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## **UNIT IV**

# **CONTEXT- FREE LANGUAGES AND SIMPLIFICATION OF CONTEXT-FREE GRAMMAR**



# UNIT IV SYLLABUS

- Ambiguity in Context Free Grammar, Language of a Context Free Grammar, Applications of Context Free Grammar, Pumping Lemma for Context Free Grammar, Normal Forms for Context Free Grammar - Chomsky Normal Form, Greibach Normal Form, Context-Free Languages and Derivation Trees, Leftmost and Rightmost derivations, Sentential forms, Construction of Reduced Grammars, Elimination of null and unit productions

# Context Free Grammar



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- Context free grammar is a formal grammar which is used to **generate all possible strings** in a given formal language.
- Context free grammar  $G$  can be defined by four tuples as:

$$G = (V, T, P, S)$$



- **N** is a set of non-terminal symbols.
- **T** is a set of terminals where  $\mathbf{N} \cap \mathbf{T} = \mathbf{NULL}$ .
- **P** is a set of rules,  $\mathbf{P}: \mathbf{N} \rightarrow (\mathbf{N} \cup \mathbf{T})^*$ , i.e., the left-hand side of the production rule **P** does have any right context or left context.
- **S** is the start symbol.



# Example

- The grammar  $(\{A\}, \{a, b, c\}, P, A)$ ,  
 $P : A \rightarrow aA, A \rightarrow abc.$
- The grammar  $(\{S, a, b\}, \{a, b\}, P, S)$ ,  
 $P: S \rightarrow aSa, S \rightarrow bSb, S \rightarrow \epsilon$
- The grammar  $(\{S, F\}, \{0, 1\}, P, S)$ ,  
 $P: S \rightarrow 00S \mid 11F, F \rightarrow 00F \mid \epsilon$



# Capabilities of CFG

- Context free grammar is useful to describe most of the **programming languages**.
- If the grammar is properly designed then an **efficient parser** can be constructed automatically.
- Using the features of associativity & precedence information, suitable **grammars for expressions** can be constructed.
- Context free grammar is capable of describing **nested structures** like: balanced parentheses, matching begin-end, corresponding if-then-else's & so on.



# Applications of CFG

- Context Free Grammar (CFG) is of great practical importance. It is used for following purposes-
- 
- For defining programming languages
- For parsing the program by constructing syntax tree
- For translation of programming languages
- For describing arithmetic expressions
- For construction of compilers



# Derivation

- Derivation is a **sequence of production rules**. It is used to get the input string through these production rules.
- During parsing we have to take **two decisions**.
- These are as follows:
  - We have to decide the **non-terminal** which is to be replaced.
  - We have to decide the **production rule** by which the non-terminal will be replaced.
  - We have **two options** to decide which non-terminal to be replaced with production rule.





## Left-most Derivation

- In the left most derivation, the input is scanned and replaced with the production rule from **left to right**.
- So in left most derivatives we read the input string from left to right.



# Example

- **Production rules:**
  - $S = S + S$
  - $S = S - S$
  - $S = a \mid b \mid c$
- **Input:**
  - $a - b + c$



- **The left-most derivation is:**

- $S = S + S$
- $S = S - S + S$
- $S = a - S + S$
- $S = a - b + S$
- $S = a - b + c$



## Right-most Derivation

- In the right most derivation, the input is scanned and replaced with the production rule from **right to left**.
- So in right most derivatives we read the input string from right to left.



# Example

- **Production rules:**
  - $S = S + S$
  - $S = S - S$
  - $S = a \mid b \mid c$
- **Input:**
  - $a - b + c$



- **The right-most derivation is:**

- $S = S - S$
- $S = S - S + S$
- $S = S - S + c$
- $S = S - b + c$
- $S = a - b + c$



# Parse Tree

- Parse tree is the **graphical representation of symbol**. The symbol can be terminal or non-terminal.
- In parsing, the string is derived using the **start symbol**. The root of the parse tree is that start symbol.
- It is the graphical representation of symbol that can be **terminals or non-terminals**.



- Parse tree follows the precedence of operators.
- The deepest sub-tree traversed first.
- So, the operator in the parent node has less precedence over the operator in the sub-tree.





The parse tree follows these points:

- All leaf nodes have to be terminals.
- All interior nodes have to be non-terminals.
- In-order traversal gives original input string.



# Example

- **Production rules:**

- $S = S + S \mid S * S$

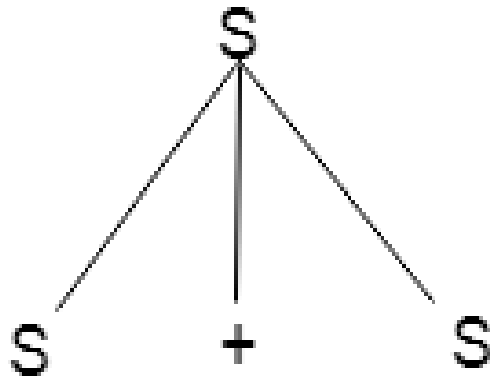
- $S = a \mid b \mid c$

- **Input:**

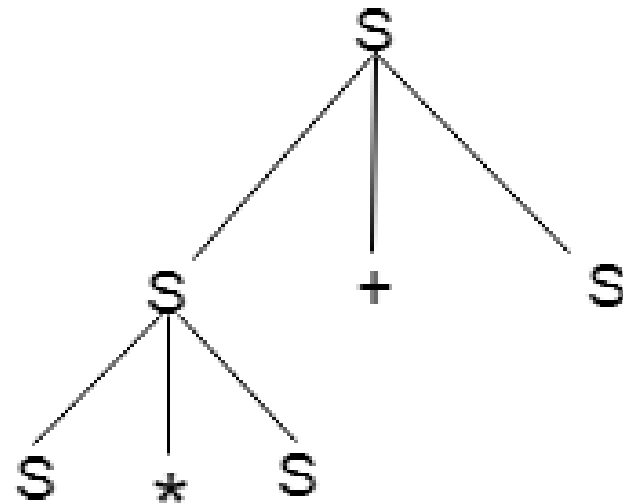
- $a * b + c$



**Step 1**

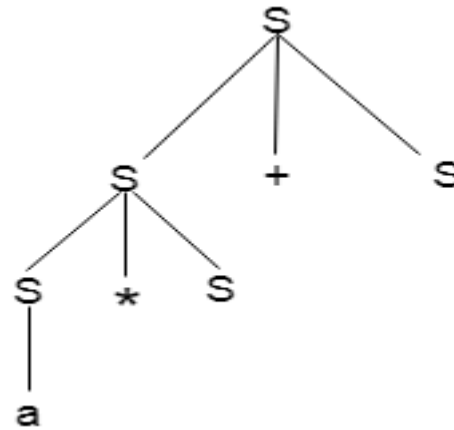


**Step 2**

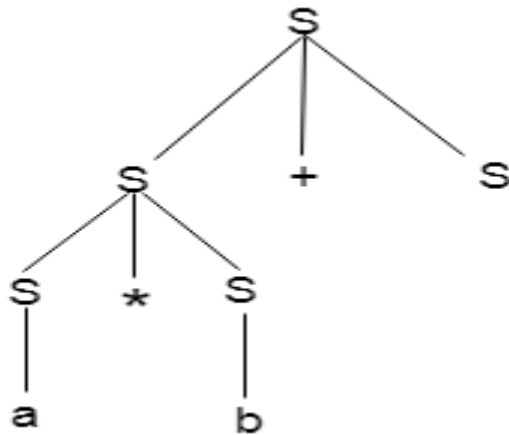




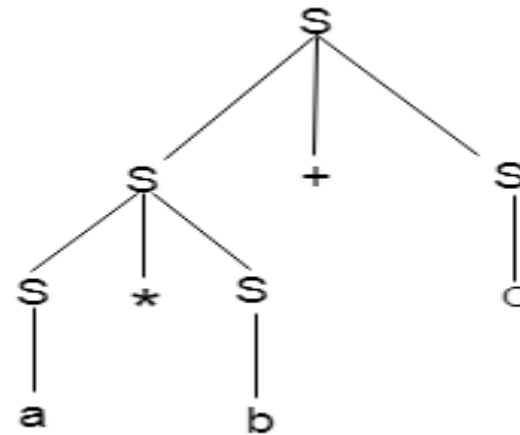
### Step 3



### Step 4



### Step 5



# POLLING QUESTIONS



1. Which of the following statement is false?
  - a) Context free language is the subset of context sensitive language
  - b) Regular language is the subset of context sensitive language
  - c) Recursively enumerable language is the super set of regular language
  - d) **Context sensitive language is a subset of context free language**



2. Which of the following statement is correct?

- a) **All Regular grammar are context free but not vice versa**
- b) All context free grammar are regular grammar but not vice versa
- c) Regular grammar and context free grammar are the same entity
- d) None of the mentioned



# Significance of CFG

- Context free languages strike a balance between what is easy enough for a computer to understand and what is expressive enough for a human to use.
- **Mathematical expressions** as well as large chunks of human languages can be modeled by context free grammars.
- Therefore they are the **basis of most programming languages and human-readable data formats.**



# Ambiguity in CFG

- A grammar is said to be **ambiguous** if there exists **more than one leftmost derivation** or **more than one rightmost derivative** or **more than one parse tree** for the given input string.
- If the grammar is not ambiguous then it is called **unambiguous**.





- If a context free grammar **G** has **more than one derivation tree** for some string **w**  $\in$  **L(G)**, it is called an **ambiguous grammar**.
- There exist **multiple right-most or left-most derivations** for some string generated from that grammar.



# Example 1

- **Problem:** Check whether the grammar G with production rules –

$$X \rightarrow X+X \mid X^*X \mid X \mid a$$

is ambiguous or not.



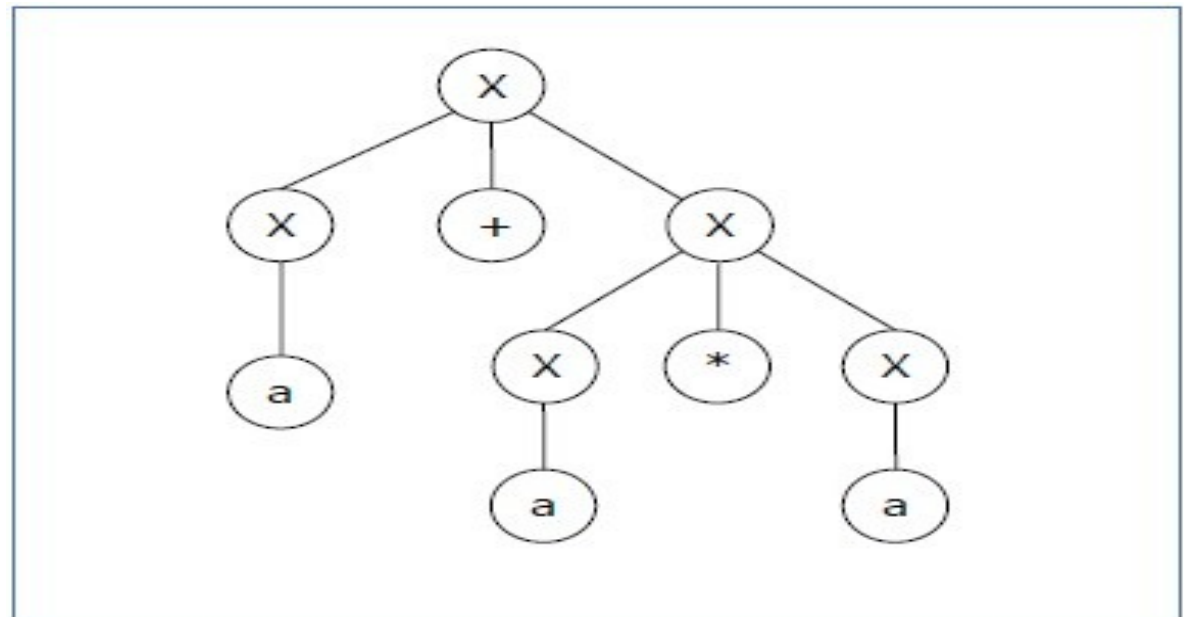
- **Solution**

- Let's find out the derivation tree for the string "**a+a\*a**". It has two leftmost derivations.

- **Derivation 1 -**

$X \rightarrow X+X \rightarrow a+X \rightarrow a+X*X \rightarrow a+a*X \rightarrow a+a*a$

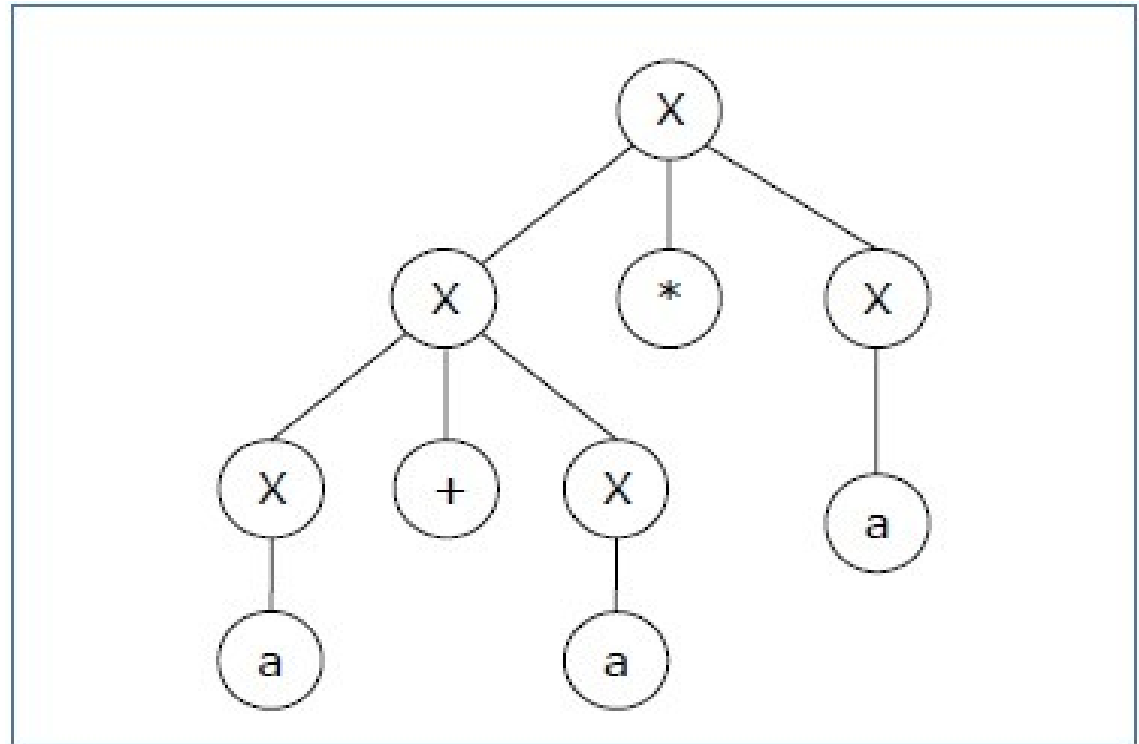
- **Parse Tree 1 -**



- **Derivation 2 –**

$X \rightarrow X^*X \rightarrow X+X^*X \rightarrow a+X^*X \rightarrow a+a^*X \rightarrow a+a^*a$

- **Parse Tree 2 –**

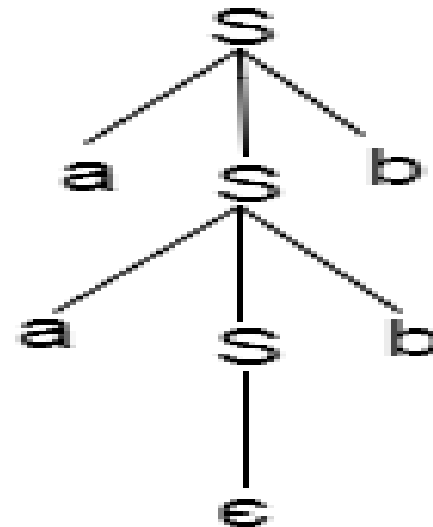
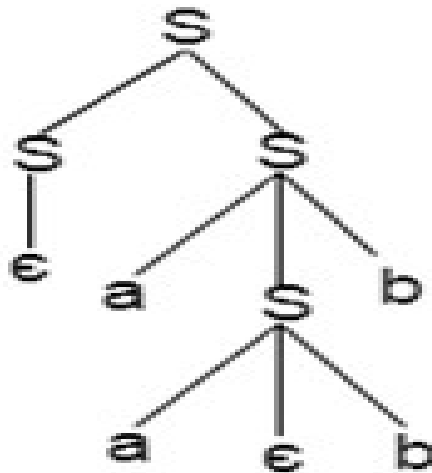


Since there are two parse trees for a single string "a+a\*a", the grammar **G is ambiguous.**



## Example 2

- P:  $S = aSb \mid SS \mid \epsilon$
- For the string **aabb**, the above grammar generates two parse trees:





# Practice Questions

1. Check whether the given grammar is ambiguous or not-  
 $S \rightarrow SS \mid a \mid b$
2. Check whether the given grammar is ambiguous or not-  
 $S \rightarrow A \mid B, A \rightarrow aAb \mid ab, B \rightarrow abB \mid \epsilon$
3. Check whether the given grammar is ambiguous or not-  
 $S \rightarrow AB \mid C, A \rightarrow aAb \mid ab, B \rightarrow cBd \mid cd, C \rightarrow aCd \mid aDd, D \rightarrow bDc \mid bc$



4. Check whether the given grammar is ambiguous or not-

$$R \rightarrow R + R / R . R / R^* / a / b$$

5. Check whether the given grammar is ambiguous or not-

$$S \rightarrow aSbS / bSaS / \epsilon$$



# CFL Closure Property

- Context-free languages are **closed** under –
- Union
- Concatenation
- Kleene Star operation





# Union

- Let  $L_1$  and  $L_2$  be two context free languages. Then  $L_1 \cup L_2$  is also context free.
- **Example**
- Let  $L_1 = \{ a^n b^n, n > 0 \}$ . Corresponding grammar  $G_1$  will have  
P:  $S_1 \rightarrow aAb \mid ab$
- Let  $L_2 = \{ c^m d^m, m \geq 0 \}$ . Corresponding grammar  $G_2$  will have  
P:  $S_2 \rightarrow cBb \mid \epsilon$
- Union of  $L_1$  and  $L_2$ ,  $L = L_1 \cup L_2 = \{ a^n b^n \} \cup \{ c^m d^m \}$
- The corresponding grammar  $G$  will have the additional production  $S \rightarrow S_1 \mid S_2$



# Concatenation

- If  $L_1$  and  $L_2$  are context free languages, then  $L_1L_2$  is also context free.
- **Example**
- Union of the languages  $L_1$  and  $L_2$ ,
- $L = L_1L_2 = \{ a^n b^n c^m d^m \}$
- The corresponding grammar  $G$  will have the additional production  $S \rightarrow S1 S2$



# Kleene Star

- If  $L$  is a context free language, then  $L^*$  is also context free.
- **Example**
- Let  $L = \{ a^n b^n, n \geq 0 \}$ . Corresponding grammar  $G$  will have  $P: S \rightarrow aAb \mid \epsilon$
- Kleene Star  $L_1 = \{ a^n b^n \}^*$
- The corresponding grammar  $G_1$  will have additional productions  $S1 \rightarrow S S1 \mid \epsilon$



- Context-free languages are **not closed** under –
- **Intersection** – If  $L_1$  and  $L_2$  are context free languages, then  $L_1 \cap L_2$  is not necessarily context free.
- **Intersection with Regular Language** – If  $L_1$  is a regular language and  $L_2$  is a context free language, then  $L_1 \cap L_2$  is a context free language.
- **Complement** – If  $L_1$  is a context free language, then  $L_1'$  may not be context free.



# CFG Simplification

- In a CFG, it may happen that all the production rules and symbols are **not needed** for the derivation of strings.
- Besides, there may be some **null productions and unit productions**.
- Elimination of these productions and symbols is called **simplification of CFGs**.



- Simplification essentially comprises of the following steps –
- Reduction of CFG
- Removal of Unit Productions
- Removal of Null Productions



# Reduction of CFG

- CFGs are reduced in two phases –
- **Phase 1** – Derivation of an equivalent grammar,  $G'$ , from the CFG,  $G$ , such that each variable derives some terminal string.
- **Derivation Procedure** –
  - **Step 1** – Include all symbols,  $W_1$ , that derive some terminal and initialize  $i=1$ .
  - **Step 2** – Include all symbols,  $W_{i+1}$ , that derive  $W_i$ .
  - **Step 3** – Increment  $i$  and repeat Step 2, until  $W_{i+1} = W_i$ .
  - **Step 4** – Include all production rules that have  $W_i$  in it.



- **Phase 2** – Derivation of an equivalent grammar,  $G''$ , from the CFG,  $G'$ , such that each symbol appears in a sentential form.
- **Derivation Procedure** –
  - **Step 1** – Include the start symbol in  $Y_1$  and initialize  $i = 1$ .
  - **Step 2** – Include all symbols,  $Y_{i+1}$ , that can be derived from  $Y_i$  and include all production rules that have been applied.
  - **Step 3** – Increment  $i$  and repeat Step 2, until  $Y_{i+1} = Y_i$ .





# Problem

1. Find a reduced grammar equivalent to the grammar  $G$ , having production rules,

$P: S \rightarrow AC \mid B, A \rightarrow a, C \rightarrow c \mid BC, E \rightarrow aA \mid e$



# Removal of Unit Productions

- Any production rule in the form  $A \rightarrow B$  where  $A, B \in \text{Non-terminal}$  is called **unit production**..
- Removal Procedure –
- **Step 1** – To remove  $A \rightarrow B$ , add production  $A \rightarrow x$  to the grammar rule whenever  $B \rightarrow x$  occurs in the grammar. [ $x \in \text{Terminal}$ ,  $x$  can be Null]
- **Step 2** – Delete  $A \rightarrow B$  from the grammar.
- **Step 3** – Repeat from step 1 until all unit productions are removed.



# Problem

1. Remove unit production from the following –

$S \rightarrow XY, X \rightarrow a, Y \rightarrow Z \mid b, Z \rightarrow M, M \rightarrow N, N \rightarrow a$



# Removal of Null Productions

- In a CFG, a non-terminal symbol '**A**' is a nullable variable if there is a production  $A \rightarrow \epsilon$  or there is a derivation that starts at **A** and finally ends up with

$$\epsilon: A \rightarrow \dots \rightarrow \epsilon$$

- Removal Procedure
  - **Step 1** – Find out nullable non-terminal variables which derive  $\epsilon$ .
  - **Step 2** – For each production  $A \rightarrow a$ , construct all productions  $A \rightarrow x$  where **x** is obtained from '**a**' by removing one or multiple non-terminals from Step 1.
  - **Step 3** – Combine the original productions with the result of step 2 and remove  $\epsilon$  - **productions**.



# Problem

1. Remove null production from the following –

$$S \rightarrow ASA \mid aB \mid b, A \rightarrow B, B \rightarrow b \mid \epsilon$$

2. Remove null production from the following –

$$S \rightarrow ABAC, A \rightarrow aA \mid \epsilon, B \rightarrow bB \mid \epsilon, C \rightarrow c$$



# POLLING QUESTIONS

**1. Context free language are closed under**

- A. union, intersection**
- B. union, kleene closure**
- C. intersection, complement**
- D. complement, kleene closure**



**2. If  $G = (\{S\}, \{a\}, \{S \rightarrow SS\}, S)$ ,**

**then language generated by  $G$  is**

**A.  $L(G) = \varphi$**

**B.  $L(G) = a^n$**

**C.  $L(G) = a^*$**

**D.  $L(G) = a^nba^n$**



### **3. A given grammar is called ambiguous if**

- A. two or more productions have the same non-terminal on the left hand side**
- B. a derivation tree has more than one associated sentence**
- C. there is a sentence with more than one derivation tree corresponding to it**
- D. brackets are not present in the grammar**





**4. Which of the following derivations does a top-down parser use while parsing an input string? The input is assumed to be scanned in left to right order**

**(A) Leftmost derivation**

(B) Leftmost derivation traced out in reverse

(C) Rightmost derivation

(D) Rightmost derivation traced out in reverse



**5. Which among the following is the root of the parse tree?**

- (A) Production P
- (B) Nonterminal V
- (C) Terminal T
- (D) Starting symbol S**



# Chomsky Normal Form

- A CFG is in Chomsky Normal Form if the Productions are in the following forms –

$$A \rightarrow a$$

$$A \rightarrow BC$$

$$S \rightarrow \varepsilon$$

- where A, B, and C are non-terminals and a is terminal.



# Algorithm to Convert into Chomsky Normal Form

- **Step 1** – If the start symbol **S** occurs on some right side, create a new start symbol **S'** and a new production  $S' \rightarrow S$ .
- **Step 2** – Remove Null productions. (Using the Null production removal algorithm discussed earlier)
- **Step 3** – Remove unit productions. (Using the Unit production removal algorithm discussed earlier)



- **Step 4** – Replace each production  $A \rightarrow B_1 \dots B_n$  where  $n > 2$  with  $A \rightarrow B_1 C$  where  $C \rightarrow B_2 \dots B_n$ . Repeat this step for all productions having two or more symbols in the right side.
- **Step 5** – If the right side of any production is in the form  $A \rightarrow aB$  where  $a$  is a terminal and  $A, B$  are non-terminal, then the production is replaced by  $A \rightarrow XB$  and  $X \rightarrow a$ . Repeat this step for every production which is in the form  $A \rightarrow aB$ .



# Problem

1. Convert the following CFG into CNF

$$S \rightarrow ASA \mid aB, A \rightarrow B \mid S, B \rightarrow b \mid \epsilon$$

2. Convert the following CFG into CNF

$$S \rightarrow a \mid aA \mid B, A \rightarrow aBB \mid \epsilon, B \rightarrow Aa \mid b$$

3. Convert the following CFG into CNF

$$S \rightarrow ASB \quad A \rightarrow aAS \mid a \mid \epsilon \quad B \rightarrow SbS \mid A \mid bb$$



# POLLING QUESTIONS

1. Suppose  $A \rightarrow xBz$  and  $B \rightarrow y$ , then the simplified grammar would be:
- a)  $A \rightarrow xyz$
  - b)  $A \rightarrow xBz \mid xyz$
  - c)  $A \rightarrow xBz \mid B \mid y$
  - d) none of the mentioned



2. Given grammar G:

$S \rightarrow aS \mid A \mid C$

$A \rightarrow a$

$B \rightarrow aa$

$C \rightarrow aCb$

Find the set of variables that can produce strings only with the set of terminals.

a)  $\{C\}$

b)  $\{A, B\}$

c)  **$\{A, B, S\}$**

d) None of the mentioned





3. Given grammar:

$S \rightarrow aS \mid A$

$A \rightarrow a$

$B \rightarrow aa$

Find the number of variables reachable from the Starting Variable?

a) 0

b) **1**

c) 2

d) None of the mentioned



4. Given a Grammar G:

$S \rightarrow aA$

$A \rightarrow a$

$A \rightarrow B$

$B \rightarrow A$

$B \rightarrow bb$

Which among the following will be the simplified grammar?

a)  **$S \rightarrow aA \mid aB$ ,  $A \rightarrow a$ ,  $B \rightarrow bb$**

b)  $S \rightarrow aA \mid aB$ ,  $A \rightarrow B$ ,  $B \rightarrow bb$

c)  $S \rightarrow aA \mid aB$ ,  $A \rightarrow a$ ,  $B \rightarrow A$

d) None of the mentioned



# Greibach Normal Form

- A CFG is in Greibach Normal Form if the Productions are in the following forms –

$$A \rightarrow b$$

$$A \rightarrow bD_1 \dots D_n$$

$$S \rightarrow \varepsilon$$

where  $A, D_1, \dots, D_n$  are non-terminals and  $b$  is a terminal.



# Algorithm to Convert a CFG into Greibach Normal Form

- **Step 1** – If the start symbol  $S$  occurs on some right side, create a new start symbol  $S'$  and a new production  $S' \rightarrow S$ .
- **Step 2** – Remove Null productions. (Using the Null production removal algorithm discussed earlier)
- **Step 3** – Remove unit productions. (Using the Unit production removal algorithm discussed earlier)
- **Step 4** – Remove all direct and indirect left-recursion.
- **Step 5** – Do proper substitutions of productions to convert it into the proper form of GNF.



# Problem

1. Convert the following CFG into GNF

$$S \rightarrow XY \mid X^n \mid p, X \rightarrow mX \mid m, Y \rightarrow X^n \mid o$$

2. Convert the following CFG into GNF

$$S \rightarrow XB \mid AA, A \rightarrow a \mid SA, B \rightarrow b, X \rightarrow a$$

3. Convert the following CFG into GNF

$$S \rightarrow CA \mid BB, B \rightarrow b \mid SB, C \rightarrow b, A \rightarrow a$$



# POLLING QUESTIONS

1. Which of the following does not have left recursions?
  - a) Chomsky Normal Form
  - b) **Greibach** Normal Form
  - c) Backus Normal Form
  - d) All of the mentioned



2. Which of the following grammars are in Chomsky Normal Form:

- a)  **$S \rightarrow AB \mid BC \mid CD$ ,  $A \rightarrow 0$ ,  $B \rightarrow 1$ ,  $C \rightarrow 2$ ,  $D \rightarrow 3$**
- b)  $S \rightarrow AB$ ,  $S \rightarrow BCA \mid 0 \mid 1 \mid 2 \mid 3$
- c)  $S \rightarrow ABa$ ,  $A \rightarrow aab$ ,  $B \rightarrow Ac$
- d) All of the mentioned



3. The format:  $A \rightarrow aB$  refers to which of the following?

- a) Chomsky Normal Form
- b) **Greibach Normal Form**
- c) Backus Normal Form
- d) None of the mentioned





4. Every grammar in Chomsky Normal Form is:

- a) regular
- b) context sensitive
- c) **context** free
- d) all of the mentioned



# Pumping Lemma for CFG

- Lemma
- If  $L$  is a context-free language, there is a pumping length  $p$  such that any string  $w \in L$  of length  $\geq p$  can be written as  $w = uvxyz$ , where  $vy \neq \epsilon$ ,  $|vxy| \leq p$ , and for all  $i \geq 0$ ,  $uv^ixy^iz \in L$ .



- If  $L$  is a CFL, there exists an integer  $n$ , such that for all  $x \in L$  with  $|x| \geq n$ , there exists  $u, v, x, y, z \in \Sigma^*$ , such that  $x = uvxyz$ , and
  - (1)  $|vxy| \leq n$
  - (2)  $|vy| \geq 1$
  - (3) for all  $i \geq 0$ :  $uv^i xy^i z \in L$



# Applications of Pumping Lemma

- Pumping lemma is used to check whether a grammar is context free or not.



# Problem

1. Find out whether the language  $L = \{a^n b^n c^n \mid n \geq 1\}$  is context free or not.
2. Show that  $L = \{ww \mid w \text{ is } \{0,1\}^*\}$  is not context free.



# POLLING QUESTIONS

1. In pumping lemma for context free language
  - a) We start by assuming the given language is context free and then we get contradict
  - b) We first convert the given language into regular language and then apply steps on
  - c) Both (a) and (b)
  - d) None of these



2. The Greibach normal form grammar for the language  $L = \{a^n b^{n+1} \mid n \geq 0\}$  is

- $a.S \rightarrow aSB, B \rightarrow bB \mid \lambda$
- $b.S \rightarrow aSB, B \rightarrow bB \mid b$
- **$c.S \rightarrow aSB \mid b, B \rightarrow b$**
- $d.S \rightarrow aSB \mid b$



r4

3. Consider the following grammar:

$A \rightarrow e$

$B \rightarrow aAbC$

$B \rightarrow bAbA$

$A \rightarrow bB$

The number of productions added on the removal of the nullable in the given grammar:

a) 3

**b) 4**

c) 2

d) 0





4. Given grammar G:

$S \rightarrow aS \mid AB$

$A \rightarrow e$

$B \rightarrow e$

$D \rightarrow b$

Reduce the grammar, removing all the  $\epsilon$  productions:

a)  $S \rightarrow aS \mid AB \mid A \mid B$ ,  $D \rightarrow b$

b)  $S \rightarrow aS \mid AB \mid A \mid B \mid a$ ,  $D \rightarrow b$

c)  **$S \rightarrow aS \mid AB \mid A \mid B$**

d) None of the mentioned



5. Given grammar G:

(1)  $S \rightarrow AS$

(2)  $S \rightarrow AAS$

(3)  $A \rightarrow SA$

(4)  $A \rightarrow aa$

Which of the following productions denies the format of Chomsky Normal Form?

a) **2,4**

b) 1,3

c) 1, 2, 3, 4

d) 2, 3, 4