City University London

IN2009

Language Processors

Week 2

Language Processing & Lexical Analysis

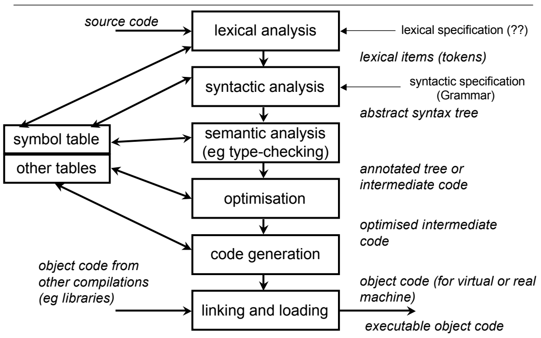
Igor Siveroni

Session Plan

Session 2

- Language processing
- Lexical analysis
- Syntax analysis
- Lexical Tokens
- Regular expressions
- Finite Automata
- Implementation
- Tools

Language processing



Lexical analysis

Straightline example program:

```
a := 5+3;
b := (print(a, a-1), 10*a);
print (b)
```

Lexical analysis converts text stream into a token stream, where tokens are the most basic symbols (words and punctuation):

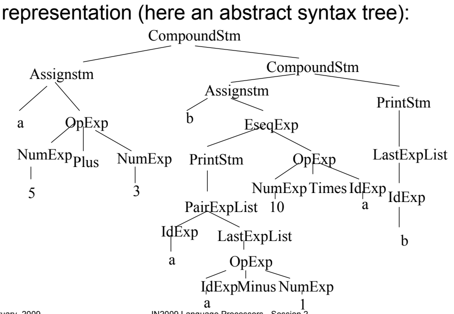
a	:=	5	+	3	;	b	:=	(	print	(	a	,	a	-	1	)	,	10	*	a	)	;	...

Each box is a lexical item or token. A possible representation:

ID(a) ASSIGN NUM(5) PLUS NUM(3) SEMI ID(b) ASSIGN LEFTPAREN KEYPRINT LEFTPAREN ID(a) COMMA ID(a) MINUS NUM(1) RIGHTPAREN COMMA NUM(10) TIMES ID(a) RIGHTPAREN SEMI ...

Syntax analysis

Converts a token stream into a useful abstract representation (here an abstract syntax tree):



Lexical Analysis: Main issues

- Syntactic Specification (Grammar)

  Stm → **Stm** `;` **Stm** | `ID :=` **Exp** | `print(` **ExpList** `)`

  Exp → `ID` | `NUM` | **Exp Binop Exp** | `(` **Stm** `,` **Exp** `)`

  ExpList → **Exp** `,` **ExpList** | **Exp**

  Binop → + | - | × | /

- Lexical Specification
  - Tokens: Sequence of characters treated as a unit in the grammar. For example: ID, NUM, +, -, etc.
  - We are concerned with the following: How do we …
    - **Specify lexical tokens?**
    - **Transform such specifications into a language recognizer that can be implemented as a computer program?**
    - **Derive (automatically) lexical analysers from such specifications?**

Lexical tokens

Type	Examples
ID	`foo n14 last`
NUM	`73 0 00 515 082`
REAL	`66.1 .5 10. 1e67 5.5e-10`
IF	`if`
COMMA	`,`
LPAREN	`(`
ASSIGN	`:=`

- Some tokens eg ID NUM REAL have *semantic values* attached to them, eg ID(n14), NUM(515)
- Reserved words: Punctuation tokens e.g. IF, VOID, RETURN constructed from alphanumeric characters, cannot be used as identifiers

Example informal specification

Identifiers in C or Java:

- *"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."*
- *"If the input stream has been divided 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.*

Identifiers in C or Java

- *Blanks, tabs, newlines and comments are ignored except as they serve to separate tokens. Some white space is required to separate otherwise adjacent identifiers, keywords and symbols."*

How do we formally specify the description above?

Formal specifications of tokens

- Approach:
  - Specify lexical tokens using the formal language of regular expressions.
  - Transform regular expressions into deterministic finite automata (DFA)
  - Implement lexical analysers (lexers) using DFA.
  - Fortunately for our sanity, there are automatic conversion tools…

Formal specifications of tokens

"a formal language is a language that is defined by precise mathematical or machine processable formulas" (Wikipedia)

- Languages
  - A language is a set of strings
  - A string is a finite sequence of symbols
  - Symbols are taken from a finite alphabet
- Many types of formal languages, at this stage we will consider **regular languages**.

Regular languages

- Regular languages can be:
  - Specified by **regular expressions**
  - Accepted by deterministic/non-deterministic finite state automata (DFA,NFA)
    - A word is accepted by the state machine if and only if the word belongs to the language I.e. it satisfies the regular expression specification
- A regular expression can be translated into an NFA.
- DFAs can be efficiently implemented.
- An NFA can be converted into a DFA.

Regular expressions

- Regular expressions (regex, regexp) - strings that describe the syntax of other strings.
- These are simply *patterns*, constructed by syntactical rules and defining a set of strings.
- Components
  - Alphabet: Valid symbols of the language
  - Operators: • | * +

Regular expressions

- There is a useful connection to real life software development here, too.
  - Regexps can be used in a number of programming languages and tools
  - TextPad, Emacs, etc. allow for searching for text given a regular expression - much more powerful than plain text searching.
  - Java contains a class RegExp, too.
- On to the rules...

Regular expressions

Symbol

- For each symbol a in the alphabet of the language, the regexp **`a`** denotes the language containing just the string **`a`**
- Lang(**`a`**) = { "`a`" }

Regular expressions

Alternation

- Given 2 regular expressions M and N then M | N is a new regexp.
- A string is in lang(M|N) if it is in lang(M) or lang(N).
- lang(M|N) = lang(M) U lang(N)
- E.g. lang(**`a|b`**) = {"`a`","`b`"} contains the 2 strings **`a`** and **`b`**.

Regular expressions

Concatenation

- Given 2 regexes M and N then M•N is a new regexp.
- A string is in lang(M•N) if it is the concatenation of 2 strings α and β s.t. α in lang(M) and β in lang(N).
- lang(M•N) = {$\alpha\beta$ s.t. α in lang(M) and β in lang(N) }
- Thus regexp **`(a|b)•a`** = {"`aa`","`ba`"} defines the language containing the 2 strings **`aa`** and **`ba`**

Regular expressions

Epsilon

- The regexp ε represents the language whose only string is the empty string.
- Lang(ε) = {`""`}
- Thus (a•b)|ε represents the language
  { `""`,`"ab"` }

Regular expressions

Repetition

- *M* - Kleene closure* (or Kleene Star) of *M*
- A string in M* if it is the concatenation of ≥0 strings, all in M.
- Thus ((a|b)•a)* represents the infinite set {**"", "aa", "ba", "aaaa", "baaa", "aaba", "baba", "aaaaaa",**...}

Examples

- (0|1)*•0
- b*(abb*)*(a|ε)
- (a|b)*aa(a|b)*
- Conventions:
  - omit • and ε, assume Kleene closure binds tighter than • and concatenation binds tighter than |
  - a • b* means a (b*)
  - ab | c means (a•b)|c
  - (a |) means (a|ε)

Abbreviations (extensions)

[abcd]	means (a | b | c | d)
[b-g]	means [bcdefg]
[^b-g] or ~[b-g]	means everything but [bcdefg]
[b-gM-Qkr]	means [bcdefgMNOPQkr]
M?	means (*M* | ε)
M+	means *M(M)**

Regular expression summary

a or "a"	ordinary character, stands for itself
ε	the empty string
	another way to write the empty string
M | *N*	alternation
M • *N*	concatenation (often written simply as *MN*)
*M**	repetition (zero or more times)
M+	repetition (one or more times)
M?	Optional, zero or one occurrence of M

Regular expression summary

["a"-"z""A"-"Z"]	Character set alternation (JavaCC)
~[]	Any single character (`~[]` is JavaCC form)
"\n" "\t" "\""	newline, tab, double quote (quoted special characters)
"a.+*"	quotation, string stands for itself (in this case **a.+***)
[a-zA-Z]	Character set alternation
.	Any single character except newline

Regular expressions for some tokens

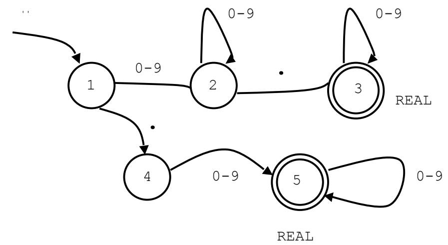
`(" "|"\n"|"\t")`	***no token; whitespace; ignore***
`if`	**IF**
`[a-z][a-z0-9]*`	**ID**
`[0-9]+`	**NUM**
`([0-9]+"."[0-9]*)|([0-9]*"."[0-9]+)`	**REAL**
`("--"[a-z]*"\n")`	***comment starting --; ignore***
`.`	***Error***

Completeness: there must always be a match for some initial substring of the input.
We always want the **longest match.**
Rule Priority: If more than one regexp matches the string, pick the first one from the lexical spec.

Finite Automata

- A finite set of states and edges.
- Edges lead from one state to another. Each edge is labeled by a symbol.
- A single start state and one or more final states.
- Each final state identifies a TOKEN from the language
- A string is accepted if, after all characters have been matched by a transition, the last state is a final state.
- Deterministic or Non-deterministic (NFA) .

Finite automaton



(From Appel Figure 2.3)

DFA Implementation

```
method Token lex() {  //example automaton for REAL only
  int state = 1; String text = "";  char ch;
  while (true) {
    ch = nextchar(); // Get the next input character
    text = text + ch; // Collect text of the token
    if (state == 1) {
      if (ch >= '0' && ch <= '9'){
        state = 2;
      } else if (ch == '.') {
        state = 4;
      } else {
        lexerror(ch);
      }
  }
…
```


DFA Implementation

```
…
else if (state == 5) {
      if ch >= '0'  && ch <= '9') {
        state = 5;
      } else {
        return new Token(REAL,new Double(text));
      }
  } else {
     error ("Illegal state: shouldn't happen");
  }
}
```

- Inefficient and verbose..use transition matrix instead

Efficient DFA implementation

- Create a table that represents the transition matrix
  - int edges[NumStates][NumCharacters]
  - Edges[s][c] = sn
    If there exists a transition labeled with character **c** that joins states **s** and **sn**
  - Index **c** can be extracted from the ASCII code
  - Create a “dead” state that loops to itself on all characters (to denote no match)
- Create an array that marks states as final and maps them to tokens.
- This table can be generated automatically

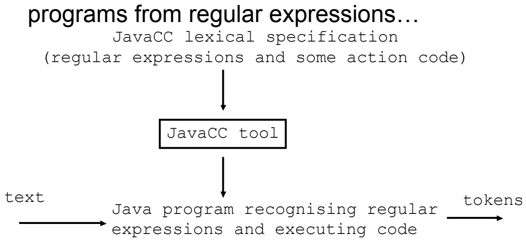
From RegExp to Implmentation

- A RegExp can be converted into an NFA.
- However, the implementation of NFAs is inefficient.
- But NFAs can be translated into DFAs!

All these steps can be automated
There are tools that generate lexical analysers from lexical specifications
E.g. JavaCC

JavaCC compiler-compiler

- Fortunately, tools can produce finite automata programs from regular expressions…



JavaCC token regexps

- Characters and strings must be quoted, eg:
  - ";" "int" "while" "\n" "\"hello\""
- Character lists […] provide a shorthand for |, eg:
  - ["a"-"z"] matches "a" through "z", ["a","e","i","o","u"] matches any single vowel, ~["a","e","i","o","u"] any non-vowel, ~[] any character
- Repetition with + and *, eg:
  - ["a"-"z","A"-"Z"]+ matches one or more letters
  - ["a"-"z"](["0"-"9"])* matches a letter followed by zero or more digits

JavaCC token regexps

- Shorthand with ? provides for optional expr, eg:
  - ("+"|"-")?(["0"-"9"])+ matches signed and unsigned integers
- Tokens can be named
  - TOKEN : {
    < IDENTIFIER: <LETTER> (<LETTER>|<DIGIT>)* >
    }
  - TOKEN : {
    < LETTER: ["a"-"z", "A"-"Z"] >
    | < DIGIT: ["0"-"9"] >
    }
  - now <IDENTIFIER> can be used later in defining syntax

JavaCC lexical analysis example

```
/* file MyParser.jj */

PARSER_BEGIN(MyParser)
   class MyParser {}
PARSER_END(MyParser)

TOKEN : {
     < IF: "if" >
  |  < #DIGIT: ["0"-"9"] >
  |  < ID: ["a"-"z"] (["a"-"z"]|<DIGIT>)* >
  |  < NUM: (<DIGIT>)+ >
  |  < REAL: ( (<DIGIT>)+"."(<DIGIT>)* ) |
             ( (<DIGIT>)*"."(<DIGIT>)+ ) >
}

SKIP : {  // skipped during lexical analysis
     < "--" (["a"-"z"])* ("\n" | "\r" | "\r\n") >
  |  " " | "\t" | "\n" | "\r"
}
```

*# means can use **only** in TOKEN definitions (local)*

JavaCC lexical analysis example

```
void Start() : // the grammar
{Token t;}
{ ( ( t=<IF> | t=<ID> | t=<NUM> | t=<REAL> )
           { System.out.println("token found: "
                 + tokenImage[t.kind]
                 + "('"+t.image+"')"); }
  )* <EOF>
} /* end of file MyParser.jj */
```

```
/* file Main.java */
class Main {
  public static void main(String args[]) throws
                        ParseException {
    …
    MyParser parser = new MyParser(System.in);
    parser.Start();
  }
}
```


JavaCC introduction

- Generates a combined lexical analyser and parser (a Java class)…here the class is called MyParser
- This session we're learning about lexical analysis
  - JavaCC does this and it is the focus of our first example – we'll see more about complete JavaCC-generated parsers later.
- You can see another example in today's lab.

JavaCC introduction

- all you need to know now is that it also generates a Java method to recognize the things we've labelled under 'Start()'
- to make it work,
  - create an object
    MyParser parser = new MyParser(inputstream)
  - and then call the method…parser.Start()

- a class Token is also generated
  - field **image** is the string matched for the token
  - field **kind** can be used to index array **tokenImage** to see the token type

What you should do now…

- Re-read chapter 2
  - You really need to understand regular expressions.
  - Understanding Finite Automata will be helpful as well.
  - Don't worry too much about the translation algorithms and other theoretical issues
  - Think about how to represent real numbers with exponents using regular expressions… because:

Coursework 1

Preamble:

- 30% of total coursework.
- Out this Wednesday.
- Due: Friday 27 February
- Individual or declared pairwork.
- Hand in using Cityspace.
- Guard your work, don't risk plagiarism charges by leaving a USB key with your work around, or "sharing answers" etc.

Assessment 1, part 1

- Use JavaCC **regular expressions** to define precisely *integer literals* and *floating point literals*.
- In this context, 'literal' means the piece of text that appears in a program to denote a number (for example, the text `'3.142'` denotes the number 3.142).
- Implement and test your expressions using JavaCC (make your expressions readable and understandable).

Integer Literals

- An integer literal may be expressed as:
  - *binary*,
  - *decimal*,
  - *hexadecimal*, or
  - *octal* numerals.
- Each may optionally be suffixed with the character `L` to denote an integer of type *long*, and may be prefixed with a `+` or a `-` character to indicate sign.

Integer Literals

- A **decimal numeral** is either the single character `0`, or consists of a digit from `1` to `9`, optionally followed by one or more digits from `0` to `9`.
- A **binary numeral** consists of the leading characters `0b` or `0B` followed by one or more of the digits `0` or `1`.

Integer Literals

- A **hexadecimal numeral** consists of leading characters `0X` or `0x` followed by one or more hexadecimal digits.
- A *hexadecimal digit* is a digit from `0` to `9` or a letter from `a` through `f` or `A` through `F`.
- An **octal numeral** consists of a digit `0` followed by one or more of the digits `0` to `7`.

Integer Literals

- Examples of integer literals:

```
0
19960372
0xDadaCafe
0L
0777L
0xC0B0L
0x00FF00FF
0b00100110
0b110010L
426355690003133711121133114641
```


Floating Point Literals

- A floating point literal has the following parts:
  - a *whole-number part,*
  - a *decimal point* (represented by the period character `.`),
  - a *fractional part,*
  - an *exponent*, and
  - a *type suffix*. A type suffix is either the letter `d` (denoting *double* type) or `f` (denoting *float* type).

Floating Point Literals

- The exponent, if present, is indicated by the letter `e` followed by an optionally signed number.
- At least one digit, in either the whole number or the fraction part is required.
- One of the following is also required:
  - a decimal point,
  - an exponent, or
  - a float type suffix

Floating Point Literals

- All other parts are optional.
- Subject to the previous constraints, the the fractional-part and the number in the exponent are sequences of digits from `0` to `9` (i.e. decimal only).
- The whole-number part is a sequence of digits from `0` to `9` and may optionally be prefixed with a `+` or a `-` character to indicate sign.

Floating Point Literals

- Examples:

```
1e1f        2.f
.3f         0f
3.14f       6.022137e23f
1e1         2.
0.3         0.0
3.14        1e-9d
1e137       -5.56e4263
-42f
```