Chap. 7 Properties of Context-free Languages

7.1 Normal Forms for Context-free Grammars

Context-free grammars

$A \to \alpha$ where $A \in N$, $\alpha \in (N \cup T)^*$. $|\alpha| \geq 0$.

Chomsky Normal Form

$A \to BC$ or $A \to a$ **except** $S \to \varepsilon$ where $A, B, C \in N$, $a \in \Sigma$.

1. Eliminating **useless symbols(non generating** and **non reachable**)
2. Eliminating ε-**productions**(no $A \to \varepsilon$ **except** $S \to \varepsilon$) $|\alpha| \geq 1$
3. Eliminating **unit productions**(no $A \to B$)

$A \to \alpha$ or $A \to a$ where $A \in N$, $\alpha \in (N \cup T)^*$, $|\alpha| \geq 2$, $a \in \Sigma$.

4. Introducing variables for each terminals($A_a \to a$, $^\forall a \in \Sigma$)

$A \to \alpha$ or $A \to a$ where $A \in N$, $\alpha \in N^*$, $|\alpha| \geq 2$, $a \in \Sigma$.

5. Reducing length of RHS to two

$A \to BC$ or$A \to a$ except $S \to \varepsilon$ where $A, B, C \in N$, $a \in \Sigma$.

7.1.1 Eliminating Useless Symbols

We say $X \in N \cup T$ *is* ***useful***, *if* $S \Rightarrow^* \alpha X \beta \Rightarrow^* w$, $X \in (N \cup T)$, $w \in T^*$;
useless *otherwise.*

1. *We say X is* ***generating***, *if* $X \Rightarrow^* w$, $w \in T^*$.
2. *We say X is* ***reachable***, *if* $S \Rightarrow^* \alpha X \beta$.

1. *Eliminate non generating symbols and productions*
2. *Eliminate non reachable symbols and productions*

Theorem 7.2 *Let* $G = (N, \Sigma, P, S)$ *be a CGF where* $L(G) \neq \emptyset$.

1. *Eliminate* ***non generating*** *symbols, and productions in G,*
   $G_2 = (N_2, \Sigma_2, P_2, S)$.
2. *Eliminate* ***non reachable*** *symbols and productions from* G_2,
   $G_1 = (N_1, \Sigma_1, P_1, S)$.

Then G_1 *has no useless symbols, and* $L(G_1) = L(G)$.

Theorem 7.4 *Finding **generating** symbols*

basis $^\forall a \in \Sigma$, *a* is ***generating***.

Rec. $^\forall A \rightarrow X_1 \ldots X_n \in P$, if $(1 \leq {}^\forall i \leq n$: X_i is ***generating***) or $(n = 0)$,

*then X is **generating**.*

Proof $^\forall X \Rightarrow^* w, w \in T^*$. (***induction*** *on number of steps in algorithm)*

basis *zero step.* $a \in \Sigma$.

Rec. *Consider* $X \Rightarrow \alpha \Rightarrow^{n-1} w, w \in T^*$.

$X \rightarrow \alpha = X_1 \ldots X_n \in P$. $\quad 1 \leq {}^\forall i \leq n, X_i \Rightarrow^* w_i, w_i \in T^*$ *by IH.*

$\therefore X \Rightarrow X_1 \ldots X_n \Rightarrow^* w_1 \ldots w_n = w, w \in \Sigma^*$.

Theorem 7.6 *Finding **reachable** symbols.*

Basis *S is **reachable**.* $G_{reach} = (N, E), (A, B) \in E$, if $A \rightarrow \alpha B \beta \in P$.

Rec. *If* $A \in N$ *is **reachable***, $^\forall A \rightarrow X_1 \ldots X_n \in P$, $1 \leq {}^\forall i \leq n$, X_i *is **reachable***.

Proof $X \in (N \cup T)$ *is **reachable**, **if*** $S \Rightarrow^* \alpha X \beta$. $G_{reach}{}^* = (N, E^*)$ *from S.*

7.1.3 Eliminating ε-Productions

*$A \to \varepsilon$ is called ε-**production**.* *G is ε-**free**, if P has **no** ε-production.*

*A is **nullable**, iff $A \Rightarrow^* \varepsilon$.*

***Theorem 7.7** Finding **nullable** symbols*

***Basis** If $A \to \varepsilon \in P$, A is **nullable**.*

***Rec.** $\forall A \to B_1 \ldots B_n \in P$: **if** $(1 \le \forall i \le n)$ $B_i \in N$ is **nullable**, then A is **nullable**.*

***Proof** $A \Rightarrow^* \varepsilon$, if and only if, A is **nullable**.*

***(If)** A is **nullable**, iff $A \Rightarrow^* \varepsilon \in P$. ∴ trivial.*

***(Only if) induction** on number the shortest derivation to ε.*

***basis** One step. $A \to \varepsilon \in P$, $A \Rightarrow^1 \varepsilon$. ∴ $A \Rightarrow^* \varepsilon$.*

***induction** Suppose $A \Rightarrow^n \varepsilon$ where $n > 1$ derivations. Then*

$A \Rightarrow B_1 \ldots B_k \Rightarrow^* \varepsilon$. *where* $1 \le \forall i \le n$: $B_i \Rightarrow^{<n} \varepsilon$.

∴ $1 \le \forall i \le n$: B_i *is in **nullable** by IH.*

∴ *A in **nullable**.*

Theorem 7.9 *Let* $G = (N, T, P, S)$ *be a cfg. Then*

$\exists G_1 = (N, T, P_1, S)$ is ε-**free** and $L(G_1) = L(G) - \{\varepsilon\}$.

P_1: $\forall A \rightarrow X_1 \ldots X_n \in P$, add $A \rightarrow Z_1 \ldots Z_n$ to P_1.

i) If X_i is **not nullable**, $Z_i = X_i$. (no change!)

ii) If X_i is **nullable**, $Z_i = (X_i \mid \varepsilon)$. (if m-nullable symbols, 2^m rules)

iii) **remove** $A \rightarrow \varepsilon$, if any. (if m=n, upper bound 2^{n-1}' rule)

Proof $A \Rightarrow_{G_1}^{*} w$ if and only if $A \Rightarrow_{G}^{*} w$ and $w \neq \varepsilon (w \in T^{+})$.

(***If***) If $A \Rightarrow_{G}^{k} w$ and $w \neq \varepsilon$, $A \Rightarrow_{G1}^{*} w$.

basis If $A \Rightarrow_{G} w$ and $w \neq \varepsilon$, and $w \in \Sigma^{+}$, then $A \rightarrow w \in P_1$. $\therefore A \Rightarrow_{G_1}^{*} w$.

induction $A \Rightarrow_{G} X_1 \ldots X_n \Rightarrow_{G}^{k-1} w = w_1 \ldots w_n$, $\forall X_i \Rightarrow_{G}^{*} w_i$ and $w \neq \varepsilon$.

If $w_i \neq \varepsilon$, $X_i \Rightarrow_{G_1}^{*} w_i$ by IH($X_i \Rightarrow_{G}^{<k} x_i$).

If $w_i = \varepsilon$, X_i is nullable.

$\therefore A \Rightarrow_G X_1 \ldots X_{i-1} X_i X_{i+1} \ldots X_n \Rightarrow_G^* w_1 \ldots w_{i-1} \varepsilon w_{i+1} \ldots w_n = w.$

$\exists A \rightarrow X_1 \ldots X_{i-1} X_{i+1} \ldots X_n \in P_1$ by **construction of** P_1.

$\therefore \exists A \Rightarrow_{G1} X_1 \ldots X_{i-1} X_{i+1} \ldots X_n \Rightarrow_{G1}^* w_1 \ldots w_{i-1} w_{i+1} \ldots w_n = w.$

(**Only if**) If $A \Rightarrow_{G_1}^k w$, $A \Rightarrow_G^* w$ and $w \neq \varepsilon$.

basis If $A \Rightarrow_{G_1} w$, $w \neq \varepsilon$(G_1 is ε-***free***).

$A \Rightarrow_G \alpha$, $\alpha \Rightarrow_G^* w$ (ε-rules only, $|\alpha| \geq |w|$)

induction Assume $A \Rightarrow_{G_1} Z_1 \ldots Z_n \Rightarrow_{G1}^{k-1} w = x_1 \ldots x_n$, $\forall Z_i \Rightarrow_{G_1}^* x_i$.

$\exists A \rightarrow Z_1 \ldots Z_n \in P_1$ comes from $A \rightarrow X_1 \ldots X_m \in P$, $(m \geq n)$.

$\therefore A \Rightarrow_G X_1 \ldots X_m \Rightarrow_G^* Z_1 \ldots Z_n$ (ε-rules only)

$\Rightarrow_G^* x_1 \ldots x_n$ and $\forall x_i \neq \varepsilon$ by IH($Z_i \Rightarrow_{G1}^{<k} x_i$)

$= x$ and $x \neq \varepsilon$.

7.1.4 Eliminating Unit productions

$A \rightarrow B$ is called a ***unit*** *production, if $A, B \in N$.*

(A, B) is called a ***unit pair****, if $A \Rightarrow^* B$.*

Theorem 7.11 *Following algorithm finds exactly unit pairs.*

> ***basis*** *(A, A) is a* ***unit pair****.*
>
> ***induction*** *If (A, B) is a* ***unit pair*** *and $B \rightarrow C \in P$,*
>
> *(A, C) is a* ***unit pair****.*

Proof *Number of derivation steps unit pair is found.*

basis *Zero steps. $A = B$, (A, A) is added in* ***basis****.*

induction *Assume $A \Rightarrow^n C$. Then $^\exists B$, $A \Rightarrow^{n-1} B \Rightarrow C$.*

> *$\therefore$ (A, C) is in unit pair(IH) and the* ***induction*** *rule $B \rightarrow C \in P$*
>
> *adds (A, B) in unit pair.*

Theorem 7.13 *Let $G = (N, \Sigma, P, S)$ be a cfg. Then*

$\exists G_1 = (N, \Sigma, P_1, S)$ *that has* **no** *unit productions and* $L(G_1) = L(G)$,

$P_1 = \{A \to \alpha \mid (A, B)$ *is a unit pair,* $B \to \alpha \in P, \alpha \notin N\}$.

Proof $A \Rightarrow_G^* w$ *if and only if* $A \Rightarrow_{G1}^* w$.

If $A \to \alpha \in P_1, \alpha \notin N. \therefore$ *Non-unit productions.*

(If) *If* $A \to \alpha \in P_1, A \to \alpha \in P$ *or* $A \Rightarrow_G^* B \Rightarrow_G \alpha$.

$\therefore$ *If* $A \to \alpha \in P_1, A \Rightarrow_G^* \alpha$.

$\therefore$ *If* $A \Rightarrow_{G1}^* w, A \Rightarrow_G^* w$.

(Only if) *If* $A \Rightarrow_G^* w, A \Rightarrow_{lm\ G}^* w$ *in G.*

Assume $A = \alpha_0 \Rightarrow_{lm} \alpha_1 \Rightarrow_{lm} \alpha_2 \ldots \Rightarrow_{lm} \alpha_n = w$ *in G.*

$0 \le \forall i < n$,

1) *If* $\alpha_i \Rightarrow_{lm} \alpha_{i+1}$ *by non unit production in G,* $\alpha_i \Rightarrow_{lm\ G1} \alpha_{i+1}$.

2) *If* $\alpha_i \Rightarrow_{lm} \alpha_{i+1}$ *in G by unit production,*

$i < {}^{\exists}k,\ .\ni.\ i \le {}^{\forall}j < k,\ \alpha_j \Rightarrow_{lm\ G} \alpha_{j+1}$ *by unit productions*

and finally $\alpha_k \Rightarrow_{lm} \alpha_{k+1}$ *by non unit production*

$\therefore\ \alpha_i \Rightarrow_{lm\ G1}^{*} \alpha_{k+1}.$

If $A \Rightarrow_{lm\ G}^{*} w,\ A \Rightarrow_{lm\ G1}^{*} w.$

7.1.5 Chomsky Normal Form(CNF)

1. $S \rightarrow \varepsilon \in P$, *or*
2. $A \rightarrow BC \in P$ *where* $B, C, \in N$, *or*
3. $A \rightarrow a \in P$ *where* $a \in \Sigma$.

Theorem 7.16 *Let* $G = (N, T, P, S)$ *be a CFG. There is a CFG* G_1 *such that* G_1 *is CNF and* $L(G) = L(G_1)$.

Proof

1. *Eliminate useless symbols and productions.*
2. *Eliminate* ε*-rules.*

3. Eliminate unit production.

No ε-productions and no unit productions.

If $\varepsilon \in L(G)$, $S \to \varepsilon \in P_1$.

$A \to a \in P$, *CNF.*

$A \to X_1 \ldots X_n \in P$ *where* $n \geq 2$, $X_i \in N \cup T$.

$\forall X_i \in \Sigma$, $B_a \to a \in P_1$ *and replace* X_i *by* B_a.

$A \to C_1 \ldots C_n \in P$ *where* $n \geq 2$, $C_i \in N$.

If $n = 2$, *CNF.*

$A \to C_1 \ldots C_n \in P$ *where* $n \geq 3$, $C_i \in N$.

$A \to C_1 D_1 \in P_1$,

$D_1 \to C_2 D_2 \in P_1$,

…

$D_{n-3} \to C_{n-2} D_{n-2} \in P_1$,

$D_{n-2} \to C_{n-1} C_n \in P_1$.

Proof *G_1 is CNF is trivail.*

1) If $A \to X_1 \ldots X_k \in P$, $A \Rightarrow_{G1}^{+} X_1 \ldots X_k$.

If $A \Rightarrow_{G}^{*} w \in \Sigma^*$, $A \Rightarrow_{G1}^{*} w \in \Sigma^*$.

2) If $A \Rightarrow_{G1}^{*} w \in \Sigma^*$ and consider the parse tree of w in G_1.
Convert the parse tree into the parse tree of w in G.

i) $A \to C_1D_1, \ldots, D_{n-3} \to C_{n-2}D_{n-2}, D_{n-2} \to C_{n-1}C_n$ into

$A \to C_1 \ldots C_{n-1}C_n$. (Fig. 7.4)

ii) $B_a \to a$ into a

$\therefore L(G) = L(G_1)$.

Regular grammar(normal form)

$A \to aB$ or b $\quad A, B \in N, a, b \in T.$ $\quad$ *right linear*

$A \to Ba$ or b $\quad A, B \in N, a, b \in T.$ $\quad$ *left linear*

(Extended)regular grammar

$A \to xB$ or y $\quad A, B \in N, x, y \in T^*.$ $\quad$ *right linear*

$A \to Bx$ or y $\quad A, B \in N, x, y \in T^*.$ $\quad$ *left linear*

Context-free grammar(Chomsky's normal form)

$A \to BC$ or a $\quad A, B, C \in N, a \in T.$

Context free grammar(extended)

$A \to \alpha$ $\quad A \in N, \alpha \in (N \cup T)^*.$

7.2 The Pumping Lemma for context-free Languages

7.2.1 The size of parse tree

Theorem 7.17 *Let $G = (N, T, P, S)$ be a Chomsky Normal Form context-free grammar and consider a parse tree for $w \in L(G)$. If n is the length(# of edges) of the longest path in the parse tree, $|w| \leq 2^{n-1}$.*

Proof *Induction on n,*

i) $n = 1, w \in \Sigma, |w| = 1 \leq 2^{1-1} = 1.$

ii) $n > 1, S \rightarrow AB$ *is the root of the tree.*

Two subtrees with roots A and B, respectively,

and assume $A \Rightarrow^* w_a, B \Rightarrow^* w_b$, *and* $w = w_a w_b$.

By induction hypothesis, $|w_a| \leq 2^{n-2}$ *and* $|w_b| \leq 2^{n-2}$.

$\therefore |w| \leq 2^{n-2} + 2^{n-2} = 2^{n-1}.$

7.2.2 Statement of the pumping Lemma

Theorem 7.18 (The pumping lemma for context-free languages)

Let L be a CFL. $\exists n \in \mathbb{N}$ *.э. if* $\forall z \in L$ *and* $|z| \geq n$*, then we write* $z = uvwxy$

1) $|vwx| \leq n$, — *the **first** pump*
2) $vx \neq \varepsilon$, — ***nontrivial** pump*
3) $\forall i \geq 0, uv^iwx^iy \in L.$ — ***pump***

Proof

Since L is CFL, $\exists G = (N, T, P, S)$ *where* $L = L(G)$ *and G is CNF.*

Choose $n = 2^{|N|}$ *and*

suppose the longest path P of the parse tree for $z \in L$ *is k+1.*

$n = 2^{|N|} \leq |z| \leq 2^{(k+1)-1} = 2^k$. *(Def. of n, and Thm. 7.17)*

$\therefore\ |N| \leq k.$

Consider the longest path(k+1), $(A_0, A_1, \ldots, A_k, a)$

$A_0 = S, 0 \le \forall i \le k: A_i \in N, a \in T.$ *(Fig. 7.5)*

$\therefore$ *Since* $|N| \le k, 1 \le \exists i < \exists j \le k$.э. $A_i = A_j = A.$

Assume $S \Rightarrow^* uA_iy \Rightarrow^* uvA_jxy \Rightarrow^* uvwxy.$ *(Fig. 7.6)*

Note that $\underline{A} = A_i \Rightarrow^* vA_jx = \underline{vAx}$ *or* $\underline{A} = A_j \Rightarrow^* \underline{w}$, *and* $S \Rightarrow^* u\underline{A}y.$

$\therefore$ (1) $S \Rightarrow^* uAy \Rightarrow^* uwy = uv^0wx^0y$; *or*

(2) *Assume* $S \Rightarrow^* uAy \Rightarrow^* uv^{i-1}wx^{i-1}y$ *for* $i \ge 1$, *and*

$S \Rightarrow^* uAy \Rightarrow^* uvAxy \Rightarrow^* uvv^{i-1}wxx^{i-1}y = uv^iwx^iy.$ *(Fig. 7.7)*

$\therefore S \Rightarrow^* uv^iwx^iy$ *for* $i \ge 0$. 3)

Since G is useful and ε-free(CNF) $v \ne \varepsilon$ *and* $x \ne \varepsilon$, $\therefore vx \ne \varepsilon$. 2)

We can select A_i *to be the closest to the bottom of the tree,* $k - i \le |N|$,

Since the length of the longest path in A_i*-subtree* $\le |N| + 1$,

$\therefore |vwx| \le n$ *(Thm. 7.17)* 1)

7.2.3 Application of the Pumping Lemma for CFL's

1. Pick L that we want to prove that L is **not** *context-free.*

2. "Adversary" pick n(any possible n)

3. Pick z, we may use n as a parameter

4. "Adversary" break z into uvwxy .϶. $|vwx| \leq n$, $vx \neq \varepsilon$.

5. To "win" the game, find i .϶. $uv^iwx^iy \notin L$.

Context-free languages cannot match ***more than two*** *groups of symbols for equality or inequality.*

Example 7.19 $L = \{0^n1^n2^n \mid n \geq 1\}$

Let K be the adversary number, and $z = 0^n1^n2^n$,

For all breaks of z into uvwxy .϶. $|vwx| \leq K$, $vx \neq \varepsilon$.

(1) $u = 0^{n-i}$, $vwx = 0^i1^{n-i}$, *and* $y = 1^i2^n$. *Since* $vx \neq \varepsilon$, $uwy \notin L$.

(2) $u = 0^n1^{n-i}$, $vwx = 1^i2^{n-i}$, *and* $y = 2^i$. *Since* $vx \neq \varepsilon$, $uwy \notin L$.

Two groups match ***cannot be interleaved****.*

Example 7.20 $L = \{0^i 1^j 2^i 3^j \mid i, j \geq 1\}$

Let n be the adversary number and $z = 0^n 1^n 2^n 3^n$.

For all breaks of z into uvwxy .϶. $|vwx| \leq n$, $vx \neq \varepsilon$,

vwy: substring of at most two consecutive symbols

Nontrivial ($vx \neq \varepsilon$) *pumping of v and x*

Less than or equal to n symbols that is in vwx.

CFL's cannot match two strings of arbitrary length

Exercise 7.21 $L_{ww} = \{ww \mid w \in (0+1)^*\}$ *vs.* $L_{wwR} = \{ww^R \mid w \in (0+1)^*\}$

Consider $z = 0^n 1^n 0^n 1^n$.

7.3 Closure properties of Context Free Languages

Context-free languages are closed under

1. *union,*
2. *concatenation,*
3. *closure,*
4. *substitution,*
5. *reversal*

Let $G_A = (N_A, T_A, P_A, S_A)$ *and* $G_B = (N_B, T_B, P_B, S_B)$ *be cfg's. Then*

$G_1 = (N_A \cup N_B \cup \{S_1\}, \Sigma_A \cup \Sigma_B, P_A \cup P_B \cup \{S_1 \to S_A \mid S_B\}, S_1)$

.э. $L(G_1) = L(G_A) \cup L(G_B)$,

$G_2 = (N_A \cup N_B \cup \{S_2\}, \Sigma_A \cup \Sigma_B, P_A \cup P_B \cup \{S_2 \to S_A S_B\}, S_2)$

.э. $L(G_2) = L(G_A)L(G_B)$,

$G_3 = (N_A \cup \{S_3\}, \Sigma_A, P_A \cup \{S_3 \to S_A S_3 \mid \varepsilon\}, S_3)$.э. $L(G_3) = L(G_A)^*$,

$G_5 = (N_A, \Sigma_A, \{A \to \alpha^R \mid A \to \alpha \in P\}, S_A)$.э. $L(G_5) = L(G_A)^R$.

Context-free language is not closed under intersection

Example 7.26 *We know that* $L = \{0^n1^n2^n \mid n \geq 1\}$ *is not* ***cfl*** *in Ex. 7.19.*
Consider

$$L_1 = \{0^n1^n2^i \mid n \geq 1, i \geq 1\}$$

$$G_1: \quad S \rightarrow AB$$
$$A \rightarrow 0A1 \mid 01$$
$$B \rightarrow 2B \mid 2.$$

$$L_2 = \{0^i1^n2^n \mid n \geq 1, i \geq 1\}$$

$$G_2: \quad S \rightarrow AB$$
$$A \rightarrow 0A \mid 0$$
$$B \rightarrow 1B2 \mid 12.$$

L_1 *and* L_2 *are context-free but* $L = L_1 \cap L_2 = \{0^n1^n2^n \mid n \geq 1\}$
is not context-free

counter example

Theorem 7.27 *If L is CFL and R is regular language, then*

$L \cap R$ *is context-free.*

Proof *Let* $P = (Q_P, T, \Gamma, \delta_P, q_P, Z_P, F_P)$ *be a PDA,* $L(P) = L$*, and*

$A = (Q_A, \Sigma, \delta_A, q_A, F_A)$ *be a FA,* $L(A) = R$*. Then*

$P' = (Q_P \times Q_A, \Sigma, \Gamma, \delta, (q_P, q_A), Z_P, F_P \times F_A)$ *where* $a \in \Sigma \cup \{\varepsilon\}$ *and*

$$\delta((q, p), a, X) = \{((r, s), \gamma) \mid s \in \delta_A^*(p, a), (r, \gamma) \in \delta_P(q, a, X)\}.$$

Induction

$$(q_P, w, Z_P) \vdash^* (q, \varepsilon, \gamma) \text{ if and only if } ((q_P, q_A), w, Z_P) \vdash^* ((q, p), \varepsilon, \gamma)$$

$$\text{and } q \in \delta_A^*(q_A, w).$$

Theorem 7.29 *If L,* L_1*, and* L_2 *are CFL's and R is regular language.*

1. $L - R$ *is context-free.*
2. $\overline{L}$ *is not (necessary) context-free.*
3. $L_1 - L_2$ *is not (necessary) context-free.*

7.4 Decision Properties of CFL's

PDA by empty stack $\Leftrightarrow$ *PDA by final state*	***Thm 6.9, 11***	$O(n)$
CFG $\Rightarrow$ *PDA*	***Thm 6.13***	$O(n)$
PDA $\Rightarrow$ *CFG*	***Thm 6.14***	$O(n^3)$

CFG $\Rightarrow$ *CNF*	$O(n^2)$	
1. Detecting reachable and generating symbol		$O(n)$
Eliminating useless symbols and productions		$O(n)$
2. Eliminating ε*-production*		$O(2^k)$
where k is maximum length of RHS		$\therefore O(2^n)$
3. Eliminating unit productions		$\mathbf{O(n^2)}$
4. Replacing terminal symbols by nonterminal symbols		$O(n)$
5. Breaking length of RHS		$O(n)$
$\therefore$ *2' Eliminating* ε*-production*	$2^2O(n)$	$O(n)$

Membership problem *CYK algorithm(Coke, Younger, Kasami)*

Given $w = a_1 \ldots a_n \in T^*$ *and a cfg G in CNF, test if* $w \in L(G)$ *or not.*

We can compute $X_{ij} = \{A \in N \mid A \Rightarrow^* a_i \ldots a_j\}$, $1 \le i \le j \le n$.

If $S \in X_{1n}$, $w \in L(G)$; *otherwise* $w \notin L(G)$.

How to compute X_{ij}.*(w.l.o.g assume CNF)*

basis $X_{ii} = \{A \mid A \rightarrow a_i \in P\}$

induction *Assume* $A \Rightarrow^* a_i \ldots a_j$. *Since* $i < j$, *and CNF(ε-free)*

$A \rightarrow BC \in P$ *where* $B \Rightarrow^* a_i \ldots a_k$ *and* $C \Rightarrow^* a_{k+1} \ldots a_j$, $i \le k < j$.

if $B \in X_{ik}$, $C \in X_{k+1,j}$, *and* $A \rightarrow BC \in P$; $A \in X_{ij}$.

Test $j-i$ *pairs* $(X_{ii}, X_{i+1,j}), (X_{i,i+1}, X_{i+2,j}), \ldots, (X_{i,j-1}, X_{jj})$

Since for each $O(n^2)$ X_{ij}, *test at most n pairs,*

$\therefore O(n^3)$.

CYK algorithm in PASCAL style

for $i:=1$ **to** n **do**

  for $j:=i$ **to** n **do** $X_{ij} := \emptyset$; (* **initalize** $O(n^2)$, $i \le j$, **see** Fig. 7.12 *)

for $i:=1$ **to** n **do** (* **basis** $O(n)$ *)

  if $A \rightarrow a_i \in P$ **then** $X_{ii} := X_{ii} \cup \{A\}$;

for $k:=1$ **to** $n-1$ **do**

  for $i:=1$ **to** $n-k$ **do** (* **consider** $X_{i,i+k}$ *)

   for $j:=i$ **to** $i+k$ **do** (* **recursion** $O(n^3)$ *)

    for $^{\forall}A \rightarrow BC \in P$ **do**

     if $(B \in X_{i,j})$ **and** $(C \in X_{j+1,i+k})$ **then** $X_{i,i+k} := X_{i,i+k} \cup \{A\}$;

      (* **See** Fig. 7.13 *)

Some undecidable problems on CFL's

1. *Is a given CFG G* ***ambiguous****?*
2. *Is a given CFL L is* ***inherently ambiguous****?*
3. *Is the* ***intersection*** *of two CFL's are* ***empty****?*
4. *Are two CFL's are* ***same****?*
5. *Is given CFL L, $L = \Sigma^*$ where Σ is the alphabet of L.*