Lexical Analysis

- Recognize tokens and ignore white spaces, comments

i	f		(	x	1		*	x	2	<	1	.	0	)	{

Generates token stream

if	(	x1	*	x2	<	1.0	)	{

- Error reporting
- Model using regular expressions
- Recognize using Finite State Automata

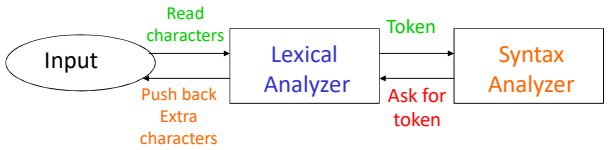
Lexical Analysis

- Sentences consist of string of tokens (a syntactic category)
  For example, number, identifier, keyword, string
- Sequences of characters in a token is a lexeme
  for example, 100.01, counter, const, "How are you?"
- Rule of description is a pattern
  for example, letter (letter | digit)*
- Task: Identify Tokens and corresponding Lexemes

Lexical Analysis

- Examples
- Construct constants: for example, convert a number to token num and pass the value as its attribute,
  - 31 becomes <num, 31>
- Recognize keyword and identifiers
  - counter = counter + increment
    becomes id = id + id
  - check that id here is not a keyword
- Discard whatever does not contribute to parsing
  - white spaces (blanks, tabs, newlines) and comments

Interface to other phases



- Why do we need Push back?
- Required due to look-ahead
  for example, to recognize >= and >
- Typically implemented through a buffer
  - Keep input in a buffer
  - Move pointers over the input

Approaches to implementation

- Use assembly language
  Most efficient but most difficult to implement
- Use high level languages like C
  Efficient but difficult to implement
- Use tools like lex, flex → regular expressions
  Easy to implement but not as efficient as the first two cases

5

Construct a lexical analyzer

- Allow white spaces, numbers and arithmetic operators in an expression
- Return tokens and attributes to the syntax analyzer
- A global variable **tokenval** is set to the value of the number
- Design requires that
  - A finite set of tokens be defined
  - Describe strings belonging to each token

6

```
#include <stdio.h>
#include <ctype.h>
int  lineno = 1;
int tokenval = NONE;
int lex() {
        int t;
        while (1) {
                t = getchar ();
                if (t ==' ' || t == '\t');
                else if (t == '\n') lineno = lineno + 1;
                else if (isdigit (t) ) {
                        tokenval = t - '0' ;
                        t = getchar ();
                        while (isdigit(t)) {
                                tokenval = tokenval * 10 + t - '0' ;
                                t = getchar();
                        }
                        ungetc(t,stdin);
                        return num;
                }
                else { tokenval = NONE; return t; }
        }
}
```

7

Problems

- Scans text character by character
- Look ahead character determines what kind of token to read and when the current token ends
- First character cannot determine what kind of token we are going to read

8

Symbol Table

- Stores information for subsequent phases
- Interface to the symbol table
  - Insert(s,t): save lexeme s and token t and return pointer
  - Lookup(s): return index of entry for lexeme s or 0 if s is not found

9

Implementation of Symbol Table

- Fixed amount of space to store lexemes.
  - Not advisable as it waste space.

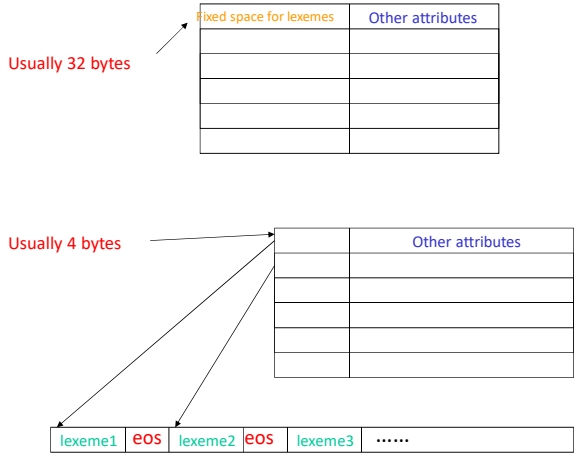
* Statically store

- Store lexemes in a separate array.
  - Each lexeme is separated by eos. → lexeme separated
  - Symbol table has pointers to lexemes. → end of separator

* we get cache benefits as well.

10

See again lect-08



11

How to handle keywords?

- Consider token DIV and MOD with lexemes div and mod.
- Initialize symbol table with insert(“div” , DIV) and insert(“mod” , MOD).
- Any subsequent insert fails (unguarded insert)
- Any subsequent lookup returns the *keyword* value, therefore, these cannot be used as an identifier.

12

Difficulties in the design of lexical analyzers

Is it as simple as it sounds?

Language that is easier for humans is challenging for compilers.

13

Lexical analyzer: Challenges

Design by position

- Lexemes in a fixed position. Fixed format vs. free format languages
- FORTRAN Fixed Format
  - 80 columns per line
  - Column 1-5 for the statement number/label column
  - Column 6 for continuation mark (?)
  - Column 7-72 for the program statements
  - Column 73-80 Ignored (Used for other purpose)
  - Letter C in Column 1 meant the current line is a comment

C6 chars

14

Lexical analyzer: Challenges

- Handling of blanks → white spaces.
  - in C, blanks separate identifiers
  - in FORTRAN, blanks are important *only* in literal strings
  - variable counter is same as count er
  - Another example

    DO 10 I = 1.25 → DO10I=1.25

    DO 10 I = 1,25 → DO10I=1,25

    do loop

i=1 to 25

15

- The first line is a variable assignment

  DO10I=1.25

- The second line is beginning of a

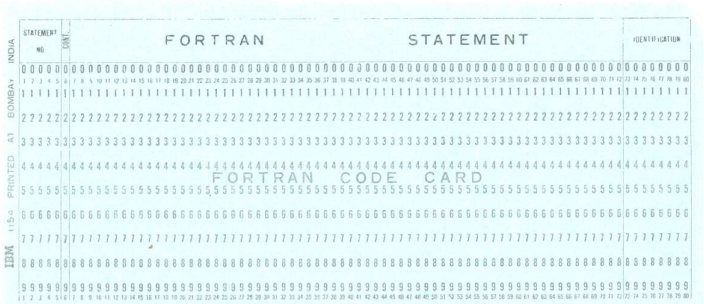
  Do loop

- Reading from left to right one can not distinguish between the two until the "," or "." is reached → We need to keep a large buffer.

16

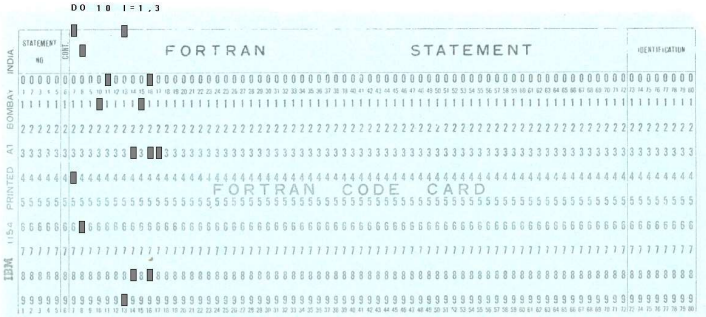
* white spaces are ignored in Fortran
  ⇒ To utilize space better
  ⇒ Readability was not an issue

Fortran white space and fixed format rules came into force due to punch cards and errors in punching



17

Fortran white space and fixed format rules came into force due to punch cards and errors in punching



18

* Python has many types which can be used as identifiers

* In C, printf can be used to confuse programmer

PL/1 Problems

- Keywords are not reserved in PL/1
  if then then then = else else else = then
  if if then then = then + 1
- PL/1 declarations
  Declare(arg_1,arg_2,arg_3,.....,arg_n)
- Cannot tell whether Declare is a keyword or array reference until after ")"
- Requires arbitrary lookahead and very large buffers.

function

19

Problem continues even today!!

- C++ template syntax: Foo<Bar>
- C++ stream syntax: cin >> var;
- Nested templates:
  Foo<Bar<Bazz>>
- Can these problems be resolved by lexical analyzers alone?

Earlier C compilers were not able to understand this.

Regular expression. → No. They sent interpretation to next phase.

20

How to specify tokens?

- How to describe tokens
  2.e0 20.e-01 2.000
- How to break text into token
  if (x==0) a = x << 1;
  if (x==0) a = x < 1;
- How to break input into tokens efficiently
  - Tokens may have similar prefixes
  - Each character should be looked at only once

21

How to describe tokens?

- Programming language tokens can be described by regular languages
- Regular languages
  - Are easy to understand
  - There is a well understood and useful theory
  - They have efficient implementation
- Regular languages have been discussed in great detail in the "Theory of Computation" course

22

Operations on languages

- L U M = {s | s is in L or s is in M}
- LM = {st | s is in L and t is in M}
- L^* = Union of L^i such that $0 \leq i \leq \infty$
  Where $L^0 = \epsilon$ and $L^i = L^{i-1} L$

23

Example

- Let L = {a, b, .., z} and D = {0, 1, 2, … 9} then
- LUD is a set of letters and digits
- LD is a set of strings consisting of a letter followed by a digit
- L^* is a set of all strings of letters including ϵ
- L(LUD)* is a set of all strings of letters and digits beginning with a letter
- D^+ is a set of strings of one or more digits

24

Notation

- Let Σ be a set of characters. A language over Σ is a set of strings of characters belonging to Σ
- A regular expression r denotes a language L(r)
- Rules that define the regular expressions over Σ
  - Є is a regular expression that denotes {ϵ} the set containing the empty string
  - If a is a symbol in Σ then a is a regular expression that denotes {a}

25

- If r and s are regular expressions denoting the languages L(r) and L(s) then
- (r)|(s) is a regular expression denoting L(r) U L(s)
- (r)(s) is a regular expression denoting L(r)L(s)
- (r)* is a regular expression denoting (L(r))*
- (r) is a regular expression denoting L(r)

26

- Let Σ = {a, b}
- The regular expression a|b denotes the set {a, b}
- The regular expression (a|b)(a|b) denotes {aa, ab, ba, bb}
- The regular expression a* denotes the set of all strings {ϵ, a, aa, aaa, …}
- The regular expression (a|b)* denotes the set of all strings containing ϵ and all strings of a's and b's
- The regular expression a|a*b denotes the set containing the string a and all strings consisting of zero or more a's followed by a character b

27

- Precedence and associativity
- *, concatenation, and | are left associative
- * has the highest precedence
- Concatenation has the second highest precedence
- | has the lowest precedence

28

How to specify tokens

- Regular definitions
  - Let r_i be a regular expression and d_i be a distinct name
  - Regular definition is a sequence of definitions of the form
  - $d_1 \rightarrow r_1$
  - $d_2 \rightarrow r_2$
  - .....
  - $d_n \rightarrow r_n$
  - Where each r_i is a regular expression over $\Sigma \cup \{d_1, d_2, \ldots, d_{i-1}\}$

Examples

- My fax number 91-(512)-259-7586
- Σ = digit U {-, (,) }
- Country → $digit^+$ $digit^2$
- Area → '(' $digit^+$ ')' $digit^3$
- Exchange → $digit^+$ $digit^3$
- Phone → $digit^+$ $digit^4$
- Number → country '-' area '-' exchange '-' phone

Examples …

- My email address karkare@iitk.ac.in
- Σ = letter U {@, . }
- letter → a| b| …| z| A| B| …| Z
- name → $letter^+$
- address → name '@' name '.' name '.' name

Examples …

- Identifier
  letter → a| b| …|z| A| B| …| Z
  digit → 0| 1| …| 9
  identifier → letter(letter|digit)*
- Unsigned number in C
  digit → '0'|'1'| …|'9'
  digits → $digit^+$
  fraction → '.' digits | ϵ
  exponent → (E ('+' | '-' | ϵ) digits) | ϵ
  number → digits fraction exponent

Regular expressions in specifications

- Regular expressions describe many useful languages
- Regular expressions are only specifications; implementation is still required
- Given a string s and a regular expression R, does s ∈ L(R) ? → lexical analyzer.
- Solution to this problem is the basis of the lexical analyzers
- However, just the yes/no answer is not sufficient
- Goal: Partition the input into tokens → lexemes.

To tell which class it is in.

1. Write a regular expression for lexemes of each token
   - number → digit+
   - identifier → letter(letter|digit)+
2. Construct R matching all lexemes of all tokens → keyword ⇒ else
   - R = R1 + R2 + R3 + …..
3. Let input be $x_1 \ldots x_n$ — elsex → else x
   - for $1 \le i \le n$ check $x_1 \ldots x_i \in L(R)$
4. $x_1 \ldots x_i \in L(R) \Rightarrow x_1 \ldots x_i \in L(Rj)$ for some j
   - smallest such j is token class of $x_1 \ldots x_i$
5. Remove $x_1 \ldots x_i$ from input; go to (3)

- The algorithm gives priority to tokens listed earlier
  - Treats "if" as keyword and not identifier
- How much input is used? What if
  - $x_1 \ldots x_i \in L(R)$
  - $x_1 \ldots x_j \in L(R)$
  - Pick up the longest possible string in L(R)
  - The principle of "maximal munch"
- Regular expressions provide a concise and useful notation for string patterns
- Good algorithms require a single pass over the input

How to break up text

- Elsex=0

else	x	=	0

elsex	=	0

- Regular expressions alone are not enough
- Normally the longest match wins
- Ties are resolved by prioritizing tokens
- Lexical definitions consist of regular definitions, priority rules and maximal munch principle

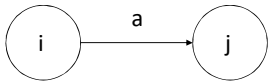
Transition Diagrams

- Regular expression are declarative specifications
- Transition diagram is an implementation
- A transition diagram consists of
  - An input alphabet belonging to Σ
  - A set of states S
  - A set of transitions $state_i \rightarrow^{input} state_j$
  - A set of final states F
  - A start state n
- Transition $s_1 \rightarrow^{a} s_2$ is read:
  - in state s_1 on input a go to state s_2
- If end of input is reached in a final state then accept, Otherwise, reject

Almost like automata

Pictorial notation

- A state
- A final state
- Transition
- Transition from state i to state j on an input a



How to recognize tokens

- Consider

  relop → < | <= | = | <> | >= | >

  id → letter(letter|digit)*

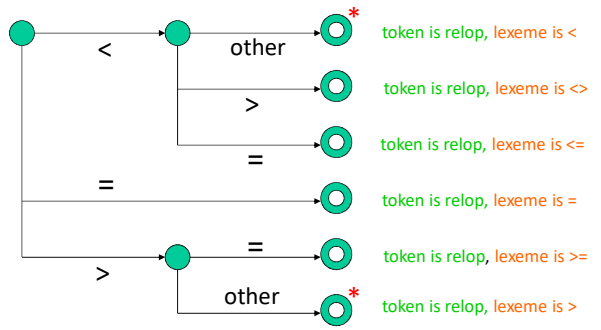
  num → digit⁺ ('.' digit⁺)? (E('+'|'-')? digit⁺)?

  delim → blank | tab | newline

  ws → delim⁺

- Construct an analyzer that will return <token, attribute> pairs

Transition diagram for relops

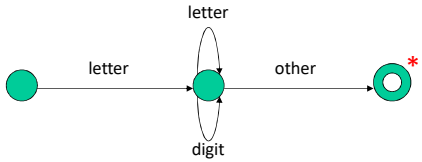


* Pascal doesn't have == comparison with =

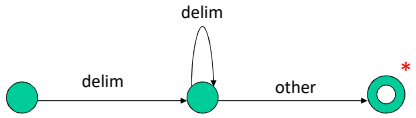
* EOF is considered.
  ↳ It is not a token of lexemes
  ⇒ Marks end of tokens.

* Also, the buffer is finite, we need to mark that as well.

Transition diagram for identifier

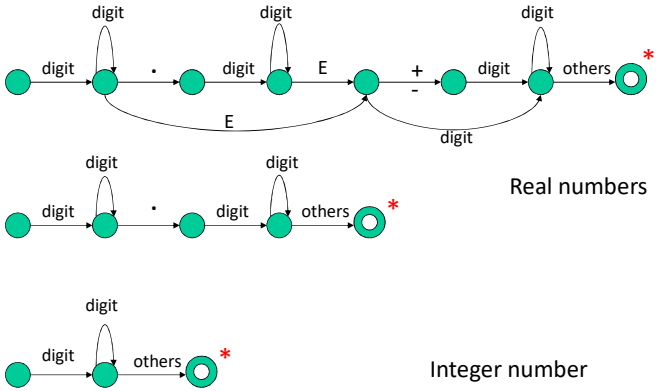


Transition diagram for white spaces



41

Transition diagram for unsigned numbers



Real numbers

Integer number

42

- The lexeme for a given token must be the longest possible
- Assume input to be 12.34E56 → Real not integer.
- Starting in the third diagram the accept state will be reached after 12
- Therefore, the matching should always start with the first transition diagram
- If failure occurs in one transition diagram then retract the forward pointer to the start state and activate the next diagram
- If failure occurs in all diagrams then a lexical error has occurred

43

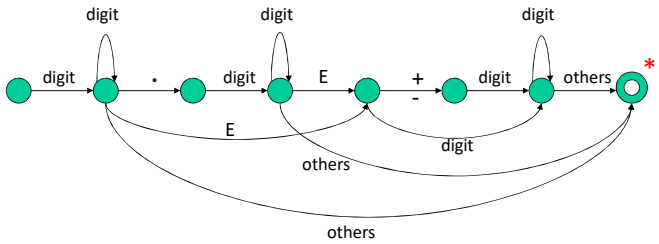
Implementation of transition diagrams

```
Token nexttoken() {
   while(1) {
        switch (state) {
                ……
                case 10: c=nextchar();
                 if(isletter(c)) state=10;
                 elseif (isdigit(c)) state=10;
                 else state=11;
                 break;
                ……
                }
        }
}
```

⇒ Identifier

44

Another transition diagram for unsigned numbers

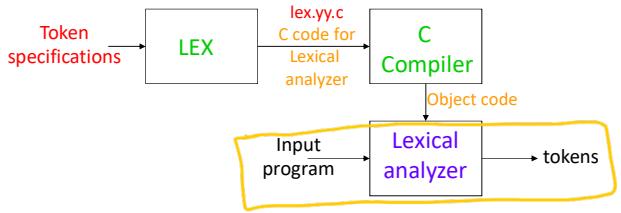


A more complex transition diagram
is difficult to implement and
may give rise to errors during coding, however,
there are ways to better implementation

Lexical analyzer generator

- Input to the generator
  - List of regular expressions in priority order
  - Associated actions for each of regular expression (generates kind of token and other book keeping information)
- Output of the generator
  - Program that reads input character stream and breaks that into tokens
  - Reports lexical errors (unexpected characters), if any

LEX: A lexical analyzer generator



Refer to LEX User's Manual

How does LEX work?

- Regular expressions describe the languages that can be recognized by finite automata
- Translate each token regular expression into a non deterministic finite automaton (NFA)
- Convert the NFA into an equivalent DFA
- Minimize the DFA to reduce number of states
- Emit code driven by the DFA tables