### Parse Trees

To illustrate a derivation, we can draw a *derivation tree* (also called a *parse tree*):

![Parse Tree Diagram]

An *abstract syntax tree* (AST) shows essential structure but eliminates unnecessary delimiters and intermediate symbols:

![AST Diagram]

If \( A \rightarrow \gamma \) is a production then

\[ \alpha A \beta \Rightarrow \alpha \gamma \beta \]

where \( \Rightarrow \) denotes a one step derivation (using production \( A \rightarrow \gamma \)).

We extend \( \Rightarrow \) to \( \Rightarrow^+ \) (derives in one or more steps), and \( \Rightarrow^* \) (derives in zero or more steps).

We can show our earlier derivation as

\[
\begin{align*}
\text{Prog} & \Rightarrow \\
\{ \text{Stmts} \} & \Rightarrow \\
\{ \text{Stmts} ; \text{Stmt} \} & \Rightarrow \\
\{ \text{Stmt} ; \text{Stmt} \} & \Rightarrow \\
\{ \text{id} = \text{Expr} ; \text{Stmt} \} & \Rightarrow \\
\{ \text{id} = \text{id} ; \text{Stmt} \} & \Rightarrow \\
\{ \text{id} = \text{id} ; \text{id} = \text{Expr} \} & \Rightarrow \\
\{ \text{id} = \text{id} ; \text{id} = \text{id} + \text{id} \} & \Rightarrow \\
\text{Prog} & \Rightarrow^+ \{ \text{id} = \text{id} ; \text{id} = \text{id} + \text{id} \}
\end{align*}
\]

When deriving a token sequence, if more than one non-terminal is present, we have a choice of which to expand next.

We must specify, at each step, which non-terminal is expanded, and what production is applied.

For simplicity we adopt a convention on what non-terminal is expanded at each step.

We can choose the leftmost possible non-terminal at each step.

A derivation that follows this rule is a *leftmost derivation*.

If we know a derivation is leftmost, we need only specify what productions are used; the choice of non-terminal is always fixed.
To denote derivations that are leftmost, we use \( \Rightarrow_L \), \( \Rightarrow_L^+ \), and \( \Rightarrow_L^* \).

The production sequence discovered by a large class of parsers (the top-down parsers) is a leftmost derivation, hence these parsers produce a leftmost parse.

\[
\text{Prog} \Rightarrow_L \\
\{ \text{Stmts} \} \Rightarrow_L \\
\{ \text{Stmts} ; \text{Stmt} \} \Rightarrow_L \\
\{ \text{Stmt} ; \text{Stmt} \} \Rightarrow_L \\
\{ \text{id} = \text{Expr} ; \text{Stmt} \} \Rightarrow_L \\
\{ \text{id} = \text{id} ; \text{Stmt} \} \Rightarrow_L \\
\{ \text{id} = \text{id} ; \text{id} = \text{Expr} \} \Rightarrow_L \\
\{ \text{id} = \text{id} ; \text{id} = \text{Expr} + \text{id} \} \Rightarrow_L \\
\{ \text{id} = \text{id} ; \text{id} = \text{id} + \text{id} \} \\
\text{Prog} \Rightarrow_L^+ \{ \text{id} = \text{id} ; \text{id} = \text{id} + \text{id} \}
\]

### Rightmost Derivations

A rightmost derivation is an alternative to a leftmost derivation. Now the rightmost non-terminal is always expanded. This derivation sequence may seem less intuitive given our normal left-to-right bias, but it corresponds to an important class of parsers (the bottom-up parsers, including CUP).

As a bottom-up parser discovers the productions used to derive a token sequence, it discovers a rightmost derivation, but in reverse order.

The last production applied in a rightmost derivation is the first that is discovered. The first production used, involving the start symbol, is discovered last.

\[
\text{Prog} \Rightarrow_R \\
\{ \text{Stmts} \} \Rightarrow_R \\
\{ \text{Stmts} ; \text{Stmt} \} \Rightarrow_R \\
\{ \text{Stmts} ; \text{id} = \text{Expr} \} \Rightarrow_R \\
\{ \text{Stmts} ; \text{id} = \text{Expr} + \text{id} \} \Rightarrow_R \\
\{ \text{Stmts} ; \text{id} = \text{id} + \text{id} \} \Rightarrow_R \\
\{ \text{Stmt} ; \text{id} = \text{id} + \text{id} \} \Rightarrow_R \\
\{ \text{id} = \text{Expr} ; \text{id} = \text{id} + \text{id} \} \Rightarrow_R \\
\{ \text{id} = \text{id} ; \text{id} = \text{id} + \text{id} \} \\
\text{Prog} \Rightarrow_R^+ \{ \text{id} = \text{id} ; \text{id} = \text{id} + \text{id} \}
\]

The sequence of productions recognized by a bottom-up parser is a rightmost parse. It is the exact reverse of the production sequence that represents a rightmost derivation.

For rightmost derivations, we use the notation \( \Rightarrow_R \), \( \Rightarrow_R^+ \), and \( \Rightarrow_R^* \).

You can derive the same set of tokens using leftmost and rightmost derivations; the only difference is the order in which productions are used.
Ambiguous Grammars

Some grammars allow more than one parse tree for the same token sequence. Such grammars are ambiguous. Because compilers use syntactic structure to drive translation, ambiguity is undesirable—it may lead to an unexpected translation.

Consider

\[ E \rightarrow E - E \]
\[ \quad | \quad \text{id} \]

When parsing the input a-b-c (where a, b and c are scanned as identifiers) we can build the following two parse trees:

\[ \text{id id id} \]

The effect is to parse a-b-c as either (a-b)-c or a-(b-c). These two groupings are certainly not equivalent.

Ambiguous grammars are usually voided in building compilers; the tools we use, like Yacc and CUP, strongly prefer unambiguous grammars.

To correct this ambiguity, we use

\[ E \rightarrow E - \text{id} \]
\[ \quad | \quad \text{id} \]

Now a-b-c can only be parsed as:

\[ \text{id id id} \]

Operator Precedence

Most programming languages have operator precedence rules that state the order in which operators are applied (in the absence of explicit parentheses). Thus in C and Java and CSX, a+b*c means compute b*c, then add in a.

These operators precedence rules can be incorporated directly into a CFG.

Consider

\[ E \rightarrow E + T \]
\[ \quad | \quad T \]
\[ T \rightarrow T \ast P \]
\[ \quad | \quad P \]
\[ P \rightarrow \text{id} \]
\[ \quad | \quad (E) \]
Does \( a+b\cdot c \) mean \((a+b)\cdot c\) or 
\( a+(b\cdot c)\)?

The grammar tells us! Look at the 
derivation tree:

```
  E
  |  
E + T
  |  
T  T * P
  |  
P  P
  |  
id  id  id
```

The other grouping can’t be 
obtained unless explicit 
parentheses are used. 
(Why?)

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**JAVA CUP**

Java CUP is a parser-generation 
tool, similar to Yacc.

CUP builds a Java parser for 
LALR(1) grammars from 
production rules and associated 
Java code fragments.

When a particular production is 
recognized, its associated code 
fragment is executed (typically to 
built an AST).

CUP generates a Java source file 
`parser.java`. It contains a class 
`parser`, with a method 
`Symbol parse()`.

The `Symbol` returned by the parser 
is associated with the grammar’s 
start symbol and contains the AST 
for the whole source program.

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The file `sym.java` is also built for 
use with a JLex-built scanner (so 
that both scanner and parser use 
the same token codes).

If an unrecovered syntax error 
occurs, `Exception()` is thrown by 
the parser.

CUP and Yacc accept exactly the 
same class of grammars—all LL(1) 
grammars, plus many useful non-
LL(1) grammars.

CUP is called as 
```
java java_cup.Main < file.cup
```

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**JAVA CUP Specifications**

Java CUP specifications are of the 
form:
- Package and import specifications
- User code additions
- Terminal and non-terminal 
declarations
- A context-free grammar, 
augmented with Java code 
fragments

**Package and Import Specifications**

You define a package name as:
```
package name ;
```
You add imports to be used as:
```
import java_cup.runtime.*;
```
User Code Additions
You may define Java code to be included within the generated parser:

- **action code**: `{: /*java code */ :}`
  This code is placed within the generated action class (which holds user-specified production actions).
- **parser code**: `{: /*java code */ :}`
  This code is placed within the generated parser class.
- **init with**: `{: /*java code */ :}`
  This code is used to initialize the generated parser.
- **scan with**: `{: /*java code */ :}`
  This code is used to tell the generated parser how to get tokens from the scanner.

Terminal and Non-terminal Declarations
You define terminal symbols you will use as:

- **terminal classname name1, name2, ...**
  `classname` is a class used by the scanner for tokens (`CSXToken`, `CSXIdentifierToken`, etc.)

You define non-terminal symbols you will use as:

- **non terminal classname name1, name2, ...**
  `classname` is the class for the AST node associated with the non-terminal (`stmtNode`, `exprNode`, etc.).

Production Rules
Production rules are of the form

```plaintext
name ::= name1 name2 ... action ;
or
name ::= name1 name2 ...
  action1
   | name3 name4 ... action2
   | ...
```

Names are the names of terminals or non-terminals, as declared earlier.

Actions are Java code fragments, of the form

```plaintext
{: /*java code */ :}
```

The Java object associated with a symbol (a token or AST node) may be named by adding a `:id` suffix to a terminal or non-terminal in a rule.

RESULT names the left-hand side non-terminal.

The Java classes of the symbols are defined in the terminal and non-terminal declaration sections.

For example,

```plaintext
prog ::= LBRACE::l stmts::s RBRACE
{: RESULT = new csxLiteNode(s,
  1.linenum,1.colnum); :}
```

This corresponds to the production

```plaintext
prog → { stmts }
```

The left brace is named `l`; the stmts non-terminal is called `s`.

In the action code, a new `CSXLiteNode` is created and assigned to `prog`. It is constructed from the AST node associated with `s`. Its line and column numbers are those given to the left brace, 1 (by the scanner).
To tell CUP what non-terminal to use as the start symbol (\texttt{prog} in our example), we use the directive:

\texttt{start with prog;}