Lexical Analysis

Roles

- Primary role: Scan a source program (a string) and break it up into small, meaningful units, called *tokens*.
  Example:
  `position := initial + rate * 60;`
  Transform into meaningful units: identifiers, constants, operators, and punctuation.
- Other roles:
  - Removal of comments
  - Case conversion
  - Removal of white spaces
  - Interpretation of compiler directives or pragmas: For instance, in Turbo Pascal `{$R+` means range checking is enabled.
  - Communication with symbol table: Store information regarding an identifier in the symbol table. Not advisable in cases where scopes can be nested.
  - Preparation of output listing: Keep track of source program, line numbers, and correspondences between error messages and line numbers.
- Why separate LA from parser?
  - Simpler design of both LA and parser
  - More efficient compiler
  - More portable compiler

Tokens, Lexemes, and Patterns

- **Token**: a certain classification of entities of a program.
  four kinds of tokens in previous example: *identifiers*, *operators*, *constraints*, and *punctuation*.
- **Lexeme**: A specific instance of a token. Used to differentiate tokens. For instance, both `position` and `initial` belong to the identifier class, however each a different lexeme.
- Lexical analyzer may return a token type to the Parser, but must also keep track of "attributes" that distinguish one lexeme from another.
  Examples of attributes:
  - Identifiers: string
  - Numbers: value

  Attributes are used during semantic checking and code generation. They are not needed during parsing.
- **Patterns**: Rule describing how tokens are specified in a program. Needed because a language can contain infinite possible strings. They all cannot be enumerated.
- Formal mechanisms used to represent these patterns. Formalism helps in describing precisely (i) which strings belong to the language, and (ii) which do not.
  Also, form basis for developing tools that can automatically determine if a string belongs to a language.

How are patterns specified?

- Using a meta-language, called *regular expressions*.
- Alphabet: finite set of symbols. Use term Σ for specifying an alphabet.
- Sentence or term: string.
- Empty string: denoted ϵ, string of length 0.
- Language: Any set of strings defined over an alphabet. From the lexical analyzer point of view, this language denotes the set of all tokens in programming language.
- Define following operators over sets of strings:
  1. Union: $L \cup U$
     $S = L \cup U = \{s | (s \in L) \vee (s \in U)\}$
  2. Concatenation: LU or $L.U$
     $S = L\ U = \{s\ t | (s \in L) \wedge (t \in U)\}$
  3. Kleene closure: L^*, set of all strings of letters, including ϵ,
     $S = L^* = \bigcup_{i=0}^{\infty} L^i$
  4. Positive closure: L^+.
     $S = LL^*$
- Regular expression: a notation for defining the set of tokens that normally occur in programming languages.
- For each regular expression r, there is a corresponding set of strings, say $L(r)$ that is said to be derived from regular expressions. Also called *regular set*.

Regular expressions

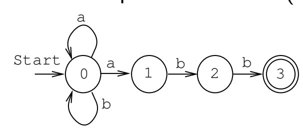
- ϵ is a regular expression.
  $L(\epsilon) = \{\epsilon\}$
  Note that this set is different from an empty set.
- If $a \in \Sigma$, then a is a regular expression.
  $L(a) = \{a\}$
- **Operators:** Assume that `r`, `s` regular expressions. The following operators construct regular expressions from r and s:
  1. Choice $|$: $r|s$
     $L(r|s) = L(r) \cup L(s)$
  2. Concatenation: rs or $r.s$
     $L(rs) = L(r)L(s)$
  3. Kleene closure: r^*
     $L(r^*) = (L(r))^*$
- Any finite set of strings can be represented by a regular expression of the form
  $s_1 | s_2 | \cdots | s_k$
- Some additional operations for notational convenience:
  1. r^+ denoting all strings consisting of one or more r.
     $r^* = (r^+ | \epsilon)$
  2. Not(r): denoting strings in set $(\Sigma^* - L(r))$
  3. r^k: denotes all strings formed by concatenating `k` strings from `L(r)`.

Examples

- $a(b|c)$ represents $\{ab, ac\}$
- a^*b represents $\{b, ab, aab, aaab, \ldots\}$
- $(a|b)^*$ represents any combination of a or b.
- $(ab)^*$ represents $\{\epsilon, ab, abab, ababab, \ldots\}$
- $(a|b)(c|d)$ represents $\{ac, ad, bc, bd\}$
- 0^*10^* represents the set of all strings over $\{0, 1\}$ containing exactly one 1.
- Let $d = (0|\cdots|9), l = (A|\cdots|Z)$
  1. A comment that begins with `--` and ends with `Eol`:
     `Comment = -- Not(Eol)* Eol`
  2. A fixed decimal literal:
     `Lit` = $d^+.d^+$
  3. An identifier, composed of letters, digits, and underscores, that begins with a letter, ends with a letter or digit, and contains no consecutive underscores:
     `Id` = $l(l|d)^*(\_(l|d)^+)^*$
  4. Comment delimited by ## markers, but allow single # within the comment body:
     `Comment2` = $\#\#((\#|\epsilon)Not(\#))^*\#\#$
- Regular expressions are limited in description power. They cannot represent many of the programming language constructs. Cannot describe languages that contain strings of the form: $\{a^n b^n\}$. This language describes balanced parentheses.

How to recognize tokens?

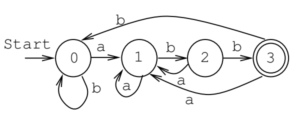
- A *recognizer* for a language L is a program that takes a string x and answers "yes" if $x \in L$ else "no".
- A recognizer, called *finite automaton*, for regular expressions can be constructed from regular expressions.
- Two classes of finite automaton: i) **Nondeterministic** and ii) **Deterministic**.
- Nondeterministic Finite Automaton (NFA): A mathematical model that consists of i) a set of states S, ii) a set of input symbols Σ, iii) a transition function that maps state-symbol pairs to sets of states, iv) a state s_0 that is distinguished as the start state, and v) a set of states F distinguished as accepting or final states.
- An NFA can be represented as a labeled directed graph, called *transition graph*: nodes are states, and labeled edges represent transition function. Also through *Transition table*.
- An NFA accepts an input string x iff there is some path in transition graph from start state to some accepting state.
  Language defined by NFA: set of strings it accepts.
- Example NFA for RE $(a|b)^*abb$:



State	a	b
0	{0, 1}	{0}
1	–	{2}
2	–	{3}

Deterministic Finite Automaton (DFA)

- DFA: special case of NFA where i) no ϵ-transition, and ii) for each state s, input a, only one transition possible. In other words, at every state s, the transition for an input a is known.
- Easy to determine if a DFA accepts a string as there is only one path.
- A nondeterministic finite automaton can be converted into a deterministic finite automaton.
  DFA for $(a|b)^*abb$:



State	a	b
0	1	0
1	1	2
2	1	3
3	1	0

- One entry for each input symbol in the transition table.
- Very easy to determine if a string is accepted by DFA: the transition graph. A scanner driver that interprets a transition table:

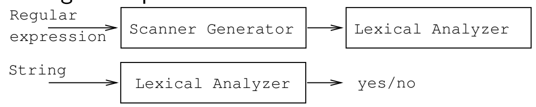
```
State := Initial State;
loop
   NextState := Table(State, CurrentChar);
   exit when NextState = Error;
   State := NextState;
   exit when CurrentChar = Eof;
   Read(CurrentChar);
end loop
if State in FinalStates then return valid token
else LexicalError;
```


Approaches to building Scanner

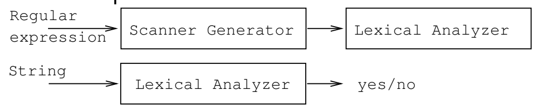
- Many ways in which a scanner can be built.
- Approach 1: Construct an NFA from the regular expression specification, and use an NFA simulator (ASU Alg.3.4) for simulating the generated NFA.
  Number of states: $O(|r|)$, where $|r|$ is the length of regular expression.
  Time Cost: $O(|r| \times |x|)$ where $|x|$ is string length.
  Space Requirements: $O(|r|)$
- Approach 2: Construct DFA from the NFA and then simulate the DFA. In this approach, there is a possibility of state explosion.
  Time: $O(|x|)$
  Space: $O(2^{|r|})$
- Approach 3: lazy transition evaluation. Construct a transition as and when needed. The computed transition table is stored in a cache. Each time a transition is about to be made, the cache is consulted. If it does not exist, compute the new transition.
  Combines the space requirements of the NFA with method with time requirement of DFA.
  Space requirements: size of cache + $|r|$
  Observed running time is almost as fast as that of DFA recognizer. Sometimes faster because does not compute transition tables that need not be computed.

Tools for constructing Scanners

- Several tools for building lexical analyzers from special purpose notation based on regular expressions.



- Lex produces an entire scanner module that can be compiled and linked with other compiler modules.



- Three components of a lex program:

```
declarations
%%
transition rules
%%
auxiliary procedures
```

  Any part may be omitted, but separators must appear.
- lex generate a function `yylex`. Every time `yylex` is called, it returns a token.

Lex - cont'd.

- Part 1: Define pattern for a token and give it a symbolic name, so that the name can be used when referring to the token in description and action part.

```
digs        [0-9]+
integer     {digs}
```

  It can also contain variables and other declarations to be included in the C code generated by Lex. Usually defined in the beginning and included in {% and %}:

```
%{
    int linecount = 1;
%}
```

- Part 3: In certain cases, actions associated with tokens may be complex enough to warrant function and procedure definitions. Such procedures can be defined in the third section.
- Second part (transition rules): specifies how to define tokens and what actions to take when tokens are identified. For instance, return the identifier (say an integer value) for the token.
  Part 1 and Part 3 are mostly to enable define second part.

```
{real}        {return FLOAT;}
begin         {return BEGIN;}
whitespace    ;
```

- Lex maintains a set of variables to define attributes of lexemes.
  - `yytext`: Actual contents of the lexeme identified.
  - `yyleng`: Length of the lexeme.
  - `yylval`: used to store lexical value of token if any.
  - `yylineno`: number of the current input line.

How are tokens specified in Lex?

[xz]	x or z
[x - z]	x through z
[^x]	Any character except x
.	Any character except end of line
^x	An x at the beginning of a line
x$	An x at the end of a line
x?	Optional x
x*	0 or more instances of x
x+	1 or more instances of x
x{m,n}	m through n occurrences of x
x|y	x or y
(x)	same as x
x/y	x only if followed by y

- Examples:
  - Single character such as b matches b in source program.
    Special characters such as ., %, (,), etc. have special meaning. Use "(".
  - `[a-dw-z] = a|b|c|d|w|y|z`
  - `a(b|c)` means ab or ac.
  - ab? is equivalent to a|ab and (ab)? is equivalent to ab|ϵ.
  - `[a-z]$    match a=z if at end of line`
    `~[a-z]    match a=z if at beginning of line`

Lex: Example 2

A scanner that adds line numbers to text:

```
%{
  #include <stdio.h>
  int lineno = 1;
%}
line  .*\n
%%
{line}   {printf("%5d %s'', lineno++, yytext);}
%%
main() {
  yylex(); return 0;
}
```

A scanner that selects only lines that end or begin with letter 'a':

```
%{
  #include <stdio.h>
%}
ends_with_a    .*a\n
begins_with_a  a.*\n
%%
{ends_with_a}     ECHO;
{begins_with_a}   ECHO;
.*\n                ;
%%
main() {
  yylex(); return 0;
}
```

Example 3: Pascal lexemes

```
digit     [0-9]
digits    {digit}+
letter    [A-Za-z]
lr        ({letter}|{digit})
sign      [+\-]
dtdgts    {dot}{digits}
exponent  {Ee]{sign}?{digits}
real      {digits}({dtdgts}|{exponent}|{dtdgts}{exponent})
ident     {letter}{l_or_d}*
newline   [\n]
quote     [\"]
wspace    [ \t]
comment   ("{"[^}]*"}"|"(*""("*([^*)]|[^*]")"|"*"[^)])*"*"*"*)")
string    \'([^'\n]|\'\')+\'
badstring {quote}['"]*{quote}
dotdot    ".."
dot       "."
other     .
```


Practical Considerations

- How to handle words such as `if` and `while`? Note that these words match lexical syntax of ordinary identifiers.
- Most languages make such words reserved. Facilitates parsing and ease of programming. If not, what does the following string really mean?

  ```
  if if then else = then;
  ```
- Reserving such words makes regular expression complicated because reserved words are similar to identifiers.
  - Use nots
  - Directly write regular expression (very hard though)
- Simple solution: Treat reserved words as ordinary identifiers and use a separate table look up to detect them.
- Another solution: Define distinct regular expression for each reserved word. A string may match more than one regular expression. Define some mechanism for choosing one of them. In Lex, order of listing of token specifications makes a difference.

  ```
  if        {return(IF);}
  then      {return(THEN);}
  {id}      {return(ID);}
  ```

  Problem: Underlying finite automaton and its transition table will be significantly larger.

Practical Considerations: multi-character lookahead

- Some languages require considerable analysis to resolve ambiguities in tokens, in particular FORTRAN.
  Example: two statements and corresponding lexical views:

  ```
  do 100 x = 1, 10       do100x=1,10
  do 100 x = 1.  10      do100x=1.10
  ```

  In one case, a do loop and another assignment to a variable `do100x`. Scanner cannot determine if it is a do loop or variable assignment until it reaches ',' char.
- Milder form in Pascal or ADA: To scan `10..100`, need two character lookahead after the 10.
- Solution: requires backtracking through the states. Fortran scanner puts a temporary marker after do, and continues looking until it has found a comma, a period, or the end of the statement. If a comma, return to marker else ignore marker and pass `do100x` to parser.
- In Ada, tic char `'` used both as as attribute symbol (`arrayname'length`) and to delimit character literals (`'x'`).
  Solution: Treat tic char as a special case. When a tic is seen, a flag (set by the parser) is checked to see if an attribute symbol or character literal may be read next.
- In Lex, use operator '/' to represent such lookaheads: r1/r2 implies recognize string denoted by `r1` if followed by `r2`.

  ```
  DO/(letter| digit)* = (letter| digit)*,
  ```


Practical Considerations - cont'd.

Lexical Errors

- Scanner may come across certain errors: invalid character, invalid token etc. Usually detected by reaching a state that is not final and there are no transitions for the current input symbol.
- Cannot uncover syntactical, semantic or logical errors: view of the lexical analyzer is localized.
- What to do when lexical errors occur?
  - Delete the characters read so far and restart scanning at the next unread character.
  - Delete the first character read by the scanner and resume scanning at the character following it.
  - Local transformations: replace a char by another, transpose adjacent chars etc.
- Note that error recovery at this stage may create errors in the parsing stage: for instance, replace `beg#in` by `beg in` which will cause error during the parsing phase.
  Other approach could be for the scanner to provide a certain warning token to the parser. Parser can use this information to do syntactic error-repair.
- Error recovery of a common problem: runaway comments and strings. Possible solutions: Introduce error token that represent a runaway string or comment. Once the runaway error token is recognized, a special error message may be issued.