CSCI 742 - Compiler Construction

Lecture 4
Manual Construction of Lexers
Instructor: Hossein Hojjat

January 24, 2018

Recap: Regular Expressions

Regular expression over alphabet Σ:

1. ϵ is a RE denoting the set $\{\epsilon\}$
2. if $a \in \Sigma$, then a is a RE denoting $\{a\}$
3. if r and s are REs, denoting $L(r)$ and $L(s)$, then:

- $r \mid s$ is a RE denoting $L(r) \cup L(s)$
- $r \; . \; s$ is a RE denoting $L(r).L(s)$
- $r*$ is a RE denoting $L(r)*$

Exercise

Which regular expression is equivalent to $(0|1) * 1(0|1)*$

- $(01|11) * (0|1)*$
- $(0|1) * (10|11|1)(0|1)*$
- $(0|1) * (0|1)(0|1)*$

Exercise

Which regular expression is equivalent to $(0|1)*1(0|1)*$

- $(01|11)*(0|1)*$ no (it allows 0)
- $(0|1)*(10|11|1)(0|1)*$
- $(0|1)*(0|1)(0|1)*$

Exercise

Which regular expression is equivalent to $(0|1) * 1(0|1)*$

- $(01|11) * (0|1)*$ no (it allows 0)
- $(0|1) * (10|11|1)(0|1)*$ yes
- $(0|1) * (0|1)(0|1)*$

Exercise

Which regular expression is equivalent to $(0|1)*1(0|1)*$

- $(01|11)*(0|1)*$ no (it allows 0)
- $(0|1)*(10|11|1)(0|1)*$ yes
- $(0|1)*(0|1)(0|1)*$ no (it allows 0)

Lexical Analysis

Input:

i	f	(	x	=	=	0	)		x	=	x	+	1	;

Output:

IF , LPAREN , ID(x) , EQUALS , INTLIT(0) , RPAREN , ID(x) , EQSIGN , ID(x) , PLUS , INTLIT(1) , SEMICOLON

Two approaches to construct lexical analyzers:

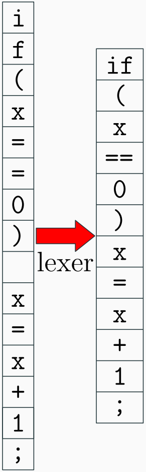
1. Manual construction: use first character to decide on token class (This lecture)
2. Automatic construction: conversion of regular expressions to automata
   - Tools like JFlex are lexer generators for Java

Interfaces for Lexer

- In practice, a lexer reads characters and generate tokens on demand
- It work with streams instead of sequences, with procedures like
  - `current` returns current element in stream
  - `next` advance the current element
- Lexer operates on a character input stream and returns a token output stream

Lexer input and Output

```java
class CharStream {
 String fileName;
 FileReader reader = new
  FileReader(fileName);
 BufferedReader file = new
  BufferedReader(reader);
 char current = ' ';
 Boolean eof = false;
 void next() throws
    Exception {
 if (eof)
 throw
    EndOfInput("reading");
  int c = file.read();
  eof = (c == -1);
 current = (char) c;
}
```




```java
// representation of a token
public class Token {
 public static final int EOF = 0;
 public static final int ID  = 1;//x
 public static final int INT = 2;
 public static final int LPAREN = 3;
 public static final int RPAREN = 4;
 public static final int SCOLON = 5;
 public static final int WHILE  = 6;
 public static final int AssignEQ = 7;
 public static final int CompareEQ = 8;
 public static final int MUL = 9;
 public static final int DIV = 10;
 public static final int PLUS = 11;
 public static final int LEQ = 12;
 public static final int IF = 13;
 // ...
}
```

Stream of Characters:
`CharStream.next()`

```java
class Lexer {
 CharStream ch;
 Token current;
 void next() {
 /*lexer code goes here*/}
}
```

Stream of Tokens:
`Lexer.next()`

Recognizing Identifiers and Keywords

```
char c = ch.current;
if (Character.isLetter(c)) {
  StringBuffer b = new
      StringBuffer();
  while (Character.isLetter(c)
      || Character.isDigit(c)){
    b.append(c);
    ch.next(); c = ch.current;
  }
}
if(!keywords.containsKey(b.toString)){
  token.kind = ID;
  token.id = b;
}
else token.kind = KW;
```

- regular expression for identifiers:

  letter (letter|digit)*

- Keywords look like identifiers but are reserved as keywords in language definition
- `keywords`: A constant Map from strings to keyword tokens
- if identifier is not in map, then it is ordinary identifier

Recognizing Identifiers and Keywords

```
char c = ch.current;
if (Character.isDigit(c)) {
 int k = 0;
 while (Character.isDigit(c)) {
  k = 10*k +
      Character.getNumericValue(c);
  ch.next(); c = ch.current;
 }
 token.kind = INT;
 token.value = k;
}
```

- regular expression for integers:

  digit digit*

Deciding which Token is Coming

- How do we know the class of the token we are supposed to analyze (string, integer, identifier, ...)?
- Manual construction: use lookahead (next symbol in stream) to decide on token class
- compute FIRST(e) - symbols with which e can start
- check in which FIRST(e) current token is
- If $L \subseteq \Sigma*$ is a language, then FIRST(L) is set of all alphabet symbols that start some word in L

$$\text{FIRST}(L) = \{a \in \Sigma \mid \exists v \in \Sigma * .\ (a.v) \in L\}$$

FIRST of Some Languages

- FIRST($\{ab, bb, a\}$) $= \{a, b\}$
- FIRST($\{a, ab\}$) $= \{a\}$
- FIRST($\{bbbbbbbbb\}$) $= \{b\}$
- FIRST($\{a\}$) $= \{a\}$
- FIRST($\{\}$) $= \{\}$
- FIRST($\{\epsilon\}$) $= \{\}$
- FIRST($\{\epsilon, ba\}$) $= \{b\}$

FIRST of a Regular Expression

- Given regular expression e, how to compute FIRST(e)?
  - Use automata (will discuss later)
  - Rules that directly compute them
    (also work for grammars, we will see them for parsing)

FIRST of a Regular Expression

- Given regular expression e, how to compute FIRST(e)?
  - Use automata (will discuss later)
  - Rules that directly compute them
    (also work for grammars, we will see them for parsing)

- Examples of FIRST(e) computation:
  - FIRST($ab*$) $= \{a\}$
  - FIRST($ab * |c$) $= \{a, c\}$
  - FIRST($a * b * c$) $= \{a, b, c\}$
  - FIRST($(cb|a * c*)d * e$) $=$

FIRST of a Regular Expression

- Given regular expression e, how to compute FIRST(e)?
  - Use automata (will discuss later)
  - Rules that directly compute them
    (also work for grammars, we will see them for parsing)

- Examples of FIRST(e) computation:
  - FIRST($ab*$) $= \{a\}$
  - FIRST($ab * |c$) $= \{a, c\}$
  - FIRST($a * b * c$) $= \{a, b, c\}$
  - FIRST($(cb|a * c*)d * e$) $= \{a, c, d, e\}$

FIRST of Regular Expression

FIRST: RegExp $\rightarrow \Sigma$, FIRST$(e) \subseteq \Sigma$

Define recursively:

- FIRST$(\emptyset) = \emptyset$
- FIRST$(\epsilon) = \emptyset$
- FIRST$(a) = \{a\}$
- FIRST$(e_1|e_2) =$ FIRST$(e_1) \cup$ FIRST(e_2)
- FIRST$(e*) =$ FIRST(e)
- FIRST$(e_1.e_2) =$ FIRST$(e_1) \cup$ FIRST(e_2) , if nullable(e_1)
  FIRST(e_1) , otherwise

We need the notion of nullable(e):
whether ϵ belongs to the regular language

nullable

Can regular expr contain empty word? nullable(L) means $\epsilon \in L$
nullable: RegExp $\rightarrow \{\text{true}, \text{false}\}$

Define recursively:

- nullable($\emptyset$) = false
- nullable(ϵ) = true
- nullable(a) = false
- nullable($e_1 \mid e_2$) = nullable(e_1) $\vee$ nullable(e_2)
- nullable($e*$) = true
- nullable($e_1.e_2$) = nullable(e_1) $\wedge$ nullable(e_2)

From RE to Programs

- Converting Well-Behaved Regular Expression into Programs

Regular Expression	Code
a	**if** (current=a) next **else** error
$r_1.r_2$	(code for r_1) ; (code for r_2)
$(r_1 \mid r_2)$ when FIRST(r_1) $\cap$ FIRST(r_2) $= \emptyset$	**if** (current in FIRST(r_1)) code for r_1 **else** code for r_2
$r*$	**while**(current in FIRST(r)) code for r

Decision Tree to Map Symbols to Tokens

```
switch (ch.current) {
  case '(' : { current = OPAREN; ch.next(); return; }
  case ')' : { current = CPAREN; ch.next(); return; }
  case '+' : { current = PLUS; ch.next(); return; }
  case '/' : { current = DIV; ch.next(); return; }
  case '*' : { current = MUL; ch.next(); return; }
  case '=' : { // more tricky because there can be =, ==
    ch.next();
    if (ch.current == '=')
      { ch.next(); current = CompareEQ; return; }
    else { current = AssignEQ; return; }
  }
  case '<' : { // more tricky because there can be <, <=
    ch.next();
    if (ch.current == '=')
      { ch.next(); current = LEQ; return; }
    else { current = LESS; return; }
  }
}
```

Subtleties in General Case

- Sometimes FIRST(e_1) and FIRST(e_2) overlap for two different token classes
  - e.g. `AssignEQ` "=" and `CompareEQ` "=="
- Must remember where we were and go back,
  or work on recognizing multiple tokens at the same time
- Example: comment begins with division sign,
  so we should not decide on division token when checking for comment

Skipping Comments

```
if (ch.current == '/') {
  ch.next();
  if (ch.current == '/') {
    while (!isEOL && !isEOF) {
      ch.next();
    }
  } else {
    token.kind = DIV;
  }
}
```

Question: how can we handle nested comments?

```
/* foo /* bar */ baz */
```

Skipping Comments

```
if (ch.current == '/') {
  ch.next();
  if (ch.current == '/') {
     while (!isEOL && !isEOF) {
       ch.next();
     }
  } else {
    token.kind = DIV;
  }
}
```

Question: how can we handle nested comments?

```
/* foo /* bar */ baz */
```

Answer: use a counter for nesting depth

White Spaces

- Whitespace can be defined as a token using space character, tabs, and various end-of-line characters
- In most languages (Java, ML, C) white spaces and comments can occur between any two other tokens
  - They have no meaning, so parser does not want to see them
- Convention: lexical analyzer removes those "tokens" from its output
- Lexical analyzer always finds the next non-whitespace non-comment token
- What kind of applications care about the comments and white spaces in source code?