City University London

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Language Processors

Week 2

Language Processing & Lexical Analysis

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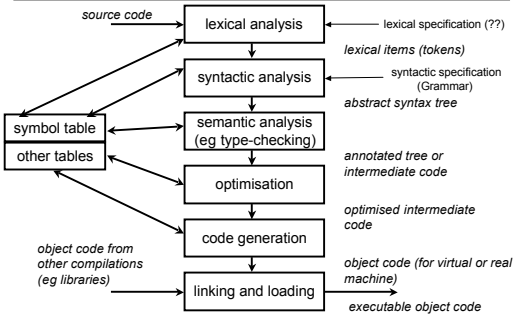
Session Plan

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):

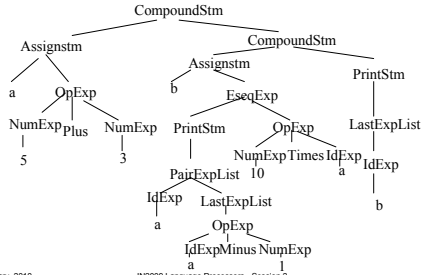
a	:=	5	+	3	;	b	:=	(	print	(	a	,	a	-	1	)	,	10	*	a	)	;	…

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	→	`+` | `-` | `x` | `/`

- 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 is 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]	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")          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.

Example: Lexical Specification

We'll assume "whitespaces" are skipped.

if	**IF**
[a-z][a-z0-9]*	**ID**
.	***Error***

Sample input: "a2", "if", "if2", "02a12".

*What happens if we put **ID** first?*

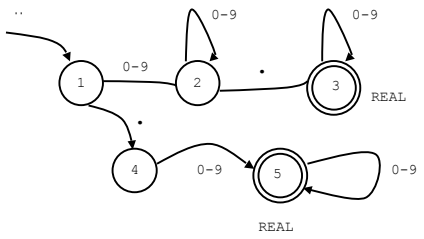
What happens if we put . first?

Can we use .?*

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



([0-9]+"."[0-9]*)|("."[0-9]+)

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

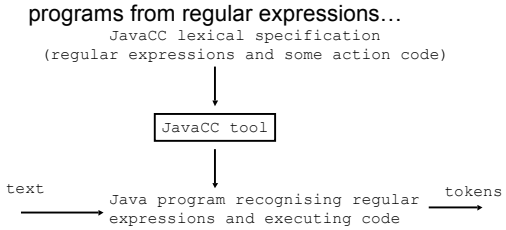
From RegExp to Implementation

- 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 MyParser.java */
class MyParser {
  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.
  - 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()' – this is the default.
  - 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