

Compiler 1: Grundlagen

Lexer/Parser-Generierung mit ANTLR



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FG Eingebettete Systeme und ihre Anwendungen
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- ▶ ANTLR - Another Tool for Language Recognition
- ▶ Kurze Einführung in ANTLR 3.x
 - ▶ **Inkompatibel** zur ANTLR 2.x!
- ▶ Inhalt basiert wieder auf Material von Theo Ruys
 - ▶ “Vertalerbouw”, Universität Twente



ANTLR

- ▶ Eingabe: Grammatik in EBNF (und mehr!)
- ▶ Ausgabe: Erkenner für Sprache

Arten von Eingabedaten

- ▶ Zeichenströme (bearbeiten mit [Scanner](#))
- ▶ Token-Ströme (bearbeiten mit [Parser](#))
- ▶ Knoten-Ströme (bearbeiten mit [Tree Walker](#))

ANTLR 3.x

- ▶ LL(*) Compiler Generator
 - ▶ Erzeugt gut lesbaren Code für rekursiven Abstieg
- ▶ Erzeugt Erkener in [Java](#), [C++](#), [C#](#), [Python](#), etc.



ANTLR erzeugt prädiktive LL(k) oder LL(*) Erkennen

- ▶ Berechnet FIRST, FOLLOW und LOOKAHEAD Mengen
- ▶ Überprüft auf syntaktische Korrektheit
- ▶ Alle erzeugten Erkennen verwenden **rekursiven Abstieg**
 - ▶ **Keine** endlichen Automaten
 - ▶ Genau das Schema aus Watt & Brown

Alternative Compiler-Generatoren

- ▶ Lexer/Scanner: lex, flex, JFlex
- ▶ Parser: yacc/bison, JCup, JavaCC, SableCC, SLADE



Internet

- ▶ <http://www.antlr.org>
- ▶ Dort: Wiki, Thema “FAQ und Getting Started”
- ▶ Sehr umfangreiche Materialsammlung
 - ▶ Leider unstrukturiert

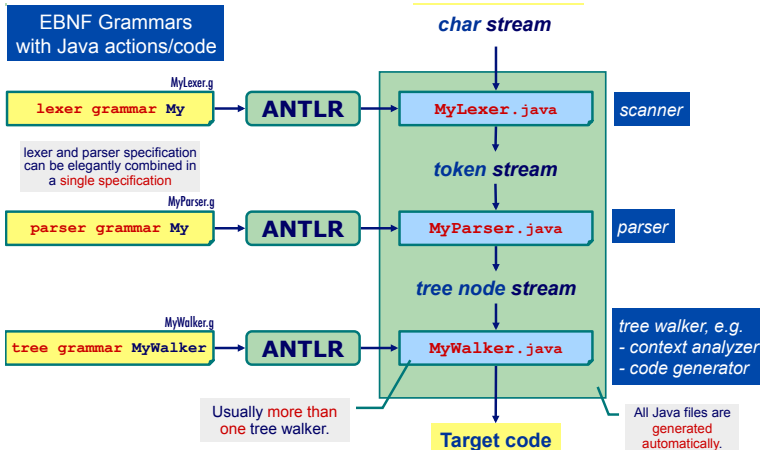
Besser: Buch *The Definitive ANTLR Reference*

- ▶ Terence Parr
- ▶ Pragmatic Bookshelf 2007
- ▶ **Sehr gut lesbar!**

Änderungen von ANTLR 2.x zu 3.x



- ▶ ANTLRWorks: IDE für Grammatiken und Debugging
- ▶ Unterstützung für LL(*)
- ▶ Aufbau von ASTs besser integriert (*rewrite rules*)
- ▶ Portableres Back-End (z.B. Ruby etc.)
- ▶ Bessere Fehlermeldungen und -behandlung
- ▶ Einbau von **StringTemplate** zur leichteren Texterzeugung
 - ▶ Sehr hilfreich für textuelle Code-Erzeugung
- ▶ Neue Syntax für Grammatiken
 - ▶ Inkompatibel zu ANTLR 2.x



Struktur der Eingabedatei



```
[gtype] grammar FooBar;
```

gtype may be empty or **lexer**, **parser** or **tree**.

```
options {
```

options for entire grammar file

```
}
```

```
tokens {
```

token definitions

```
}
```

```
@header {
```

will be copied to the generated Java file(s)

e.g. **imports**

```
}
```

```
@rulecatch {
```

*error handling: how to deal with **exceptions**?*

```
}
```

```
@members {
```

*optional **class definitions**: instance variables, methods*

```
}
```

```
rulename : all rules for FooBar
```

A single **.g** file can contain a **Lexer** and/or **Parser**, or a **TreeParser**.

Aufbau einer Regel

Wird in Java-Methode umgesetzt

```
rulename [args] returns [T val]
{
  options { local options }
  : alternative1
  | alternative2
  | ...
  | alternativen
  ;
}
```

optional, used for **passing information** around

An **alternative** is an EBNF **regular expression** containing:

- **rule**name****
- **TOKEN**
- **EBNF operator**
- **Java code in braces**

EBNF operators

A B	A or B
A*	zero or more A's
A+	one or more A's
A?	an optional A

When using **EBNF operators** in ANTLR: use **parentheses** to enclose more than one symbol..

+ optional **code sections** to insert at **start** of **end** of method

```
@init { ... }
@after { ... }
```

Example

```
expr      : operand (PLUS operand)*
          ;
operand   : LPAREN expr RPAREN
          | NUMBER
          ;
```

Kommandozeile

```
java org.antlr.Tool eingabe.g
```

CLASSPATH muss enthalten

- ▶ antlr.jar stringtemplate.jar antlr3.jar antlr3-runtime.jar

GUIs

- ▶ ANTLRWorks (IntelliJ): <http://www.antlr.org/works>
- ▶ AntlrDT (Eclipse): <http://www.certiv.net/projects/plugins/antlrdt.html>
- ▶ ANTLR IDE (Eclipse): <http://antlr3ide.sourceforge.net/>

Beispielsprache: Calc 1

Einfache Sprache für Taschenrechner



- ▶ **Deklarationen**
 - ▶ Nur Integer-Variablen
 - ▶ Müssen vor Anweisungen stehen
- ▶ **Anweisungen**
 - ▶ Zuweisung zu Variablen
 - ▶ Ausgabe von ausgewerteten Ausdrücken
- ▶ **Ausdrücke**
 - ▶ Zunächst nur Addition und Subtraktion

```
// ex1.calc  
var n: integer;  
var x: integer;  
n := 2+4-1;  
x := n+3+7;  
print(x);
```



EBNF for Calc

program	::=	declarations statements EOF
declarations	::=	(declaration SEMICOLON)*
declaration	::=	VAR IDENTIFIER COLON type
statements	::=	(statement SEMICOLON)+
statement	::=	assignment printStatement
assignment	::=	lvalue BECOMES expr
printStatement	::=	PRINT LPAREN expr RPAREN
lvalue	::=	IDENTIFIER
expr	::=	operand ((PLUS MINUS) operand)*
operand	::=	IDENTIFIER NUMBER LPAREN expr RPAREN
type	::=	INTEGER

```
// ex1.calc
var n: integer;
var x: integer;
n := 2+4-1;
x := n+3+7;
print(x);
```

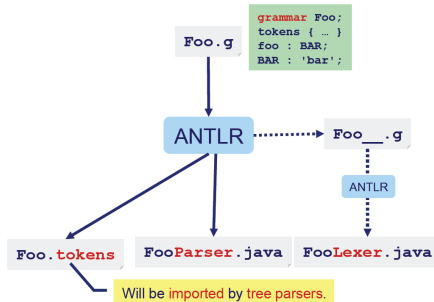
All terminals are written
as UPPERCASE symbols.



ANTLR wird vier unterschiedliche Erkenner erzeugen

- ▶ **CalcLexer** (erweitert `Lexer`)
Übersetzt Zeichenstrom in Tokenstrom
- ▶ **CalcParser** (erweitert `Parser`)
Übersetzt Token-Strom in Knoten-Strom (von AST-Knoten)
- ▶ **CalcChecker** (erweitert `TreeParser`)
Läuft über Knoten-Strom des AST und führt kontextuelle Überprüfung durch
↳ automatisch erzeugtes **Visitor-Pattern**
- ▶ **CalcInterpreter** (erweitert `TreeParser`)
Läuft über Knoten-Strom des AST und interpretiert Programm
↳ automatisch erzeugtes **Visitor-Pattern**

- ▶ Enge Zusammenarbeit zwischen Lexer und Parser
 - ▶ Lexer produziert Tokens aus Zeichenstrom
 - ▶ Parser konsumiert Tokens
- ▶ ANTLR 3.x erlaubt Kombinieren von Lexer und Parser in einer Spezifikation





- ▶ **Literale** Zeichenketten sind in einfache Anführungszeichen eingeschlossen
 - ▶ Beispiele: `'foo'`, `'bar'`
- ▶ **Token-Namen** im Lexer beginnen immer mit Großbuchstaben
 - ▶ Beispiele: `PLUS`, `MINUS`, `Div`
- ▶ **Nichtterminalsymbole** im Parser beginnen immer mit einem Kleinbuchstaben
 - ▶ Beispiele: `program`, `statement`, `dSpace`

Parser und Lexer für Calc 1

Optionen und Tokens

```
grammar Calc;

options {
  k = 1;
  language = Java;
  output = AST;
}

tokens {
  PLUS      = '+' ;
  MINUS     = '-' ;
  BECOMES   = ':=' ;
  COLON     = ':' ;
  SEMICOLON = ';' ;
  LPAREN    = '(' ;
  RPAREN    = ')' ;

  // keywords
  PROGRAM   = 'program' ;
  VAR       = 'var' ;
  PRINT     = 'print' ;
  INTEGER   = 'integer' ;
}
```

This is a **combined specification** (not prefixed by lexer, parser or tree).

amount of **lookahead**, disables LL(*)

Target language is **Java**.

build an **AST**

token definitions (literals)

tokens always **start** with an **uppercase letter** and specify the text for a token

Parser und Lexer für Calc 2

Parser-Produktionen für reine Erkennung, noch keine AST-Konstruktion



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```
program      : declarations statements EOF
              ;
declarations  : (declaration SEMICOLON)*
              ;
statements   : (statement SEMICOLON)+
              ;
declaration  : VAR IDENTIFIER COLON type
              ;
statement    : assignment
              | print
              ;
assignment   : lvalue BECOMES expr
              ;
print        : PRINT LPAREN expr RPAREN
              ;
lvalue       : IDENTIFIER
              ;
expr         : operand ((PLUS | MINUS) operand)*
              ;
operand      : IDENTIFIER
              | NUMBER
              | LPAREN expr RPAREN
              ;
type         : INTEGER
              ;
```

parser specific rules

special "end-of-file" token

parser rules start with a lowercase letter

```
// ex1.calc
var n: integer;
var x: integer;
n := 2+4-1;
x := n+3+7;
print(x);
```

In this example, all tokens are **explicitly named** (as UPPERCASE tokens). It is also possible to use **literals** in the parser specification.

For example:

```
print : 'print' '(' expr ')'
expr  : operand (('+' | '-') operand)*
```

Parser und Lexer für Calc 3

Lexer-Regeln

```
IDENTIFIER : LETTER (LETTER | DIGIT)*
```

lexer specific rules

```
;
```

```
NUMBER : DIGIT+
```

“.*” matches everything except the character that follows it (i.e. ‘\n’).

```
;
```

```
COMMENT : '//' .* '\n'  
         { $channel=HIDDEN; }
```

There are **multiple token channels**. The parser reads from the **DEFAULT** channel. By setting a token’s channel to **HIDDEN** it will be **ignored** by the parser.

```
;
```

```
WS : (' ' | '\t' | '\f' | '\r' | '\n')+  
     { $channel=HIDDEN; }
```

```
;
```

```
fragment DIGIT : ('0'..'9') ;
```

```
fragment LOWER : ('a'..'z') ;
```

shorthand for (the complete)
'a'|'b'|'c'| ...|'y'|'z'

```
fragment UPPER : ('A'..'Z') ;
```

```
fragment LETTER : LOWER | UPPER ;
```

fragment lexer rules can be used by other lexer rules, but **do not** return tokens by themselves

No need to worry about counting the **newlines**; the lexer takes care of this **automatically**.

Parser und Lexer für Calc 4

Parser mit AST-Konstruktion



parser building the AST

```
program      : declarations statements EOF
              -> ^ (PROGRAM declarations statements)
;
declarations : (declaration SEMICOLON!)*
;
statements  : (statement SEMICOLON!)+
;
declaration : VAR^ IDENTIFIER COLON! type
;
statement   : assignment
            | print
;
assignment  : lvalue BECOMES^ expr
;
print       : PRINT^ LPAREN! expr RPAREN!
;
lvalue      : IDENTIFIER
;
expr        : operand ((PLUS^ | MINUS^ ) operand)*
;
operand     : IDENTIFIER
            | NUMBER
            | LPAREN! expr RPAREN!
;
type        : INTEGER
;

```

Imaginary token that is used as the root AST node (not really needed).

Annotations for building AST nodes	
T^	make T the root of this (sub)rule
T!	discard T
-> ^ (...)	tree construction for a rule

For example:

```
VAR^ IDENTIFIER COLON! type
= ^ (VAR IDENTIFIER type)
=
  VAR      VAR
  / \      |
ID  type  ID — type

```

(due to rule of operand) this builds: ^ (PLUS expr expr)

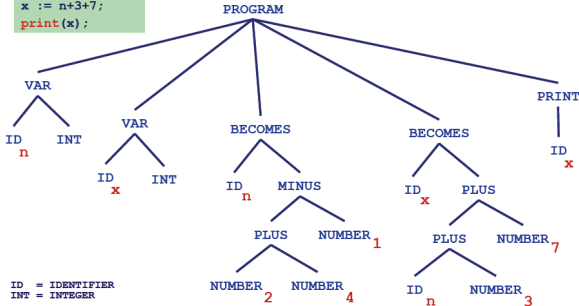
first child, next sibling notation

Konstruierter AST



```
// ex1.calc  
var n: integer;  
var x: integer;  
n := 2+4-1;  
x := n+3+7;  
print(x);
```

```
program : decls stats EOF  
        -> ^(PROGRAM decls stats);  
decls  : (decl SEMICOLON!)*  
stats  : (stat SEMICOLON!)+ ;  
decl   : VAR^ ID COLON! type ;  
stat   : assign | print ;  
assign : lvalue BECOMES^ expr ;  
print  : PRINT^ LPAREN! expr RPAREN! ;  
lvalue : ID ;  
expr   : oper ((PLUS^ | MINUS^) oper)* ;  
oper   : ID | NUM | LPAREN! expr RPAREN! ;  
type   : INT ;
```



Automatische Erzeugung von Visitor

TreeWalker anhand von Baum-Grammatik, führt noch keine Aktionen aus



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```
program : decls stats EOF -> ^(PROGRAM decls stats);
decls  : (decl SEMICOLON!)*
stats  : (stat SEMICOLON!)+ ;
decl   : VAR^ IDENTIFIER COLON! type ;
stat   : assign | print ;
assign : lvalue BECOMES^ expr ;
print  : PRINT^ LPAREN! expr RPAREN! ;
lvalue : ID ;
expr   : operand {(PLUS^ | MINUS^) operand}* ;
operand : ID | NUM | LPAREN! expr RPAREN! ;
type   : INT ;
```

```
tree grammar CalcTreeWalker;
options {
  tokenVocab = Calc;
  ASTLabelType = CommonTree;
}

program      :  ^(PROGRAM (declaration | statement)+);
declaration  :  ^(VAR IDENTIFIER type);
statement    :  ^(BECOMES IDENTIFIER expr)
               |  ^(PRINT expr);
expr         :  operand
               |  ^(PLUS expr expr)
               |  ^(MINUS expr expr);
operand      :  IDENTIFIER | NUMBER ;
type         :  INTEGER ;
```

This is a specification of a **tree walker**.

Import tokens from **Calc.tokens**.

The AST nodes are of type **CommonTree**.

The AST has a **root node PROGRAM** with many (declaration or statement) children.

Match a tree whose root is a **PLUS** token with two children that match the **expr** rule.

This **tree walker does not do anything** (yet). Note the **conciseness** of the grammar and the correspondence with the **"abstract syntax"** of the language Calc.

Kontextuelle Überprüfung für Calc 1

Infrastruktur



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The `CalcChecker` checks the context rules of the language:

- each identifier can be declared **only once**
- identifiers that are **used** must have been declared.

```
tree grammar CalcChecker;
```

```
options {  
    tokenVocab = Calc;  
    ASTLabelType = CommonTree;  
}
```

```
@header {  
import java.util.Set;  
import java.util.HashSet;  
}
```

```
@rulecatch {  
catch (RecognitionException e) {  
    throw e;  
}  
}
```

```
@members {  
    private Set<String> idset = new HashSet<String>();  
    public boolean isDeclared(String s) {  
        return idset.contains(s);  
    }  
    public void declare(String s) {  
        idset.add(s);  
    }  
}
```

@header: code block which is copied verbatim to the beginning of `CalcChecker.java`.

@rulecatch: specify your own error handler. Here: no error handler; exceptions are propagated to the method calling this checker.

@members: code block which is copied verbatim to the class definition of `CalcChecker.java`.

The Calc language uses a monolithic block structure. For checking the scope rules we can use a `Set`.

The methods `isDeclared` and `declare` become methods of the class `CalcChecker`.

Kontextuelle Überprüfung für Calc 2

Regeln für kontextuelle Einschränkungen prüfen

```
program
: ^ (PROGRAM (declaration | statement)+)
;
```

With `name=NODE` we can refer to the AST node using `name` ...

```
declaration
: { (VAR id=IDENTIFIER type)
  { if (isDeclared($id.getText()))
    throw new CalcException($id.getText() +
      " is already declared");
  else
    declare($id.getText());
  }
};
```

... and get its `String` representation.

Java code block which is copied `verbatim` to the parse method of 'declaration' in `CalcChecker.java`.

Within `Java` code, the ANTLR variables are (usually) prefixed with `$`.

```
statement
: ^ (BECOMES id=IDENTIFIER expr)
  { if (!isDeclared($id.text))
    throw new CalcException($id.text +
      " is used but not declared");
  }
| ^ (PRINT expr)
;
...

```

... or use the attribute `text`.

`CalcException` is an user-defined Exception (subclass of `org.antlr.runtime.RecognitionException`) to express some `problem in the input`.

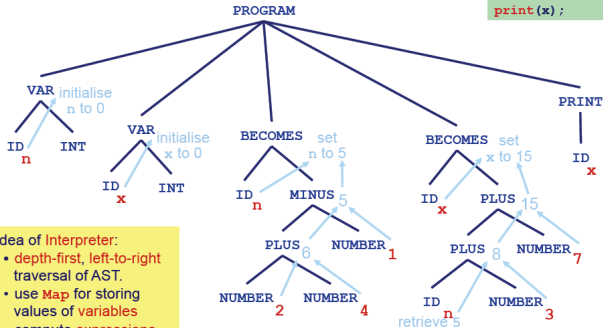
Interpreter für Calc 1

Grundsätzliche Vorgehensweise



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```
// ex1.calc  
var n: integer;  
var x: integer;  
n := 2+4-1;  
x := n+3+7;  
print(x);
```



Idea of Interpreter:

- depth-first, left-to-right traversal of AST.
- use **Map** for storing values of variables
- compute expressions bottom up

Interpreter für Calc 2

Verwende weiteren TreeWalker



```
tree grammar CalcInterpreter;
```

```
options {  
    tokenVocab = Calc;  
    ASTLabelType = CommonTree;  
}
```

```
@header {  
import java.util.Map;  
import java.util.HashMap;  
}
```

```
@members {  
    Map<String,Integer> store = new HashMap<String,Integer>();  
}
```

```
program : ^(PROGRAM (declaration | statement)+  
;
```

```
declaration : ^(VAR id=IDENTIFIER type  
    { store.put($id.text, 0); }  
;
```

```
...
```

Idea of Interpreter:

- depth-first, left-to-right traversal of AST.
- use **Map** for storing values of **variables**
- compute **expressions** bottom up

To store the values of the variables.

Initialized on 0.

Interpreter für Calc 3

Verwende weiteren TreeWalker



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```
statement
:  ^ (BECOMES id=IDENTIFIER v=expr)
   { store.put($id.text, $v); }

|  ^ (PRINT v=expr)
   { System.out.println(" " + $v); }
;
```

The rule **expr** returns a value.

The value returned by **expr** is put into the store for **id**.

A rule can return a value: **rulename** returns **[T x]**
The **type** of the return value is **T** and the **value** returned is the value of **x** at the end of the rule.

ANTLR deduces from the context the **types** of the variables: **id** is a **CommonTree**, **v** is an **int**.

```
expr returns [int val = 0]
:  z=operand          { val = z; }
|  ^ (PLUS  x=expr y=expr) { val = x + y; }
|  ^ (MINUS x=expr y=expr) { val = x - y; }
;
```

Note that it is also possible to **pass** arguments to a rule.

Get the value of **IDENTIFIER** out of the **store**.

```
operand returns [int val = 0]
:  id=IDENTIFIER { val = store.get($id.text); }
|  n=NUMBER      { val = Integer.parseInt($n.text); }
;
```

Parse the string representation of the **NUMBER**.

Hauptprogramm für Interpreter

compiler driver



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```
public static void main(String[] args) {
```

```
    CalcLexer lex = new CalcLexer(  
        new ANTLRInputStream(System.in));  
    CommonTokenStream tokens = new CommonTokenStream(lex);  
    CalcParser parser = new CalcParser(tokens);
```

lexer

A lexer gets an ANTLR stream as input.

Call the start symbol to start parsing.

The parser gets the lexer's output tokens.

```
    CalcParser.program_result result = parser.program();  
    CommonTree tree = (CommonTree) result.getTree();
```

parser

```
    CommonTreeNodeStream nodes = new CommonTreeNodeStream(tree);  
    CalcChecker checker = new CalcChecker(nodes);  
    checker.program();
```

checker

```
    CommonTreeNodeStream nodes = new CommonTreeNodeStream(tree);  
    CalcInterpreter interpreter = new CalcInterpreter(nodes);  
    interpreter.program();  
}
```

inter-
preter

The recognition methods may all throw **Exceptions** (e.g. **RecognitionException**, **TokenStreamException**); These have to be caught in **main**-method. See **Calc.java**.

AST Visualisierung 1

Textuell und graphisch



```
public static void main(String[] args) {  
  
    CalcLexer lexer = new CalcLexer(  
        new ANTLRInputStream(System.in));  
    CommonTokenStream tokens = new CommonTokenStream(lexer);  
    CalcParser parser = new CalcParser(tokens);  
  
    CalcParser.program_return result = parser.program();  
    CommonTree tree = (CommonTree) result.getTree();  
    ...  
  
    // show S-Expression representation of the AST  
    String s = tree.toStringTree();  
    System.out.println(s);  
  
    // print the AST as DOT specification  
    DOTTreeGenerator gen = new DOTTreeGenerator();  
    StringTemplate st = gen.toDOT(tree);  
    System.out.println(st);  
}
```

-ast

-dot

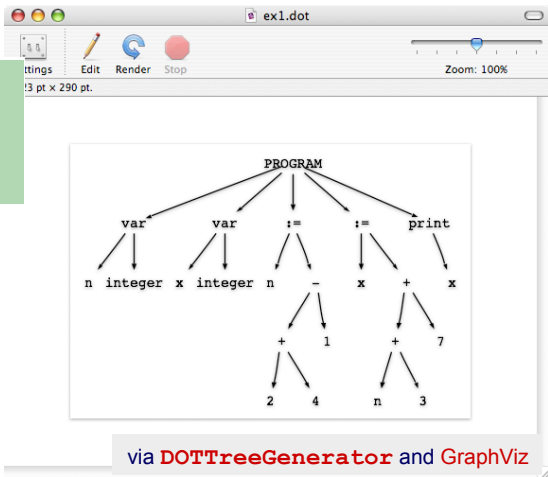
.dot files can be visualized
using the **GraphViz** program:
<http://www.graphviz.org/>

DOTTreeGenerator is defined in package
org.antlr.stringtemplate

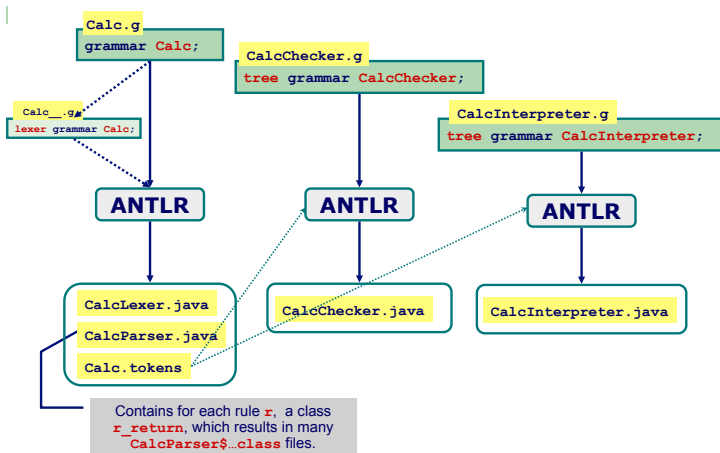

```
[ruys@jay]$ java Calc -no_interpreter -ast < ex1.calc
(PROGRAM (var n integer) (var x integer) (:= n (- (+ 2 4) 1)) (:= x (+ (+ n 3) 7)) (print x))
[ruys@jay]$
```

via `tree.toStringTree()`

```
// ex1.calc
var n: integer;
var x: integer;
n := 2+4-1;
x := n+3+7;
print(x);
```



Struktur des erzeugten Java-Codes



Auszug aus Parser

Hauptmethode `program()`



```
public class CalcParser extends Parser {
    ...
    public final program_return program() throws RecognitionException {
        program_return retval = new program_return();
        ...
        try {
            // Calc.g:44:9: declarations statements EOF
            {
                pushFollow(FOLLOW_declarations_in_program412);
                declarations1=declarations();
                _fsp--;

                stream_declarations.add(declarations1.getTree());
                pushFollow(FOLLOW_statements_in_program414);
                statements2=statements();
                _fsp--;

                stream_statements.add(statements2.getTree());
                EOF3=(Token)input.LT(1);
                match(input,EOF,FOLLOW_EOF_in_program416);
                stream_EOF.add(EOF3);
                ...
            }
        }
        catch (RecognitionException re) {
            reportError(re);
            recover(input,re);
        } ...
        return retval;
    }
}
```

Most code that builds
the AST is omitted!

```
program
: declarations statements EOF!
;
```

Auszug aus Parser

Parse Deklarationen mit `declarations()`



```
public final declarations_return declarations() throws RecognitionException {
    declarations_return retval = new declarations_return();
    ...
    try {
        ...
        loop1:
        do {
            int alt1=2;
            int LA1_0 = input.LA(1);

            if ( (LA1_0==VAR) )
                alt1=1;

            switch (alt1) {
                case 1 :
                    {
                        pushFollow(FOLLOW_declaration_in_declarations463);
                        declaration4=declaration();
                        ...
                        match(input,SEMICOLON,FOLLOW_SEMICOLON_in_declarations465);
                    }
                    break;
                default :
                    break loop1;
            }
        } while (true);
    } catch (RecognitionException re) {
        ...
        return retval;
    }
}
```

LA(1) - current lookahead Token.

```
declarations
: (declaration SEMICOLON!)*
;
```



- ▶ ANTLR erlaubt Entwickler ...
 - ▶ ... sich auf **Spezifikation** des Compiler zu konzentrieren
 - ▶ Übernimmt dann **Implementation** des Compilers
- ▶ Gleiche **Syntax** zur Spezifikation von
 - ▶ Lexer/Scanner
 - ▶ Parser
 - ▶ TreeWalker
- ▶ Portable Code-Generierung
 - ▶ Java, C, C#, Python, Objective-C, etc
 - ▶ ... gilt aber nicht für in Spezifikationen eingebetteten Code
- ▶ Gut unterstützt und aktive Benutzergemeinschaft



- ▶ Links- und Rechtsassoziativität
- ▶ Operatorpräzedenz
- ▶ Hängendes `else`

- ▶ Linksassoziativer Operator \otimes :

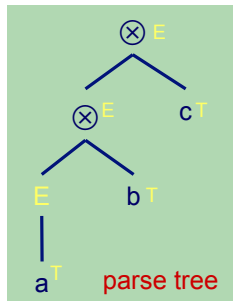
$$a \otimes b \otimes c = (a \otimes b) \otimes c$$

- ▶ Produktion (linksrekursiv!)

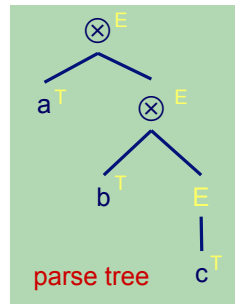
$$E ::= E \otimes T \mid T$$

- ▶ In EBNF

$$E ::= T(\otimes T)^*$$

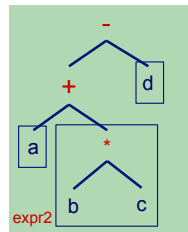


- ▶ Rechtsassoziativer Operator \otimes :
 $a \otimes b \otimes c = a \otimes (b \otimes c)$
- ▶ Produktion (linksrekursiv!)
 $E ::= T \otimes E \mid T$
- ▶ In EBNF (? = 0- oder 1-mal)
 $E ::= T(\otimes E)?$



Operatorpräzedenz 1

- ▶ Beispiel:
 $a + b \times c - d$
- ▶ ... sollte geparsed werden als
 $(a + (b \times c)) - d$



- ▶ Operator \times hat höhere Präzedenz als $+$ und $-$
- ▶ In Grammatik ausdrücken, durch Platzieren von \times “näher an Operanden” als $+$ und $-$

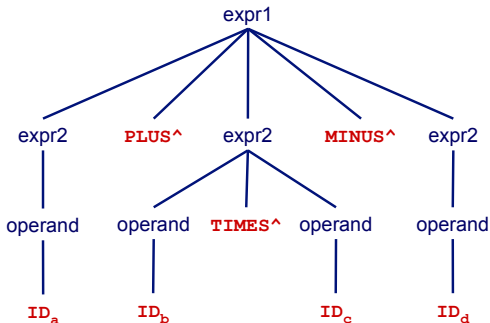
```
expr1 : expr2 ((PLUS^ | MINUS^) expr2)*  
expr2 : operand (TIMES^ operand)*  
operand : IDENTIFIER
```

Operatorpräzedenz 2

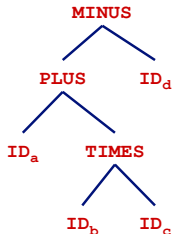
$$a + b \times c - d$$

parse tree:

```
expr1 : expr2 ((PLUS^ | MINUS^) expr2)*  
expr2 : operand (TIMES^ operand)*  
operand : IDENTIFIER
```



constructed AST:



Hängendes `else` 1

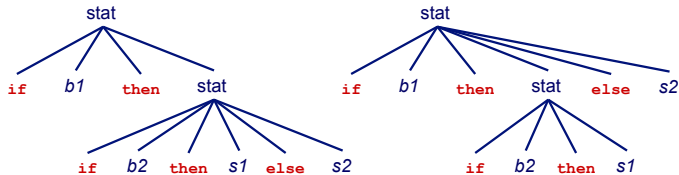
dangling else

Klassisches Problem von Mehrdeutigkeit beim Parsen

```
stat : 'if' expr 'then' stat ('else' stat)?  
      | ...      ;
```

```
if b1 then if b2 then s1 else s2
```

Zwei mögliche Parse-Bäume





ANTLR gibt Warnung aus

```
warning(200): Foo.g:12:33: Decision can match input
such as "'else'" using multiple alternatives: 1, 2
As a result, alternative(s) 2 were disabled for that
input
```

... tut aber das Richtige (*greedy matching* → 1. Baum):

```
stat : 'if' expr 'then' stat
      (options {greedy=true;} : 'else' stat)?
    | ... ;
```

Muss nicht explizit hingeschrieben werden, da Default.



Vertiefung von

- ▶ Aufbauen von ASTs beim Parsen
- ▶ Heterogene ASTs
- ▶ Fehlerbehandlung
- ▶ Syntaktische Prädikate
- ▶ Semantische Prädikate
- ▶ Texterzeugung mit StringTemplate
- ▶ Automatisches Testen mit gUnit

Aufbau von ASTs

Annotationen in Produktion oder *rewrite rule*



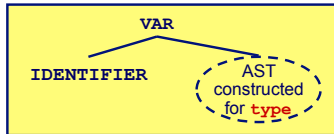
e.g. `declaration : VARbecomes top-node IDENTIFIER COLON! type ;` ^{will be discarded}

or: `declaration : VAR IDENTIFIER COLON type
-> ^(VAR IDENTIFIER type);`

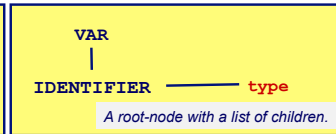
Notations **cannot**
be **mixed!**

Ergebnis

constructs the
following **AST**



or seen alternatively:



AST kann nun mit ANTLR Tree Parser geparsed werden:

```
declaration : ^(VAR IDENTIFIER type) ;
```

ANTLR uses a **prefix pattern language** for AST nodes.



Bisher: AST aufgebaut aus *Default*-Knoten `tree.CommonTree`

- ▶ Ausreichend für viele einfache Sprachen
- ▶ Ungeeignet, wenn Knoten noch weitere Informationen halten sollen
 - ▶ Typen, Bezeichner, runtime entities, etc.

- ▶ Dann benutzerdefinierte AST-Klasse verwenden
 - ▶ Benötigt **zwei** Klassendefinitionen
 - ▶ **MyTree** **extends** **CommonTree**
benutzerdefinierte AST-Knoten
 - ▶ **MyTreeAdaptor** **extends** **CommonTreeAdaptor**
Adapter-Entwurfsmuster zum Anlegen neuer **MyTree** Knoten

Benutzerdefinierte AST-Klassen 2

Verwendung in ANTLR



1. Definiere Unterklasse `MyTree` von `CommonTree`

```
public class MyTree extends CommonTree { ...
```

2. Definiere Unterklasse `MyTreeAdaptor` von `CommonTreeAdaptor`

```
class MyTreeAdaptor extends CommonTreeAdaptor { ...
```

3. Veranlasse `Parser`, AST aus `MyTree`-Knoten aufzubauen

```
MyParser parser = new MyParser(tokens);  
parser.setTreeAdaptor(new MyTreeAdaptor());
```

4. Wähle `MyTree` als AST-Klasse in Optionen im `Tree Parser` aus

```
options { ... ASTLabelType = MyTree; }
```


Beispiel: LIST

Einfache Sprache für Listen und Operationen



- ▶ Aufbau von (verschachtelten) Listen
- ▶ Atomare Elemente sind Zahlen
- ▶ Arithmetische Operationen auf Listen
- ▶ Beispiel

`+ [3, 5, * [2, 5], + [3, 7, + [2, 5], 11], 27, 51]`

➡ Verwende eigene AST-Knoten für Operationen



- 1a) Berechne Teilsummen/produkte für jede der Unterlisten
- 1b) Speichere Zwischenergebnisse für die (Unter)Listen ab
 - ▶ **Nicht:** Nur ein Ergebnis nach oben weitergeben
- 2) Fasse Teilergebnisse aller echten Unterlisten zusammen
 - ▶ $+ [3, + [2, 7], * [4, + [2, 3]], 7]$
→ $+ [3, 9, 20, 7]$
 - ▶ Oberste Liste besteht nur noch aus Operator und Zahlen

LIST – Eigene AST-Knoten



ListNode is a subclass of ANTLR's default AST class: **CommonTree**.

```
public class ListNode extends CommonTree {
    protected int value = 0;

    public ListNode()          { super();          }
    public ListNode(Token t)   { super(t);        }

    /** Get the List value of this node. */
    public int getValue()      { return value;    }

    /** Set the List value of this node. */
    public void setValue(int value) { this.value = value; }

    public String toString() {
        String s = super.toString();
        try { Integer.parseInt(this.getText()); }
        catch (NumberFormatException ex)
            { s = s + " {" + getValue() + "}; }
        return s;
    }
}
```

For the **string** representation, add the value to **non-numeric** nodes.

Usual **set-** and **get-**methods for the extra instance variable of **ListNode**.

Warning: do not override **CommonTree's** **getType** or **getText**.



```
class ListNodeAdaptor extends CommonTreeAdaptor {  
    public Object create(Token t) {  
        return new ListNode(t);  
    }  
}
```

The method `create` is used to build to `ListNode` objects.

- ▶ Agiert als **Adapter** zwischen ANTLR-Innereien und eigenen Klassen
- ▶ Fungiert als *Factory*-Objekt
 - ▶ Ist verantwortlich für ein API zur Erzeugung neuer Objekte der gewünschten Klasse

LIST – Lexer und Parser

Baut AST auf

```
grammar List;
```

```
options {
```

```
  k=1;
```

```
  language=Java;
```

```
  output=AST;
```

```
}
```

```
tokens {
```

```
  ...
```

```
}
```

```
top      : list EOF! ;
```

```
list     : operator^ elems ;
```

```
elems    : LBRACKET! elem (COMMA! elem)* RBRACKET! ;
```

```
elem     : NUMBER
```

```
         | list
```

```
         ;
```

```
operator : PLUS      = "+"
```

```
         | TIMES    = "*" ;
```

```
         ;
```

```
...
```

As usual, we only let the parser **construct the AST**.

build an AST

A (List)AST node is created: the **operator-TOKEN** is the root-node, and the elements of **elems** are the children.

Straightforward lexer rules for **NUMBER**, whitespace and comments have been **omitted**.

LIST – Tree Parser 1

Wertet Ausdrücke im AST aus (Op 1a) und speichert Ergebnisse (Op 1b)



Computes the values of List-nodes (i.e. PLUS- or TIMES-nodes) and stores this value in the corresponding `ListNode` node.

```
tree grammar ListWalker;
```

```
options { ... ASTLabelType=ListNode; }  
@members { /* ... see next slide ... */ }
```

```
list      :      { int sum=0; ListNode l=null; }  
           ^ (p=PLUS  
             (      { l=(ListNode)input.LT(1); }  
               list  
               { sum += l.getValue(); }  
             )+  
           ) { $p.setValue(sum); }  
           | ^ (t=TIMES list+)  
             { $t.setValue(product(t)); }  
           | n=NUMBER  
             { $n.setValue(Integer.parseInt($n.text)); }  
           ;
```

We need to refer to the actual `ListNodes` of the elements of the sublist.

The alternative for `PLUS` computes the sum while walking its children (preferred way).

The alternative for `TIMES` computes the product after all children have been parsed (see the method `product` on the next slide).

```
list      : operator^ elems ;  
elems    : elem+  
elem     : NUMBER | list ;  
operator : PLUS | TIMES ;
```

LIST – Tree Parser 2

Hilfsmethode für verzögerte Auswertung von Produkten



Private Methode im ListWalker Tree Parser

```
tree grammar ListWalker;
```

```
...
```

```
@members {
```

```
...
```

Walk the children of a node `root` and computes the product.

```
private int product(ListNode root) {
```

```
    int prod = 1;
```

```
    for (int i=0; i<root.getChildCount(); i++)
```

```
        prod *= ((ListNode) root.getChild(i)).getValue();
```

```
    return prod;
```

```
}
```

```
}
```

```
list  
: ...  
| ^(t=TIMES list+)  
  { $t.setValue(product(t)); }  
;
```

Basis-Klassen für AST Knoten

In ANTLR: `BaseTree` und `CommonTree`



```
public class BaseTree implements Tree
{
    public int      getChildCount()
    public Tree   getChild(int i)
    public List     getChildren()

    public void     addChild(Tree t)
    public void     addChildren(List kids)
    public void     setChild(int i, Tree t)

    public int      getChildIndex()
    public void     setChildIndex(int ix)
    public Tree    getParent()
    public void     setParent(Tree t)

    public String   toString();
    public String   toStringTree();

    ...
}
```

```
public class CommonTree extends BaseTree
{
    public Token   getToken()
    public Tree    dupNode()
    public boolean  isNil()

    public int      getType()
    public String   getText()
    public int      getLine()

    ...
}
```

- The `BaseTree` is a generic tree implementation with no payload. You must subclass `BaseTree` to actually have any user data.
- A `CommonTree` node is wrapper for a `Token` object.

LIST – ListTopLevel 1

Baut Liste nur aus Ergebnissen aller Unterlisten (Op 2)



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- ▶ Alle Elemente sind **NUMBER**-Knoten
 - ▶ Werden neu angelegt (*imaginary nodes*)
 - ▶ Verweisen auf Ursprungstokens (Zeile/Spalte, Text)
- ▶ Liste wird direkt umgeschrieben
 - ▶ Alle Elemente ohne *rewrite rules* werden unmodifiziert ausgegeben

LIST – ListTopLevel 2



```
tree grammar ListTopLevel;

options {
    tokenVocab=List;
    ASTLabelType=ListNode;
    output=AST;
    rewrite=true;
}

root : ^ (PLUS (elem)+
        | ^ (TIMES (elem)+
        ;

list : ( ^ (p=PLUS (elem)+ -> ^ (NUMBER[p.getToken()], "+" + p.getValue())
        | ^ (t=TIMES (elem)+ -> ^ (NUMBER[t.getToken()], "+" + t.getValue())
        )
        ;

elem : NUMBER
      | list
      ;
```

output a (new) AST

in-line replacement of nodes

in-line replacement of nodes

LIST – Hauptprogramm

Für Operation 1: Berechnen und Speichern der Zwischenergebnisse



```
public static void main(String[] args) {
    ...
    try {
        ListLexer lexer =
            new ListLexer(new ANTLRInputStream(System.in));
        CommonTokenStream tokens = new CommonTokenStream(lexer);
        ListParser parser = new ListParser(tokens);
        parser.setTreeAdaptor(new ListNodeAdaptor());

        ListParser.top_return result = parser.top();
        ListNode tree = (ListNode) result.getTree();

        TreeNodeStream nodes = new CommonTreeNodeStream(tree);
        ListWalker walker = new ListWalker(nodes);
        walker.top();
        ...
        System.out.println(">> Total: " + tree.getValue());

    } catch (RecognitionException e) { ... }
}
```

Make sure that **ListNode** objects are created.

Print the value of the root node.

Bisher in ANTLR: Homogene ASTs, alle Knoten haben denselben Typ

- ▶ Problem: Was, wenn unterschiedliche Attribute gespeichert werden müssen?

Ein Ansatz: `Map<String, Object> properties` als Feld in Knoten

- ▶ Flexibel, beliebige Dinge abspeicherbar
- ▶ Nachteil: Nicht typsicher, schwer wartbar

➡ Heterogene Bäume

Verschiedene Knotenarten in einem Baum

Heterogene ASTs 2

Gezielt verschiedene Knotenarten anlegen durch `<...>`



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```
program      :  declarations statements EOF
               -> ^(PROGRAM declarations statements)
           ;

declarations :  (declaration SEMICOLON!)*
           ;

statements  :  (statement SEMICOLON!)+
           ;

declaration :  VAR^ IDENTIFIER<IdNode> COLON! type
           ;

statement   :  assignment
               | print
           ;

assignment  :  lvalue BECOMES^ expr
           ;

print       :  PRINT^ LPAREN! expr RPAREN!
           ;

lvalue      :  IDENTIFIER<IdNode>
           ;

expr        :  operand (( PLUS<BinExprNode>^
                       | MINUS<BinExprNode>^ ) operand)*
           ;

operand     :  IDENTIFIER<IdNode>
               | NUMBER
               | LPAREN! expr RPAREN!
           ;

type        :  INTEGER<TypeNode>
           ;
```

With the `<...>` suffix annotation, one can specify the **node type** of a node.

In this example for Calc, there are three extra node types:

IdNode
BinExprNode
TypeNode

All these classes have to be defined as subclasses of (a subclass of) `CommonTree`. Just like we did for `ListNode`.

Resist the urge to define and use many (>10) heterogeneous AST nodes.

With ANTLR (usually) at most a handful is needed. Due to the complete OO approach, W&B had to use a complete heterogenous approach.



- ▶ ANTLR-generierte Erkenner behandeln Fehler durch Java Exceptions
 - ▶ `RecognitionException` ist Basisklasse aller ANTLR Exceptions
- ▶ Schon gesehen in: `CalcChecker`
 - ▶ Wirft `CalcException` bei kontextuellen Fehlern
 - ▶ Bricht dann Programm ab

```
@rulecatch {  
    catch (RecognitionException e) {  
        throw e;  
    }  
}
```

With this `@rulecatch` clause, we specified that an `RecognitionException` is **not handled**, but re-thrown to the `main` method. This essentially means that the Calc compiler stops at the first error.



Default Exception Handler in `Parser` und `TreeParser`

- ▶ Fängt alle `RecognitionExceptionS`
- ▶ Gibt Fehlermeldung aus
- ▶ Setzt dann Parsing fort

```
list : ...
      | n=NUMBER
        { if ($n.text.equals("211035"))
          throw new RecognitionException(
            "211035 on line " + $n.getLine() +
            " is not a valid number");
          else
            $n.setValue(Integer.parseInt($n.text));
          }
      ;
```

ListWalker

The number "211035" is tagged as a `RecognitionException`. The `ListWalker` class will catch the `Exception` and report the error. Then it will proceed in walking the tree. Note that we use the **line number** that is associated with the Token of the NUMBER node.

Fehlerbehandlung 3

Benutzerdefinierte Fehlerbehandlung – Beispiel



- ▶ Definiere eigene Exception-Klasse `ListException`
- ▶ Redefinieren von `displayRecognitionError()`
 - ▶ Definiert in `BaseRecognizer`

```
tree grammar ListWalker;
...
@members {
    protected int nrErr = 0;
    public int nrErrors() { return nrErr; }

    public void displayRecognitionError(
        String[] tokenNames, RecognitionException e) {
        nrErr = nrErr+1;
        if (e instanceof ListException)
            emitErrorMessage("[List] error: " + e.getMessage());
        else
            super.displayRecognitionError(tokenNames, e);
    }
}
```

Counting the total number of errors.

`ListException` is a user defined exception (in the style of `CalcException`).



Exceptions können auch direkt in Produktionen behandelt werden

```
rule : foo BAR SEMI!  
    ;  
    catch [RecognitionException re] {  
        reportError(re);  
        consumeUntil(input, SEMI);  
        input.consume();  
    }
```

Error recovery: consume all
tokens until and including
the SEMI token.

Beispiel für nicht-LL(1) Grammatik

```
rule : X Y  
      | X Z  
      ;
```

LL(1) problem.

can be solved using
left-factorization:

```
rule : X ( Y | Z ) ;
```

Anderer Lösungsansatz: Syntaktische Prädikate

```
rule : ( X Y ) => X Y  
      | X Z  
      ;
```

Only when **X Y** appears in the
tokenstream take this alternative.

This can be regarded as
'locally setting **k** to **2**'.

Syntax für syntaktische Prädikate

```
( prediction block ) => production
```



- ▶ Können beliebig weiten Lookahead benutzen
- ▶ Mächtiger als LL(*)
 - ▶ Lokale CFG statt lokalem DFA für Lookahead
- ▶ Führen selektives Backtracking durch, um Mehrdeutigkeiten aufzulösen
 - ▶ Eventuell vorhandene Aktionen werden dabei ignoriert

```
expr : (ID LPAREN) => ID LPAREN params RPAREN  
      | ID BECOMES ...  
      | ...  
;
```

```
foo(int x);  
x=...
```



- ▶ Erlauben Angabe von **beliebiger** Bedingung beim Parsing
- ▶ Beschreibung der Bedingung durch Java-Code

```
{ semantic-predicate-expression } ?
```

Verwendung auf zwei Arten

- ▶ Validierende Prädikate
- ▶ Vereindeutigende Prädikate
(*disambiguating predicates*)

Semantische Prädikate 2

Validierende Prädikate

Lösen Exception aus, wenn Bedingung verletzt wird
Beispiel:

```
decl : ^(VAR id=IDENTIFIER type)
      { if (isDeclared($id.text))
        throw new CalcException(...);
        else
          declare($id.text); };
```

CalcChecker

```
decl : ^(VAR id=IDENTIFIER type)
      { !isDeclared($id.text) }?
      { declare($id.text); }
      ;
```

with validating predicate

Validierendes Prädikat steht **nach** erkanntem Symbol
(Terminal/Nichtterminal/Knoten)

Semantische Prädikate 3

Vereindeutigende Prädikate



Lösen Mehrdeutigkeiten beim Parsen aufgebaut

- ▶ Stehen **als Erstes** in jeder Parsing-Alternative

```
stat : // declaration "type varName;"           int x;  
      { isTypeName(input.LT(1).getText()) }?     x=3;  
      ID ID SEMICOLON // declaration  
      | ID BECOMES expr SEMICOLON // assignment  
      ;
```

Disambiguating predicates must be the first item of an alternative.

first lookahead-Token

```
public interface TokenStream {  
    ...  
  
    /** Return the i-th token of lookahead */  
    public Token LT(int i);  
}
```



- ▶ Inverse Operation zum Parsen
- ▶ Erzeuge strukturierten Text
- ▶ “Ausfüllen” von Textfeldern in Vorlagen

Beispiel: Code-Generierung für TAM in ANTLR Tree Walker

```
assignment
: ^(BECOMES id=IDENTIFIER expr)
  { int addr = dict.get($id.text);
    emit("STORE(1)" + addr + "[SB]");
  }
;
```

ANTLR's **StringTemplates** can be used to collect all these **emit strings** in a separate file (i.e., a **template**).

```
operand
: id=IDENTIFIER
  { int addr = dict.get($id.text);
    emit("LOAD(1)" + addr + "[SB]");
  }
| n=NUMBER
  { emit("LOADL" + $n.text); }
;
```

```
expr
: operand
| ^(PLUS expr expr)
  { emit("CALL add"); }
| ^(TIMES expr expr)
  { emit("CALL mult"); }
...
;
```

StringTemplate 2

Code-Erzeugung für TAM

CalcCodeGeneratorStringTemplate.g

```
tree grammar Generator;  
options { ...  
    output=template;  
}
```

build a template

```
statement  
: ^ (BECOMES id=IDENTIFIER expr)  
  -> assign(addr={dict.get($id.text)},  
            expr={$expr.st})  
| ^ (PRINT expr)  
  -> print(expr={$expr.st})
```

```
operand  
: id=IDENTIFIER  
  -> loadvar(addr={dict.get($id.text)})  
| n=NUMBER  
  -> loadnum(val={$n.text})  
;
```

Every non-terminal has a variable `st` which corresponds with the string template that it returns.

A string template allows another level of **indirection** to isolate the target instructions.

tam.stg

```
assign(addr,expr) ::= <<  
<expr>  
STORE(1) <addr>[SB]  
>>
```

```
print(expr) ::= <<  
<expr>  
CALL putint  
CALL puteol  
>>
```

```
loadvar(addr) ::= <<  
LOAD(1) <addr>[SB]  
>>
```

```
loadnum(val) ::= <<  
LOADL <val>  
>>
```

Note the resemblance between string templates and **W&B's code templates**.

StringTemplate 3

Code-Erzeugung für TAM



CalcCodeGeneratorStringTemplate.g

```
expr
: operand
  { $st = $operand.st; }

| ^ (PLUS x=expr y=expr
  -> binexpr(e1=x.st, e2=y.st),
      instr="add")

| ^ (TIMES x=expr y=expr
  -> binexpr(e1=x.st, e2=y.st),
      instr="mult")
;
```

You have to explicitly state that the child's string template has to be copied.

original code generator

```
expr
: operand
| ^ (PLUS expr expr)
  { emit("CALL add"); }
| ^ (TIMES expr expr)
  { emit("CALL mult"); }
;
```

Note that each node (expr) of the AST is responsible for generating its code.

tam.stg

```
binexpr(e1,e2,instr) ::= <<
<e1>
<e2>
CALL <instr>
>>
```

All machine specific code generation definitions appear together within the template definition (i.e., tam.stg).

It is 'easier' to port the code generator to a different target machine: "just" write a new template definition.

Automatischer Test von ANTLR-Grammatiken mit gUnit



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```
gunit SimpleC;

// Teste Produktion variable
variable:
"int x" FAIL // Erwartet Fehler wegen fehlendem ';'
"int x;" OK // Erwartet fehlerfreies Parsen

// Test Produktion functionHeader
functionHeader:
"void bar(int x)" returns ["int"] // erwartet Ergebnis "int" von Produktion

// Teste Produktion program mit mehrzeiliger Eingabe
program:
<<
char c;
int x;
>> OK // Erwarte erfolgreiches Parsen

// Teste lexikalische Regeln
ID:
"abc123" OK // Erfolg erwartet
"XYZ@999" OK // Erfolg erwartet
"123abc" FAIL // erwarte Fehler

INT:
"00000" OK
"123456789" OK
```