Lexical Analysis

Lecture 3

Instructor: Fredrik Kjolstad
Slide design by Prof. Alex Aiken, with modifications

Outline

- Informal sketch of lexical analysis
  - Identifies tokens in input string
- Issues in lexical analysis
  - Lookahead
  - Ambiguities
- Specifying lexers (aka. scanners)
  - By regular expressions (aka. regex)
  - Examples of regular expressions

Lexical Analysis

- What do we want to do? Example:

```
if (i == j)
    Z = 0;
else
    Z = 1;
```

- The input is just a string of characters:

  \tif (i == j)\n\t\tz = 0;\n\telse\n\t\tz = 1;

- Goal: Partition input string into substrings
  - Where the substrings are called tokens

What's a Token?

- A syntactic category
  - In English:

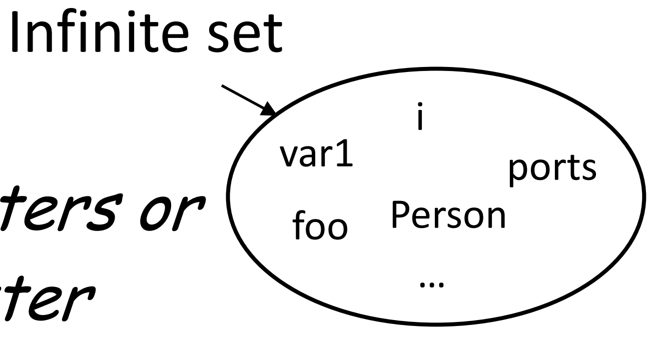
    noun, verb, adjective, …

  - In a programming language:

    Identifier, Integer, Keyword, Whitespace, …

Tokens

- A token class corresponds to a set of strings



- Examples
  - Identifier: *strings of letters or digits, starting with a letter*
  - Integer: *a non-empty string of digits*
  - Keyword: *"else" or "if" or "begin" or …*
  - Whitespace: *a non-empty sequence of blanks, newlines, and tabs*

What are Tokens For?

- Classify program substrings according to role

- Lexical analysis produces a stream of tokens
- … which is input to the parser

- Parser relies on token distinctions
  - An identifier is treated differently than a keyword

Designing a Lexical Analyzer: Step 1

- Define a finite set of tokens
  - Tokens describe all items of interest
    - Identifiers, integers, keywords
  - Choice of tokens depends on
    - language
    - design of parser

Example

- Recall

  \tif (i == j)\n\t\tz = 0;\n\telse\n\t\tz = 1;

- Useful tokens for this expression:

  Integer, Keyword, Relation, Identifier, Whitespace, (,), =, ;

- N.B., (,), =, ; above are tokens, not characters

Designing a Lexical Analyzer: Step 2

- Describe which strings belong to each token

- Recall:
  - Identifier: *strings of letters or digits, starting with a letter*
  - Integer: *a non-empty string of digits*
  - Keyword: *"else" or "if" or "begin" or …*
  - Whitespace: *a non-empty sequence of blanks, newlines, and tabs*

Lexical Analyzer: Implementation

- An implementation must do two things:

  1. Classify each substring as a token

  2. Return the value or *lexeme* (value) of the token
     - The lexeme is the actual substring
     - From the set of substrings that make up the token

- The lexer thus returns token-lexeme pairs
  - And potentially also line numbers, file names, etc. to improve later error messages

Example

- Recall:

  \tif (i == j)\n\t\tz = 0;\n\telse\n\t\tz = 1;

Lexical Analyzer: Implementation

- The lexer usually discards “uninteresting” tokens that don’t contribute to parsing.
- Examples: Whitespace, Comments

True Crimes of Lexical Analysis

- Is it as easy as it sounds?
- Not quite!
- Look at some history . . .

Lexical Analysis in FORTRAN

- FORTRAN rule: Whitespace is insignificant
- E.g., VAR1 is the same as VA   R1
- A terrible design!
- Historical footnote: FORTRAN Whitespace rule motivated by inaccuracy of punch card operators

FORTRAN Example

- Consider
  - DO 5 I = 1,25
  - DO 5 I = 1.25

Lexical Analysis in FORTRAN (Cont.)

- Two important points:
  1. The goal is to partition the string. This is implemented by reading left-to-right, recognizing one token at a time

  2. "Lookahead" may be required to decide where one token ends and the next token begins

Lookahead

- Even our simple example has lookahead issues
  - i vs. if
  - = vs. ==

Lexical Analysis in PL/I

- PL/I keywords are not reserved

  IF ELSE THEN THEN = ELSE; ELSE ELSE = THEN

Lexical Analysis in PL/I (Cont.)

- PL/I Declarations:

  DECLARE (ARG1,. . ., ARGN)

- Can't tell whether DECLARE is a keyword or array reference until after the).
  - Requires arbitrary lookahead!

- More on PL/I's quirks later in the course . . .

Lexical Analysis in C++

- Unfortunately, the problems continue today

- C++ template syntax:

  Foo<Bar>

- C++ stream syntax:

  cin >> var;

- But there is a conflict with nested templates:

  Foo<Bar<Bazz>>

Review

- The goal of lexical analysis is to
  - Partition the input string into lexemes
  - Identify the token of each lexeme

- Left-to-right scan => lookahead sometimes required

Next

- We still need
  - A way to describe the lexemes of each token

  - A way to resolve ambiguities
    - Is if two variables i and f?
    - Is == two equal signs = =?

Regular Languages

- There are several formalisms for specifying tokens

- *Regular languages* are the most popular
  - Simple and useful theory
  - Easy to understand
  - Efficient implementations

Languages

Def. Let **S** be a set of characters. *A language over* **S** is a set of strings of characters drawn from **S**

Examples of Languages

- Alphabet = English characters
- Language = English sentences
- Not every string of English characters is an English sentence

- Alphabet = ASCII
- Language = C programs
- Note: ASCII character set is different from English character set

Notation

- Languages are sets of strings.
- Need some notation for specifying which sets we want
- The standard notation for regular languages is *regular expressions.*

Atomic Regular Expressions

- Single character

$$'c' = \{"c"\}$$

- Epsilon

$$\varepsilon = \{""\}$$

Not the empty set, but set with a single, empty, string.

Compound Regular Expressions

- Union

$$A + B = \{s \mid s \in A \text{ or } s \in B\}$$

- Concatenation

$$AB = \{ab \mid a \in A \text{ and } b \in B\}$$

- Iteration

$$A^* = \bigcup_{i \geq 0} A^i \quad \text{where} \quad A^i = A \ldots i \text{ times} \ldots A$$

Regular Expressions

- **Def.** The *regular expressions over* S are the smallest set of expressions including

$$
\begin{array}{ll}
\varepsilon & \\
'c' & \text{where } c \in \Sigma \\
A + B & \text{where } A, B \text{ are rexp over } \Sigma \\
AB & \text{"} \qquad\qquad\qquad \text{"} \qquad\qquad\qquad \text{"} \\
A^{*} & \text{where } A \text{ is a rexp over } \Sigma
\end{array}
$$

Syntax vs. Semantics

- To be careful, we should distinguish syntax and semantics.

$$
\begin{aligned}
L(\varepsilon) &= \{""\} \\
L('c') &= \{"c"\} \\
L(A+B) &= L(A) \cup L(B) \\
L(AB) &= \{ab \mid a \in L(A) \text{ and } b \in L(B)\} \\
L(A^*) &= \bigcup_{i \geq 0} L(A^i)
\end{aligned}
$$

Segue

- Regular expressions are simple, almost trivial
  - But they are useful!

- We can describe tokens in regular expressions. . .

Example: Keyword

Keyword: *“else” or “if” or “begin” or …*

‘else’ + ‘if’ + ‘begin’ + . . .

Note: ‘else’ abbreviates
‘e’ ’ l’ ’ s’ ’ e’

Example: Integers

Integer: *a non-empty string of digits*

digit = '0'+'1'+'2'+'3'+'4'+'5'+'6'+'7'+'8'+'9'

integer = digit digit*

Abbreviation: $A^+ = AA^*$

Example: Identifier

Identifier: *strings of letters or digits, starting with a letter*

letter = 'A' + . . . + 'Z' + 'a' + . . . + 'z'

identifier = letter (letter + digit)*

Breakout: is (letter* + digit*) the same as (letter + digit)*?

Example: Whitespace

Whitespace: *a non-empty sequence of blanks, newlines, and tabs*

$$(\text{'~'} + \text{'\textbackslash n'} + \text{'\textbackslash t'})^{+}$$

Example: Phone Numbers

- Regular expressions are all around you!
- Consider (650)-723-3232

$$\Sigma = \text{digits} \cup \{-,(,)\}$$
$$\text{exchange} = \text{digit}^3$$
$$\text{phone} = \text{digit}^4$$
$$\text{area} = \text{digit}^3$$
$$\text{phone\_number} = \text{'('}\ \text{area}\ \text{')-'}\ \text{exchange}\ \text{'-'}\ \text{phone}$$

Example: Email Addresses

- Consider *anyone@cs.stanford.edu*

$$\Sigma \quad = \quad \text{letters} \cup \{.,@\}$$

$$\text{name} \quad = \quad \text{letter}^{+}$$

$$\text{address} \quad = \quad \text{name '@' name '.' name '.' name}$$

Example: Unsigned Pascal Numbers

$$\begin{aligned}
\text{digit} &= \text{'0'} + \text{'1'} + \text{'2'} + \text{'3'} + \text{'4'} + \text{'5'} + \text{'6'} + \text{'7'} + \text{'8'} + \text{'9'} \\
\text{digits} &= \text{digit}^{+} \\
\text{opt_fraction} &= (\text{'.'}\ \text{digits}) + \varepsilon \\
\text{opt_exponent} &= (\text{'E'}\ (\text{'+'} + \text{'-'} + \varepsilon)\ \text{digits}) + \varepsilon \\
\text{num} &= \text{digits opt_fraction opt_exponent}
\end{aligned}$$

Other Examples

- File names
- Grep tool family

Summary

- Regular expressions describe many useful languages
  - We will look at non-regular languages next week
- Regular languages are a language specification
  - We still need an implementation
- Next time: Given a string *s* and a rexp *R*, is

$$s \in L(R)?$$