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.

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 Σ.

Let R be the set of all regular expressions over Σ. 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.

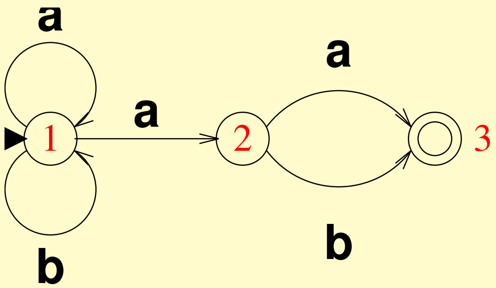
- A finite set of *states* (vertices).
- *Transitions* between states (edges).
- *Labels* on transitions are drawn from $\Sigma \cup \{\epsilon\}$.
- One distinguished *start* state.
- One or more distinguished *final* states.

Finite State Automata: An Example

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

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

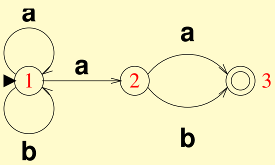
The following (non-deterministic) automaton determines whether an input string belongs to $\mathcal{L}((a \mid b)^* a(a \mid b))$:



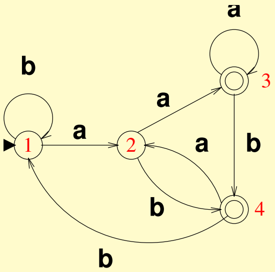
Determinism

$(a \mid b)^* a(a \mid b)$:

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
- `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

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

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

Ambiguity

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

$$
\begin{array}{ccccc}
\texttt{num} & \texttt{-} & \texttt{num} & \texttt{-} & \texttt{num} \\
E & \texttt{-} & \texttt{num} & \texttt{-} & \texttt{num} \\
E & \texttt{-} & E & \texttt{-} & \texttt{num} \\
 & & E & \texttt{-} & \texttt{num} \\
 & & E & \texttt{-} & E \\
 & & E & &
\end{array}
$$

5 - 3 - 1 ≡ (5-3)-1

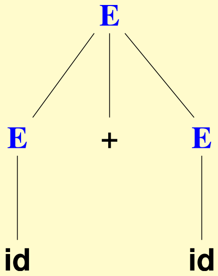
$$
\begin{array}{ccccc}
\texttt{num} & \texttt{-} & \texttt{num} & \texttt{-} & \texttt{num} \\
\texttt{num} & \texttt{-} & \texttt{num} & \texttt{-} & E \\
\texttt{num} & \texttt{-} & E & \texttt{-} & E \\
\texttt{num} & \texttt{-} & E & & \\
E & - & E & & \\
 & & E & &
\end{array}
$$

5 - 3 - 1 ≡ 5-(3-1)

Parse Trees

Graphical Representation of Derivations

$$
\begin{aligned}
E &\Longrightarrow E + E \\
&\Longrightarrow \texttt{id} + E \\
&\Longrightarrow \texttt{id} + \texttt{id}
\end{aligned}
$$



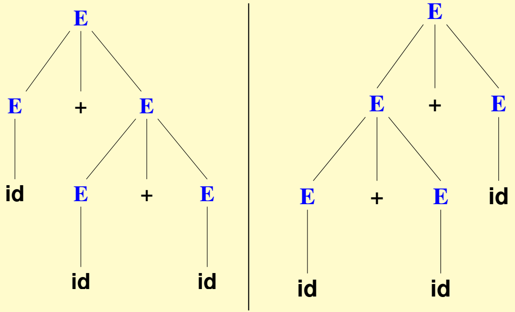
$$
\begin{aligned}
E &\Longrightarrow E + E \\
&\Longrightarrow E + \texttt{id} \\
&\Longrightarrow \texttt{id} + \texttt{id}
\end{aligned}
$$

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: `id` + `id` + `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: $s \rightarrow \mathbf{while}(e, s)$
- Abstract syntax are “data types” in an interpreter/compiler.

Grammars in Practice

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

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)

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