# CSE 307: Principles of Programming Languages

Syntax





## Topics







Section 1

## Intro

# Syntax Vs Semantics

- Syntax describes the structure of a program
  - Determines which programs are legal
  - Consists of two parts
    - Lexical structure: Structure of words
      Distinguish between words in the language from random strings
    - Grammar: How words are combined into programs
      Similar to how English grammar governs the structure of sentences in English
- Programs following syntactic rules may or may not be semantically correct.
  - Compare with grammatically correct but nonsensical English sentences
- Formal mechanisms used to describe syntax and semantics to ensure that a language specification is unambiguous and precise





# Meta Languages

- Formal mechanisms are used to describe all allowable programs in a language
  - Backus-Naur Form
  - Grammars
- We need *languages to define languages* (called meta-languages)
  BNFs, Grammars etc. will be described in meta languages





Section 2

# Lexical Structure

# Lexical Structure

Constants and Literals: ($6.023e + 23$, `"Enter:"`, etc.)

White space: Typically, blank, tab, or new line characters. Used to separate words, but otherwise ignored

Special Symbols: "<", ";", etc. Can be used as separator, but not ignored.

Identifiers: (`x`, `getChar`, `id_f2`)

Words with prespecified meaning: `if`, `boolean`, `class`.

- In some languages, these words could also be used as identifiers — in this case, they are called keywords as their use is not reserved.



Intro Lexical Structure Syntactic Structure Regular expressions Finite-State Automata

# Describing the Lexical Structure

**Regular Expressions are used as the meta language.**

- $(0 \mid 1 \mid \ldots \mid 9)+$

  (describes non-negative integer constants)
- Short-hand notations are often used: e.g.,
  - $[0-9]+$ (one more more occurrences of characters in range $[0-9]$)
  - $//.*$ (two slashes followed by sequence of zero or more non-newline characters) (C++-style single-line comments)





# Language of Regular Expressions

Notation to represent (potentially) infinite sets of strings over alphabet $\Sigma$.
Let $R$ be the set of all regular expressions over $\Sigma$. Then,

Empty String : $\epsilon \in R$

Unit Strings : $\alpha \in \Sigma \Rightarrow \alpha \in R$

Concatenation : $r_1, r_2 \in R \Rightarrow r_1 r_2 \in R$

Alternative : $r_1, r_2 \in R \Rightarrow (r_1 \mid r_2) \in R$

Kleene Closure : $r \in R \Rightarrow r^* \in R$

# Regular Expression

$a$ : stands for the set of strings $\{\texttt{a}\}$

$a \mid b$ : stands for the set $\{\texttt{a}, \texttt{b}\}$

- *Union* of sets corresponding to REs $a$ and $b$

$ab$ : stands for the set $\{\texttt{ab}\}$

- Analogous to set *product* on REs for $a$ and $b$
  - $(a|b)(a|b)$: stands for the set $\{\texttt{aa}, \texttt{ab}, \texttt{ba}, \texttt{bb}\}$.

$a^*$ : stands for the set $\{\epsilon, \texttt{a}, \texttt{aa}, \texttt{aaa}, \ldots\}$ that contains all strings of zero or more a's.

- Analogous to *closure* of the product operation.





# Regular Expression Examples

$(a|b)^*$ : Set of strings with zero or more a's and zero or more b's:

$\{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, \ldots\}$

$(a^*b^*)$ : Set of strings with zero or more a's and zero or more b's such that all a's occur before any b:

$\{\epsilon, a, b, aa, ab, bb, aaa, aab, abb, \ldots\}$

$(a^*b^*)^*$ : Set of strings with zero or more a's and zero or more b's:

$\{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, \ldots\}$





# Semantics of Regular Expressions

*Semantic Function $\mathcal{L}$*: Maps regular expressions to sets of strings.

$$
\begin{aligned}
\mathcal{L}(\epsilon) &= \{\epsilon\} \\
\mathcal{L}(\alpha) &= \{\alpha\} \qquad (\alpha \in \Sigma) \\
\mathcal{L}(r_1 \mid r_2) &= \mathcal{L}(r_1) \cup \mathcal{L}(r_2) \\
\mathcal{L}(r_1\ r_2) &= \mathcal{L}(r_1) \cdot \mathcal{L}(r_2) \\
\mathcal{L}(r^*) &= \{\epsilon\} \cup (\mathcal{L}(r) \cdot \mathcal{L}(r^*))
\end{aligned}
$$

# Finite State Automata

Regular expressions are used for *specification,* while FSA are used for computation. FSAs are represented by a labeled directed graph.

- A finite set of *states* (vertices).
- *Transitions* between states (edges).
- *Labels* on transitions are drawn from $\Sigma \cup \{\epsilon\}$.
- One distinguished *start* state.
- One or more distinguished *final* states.



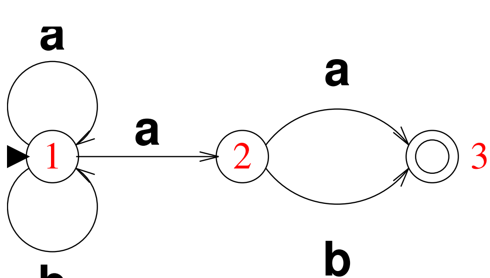


# Finite State Automata: An Example

Consider the Regular Expression $\mathbf{(a \mid b)^* a(a \mid b)}$.

$\mathcal{L}((a \mid b)^* a(a \mid b)) = \{\texttt{aa}, \texttt{ab}, \texttt{aaa}, \texttt{aab}, \texttt{baa}, \texttt{bab},$
$\texttt{aaaa}, \texttt{aaab}, \texttt{abaa}, \texttt{abab}, \texttt{baaa}, \ldots\}$.

The following (non-deterministic) automaton determines whether an input string belongs to $\mathcal{L}((a \mid b)^* a(a \mid b))$:



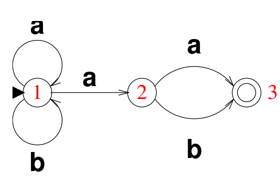




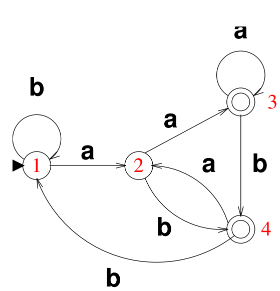

# Determinism

$\mathbf{(a \mid b)^* a(a \mid b)}$:

Nondeterministic:
(NFA)




Deterministic:
(DFA)



# Lexical Analysis

- Regular expressions describing the lexical structure are converted into a finite-state machine
- This FSM can recognize words very quickly
  - algorithm linear in the size of input program
- Efficient FSMs generated automatically from RE-based definitions
- Lex was the first lexical-analyzer generator
  - Now superceded by Flex (and other similar tools)





# Ambiguity Resolution

- Consider a language with lexical definitions

$$\begin{aligned} \textit{Integer} &::= [0-9]+ \; (i.e., [0-9][0-9]*) \\ \textit{Identifier} &::= [a-z]*([a-z]|[0-9])* \end{aligned}$$

- Consider the string "xx21"
  - Is this to be treated as a single identifier,
  - or as an identifier "xx" followed by an integer 21?
- Need disambiguation rules

  Bad: give priority to RE that occurs first in the language specification

  Better: prefer longer matches to shorter ones





## Section 3

## Syntactic Structure

# Syntactic Structure

"How to combine words to form programs"

- Context-free grammars (CFG) and Backus-Naur form (BNF)
  - terminals
  - nonterminals
  - productions of the form nonterminal *rightarrow* sequence of terminals and nonterminals
- EBNF and syntax diagrams





# Syntactic (phrase) structure

Context-Free Grammars:

$$\begin{aligned} E &\rightarrow E + E \\ E &\rightarrow E * E \\ E &\rightarrow \texttt{num} \end{aligned}$$

- $E$: Non-terminal symbol
- $\texttt{num}$, +: Terminal symbol
- $E \rightarrow \texttt{num}$: Grammar "rule" or *production*
- $\mathcal{L}(E)$: set of strings that can be derived from $E$ (Language of $E$)





# Grammars and Derivations

$$\begin{aligned} \langle sent \rangle &\rightarrow \langle np \rangle\ \langle vp \rangle \\ \langle np \rangle &\rightarrow \langle art \rangle\ \langle noun \rangle \\ \langle art \rangle &\rightarrow \texttt{a} \mid \texttt{the} \\ \langle noun \rangle &\rightarrow \texttt{student} \mid \texttt{test} \\ \langle vp \rangle &\rightarrow \langle verb \rangle\ \langle np \rangle \\ \langle verb \rangle &\rightarrow \texttt{takes} \mid \texttt{ruins} \end{aligned}$$

$$\begin{aligned} \langle sent \rangle &\Rightarrow \langle np \rangle\ \langle vp \rangle \\ &\Rightarrow \langle art \rangle\ \langle noun \rangle\ \langle vp \rangle \\ &\Rightarrow \texttt{the}\ \langle noun \rangle\ \langle vp \rangle \\ &\Rightarrow \texttt{the test}\ \langle vp \rangle \\ &\vdots \\ \langle sent \rangle &\Rightarrow \langle np \rangle\ \langle vp \rangle \\ &\Rightarrow \langle np \rangle\ \langle verb \rangle\ \langle np \rangle \\ &\Rightarrow \langle np \rangle\ \langle \texttt{ruins} \rangle\ \langle np \rangle \\ &\Rightarrow \langle np \rangle\ \langle \texttt{ruins} \rangle\ \langle art \rangle\ \langle noun \rangle \\ &\Rightarrow \langle np \rangle\ \langle \texttt{ruins} \rangle\ \langle art \rangle\ \texttt{student} \\ &\vdots \end{aligned}$$

# Ambiguity

$$E \rightarrow E - E$$
$$E \rightarrow \texttt{num}$$

| | | | | |
|---|---|---|---|---|
| num | - | num | - | num |
| $E$ | - | num | - | num |
| $E$ | - | $E$ | - | num |
| | | $E$ | - | num |
| | | $E$ | - | $E$ |
| | | $E$ | | |

5 - 3 - 1 ≡ (5-3)-1

| | | | | |
|---|---|---|---|---|
| num | - | num | - | num |
| num | - | num | - | $E$ |
| num | - | $E$ | - | $E$ |
| num | - | $E$ | | |
| $E$ | − | $E$ | | |
| | | $E$ | | |

5 - 3 - 1 ≡ 5-(3-1)

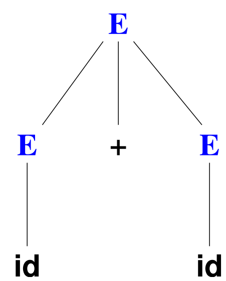




# Parse Trees

Graphical Representation of Derivations

$$E \Longrightarrow E + E \Longrightarrow \texttt{id} + E \Longrightarrow \texttt{id} + \texttt{id}$$




$$E \Longrightarrow E + E \Longrightarrow E + \texttt{id} \Longrightarrow \texttt{id} + \texttt{id}$$

A Parse Tree succinctly captures the *structure* of a sentence.

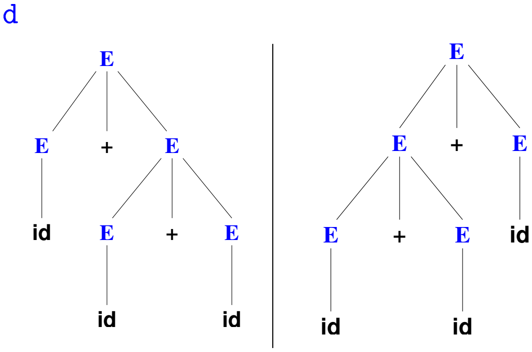




# Ambiguity (revisited)

A Grammar is **ambiguous** if there are *multiple parse trees* for the same sentence.

Example: $\texttt{id} + \texttt{id} + \texttt{id}$



# Associativity and Precedence

- Binary operators may be left-, right-, or non-associative.
- Precedence specifies how tightly arguments are bound to an operator.
- Associativity and precedence are specified to remove ambiguity.

A sampling of operators in C:

| **Operator** | **Associativity** |
|---|---|
| `=` | right |
| `\|\|` | left |
| `&&` | left |
| ⋮ | ⋮ |
| `-, +` | left |
| `*, /, %` | left |





# Parsing

Techniques to determine whether a sentence belongs to a language

- Parsing algorithms are more expensive than recognizers for regular languages.
- Grammar may need to be modified to accomodate parsing algorithms (Recursive descent, LALR, . . .).
- Parsers typically build an *abstract syntax tree* which omits syntactic details and preserves the overall structure of a sentence.

  e.g.:

  Concrete Syntax: $\langle s \rangle \rightarrow$ `while` $\langle e \rangle$ `do` $\langle s \rangle$

  Abstract Syntax: $s \rightarrow \textbf{while}(e, s)$
- Abstract syntax are "data types" in an interpreter/compiler.





# Grammars in Practice

$$
\begin{array}{rcl}
\langle md \rangle & \rightarrow & \langle mod \rangle\ \langle type \rangle\ \langle id \rangle\ (\ \langle params \rangle\ )\ \langle block \rangle \\
& \vdots & \\
\langle params \rangle & \rightarrow & \langle param \rangle , \langle params \rangle \\
\langle params \rangle & \rightarrow & \langle param \rangle \\
& \vdots & \\
\langle block \rangle & \rightarrow & \{\ \langle stmts \rangle\ \} \\
\langle stmts \rangle & \rightarrow & \langle stmt \rangle\ \langle stmts \rangle \\
\langle stmts \rangle & \rightarrow & \epsilon \\
& \vdots &
\end{array}
$$

# EBNF

*Extended* BNF: with “regular expression”-like operators to make grammars more concise.

- { $A$ }: zero or more occurrences of $A$.
- [ $A$ ]: zero or one occurrence of $A$.
- Additionally, we can write rules of the form

$$\langle s \rangle \rightarrow \langle t_1 \rangle \; (\mathtt{a} \;\mid \langle p \rangle \;) \; \langle t_2 \rangle$$

to represent two rules in BNF:

$$\begin{aligned} \langle s \rangle &\rightarrow \langle t_1 \rangle \; \mathtt{a} \; \langle t_2 \rangle \\ \langle s \rangle &\rightarrow \langle t_1 \rangle \; \langle p \rangle \; \langle t_2 \rangle \end{aligned}$$





# EBNF (example)

$$\begin{aligned} \langle md \rangle &\rightarrow [\langle mod \rangle] \; \langle type \rangle \; \langle id \rangle \; ( \; \langle params \rangle \; ) \; \langle block \rangle \\ &\vdots \\ \langle params \rangle &\rightarrow \langle param \rangle \; \{, \; \langle param \rangle\} \\ \langle params \rangle &\rightarrow \langle param \rangle \\ &\vdots \\ \langle block \rangle &\rightarrow \{ \; \{\langle stmt \rangle\} \; \} \\ &\vdots \end{aligned}$$