Lexical Analysis

- Recognize tokens and ignore white spaces, comments

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

Generates token stream

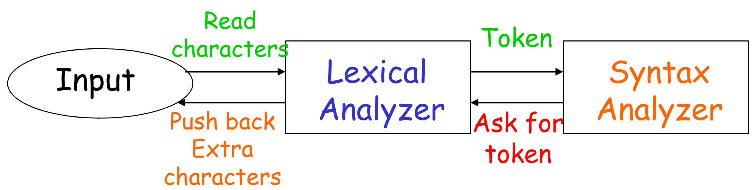
if	(	x1	*	x2	<	1.0	)	{

- 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)*
- Discard whatever does not contribute to parsing like white spaces (blanks, tabs, newlines) and comments
- construct constants: convert numbers to token num and pass number as its attribute, for example, integer 31 becomes <num, 31>
- recognize keyword and identifiers
  for example counter = counter + increment
  becomes id = id + id /*check if id is a keyword*/

Interface to other phases



- Push back is required due to lookahead for example > = and >
- It is 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
  Easy to implement but not as efficient as the first two cases

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


```
#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; }
        }
}
```


Problems

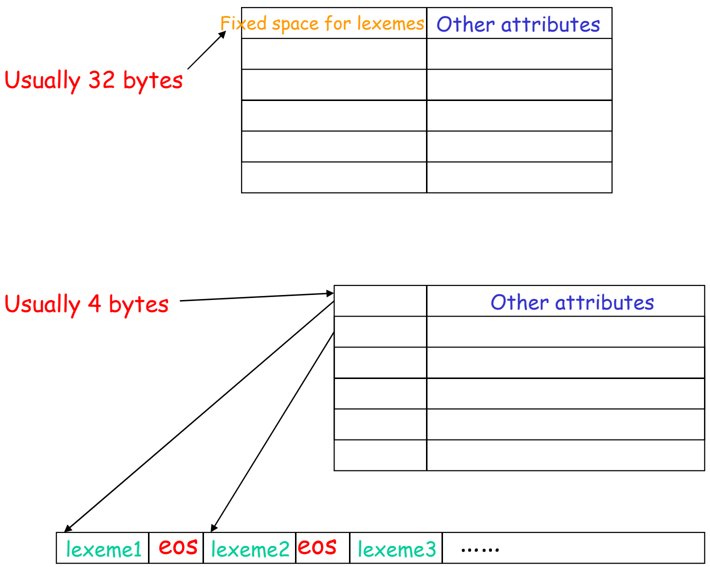
- Scans text character by character
- Look ahead character determines what kind of token to read and when the current token ends
- First character cannot determine what kind of token we are going to read

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

Implementation of symbol table

- Fixed amount of space to store lexemes. Not advisable as it waste space.
- Store lexemes in a separate array. Each lexeme is separated by eos. Symbol table has pointers to lexemes.



How to handle keywords?

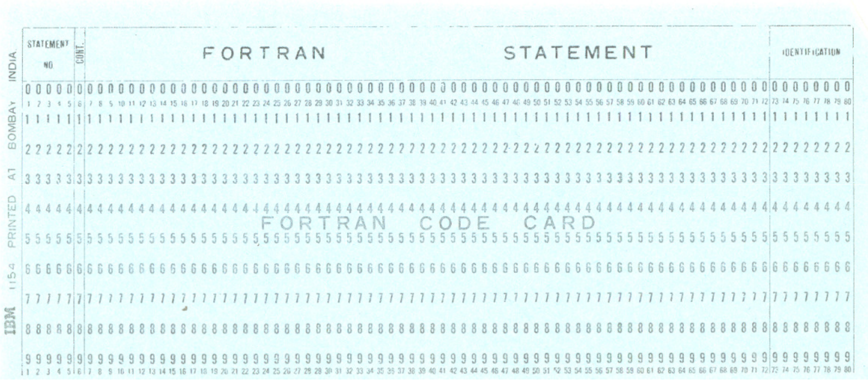
- Consider token DIV and MOD with lexemes div and mod.
- Initialize symbol table with insert("div" , DIV) and insert("mod" , MOD).
- Any subsequent lookup returns a nonzero value, therefore, cannot be used as an identifier.

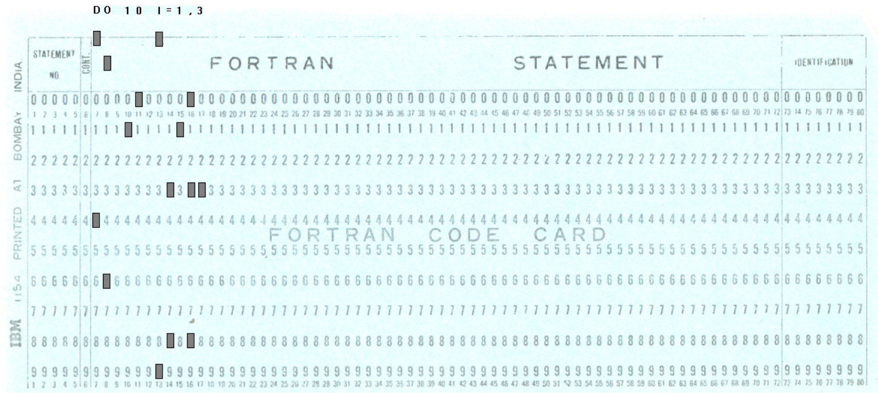
Difficulties in design of lexical analyzers

- Is it as simple as it sounds?
- Lexemes in a fixed position. Fix format vs. free format languages
- Handling of blanks
  - in Pascal, blanks separate identifiers
  - in Fortran, blanks are important only in literal strings for example 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

- The first line is a variable assignment
  DO10I=1.25
- 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

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





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. Worse, the buffers may have to be reloaded.

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?

How to specify tokens?

- How to describe tokens
  2.e0 20.e-01 2.000
- How to break text into tokens
  if (x==0) a = x << 1;
  iff (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

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

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
  - ϵ 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}

- 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)

- Let $\Sigma = \{a, b\}$
- 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

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 = digits 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
  ska@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 Pascal
  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 $s \in L(R)$?
- Solution to this problem is the basis of the lexical analyzers
- However, just the yes/no answer is not important
- Goal: Partition the input into tokens

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
   - R = R1 + R2 + R3 + …..
3. Let input be $x_1 \ldots x_n$
   - 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

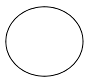
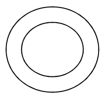
- Elsex=0 | else | x | = | 0 | | elsex | = | 0 |

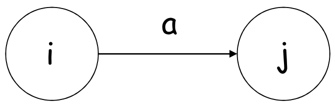
- Regular expressions alone are not enough
- Normally the longest match wins
- Ties are resolved by prioritizing tokens
- Lexical definitions consist of regular definitions, priority rules and maximal munch principle

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 $\text{state}_i \xrightarrow{\text{input}} \text{state}_j$
  - A set of final states F
  - A start state n
- Transition $s1 \xrightarrow{a} s2$ is read:
  in state s1 on input a go to state s2
- If end of input is reached in a final state then accept
- Otherwise, reject

Pictorial notation

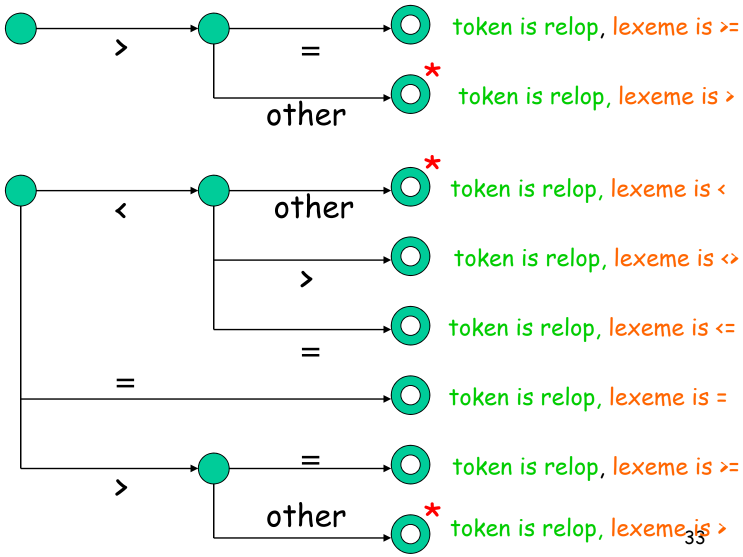
- A state 
- A final state 
- Transition
- Transition from state i to state j on an input a



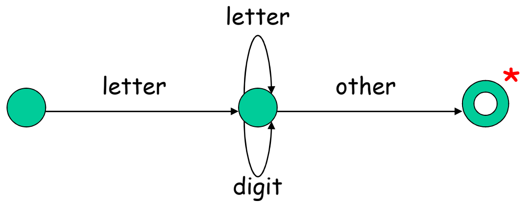
How to recognize tokens

- 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

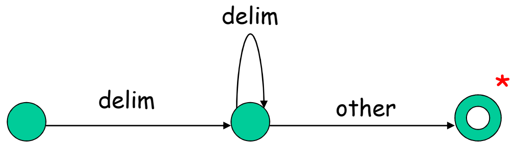
Transition diagram for relops



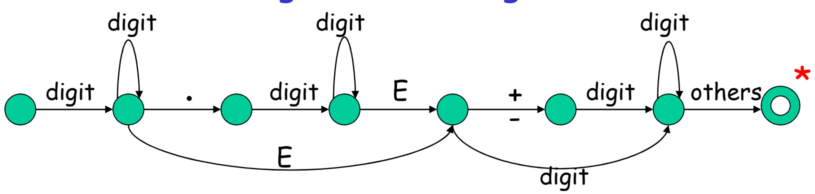
Transition diagram for identifier

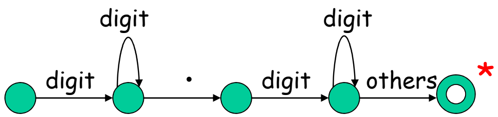


Transition diagram for white spaces

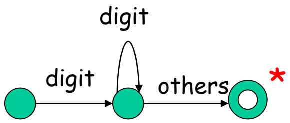


Transition diagram for unsigned numbers





Real numbers



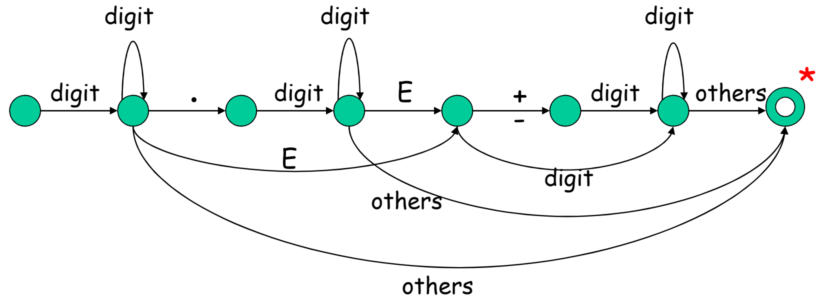
Integer number

- The lexeme for a given token must be the longest possible
- Assume input to be 12.34E56
- 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

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;
                ……
                }
        }
}
```


Another transition diagram for unsigned numbers

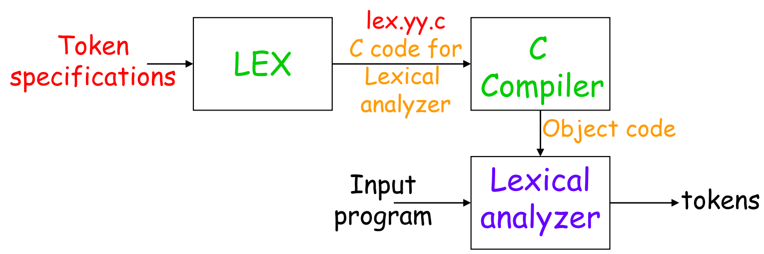


A more complex transition diagram
is difficult to implement and
may give rise to errors during coding,
however,
there are ways to better implementation

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