

Foundations of Informatics: a Bridging Course

Week 3: Formal Languages and Semantics

Part B: Context-Free Languages

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<https://cosec.bit.uni-bonn.de/students/teaching/13us/13us-bridgingcourse/>

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- 1 Context-Free Grammars and Languages
- 2 Context-Free vs. Regular Languages
- 3 The Word Problem for CFLs
- 4 The Emptiness Problem for CFLs
- 5 Pushdown Automata
- 6 Closure Properties of CFLs
- 7 Outlook

Example B.1

Syntax definition of programming languages by “Backus-Naur” rules

Here: **simple arithmetic expressions**

$$\begin{aligned}\langle \textit{Expression} \rangle &::= 0 \\ &| 1 \\ &| \langle \textit{Expression} \rangle + \langle \textit{Expression} \rangle \\ &| \langle \textit{Expression} \rangle * \langle \textit{Expression} \rangle \\ &| (\langle \textit{Expression} \rangle)\end{aligned}$$

Meaning:

*An expression is either 0 or 1, or it is of the form $u + v$, $u * v$, or (u) where u, v are again expressions*

Example B.2 (continued)

Here we abbreviate $\langle \textit{Expression} \rangle$ as E , and use “ $\rightarrow$ ” instead of “ $::=$ ”.

Thus:

$$E \rightarrow 0 \mid 1 \mid E + E \mid E * E \mid (E)$$

Example B.2 (continued)

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Thus:

$$E \rightarrow 0 \mid 1 \mid E + E \mid E * E \mid (E)$$

Now expressions can be generated by **applying rules** to the start symbol E :

$$\begin{aligned} E &\Rightarrow E * E \\ &\Rightarrow (E) * E \\ &\Rightarrow (E) * 1 \\ &\Rightarrow (E + E) * 1 \\ &\Rightarrow (0 + E) * 1 \\ &\Rightarrow (0 + 1) * 1 \end{aligned}$$

Definition B.3

A **context-free grammar** (CFG) is a quadruple

$$G = \langle N, \Sigma, P, S \rangle$$

where

- N is a finite set of **nonterminal symbols**
- Σ is the (finite) alphabet of **terminal symbols** (disjoint from N)
- P is a finite set of **production rules** of the form $A \rightarrow \alpha$ where $A \in N$ and $\alpha \in (N \cup \Sigma)^*$
- $S \in N$ is a **start symbol**

Example B.4

For the above example, we have:

- $N = \{E\}$
- $\Sigma = \{0, 1, +, *, (,)\}$
- $P = \{E \rightarrow 0, E \rightarrow 1, E \rightarrow E + E, E \rightarrow E * E, E \rightarrow (E)\}$
- $S = E$

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- $S = E$

Naming conventions:

- nonterminals start with uppercase letters
- terminals start with lowercase letters
- start symbol = symbol on LHS of first production

⇒ grammar completely defined by productions

Definition B.5

Let $G = \langle N, \Sigma, P, S \rangle$ be a CFG.

- A **sentence** $\gamma \in (N \cup \Sigma)^*$ is **directly derivable** from $\beta \in (N \cup \Sigma)^*$ if there exist $\pi = A \rightarrow \alpha \in P$ and $\delta_1, \delta_2 \in (N \cup \Sigma)^*$ such that $\beta = \delta_1 A \delta_2$ and $\gamma = \delta_1 \alpha \delta_2$ (notation: $\beta \xRightarrow{\pi} \gamma$ or just $\beta \Rightarrow \gamma$).
- A **derivation** (of length n) of γ from β is a sequence of direct derivations of the form $\delta_0 \Rightarrow \delta_1 \Rightarrow \dots \Rightarrow \delta_n$ where $\delta_0 = \beta$, $\delta_n = \gamma$, and $\delta_{i-1} \Rightarrow \delta_i$ for every $1 \leq i \leq n$ (notation: $\beta \Rightarrow^* \gamma$).
- A word $w \in \Sigma^*$ is called **derivable** in G if $S \Rightarrow^* w$.

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- A **derivation** (of length n) of γ from β is a sequence of direct derivations of the form $\delta_0 \Rightarrow \delta_1 \Rightarrow \dots \Rightarrow \delta_n$ where $\delta_0 = \beta$, $\delta_n = \gamma$, and $\delta_{i-1} \Rightarrow \delta_i$ for every $1 \leq i \leq n$ (notation: $\beta \Rightarrow^* \gamma$).
- A word $w \in \Sigma^*$ is called **derivable** in G if $S \Rightarrow^* w$.
- The **language generated by G** is $L(G) := \{w \in \Sigma^* \mid S \Rightarrow^* w\}$.
- A language $L \subseteq \Sigma^*$ is called **context-free (CFL)** if it is generated by some CFG.
- Two grammars G_1, G_2 are **equivalent** if $L(G_1) = L(G_2)$.

Example B.6

The language $\{a^n b^n \mid n \geq 1\}$ is context-free (but not regular—see Ex. A.59). It is generated by the grammar $G = \langle N, \Sigma, P, S \rangle$ with

- $N = \{S\}$
- $\Sigma = \{a, b\}$
- $P = \{S \rightarrow aSb \mid ab\}$

(proof: on the board)

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(proof: on the board)

Remark: illustration of derivations by **derivation trees**

- root labeled by start symbol
- leafs labeled by terminal symbols
- successors of node labeled according to right-hand side of production rule

(example on the board)

Seen:

- Context-free grammars
- Derivations
- Context-free languages

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Open:

- Relation between context-free and regular languages

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Theorem B.7

- ① *Every regular language is context-free.*
- ② *There exist CFLs which are not regular.*

(In other words: the class of regular languages is a **proper subset** of the class of CFLs.)

Context-Free vs. Regular Languages

Theorem B.7

- 1 Every regular language is context-free.
- 2 There exist CFLs which are not regular.

(In other words: the class of regular languages is a **proper subset** of the class of CFLs.)

Proof.

- 1 Let L be a regular language, and let $\mathfrak{A} = \langle Q, \Sigma, \delta, q_0, F \rangle$ be a DFA which recognizes L . $G := \langle N, \Sigma, P, S \rangle$ is defined as follows:
 - $N := Q$, $S := q_0$
 - if $\delta(q, a) = q'$, then $q \rightarrow aq' \in P$
 - if $q \in F$, then $q \rightarrow \varepsilon \in P$

Obviously a w -labeled run in $\mathfrak{A}$ from q_0 to F corresponds to a derivation of w in G , and vice versa. Thus $L(\mathfrak{A}) = L(G)$ (example on the board).

- 2 An example is $\{a^n b^n \mid n \geq 1\}$ (see Ex. A.59 and B.6).

Seen:

- CFLs are more expressive than regular languages

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Open:

- Decidability of word problem

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- **Goal:** given $G = \langle N, \Sigma, P, S \rangle$ and $w \in \Sigma^*$, decide whether $w \in L(G)$ or not
 - For regular languages this was easy: just let the corresponding DFA run on w .
 - But here: how to decide **when to stop** a derivation?
 - **Solution:** establish **normal form** for grammars which guarantees that each nonterminal produces at least one terminal symbol
- ⇒ only **finitely many combinations** to be inspected

Definition B.8

A CFG is in **Chomsky Normal Form (Chomsky NF)** if every of its productions is of the form

$$A \rightarrow BC \quad \text{or} \quad A \rightarrow a$$

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Example B.9

Let $S \rightarrow ab \mid aSb$ be the grammar which generates $L := \{a^n b^n \mid n \geq 1\}$.
An equivalent grammar in Chomsky NF is

$$\begin{array}{ll} S \rightarrow AB \mid AC & (\text{generates } L) \\ A \rightarrow a & (\text{generates } \{a\}) \\ B \rightarrow b & (\text{generates } \{b\}) \\ C \rightarrow SB & (\text{generates } \{a^n b^{n+1} \mid n \geq 1\}) \end{array}$$

Theorem B.10

Every CFL L (with $\epsilon \notin L$) is generatable by a CFG in Chomsky NF.

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Proof.

Let L be a CFL, and let $G = \langle N, \Sigma, P, S \rangle$ be some CFG which generates L . The transformation of P into rules of the form $A \rightarrow BC$ and $A \rightarrow a$ proceeds in three steps:

- 1 terminal symbols only in rules of the form $A \rightarrow a$
(thus all other rules have the shape $A \rightarrow A_1 \dots A_n$)
- 2 elimination of “chain rules” of the form $A \rightarrow B$
- 3 elimination of rules of the form $A \rightarrow A_1 \dots A_n$ where $n > 2$



Proof of Theorem B.10 (continued).

Step 1: (only $A \rightarrow a$)

- ① let $N' := \{B_a \mid a \in \Sigma\}$
- ② let $P' := \{A \rightarrow \alpha' \mid A \rightarrow \alpha \in P\} \cup \{B_a \rightarrow a \mid a \in \Sigma\}$
where α' is obtained from α by replacing every $a \in \Sigma$ with B_a

This yields G' (example: on the board)

Proof of Theorem B.10 (continued).

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Step 2: (elimination of $A \rightarrow B$)

- ① determine all derivations $A_1 \Rightarrow \dots \Rightarrow A_n$ with rules of the form $A \rightarrow B$ without repetition of nonterminals ($\Rightarrow$ only finitely many!)
- ② let $P'' := (P \cup \{A_1 \rightarrow \alpha \mid A_1 \Rightarrow \dots \Rightarrow A_n \Rightarrow \alpha, \alpha \notin N\}) \setminus \{A \rightarrow B \mid A \rightarrow B \in P'\}$

This yields G'' (example: on the board)

Proof of Theorem B.10 (continued).

Step 3: for every $A \rightarrow A_1 \dots A_n$ with $n > 2$:

- ① add new symbols $B_1, \dots, B_{n-2}$ to N''
- ② replace $A \rightarrow A_1 \dots A_n$ by

$$\begin{aligned} A &\rightarrow A_1 B_1 \\ B_1 &\rightarrow A_2 B_2 \\ &\vdots \\ B_{n-3} &\rightarrow A_{n-2} B_{n-2} \\ B_{n-2} &\rightarrow A_{n-1} A_n \end{aligned}$$

This yields G''' (example: on the board)

One can show: G, G', G'', G''' are equivalent



The Word Problem Revisited

Goal: given $w \in \Sigma^+$ and $G = \langle N, \Sigma, P, S \rangle$ such that $\varepsilon \notin L(G)$, decide if $w \in L(G)$ or not

(If $w = \varepsilon$, then $w \in L(G)$ easily decidable for arbitrary G)

Approach by Cocke, Younger, Kasami (**CYK algorithm**):

- 1 transform G into Chomsky NF
- 2 let $w = a_1 \dots a_n$ ($n \geq 1$)
- 3 let $w[i, j] := a_i \dots a_j$ for every $1 \leq i \leq j \leq n$
- 4 consider segments $w[i, j]$ in order of increasing length, starting with $w[i, i]$ (i.e., single letters)
- 5 in each case, determine $N_{i,j} := \{A \in N \mid A \Rightarrow^* w[i, j]\}$
- 6 test whether $S \in N_{1,n}$ (and thus, whether $S \Rightarrow^* w[1, n] = w$)

The CYK Algorithm I

Algorithm B.11 (CYK Algorithm)

Input: $G = \langle N, \Sigma, P, S \rangle$ in Chomsky NF, $w = a_1 \dots a_n \in \Sigma^+$

Question: $w \in L(G)$?

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

$N_{i,i} := \{A \in N \mid A \rightarrow a_i \in P\}$

next i

for $d := 1$ to $n - 1$ do % compute $N_{i,i+d}$

for $i := 1$ to $n - d$ do

$j := i + d$; $N_{i,j} := \emptyset$;

for $k := i$ to $j - 1$ do

$N_{i,j} := N_{i,j} \cup \{A \in N \mid \text{there is } A \rightarrow BC \in P$
with $B \in N_{i,k}, C \in N_{k+1,j}\}$

next k

next i

next d

Output: “yes” if $S \in N_{1,n}$, otherwise “no”

Example B.12

- $G : S \rightarrow SA \mid a$
 $A \rightarrow BS$
 $B \rightarrow BB \mid BS \mid b \mid c$
- $w = abaaba$
- Matrix representation of $N_{i,j}$

(on the board)

Seen:

- Word problem decidable using CYK algorithm

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Open:

- Emptiness problem

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The Emptiness Problem

- **Goal:** given $G = \langle N, \Sigma, P, S \rangle$, decide whether $L(G) = \emptyset$ or not
- For regular languages this was easy: check in the corresponding DFA whether some final state is reachable from the initial state.
- Here: test whether start symbol is **productive**, i.e., whether it generates a terminal word

The Emptiness Test

Algorithm B.13 (Emptiness Test)

Input: $G = \langle N, \Sigma, P, S \rangle$

Question: $L(G) = \emptyset?$

Procedure: *mark every $a \in \Sigma$ as productive;*

repeat

*if there is $A \rightarrow \alpha \in P$ such that
all symbols in α productive then
mark A as productive;*

end;

until no further productive symbols found;

Output: *"no" if S productive, otherwise "yes"*

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Question: $L(G) = \emptyset?$

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*if there is $A \rightarrow \alpha \in P$ such that
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end;

until no further productive symbols found;

Output: *"no" if S productive, otherwise "yes"*

Example B.14

$G : S \rightarrow AB \mid CA$

$A \rightarrow a$

$B \rightarrow BC \mid AB$

$C \rightarrow aB \mid b$

(on the board)

Seen:

- Emptiness problem decidable based on productivity of symbols

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- Emptiness problem decidable based on productivity of symbols

Open:

- Characterizing automata model

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- **Goal:** introduce an automata model which **exactly accepts CFLs**
- **Clear:** DFA not sufficient
(missing “counting capability”, e.g. for $\{a^n b^n \mid n \geq 1\}$)
- DFA will be extended to **pushdown automata** by
 - adding a pushdown store which stores symbols from a pushdown alphabet and uses a specific bottom symbol
 - adding push and pop operations to transitions

Definition B.15

A **pushdown automaton (PDA)** is of the form $\mathfrak{A} = \langle Q, \Sigma, \Gamma, \Delta, q_0, Z_0, F \rangle$ where

- Q is a finite set of **states**
- Σ is the (finite) **input alphabet**
- Γ is the (finite) **pushdown alphabet**
- $\Delta \subseteq (Q \times \Gamma \times \Sigma_\epsilon) \times (Q \times \Gamma^*)$ is a finite set of **transitions**
- $q_0 \in Q$ is the **initial state**
- Z_0 is the (**pushdown**) **bottom symbol**
- $F \subseteq Q$ is a set of **final states**

Interpretation of $((q, Z, x), (q', \delta)) \in \Delta$: if the PDA $\mathfrak{A}$ is in state q where Z is on top of the stack and x is the next input symbol (or empty), then $\mathfrak{A}$ reads x , replaces Z by δ , and changes into the state q' .

Definition B.16

Let $\mathcal{A} = \langle Q, \Sigma, \Gamma, \Delta, q_0, Z_0, F \rangle$ be a PDA.

- An element of $Q \times \Gamma^* \times \Sigma^*$ is called a **configuration** of $\mathcal{A}$.
- The **initial configuration** for input $w \in \Sigma^*$ is given by (q_0, Z_0, w) .
- The set of **final configurations** is given by $F \times \{\varepsilon\} \times \{\varepsilon\}$.
- If $((q, Z, x), (q', \delta)) \in \Delta$, then $(q, Z\gamma, xw) \vdash (q', \delta\gamma, w)$ for every $\gamma \in \Gamma^*, w \in \Sigma^*$.
- $\mathcal{A}$ **accepts** $w \in \Sigma^*$ if $(q_0, Z_0, w) \vdash^* (q, \varepsilon, \varepsilon)$ for some $q \in F$.
- The **language accepted by** $\mathcal{A}$ is $L(\mathcal{A}) := \{w \in \Sigma^* \mid \mathcal{A} \text{ accepts } w\}$.
- A language L is called **PDA-recognizable** if $L = L(\mathcal{A})$ for some PDA $\mathcal{A}$.
- Two PDA $\mathcal{A}_1, \mathcal{A}_2$ are called **equivalent** if $L(\mathcal{A}_1) = L(\mathcal{A}_2)$.

Example B.17

- ① PDA which recognizes $L = \{a^n b^n \mid n \geq 1\}$
(on the board)

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(**palindromes** of even length; on the board)

Example B.17

- 1 PDA which recognizes $L = \{a^n b^n \mid n \geq 1\}$
(on the board)
- 2 PDA which recognizes $L = \{ww^R \mid w \in \{a, b\}^*\}$
(**palindromes** of even length; on the board)

Observation: $\mathcal{A}_2$ is nondeterministic: whenever a construction transition is applicable, the pushdown could also be deconstructed

Definition B.18

A PDA $\mathcal{A} = \langle Q, \Sigma, \Gamma, \Delta, q_0, Z_0, F \rangle$ is called **deterministic (DPDA)** if for every $q \in Q, Z \in \Gamma$,

- ① for every $x \in \Sigma_\epsilon$, at most one (q, Z, x) -transition in Δ and
- ② if there is a (q, Z, a) -transition in Δ for some $a \in \Sigma$, then there is no (q, Z, ϵ) -transition in Δ .

Remark: this excludes two types of nondeterminism:

- ① if $((q, Z, x), (q'_1, \delta_1)), ((q, Z, x), (q'_2, \delta_2)) \in \Delta$:
 $(q'_1, \delta_1 \gamma, w) \vdash (q, Z \gamma, xw) \vdash (q'_2, \delta_2 \gamma, w)$
- ② if $((q, Z, a), (q'_1, \delta_1)), ((q, Z, \epsilon), (q'_2, \delta_2)) \in \Delta$:
 $(q'_1, \delta_1 \gamma, w) \vdash (q, Z \gamma, aw) \vdash (q'_2, \delta_2 \gamma, aw)$

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- ② if $((q, Z, a), (q'_1, \delta_1)), ((q, Z, \varepsilon), (q'_2, \delta_2)) \in \Delta$:
 $(q'_1, \delta_1 \gamma, w) \vdash (q, Z \gamma, aw) \vdash (q'_2, \delta_2 \gamma, aw)$

Corollary B.19

In a DPDA, every configuration has at most one $\vdash$ -successor.

One can show: determinism restricts the set of acceptable languages (DPDA-recognizable languages are **closed under complement**, which is generally not true for PDA-recognizable languages)

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Example B.20

The set of palindromes of even length is PDA-recognizable, but not DPDA-recognizable (without proof).

Theorem B.21

A language is context-free iff it is PDA-recognizable.

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Proof.

$\Leftarrow$ omitted

$\Rightarrow$ let $G = \langle N, \Sigma, P, S \rangle$ be a CFG. Construction of PDA $\mathcal{A}_G$ recognizing $L(G)$:

- $\mathcal{A}_G$ simulates a derivation of G where the leftmost nonterminal of a sentence form is replaced (“leftmost derivation”)
- begin with S on pushdown
- if nonterminal on top: apply a corresponding production rule
- if terminal on top: match with next input symbol



Proof of Theorem B.21 (continued).

$\Rightarrow$ Formally: $\mathfrak{A}_G := \langle Q, \Sigma, \Gamma, \Delta, q_0, Z_0, F \rangle$ is given by

- $Q := \{q_0\}$
- $\Gamma := N \cup \Sigma$
- for each $A \rightarrow \alpha \in P$: $((q_0, A, \varepsilon), (q_0, \alpha)) \in \Delta$
- for each $a \in \Sigma$: $((q_0, a, a), (q_0, \varepsilon)) \in \Delta$
- $Z_0 := S$
- $F := Q$



Proof of Theorem B.21 (continued).

$\implies$ Formally: $\mathfrak{A}_G := \langle Q, \Sigma, \Gamma, \Delta, q_0, Z_0, F \rangle$ is given by

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- for each $a \in \Sigma$: $((q_0, a, a), (q_0, \varepsilon)) \in \Delta$
- $Z_0 := S$
- $F := Q$



Example B.22

“Bracket language”, given by G :

$$S \rightarrow \langle \rangle \mid \langle S \rangle \mid SS$$

(on the board)

Seen:

- Definition of PDA
- Equivalence of PDA-recognizable and context-free languages

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- Equivalence of PDA-recognizable and context-free languages

Open:

- Closure properties of CFLs

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Theorem B.23

The set of CFLs is closed under concatenation, union, and iteration.

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Proof.

For $i = 1, 2$, let $G_i = \langle N_i, \Sigma, P_i, S_i \rangle$ with $L_i := L(G_i)$ and $N_1 \cap N_2 = \emptyset$.
Then

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Then

- $G := \langle N, \Sigma, P, S \rangle$ with $N := \{S\} \cup N_1 \cup N_2$ and $P := \{S \rightarrow S_1 S_2\} \cup P_1 \cup P_2$ generates $L_1 \cdot L_2$;

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Then

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- $G := \langle N, \Sigma, P, S \rangle$ with $N := \{S\} \cup N_1 \cup N_2$ and $P := \{S \rightarrow S_1 \mid S_2\} \cup P_1 \cup P_2$ generates $L_1 \cup L_2$; and

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For $i = 1, 2$, let $G_i = \langle N_i, \Sigma, P_i, S_i \rangle$ with $L_i := L(G_i)$ and $N_1 \cap N_2 = \emptyset$.
Then

- $G := \langle N, \Sigma, P, S \rangle$ with $N := \{S\} \cup N_1 \cup N_2$ and $P := \{S \rightarrow S_1 S_2\} \cup P_1 \cup P_2$ generates $L_1 \cdot L_2$;
- $G := \langle N, \Sigma, P, S \rangle$ with $N := \{S\} \cup N_1 \cup N_2$ and $P := \{S \rightarrow S_1 \mid S_2\} \cup P_1 \cup P_2$ generates $L_1 \cup L_2$; and
- $G := \langle N, \Sigma, P, S \rangle$ with $N := \{S\} \cup N_1$ and $P := \{S \rightarrow \varepsilon \mid S_1 S\} \cup P_1$ generates L_1^* .



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- Both $L_1 := \{a^k b^k c^l \mid k, l \in \mathbb{N}\}$ and $L_2 := \{a^k b^l c^l \mid k, l \in \mathbb{N}\}$ are CFLs, but not $L_1 \cap L_2 = \{a^n b^n c^n \mid n \in \mathbb{N}\}$ (without proof).

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- If CFLs were closed under complement, then also under intersection (as $L_1 \cap L_2 = \overline{\overline{L_1} \cup \overline{L_2}}$).



Overview of Decidability and Closure Results

Decidability Results			
	$w \in L$	$L = \emptyset$	$L_1 = L_2$
Reg	+ (A.38)	+ (A.40)	+ (A.42)
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Closure Results					
	$L_1 \cdot L_2$	$L_1 \cup L_2$	$L_1 \cap L_2$	$\overline{L}$	L^*
Reg	+ (A.28)	+ (A.18)	+ (A.16)	+ (A.14)	+ (A.29)
CFL	+ (B.23)	+ (B.23)	– (B.24)	– (B.24)	+ (B.23)

- 1 Context-Free Grammars and Languages
- 2 Context-Free vs. Regular Languages
- 3 The Word Problem for CFLs
- 4 The Emptiness Problem for CFLs
- 5 Pushdown Automata
- 6 Closure Properties of CFLs
- 7 Outlook

- **Equivalence problem** for CFG and PDA (“ $L(X_1) = L(X_2)$?”)
(generally undecidable, decidable for DPDA)
- **Pumping Lemma** for CFL
- **Greibach Normal Form** for CFG
- Construction of **parsers** for compilers
- Non-context-free grammars and languages (**context-sensitive** and **recursively enumerable languages**, **Turing machines**—see Week 4)