Context-Free Grammars

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Context-Free Grammar

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

- N alphabet of nonterminals
- T alphabet of terminals
- P finite set of productions of the form

$$A \rightarrow x$$

  with $A \in N$ and $x \in (N \cup T)^*$
- S the start symbol, $S \in N$

Proper Context-Free Grammar

Useful Symbol

A symbol $X \in N \cup T$ is useful if

1. $S \Rightarrow^* uXv$
2. $X \Rightarrow^* y$

for some $u, v \in (N \cup T)^*$ and $y \in T^*$

Proper Context-Free Grammar

A context-free grammar $G = (N, T, P, S)$ is proper if

1. $N \cup T$ contains only useful symbols
2. G is ε-free
3. G is unit-free

Properties of Proper Context-Free Grammars

Theorem

For every context-free language L, there is a proper context-free grammar G such that

$$L - \{\varepsilon\} = L(G)$$

Claim

If $G = (N, T, P, S)$ is proper, then for every $A \in N$

$$S \Rightarrow^* uAy \Rightarrow^* uwy$$

with $u, w, y \in T^*$

Weak Pumping Lemma

Weak Pumping Lemma

Let L be an infinite context-free language. Then, L contains a string $z = uvwxy$ such that

1. $uv^i wx^i y \in L$ for every $i \geq 0$
2. $|vx| \geq 1$

Weak Pumping Lemma – Proof

Let G be a proper context-free grammar such that $L = L(G)$

1. By contradiction: assume that no derivation in G contains two identical nonterminals. Then, $L(G)$ is finite – a contradiction.
2. Thus, there is

$$S \Rightarrow^* u'Ay' \Rightarrow^+ u'v'Ax'y' \Rightarrow^* u'v'wx'y'$$

in G, where $u', v', x', y' \in (N \cup T)^*$, $A \in N$, $w \in T^*$, $|v'x'| \geq 1$. As G is proper,

$$u' \Rightarrow^* u, v' \Rightarrow^* v, x' \Rightarrow^* x, \text{ and } y' \Rightarrow^* y$$

for some $u, v, x, y \in T^*$, $|vx| \geq 1$. Therefore,

$$S \Rightarrow^* uAy \Rightarrow^+ uvAxy \Rightarrow^* uvwxy.$$

Thus, $uv^iwx^iy \in L$ for every $i \geq 0$. □

Weak Pumping Lemma – Example

Example

Consider $L = \{a^n b^n c^n : n \geq 0\}$. By weak pumping lemma, L contains $z = uvwxy$ such that $|vx| \geq 1$ and $uv^i wx^i y \in L$ for every $i \geq 0$.

1. Let v or x be in
$$\{a\}^+\{b\}^+ \cup \{b\}^+\{c\}^+ \cup \{a\}^+\{b\}^+\{c\}^+.$$
Then, $uvvwxxy \notin L$ – contradiction.
2. Let v or x be in
$$\{a\}^+ \cup \{b\}^+ \cup \{c\}^+.$$
Then, $uwy \notin L$ – contradiction. □

Pumping Lemma

Pumping Lemma

Let L be a context-free language. Then, there is $k \geq 1$ such that for every $z \in L$ with $|z| \geq k$,

$$z = uvwxy$$

so that

1. $vx \neq \varepsilon$
2. $|vwx| \leq k$
3. $uv^m wx^m y \in L$ for all $m \geq 0$.

Pumping Lemma – Example

Example

Consider $L = \{a^{n^2} : n \geq 1\}$. Set $z = a^{k^2}$, where k is the pumping lemma constant. As $k^2 \geq k$, $|z| \geq k$. Express z as

$$z = uvwxy.$$

By pumping lemma, $uv^2wx^2y \in L$. Observe that $|vx| \leq k$, so

$$k^2 = |uvwxy| < |uv^2wx^2y| = |uvwxy| + |vx| \leq \\ k^2 + k < k^2 + 2k + 1 = (k+1)^2.$$

As $k^2 < |uv^2wx^2y| < (k+1)^2$, $uv^2wx^2y \notin L$ – contradiction. L is not a context-free language. $\square$

Homework Assignment

1. Establish a pumping lemma for regular languages (based on regular grammars). Use this lemma to prove that some context-free languages are not regular.
2. By using this lemma, demonstrate that a computer program that decides whether a positive integer n is prime cannot be based on any finite automaton.

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