CS 335: Syntax Analysis

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Semester 2022-2023-II
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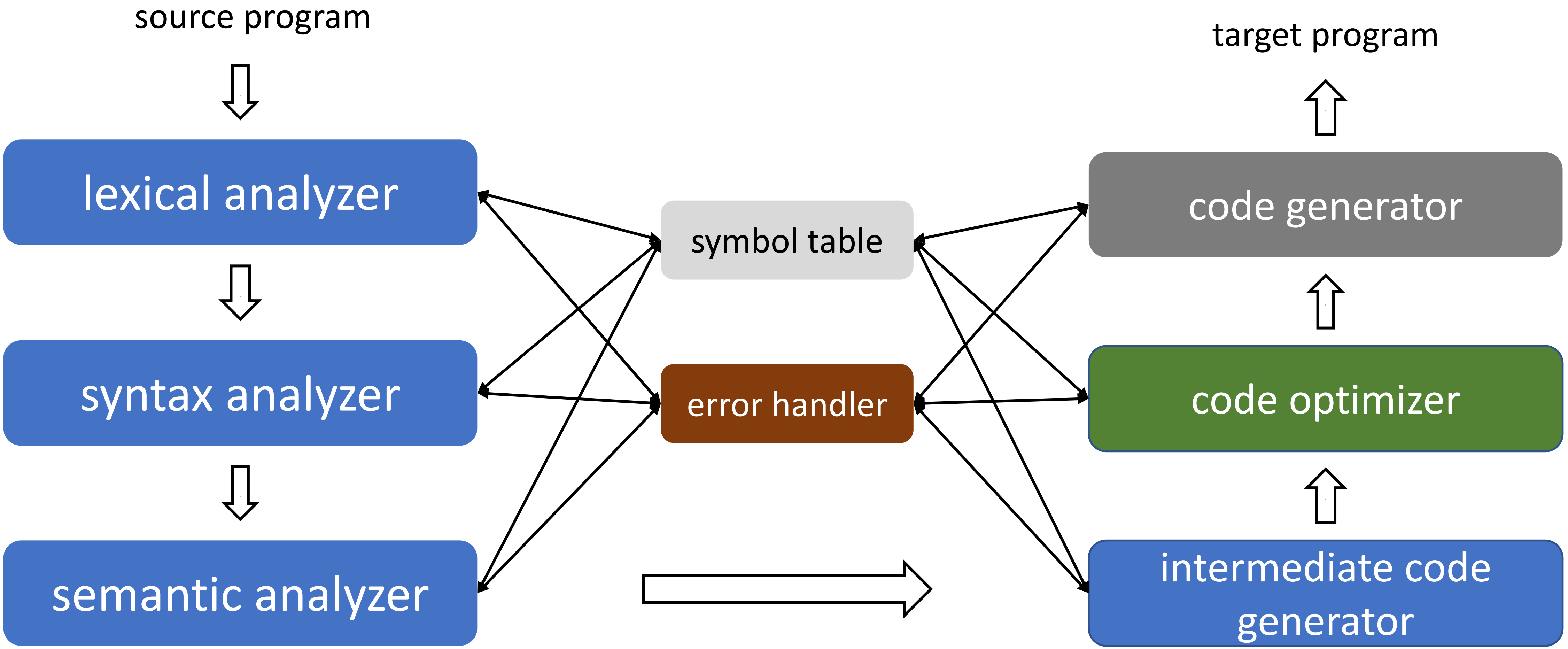
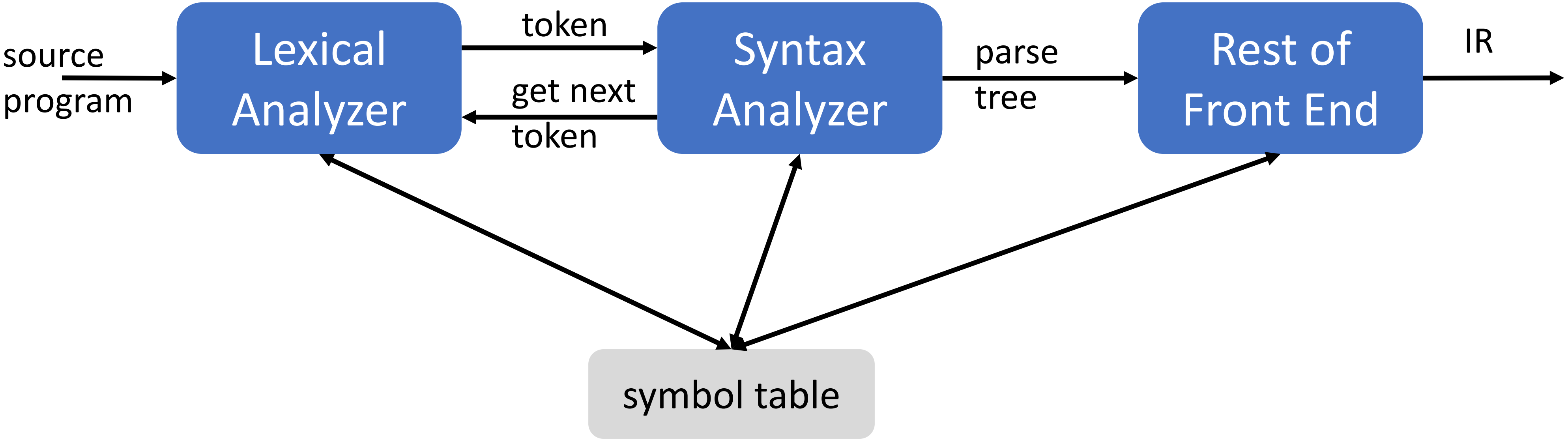
Content influenced by many excellent references, see References slide for acknowledgements.

An Overview of Compilation



Parser Interface



Need for Checking Syntax

- Given an input program, scanner generates a **stream of tokens** classified according to the syntactic category
- The parser determines if the input program, represented by the token stream, is a **valid sentence** in the programming language
- The parser attempts to **build a derivation** for the input program, using a grammar for the programming language
    - If the input stream is a valid program, parser builds a valid model for later phases
    - If the input stream is invalid, parser reports the problem and diagnostic information to the user

Syntax Analysis

- Given a programming language grammar G and a stream of tokens s, parsing tries to find a derivation in G that produces s
- In addition, a syntax analyser
    i. Forwards the information as IR to the next compilation phases
    ii. Handle errors if the input string is not in $L(G)$

Context-Free Grammars

- A context-free grammar (CFG) G is a quadruple (T, NT, S, P)

T	Set of terminal symbols (also called words) in the language $L(G)$. A terminal symbol is a word that can occur in a sentence, and correspond to syntactic categories returned by the scanner.
NT	Set of nonterminal symbols that appear in the productions of G. Nonterminals are syntactic variables that provide abstraction and structure in the productions.
S	Goal or start symbol of the grammar G. S represents the set of sentences in $L(G)$.
P	Set of productions (or rules) in G. Each rule in P is of the form $NT \rightarrow (T \cup NT)^*$.

Definitions

- Derivation is a a sequence of rewriting steps that begins with the grammar G's start symbol and ends with a sentence in the language

$$S \overset{+}{\Rightarrow} w \text{ where } w \in L(G)$$

- At each point during derivation process, the string is a collection of terminal or nonterminal symbols

$$\alpha A\beta \rightarrow \alpha\gamma\beta \text{ if } A \rightarrow \gamma$$

  - Such a string is called a **sentential form** if it occurs in some step of a valid derivation
  - A sentential form can be derived from the start symbol in zero or more steps

Example of a CFG

CFG

$Expr \rightarrow (\ Expr\ )$

$\quad\quad \mid Expr\ Op\ \text{name}$

$\quad\quad \mid \text{name}$

$Op \rightarrow + \mid - \mid \times \mid \div$

$(\boldsymbol{a} + \boldsymbol{b}) \times \boldsymbol{c}$

$Expr \rightarrow Expr\ Op\ \text{name}$

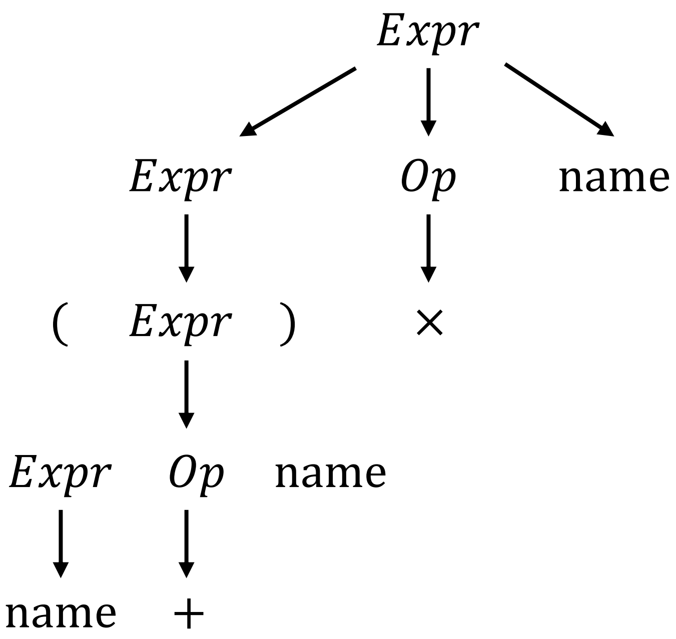
$\quad \rightarrow Expr \times \text{name}$

$\quad \rightarrow (Expr) \times \text{name}$

$\quad \rightarrow (Expr\ Op\ \text{name}) \times \text{name}$

$\quad \rightarrow (Expr + \text{name}) \times \text{name}$

$\quad \rightarrow (\text{name} + \text{name}) \times \text{name}$



Parse Tree

Parse Tree

- A parse tree is a **graphical representation of a derivation**
  - Root is labeled with the start symbol S
  - Each internal node is a nonterminal, and represents the application of a production
  - Leaves are labeled by terminals and constitute a sentential form, read from left to right, called the **yield** or **frontier** of the tree
- Parse tree filters out the order in which productions are applied to replace nonterminals, and **just represents** the rules applied

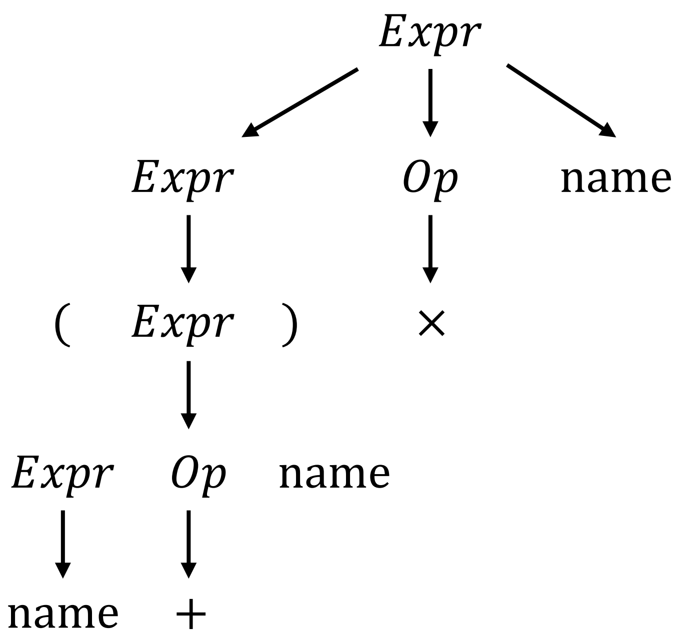
Derivations

- At each step during derivation, we have **two choices** to make
  1. Which nonterminal to rewrite?
  2. Which production rule to pick?

- A leftmost derivation rewrites the leftmost nonterminal at each step, denoted by $\alpha \underset{lm}{\Rightarrow} \beta$
  - Every leftmost derivation can be written as $wA\gamma \underset{lm}{\Rightarrow} w\delta\gamma$
- Rightmost (or canonical) derivation rewrites the rightmost nonterminal at each step, denoted by $\alpha \underset{rm}{\Rightarrow} \beta$

Leftmost Derivation

$$\begin{aligned} Expr &\rightarrow Expr\ Op\ \text{name} \\ &\rightarrow (Expr)\ Op\ \text{name} \\ &\rightarrow (Expr\ Op\ \text{name})\ Op\ \text{name} \\ &\rightarrow (\text{name}\ Op\ \text{name})\ Op\ \text{name} \\ &\rightarrow (\text{name} + \text{name})\ Op\ \text{name} \\ &\rightarrow (\text{name} + \text{name}) \times \text{name} \end{aligned}$$



Parse Tree

Ambiguous Grammars

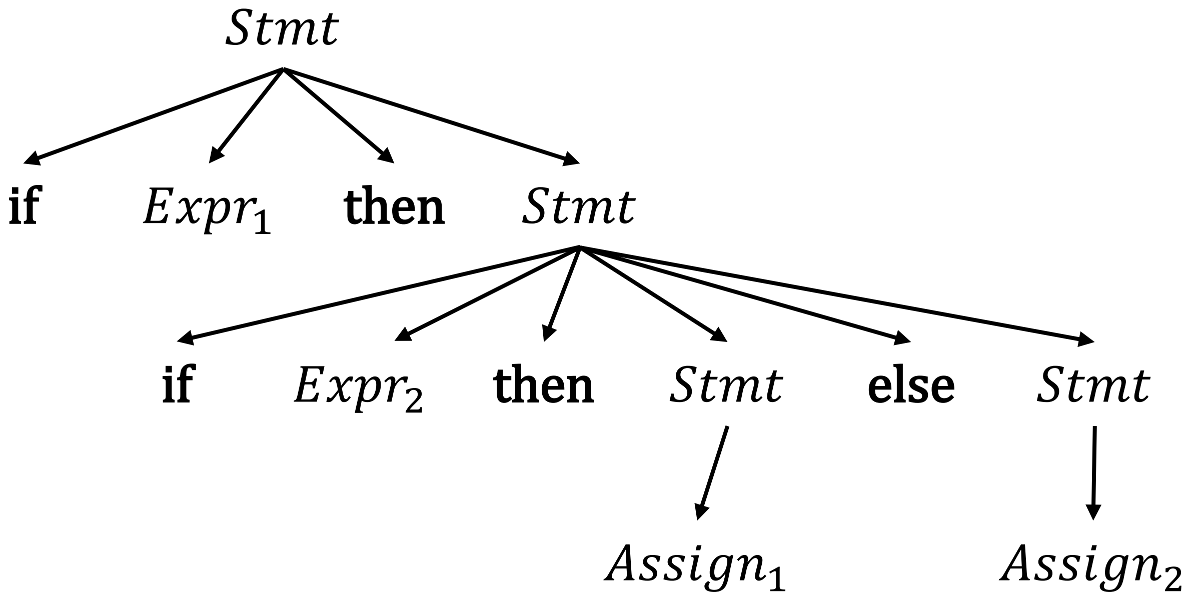
- A grammar G is ambiguous if some sentence in $L(G)$ has more than one rightmost (or leftmost) derivation

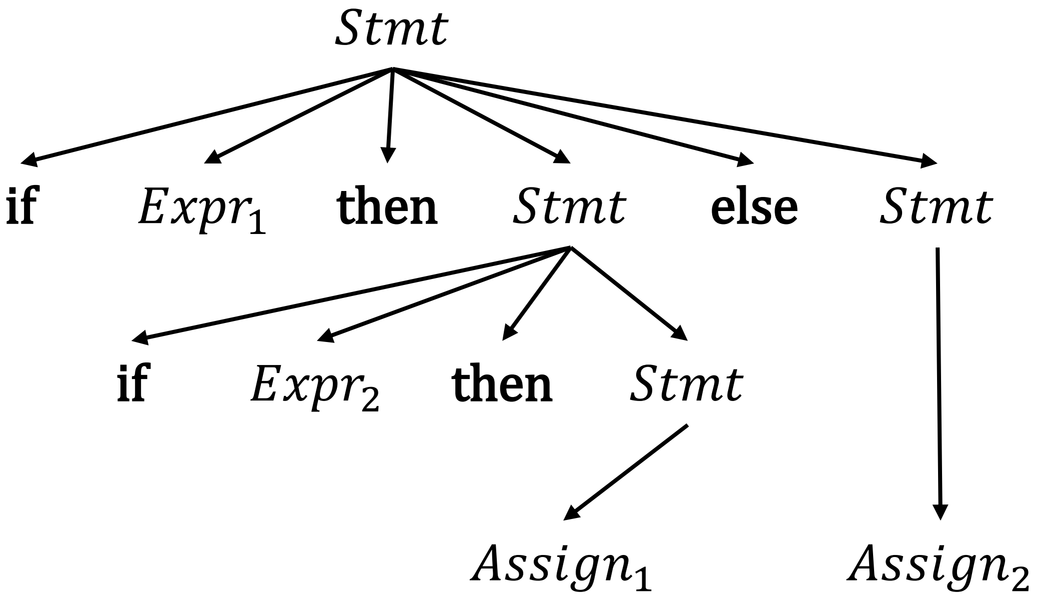
- An ambiguous grammar can produce multiple derivations and parse trees

$$
\begin{aligned}
Stmt \rightarrow\ & \textbf{if}\ Expr\ \textbf{then}\ Stmt \\
\mid\ & \textbf{if}\ Expr\ \textbf{then}\ Stmt\ \textbf{else}\ Stmt \\
\mid\ & Assign
\end{aligned}
$$

Ambiguous Dangling-Else Grammar

if $Expr_1$ **then if** $Expr_2$ **then** $Assign_1$ **else** $Assign_2$





Dealing with Ambiguous Grammars

- Compilers use parse trees to interpret the meaning of the expressions during later stages
- Ambiguous grammars are problematic for compilers since multiple parse trees can give rise to multiple interpretations

- Fixing ambiguous grammars
  1. Transform the grammar to remove the ambiguity
  2. Include rules to disambiguate during derivations (e.g., associativity and precedence)

Fixing the Ambiguous Dangling-Else Grammar

- In all programming languages, an `else` is matched with the closest `then`

$$
\begin{aligned}
Stmt &\rightarrow \textbf{if } Expr \textbf{ then } Stmt \\
&\mid \textbf{if } Expr \textbf{ then } ThenStmt \textbf{ else } Stmt \\
&\mid Assign \\
ThenStmt &\rightarrow \textbf{if } Expr \textbf{ then } ThenStmt \textbf{ else } ThenStmt \\
&\mid Assign
\end{aligned}
$$

Derivation with Fixed Dangling-Else Grammar

$$\textbf{if } Expr_1 \textbf{ then if } Expr_2 \textbf{ then } Assign_1 \textbf{ else } Assign_2$$

$$\begin{aligned}
Stmt &\rightarrow \textbf{if } Expr \textbf{ then } Stmt \\
&\rightarrow \textbf{if } Expr \textbf{ then if } Expr \textbf{ then } ThenStmt \textbf{ else } Stmt \\
&\rightarrow \textbf{if } Expr \textbf{ then if } Expr \textbf{ then } ThenStmt \textbf{ else } Assign \\
&\rightarrow \textbf{if } Expr \textbf{ then if } Expr \textbf{ then } Assign \textbf{ else } Assign
\end{aligned}$$

Interpreting the Meaning of Programs

CFG

$Expr \rightarrow (Expr)$

$\quad\quad | \; Expr \; Op \; \text{name}$

$\quad\quad | \; \text{name}$

$Op \rightarrow + \mid - \mid \times \mid \div$

$\boldsymbol{a + b \times c}$

$Expr \rightarrow Expr \; Op \; \text{name}$

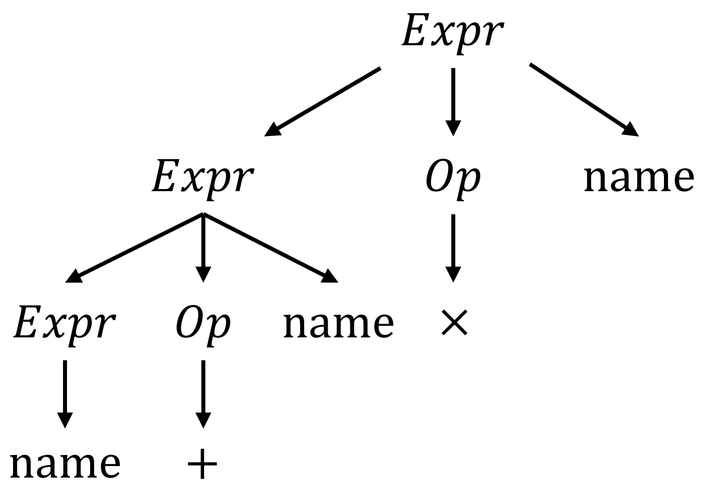
$\rightarrow Expr \times \text{name}$

$\rightarrow Expr \; Op \; \text{name} \times \text{name}$

$\rightarrow Expr + \text{name} \times \text{name}$

$\rightarrow \text{name} + \text{name} \times \text{name}$

rightmost derivation

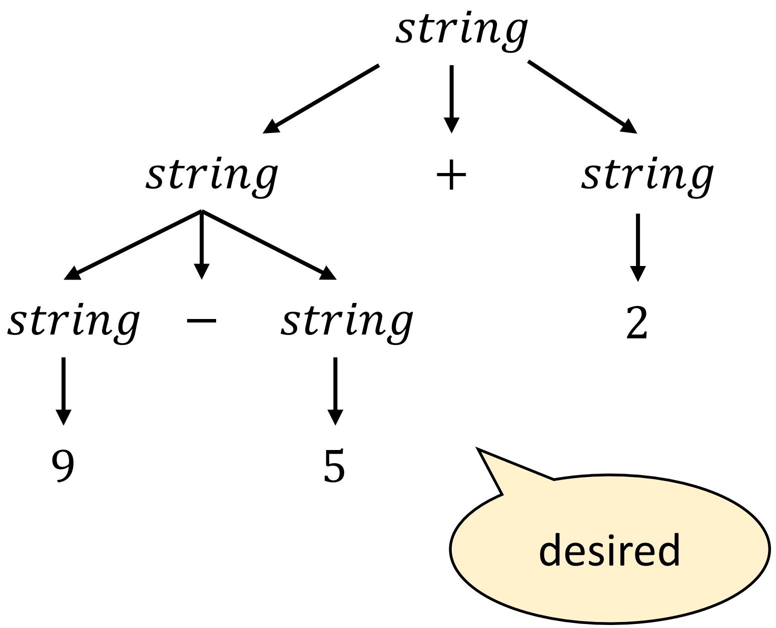


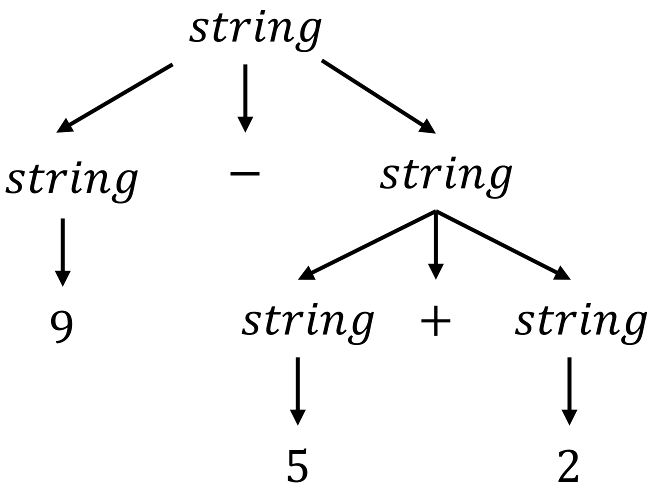
How do we evaluate the expression?

Associativity

$$string \rightarrow string + string \,|\, string - string \,|\, 0 \,|\, 1 \,|\, 2 \,|\, \dots \,|\, 9$$

$$9 - 5 + 2$$





Associativity

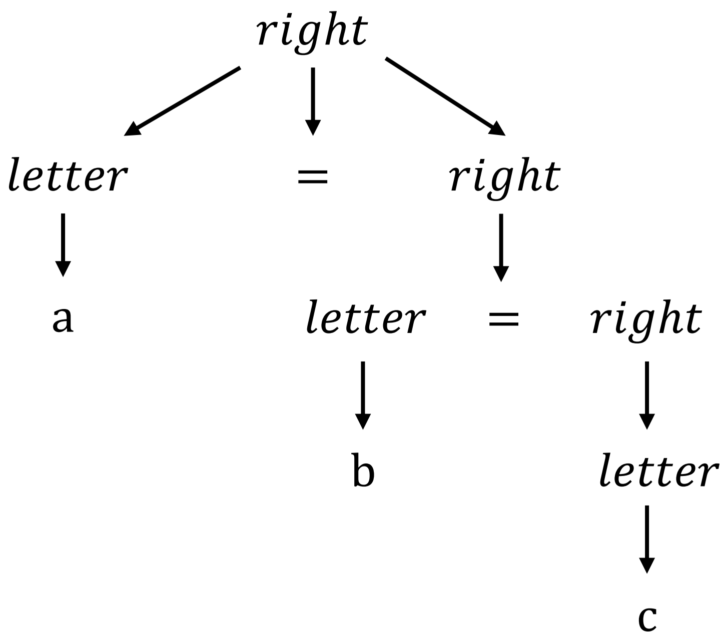
- If an operand has operator on both the sides, the **side on which operator takes this operand** is the associativity of that operator
    - E.g., +, -, *, and / are left associative and ^ and = are right associative

- Grammar to generate strings with right associative operators

$$right \rightarrow letter = right | letter$$
$$letter \rightarrow a | b | \ldots | z$$

Parse Tree for Right Associative Grammars

```
a = b = c
```



Encode Precedence into the Grammar

$$Start \rightarrow Expr$$

$$Expr \rightarrow Expr + Term \mid Expr - Term \mid Term$$

$$Term \rightarrow Term \times Factor \mid Term \div Factor \mid Factor$$

$$Factor \rightarrow (Expr) \mid \mathrm{num} \mid \mathrm{name}$$

Corresponding Parse Tree

$$\boldsymbol{a - b + c}$$

$Start \rightarrow Expr$

$\rightarrow Expr + Term$

$\rightarrow Expr + Factor$

$\rightarrow Expr + \text{ name}$

$\rightarrow Expr \; - Term + \text{name}$

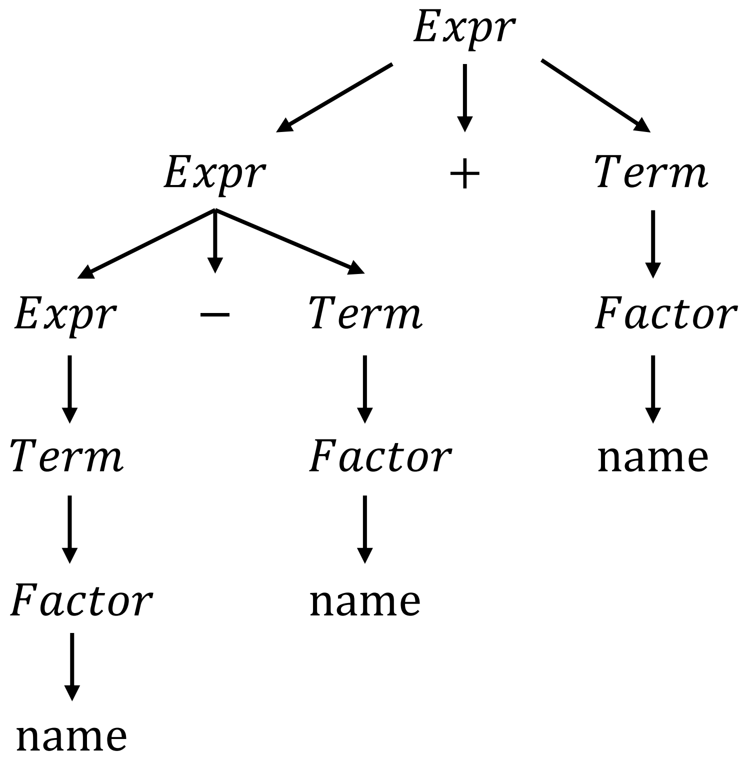
$\rightarrow Expr - Factor + \text{name}$

$\rightarrow Expr - \text{name} + \text{name}$

$\rightarrow Term - \text{name} + \text{name}$

$\rightarrow Factor - \text{name} + \text{name}$

$\rightarrow \text{name} - \text{name} + \text{name}$



Types of Parsers

Top-down

- Starts with the root and grows the parse tree toward the leaves

Bottom-up

- Starts with the leaves and grows the parse tree toward the root

Universal

- More general algorithms, but inefficient to use in production compilers

Programming Errors

- Common source of programming errors
    - Lexical errors, e.g., illegal characters and missing quotes around strings
    - Syntactic errors, e.g., misspelled keywords, misplaced semicolons, or extra or missing braces
    - Semantic errors, e.g., type mismatches between operators and operands, undeclared variables
    - Logical errors
- The scanner cannot deal with all errors, e.g., it will mark misspelled keywords as IDs

Goals in Error Handling

1. Report errors accurately
2. Recover from the error and detect subsequent errors
3. Add minimal overhead to the compilation of correct programs

- Report the source location where the error is **detected,** chances are the actual error location is close by

Error Recovery Strategies in the Parser

Panic-mode recovery

- Parser **discards input symbols** until a **synchronizing** token is found, restarts processing from the synchronizing token
- Synchronizing tokens are usually delimiters (e.g., ; or })

Phrase-level recovery

- Perform local correction on the remaining input (e.g., replace comma by semicolon)
- Can go into an infinite loop because of wrong correction, or the error may have occurred before it is detected

Handling Errors in the Parser

Error productions

- Augment the grammar with productions that generate erroneous constructs
- Works only for common mistakes and complicates the grammar

Global correction

- Given an incorrect input string x and grammar G, find a parse tree for a related string y such that the number of modifications (i.e., insertions, deletions, and changes) of tokens required to transform x into y is as small as possible

Context-Free vs Regular Grammar

- CFGs are more powerful than REs
  - Every regular language is context-free, but not vice versa
  - We can create a CFG for every NFA that simulates some RE

- Language that can be described by a CFG but not by a RE

$$\boxed{L = \{a^n b^n \mid n \geq 1\}}$$

Limitations of Syntax Analysis

- Cannot determine whether
  1. A variable has been declared before use
  2. A variable has been initialized
  3. Variables are of types on which operations are allowed
  4. Number of formal and actual arguments of a function match

- These limitations are handled during semantic analysis

References

- A. Aho et al. Compilers: Principles, Techniques, and Tools, 2nd edition, Chapters 2 and 4.
- K. Cooper and L. Torczon. Engineering a Compiler, 2nd edition, Chapter 3.