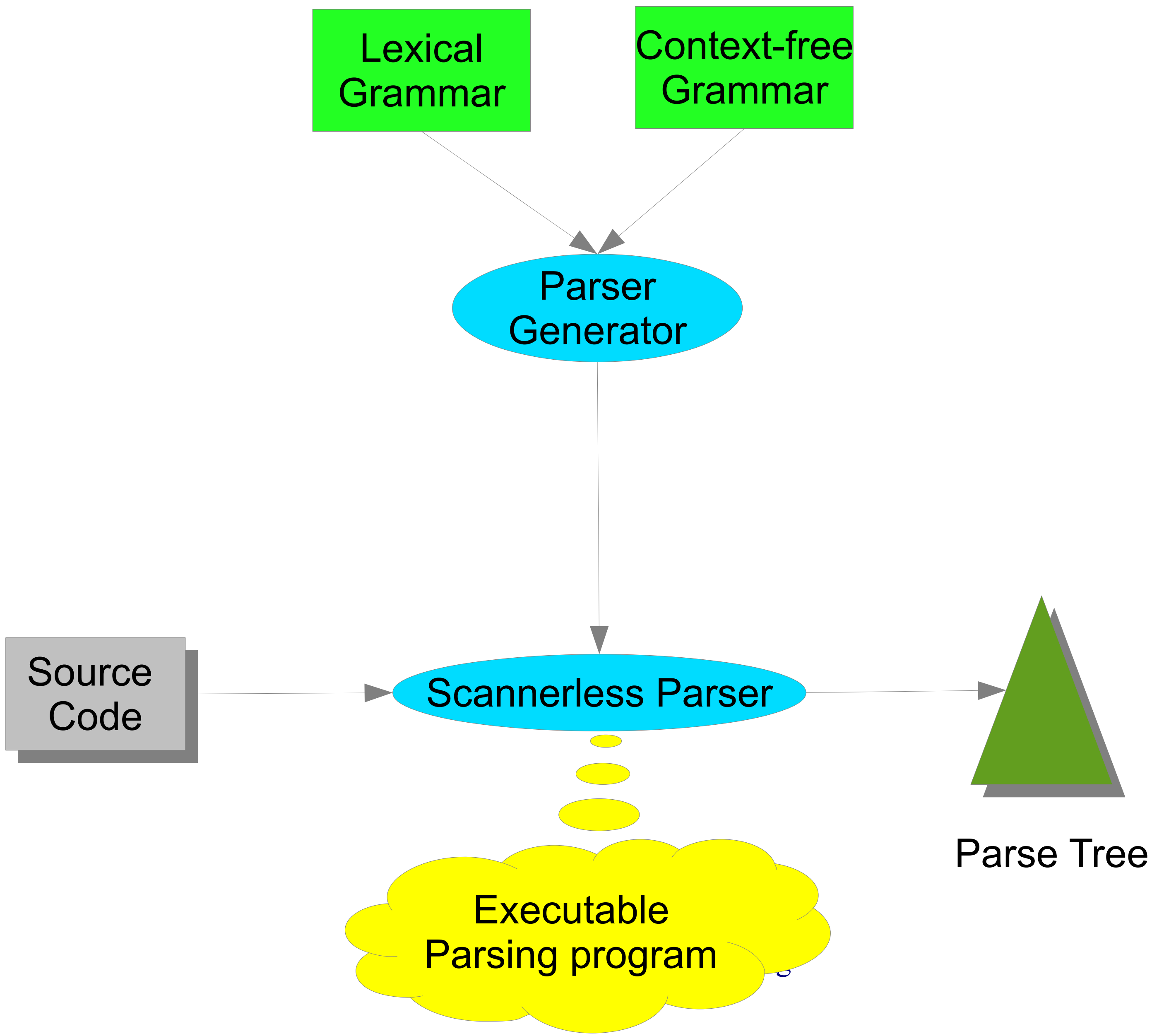
Parser Generation Architecture
(table-generator)



Parser Generation Architecture
(program-generator)



Parser Generation Architecture



Pragmatic Issues

- How do I get my grammar in a form accepted by the parser generator:
  - Rewriting, refactoring, renaming, ...
  - May be very hard (or impossible!)
- How does the scanner get its input?
- How are scanner and parser interfaced?
- How are actions attached to grammar rules?
  - Semantic actions in C/Java code + Interface variables
- How to define error recovery?

Parsing in Rascal

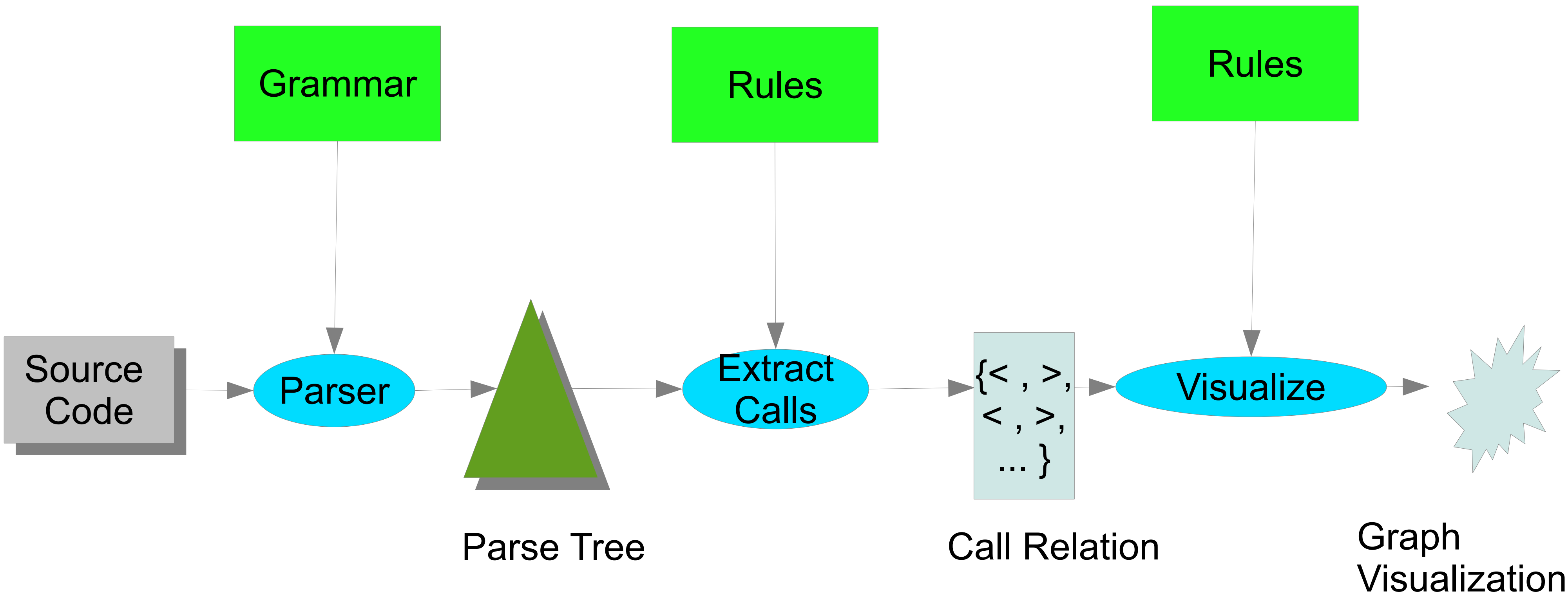
- Scannerless, GLL+ parser
- Grammars can easily be composed (this is not possible with other technologies)
- Parsing and executing Rascal code can be mixed.
- Work in progress: error recovery.

Conclusions

- Parsing is a vital ingredient for many systems
- Formal languages, grammars, etc. are a well-established but rather theoretical part of computer science. Learn the basic notions!
- Not always easy to get to grips with a specific parsing technology
  - Grammar rewriting/refactoring is difficult
- Rascal's scannerless GLL+ parser makes this unnecessary.

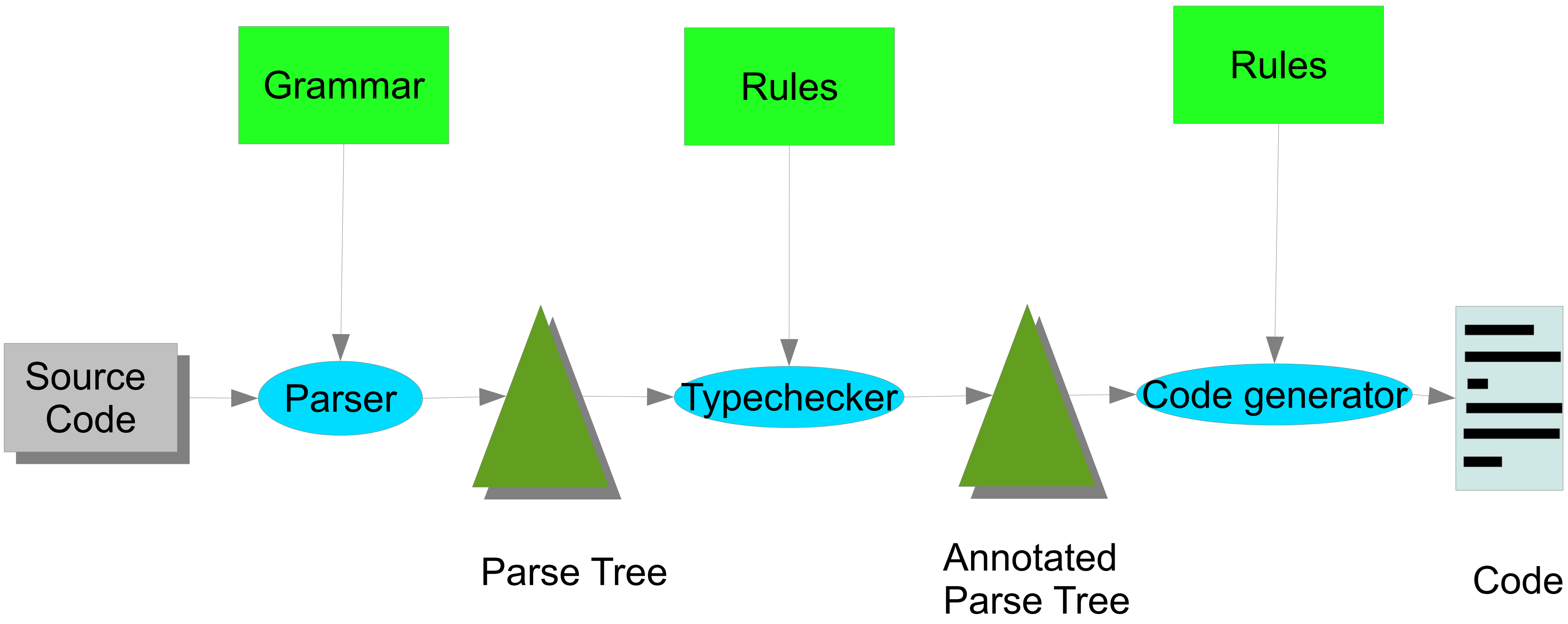
Parser in a Bigger Picture

Call Graph Visualization

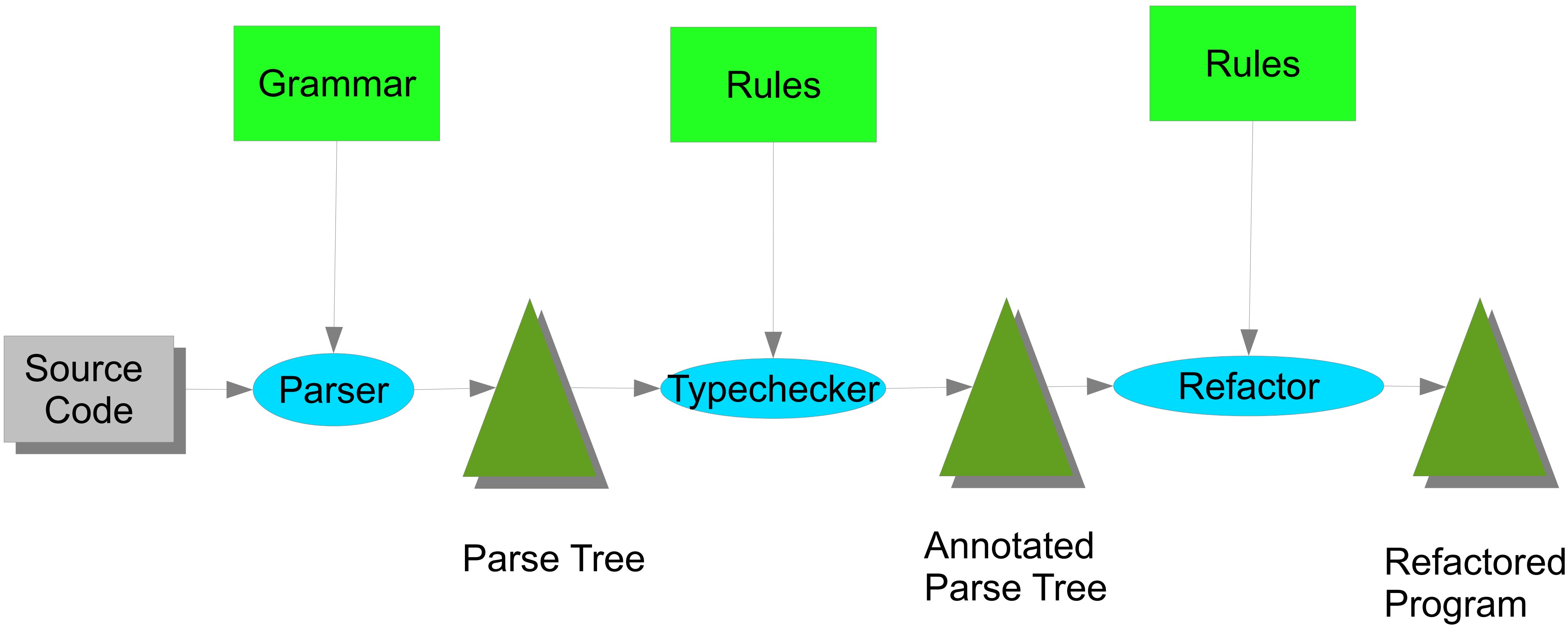


Parser in a Bigger Picture

Compiler



Parser in a Bigger Picture
Refactoring



Further Reading

- http://en.wikipedia.org/wiki/Chomsky_hierarchy
- D. Grune & C.J.H. Jacobs, *Parsing Techniques: A Practical Guide*, Second Edition, Springer, 2008
- Tutor/Rascalopedia (Grammar, Language, LanguageDefinition)
- Tutor/Rascal (Concepts/SyntaxDefinitionAndParsing, Declarations/Syntaxdefinition)
- Tutor/Recipes/Languages