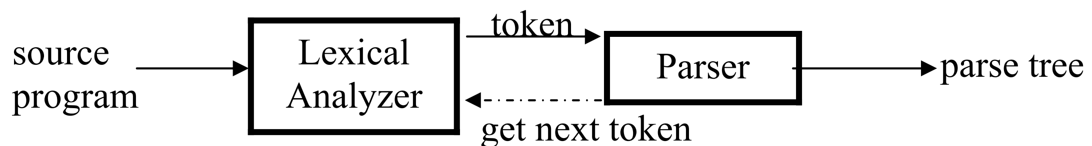
Syntax Analyzer

- *Syntax Analyzer* creates the syntactic structure of the given source program.
- This syntactic structure is mostly a *parse tree*.
- Syntax Analyzer is also known as *parser*.
- The syntax of a programming is described by a *context-free grammar (CFG)*. We will use BNF (Backus-Naur Form) notation in the description of CFGs.
- The syntax analyzer (parser) checks whether a given source program satisfies the rules implied by a context-free grammar or not.
  - If it satisfies, the parser creates the parse tree of that program.
  - Otherwise the parser gives the error messages.
- A context-free grammar
  - gives a precise syntactic specification of a programming language.
  - the design of the grammar is an initial phase of the design of a compiler.
  - a grammar can be directly converted into a parser by some tools.

Parser

- Parser works on a stream of tokens.
- The smallest item is a token.



- We categorize the parsers into two groups:

- **Top-Down Parser**
  - the parse tree is created top to bottom, starting from the root.
- **Bottom-Up Parser**
  - the parse is created bottom to top; starting from the leaves

- Both top-down and bottom-up parsers scan the input from left to right (one symbol at a time).
- Efficient top-down and bottom-up parsers can be implemented only for sub-classes of context-free grammars.
  - LL for top-down parsing
  - LR for bottom-up parsing

Context-Free Grammars

- Inherently recursive structures of a programming language are defined by a context-free grammar.

- In a context-free grammar, we have:
  - A finite set of terminals (in our case, this will be the set of tokens)
  - A finite set of non-terminals (syntactic-variables)

- A finite set of productions rules in the following form
  - $A \rightarrow \alpha$

    where A is a non-terminal and α is a string of terminals and non-terminals (including the empty string)
- A start symbol (one of the non-terminal symbol)

- Example:

  $E \rightarrow E + E \mid E - E \mid E * E \mid E / E \mid -E$

  $E \rightarrow (E)$

  $E \rightarrow id$

Derivations

$E \Rightarrow E+E$

- E+E derives from E
  - we can replace E by E+E
  - to able to do this, we have to have a production rule $E \rightarrow E+E$ in our grammar.

$E \Rightarrow E+E \Rightarrow id+E \Rightarrow id+id$

- A sequence of replacements of non-terminal symbols is called a **derivation** of id+id from E.
- In general a derivation step is

  $\alpha A \beta \Rightarrow \alpha \gamma \beta$

  if there is a production rule $A \rightarrow \gamma$ in our grammar where α and β are arbitrary strings of terminal and non-terminal symbols

$\alpha_1 \Rightarrow \alpha_2 \Rightarrow ... \Rightarrow \alpha_n$ (α_n derives from α_1 or α_1 derives α_n)

CFG - Terminology

- L(G) is *the language of G* (the language generated by G) which is a set of sentences.
- *A sentence of L(G)* is a string of terminal symbols of G.
- If S is the start symbol of G then

  ω is a sentence of L(G) iff $S \Rightarrow \omega$ where ω is a string of terminals of G.

- If G is a context-free grammar, L(G) is a *context-free language*.
- Two grammars are *equivalent* if they produce the same language.

- $S \Rightarrow \alpha$ - If α contains non-terminals, it is called as a *sentential* form of G.

  - If α does not contain non-terminals, it is called as a *sentence* of G.

Derivation Example

$E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(E+E) \Rightarrow -(id+E) \Rightarrow -(id+id)$

OR

$E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(E+E) \Rightarrow -(E+id) \Rightarrow -(id+id)$

- At each derivation step, we can choose any of the non-terminal in the sentential form of G for the replacement.
- If we always choose the left-most non-terminal in each derivation step, this derivation is called as **left-most derivation**.
- If we always choose the right-most non-terminal in each derivation step, this derivation is called as **right-most derivation**.

Left-Most Derivation

$E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(E+E) \Rightarrow -(id+E) \Rightarrow -(id+id)$

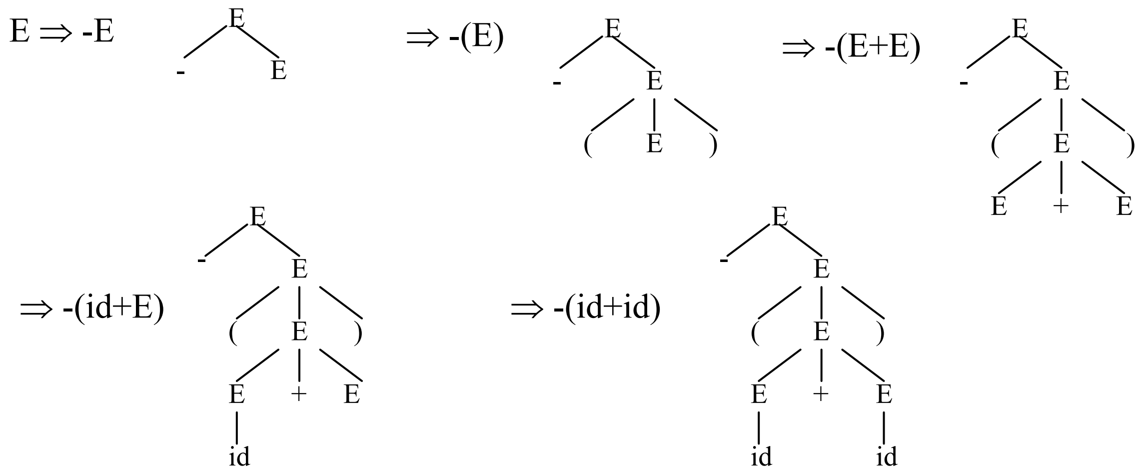
Right-Most Derivation

$E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(E+E) \Rightarrow -(E+id) \Rightarrow -(id+id)$

- We will see that the top-down parsers try to find the left-most derivation of the given source program.
- We will see that the bottom-up parsers try to find the right-most derivation of the given source program in the reverse order.

Parse Tree

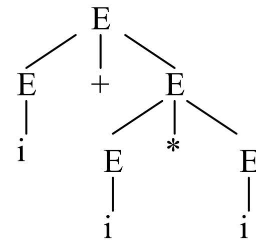
- Inner nodes of a parse tree are non-terminal symbols.
- The leaves of a parse tree are terminal symbols.
- A parse tree can be seen as a graphical representation of a derivation.



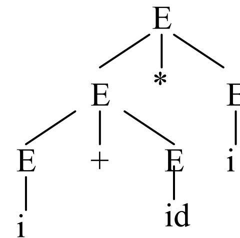
Ambiguity

- A grammar produces more than one parse tree for a sentence is called as an ***ambiguous*** grammar.

$E \Rightarrow E+E \Rightarrow id+E \Rightarrow id+E*E$
$\Rightarrow id+id*E \Rightarrow id+id*id$



$E \Rightarrow E*E \Rightarrow E+E*E \Rightarrow id+E*E$
$\Rightarrow id+id*E \Rightarrow id+id*id$



- For the most parsers, the grammar must be unambiguous.

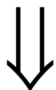
- unambiguous grammar
  ➔ unique selection of the parse tree for a sentence

- We should eliminate the ambiguity in the grammar during the design phase of the compiler.
- An unambiguous grammar should be written to eliminate the ambiguity.
- We have to prefer one of the parse trees of a sentence (generated by an ambiguous grammar) to disambiguate that grammar to restrict to this choice.

Ambiguity – Operator Precedence

- Ambiguous grammars (because of ambiguous operators) can be disambiguated according to the precedence and associativity rules.

$E \rightarrow E+E \mid E*E \mid E\char`^E \mid id \mid (E)$



Disambiguate the grammar precedence:
^ (right to left)
* (left to right)
\+ (left to right)

$E \rightarrow E+T \mid T$
$T \rightarrow T*F \mid F$
$F \rightarrow G\char`^F \mid G$
$G \rightarrow id \mid (E)$

Left Recursion

- A grammar is left ***recursive*** if it has a non-terminal A such that there is a derivation.
  $A \Rightarrow A\alpha$ for some string α

- Top-down parsing techniques **cannot** handle left-recursive grammars.
- So, we have to convert our left-recursive grammar into an equivalent grammar which is not left-recursive.
- The left-recursion may appear in a single step of the derivation (*immediate left-recursion*), or may appear in more than one step of the derivation.

Left-Recursion

$A \rightarrow A\ \alpha\ |\ \beta$ where β does not start with A

$\Downarrow$ eliminate immediate left recursion

$A \rightarrow \beta\ A'$
$A' \rightarrow \alpha\ A'\ |\ \varepsilon$ an equivalent grammar

In General,
$A \rightarrow A\ \alpha 1\ |\ ...\ |\ A\ \alpha m\ |\ \beta 1\ |\ ...\ |\ \beta n$ where $\beta 1$ ... βn do not start with A

$\Downarrow$ eliminate immediate left recursion

$A \rightarrow \beta 1\ A'\ |\ ...\ |\ \beta n\ A'$
$A' \rightarrow \alpha 1\ A'\ |\ ...\ |\ \alpha m\ A'\ |\ \varepsilon$ an equivalent grammar

Eliminate Left-Recursion – Algorithm

- Arrange non-terminals in some order: A_1 ... A_n
- for i **from** 1 **to** n **do** {
  - **for** j **from** 1 **to** i-1 **do** {
    replace each production
      $A_i \rightarrow A_j\ \gamma$
      by
      $A_i \rightarrow \alpha_1\ \gamma\ |\ ...\ |\ \alpha_k\ \gamma$
      where $A_j \rightarrow \alpha_1\ |\ ...\ |\ \alpha_k$
  }
  - eliminate immediate left-recursions among A_i productions
}

Left-Factoring

- A predictive parser (a top-down parser without backtracking) insists that the grammar must be *left-factored*.

  grammar ➔ a new equivalent grammar suitable for predictive parsing

stmt → `if` expr `then` stmt `else` stmt |
`if` expr `then` stmt

- when we see `if`, we cannot now which production rule to choose to re-write *stmt* in the derivation.

In general,

$A \rightarrow \alpha\beta_1 \mid \alpha\beta_2$ where α is non-empty and the first symbols of β_1 and β_2 (if they have one)are different.

- when processing α we cannot know whether expand
  A to $\alpha\beta_1$ or
  A to $\alpha\beta_2$
- But, if we re-write the grammar as follows
  $A \rightarrow \alpha A'$
  $A' \rightarrow \beta_1 \mid \beta_2$ so, we can immediately expand A to $\alpha A'$

Left-Factoring -- Algorithm

- For each non-terminal A with two or more alternatives (production rules) with a common non-empty prefix, let say

  $A \rightarrow \alpha\beta_1 \mid \ldots \mid \alpha\beta_n \mid \gamma_1 \mid \ldots \mid \gamma_m$

  convert it into

  $A \rightarrow \alpha A' \mid \gamma_1 \mid \ldots \mid \gamma_m$
  $A' \rightarrow \beta_1 \mid \ldots \mid \beta_n$

Left-Factoring – Example1

$A \rightarrow \underline{a}bB \mid \underline{a}B \mid cdg \mid cdeB \mid cdfB$
$\Downarrow$
$A \rightarrow aA' \mid \underline{cd}g \mid \underline{cd}eB \mid \underline{cd}fB$
$A' \rightarrow bB \mid B$
$\Downarrow$
$A \rightarrow aA' \mid cdA''$
$A' \rightarrow bB \mid B$
$A'' \rightarrow g \mid eB \mid fB$

Left-Factoring – Example2

$A \rightarrow ad \mid a \mid ab \mid abc \mid b$
$\Downarrow$
$A \rightarrow aA' \mid b$
$A' \rightarrow d \mid \varepsilon \mid b \mid bc$
$\Downarrow$
$A \rightarrow aA' \mid b$

$A' \rightarrow d \mid \varepsilon \mid bA''$
$A'' \rightarrow \varepsilon \mid c$

Non-Context Free Language Constructs

- There are some language constructions in the programming languages which are not context-free. This means that, we cannot write a context-free grammar for these constructions.

- $L1 = \{ \omega c \omega \mid \omega \text{ is in } (a|b)^* \}$ is not context-free
  ➔ declaring an identifier and checking whether it is declared or not later. We cannot do this with a context-free language. We need semantic analyzer (which is not context-free).

- $L2 = \{a^n b^m c^n d^m \mid n \geq 1 \text{ and } m \geq 1 \}$ is not context-free
  ➔ declaring two functions (one with n parameters, the other one with m parameters), and then calling them with actual parameters.