Theory of Computer Science

B7. Context-free Languages: ε-Rules & Chomsky Normal Form

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B7.1 Context-free Grammars and ε-Rules

Repetition: Context-free Grammars

Definition (Context-free Grammar)

A context-free grammar is a 4-tuple $\langle V, \Sigma, P, S\rangle$ with

1. V finite set of variables,
2. Σ finite alphabet of terminal symbols (with $V \cap \Sigma = \emptyset$),
3. $P \subseteq (V \times (V \cup \Sigma)^+) \cup \{\langle S, \varepsilon\rangle\}$ finite set of rules,
4. If $S \to \varepsilon \in P$, then all other rules in $V \times ((V \setminus \{S\}) \cup \Sigma)^+$.
5. $S \in V$ start variable.

Rule $X \to \varepsilon$ is only allowed if $X = S$
and S never occurs on a right-hand side.

With regular grammars, this restriction could be lifted.
How about context-free grammars?

Short-hand Notation for Rule Sets

We abbreviate several rules with the same left-hand side variable in a single line, using "|" for separating the right-hand sides.

For example, we write

$$X \to 0Y1 \mid XY$$

for:

$X \to 0Y1$ and
$X \to XY$

Context-free Grammars: Exercise

We have used the pumping lemma for regular languages to show that $L = \{\mathtt{a}^n\mathtt{b}^n \mid n \in \mathbb{N}_0\}$ is not regular.

Show that it is context-free by specifying a suitable grammar G with $\mathcal{L}(G) = L$.

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Reminder: Start Variable in Right-Hand Side of Rules

For every type-0 language L there is a grammar where the start variable does not occur on the right-hand side of any rule.

Theorem

For every grammar $G = \langle V, \Sigma, P, S\rangle$ there is a grammar $G' = \langle V', \Sigma, P', S\rangle$ with rules $P' \subseteq (V' \cup \Sigma)^+ \times (V' \setminus \{S\} \cup \Sigma)^*$ such that $\mathcal{L}(G) = \mathcal{L}(G')$.

In the proof we constructed a suitable grammar, where the rules in P' were not fundamentally different from the rules in P:

- for rules from $V \times (V \cup \Sigma)^+$, we only introduced additional rules from $V' \times (V' \cup \Sigma)^+$, and
- for rules from $V \times \varepsilon$, we only introduced rules from $V' \times \varepsilon$,

where $V' = V \cup \{S'\}$ for some new variable $S' \notin V$.

ε-Rules

Theorem

For every grammar G with rules $P \subseteq V \times (V \cup \Sigma)^*$ there is a context-free grammar G' with $\mathcal{L}(G) = \mathcal{L}(G')$.

Proof.

Let $G = \langle V, \Sigma, P, S \rangle$ be a grammar with $P \subseteq V \times (V \cup \Sigma)^*$.

Let $G' = \langle V', \Sigma, P', S \rangle$ be a grammar with $\mathcal{L}(G) = \mathcal{L}(G')$ with $P' \subseteq V' \times ((V' \setminus S) \cup \Sigma)^*$.

Let $V_\varepsilon = \{A \in V' \mid A \Rightarrow^*_{G'} \varepsilon\}$. We can find this set V_ε by first collecting all variables A with rule $A \to \varepsilon \in P'$ and then successively adding additional variables B if there is a rule $B \to A_1 A_2 \dots A_k \in P'$ and the variables A_i are already in the set for all $1 \leq i \leq k$. ...

ε-Rules

Theorem

For every grammar G with rules $P \subseteq V \times (V \cup \Sigma)^*$ there is a context-free grammar G' with $\mathcal{L}(G) = \mathcal{L}(G')$.

Proof (continued).

Let P'' be the rule set that is constructed from P' by

- adding rules that obviate the need for $A \to \varepsilon$ rules: for every existing rule $B \to w$ with $B \in V', w \in (V' \cup \Sigma)^+$, let I_ε be the set of positions where w contains a variable $A \in V_\varepsilon$. For every non-empty set $I' \subseteq I_\varepsilon$, add a new rule $B \to w'$, where w' is constructed from w by removing the variables at all positions in I'.
- removing all rules of the form $A \to \varepsilon$ $(A \neq S)$.

Then $G'' = \langle V', \Sigma, P'', S \rangle$ is context-free and $\mathcal{L}(G) = \mathcal{L}(G'')$. □

Example

Consider $G = \langle\{\mathsf{X}, \mathsf{Y}, \mathsf{Z}, \mathsf{S}\}, \{\mathtt{a}, \mathtt{b}\}, R, S\rangle$ with rules:

$$\begin{aligned} \mathsf{S} &\to \varepsilon \mid \mathsf{XY} \\ \mathsf{X} &\to \mathtt{a}\mathsf{XY}\mathtt{b}\mathsf{X} \mid \mathsf{YZ} \\ \mathsf{Y} &\to \varepsilon \mid \mathtt{b} \\ \mathsf{Z} &\to \varepsilon \mid \mathtt{a} \end{aligned}$$

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B7.2 Chomsky Normal Form

Chomsky Normal Form: Motivation

As in logical formulas (and other kinds of structured objects), normal forms for grammars are useful:

- they show which aspects are critical for defining grammars and which ones are just syntactic sugar
- they allow proofs and algorithms to be restricted to a limited set of grammars (inputs): those in normal form

Hence we now consider a normal form for context-free grammars.

Chomsky Normal Form: Definition

Definition (Chomsky Normal Form)

A context-free grammar G is in Chomsky normal form (CNF) if all rules have one of the following three forms:

- $A \to BC$ with variables A, B, C, or
- $A \to a$ with variable A, terminal symbol a, or
- $S \to \varepsilon$ with start variable S.

German: Chomsky-Normalform

in short:

rule set $P \subseteq (V \times (V'V' \cup \Sigma)) \cup \{\langle S, \varepsilon \rangle\}$ with $V' = V \setminus \{S\}$

Chomsky Normal Form: Theorem

Theorem

For every context-free grammar G there is a context-free grammar G' in Chomsky normal form with $\mathcal{L}(G) = \mathcal{L}(G')$.

Proof.

The following algorithm converts the rule set of G into CNF:

Step 1: Eliminate rules of the form $A \to B$ with variables A, B.

If there are sets of variables $\{B_1, \dots, B_k\}$ with rules
$B_1 \to B_2, B_2 \to B_3, \dots, B_{k-1} \to B_k, B_k \to B_1$,
then replace these variables by a new variable B.

Define a strict total order $<$ on the variables such that $A \to B \in P$ implies that $A < B$. Iterate from the largest to the smallest variable A and eliminate all rules of the form $A \to B$ while adding rules $A \to w$ for every rule $B \to w$ with $w \in (V \cup \Sigma)^+$. ...

Chomsky Normal Form: Theorem

Theorem

For every context-free grammar G there is a context-free grammar G' in Chomsky normal form with $\mathcal{L}(G) = \mathcal{L}(G')$.

Proof (continued).

Step 2: Eliminate rules with terminal symbols on the right-hand side that do not have the form $A \to a$.

For every terminal symbol $a \in \Sigma$ add a new variable A_a and the rule $A_a \to a$.

Replace all terminal symbols in all rules that do not have the form $A \to a$ with the corresponding newly added variables. ...

Chomsky Normal Form: Theorem

Theorem

For every context-free grammar G there is a context-free grammar G' in Chomsky normal form with $\mathcal{L}(G) = \mathcal{L}(G')$.

Proof (continued).

Step 3: Eliminate rules of the form $A \to B_1 B_2 \dots B_k$ with $k > 2$

For every rule of the form $A \to B_1 B_2 \dots B_k$ with $k > 2$, add new variables $C_2, \dots, C_{k-1}$ and replace the rule with

$$\begin{aligned} A &\to B_1 C_2 \\ C_2 &\to B_2 C_3 \\ &\vdots \\ C_{k-1} &\to B_{k-1} B_k \end{aligned}$$

□

Example

Consider $G = \langle\{\mathsf{Y}, \mathsf{Z}, \mathsf{S}\}, \{\mathtt{a}, \mathtt{b}\}, R, S\rangle$ with rules:

$$\mathsf{S} \rightarrow \mathtt{a}\mathsf{Z}\mathtt{b}\mathsf{Y} \mid \mathsf{Y} \mid \mathtt{ab}$$
$$\mathsf{Y} \rightarrow \mathsf{Z} \mid \mathtt{b}$$
$$\mathsf{Z} \rightarrow \mathsf{Y} \mid \mathtt{b}\mathsf{S}\mathtt{a}$$

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Chomsky Normal Form: Length of Derivations

Observation

Let G be a grammar in Chomsky normal form,
and let $w \in \mathcal{L}(G)$ be a non-empty word generated by G.
Then all derivations of w have exactly $2|w| - 1$ derivation steps.

Why?

B7.3 Summary

Summary

- The restriction of ε-occurrences in rules is not necessary to characterize the set of context-free languages.
- Every context-free language has a grammar in Chomsky normal form. All rules have form
  - $A \to BC$ with variables A, B, C, or
  - $A \to a$ with variable A, terminal symbol a, or
  - $S \to \varepsilon$ with start variable S.