Closure properties of CFLs

- There are some differences when compared with regular languages.
- We deviate from both text books (to simplify the things).
- We want to skip homomorphism.

CFLs are --

- Closed under
  - Union
  - Concatenation
  - Kleene star
  - Reversal
  - Intersection with regular languages
  -
  -

- Not closed under
  - Intersection
  - Difference
  - Complement
  - Repetition
  -
  -

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- $L_1$and L_2 are CFLs $\Rightarrow L_1 \cup L_2$ is a CFL.

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- Proof: Let the CFG for these are $G_1 = (V_1, T_1, P_1, S_1)$ and $G_2 = (V_2, T_2, P_2, S_2)$.
- We rename variables so that V_1 and V_2 such that they are disjoint and does not have a variable with name S. Note T_1 and T_2 need not be disjoint. Perhaps they are same.
- Now the grammar $(V_1 \cup V_2 \cup \{S\}, T_1 \cup T_2, P_1 \cup P_2 \cup \{S \rightarrow S_1 | S_2\}, S)$ will generate the union.

Closed under concatenation

- Add the production $S \to S_1 S_2$

Closed under Kleene star

- Add productions $S \to S_1 S | \epsilon$

Closed under reversal

Theorem 7.25 : If L is a CFL, then so is L^R.

PROOF: Let $L = L(G)$ for some CFL $G = (V, T, P, S)$. Construct $G^R = (V, T, P^R, S)$, where P^R is the "reverse" of each production in P. That is, if $A \to \alpha$ is a production of G, then $A \to \alpha^R$ is a production of G^R. It is an easy induction on the lengths of derivations in G and G^R to show that $L(G^R) = L^R$. Essentially, all the sentential forms of G^R are reverses of sentential forms of G, and vice-versa. We leave the formal proof as an exercise. $\square$

Not closed under intersection☹

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- Proof [by counter example]:

$L = \{0^n 1^n 2^n \mid n \geq 1\}$ is not a context-free language.

However, the following two languages *are* context-free:

$$L_1 = \{0^n 1^n 2^i \mid n \geq 1, i \geq 1\}$$
$$L_2 = \{0^i 1^n 2^n \mid n \geq 1, i \geq 1\}$$

- And, $L = L_1 \cap L_2$

A grammar for L_1 is:

$$
\begin{aligned}
&S \rightarrow AB \\
&A \rightarrow 0A1 \mid 01 \\
&B \rightarrow 2B \mid 2
\end{aligned}
$$

In this grammar, A generates all strings of the form 0^n1^n, and B generates all strings of 2's.

A grammar for L_2 is:

$$
\begin{aligned}
&S \rightarrow AB \\
&A \rightarrow 0A \mid 0 \\
&B \rightarrow 1B2 \mid 12
\end{aligned}
$$

CFLs are closed when intersected with regular languages

Theorem 7.27 : If L is a CFL and R is a regular language, then $L \cap R$ is a CFL.

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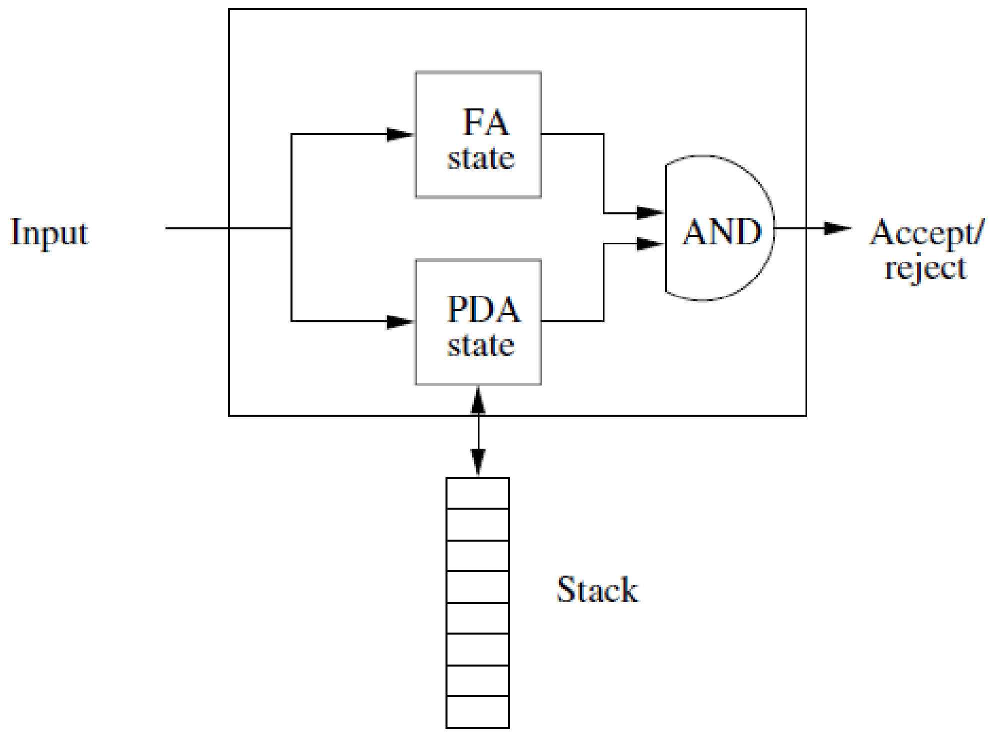

Figure 7.9: A PDA and a FA can run in parallel to create a new PDA

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We need to define δ for the PDA.

Note that, PDA can change its state with ϵ from input, but DFA cannot. But we can use $\hat{\delta}$, the extended transition for DFA which says $\hat{\delta}(p, a) = p, \text{if } a = \epsilon$

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where $\delta\big((q,p),a,X\big)$ is defined to be the set of all pairs $\big((r,s),\gamma\big)$ such that:

1. $s = \hat{\delta}_A(p,a)$, and
2. Pair (r,γ) is in $\delta_P(q,a,X)$.

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We could have taken NFA for R instead of a DFA, But the things will be more complicated (it can be done). Note, product of DFAs is simple; can be extended to NFAs also, but things are complicated !!

An application

- Dyck set (strings of balanced parentheses) is a CFL
- $(^*)^*$ is a regular language
- Intersection of above two is a CFL .
  - That is $\{\ (^k\ \ )^k \,\big|\, k \geq 1\}$ is a CFL

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- The language L where each string has equal number of 0s, 1s and 2s (may be interleaved) is not CFL.

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Of course, pumping lemma for CFLs can directly applied on L and shown to fail.

CFLs are not closed under complementation

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CFLs are not closed under complementation

- We know $L = \{ww | w \in \{0,1\}^* \}$ is not a CFL.
- But its complement is a CFL !!
- This is a proof by counter example.

CFG for the $\overline{L}$

- $S \to S_o | S_e$
- $S_o \to 0R|1R|0|1,\ R \to 0S_o|1S_o$
- $S_e \to XY|YX,\ X \to ZXZ\ |0\ ,\ Y \to ZYZ\ |1\ , Z \to 0|1$

- S_o generates odd length strings, whereas S_e generates even length strings.

Other proof

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- If it is closed under complementation then it has to be closed under intersection.
- Depends on the identity

$$L_1 \cap L_2 = \overline{\overline{L_1} \cup \overline{L_2}}$$

Not closed under set difference

- Proof by contradiction.
- If closed under set difference, then it has to be closed under complementation.

Not closed under set difference

- Proof by contradiction.
- If closed under set difference, then it has to be closed under complementation.
- Assuming it is closed under set difference.
- Let $L_1 = \Sigma^*$ which is a CFL
- Consider any other CFL L_2
- Then $L_1 - L_2$ which is the complement of L_2 must be a CFL. Contradiction.

Not closed under set difference

- Proof by contradiction.
- If closed under set difference, then it has to be closed under complementation.
- Σ^* is a CFL
- Let L be any CFL
- If $\Sigma^* - L$ is a CFL, then $\overline{L} = \Sigma^* - L$ must be a CFL.

Set difference with regular is okay☺

- If L is a CFL and R is a regular language, then $L - R$ is a CFL.
- $L - R = L \cap \bar{R}$
- If R is regular then $\bar{R}$ is regular.