Parul® University

COMPILER DESIGN

SUBJECT CODE: 303105349

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CHAPTER-2

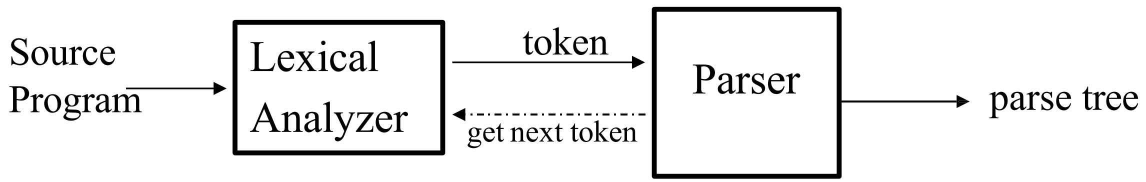
Introduction to syntax analysis

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

      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)

$\Rightarrow$: derives in one step

$\Rightarrow$: derives in zero or more steps

$\Rightarrow$: 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

    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 and Right-Most Derivations

Left-Most Derivation

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

Right-Most Derivation

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

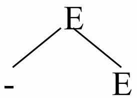
- We will see that the top-down parsers try to find the left-most derivation of the given source program.

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

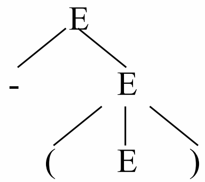
Parse Tree

- 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.

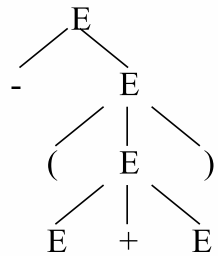
$E \Rightarrow -E$



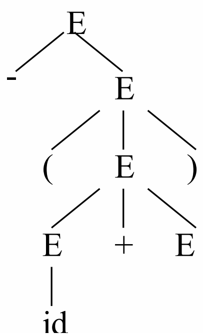
$\Rightarrow -(E)$



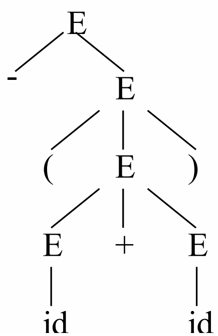
$\Rightarrow -(E+E)$



$\Rightarrow -(id+E)$



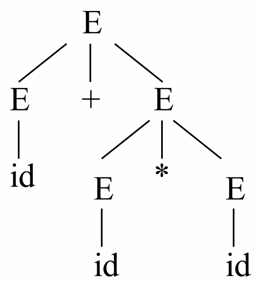
$\Rightarrow -(id+id)$



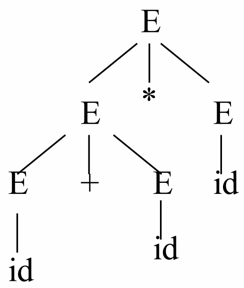
Ambiguity

- 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

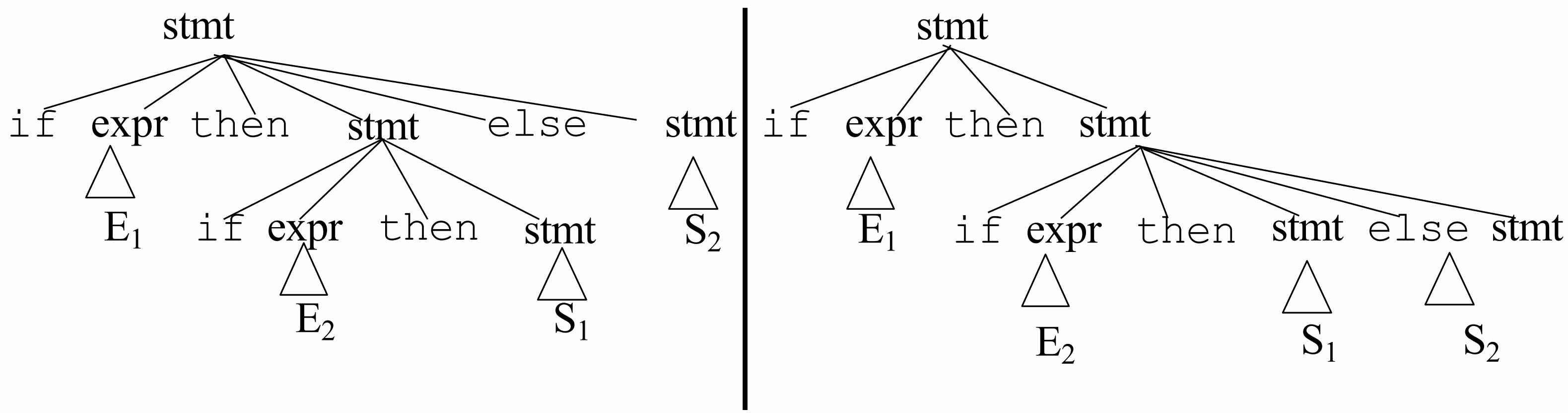
  ⍰ unique selection of the parse tree for a sentence

- 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 → 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 → E+E | E*E | E^E | id | (E)

disambiguate the grammar

precedence:

^ (right to left)

* (left to right)

+ (left to right)

E → E+T | T

T → T*F | F

F → G^F | G

G → id | (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.

Immediate Left-Recursion

$A \rightarrow A\,\alpha \mid \beta$ where β 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

$E \rightarrow E+T \mid T$

$T \rightarrow T*F \mid F$

$F \rightarrow id \mid (E)$

U 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 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

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

convert it into

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

Left-Factoring – Example1

$A \rightarrow \underline{a}bB \mid \underline{a}B \mid cdg \mid cdeB \mid cdfB$

U

$A \rightarrow aA' \mid \underline{cdg} \mid \underline{cd}eB \mid \underline{cd}fB$

$A' \rightarrow bB \mid B$

U

$A \rightarrow aA' \mid cdA''$

$A' \rightarrow bB \mid B$

$A'' \rightarrow g \mid eB \mid fB$

Left-Factoring – Example2

A → ad | a | ab | abc | b

U

A → aA' | b

A' → d | ε | b | bc

U

A → aA' | b

A' → d | ε | bA''

A'' → ε | 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 = { ωcω | ω 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.

Top-Down Parsing

- The parse tree is created top to bottom.
- Top-down parser
  - Recursive-Descent Parsing
    - Backtracking is needed (If a choice of a production rule does not work, we backtrack to try other alternatives.)
    - It is a general parsing technique, but not widely used.
    - Not efficient
  - Predictive Parsing
    - no backtracking
    - efficient
    - needs a special form of grammars (LL(1) grammars).
    - Recursive Predictive Parsing is a special form of Recursive Descent parsing without backtracking.
    - Non-Recursive (Table Driven) Predictive Parser is also known as LL(1) parser.

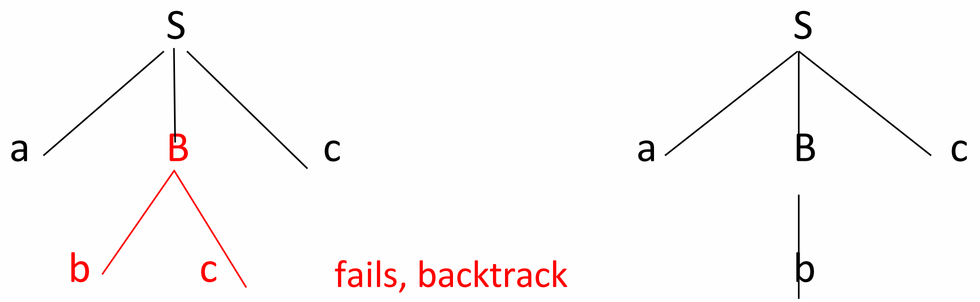
Recursive-Descent Parsing (uses Backtracking)

- Backtracking is needed.
- It tries to find the left-most derivation.

S → aBc

B → bc | b

input: abc



Predictive Parser

a grammar ⍰ eliminate left recursion ⍰ left factor a grammar suitable for predictive parsing (a LL(1) grammar) no %100 guarantee.

- When re-writing a non-terminal in a derivation step, a predictive parser can uniquely choose a production rule by just looking the current symbol in the input string.

$A \rightarrow \alpha_1 \mid \ldots \mid \alpha_n$ input: ... a ....

current token

Predictive Parser (example)

stmt → `if ......` |
`while ......` |
`begin ......` |
`for .....`

- When we are trying to write the non-terminal *stmt*, if the current token is `if` we have to choose first production rule.
- When we are trying to write the non-terminal *stmt*, we can uniquely choose the production rule by just looking the current token.
- We eliminate the left recursion in the grammar, and left factor it. But it may not be suitable for predictive parsing (not LL(1) grammar).

Recursive Predictive Parsing

- Each non-terminal corresponds to a procedure.

Ex: A → aBb(This is only the production rule for A)

proc A {
- match the current token with a, and move to the next token;
- call ‘B’;
- match the current token with b, and move to the next token;

}

Recursive Predictive Parsing (cont.)

A → aBb | bAB

```
proc A {
        case of the current token {
                'a':  - match the current token with a, and move to the next token;
                      - call 'B';
                      - match the current token with b, and move to the next token;
                'b':  - match the current token with b, and move to the next token;
                      - call 'A';
               - call 'B';
        }
}
```

Recursive Predictive Parsing (cont.)

- When to apply ε-productions.

$$A \rightarrow aA \mid bB \mid \varepsilon$$

- If all other productions fail, we should apply an ε-production. For example, if the current token is not a or b, we may apply the ε-production.
- Most correct choice: We should apply an ε-production for a non-terminal A when the current token is in the follow set of A (which terminals can follow A in the sentential forms).

Recursive Predictive Parsing (Example)

- Content inside

A → aBe | cBd | C
B → bB | ε
C → f

```
proc A {
        case of the current token {
          a:      - match the current token with a,
                    and move to the next token;
                  - call B;
                  - match the current token with e,
                    and move to the next token;
          c:      - match the current token with c,
                    and move to the next token;
                  - call B;
                  - match the current token with d,
                    and move to the next token;
          f:      - call C
        }
}
```

first set of C

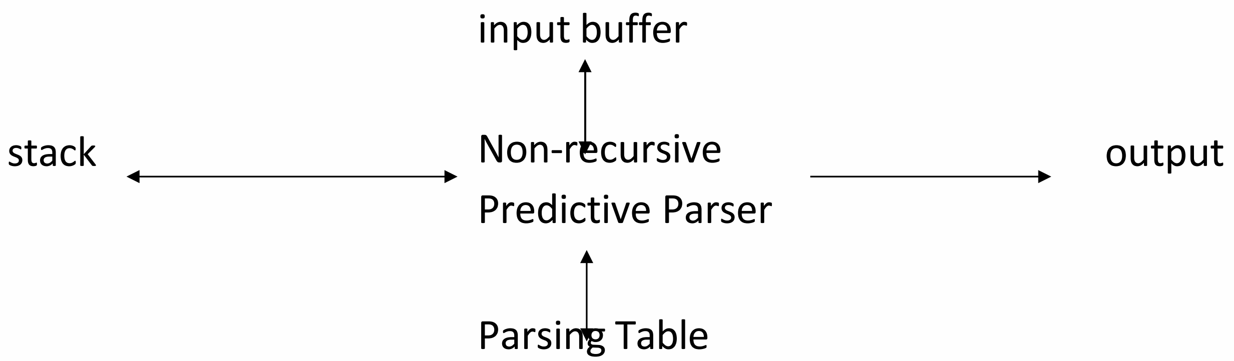
```
proc C {     match the current token with f,
and move to the next token; }
```

```
proc B {
   case of the current token {
      b:    - match the current token with b,
              and move to the next token;
            - call B
     e,d:  do nothing
   }
}
```

follow set of B

Non-Recursive Predictive Parsing -- LL(1) Parser

- Non-Recursive predictive parsing is a table-driven parser.
- It is a top-down parser.
- It is also known as LL(1) Parser.



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