

# Theory of Computer Science

## C6. Context-free Languages: Closure & Decidability

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## April 6, 2020 — C6. Context-free Languages: Closure & Decidability

### C6.1 Pumping Lemma

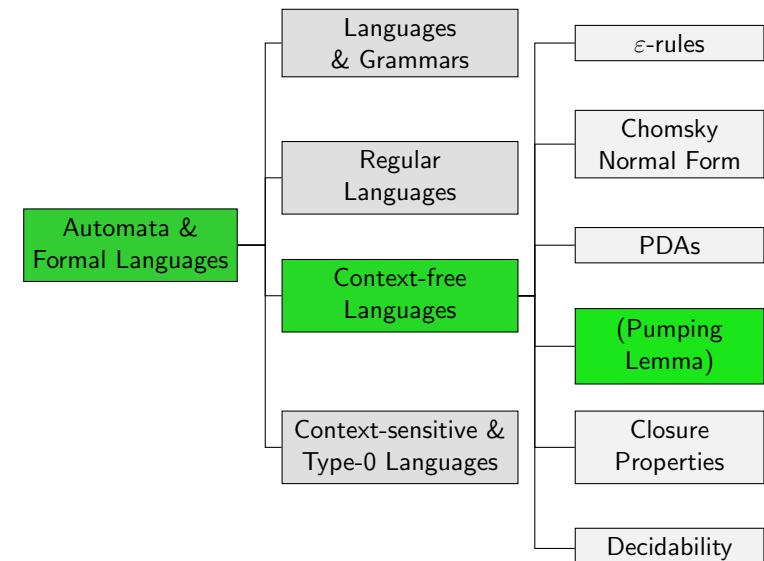
### C6.2 Closure Properties

### C6.3 Decidability

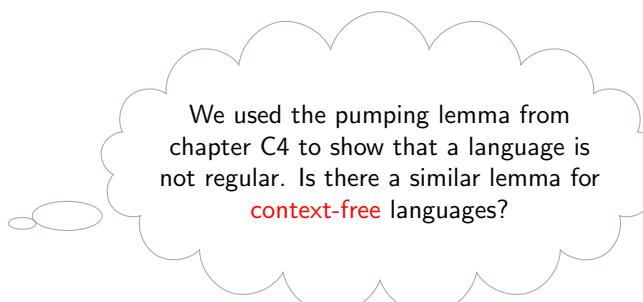
### C6.4 Summary

## C6.1 Pumping Lemma

### Overview



## Pumping Lemma for Context-free Languages



Yes!

Picture courtesy of imagerymajestic / FreeDigitalPhotos.net

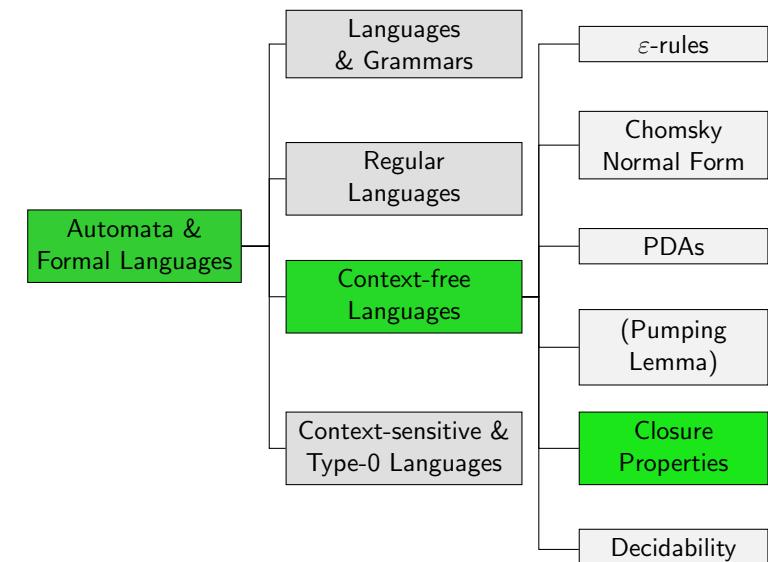
## Pumping Lemma for Context-free Languages

Pumping lemma for context-free languages:

- ▶ It is possible to prove a variant of the **pumping lemma** for context-free languages.
- ▶ Pumping is more complex than for regular languages:
  - ▶ word is decomposed into the form  $uvwxy$  with  $|vx| \geq 1$ ,  $|vwx| \leq n$
  - ▶ pumped words have the form  $uv^iwx^iy$
- ▶ This allows us to prove that certain languages are **not context-free**.
- ▶ **example:**  $\{a^n b^n c^n \mid n \geq 1\}$  is not context-free (we will later use this without proof)

## C6.2 Closure Properties

## Overview



## Closure under Union, Concatenation, Star

### Theorem

The context-free languages are closed under:

- ▶ union
- ▶ concatenation
- ▶ star

## Closure under Union, Concatenation, Star: Proof

### Proof (continued).

#### Closed under concatenation:

Let  $G_1 = \langle \Sigma_1, V_1, P_1, S_1 \rangle$  and  $G_2 = \langle \Sigma_2, V_2, P_2, S_2 \rangle$  be context-free grammars. W.l.o.g.,  $V_1 \cap V_2 = \emptyset$ .

Then  $\langle \Sigma, V_1 \cup V_2 \cup \{S\}, P_1 \cup P_2 \cup \{S \rightarrow S_1 S_2\}, S \rangle$  (where  $S \notin V_1 \cup V_2$ ) is a context-free grammar for  $\mathcal{L}(G_1)\mathcal{L}(G_2)$  (possibly requires rewriting  $\varepsilon$ -rules).  $\dots$

## Closure under Union, Concatenation, Star: Proof

### Proof.

#### Closed under union:

Let  $G_1 = \langle \Sigma_1, V_1, P_1, S_1 \rangle$  and  $G_2 = \langle \Sigma_2, V_2, P_2, S_2 \rangle$  be context-free grammars. W.l.o.g.,  $V_1 \cap V_2 = \emptyset$ .

Then  $\langle \Sigma_1 \cup \Sigma_2, V_1 \cup V_2 \cup \{S\}, P_1 \cup P_2 \cup \{S \rightarrow S_1, S \rightarrow S_2\}, S \rangle$  (where  $S \notin V_1 \cup V_2$ ) is a context-free grammar for  $\mathcal{L}(G_1) \cup \mathcal{L}(G_2)$  (possibly requires rewriting  $\varepsilon$ -rules).  $\dots$

## Closure under Union, Concatenation, Star: Proof

## Closure under Union, Concatenation, Star: Proof

### Proof (continued).

#### Closed under star:

Let  $G = \langle \Sigma, V, P, S \rangle$  be a context-free grammar where w.l.o.g.  $S$  never occurs on the right-hand side of a rule.

Then  $G' = \langle \Sigma, V \cup \{S'\}, P', S' \rangle$  with  $S' \notin V$  and  $P' = (P \cup \{S' \rightarrow \varepsilon, S' \rightarrow S, S' \rightarrow SS'\}) \setminus \{S \rightarrow \varepsilon\}$  is a context-free grammar for  $\mathcal{L}(G)^*$  after rewriting  $\varepsilon$ -rules.  $\square$

## No Closure under Intersection or Complement

### Theorem

The context-free languages are not closed under:

- ▶ intersection
- ▶ complement

## No Closure under Intersection or Complement: Proof

Proof.

Not closed under intersection:

The languages  $L_1 = \{a^i b^j c^j \mid i, j \geq 1\}$  and  $L_2 = \{a^i b^j c^i \mid i, j \geq 1\}$  are context-free.

- ▶ For example,  $G_1 = \langle \{a, b, c\}, \{S, A, X\}, P, S \rangle$  with  $P = \{S \rightarrow AX, A \rightarrow a, A \rightarrow aA, X \rightarrow bc, X \rightarrow bXc\}$  is a context-free grammar for  $L_1$ .
- ▶ For example,  $G_2 = \langle \{a, b, c\}, \{S, B\}, P, S \rangle$  with  $P = \{S \rightarrow aSc, S \rightarrow B, B \rightarrow b, B \rightarrow bB\}$  is a context-free grammar for  $L_2$ .

Their intersection is  $L_1 \cap L_2 = \{a^n b^n c^n \mid n \geq 1\}$ .

We have remarked before that this language is not context-free.

...

## No Closure under Intersection or Complement: Proof

Proof (continued).

Not closed under complement:

By contradiction: assume they were closed under complement.

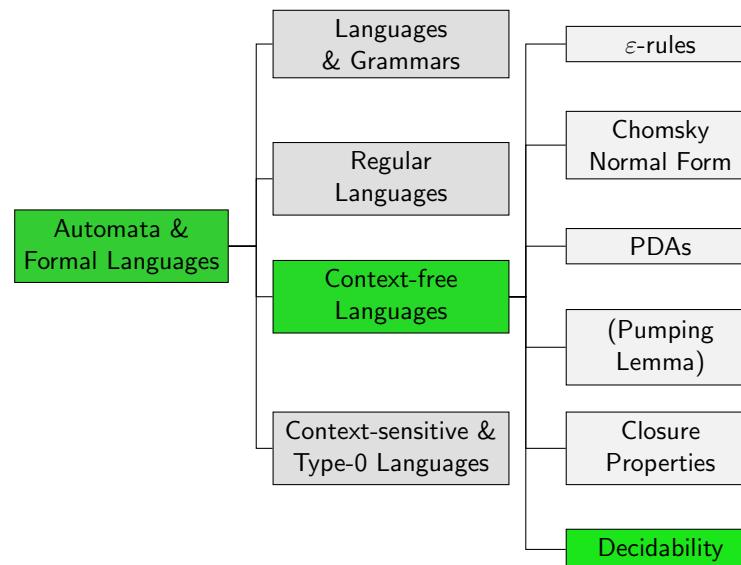
Then they would also be closed under intersection because they are closed under union and

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

This is a contradiction because we showed that they are not closed under intersection. □

## C6.3 Decidability

## Overview



## Word Problem

### Definition (Word Problem for Context-free Languages)

The **word problem**  $P_{\in}$  for context-free languages is:

**Given:** context-free grammar  $G$  with alphabet  $\Sigma$  and word  $w \in \Sigma^*$

**Question:** Is  $w \in \mathcal{L}(G)$ ?

## Decidability: Word Problem

### Theorem

The word problem  $P_{\in}$  for context-free languages is **decidable**.

### Proof.

If  $w = \varepsilon$ , then  $w \in \mathcal{L}(G)$  iff  $S \rightarrow \varepsilon$  with start variable  $S$  is a rule of  $G$ .

Since for all other rules  $w_l \rightarrow w_r$  of  $G$  we have  $|w_l| \leq |w_r|$ , the intermediate results when deriving a non-empty word never get shorter.

So it is possible to systematically consider all (finitely many) derivations of words up to length  $|w|$  and test whether they derive the word  $w$ . □

**Note:** This is a terribly inefficient algorithm.

## Emptiness Problem

### Definition (Emptiness Problem for Context-free Languages)

The **emptiness problem**  $P_{\emptyset}$  for context-free languages is:

**Given:** context-free grammar  $G$

**Question:** Is  $\mathcal{L}(G) = \emptyset$ ?

## Decidability: Emptiness Problem

### Theorem

The emptiness problem for context-free languages is **decidable**.

### Proof.

Given a grammar  $G$ , determine all variables in  $G$  that allow deriving words that only consist of terminal symbols:

- ▶ First mark all variables  $A$  for which a rule  $A \rightarrow w$  exists such that  $w$  only consists of terminal symbols.
- ▶ Then mark all variables  $A$  for which a rule  $A \rightarrow w$  exists such that all nonterminal symbols in  $w$  are already marked.
- ▶ Repeat this process until no further markings are possible.

$\mathcal{L}(G)$  is empty iff the start variable is unmarked at the end of this process. □

## Finiteness Problem

### Definition (Finiteness Problem for Context-free Languages)

The **finiteness problem**  $P_\infty$  for context-free languages is:

Given: context-free grammar  $G$   
 Question: Is  $|\mathcal{L}(G)| < \infty$ ?

## Decidability: Finiteness Problem

### Theorem

The finiteness problem for context-free languages is **decidable**.

We omit the proof. A possible proof uses the pumping lemma for context-free languages.

### Proof sketch:

- ▶ We can compute certain bounds  $l, u \in \mathbb{N}_0$  for a given context-free grammar  $G$  such that  $\mathcal{L}(G)$  is infinite iff there exists  $w \in \mathcal{L}(G)$  with  $l \leq |w| \leq u$ .
- ▶ Hence we can decide finiteness by testing all (finitely many) such words by using an algorithm for the word problem.

## Intersection Problem

### Definition (Intersection Problem for Context-free Languages)

The **intersection problem**  $P_\cap$  for context-free languages is:

Given: context-free grammars  $G$  and  $G'$   
 Question: Is  $\mathcal{L}(G) \cap \mathcal{L}(G') = \emptyset$ ?

## Equivalence Problem

### Definition (Equivalence Problem for Context-free Languages)

The **equivalence problem**  $P_{\equiv}$  for context-free languages is:

Given: context-free grammars  $G$  and  $G'$

Question: Is  $\mathcal{L}(G) = \mathcal{L}(G')$ ?

## Undecidability: Equivalence and Intersection Problem

### Theorem

*The equivalence problem for context-free languages and the intersection problem for context-free languages are **not decidable**.*

We cannot show this with the means currently available, but we will get back to this in Part D (computability theory).

## C6.4 Summary

## Summary

- ▶ The context-free languages are **closed** under **union**, **concatenation** and **star**.
- ▶ The context-free languages are **not closed** under **intersection** or **complement**.
- ▶ The **word problem**, **emptiness problem** and **finiteness problem** for the class of context-free languages are **decidable**.
- ▶ The **equivalence problem** and **intersection problem** for the class of context-free languages are **not decidable**.

## Further Topics on Context-free Languages and PDAs

- ▶ With the **CYK-algorithm** (Cocke, Younger and Kasami) it is possible to decide  $w \in \mathcal{L}(G)$  in time  $O(|w|^3)$  for a grammar in Chomsky normal form and a word  $w$ .
- ▶ **Deterministic push-down automata** have the restriction  $|\delta(q, a, A)| + |\delta(q, \varepsilon, A)| \leq 1$  for all  $q \in Q, a \in \Sigma, A \in \Gamma$ . They accept with **end states** rather than empty stack.
- ▶ The languages accepted by deterministic PDAs are called **deterministic context-free languages**. They form a strict superset of the regular languages and a strict subset of the context-free languages.