Lexical Analysis with Regular Expressions

Thursday, October 23, 2008
Reading: Stoughton 3.14, Appel Chs. 1 and 2

CS235 Languages and Automata

Department of Computer Science
Wellesley College

Lecture Overview

Lexical analysis = breaking programs into tokens is the first stage of a compiler.

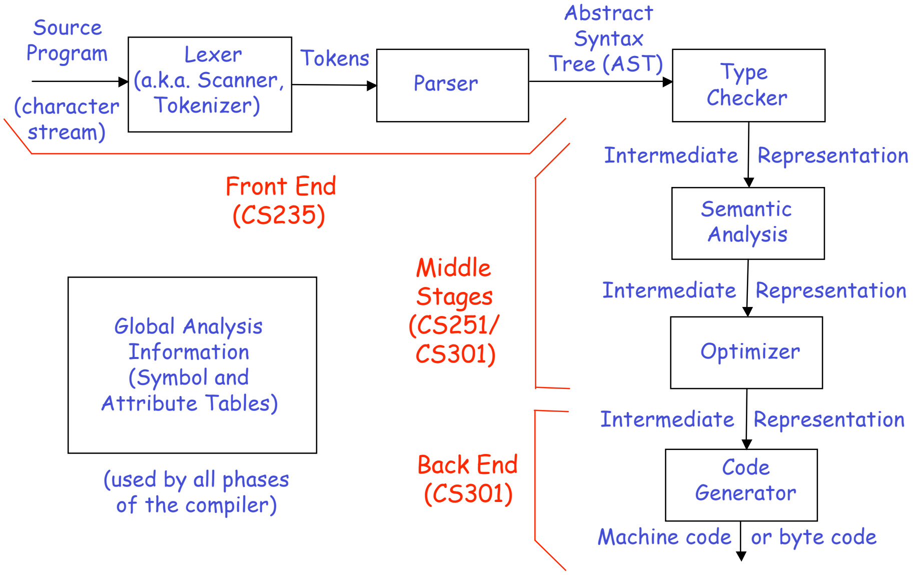
The structure of tokens can be specified by regular expressions.

The ML-Lex tool can automatically derive a lexical analyzer from a description of tokens specified by regular expressions.

To use ML-Lex, we'll need to learn a few more ML features:

- sum-of-product data structures
- mutable cells

Compiler Structure



Source Program

(character stream)

Lexer (a.k.a. Scanner, Tokenizer)

Tokens

Parser

Abstract Syntax Tree (AST)

Type Checker

Intermediate Representation

Semantic Analysis

Intermediate Representation

Optimizer

Intermediate Representation

Code Generator

Machine code or byte code

Front End (CS235)

Middle Stages (CS251/ CS301)

Back End (CS301)

Global Analysis Information (Symbol and Attribute Tables)

(used by all phases of the compiler)

Front End Example

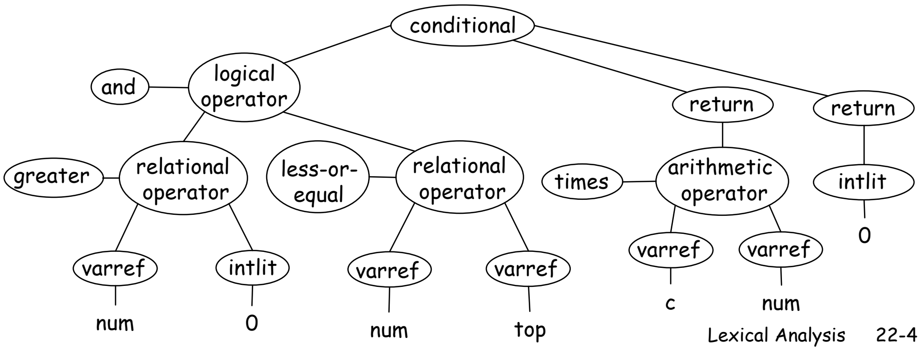
```
if (num > 0 && num <= top) { // Is num in range?
   return c*num
} else {return 0;}
```

Lexer (ignores whitespace, comments)

if (num > 0 && num <= top) { return c * num }

else { return 0 ; }

Parser (creates AST)



Sample English Description of Lexer Rules

An integer is a sequence of digits. A nonempty sequence of digits followed by E followed by a nonempty sequence of digits is scientific notation (e.g., 12E34 stands for 12x10^{34}).

An identifier is a sequence of letters and digits; the first character must be a letter. The underscore _ counts as a letter. Upper- and lowercase letters are different.

Certain names are reserved as **keywords** in the language and cannot be used as identifiers. E.g., Java keywords include **while**, **for**, **if**, **else**, **public**, **private**, **static**, **class**, **int**, **void**. ML keywords include **fun**, **let**, **in**, **end**, **if**, **then**, **else**.

If the input character stream has been parsed into tokens up to a given character, the next token is taken to include the longest string of characters that could possibly constitute a token. Blanks, tabs, newlines, and comments (known collectively as **whitespace**) are ignored except as they serve to separate tokens. Some whitespace is required to separate otherwise adjacent identifiers, keywords, and constants.

Some ML-Lex Regular Expression Patterns

Pattern	Matches
"abc"	the literal string of characters abc
.	any character except newline
[a-zA-Z0-9]	any alphanumeric character
[^d-g]	any character except lowercase d,e,f,g
r_1r_2	r_1 followed by r_2, where r_1, r_2 are reg. exps.
$r_1\|r_2$	r_1 or r_2
*r**	zero or more *r*s, where *r* a reg. exp.
r+	one or more *r*s
r?	zero or one *r*s
(*r*)	*r* (parens for grouping)
{*REName*}	regular expression with name *REName*

Regular Expressions for Some Tokens

"if"	if keyword
[a-zA-Z_][a-zA-Z0-9_]*	identifiers (variable names)
[0-9]+(E[0-9]+)?	integers

How should the following be split into tokens?

if	12
if89	1289
ifE89	12E89
ifEat34	12Eat34

Disambiguation rules:

Longest match. The longest initial substring of the input that can match any regular expression is taken as the next token.

Rule Priority. For a particular longest initial substring, the first regular expression that can match determines its token.

A SLiP Program

Here is a simple program in the straight-line programming language of Appel Ch. 1 (which I call SLiP):

```
sum := 5+3;
prod := (print (sum, sum-1), 10*sum);
print(prod);
```

Imagine that this is in the file test.slip.

We expect it to have the following tokens:

```
sum  :=  5  +  3  ;
prod  :=  (  print  (  sum  ,  sum  -  1  )  ,
                         10  *  sum  )  ;
print  (  prod  )  ;  EOF
```

How do we represent these tokens in SML?

SML Digression: Sum-of-Product Data Types

```
(* contents of the file figure.sml *)
datatype figure =
    Square of int (* <constructor function> of <components> *)
  | Rectangle of int * int
  | Triangle of int * int * int

fun perimeter (Square side) = 4*side
  | perimeter (Rectangle(w,h)) = 2*(w+h)
  | perimeter (Triangle(s1,s2,s3)) = s1+s2+s3

fun scale c (Square side) = Square(c*side)
  | scale c (Rectangle(w,h)) = Rectangle(c*w,c*h)
  | scale c (Triangle(s1,s2,s3)) = Triangle(c*s1,c*s2,c*s3)
```

```
- use "figure.sml";
[opening figure.sml]
datatype figure
  = Rectangle of int * int | Square of int | Triangle of int * int * int
val perimeter = fn : figure -> int
val scale = fn : int -> figure -> figure
val it = () : unit

- map perimeter [Square 1, Rectangle(2,3), Triangle(4,5,6)];
val it = [4,10,15] : int list

- map (scale 10) [Square 1, Rectangle(2,3), Triangle(4,5,6)];
val it = [Square 10,Rectangle (20,30),Triangle (40,50,60)] : figure list
```

We Can Define our Own List Data Type

```
(* contents of the file mylist.sml *)
datatype 'a mylist = Nil | Cons of 'a * ('a mylist)

fun sum Nil = 0
  | sum (Cons(n,ns)) = n + (sum ns)

fun map f Nil = Nil
  | map f (Cons(x,xs)) = Cons(f x, map f xs)
```

```
- use "mylist.sml";
[opening mylist.sml]
datatype 'a mylist = Cons of 'a * 'a mylist | Nil
val sum = fn : int mylist -> int
val map = fn : ('a -> 'b) -> 'a mylist -> 'b mylist
val it = () : unit

- sum (Cons(1, Cons(2, Cons(3, Nil))));
val it = 6 : int

- map (fn x => x*2) (Cons(1, Cons(2, Cons(3, Nil))));
val it = Cons (2,Cons (4,Cons (6,Nil))) : int mylist
```

A Token Data Type

```
datatype binop = Add | Mul | Sub | Div

datatype token = EOF
          |  ID of string
          |  INT of int
          |  OP of binop
          |  PRINT
          |  LPAREN |  RPAREN | COMMA | SEMI | GETS
```

token data type definition

```
sum := 5+3;
prod := (print (sum, sum-1), 10*sum);
print(prod);
```

Sample program

SML token list for sample program

```
[ID "sum", GETS, INT 5, OP Add, INT 3, SEMI,
 ID "prod", GETS, LPAREN, PRINT, LPAREN, ID "sum", COMMA, ID "sum",
 OP Sub, INT 1, RPAREN, COMMA, INT 10, OP Mul, ID "sum",  RPAREN, SEMI,
 PRINT, LPAREN, ID "prod", RPAREN, SEMI, EOF]
```

Some Token Operations

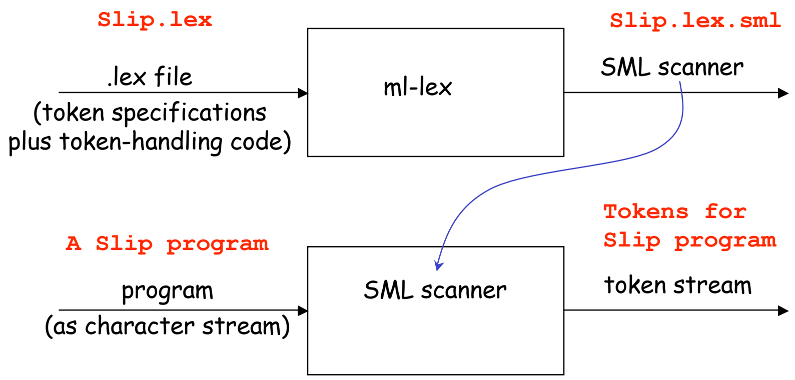
```
fun eof() = EOF

fun isEof(EOF) = true
  | isEof(_) = false

fun binopToString(Add) = "+"
  | binopToString(Sub) = "-"
  | binopToString(Mul) = "*"
  | binopToString(Div) = "/"

 fun toString(EOF) = "[EOF]"
  | toString(ID(s)) = "[" ^ s ^ "]"
  | toString(INT(i)) = "[" ^ (Int.toString(i)) ^ "]"
  | toString(OP(opr)) = "[" ^ (binopToString(opr)) ^ "]"
  | toString(PRINT) = "[PRINT]"
  | toString(LPAREN) = "[(]"
  | toString(RPAREN) = "[)]"
  | toString(COMMA) = "[,]"
  | toString(SEMI) = "[;]"
  | toString(GETS) = "[:=]"
```

ml-lex: A Scanner Generator



Slip.lex

.lex file

(token specifications
plus token-handling code)

ml-lex

Slip.lex.sml

SML scanner

A Slip program

program

(as character stream)

SML scanner

Tokens for
Slip program

token stream

Format of a .lex File

Header section with SML code
%%
Definitions of named regular expressions with form:
name=*regexp*
%%
Rules with pairs of token patterns & SML code having the form:
regexp => *SML-expression*

In *SML-expression*, the following special expressions may be used:

yytext	Stands for the string matching the expression
yypos	Character index of the first character of yytext in the input character stream
lex()	Ignores current token string and continues lexing
YYBEGIN <state>	Change state of lexer to <state>

Slip.lex Header Code

```
open Token

type lexresult = token

fun eof () = Token.eof()

fun pluck (SOME(v)) = v
  | pluck NONE = raise Fail ("Shouldn't happen -- pluck(NONE)")
```

Note: functions like eof() and pluck can be put in a separate file and then loaded into header.

Slip.lex Definitions and Rules

```
alpha=[a-zA-Z];
alphaNumUnd=[a-zA-Z0-9_];
digit=[0-9];
whitespace=[\ \t\n];
any= [^];
%%
"print" => (PRINT);
{alpha}{alphaNumUnd}*  => (ID(yytext));
{digit}+  => (INT(pluck(Int.fromString(yytext))));
"+" => (OP(Add));
"-" => (OP(Sub));
"*" => (OP(Mul));
"/" => (OP(Div));
"(" => (LPAREN);
")" => (RPAREN);
"," => (COMMA);
";" => (SEMI);
":=" => (GETS);
{whitespace} => (lex());
{any} => ((* Signal a failure exception when encounter unexpected character.
               A more flexible implementation might raise a more refined
                exception that could be handled. *)
             raise Fail(“Slip scanner: unexpected character \"" ^ yytext ^ "\"")
```

Definitions

String matched by regular expression

Remove SOME from option type.

Rules

Discard current token and continue lexing

Using ml-lex to Generate a Scanner

```
[fturbak@sampras slip] ls -al Slip.lex.sml
ls: cannot access Slip.lex.sml: No such file or directory

[fturbak@sampras slip] ml-lex Slip.lex

Number of states = 27
Number of distinct rows = 10
Approx. memory size of trans. table = 1290 bytes

[fturbak@sampras slip] ls -al Slip.lex.sml
-rw-rw---- 1 fturbak fturbak 10277 2008-10-23 09:34 Slip.lex.sml
```

Contents of the file Slip.lex.sml

```
structure Mlex= struct
   structure UserDeclarations = struct …  end
   exception LexError
   structure Internal = struct …  end
   fun makeLexer yyinput = …
   fun lex () = …
 end
```

SML Digression: Mutable Cells (References)

ref : 'a -> 'a ref
   ref *<exp>* creates a cell whose contents is the value of *<exp>*.

! : 'a ref -> 'a
   ! *<exp>* returns the contents of the cell denoted by *<exp>*.

:= : 'a ref * 'a -> unit
   <exp1> := *<exp2>* changes the contents of the cell denoted by *<exp1>* to the value denoted by *<exp2>*.

; : 'a * 'b -> 'b
   <exp1> ; <exp2> first evaluates *<exp1>*, then evaluates *<exp2>*, and then returns the value of *<exp2>*. (The value of *<exp1>* value is discarded).

```
- val c = ref 17;
val c = ref 17 : int ref

- c;
val it = ref 17 : int ref

- !c;
val it = 17 : int

- fun add c x = x + !c;
val add_c = fn : int -> int

- add c 10;
val it = 27 : int

- !c;
val it = 17 : int

- c := 42;
val it = () : unit

- add c 10; !c
val it = 42 : int
```

Incrementing a cell in SML

```
fun inc cell = (cell := !cell + 1; !cell)
```

```
- val a = ref 0;
val a = ref 0 : int ref

- val b = ref 0;
val b = ref 0 : int ref

- inc a;
val it = 1 : int

- inc a;
val it = 2 : int

- inc b;
val it = 1 : int

- inc a;
val it = 3 : int

- inc b;
val it = 2 : int
```

Scanner Utilities

```
fun stringToScanner str =
     let val done = ref false
      in Mlex.makeLexer (fn n => if (!done) then ""
                                            else  (done := true; str)
                              )
     end

 fun fileToScanner filename =
     let val inStream = TextIO.openIn(filename)
      in Mlex.makeLexer (fn n => TextIO.inputAll(inStream))
     end

 fun scannerToTokens scanner =
    let fun recur () =
            let val token = scanner()
             in if Token.isEof(token) then
                  []
                else
                  token::(recur())
            end
     in recur()
    end
```

More Scanner Utilities

```
fun printScanner scanner =
    let fun loop () =
            let val token = scanner()
             in if Token.isEof(token) then
                  ()
                else
                  (print(Token.toString(token) ^ "\n");
                  loop())
            end
      in loop()
     end
```

```
(* Below, "o" is ML's infix composition operator. *)
val stringToTokens = scannerToTokens o stringToScanner
val fileToTokens = scannerToTokens o fileToScanner
val printTokensInString = printScanner o stringToScanner
val printTokensInFile = printScanner o fileToScanner
```

Testing our Scanner

```
sum := 5+3;
prod := (print (sum, sum-1), 10*sum);
print(prod);
```

Sample program in file named “test.slip”

```
- Scanner.fileToTokens "test.slip";
val it =
  [ID "sum", GETS,INT 5, OP Add, INT 3, SEMI, ID "prod", GETS,
    LPAREN, PRINT, LPAREN, ID "sum", COMMA, ID "sum",
    OP Sub, INT 1, RPAREN, COMMA, INT 10, OP Mul, ID "sum",
    RPAREN, SEMI, PRINT, LPAREN, ID "prod", RPAREN, SEMI] :
    Token.token list
```

Adding Line Comments

How to add line-terminated comments introduced by #?

```
sum := 5+3; # Set sum to 8
prod := (print (sum, sum-1), # First print sum and (sum-1),
        10*sum);                  # then set prod to 10*sum
print(prod); # Finally print prod
```

The following ml-lex rule doesn’t work. Why?

```
"#"{any}*"\n" => (lex() (* read a line comment *));
```

How can we fix it?

Adding Block Comments

How to add block (multi-line) comments delimited by { and } ?
(They needn’t be nestable yet.)

```
sum := 5+3; # Set sum to 8
prod := (print (sum, sum-1), # First print sum and (sum-1),
        10*sum);                  # then set prod to 10*sum
{ Comment out several lines:
  x := sum * 2;
  z := x * x; }
print(prod); # Finally print prod
```

Adding Nestable Block Comments

How to make block (multi-line) comments nestable ?

```
sum := 5+3; # Set sum to 8
prod := (print (sum, sum-1), # First print sum and (sum-1),
        10*sum);                 # then set prod to 10*sum
{ Comment out several lines:
  x := sum * 2;
  { Illustrate nested block comments:
     y = prod + 3:}
  z := x * x; }
print(prod); # Finally print prod
```

Can’t do this with regular expressions alone.
Need some extra support !

Using Lexer States for Nested Comments

```
(* Keeping track of nesting level of block comments *)
val commentNestingLevel = ref 0

fun incrementNesting() =
  (print "Incrementing comment nesting level";
   commentNestingLevel := (!commentNestingLevel) + 1)

fun decrementNesting() =
  (print "Decrementing comment nesting level";
   commentNestingLevel := (!commentNestingLevel) - 1)
%%
%s COMMENT;
alpha=[a-zA-Z];
alphaNumUnd=[a-zA-Z0-9_];
digit=[0-9];
whitespace=[\ \t\n];
any= [^];
%%
```

New header functions

Declare a new state named COMMENT

Definitions

rules shown on next slide

Lexer Rules for Nested Comments

```
<INITIAL>"print" => (PRINT);
<INITIAL>{alpha}{alphaNumUnd}*  => (ID(yytext));
<INITIAL>{digit}+  => (INT(pluck(Int.fromString(yytext))));
<INITIAL>"+" => (OP(Add));
<INITIAL>"-" => (OP(Sub));
<INITIAL>"*" => (OP(Mul));
<INITIAL>"/" => (OP(Div));
<INITIAL>"(" => (LPAREN);
<INITIAL>")" => (RPAREN);
<INITIAL>"," => (COMMA);
<INITIAL>";" => (SEMI);
<INITIAL>":=" => (GETS);
<INITIAL>"#".*"\n" => (lex() (* read a line comment *));
<INITIAL>"{" => (YYBEGIN COMMENT; incrementNesting(); lex());
<INITIAL>{whitespace} => (lex());
<COMMENT>"{" => (incrementNesting(); lex());
<COMMENT>"}" => (decrementNesting(); if (!commentNestingLevel) = 0 then
                      (YYBEGIN INITIAL; lex()) else lex());
<COMMENT>{any} => (lex());
{any} => ((* Signal a failure exception when encounter unexpected character.
            A more flexible implementation might raise a more refined
            exception that could be handled. *)
           raise Fail(”Slip scanner: unexpected character \"" ^ yytext ^ "\""));
```