NEW YORK UNIVERSITY

CSCI-GA.2130-001

Compiler Construction

Lecture 2:

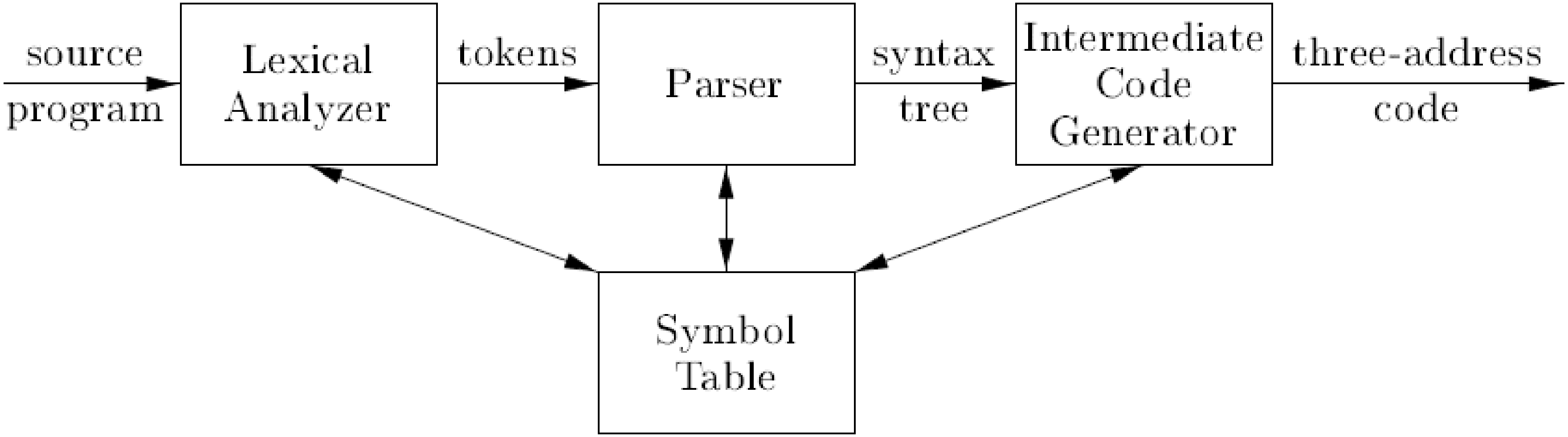
Syntax-Directed Translator

Mohamed Zahran (aka Z)
mzahran@cs.nyu.edu

Copyright © Randy Glasbergen. www.glasbergen.com

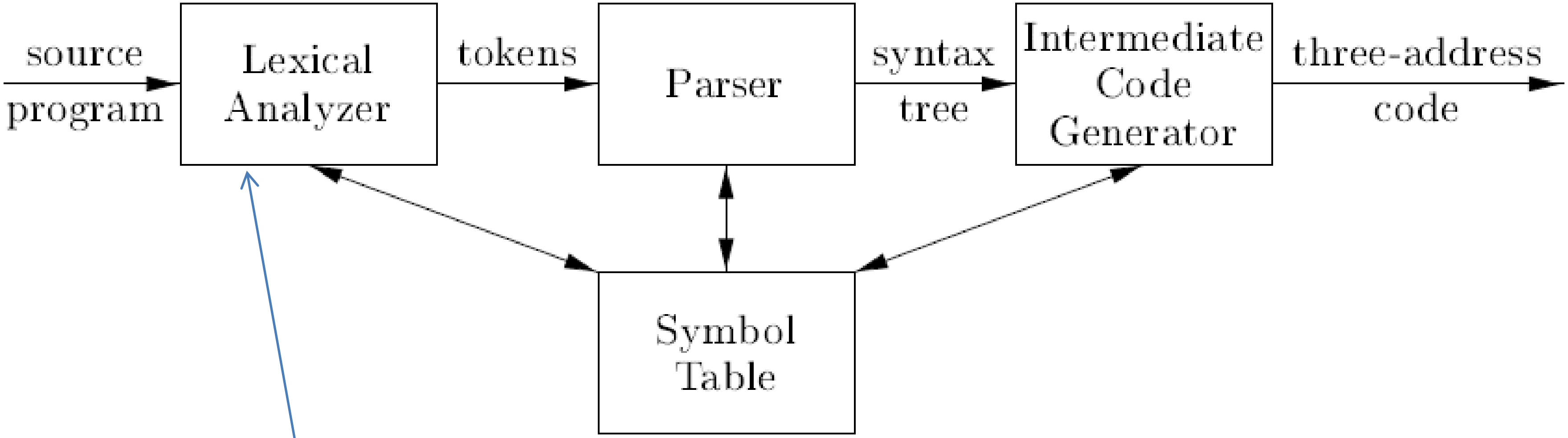
What Will We Do?

- Build a very simple compiler
- Only the front end
  - Code generation
- Easy and limited source language
- Will touch upon everything quickly
- Chapters 3-8 give more details

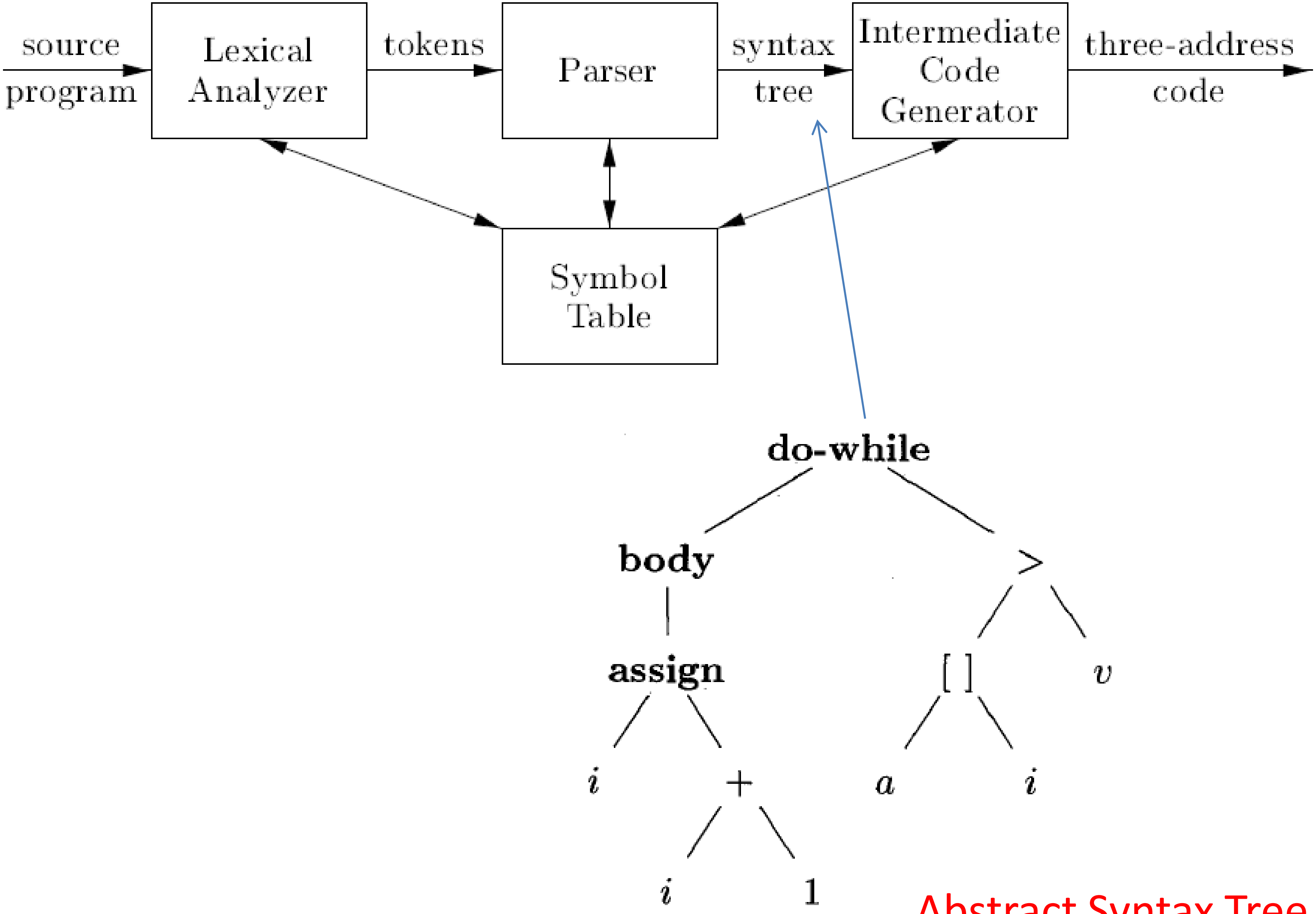


ANALYSIS PHASE

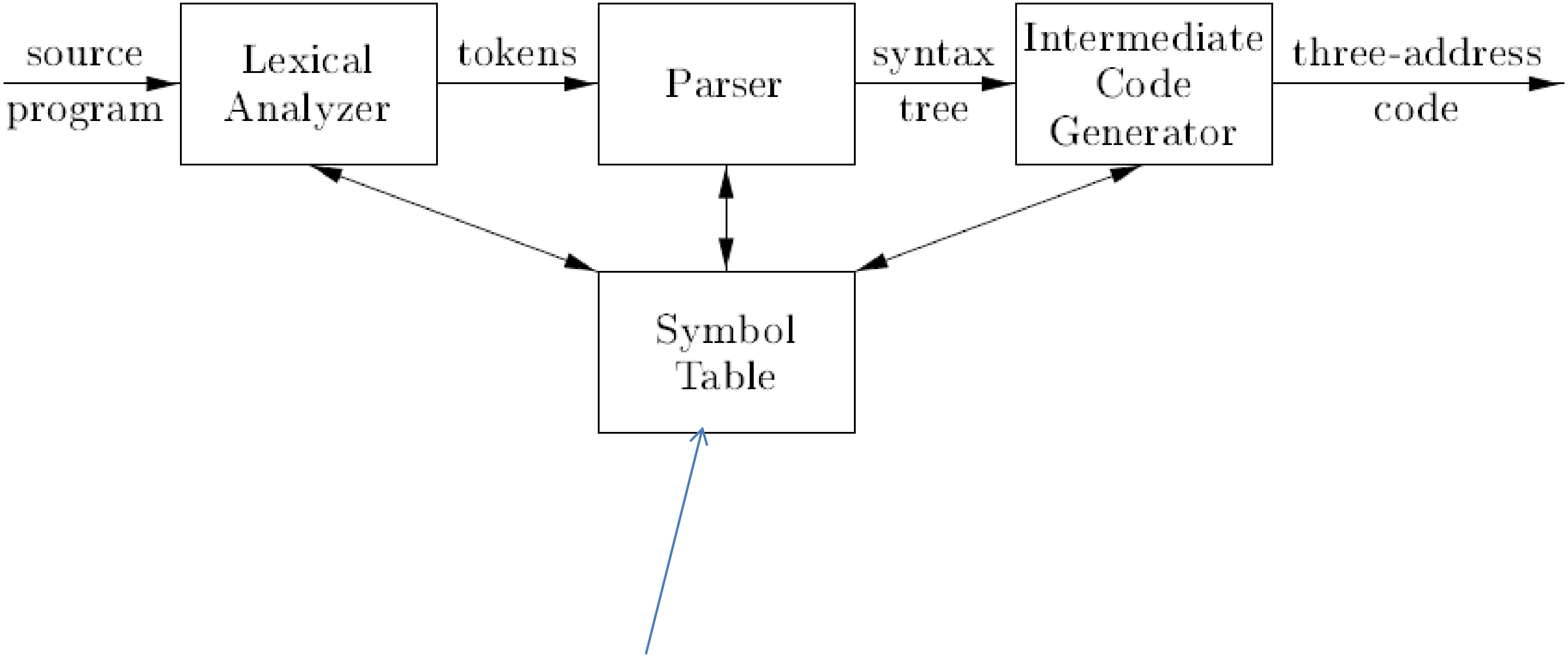
- Break your program into pieces
- Produce an internal presentation of it



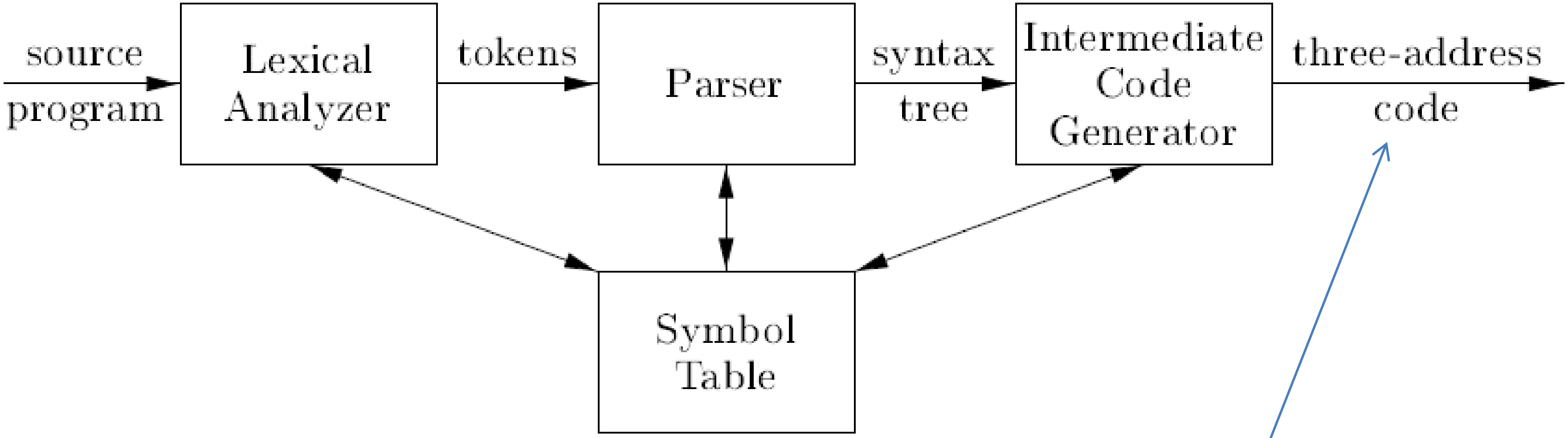
Allows a translator to handle multicharacter constructs



Abstract Syntax Tree



- A data structure
- Hold information about source code constructs
- Information collected incrementally at analysis phase
- Used by synthesis phase



source program

Lexical Analyzer

tokens

Parser

syntax tree

Intermediate Code Generator

three-address code

Symbol Table

```
 1:   i = i + 1
 2:   t1 = a [ i ]
 3:   if t1 < v goto 1
 4:   j = j - 1
 5:   t2 = a [ j ]
 6:   if t2 > v goto 4
 7:   ifFalse i >= j goto 9
 8:   goto 14
 9:   x = a [ i ]
10:   t3 = a [ j ]
11:   a [ i ] = t3
12:   a [ j ] = x
13:   goto 1
14:
```

How Do We Define Language Syntax?

- Using a special notation
- Context-free grammar
- Set of rules

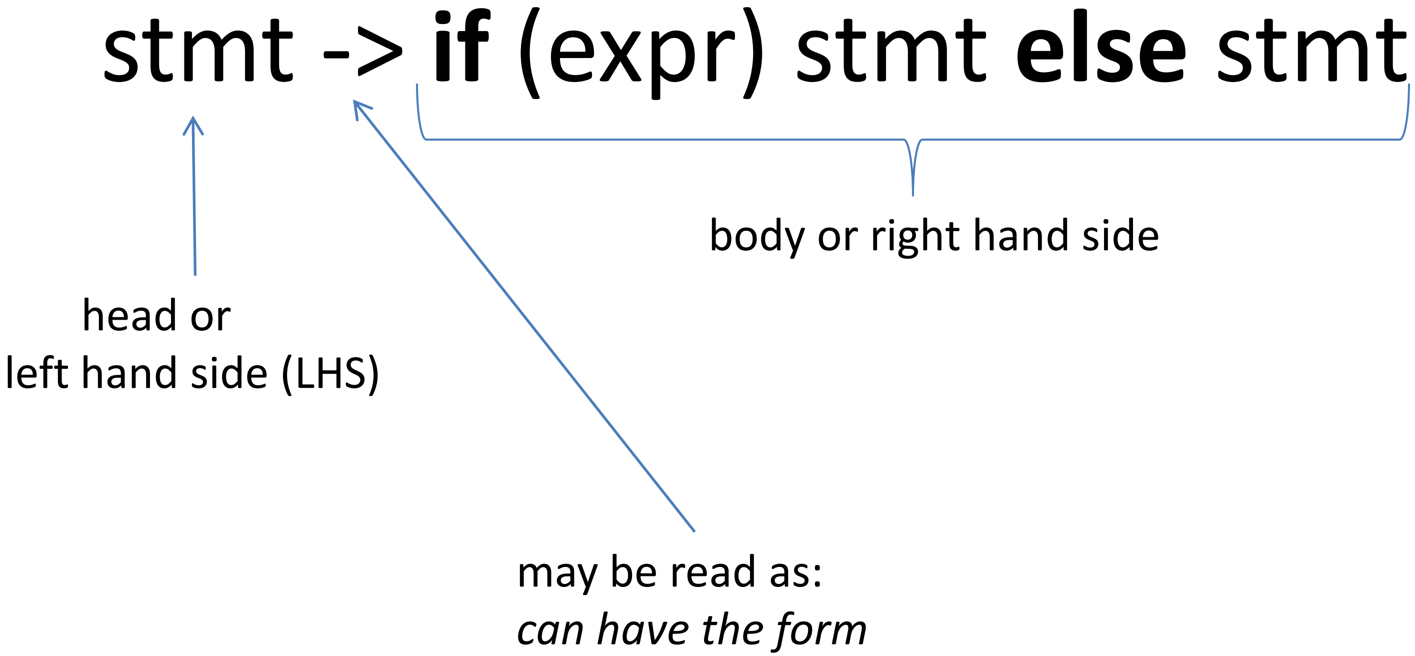
Example:

If (expression **)** statement **else** statement

Corresponds to a rule:

stmt -> **if** (expr) stmt **else** stmt

Production Rules



stmt -> **if** (expr) stmt **else** stmt

body or right hand side

head or
left hand side (LHS)

may be read as:
can have the form

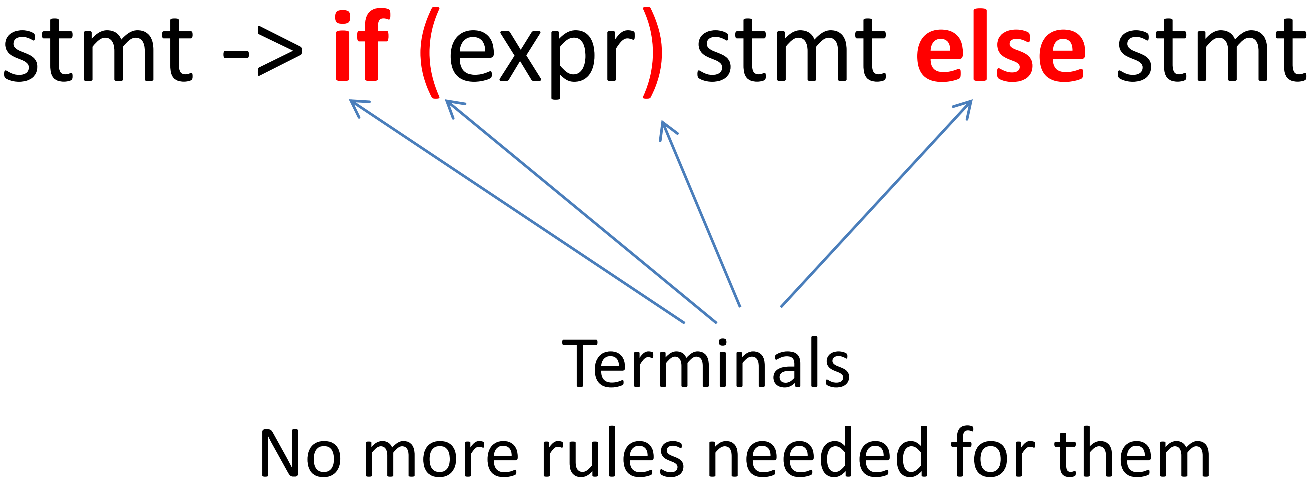
Production Rules

stmt -> **if** (expr) stmt **else** stmt

Nonterminals

They need more rules to define them.

Production Rules



stmt -> **if** (expr) stmt **else** stmt

Terminals

No more rules needed for them

Components of Context-Free Grammar

- Set of terminal symbols
- Set of nonterminals
- set of productions
  - The head is nonterminal
  - The body is a sequence of teminals and/or nonterminals
- Designation of one nonterminal as starting symbol

Example

$$
\begin{aligned}
\mathit{list} &\rightarrow \mathit{list}\ \texttt{+}\ \mathit{digit} \\
\mathit{list} &\rightarrow \mathit{list}\ \texttt{-}\ \mathit{digit} \\
\mathit{list} &\rightarrow \mathit{digit} \\
\mathit{digit} &\rightarrow \texttt{0} \mid \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}
\end{aligned}
$$

What are the terminals here?

What are the nonterminals?

What does this grammar generate?

Some Definitions

- String of terminals: sequence of zero or more terminals
- Derivation:
  - given the grammar (i.e. productions)
  - begin with the start symbol
  - repeatedly replacing nonterminal by the body
  - We obtain the language defined by the grammar (i.e. group of terminal strings)
- Parsing:
  - Given a string of terminals
  - Figure out how to derive it from the start symbol of the grammar

Example

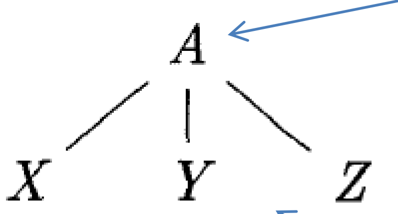
$$\begin{array}{lcl} \mathit{list} & \rightarrow & \mathit{list} + \mathit{digit} \mid \mathit{list} - \mathit{digit} \mid \mathit{digit} \\ \mathit{digit} & \rightarrow & 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9 \end{array}$$

How to derive: 9-5+7 from the above rules?

Parse Tree

- Pictorially shows how the start symbol of a grammar derives a given string

A -> XYX



Root is labeled by the start symbol

Interior nodes are nonterminals

Each leave is a terminal or ε

The process of finding a parse tree for a given string of terminals is called parsing.

Example

Deriving 9-5+2 from

$$
\begin{array}{lcl}
\mathit{list} & \rightarrow & \mathit{list} \ \texttt{+} \ \mathit{digit} \ | \ \mathit{list} \ \texttt{-} \ \mathit{digit} \ | \ \mathit{digit} \\
\mathit{digit} & \rightarrow & \texttt{0} \ | \ \texttt{1} \ | \ \texttt{2} \ | \ \texttt{3} \ | \ \texttt{4} \ | \ \texttt{5} \ | \ \texttt{6} \ | \ \texttt{7} \ | \ \texttt{8} \ | \ \texttt{9}
\end{array}
$$

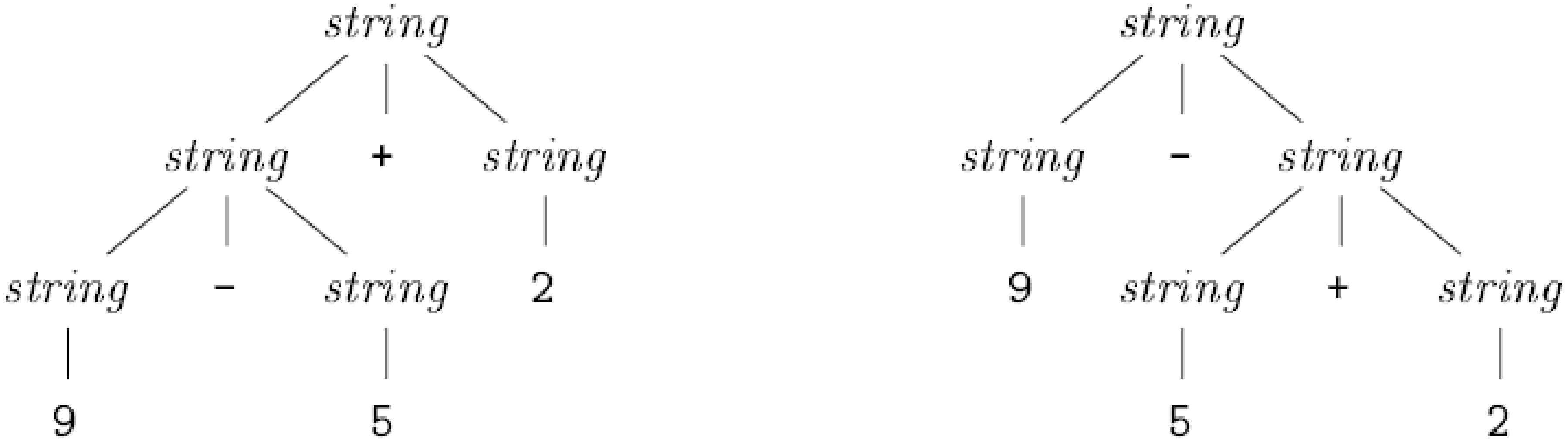
Example

Can we derive 9-5+2 from

$$string \rightarrow string + string \mid string - string \mid 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

Ambiguity

- A grammar is ambiguous if it has more than one parse tree generating the same string of terminals



Two parse trees for 9-5+2

$$\mathit{string} \rightarrow \mathit{string} + \mathit{string} \mid \mathit{string} - \mathit{string} \mid 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

Example

Is the following grammar ambiguous?

S -> +SS | -SS | a

Example

Is the following grammar ambiguous?

$S \rightarrow S(S)S \mid \varepsilon$

Example

Is the following grammar ambiguous?

S -> a | S + S | SS | S* | (S)

Associativity of Operators

How will you evaluate this?

9-5-2

Will ‘5’ go with the ‘-’ on the left or the one on the right?

If it goes with the one on the left: (9-5)-2 we say that the operator ‘-’ is left-associative

If it goes with the one on the right: 9-(5-2) we say that the operator ‘-’ is right-associative

Associativity of Operators

How to express associativity in production rules?

term-> term – digit
digit -> 0|1|2|3|4|5|6|7|8|9

Left-associative
(9-5)-2

term->digit-term
digit -> 0|1|2|3|4|5|6|7|8|9

Right-associative
9-(5-2)

Precedence of Operators

- Associativity applies to occurrence of the *same* operator
- What if operators are different?
- How will you evaluate: 9-5*2
- We say '*' has higher precedence than '-' if it takes its operands before '-'

Precedence of Operators

How to present this in productions?

$$
\begin{array}{lcl}
expr & \rightarrow & expr + term \\
 & | & expr - term \\
 & | & term \\
 & & \\
term & \rightarrow & term * factor \\
 & | & term \,/\, factor \\
 & | & factor \\
 & & \\
factor & \rightarrow & \textbf{digit} \;|\; (\; expr \;)
\end{array}
$$

The above example shows both precedence and associativity
* / have higher precedence then + -
All of them are left associative

Example

Construct unambiguous context-free grammar for left-associate list of identifiers separated by commas

Syntax-Directed Translation

- We have built a parse-tree, now what?
- How will this tree and production rules help in translation?
- This means we have to associate *something* with each production and with each tree node

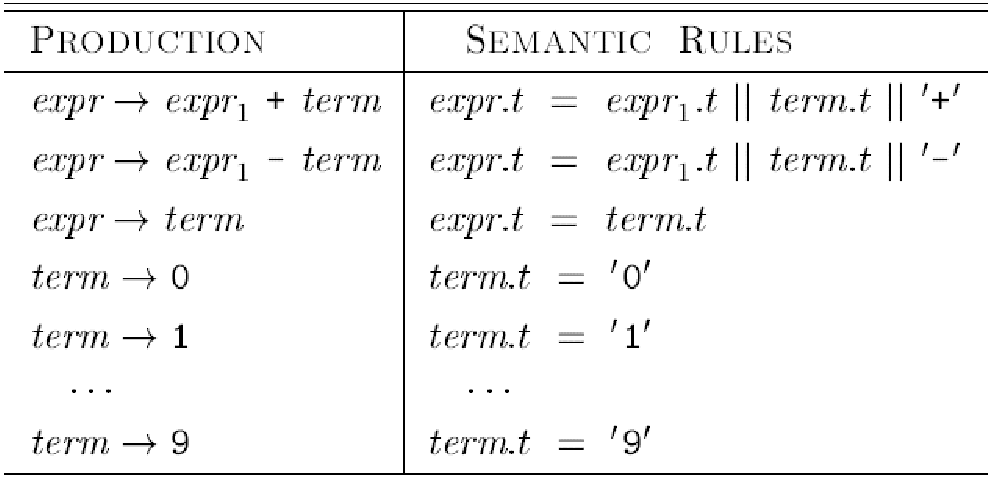
Syntax-Directed Translation

- Attributes
  - Each symbol (terminal or nonterminal) has an attribute
  - Semantic rules for calculating attributes of a node from its children
- Translation scheme is a notation for attaching program fragments to productions

$$\begin{array}{lcl} expr & \rightarrow & expr + term \\ & | & expr - term \\ & | & term \end{array}$$

expr and *term* each has an attribute: expr.t and term.t

$$term \rightarrow 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

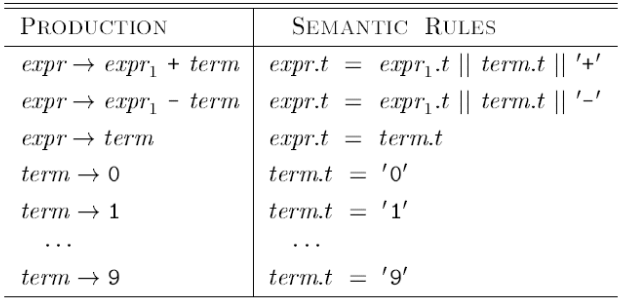


PRODUCTION	SEMANTIC RULES
$expr \rightarrow expr_1 + term$	$expr.t = expr_1.t \mathbin{\|\|} term.t \mathbin{\|\|} '+'$
$expr \rightarrow expr_1 - term$	$expr.t = expr_1.t \mathbin{\|\|} term.t \mathbin{\|\|} '-'$
$expr \rightarrow term$	$expr.t = term.t$
$term \rightarrow 0$	$term.t = '0'$
$term \rightarrow 1$	$term.t = '1'$
...	...
$term \rightarrow 9$	$term.t = '9'$

|| means concatenate

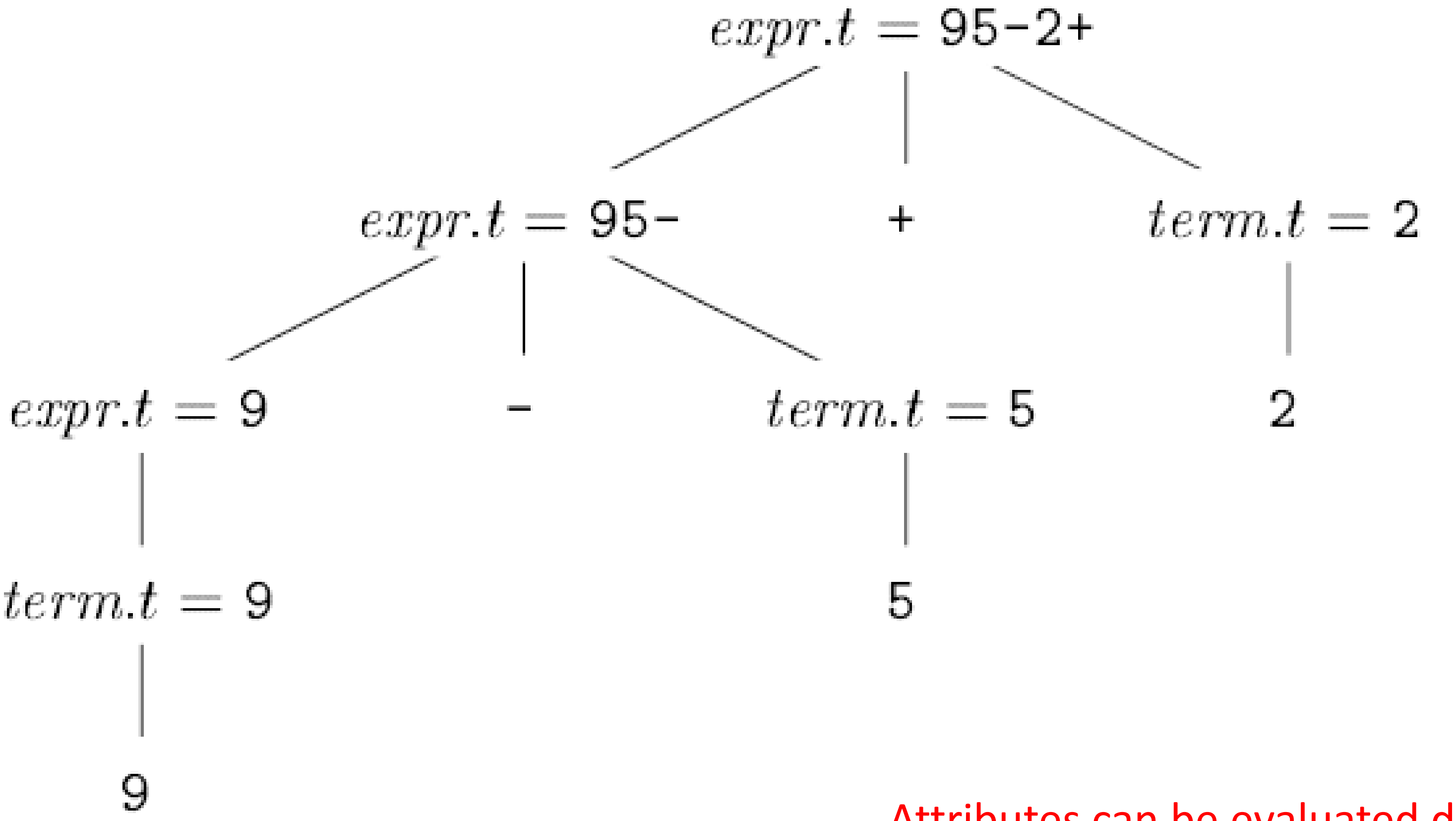
Attribute values at nodes for 9-5+2

- Build the tree
- Start from leaves
- Using semantic rules till you reach root



PRODUCTION	SEMANTIC RULES
$expr \to expr_1 + term$	$expr.t = expr_1.t \,\|\|\, term.t \,\|\|\, '+'$
$expr \to expr_1 - term$	$expr.t = expr_1.t \,\|\|\, term.t \,\|\|\, '-'$
$expr \to term$	$expr.t = term.t$
$term \to 0$	$term.t = '0'$
$term \to 1$	$term.t = '1'$
$\cdots$	$\cdots$
$term \to 9$	$term.t = '9'$

Figure 2.10: Syntax-directed definition for infix to postfix translation

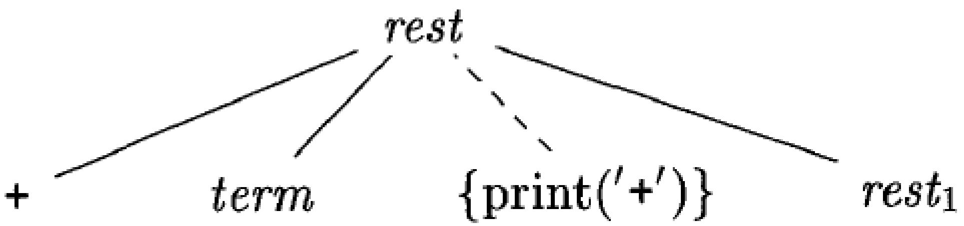


Attributes can be evaluated during a single bottom-up traversal of a parse tree.

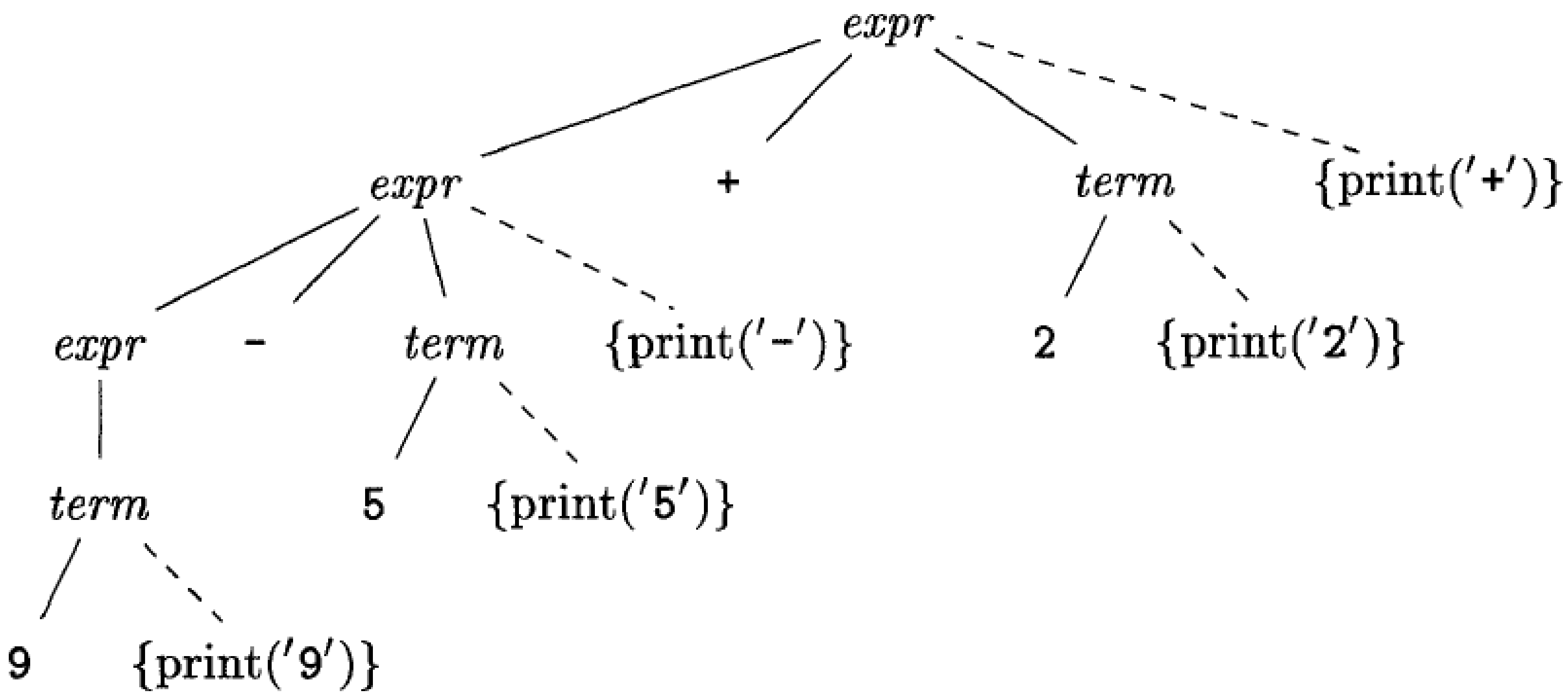
Another Way: Translation Schemes

- Another notation
- Attaching program fragments to productions
- These program fragments are called semantic actions

example: $rest \rightarrow + \; term \; \{\text{print}('+')\} \; rest_1$

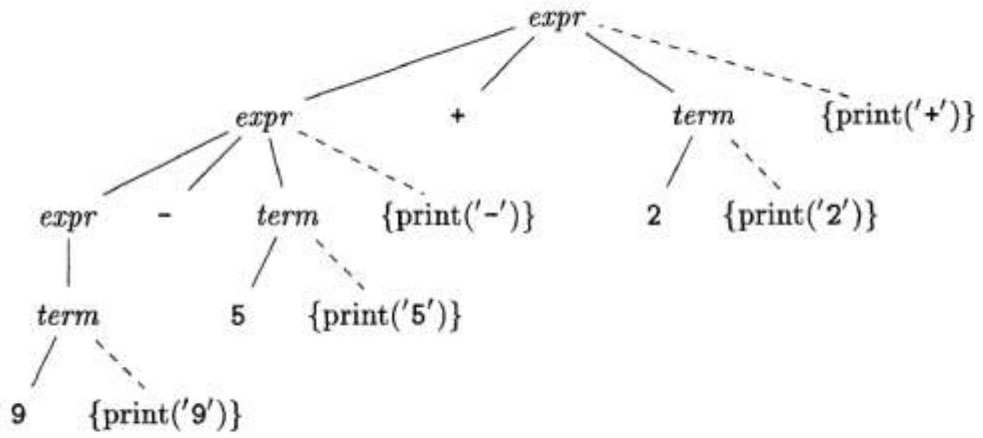


9-5+2

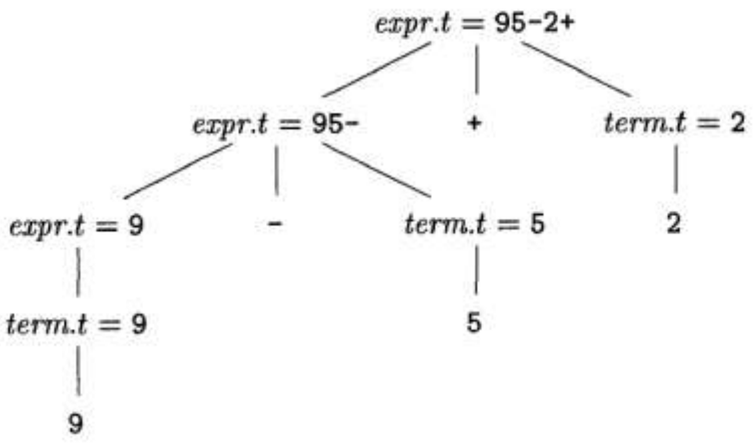


expr
expr
+
term
{print('+')}
expr
-
term
{print('-')}
2
{print('2')}
term
5
{print('5')}
9
{print('9')}

9-5+2

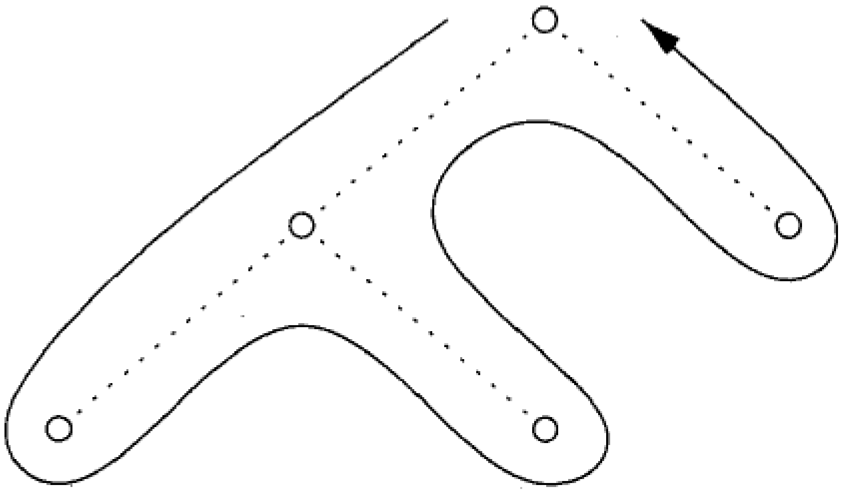


With semantic actions



With attributes

Concerning Tree Traversal

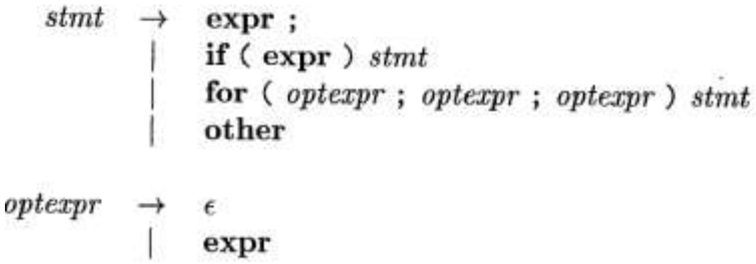


Depth first
- Preorder
- Postorder

Back to Parsing!

- We have a set of productions
- We have a string of terminals
- We need to form the parse-tree that will generate that string

Given this set of productions:



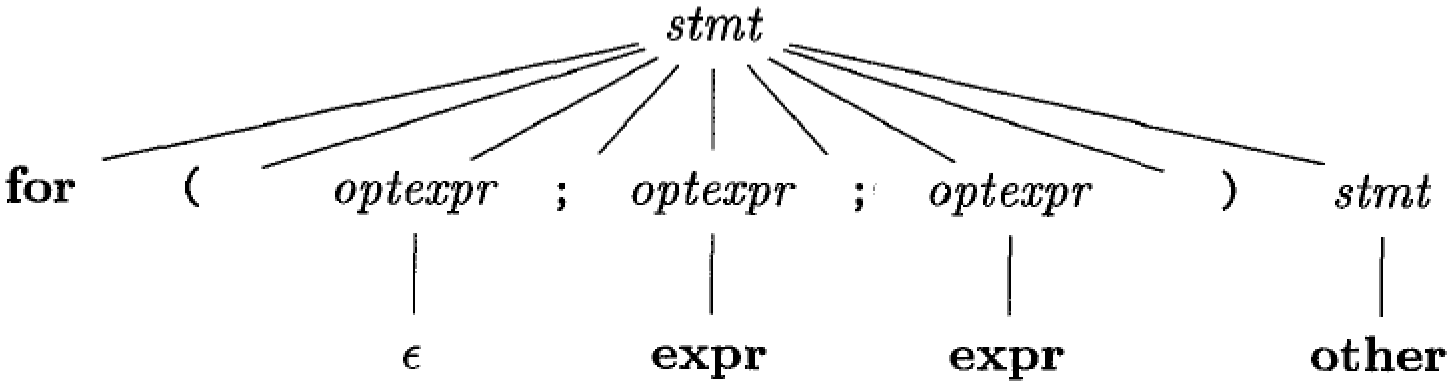
stmt → **expr** ;
| **if** (**expr**) *stmt*
| **for** (*optexpr* ; *optexpr* ; *optexpr*) *stmt*
| **other**

optexpr → ϵ
| **expr**

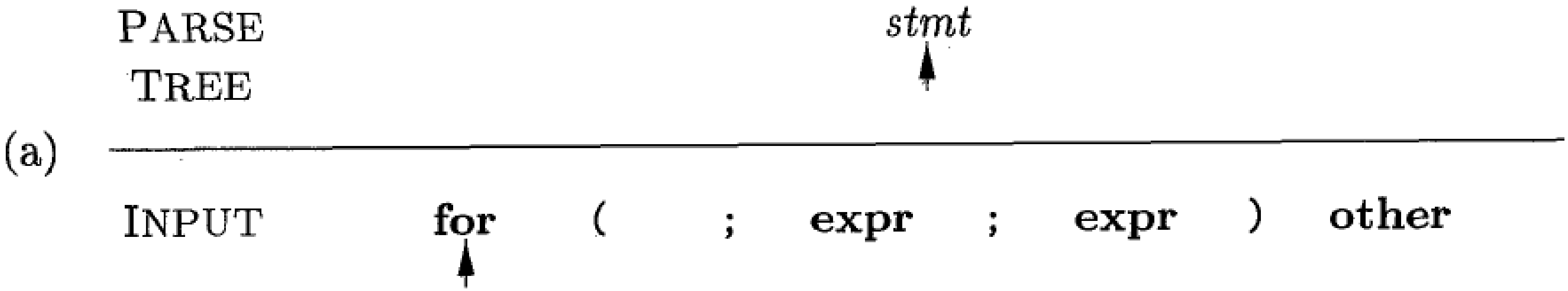
and this string:

for(; expr ; expr) other

How can we generate this?

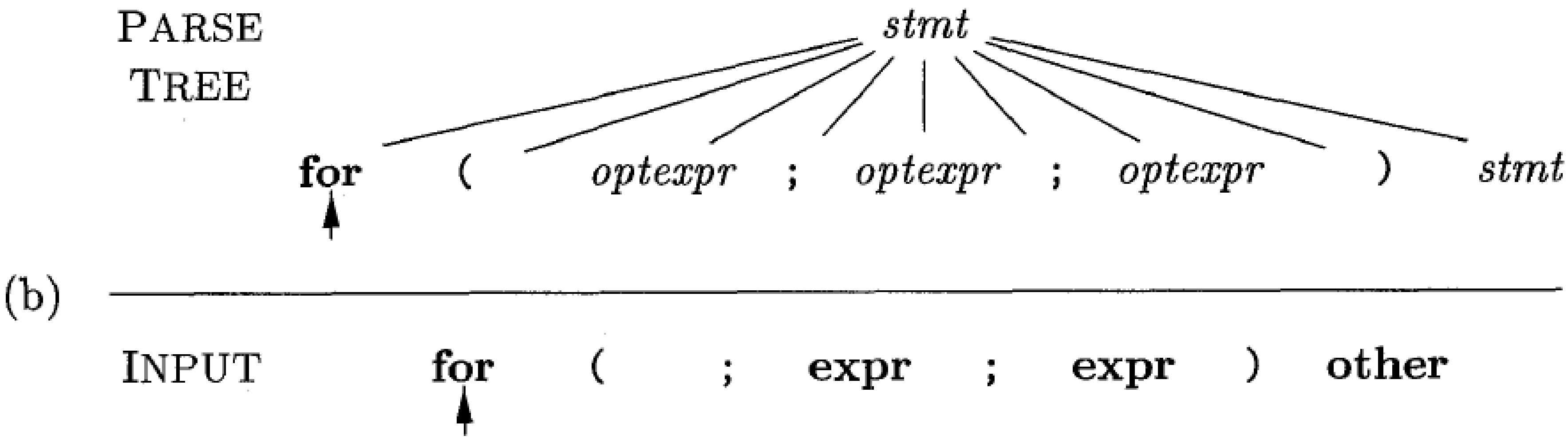


$$\begin{array}{lcl}
stmt & \to & \textbf{expr} \; ; \\
 & | & \textbf{if} \; (\; \textbf{expr} \;) \; stmt \\
 & | & \textbf{for} \; (\; optexpr \; ; \; optexpr \; ; \; optexpr \;) \; stmt \\
 & | & \textbf{other} \\
 & & \\
optexpr & \to & \epsilon \\
 & | & \textbf{expr}
\end{array}$$



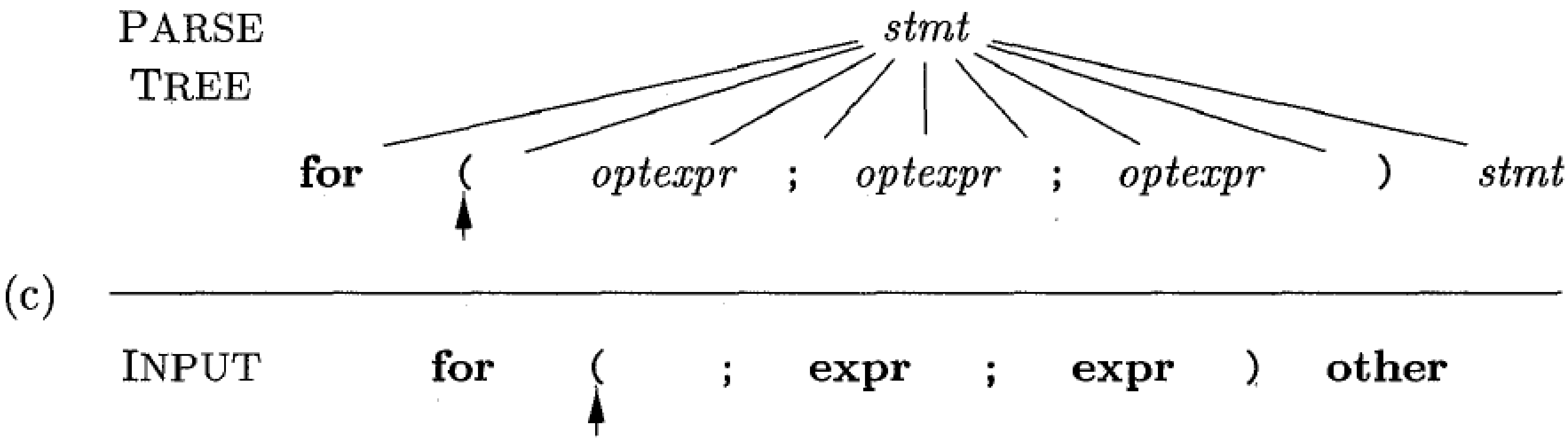
stmt → **expr** ;
| **if** (**expr**) *stmt*
| **for** (*optexpr* ; *optexpr* ; *optexpr*) *stmt*
| **other**

optexpr → ϵ
| **expr**



stmt → **expr** ;
| **if** (**expr**) *stmt*
| **for** (*optexpr* ; *optexpr* ; *optexpr*) *stmt*
| **other**

optexpr → ϵ
| **expr**



PARSE TREE

stmt

for (*optexpr* ; *optexpr* ; *optexpr*) *stmt*

(c)

INPUT **for** (; **expr** ; **expr**) **other**

Note: Sometimes choosing the right production may involve trial and error, and backtracking

Parsing With No-Backtracking

- Top-down method
- Based on recursive procedures
- Part of a parsing category called: Recursive-descent parsing
- The lookahead symbol unambiguously determines the flow-of control

```
stmt    →  expr ;
        |  if ( expr ) stmt
        |  for ( optexpr ; optexpr ; optexpr ) stmt
        |  other

optexpr →  ϵ
        |  expr
```

```
void stmt() {
        switch ( lookahead ) {
        case expr:
                match(expr); match(';'); break;
        case if:
                match(if); match('('); match(expr); match(')'); stmt();
                break;
        case for:
                match(for); match('(');
                optexpr(); match(';'); optexpr(); match(';'); optexpr();
                match(')'); stmt(); break;
        case other;
                match(other); break;
        default:
                report("syntax error");
        }
}

void optexpr() {
        if ( lookahead == expr ) match(expr);
}

void match(terminal t) {
        if ( lookahead == t ) lookahead = nextTerminal;
        else report("syntax error");
}
```

Designing Predictive Parser

- By examining the lookahead symbol we choose a production
- There must not be any conflict between two bodies with same head otherwise we cannot use predictive-parsing
- The procedure mimics the body of the chosen production
  - nonterminal is a procedure call
  - terminal is matched and lookahead advances

Example

expr -> expr + term | term

term
term + term
term + term + term
…

expr -> term factor
factor -> + term factor | ε

Enough for Today

- Next time we will continue our trip for building simple translator
- This lecture covered 2.1 -> 2.4