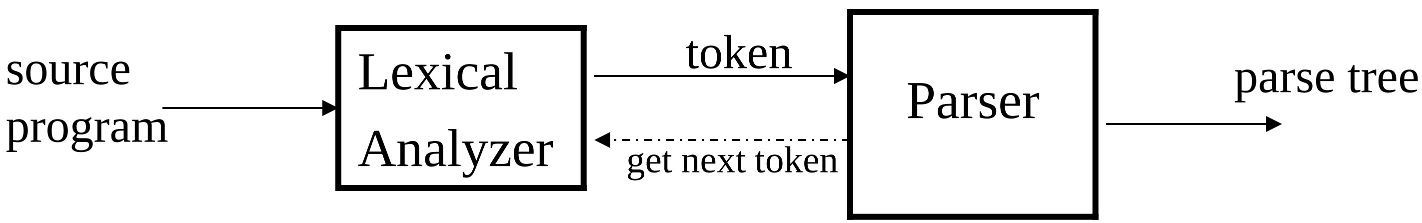
# Syntax Analyzer

- *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.



# Parsers (cont.)

- We categorize the parsers into two groups:

1. **Top-Down Parser**
   - the parse tree is created top to bottom, starting from the root.
2. **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
      $\alpha$ 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 $\alpha$ and $\beta$ are arbitrary strings of terminal and non-terminal symbols

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

$\Rightarrow$ : derives in one step
$\overset{*}{\Rightarrow}$ : derives in zero or more steps
$\overset{+}{\Rightarrow}$ : derives in one or more steps

# 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

  $\omega$ is a sentence of L(G) iff $S \overset{+}{\Rightarrow} \omega$ where $\omega$ 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.

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

  - If $\alpha$ 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 and Right-Most Derivations

Left-Most Derivation

$$E \underset{lm}{\Rightarrow} -E \underset{lm}{\Rightarrow} -(E) \underset{lm}{\Rightarrow} -(E+E) \underset{lm}{\Rightarrow} -(id+E) \underset{lm}{\Rightarrow} -(id+id)$$

Right-Most Derivation

$$E \underset{rm}{\Rightarrow} -E \underset{rm}{\Rightarrow} -(E) \underset{rm}{\Rightarrow} -(E+E) \underset{rm}{\Rightarrow} -(E+id) \underset{rm}{\Rightarrow} -(id+id)$$

- We will see that the top-down parsers try to find the left-most derivation of the given source program.

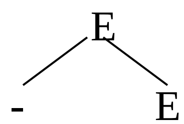
- We will see that the bottom-up parsers try to find the right-most derivation of the given source program in the reverse order.

# Parse Tree

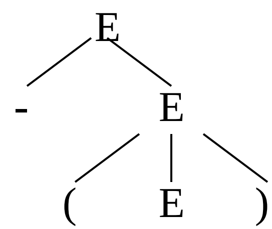
- Inner nodes of a parse tree are non-terminal symbols.
- The leaves of a parse tree are terminal symbols.

- A parse tree can be seen as a graphical representation of a derivation.

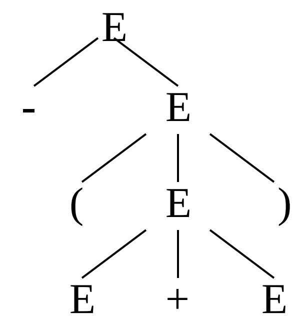
$E \Rightarrow -E$



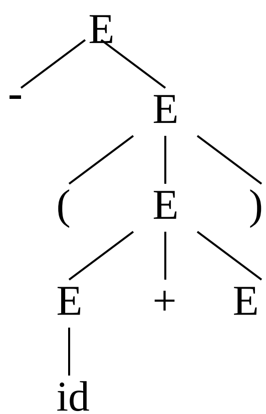

$\Rightarrow -(E)$



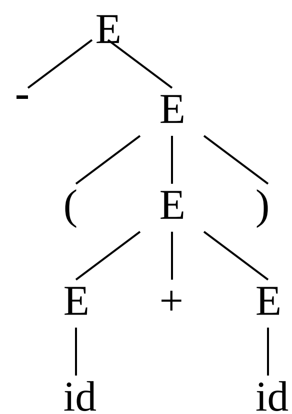

$\Rightarrow -(E+E)$




$\Rightarrow -(id+E)$



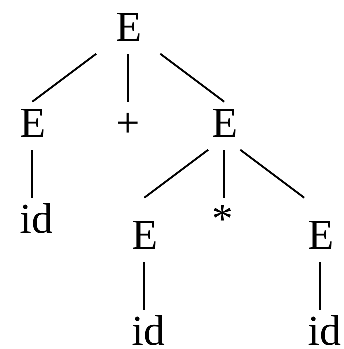

$\Rightarrow -(id+id)$



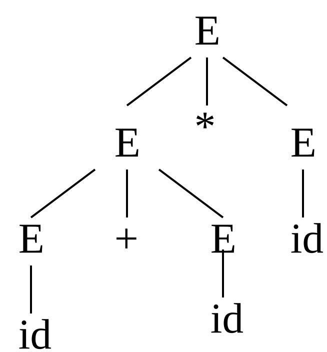
# Ambiguity

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

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




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



# Ambiguity (cont.)

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

- unambiguous grammar

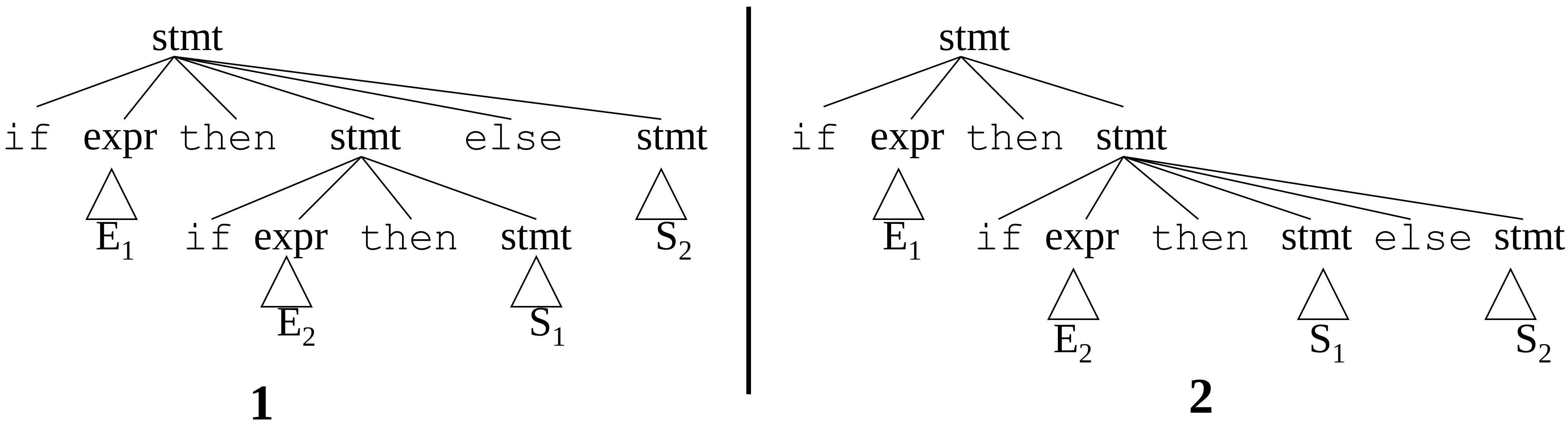
    ➔ unique selection of the parse tree for a sentence

- 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 (cont.)

stmt $\rightarrow$ `if` expr `then` stmt |
`if` expr `then` stmt `else` stmt | otherstmts

`if` $E_1$ `then` `if` $E_2$ `then` $S_1$ `else` $S_2$



# Ambiguity (cont.)

- We prefer the second parse tree (else matches with closest if).
- So, we have to disambiguate our grammar to reflect this choice.

- The unambiguous grammar will be:

stmt → matchedstmt | unmatchedstmt

matchedstmt → `if` expr `then` matchedstmt `else` matchedstmt | otherstmts

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

# Ambiguity – Operator Precedence

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

$$E \rightarrow E+E \mid E*E \mid E\text{^}E \mid id \mid (E)$$

$\Downarrow$ disambiguate the grammar

precedence:

^ (right to left)

* (left to right)

\+ (left to right)

$$E \rightarrow E+T \mid T$$

$$T \rightarrow T*F \mid F$$

$$F \rightarrow G\text{^}F \mid G$$

$$G \rightarrow id \mid (E)$$

# Left Recursion

- A grammar is ***left recursive*** if it has a non-terminal A such that there is a derivation.

  $A \stackrel{+}{\Rightarrow} A\alpha$ for some string $\alpha$

- 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.

# Immediate Left-Recursion

$A \rightarrow A\,\alpha \mid \beta$ where $\beta$ does not start with A

$\Downarrow$ eliminate immediate left recursion

$A \rightarrow \beta\,A'$

$A' \rightarrow \alpha\,A' \mid \varepsilon$ an equivalent grammar

In general,

$A \rightarrow A\,\alpha_1 \mid \ldots \mid A\,\alpha_m \mid \beta_1 \mid \ldots \mid \beta_n$ where $\beta_1 \ldots \beta_n$ do not start with A

$\Downarrow$ eliminate immediate left recursion

$A \rightarrow \beta_1\,A' \mid \ldots \mid \beta_n\,A'$

$A' \rightarrow \alpha_1\,A' \mid \ldots \mid \alpha_m\,A' \mid \varepsilon$ an equivalent grammar

# Immediate Left-Recursion -- Example

$E \rightarrow E{+}T \mid T$

$T \rightarrow T{*}F \mid F$

$F \rightarrow id \mid (E)$

$\Downarrow$ eliminate immediate left recursion

$E \rightarrow T\,E'$

$E' \rightarrow +T\,E' \mid \varepsilon$

$T \rightarrow F\,T'$

$T' \rightarrow *F\,T' \mid \varepsilon$

$F \rightarrow id \mid (E)$

# Left-Recursion -- Problem

- A grammar cannot be immediately left-recursive, but it still can be left-recursive.
- By just eliminating the immediate left-recursion, we may not get a grammar which is not left-recursive.

$S \rightarrow Aa \mid b$

$A \rightarrow Sc \mid d$ This grammar is not immediately left-recursive, but it is still left-recursive.

$\underline{S} \Rightarrow Aa \Rightarrow \underline{S}ca$ or

$\underline{A} \Rightarrow Sc \Rightarrow \underline{A}ac$ causes to a left-recursion

- So, we have to eliminate all left-recursions from our grammar

# Eliminate Left-Recursion -- Algorithm

- Arrange non-terminals in some order: $A_1 \ldots A_n$
- **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

    $$A_i \rightarrow \alpha_1 \gamma \mid \ldots \mid \alpha_k \gamma$$

    where $A_j \rightarrow \alpha_1 \mid \ldots \mid \alpha_k$

    }
  - eliminate immediate left-recursions among $A_i$ productions

}

# Eliminate Left-Recursion -- Example

$S \rightarrow Aa \mid b$
$A \rightarrow Ac \mid Sd \mid f$

- Order of non-terminals: S, A

for S:

- we do not enter the inner loop.
- there is no immediate left recursion in S.

for A:

- Replace $A \rightarrow Sd$ with $A \rightarrow Aad \mid bd$
  So, we will have $A \rightarrow Ac \mid Aad \mid bd \mid f$
- Eliminate the immediate left-recursion in A

$$A \rightarrow bdA' \mid fA'$$
$$A' \rightarrow cA' \mid adA' \mid \varepsilon$$

So, the resulting equivalent grammar which is not left-recursive is:

$S \rightarrow Aa \mid b$
$A \rightarrow bdA' \mid fA'$
$A' \rightarrow cA' \mid adA' \mid \varepsilon$

# Eliminate Left-Recursion – Example2

$S \rightarrow Aa \mid b$
$A \rightarrow Ac \mid Sd \mid f$

- Order of non-terminals: A, S

for A:

- we do not enter the inner loop.
- Eliminate the immediate left-recursion in A

$$A \rightarrow SdA' \mid fA'$$
$$A' \rightarrow cA' \mid \varepsilon$$

for S:

- Replace $S \rightarrow Aa$ with $S \rightarrow SdA'a \mid fA'a$
  So, we will have $S \rightarrow SdA'a \mid fA'a \mid b$
- Eliminate the immediate left-recursion in S

$$S \rightarrow fA'aS' \mid bS'$$
$$S' \rightarrow dA'aS' \mid \varepsilon$$

So, the resulting equivalent grammar which is not left-recursive is:

$S \rightarrow fA'aS' \mid bS'$
$S' \rightarrow dA'aS' \mid \varepsilon$
$A \rightarrow SdA' \mid fA'$
$A' \rightarrow cA' \mid \varepsilon$

# 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.

# Left-Factoring (cont.)

- In general,

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

- when processing $\alpha$ 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 = { $\omega c \omega \mid \omega$ 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 = {$a^n b^m c^n d^m \mid n \geq 1$ 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.