Lexical Analysis

Lecture 3

Outline

- Informal sketch of lexical analysis
  - Identifies tokens in input string
- Issues in lexical analysis
  - Lookahead
  - Ambiguities
- Specifying lexers
  - Regular expressions
  - 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 tokens

What's a Token?

- A syntactic category
  - In English:
    noun, verb, adjective, …
  - In a programming language:
    Identifier, Integer, Keyword, Whitespace, …

Tokens

- Tokens correspond to sets of strings.
- 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
- Output of lexical analysis is 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
  - 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., (,), =, ; are tokens, not characters, here

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. Recognize substrings corresponding to tokens
2. Return the value or *lexeme* of the token
   - The lexeme is the substring

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!

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. ==

- Footnote: FORTRAN Whitespace rule motivated by inaccuracy of punch card operators

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 Σ be a set of characters. A *language over* Σ is a set of strings of characters drawn from Σ

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

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

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

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

Regular Expressions

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

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

Syntax vs. Semantics

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

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

Segue

- Regular expressions are simple, almost trivial
  - But they are useful!
- Reconsider informal token descriptions . . .

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)*

Is (letter* + digit*) the same?

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

Σ = digits $\cup$ $\{-,(,)\}$
exchange = digit^3
phone = digit^4
area = digit^3
phone_number = '(' area ')-' exchange '-' phone

Example: Email Addresses

- Consider *anyone@cs.stanford.edu*

$$\Sigma = \text{letters} \cup \{.,@\}$$
$$\text{name} = \text{letter}^{+}$$
$$\text{address} = \text{name '@' name '.' name '.' name}$$

Example: Unsigned Pascal Numbers

$$\text{digit} = \text{'0' +'1'+'2'+'3'+'4'+'5'+'6'+'7'+'8'+'9'}$$
$$\text{digits} = \text{digit}^{+}$$
$$\text{opt\_fraction} = (\text{'.' digits}) + \varepsilon$$
$$\text{opt\_exponent} = (\text{'E' } (\text{'+'} + \text{'-'} + \varepsilon) \text{ digits}) + \varepsilon$$
$$\text{num} = \text{digits opt\_fraction opt\_exponent}$$

Other Examples

- File names
- Grep tool family

Summary

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

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