



## 3. Syntax Analysis

Andrea Polini

Formal Languages and Compilers  
Master in Computer Science  
University of Camerino

# ToC

- 1 Syntax Analysis: the problem
- 2 Theoretical Background
- 3 Syntax Analysis: solutions
  - Top-Down parsing
  - Bottom-Up Parsing

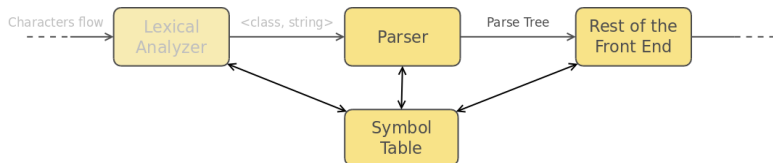
# Syntax analysis

## Parsing

Parsing is the activity of taking a string of terminals and **figuring out how to derive it from the start symbol** of the grammar, and if it cannot be derived from the start symbol of the grammar, then reporting syntax errors within the string.

## The Parser

The parser obtains a sequence of tokens and **verifies that the sequence can be correctly generated by the grammar for the source language**. For well-formed programs the parser will generate a **parse tree** that will be passed to the next compiler stage.



# Parse Tree

## Parse tree

A parse tree show how the start symbol of a grammar derives the string in the language. If  $A \rightarrow XYZ$  is a production applied in a derivation the parse tree will have an interior node labeled  $A$  with three children labeled  $X, Y, Z$  from left to right:

- ▶ root is always labeled with the start symbols
- ▶ leaves are labeled with terminals or  $\epsilon$
- ▶ interior nodes are labeled with non terminal symbols
- ▶ parent-children relations among node are dependent from the rule defined by the grammar

# Parsing Example

## Expressions grammar I

$$E \rightarrow E + E \mid E - E \mid E * E \mid E / E \mid (E) \mid id$$

Find the sequence or productions for the string “*id + id \* id*” and derive the corresponding parse tree

## Expressions grammar II

$$E \rightarrow E + T \mid E - T \mid T$$

$$T \rightarrow T * F \mid T / F \mid F$$

$$F \rightarrow (E) \mid id$$

# Parsing Example

## Expressions grammar I

$$E \rightarrow E + E \mid E - E \mid E * E \mid E / E \mid (E) \mid id$$

Find the sequence or productions for the string “ $id + id * id$ ” and derive the corresponding parse tree

## Expressions grammar II

$$E \rightarrow E + T \mid E - T \mid T$$

$$T \rightarrow T * F \mid T / F \mid F$$

$$F \rightarrow (E) \mid id$$

# Type of parsers

Three general type of parsers:

- ▶ universal (any kind of grammar)
- ▶ top-down
- ▶ bottom-up

# ToC

- 1 Syntax Analysis: the problem
- 2 Theoretical Background**
- 3 Syntax Analysis: solutions
  - Top-Down parsing
  - Bottom-Up Parsing



# Chomsky Hierarchy

A hierarchy of grammars can be defined imposing constraints on the structure of the productions in set  $\mathcal{P}$  ( $\alpha, \beta, \gamma \in \mathcal{V}^*$ ,  $a \in \mathcal{V}_T$ ,  $A, B \in \mathcal{V}_N$ ):

## T0. Unrestricted Grammars:

- Production Schema: *no constraints*
- Recognizing Automaton: **Turing Machines**

## T1. Context Sensitive Grammars:

- Production Schema:  $\alpha A \beta \rightarrow \alpha \gamma \beta$
- Recognizing Automaton: **Linear Bound Automaton (LBA)**

## T2. Context-Free Grammars:

- Production Schema:  $A \rightarrow \gamma$
- Recognizing Automaton: **Non-deterministic Push-down Automaton**

## T3. Regular Grammars:

- Production Schema:  $A \rightarrow a$  or  $A \rightarrow aB$
- Recognizing Automaton: **Finite State Automaton**

# Grammar Definition

## Context Free Grammar

A **Context Free Grammar** is given by a tuple  $\mathcal{G} = \langle \mathcal{V}_T, \mathcal{V}_N, \mathcal{S}, \mathcal{P} \rangle$  where:

- ▶  $\mathcal{V}_T$ : finite and non empty set of terminal symbols (alphabet)
- ▶  $\mathcal{V}_N$ : finite set of non terminal symbols s.t.  $\mathcal{V}_N \cap \mathcal{V}_T = \emptyset$
- ▶  $\mathcal{S}$ : start symbol of the grammar s.t.  $\mathcal{S} \in \mathcal{V}_N$
- ▶  $\mathcal{P}$ : is the set of productions s.t.  $\mathcal{P} \subseteq \mathcal{V}_N \times \mathcal{V}^*$  where  $\mathcal{V}^* = \mathcal{V}_T \cup \mathcal{V}_N$

# Push-down Automata

## Definition

A Push-down Automaton is a tuple  $\langle \Sigma, \Gamma, Z_0, \mathcal{S}, s_0, \mathcal{F}, \delta \rangle$  where:

- ▶  $\Sigma$  defines the input alphabet
- ▶  $\Gamma$  defines the alphabet for the stack
- ▶  $Z_0 \in \Gamma$  is the symbol used to represent the empty stack
- ▶  $\mathcal{S}$  represents the set of states
- ▶  $s_0 \in \mathcal{S}$  is the initial state of the automaton
- ▶  $\mathcal{F} \subseteq \mathcal{S}$  is the set of final states
- ▶  $\delta : \mathcal{S} \times (\Sigma \cup \{\epsilon\}) \times \Gamma \rightarrow \dots$  represents the transition function

## Deterministic vs. Non-Deterministic

Push-down automata can be defined according to a deterministic strategy or a non-deterministic one. In the first case the transition function returns elements in the set  $\mathcal{S} \times \Gamma^*$ , in the second case the returned element belongs to the set  $\mathcal{P}(\mathcal{S} \times \Gamma^*)$

# Push-down Automata - How do they proceed?

## Intuition

- ▶ The automaton starts with an **empty stack** and a **string to read**
- ▶ On the base of its **status** (state, symbol at the top of the stack), and of the **character at the beginning of the input string** it changes its status consuming the character from the input string.
- ▶ The status change consists in the **insertion of one or more symbol in the stack** after having removed the one at the top, and in the **transition to another internal state**
- ▶ the string is accepted when all the symbols in the input stream have been considered and the automaton reach a status in which the **state is final or the stack is empty**

# Push-down Automata

## Configuration

Given a Push-down Automaton  $\mathcal{A} = \langle \Sigma, \Gamma, Z_0, \mathcal{S}, s_0, \mathcal{F}, \delta \rangle$  a configuration is given by the tuple  $\langle s, x, \gamma \rangle$  where:

- ▶  $s \in \mathcal{S}, x \in \Sigma^*, \gamma \in \Gamma^*$

The configuration of an automaton represent its global state and contains the information to know its future states.

## Transition

Given  $\mathcal{A} = \langle \Sigma, \Gamma, Z_0, \mathcal{S}, s_0, \mathcal{F}, \delta \rangle$  and two configurations  $\chi = \langle s, x, \gamma \rangle$  and  $\chi' = \langle s', x', \gamma' \rangle$  it can happen that the automaton passes from the first configuration to the second ( $\chi \vdash_{\mathcal{A}} \chi'$ ) iff:

- ▶  $\exists a \in \Sigma. x = ax'$
- ▶  $\exists Z \in \Gamma, \eta, \sigma \in \Gamma^*. \gamma = Z\eta \wedge \gamma' = \sigma\eta$
- ▶  $\delta(s, a, Z) = (s', \sigma)$

# Push-down Automata

## Acceptance by empty stack

Given  $\mathcal{A} = \langle \Sigma, \Gamma, Z_0, \mathcal{S}, s_0, \mathcal{F}, \delta \rangle$  a configuration  $\chi = \langle s, x, \gamma \rangle$  accepts a string iff  $x = \gamma = \epsilon$

## Acceptance by final state

Given  $\mathcal{A} = \langle \Sigma, \Gamma, Z_0, \mathcal{S}, s_0, \mathcal{F}, \delta \rangle$  a configuration  $\chi = \langle s, x, \gamma \rangle$  accepts a string iff  $x = \epsilon$  and  $s \in \mathcal{F}$

# Push-down Automata - Exercise

- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{a^n b^n \mid n \in \mathbb{N}^+\}$
- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{w\bar{w} \mid w \in \{a, b\}^+\}$
- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{a^n b^m c^{2n} \mid n \in \mathbb{N}^+ \wedge m \in \mathbb{N}\}$

# Push-down Automata - Exercise

- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{a^n b^n | n \in \mathbb{N}^+\}$
- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{w\bar{w} | w \in \{a, b\}^+\}$
- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{a^n b^m c^{2n} | n \in \mathbb{N}^+ \wedge m \in \mathbb{N}\}$



# Push-down Automata - Exercise

- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{a^n b^n \mid n \in \mathbb{N}^+\}$
- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{w\bar{w} \mid w \in \{a, b\}^+\}$
- ▶ Define a push-down automaton that accept the language  $\mathcal{L} = \{a^n b^m c^{2n} \mid n \in \mathbb{N}^+ \wedge m \in \mathbb{N}\}$

# Derivations

## Derivation

The construction of a parse tree can be made precise by taking a derivational view, in which **production are considered as rewriting rules**.

A sentence belongs to a language if there is a **derivation from the initial symbol to the sentence**.

e.g.  $E \rightarrow E + E | E * E | - E | (E) | \mathbf{id}$

## Kind of derivations

Each sentence can be generated according to two different strategies **leftmost and rightmost**. Parsers generally return one of this two derivations.

# Derivations

## Derivation

The construction of a parse tree can be made precise by taking a derivational view, in which **production are considered as rewriting rules**.

A sentence belongs to a language if there is a **derivation from the initial symbol to the sentence**.

e.g.  $E \rightarrow E + E \mid E * E \mid - E \mid (E) \mid \mathbf{id}$

## Kind of derivations

Each sentence can be generated according to two different strategies **leftmost** and **rightmost**. Parsers generally return one of this two derivations.

# Ambiguity

A grammar that produces **more than one parse tree** for some sentence is said to be ambiguous. An ambiguous grammar has **more than one left-most derivation** or **more than one rightmost derivation** for the same sentence.

## Ambiguity and Precedence of Operators

Using the simplest grammar for expressions let's derive again the parse tree for:

**id + id \* id**

Now consider the following grammar:

$$E \rightarrow E + T \mid E - T \mid T$$

$$T \rightarrow T * F \mid T / F \mid F$$

$$F \rightarrow (E) \mid \text{id}$$

## Use of ambiguous grammar

In some case it can be convenient to use ambiguous grammar, but then it is necessary to define precise disambiguating rules

# Ambiguity

A grammar that produces **more than one parse tree** for some sentence is said to be ambiguous. An ambiguous grammar has **more than one left-most derivation** or **more than one rightmost derivation** for the same sentence.

## Ambiguity and Precedence of Operators

Using the simplest grammar for expressions let's derive again the parse tree for:

**id + id \* id**

Now consider the following grammar:

$$E \rightarrow E + T \mid E - T \mid T$$

$$T \rightarrow T * F \mid T / F \mid F$$

$$F \rightarrow (E) \mid \mathbf{id}$$

## Use of ambiguous grammar

In some case it can be convenient to use ambiguous grammar, but then it is necessary to define precise disambiguating rules

# Ambiguity

A grammar that produces **more than one parse tree** for some sentence is said to be ambiguous. An ambiguous grammar has **more than one left-most derivation** or **more than one rightmost derivation** for the same sentence.

## Ambiguity and Precedence of Operators

Using the simplest grammar for expressions let's derive again the parse tree for:

**id + id \* id**

Now consider the following grammar:

$$E \rightarrow E + T \mid E - T \mid T$$

$$T \rightarrow T * F \mid T / F \mid F$$

$$F \rightarrow (E) \mid \text{id}$$

## Use of ambiguous grammar

In some case it can be convenient to use ambiguous grammar, but then it is necessary to define **precise disambiguating rules**

# Ambiguity

## Conditional statements

Consider the following grammar:

$$\begin{array}{l} stmt \rightarrow \mathbf{if\ expr\ then\ stmt} \\ \quad | \mathbf{if\ expr\ then\ stmt\ else\ stmt} \\ \quad | \mathbf{other} \end{array}$$

decide if the following sentence belongs to the generated language:

**if  $E_1$  then if  $E_2$  then  $S_1$  else  $S_2$**

# Exercises

Consider the grammar:

$$S \rightarrow SS + \mid SS * \mid a$$

and the string  $aa + a*$

- ▶ Give the leftmost derivation for the string
- ▶ Give the rightmost derivation for the string
- ▶ Give a parse tree for the string
- ▶ Is the grammar ambiguous or unambiguous?
- ▶ Describe the language generated by this grammar?

Define grammars for the following languages:

- ▶  $\mathcal{L} = \{w \in \{0, 1\}^* \mid w \text{ is palindrom}\}$
- ▶  $\mathcal{L} = \{w \in \{0, 1\}^* \mid w \text{ contains the same occurrences of 0 and 1}\}$
- ▶  $\mathcal{L} = \{w \in \{0, 1\}^* \mid w \text{ does not contain the substring } 011\}$



# Exercises

Consider the grammar:

$$S \rightarrow SS + \mid SS * \mid a$$

and the string  $aa + a*$

- ▶ Give the leftmost derivation for the string
- ▶ Give the rightmost derivation for the string
- ▶ Give a parse tree for the string
- ▶ Is the grammar ambiguous or unambiguous?
- ▶ Describe the language generated by this grammar?

Define grammars for the following languages:

- ▶  $\mathcal{L} = \{w \in \{0, 1\}^* \mid w \text{ is palindrom}\}$
- ▶  $\mathcal{L} = \{w \in \{0, 1\}^* \mid w \text{ contains the same occurrences of 0 and 1}\}$
- ▶  $\mathcal{L} = \{w \in \{0, 1\}^* \mid w \text{ does not contain the substring } 011\}$

CF grammars are capable to describe most, **but not all**, of the syntax of programming languages. For instance, the requirement that **identifiers must be declared before their usage cannot be expressed** in CF grammar.

So what we can do?

## Ambiguity

- Many languages admit both ambiguous and unambiguous grammars, while some languages admit only ambiguous grammars.

CF grammars are capable to describe most, **but not all**, of the syntax of programming languages. For instance, the requirement that **identifiers must be declared before their usage cannot be expressed** in CF grammar.

So what we can do?

## Ambiguity

- ▶ Many languages admit both ambiguous and unambiguous grammars, while some languages admit only ambiguous grammars
- ▶ A language that only admits ambiguous grammars is called an inherently ambiguous language
- ▶ A Turing machine cannot decide whether a context-free language is ambiguous or not

CF grammars are capable to describe most, **but not all**, of the syntax of programming languages. For instance, the requirement that **identifiers must be declared before their usage cannot be expressed** in CF grammar.

So what we can do?

## Ambiguity

- ▶ Many languages admit both ambiguous and unambiguous grammars, while **some languages admit only ambiguous grammars**
- ▶ A language that only admits ambiguous grammars is called an inherently ambiguous language
- ▶ A Turing machine cannot decide whether a context-free language is ambiguous or not

CF grammars are capable to describe most, **but not all**, of the syntax of programming languages. For instance, the requirement that **identifiers must be declared before their usage cannot be expressed** in CF grammar.

So what we can do?

## Ambiguity

- ▶ Many languages admit both ambiguous and unambiguous grammars, while **some languages admit only ambiguous grammars**
- ▶ A language that only admits ambiguous grammars is called an **inherently ambiguous language**
- ▶ A Turing machine cannot decide whether a context-free language is ambiguous or not

CF grammars are capable to describe most, **but not all**, of the syntax of programming languages. For instance, the requirement that **identifiers must be declared before their usage cannot be expressed** in CF grammar.

So what we can do?

## Ambiguity

- ▶ Many languages admit both ambiguous and unambiguous grammars, while **some languages admit only ambiguous grammars**
- ▶ A language that only admits ambiguous grammars is called an **inherently ambiguous language**
- ▶ A Turing machine cannot decide whether a context-free language is ambiguous or not

# ToC

- 1 Syntax Analysis: the problem
- 2 Theoretical Background
- 3 Syntax Analysis: solutions**
  - Top-Down parsing
  - Bottom-Up Parsing

# ToC

- 1 Syntax Analysis: the problem
- 2 Theoretical Background
- 3 Syntax Analysis: solutions**
  - **Top-Down parsing**
  - Bottom-Up Parsing



# Left Recursion

## Left recursive grammars

A grammar  $\mathcal{G}$  is **left recursive** if it has a non terminal  $A$  such that there is a derivation  $A \xrightarrow{*} A\alpha$  for some string  $\alpha$ . **Top-down parsing strategies cannot handle left-recursive grammars**

## Immediate left recursion

A grammar has an immediate left recursion if there is a production of the form  $A \rightarrow A\alpha$ . It is possible to transform the grammar still generating the same language and removing the left recursion. Consider the general case  $A \rightarrow A\alpha|\beta$  an equivalent non recursive grammar is:

$$\begin{aligned} A &\rightarrow \beta A' \\ A' &\rightarrow \alpha A' | \epsilon \end{aligned}$$

$$\begin{aligned} S &\rightarrow Aa | b \\ A &\rightarrow Ac | Sd | \epsilon \end{aligned}$$

# Left Recursion

## Left recursive grammars

A grammar  $\mathcal{G}$  is **left recursive** if it has a non terminal  $A$  such that there is a derivation  $A \xrightarrow{*} A\alpha$  for some string  $\alpha$ . **Top-down parsing strategies cannot handle left-recursive grammars**

## Immediate left recursion

A grammar has an **immediate left recursion** if there is a production of the form  $A \rightarrow A\alpha$ . It is possible to transform the grammar still generating the same language and removing the left recursion. Consider the general case  $A \rightarrow A\alpha|\beta$  an equivalent non recursive grammar is:

$$\begin{aligned} A &\rightarrow \beta A' \\ A' &\rightarrow \alpha A' | \epsilon \end{aligned}$$

$$\begin{aligned} S &\rightarrow Aa | b \\ A &\rightarrow Ac | Sd | \epsilon \end{aligned}$$

# Left Recursion

## Left recursive grammars

A grammar  $\mathcal{G}$  is **left recursive** if it has a non terminal  $A$  such that there is a derivation  $A \xrightarrow{*} A\alpha$  for some string  $\alpha$ . **Top-down parsing strategies cannot handle left-recursive grammars**

## Immediate left recursion

A grammar has an **immediate left recursion** if there is a production of the form  $A \rightarrow A\alpha$ . It is possible to transform the grammar still generating the same language and removing the left recursion. Consider the general case  $A \rightarrow A\alpha|\beta$  an equivalent non recursive grammar is:

$$\begin{aligned} A &\rightarrow \beta A' \\ A' &\rightarrow \alpha A' | \epsilon \end{aligned}$$

$$\begin{aligned} S &\rightarrow Aa | b \\ A &\rightarrow Ac | Sd | \epsilon \end{aligned}$$

# Eliminating Left Recursion

The following is a general algorithm to eliminate left recursion at any level

**Input:** Grammar  $G$  with no cycles or  $\epsilon$  – *productions*

**Output:** An equivalent grammar with no left recursion

Arrange the non terminals in some order  $A_1, A_2, \dots, A_n$

**for all**  $i \in [1 \dots n]$  **do**

**for all**  $j \in [1 \dots i - 1]$  **do**

        replace each production of the form  $A_i \rightarrow A_j \gamma$  by the  
        productions  $A_i \rightarrow \delta_1 \gamma | \delta_2 \gamma | \dots | \delta_k \gamma$  where  $A_j \rightarrow \delta_1 | \delta_2 | \dots | \delta_k$  are all current  
         $A_j$  – *productions*

**end for**

        eliminate the immediate left recursion among the  $A_i$  – *productions*

**end for**

# Left Factoring

## Left Factoring

**Left Factoring** is a grammar transformation that is useful for producing a grammar suitable for predictive, or top-down, parsing. When the choice between two alternative productions is not clear, we may be able to rewrite the productions to defer the decision until enough of the input has been seen that we can make the right choice

### Transformation rule

In general the grammar:

$$A \rightarrow \alpha\beta_1 \mid \alpha\beta_2$$

can be rewritten in:

$$\begin{aligned} A &\rightarrow \alpha A' \\ A' &\rightarrow \beta_1 \mid \beta_2 \end{aligned}$$

In general find the longest prefix and then iterate till no two alternatives for a nonterminal have a common prefix

# Left Factoring

## Left Factoring

**Left Factoring** is a grammar transformation that is useful for producing a grammar suitable for predictive, or top-down, parsing. When the choice between two alternative productions is not clear, we may be able to rewrite the productions to defer the decision until enough of the input has been seen that we can make the right choice

## Transformation rule

In general the grammar:

$$A \rightarrow \alpha\beta_1 \mid \alpha\beta_2$$

can be rewritten in:

$$\begin{aligned} A &\rightarrow \alpha A' \\ A' &\rightarrow \beta_1 \mid \beta_2 \end{aligned}$$

In general find the longest prefix and then iterate till no two alternatives for a nonterminal have a common prefix

# Top-down parsing

## Top-down parsing

Top-down parsing can be viewed as the problem of constructing a parse tree for the input string starting from the root and creating the nodes of the parse tree in pre-order (depth-first). Equivalently ... finding the left-most derivation for an input string.

## Recursive descent parsing

A recursive descent (top-down) parsing consist of a set of procedures, one for each nonterminal.

### **function A**

Choose an *A-production*,  $A \rightarrow X_1 X_2 \cdots X_k$ ;

**for all**  $i \in [1 \cdots k]$  **do**

**if** ( $X_i$  is a non terminal) **then** call procedure  $X_i()$ ;

**else if** ( $X_i$  equals the current input symbol  $a$ ) **then**

        advance the input to the next symbol;

**else** an error has occurred;

**end if**

**end for**

**end function**

# Top-down parsing

Backtracking is expensive and not easy to manage. With grammar with no left-factoring and left-recursion we can do better:

## At work

At each step of a top-down parsing the key problem is that of determining the production to be applied for a nonterminal.

Let's consider the usual sentence **id + id \* id** and a suitable grammar for top-down parsing:

$$E \rightarrow TE' \quad E' \rightarrow +TE' | \epsilon \quad T \rightarrow FT' \quad T' \rightarrow *FT' | \epsilon \quad F \rightarrow (E) | \text{id}$$



# FIRST and FOLLOW sets

$FIRST(\alpha)$	set of terminals that begin strings derived from $\alpha$
$FOLLOW(A)$	set of terminals $a$ that can appear immediately to the right of $A$ in some sentential form
$nullable(X)$	it is true if it is possible to derive $\epsilon$ from $X$

## FIRST

To compute  $FIRST(X)$  for all grammar symbols  $X$ , apply the following rules until no more terminals or  $\epsilon$  can be added to any  $FIRST$  set

- 1 if  $X$  is a terminal, then  $FIRST(X) = \{X\}$
- 2 if  $X$  is a non terminal and  $X \rightarrow Y_1 Y_2 \cdots Y_k$  is a production for some  $k \geq 1$ , then place  $a$  in  $FIRST(X)$  if for some  $i$ ,  $a$  is in  $FIRST(Y_i)$ , and  $\epsilon$  is in all of  $FIRST(Y_1) \cdots FIRST(Y_{j-1})$ . If  $\epsilon$  is in  $FIRST(Y_j)$  for all  $j = 1, 2, \dots, k$  then add  $\epsilon$  to  $FIRST(X)$ . If  $Y_1$  does not derive  $\epsilon$ , then we add nothing more to  $FIRST(X)$ , but if  $Y_1 \rightarrow^* \epsilon$ , then we add  $FIRST(Y_2)$ , and so on.
- 3 if  $X \rightarrow \epsilon$  is a production, then add  $\epsilon$  to  $FIRST(X)$

It is then possible to compute  $FIRST$  for any string  $X_1 X_2 \cdots X_k$

# FIRST and FOLLOW sets

$FIRST(\alpha)$	set of terminals that begin strings derived from $\alpha$
$FOLLOW(A)$	set of terminals $a$ that can appear immediately to the right of $A$ in some sentential form
$nullable(X)$	it is true if it is possible to derive $\epsilon$ from $X$

## FIRST

To compute  $FIRST(X)$  for all grammar symbols  $X$ , apply the following rules until no more terminals or  $\epsilon$  can be added to any  $FIRST$  set

- 1 if  $X$  is a terminal, then  $FIRST(X) = \{X\}$
- 2 if  $X$  is a non terminal and  $X \rightarrow Y_1 Y_2 \cdots Y_k$  is a production for some  $k \geq 1$ , then place  $a$  in  $FIRST(X)$  if for some  $i$ ,  $a$  is in  $FIRST(Y_j)$ , and  $\epsilon$  is in all of  $FIRST(Y_1) \cdots FIRST(Y_{j-1})$ . If  $\epsilon$  is in  $FIRST(Y_j)$  for all  $j = 1, 2, \dots, k$  then add  $\epsilon$  to  $FIRST(X)$ . If  $Y_1$  does not derive  $\epsilon$ , then we add nothing more to  $FIRST(X)$ , but if  $Y_1 \rightarrow^* \epsilon$ , then we add  $FIRST(Y_2)$ , and so on.
- 3 if  $X \rightarrow \epsilon$  is a production, then add  $\epsilon$  to  $FIRST(X)$

It is then possible to compute  $FIRST$  for any string  $X_1 X_2 \cdots X_k$

# FIRST and FOLLOW sets

## *FOLLOW*

To compute  $FOLLOW(A)$  for all non terminals  $A$ , apply the following rules until nothing can be added to any  $FOLLOW$  set

- 1 Place  $\$$  in  $FOLLOW(S)$ , where  $S$  is the start symbol, and  $\$$  is the input right endmarker.
- 2 if there is a production  $A \rightarrow \alpha B \beta$ , then everything in  $FIRST(\beta)$  except  $\epsilon$  is in  $FOLLOW(B)$
- 3 if there is a production  $A \rightarrow \alpha B$ , or a production  $A \rightarrow \alpha B \beta$ , where  $FIRST(\beta)$  contains  $\epsilon$ , then everything in  $FOLLOW(A)$  is in  $FOLLOW(B)$

# FIRST and FOLLOW sets

Derive *FIRST*, *FOLLOW*, *nullable* sets for the expression grammar

Now consider the following grammar:

$$E \rightarrow TE' \quad E' \rightarrow +TE' | \epsilon \quad T \rightarrow FT' \quad T' \rightarrow *FT' | \epsilon \quad F \rightarrow (E) | id$$

# LL(1) Grammars

## LL(k)

Predictive parsing that does not need backtracking. **L** stands for **Left-to-right** second **L** stands for **Leftmost** and **K** indicates the maximum number of symbol to **lookahead** before taking a decision

Most programming constructs can be expressed using an LL(1) grammar. A grammar  $G$  is LL(1) iff whenever  $A \rightarrow \alpha | \beta$  are two distinct productions of  $G$ , the following conditions hold:

- 1 for no terminal  $a$  do both  $\alpha$  and  $\beta$  derive strings beginning with  $a$
- 2 At most one of  $\alpha$  and  $\beta$  can derive the empty string
- 3 if  $\beta \rightarrow^* \epsilon$ , then  $\alpha$  does not derive any string belonging with a terminal in  $FOLLOW(A)$ . Likewise if  $\alpha \rightarrow^* \epsilon$ , then  $\beta$  does not derive any string belonging with a terminal in  $FOLLOW(A)$

# LL(1) Grammars

## LL(k)

Predictive parsing that does not need backtracking. **L** stands for **Left-to-right** second **L** stands for **Leftmost** and **K** indicates the maximum number of symbol to **lookahead** before taking a decision

Most programming constructs can be expressed using an LL(1) grammar. A grammar  $G$  is LL(1) iff whenever  $A \rightarrow \alpha | \beta$  are two distinct productions of  $G$ , the following conditions hold:

- 1 for no terminal  $a$  do both  $\alpha$  and  $\beta$  derive strings beginning with  $a$
- 2 At most one of  $\alpha$  and  $\beta$  can derive the empty string
- 3 if  $\beta \rightarrow^* \epsilon$ , then  $\alpha$  does not derive any string belonging with a terminal in  $FOLLOW(A)$ . Likewise if  $\alpha \rightarrow^* \epsilon$ , then  $\beta$  does not derive any string belonging with a terminal in  $FOLLOW(A)$

# LL(1) - Parsing table

The parsing table is a two dimension array in which rows a nonterminal symbols and columns are terminal symbols. In each cell a production is then stored (determinism).

## Construction of the Parsing Table

**Input:** Grammar  $\mathcal{G} = \langle \mathcal{V}_T, \mathcal{V}_N, \mathcal{S}, \mathcal{P} \rangle$

**Output:** Parsing table M

**for all**  $A \rightarrow \alpha \in \mathcal{P}$  **do**

**for all**  $a \in \text{FIRST}(A)$  **do**

    add  $A \rightarrow \alpha$  to  $M[A,a]$

**end for**

**if**  $\epsilon \in \text{FIRST}(\alpha)$  **then**

**for all**  $b \in \text{FOLLOW}(A)$  **do**

      add  $A \rightarrow \alpha$  to  $M[A,b]$

**end for**

**if**  $\epsilon \in \text{FIRST}(\alpha) \wedge \$ \in \text{FOLLOW}(A)$  **then**

      add  $A \rightarrow \alpha$  to  $M[A,\$]$

**end if**

**end if**

**end for**

# FIRST and FOLLOW sets

Derive the parsing table for the expression grammar:

$$E \rightarrow TE' \quad E' \rightarrow +TE' | \epsilon \quad T \rightarrow FT' \quad T' \rightarrow *FT' | \epsilon \quad F \rightarrow (E) | id$$

	<b>FIRST</b>	<b>FOLLOW</b>	<b>Null.</b>
$E$	(, $id$	), \$	
$E'$	+	), \$	yes
$T$	(, $id$	+, ), \$	
$T'$	*	+, ), \$	yes
$F$	(, $id$	*, +, ), \$	



# Parsing table

Derive *FIRST*, *FOLLOW*, *nullable* sets and parsing table for the following grammar:

$$S \rightarrow iEtSS'|a \quad S' \rightarrow eS|\epsilon \quad E \rightarrow b$$

# Non-recursive predictive parsing

## Table-driven predictive parsing

**Input:** A string  $w$  and a parsing table  $M$  for grammar  $\mathcal{G}$

**Output:** if  $w$  is in  $\mathcal{L}(\mathcal{G})$ , a leftmost derivation of  $w$ , otherwise an error indication

set  $ip$  to point to the first symbol of  $w$ ;

set  $X$  to the top stack symbol;

**while** ( $X \neq \$$ ) **do**

**if** ( $X$  is  $a$ ) **then** pop the stack and advance  $ip$ ;

**else if** ( $X$  is a terminal) **then** error();

**else if** ( $M[X,a]$  is an error entry) **then** error();

**else if** ( $M[X,a] = X \rightarrow Y_1 Y_2 \cdots Y_k$ ) **then c**

    output the production  $X \rightarrow Y_1 Y_2 \cdots Y_k$ ;

    pop the stack;

    push  $Y_k Y_{k-1} \cdots Y_1$  onto the stack, with  $Y_1$  on top;

**end if**

  Set  $X$  to the top stack symbol;

**end while**

# LL(1) parser moves (1/2)

MATCHED	STACK	INPUT	ACTION
	E\$	<b>id + id * id</b> \$	

# LL(1) parser moves (2/2)

MATCHED	STACK	INPUT	ACTION
	S\$	ibtibtaea\$	

# Error Recovery in Predictive Parsing

## Error detection

An error is detected during predictive parsing when the terminal on top of the stack does not match the next input symbol or when nonterminal  $A$  is on top of the stack,  $a$  is the next input symbol, and  $M[A,a]$  is ERROR.

# Error Recovery in Predictive Parsing

## Error detection

An error is detected during predictive parsing when the terminal on top of the stack does not match the next input symbol or when nonterminal  $A$  is on top of the stack,  $a$  is the next input symbol, and  $M[A,a]$  is ERROR.

## Panic Mode

Based on the idea of skipping symbols on the input until a token in a synchronizing set appears. Strategies:

- ▶ place all symbols in  $FOLLOW(A)$  into the synchronizing set for nonterminal  $A$ .
- ▶ symbols starting higher level constructs
- ▶ use of  $\epsilon$ -productions to change the symbol in the stack
- ▶ just pop the symbol in the stack and send alert

# Error Recovery in Predictive Parsing

## Error detection

An error is detected during predictive parsing when the terminal on top of the stack does not match the next input symbol or when nonterminal  $A$  is on top of the stack,  $a$  is the next input symbol, and  $M[A,a]$  is ERROR.

## Phrase-level recovery

Fill the blank entries in the predictive parsing table with entries to recovery routines.

# ToC

- 1 Syntax Analysis: the problem
- 2 Theoretical Background
- 3 Syntax Analysis: solutions**
  - Top-Down parsing
  - Bottom-Up Parsing**



# Bottom-up Parsing

## Bottom-up Parsing

The problem of Bottom-up parsing can be viewed as the problem of constructing a parse tree for an input string beginning at the leaves and working up towards the root.

In particular we will consider the problem of finding the right-most derivation given an input string, through a series of reductions to reach the initial symbol

Let's consider the input string `id * id` using the simple grammar for expressions

# Bottom-up Parsing

## Bottom-up Parsing

The problem of Bottom-up parsing can be viewed as the problem of constructing a parse tree for an input string beginning at the leaves and working up towards the root.

In particular we will consider the problem of finding the right-most derivation given an input string, through a series of reductions to reach the initial symbol

Let's consider the input string **id \* id** using the simple grammar for expressions

# Tools for Bottom-up Parsing

## Reductions

In a bottom-up parser at each step a **reduction** is applied. A certain string is reduced to the non terminal applying in reverse a production. The **key decision** is when to reduce!

## Handle Pruning

A **handle** is a substring that matches the body of a production, and whose reduction represents a step in, along the reverse of a rightmost derivation.

Consider the grammar  $S \rightarrow 0S1|01$  and the two sentential forms  
000111,00S11

# Tools for Bottom-up Parsing

## Reductions

In a bottom-up parser at each step a **reduction** is applied. A certain string is reduced to the non terminal applying in reverse a production. The **key decision** is when to reduce!

## Handle Pruning

A **handle** is a substring that matches the body of a production, and whose reduction represents a step in, along the reverse of a rightmost derivation.

Consider the grammar  $S \rightarrow 0S1|01$  and the two sentential forms  
000111,00S11

# Shift-reduce parsing

## Shift-reduce parsing

A **shift-reduce** parser is a particular kind of bottom-up parser in which a stack holds grammar symbols and an input buffer holds the rest of the string to be parsed. Four possible actions are possible:

- ▶ shift
- ▶ reduce
- ▶ accept
- ▶ error

## Conflicts

- ▶ shift/reduce
- ▶ reduce/reduce

# Shift-reduce parsing

## Shift-reduce parsing

A **shift-reduce** parser is a particular kind of bottom-up parser in which a stack holds grammar symbols and an input buffer holds the rest of the string to be parsed. Four possible actions are possible:

- ▶ shift
- ▶ reduce
- ▶ accept
- ▶ error

## Conflicts

- ▶ shift/reduce
- ▶ reduce/reduce

# Shift-reduce parsing

Consider the grammar  $S \rightarrow SS + \mid SS * \mid a$  and the following sentential forms:  
 $SSS + a * +$ ,  $SS + a * a +$ ,  $aaa * a + +$

# LR Parsing

## LR Parsers

LR parsers show interesting good properties:

- ▶ all programming languages admit a grammar that can be parsed by an LR parser
- ▶ most general non-backtracking shift-reduce parser
- ▶ syntactic errors can be detected as soon as it is possible to do so on a left-to right scan of the input
- ▶ the class of grammars that can be parsed by an LR is a proper superset of that parsable with a predictive parsing strategy



# Items and LR(0) Automaton

## Item

An **Item** is a production in which a dot has been added in the body. Intitively indicates how much of a production we have seen during parsing.

One collection of sets of LR(0) items, called the **canonical LR(0)** collection, provides the basis for constructing a DFA that is used to make decisions.

The construction of the canonical LR(0) is based on two functions **CLOSURE** and **GOTO**

# CLOSURE

If  $I$  is a set of items for a grammar  $\mathcal{G}$ , then  $\text{CLOSURE}(I)$  is the set of items constructed from  $I$  by the two rules:

- 1 Initially, add every item in  $I$  to  $\text{CLOSURE}(I)$
- 2 if  $A \rightarrow \alpha \cdot B\beta$  is in  $\text{CLOSURE}(I)$  and  $B \rightarrow \gamma$  is a production, then add the item  $B \rightarrow \cdot\gamma$  to  $\text{CLOSURE}(I)$ , if it is not already there. Apply this rule until no more items can be added to  $\text{CLOSURE}(I)$

Consider the expression grammar:

$$E' \rightarrow E \quad E \rightarrow E + T \mid T \quad T \rightarrow T * F \mid F \quad F \rightarrow (E) \mid id$$

Compute the closure of the item  $E' \rightarrow \cdot E$

## GOTO

**GOTO( $I, X$ )**

**GOTO( $I, X$ )** is defined to be the closure of the set of all items  $[A \rightarrow \alpha X \cdot \beta]$  such that  $[A \rightarrow \alpha \cdot X \beta]$  is in  $I$ .

- ▶ Intuitively the **GOTO** function is used to define the transition of the LR(0) automaton for a grammar. The states of the automaton correspond to sets of items, and **GOTO( $I, X$ )** specifies the transition from the state for  $I$  under input  $X$

# Use of the LR(0) automaton

The LR(0) automaton can be used for **deriving a parsing table**, which has a number of states equal to the states of the LR(0) automaton and the actions are dependent from the action of the automaton itself. The parsing table will have two different sections, one named ACTION and the other GOTO:

## Parsing table

- 1 The ACTION table has a row for each state of the LR(0) automaton and a column for each terminal symbol. The value of  $\text{ACTION}[i, a]$  can have one of the following forms:
  - 1 **Shift  $j$**  where  $j$  is a state (generally abbreviated as  $S_j$ ).
  - 2 **Reduce  $A \rightarrow \beta$** . The action of the parser reduces  $\beta$  to  $A$  in the stack (generally abbreviated as  $R(A \rightarrow \beta)$ )
  - 3 **Accept**
  - 4 **Error**
- 2 The GOTO table has a row for each state of the LR(0) automaton and a column for each nonterminal. The value of  $\text{GOTO}[i, A] = j$  if the GOTO function maps set of items accordingly on the LR(0) automaton

# Use of the LR(0) automaton

Consider the string **id\*id** and parse it

STACK	SYMBOLS	INPUT	ACTION
0	\$	<b>id*id</b> \$	...
...	\$...	...\$	...

# LR Parsing algorithm

## General LR parsing program

The initial state of the parser is  $s_0$  for the state and  $w$  (the whole string) on the input buffer.

Let  $a$  be the first symbol of  $w\$$ ;

**while** true **do**

  let  $s$  be the state on top of the stack;

**if** ( $\text{ACTION}[s,a] = \text{shift } t$ ) **then**

    push  $t$  onto the stack;

    let  $a$  be the next input symbol;

**else if** ( $\text{ACTION}[s,a] = \text{reduce } A \rightarrow \beta$ ) **then**

    pop  $|\beta|$  off the stack;

    let state  $t$  now be on top of the stack;

    push  $\text{GOTO}[t,A]$  onto the stack;

    output the production  $A \rightarrow \beta$ ;

**else if** ( $\text{ACTION}[s,a] = \text{accept}$ ) **then break**;

**else** call error-recovery routine;

**end if**

**end while**

# LR(0) table construction

## LR(0) table

The LR(0) table is built according to the following rules, where “ $i$ ” is the considered state and “ $a$ ” a symbol in the input alphabet:

- 1 ACTION  $[i, a] \leftarrow$  shift  $j$   
if  $[A \rightarrow \alpha \cdot a\beta]$  is in state  $i$  and  $\text{GOTO}(i, a) = j - (S_j)$
- 2 ACTION  $[i, *] \leftarrow$  reduce  $(A \rightarrow \beta)$   
if state  $i$  includes the item  $(A \rightarrow \beta \cdot) - R(A \rightarrow \beta)$
- 3 ACTION  $[i, *] \leftarrow$  accept  
if the state includes the item  $S' \rightarrow S \cdot$
- 4 ACTION  $[i, *] \leftarrow$  error  
in all the other situations

Consider the following grammars and sentences:

$S \rightarrow CC$	$C \rightarrow cC d$	sentence: “ccd”
$S \rightarrow aS Ba$	$B \rightarrow Ba b$	sentence: “aaba”

# SLR table construction

## SLR(1) table

The LR(0) table is built according to the following rules, where “ $i$ ” is the considered state and “ $a$ ” a symbol in the input alphabet:

- 1 ACTION  $[i, a] \leftarrow \text{shift } j$   
if  $[A \rightarrow \alpha \cdot a\beta]$  is in state  $i$  and  $\text{GOTO}(i, a) = j$
- 2 ACTION  $[i, a] \leftarrow \text{reduce}(A \rightarrow \beta)$   
forall  $a$  in FOLLOW( $A$ ) and if state  $i$  includes the item  $(A \rightarrow \beta \cdot)$
- 3 ACTION  $[i, \$] \leftarrow \text{accept}$   
if the state includes the item  $S' \rightarrow S \cdot$
- 4 ACTION  $[i, *] \leftarrow \text{error}$   
in all the other situations

Consider the following grammars and sentences:

$S \rightarrow aS \mid Ba \quad B \rightarrow Ba \mid b$

sentence: “aaba”



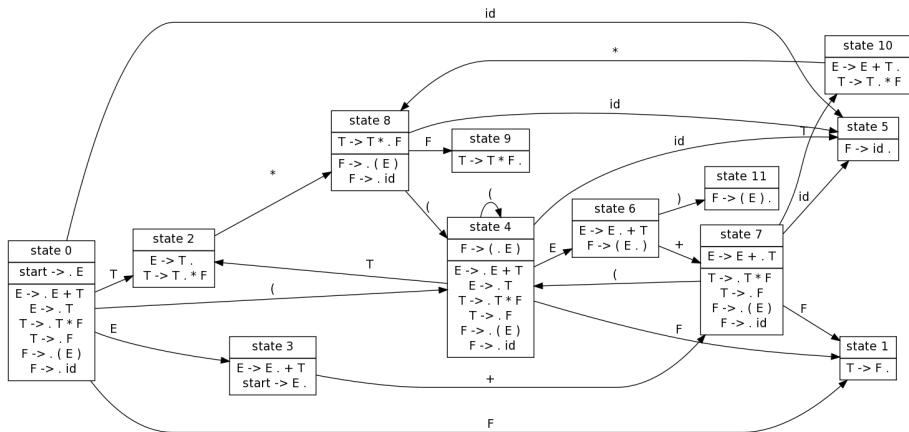
# LR(0) vs. SLR parsing

Consider the usual expression grammar:

$$E' \rightarrow E \quad E \rightarrow E + T \mid T \quad T \rightarrow T * F \mid F \quad F \rightarrow (E) \mid id$$

build LR(0) and SLR tables for the grammar, and then parse the sentence:

**id\*id+id**



<http://smlweb.cpsc.ucalgary.ca/start.html>

# Towards more powerful parsers

Consider the following grammar and derive the SLR parsing table:  
 $S \rightarrow L = R \mid R \quad L \rightarrow *R \mid id \quad R \rightarrow L$

## Viable prefix

A **Viable prefix** is a prefix of a right-sentential form that can appear on the stack of a shift-reduce parser.

We say item  $A \rightarrow \beta_1 \cdot \beta_2$  is valid for a viable prefix  $\alpha\beta_1$  if there is a derivation  $S \Rightarrow^* \alpha A w \Rightarrow \alpha\beta_1\beta_2 w$ .

# LR parsers with lookahead

In order to enlarge the class of grammars that can be parsed we need to consider more powerful parsing strategies. In particular we will study:

- ▶ LR(1) parsers
- ▶ LALR parsers

# LR(1) items

## LR(1) items structure

The very general idea is to encapsulate more information in the items of an automaton to decide when to reduce. The solution is to differentiate items on the base of lookaheads. As a result a general item follows now the template  $[A \rightarrow \alpha \cdot \beta, a]$

## LR(1) items and reductions

Given the new form on an item, the parser will call for a reduction  $A \rightarrow \alpha$  only for item sets including the item  $[A \rightarrow \alpha \cdot, a]$  and only for symbol  $a$

# LR(1) CLOSURE and GOTO functions

## Closure of an item

If  $[A \rightarrow \alpha \cdot B\beta, a]$  is an  $I$  then for each production  $B \rightarrow \gamma$  and for each terminal  $b$  in  $\text{FIRST}(\beta a)$  add the item  $[B \rightarrow \cdot \gamma, b]$

## GOTO( $I, X$ )

Let  $J$  initially empty. For each item  $[A \rightarrow \alpha \cdot X\beta, a]$  in  $I$  add item  $[A \rightarrow \alpha X \cdot \beta, a]$  to set  $J$ . Then compute  $\text{CLOSURE}(J)$

Consider the starting item as the closure of the item  $[S' \rightarrow S, \$]$ .

## Exercise

Compute the LR(1) item sets for the following grammar:

$$S \rightarrow CC \quad C \rightarrow cC|d$$

# LR(1) parsing table

## How to build the LR(1) parsing table

- 1 build the collection of sets of LR(1) items for the grammar
- 2 Parsing actions for state  $i$  are:
  - 1 if  $[A \rightarrow \alpha \cdot a\beta, b]$  is in  $I_i$  and  $\text{GOTO}(I_i, a) = I_j$  then set  $\text{ACTION}[i, a]$  to shift  $J$ .
  - 2 if  $[A \rightarrow \alpha \cdot, a]$  is in  $I_i$   $A \neq S'$  then set  $\text{ACTION}[i, a]$  to reduce( $A \rightarrow \alpha$ )
  - 3 if  $[S' \rightarrow S \cdot, \$]$  is in  $I_i$  then set  $\text{ACTION}[i, \$]$  to accept
- 3 if  $\text{GOTO}(I_i, A) = I_j$  then  $\text{GOTO}[i, A] = j$
- 4 All entries not defined so far are marked "error"
- 5 The initial state of the parse is the one constructed from the set of items containing  $[S' \rightarrow \cdot S, \$]$

Consider the following grammar and derive the LR(1) parsing table:

$$S \rightarrow L = R \mid R \quad L \rightarrow *R \mid id \quad R \rightarrow L$$

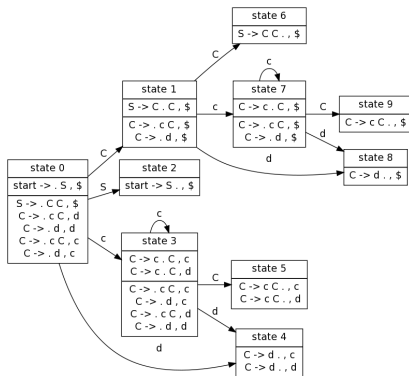
# LALR parsing

- ▶ LR(1) for a real language a SLR parser has several hundred states. For the same language an LR(1) parser has several thousand states
- ▶ Can we produce a parser with power similar to LR(1) and table dimension similar to SLR?



# LALR parsing

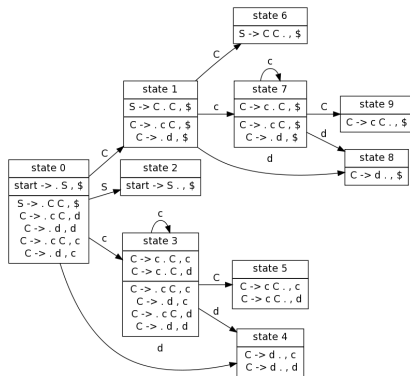
Let's consider the LR(1) automaton for the grammar

$$S \rightarrow CC \quad C \rightarrow cC|d$$


LALR table can be built from LR(1) automaton merging "similar" item sets.

# LALR parsing

Let's consider the LR(1) automaton for the grammar

$$S \rightarrow CC \quad C \rightarrow cC|d$$


LALR table can be built from LR(1) automaton merging “similar” item sets.

# Exercises

Consider the grammar:

$$S \rightarrow Aa|bAc|dc|bda \quad A \rightarrow d$$

show that is LALR(1) but not SLR(1)

Consider the grammar:

$$S \rightarrow Aa|bAc|Bc|bBa \quad A \rightarrow d \quad B \rightarrow d$$

show that is LR(1) but not LALR(1)

# Exercises

Consider the grammar:

$$S \rightarrow Aa|bAc|dc|bda \quad A \rightarrow d$$

show that is LALR(1) but not SLR(1)

Consider the grammar:

$$S \rightarrow Aa|bAc|Bc|bBa \quad A \rightarrow d \quad B \rightarrow d$$

show that is LR(1) but not LALR(1)