

Compiler Construction

Lecture 5: Syntax Analysis I (Introduction)

Thomas Noll

Lehrstuhl für Informatik 2
(Software Modeling and Verification)

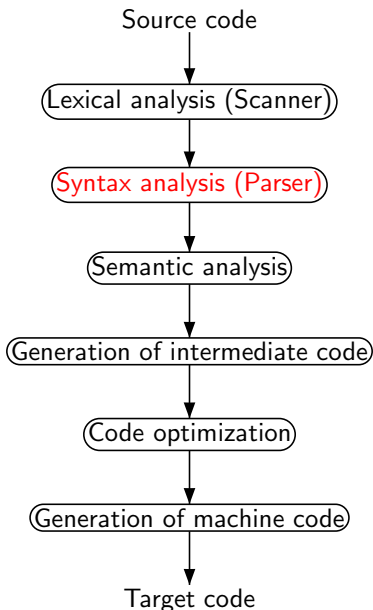
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Summer Semester 2012

Conceptual Structure of a Compiler



- 1 Problem Statement
- 2 Context-Free Grammars and Languages
- 3 Parsing Context-Free Languages
- 4 Nondeterministic Top-Down Parsing

From Merriam-Webster's Online Dictionary

Syntax: the way in which linguistic elements (as words) are put together to form constituents (as phrases or clauses)

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- **Starting point:** sequence of symbols as produced by the scanner
Here: ignore attribute information
 - Σ (finite) set of **tokens** (= syntactic atoms; **terminals**)
(e.g., $\{\text{id, if, int, \dots}\}$)
 - $w \in \Sigma^*$ **token sequence**
(of course, not every $w \in \Sigma^*$ forms a valid program)

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 - atomic:** keywords, variable/type/procedure/... identifiers, numerals, arithmetic/Boolean operators, ...
 - complex:** declarations, arithmetic/Boolean expressions, statements, ...

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- **Syntactic units:**
 - atomic:** keywords, variable/type/procedure/... identifiers, numerals, arithmetic/Boolean operators, ...
 - complex:** declarations, arithmetic/Boolean expressions, statements, ...
- **Observation:** the hierarchical structure of syntactic units can be described by **context-free grammars**

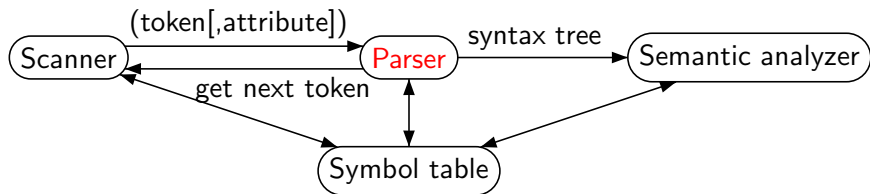
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The goal of **syntax analysis** is to determine the syntactic structure of a program, given by a token sequence, according to a context-free grammar.

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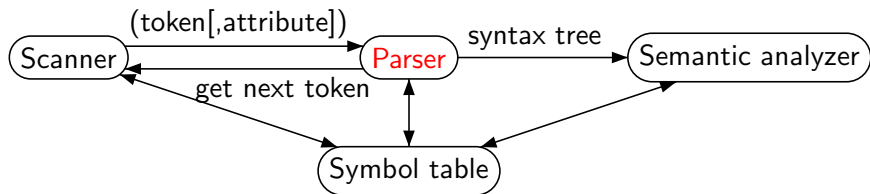
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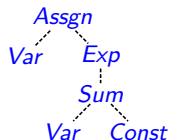


Example: ...`x1` := `y2` + `1`; ...

↓ Scanner

... (id, p_1) (gets,) (id, p_2) (plus,) (int, 1) (sem,) ...

Parser →



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Definition 5.2 (Syntax of context-free grammars)

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

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

where

- N is a finite set of **nonterminal symbols**,
- Σ is a (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 $\alpha \in X^*$ for $X := N \cup \Sigma$, and
- $S \in N$ is a **start symbol**.

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Remarks: as denotations we generally use

- $A, B, C, \dots \in N$ for nonterminal symbols
- $a, b, c, \dots \in \Sigma$ for terminal symbols
- $u, v, w, x, y, \dots \in \Sigma^*$ for terminal words
- $\alpha, \beta, \gamma, \dots \in X^*$ for **sentences**

Context-Free Grammars II

Context-free grammars generate context-free languages:

Definition 5.3 (Semantics of context-free grammars)

Let $G = \langle N, \Sigma, P, S \rangle$ be a context-free grammar.

- The **derivation relation** $\Rightarrow \subseteq X^+ \times X^*$ of G is defined by

$\alpha \Rightarrow \beta$ iff there exist $\alpha_1, \alpha_2 \in X^*, A \rightarrow \gamma \in P$
such that $\alpha = \alpha_1 A \alpha_2$ and $\beta = \alpha_1 \gamma \alpha_2$.

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Remark: obviously, $L(G) = \{w \in \Sigma^* \mid S \Rightarrow_l^* w\} = \{w \in \Sigma^* \mid S \Rightarrow_r^* w\}$

Example 5.4

The grammar $G = \langle N, \Sigma, P, S \rangle \in CFG_\Sigma$ over $\Sigma := \{a, b\}$, given by the productions

$$S \rightarrow aSb \mid \varepsilon,$$

generates the context-free (and non-regular) language

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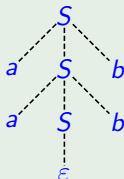
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The example derivation

$$S \Rightarrow aSb \Rightarrow aaSbb \Rightarrow aabb$$

can be represented by the following **syntax tree** for $aabb$:



Observations:

- 1 Every syntax tree yields exactly one word
(= concatenation of leaves).
- 2 Every syntax tree corresponds to exactly one leftmost derivation,
and vice versa.
- 3 Every syntax tree corresponds to exactly one rightmost derivation,
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Thus: syntax trees are **uniquely** representable by leftmost/rightmost derivations

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Thus: syntax trees are **uniquely** representable by leftmost/rightmost derivations

But: a word can have **several** syntax trees (see next slide)

Definition 5.5 (Ambiguity)

- A context-free grammar $G \in CFG_\Sigma$ is called **unambiguous** if every word $w \in L(G)$ has exactly one syntax tree. Otherwise it is called **ambiguous**.

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Example 5.6

on the board

Ambiguity of CFGs and CFLs

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Corollary 5.7

A grammar $G \in CFG_{\Sigma}$ is unambiguous
iff every word $w \in L(G)$ has exactly one leftmost derivation
iff every word $w \in L(G)$ has exactly one rightmost derivation.

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Problem 5.8 (Word problem for context-free languages)

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- (for CFGs in Chomsky Normal Form)
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- Using the **predecessor method**:

$$w \in L(G) \iff S \in \text{pre}^*(\{w\})$$

where $\text{pre}^*(M) := \{\alpha \in X^* \mid \alpha \Rightarrow^* \beta \text{ for some } \beta \in M\}$
(polynomial [non-linear] time complexity)

Goal: exploit the special syntactic structures as present in programming languages (usually: no ambiguities) to devise parsing methods which are based on **deterministic pushdown automata with linear space and time complexity**

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Two approaches:

Top-down parsing: construction of syntax tree from the **root towards the leaves**, representation as **leftmost derivation**

Bottom-up parsing: construction of syntax tree from the **leaves towards the root**, representation as (reversed) **rightmost derivation**

Leftmost/Rightmost Analysis I

Goal: compact representation of left-/rightmost derivations by index sequences

Definition 5.9 (Leftmost/rightmost analysis)

Let $G = \langle N, \Sigma, P, S \rangle \in CFG_{\Sigma}$ where $P = \{\pi_1, \dots, \pi_p\}$.

- If $i \in [p]$, $\pi_i = A \rightarrow \gamma$, $w \in \Sigma^*$, and $\alpha \in X^*$, then we write

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- If $z = i_1 \dots i_n \in [p]^*$, we write $\alpha \xRightarrow{z}_l \beta$ if there exist $\alpha_0, \dots, \alpha_n \in X^*$ such that $\alpha_0 = \alpha$, $\alpha_n = \beta$, and $\alpha_{j-1} \xRightarrow{i_j}_l \alpha_j$ for every $j \in [n]$ (analogously for $\xRightarrow{z}_r$).

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- An index sequence $z \in [p]^*$ is called a **leftmost analysis** (**rightmost analysis**) of α if $S \xRightarrow{z}_l \alpha$ ($S \xRightarrow{z}_r \alpha$), respectively.

Example 5.10

Grammar for arithmetic expressions:

$$\begin{aligned} G_{AE} : \quad E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T * F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost/Rightmost Analysis

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Leftmost derivation of $(a)*b$:

$$\begin{array}{ccccccc}E & \xRightarrow{2}_I & T & \xRightarrow{3}_I & T*F & \xRightarrow{4}_I & F*F & \xRightarrow{5}_I & (E)*F \\& \xRightarrow{2}_I & (T)*F & \xRightarrow{4}_I & (F)*F & \xRightarrow{6}_I & (a)*F & \xRightarrow{7}_I & (a)*b\end{array}$$

$\Rightarrow$ leftmost analysis: 23452467

Leftmost/Rightmost Analysis

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Rightmost derivation of $(a)*b$:

$$\begin{array}{ccccccc} E & \xRightarrow{2}_r & T & \xRightarrow{3}_r & T*F & \xRightarrow{7}_r & T*b & \xRightarrow{4}_r & F*b \\ & \xRightarrow{5}_r & (E)*b & \xRightarrow{2}_r & (T)*b & \xRightarrow{4}_r & (F)*b & \xRightarrow{6}_r & (a)*b \end{array}$$

$\Rightarrow$ rightmost analysis: 23745246

General assumption in the following: every grammar is reduced

Definition 5.11 (Reduced CFG)

A grammar $G = \langle N, \Sigma, P, S \rangle \in \text{CFG}_{\Sigma}$ is called **reduced** if for every $A \in N$ there exist $\alpha, \beta \in X^*$ and $w \in \Sigma^*$ such that

$$S \Rightarrow^* \alpha A \beta \quad (A \text{ reachable}) \text{ and}$$

$$A \Rightarrow^* w \quad (A \text{ productive}).$$

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Approach:

- 1 Given $G \in CFG_{\Sigma}$, construct a **nondeterministic pushdown automaton** (PDA) which accepts $L(G)$ and which additionally computes corresponding leftmost derivations (similar to the proof of " $L(CFG_{\Sigma}) \subseteq L(PDA_{\Sigma})$ ")
 - input alphabet: Σ
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 - input alphabet: Σ
 - pushdown alphabet: X
 - output alphabet: $[p]$
 - state set: not required
- 2 **Remove nondeterminism** by allowing **lookahead** on the input:
 $G \in LL(k)$ iff $L(G)$ recognizable by deterministic PDA with lookahead of k symbols

The Nondeterministic Top-Down Automaton I

Definition 5.12 (Nondeterministic top-down parsing automaton)

Let $G = \langle N, \Sigma, P, S \rangle \in CFG_{\Sigma}$. The **nondeterministic top-down parsing automaton** of G , $NTA(G)$, is defined by the following components.

- **Input alphabet:** Σ
- **Pushdown alphabet:** X
- **Output alphabet:** $[p]$
- **Configurations:** $\Sigma^* \times X^* \times [p]^*$ (top of pushdown to the left)
- **Transitions** for $w \in \Sigma^*$, $\alpha \in X^*$, and $z \in [p]^*$:
 - expansion steps: if $\pi_i = A \rightarrow \beta$, then $(w, A\alpha, z) \vdash (w, \beta\alpha, zi)$
 - matching steps: for every $a \in \Sigma$, $(aw, a\alpha, z) \vdash (w, \alpha, z)$
- **Initial configuration** for $w \in \Sigma^*$: (w, S, ε)
- **Final configurations:** $\{\varepsilon\} \times \{\varepsilon\} \times [p]^*$

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- **Initial configuration** for $w \in \Sigma^*$: (w, S, ε)
- **Final configurations:** $\{\varepsilon\} \times \{\varepsilon\} \times [p]^*$

Remark: $NTA(G)$ is nondeterministic iff G contains $A \rightarrow \beta \mid \gamma$

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(cf. Example 5.10):

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Leftmost analysis of $(a)*b$:

$((a)*b, E, \varepsilon)$

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$$\begin{aligned}G_{AE} : \quad & E \rightarrow E+T \mid T & (1, 2) \\ & T \rightarrow T*F \mid F & (3, 4) \\ & F \rightarrow (E) \mid a \mid b & (5, 6, 7)\end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned}& ((a)*b, E, \varepsilon) \\ \vdash & ((a)*b, T, 2) \\ \vdash & ((a)*b, T*F, 23) \\ \vdash & ((a)*b, F*F, 234) \\ \vdash & ((a)*b, (E)*F, 2345) \\ \vdash & (a)*b, E)*F, 2345)\end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned} G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T*F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned} &((a)*b, E, \varepsilon) \\ \vdash &((a)*b, T, 2) \\ \vdash &((a)*b, T*F, 23) \\ \vdash &((a)*b, F*F, 234) \\ \vdash &((a)*b, (E)*F, 2345) \\ \vdash &((a)*b, E)*F, 2345) \\ \vdash &((a)*b, T)*F, 23452) \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned} G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T*F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned} &((a)*b, E, \varepsilon) \\ \vdash &((a)*b, T, 2) \\ \vdash &((a)*b, T*F, 23) \\ \vdash &((a)*b, F*F, 234) \\ \vdash &((a)*b, (E)*F, 2345) \\ \vdash &((a)*b, E)*F, 2345) \\ \vdash &((a)*b, T)*F, 23452) \\ \vdash &((a)*b, F)*F, 234524) \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned} G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T*F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned} &((a)*b, E, \varepsilon) \\ \vdash &((a)*b, T, 2) \\ \vdash &((a)*b, T*F, 23) \\ \vdash &((a)*b, F*F, 234) \\ \vdash &((a)*b, (E)*F, 2345) \\ \vdash &((a)*b, E)*F, 2345) \\ \vdash &((a)*b, T)*F, 23452) \\ \vdash &((a)*b, F)*F, 234524) \\ \vdash &((a)*b, a)*F, 2345246) \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned} G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T*F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned} &((a)*b, E, \varepsilon) \\ \vdash &((a)*b, T, 2) \\ \vdash &((a)*b, T*F, 23) \\ \vdash &((a)*b, F*F, 234) \\ \vdash &((a)*b, (E)*F, 2345) \\ \vdash &((a)*b, E)*F, 2345) \\ \vdash &((a)*b, T)*F, 23452) \\ \vdash &((a)*b, F)*F, 234524) \\ \vdash &((a)*b, a)*F, 2345246) \\ \vdash &((\textcolor{red}{a})*b, \textcolor{red}{a})*F, 2345246) \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned} G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T*F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned} &((a)*b, E, \varepsilon) \\ \vdash &((a)*b, T, 2) \\ \vdash &((a)*b, T*F, 23) \\ \vdash &((a)*b, F*F, 234) \\ \vdash &((a)*b, (E)*F, 2345) \\ \vdash &((a)*b, E)*F, 2345) \\ \vdash &((a)*b, T)*F, 23452) \\ \vdash &((a)*b, F)*F, 234524) \\ \vdash &((a)*b, a)*F, 2345246) \\ \vdash &(()*b,)*F, 2345246) \\ \vdash &((*b, *F, 2345246) \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned}
 G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\
 T &\rightarrow T*F \mid F & (3, 4) \\
 F &\rightarrow (E) \mid a \mid b & (5, 6, 7)
 \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned}
 &((a)*b, E, \varepsilon) \\
 \vdash &((a)*b, T, 2) \\
 \vdash &((a)*b, T*F, 23) \\
 \vdash &((a)*b, F*F, 234) \\
 \vdash &((a)*b, (E)*F, 2345) \\
 \vdash &((a)*b, E)*F, 2345) \\
 \vdash &((a)*b, T)*F, 23452) \\
 \vdash &((a)*b, F)*F, 234524) \\
 \vdash &((a)*b, a)*F, 2345246) \\
 \vdash &(()*b,)*F, 2345246) \\
 \vdash &((*b, *F, 2345246) \\
 \vdash &((b, F, 2345246)
 \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned} G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\ T &\rightarrow T*F \mid F & (3, 4) \\ F &\rightarrow (E) \mid a \mid b & (5, 6, 7) \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned} &((a)*b, E, \varepsilon) \\ \vdash &((a)*b, T, 2) \\ \vdash &((a)*b, T*F, 23) \\ \vdash &((a)*b, F*F, 234) \\ \vdash &((a)*b, (E)*F, 2345) \\ \vdash &((a)*b, E)*F, 2345) \\ \vdash &((a)*b, T)*F, 23452) \\ \vdash &((a)*b, F)*F, 234524) \\ \vdash &((a)*b, a)*F, 2345246) \\ \vdash &(()*b,)*F, 2345246) \\ \vdash &((*b, *F, 2345246) \\ \vdash &((b, F, 2345246) \\ \vdash &((\textcolor{red}{b}, \textcolor{red}{b}, 23452467) \end{aligned}$$

Example 5.13

Grammar for
arithmetic expressions
(cf. Example 5.10):

$$\begin{aligned}
 G_{AE} : E &\rightarrow E+T \mid T & (1, 2) \\
 T &\rightarrow T*F \mid F & (3, 4) \\
 F &\rightarrow (E) \mid a \mid b & (5, 6, 7)
 \end{aligned}$$

Leftmost analysis of $(a)*b$:

$$\begin{aligned}
 &((a)*b, E, \varepsilon) \\
 \vdash &((a)*b, T, 2) \\
 \vdash &((a)*b, T*F, 23) \\
 \vdash &((a)*b, F*F, 234) \\
 \vdash &((a)*b, (E)*F, 2345) \\
 \vdash &((a)*b, E)*F, 2345) \\
 \vdash &((a)*b, T)*F, 23452) \\
 \vdash &((a)*b, F)*F, 234524) \\
 \vdash &((a)*b, a)*F, 2345246) \\
 \vdash &(()*b,)*F, 2345246) \\
 \vdash &((*b, *F, 2345246) \\
 \vdash &((b, F, 2345246) \\
 \vdash &((b, b, 23452467) \\
 \vdash &((\varepsilon, \varepsilon, \textcolor{red}{23452467})
 \end{aligned}$$