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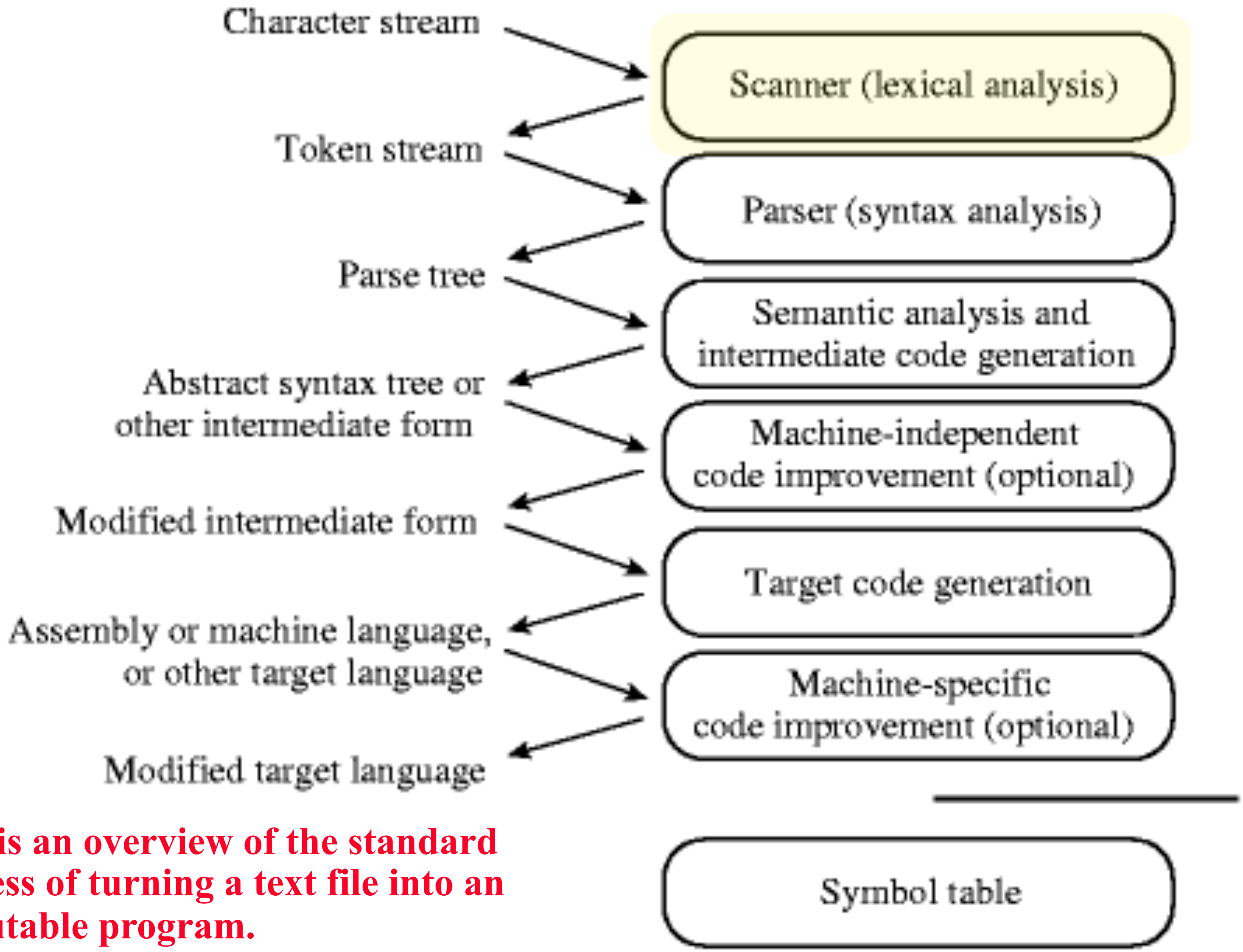
Lexical analysis

Concepts

- Lexical scanning
- Regular expressions
- DFAs and FSAs
- Lex

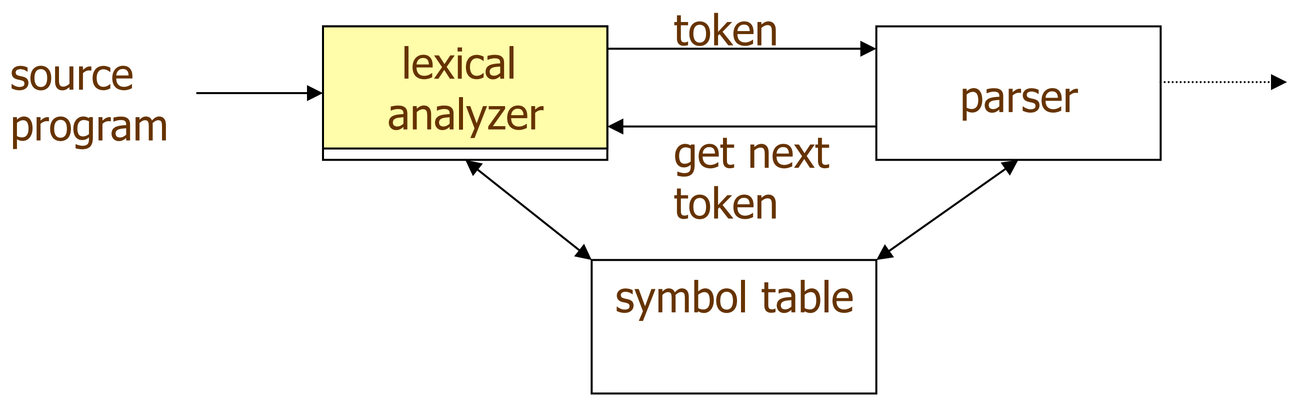


This is an overview of the standard process of turning a text file into an executable program.

Lexical analysis in perspective

LEXICAL ANALYZER: Transforms character stream to token stream

– Also called scanner, lexer, linear analysis, or tokenizer



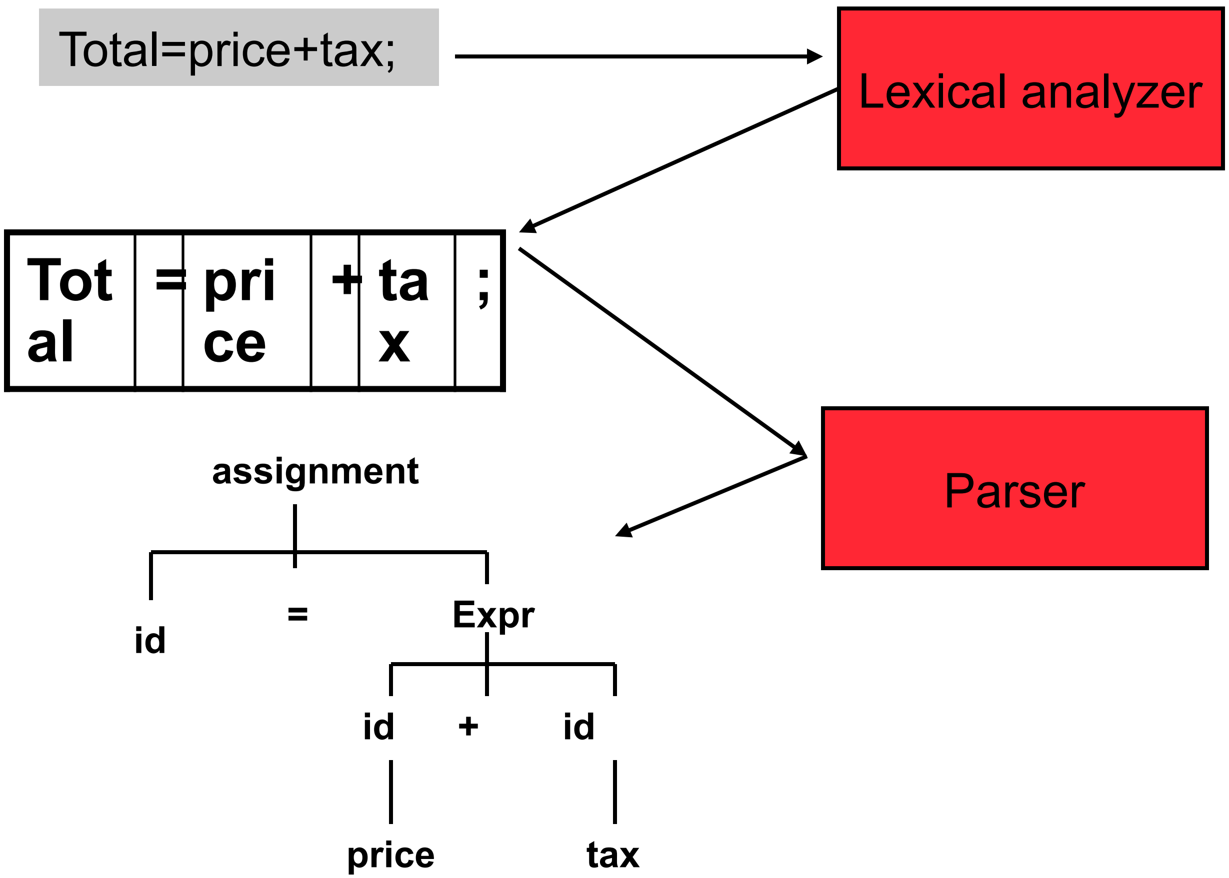
LEXICAL ANALYZER

– Scans Input
– Removes whitespace, newlines, …
– Identifies Tokens
– Creates Symbol Table
– Inserts Tokens into symbol table
– Generates Errors
– Sends Tokens to Parser

PARSER

– Performs Syntax Analysis
– Actions Dictated by Token Order
– Updates Symbol Table Entries
– Creates Abstract Rep. of Source
– Generates Error messages

Where we are



Total=price+tax;
Lexical analyzer
Tot al
=
pri ce
+
ta x
;
Parser
assignment
id
=
Expr
id
+
id
price
tax

Basic lexical analysis terms

- Token
  - A classification for a common set of strings
  - Examples: <identifier>, <number>, etc.
- Pattern
  - The rules which characterize the set of strings for a token
  - Recall file and OS wildcards (*.java)
- Lexeme
  - Actual sequence of characters that matches a pattern and is classified by a token
  - Identifiers: x, count, name, etc…

Examples of token, lexeme and pattern

if (price + gst – rebate <= 10.00) gift := false

Token	lexeme	Informal description of pattern
if	if	if
Lparen	(	(
Identifier	price	String consists of letters and numbers and starts with a letter
operator	+	+
identifier	gst	String consists of letters and numbers and starts with a letter
operator	-	-
identifier	rebate	String consists of letters and numbers and starts with a letter
Operator	<=	Less than or equal to
constant	10.00	Any numeric constant
rparen	)	)
identifier	gift	String consists of letters and numbers and starts with a letter
Operator	:=	Assignment symbol
identifier	false	String consists of letters and numbers and starts with a letter

Regular Expressions (REs)

- Scanners are based on *regular expressions* that define simple patterns
- REs are simpler and less expressive than BNF
- Examples of regular expressions:

  letter: a|b|c|...|z|A|B|C...|Z

  digit: 0|1|2|3|4|5|6|7|8|9

  identifier: letter (letter | digit)*

- Basic operations are (1) set union, (2) concatenation and (3) Kleene closure
- Plus: parentheses, naming patterns
- No recursion! (Why not? We'll see…)

Regular expression (REs)

Example

letter: a|b|c|...|z|A|B|C...|Z

digit: 0|1|2|3|4|5|6|7|8|9

identifier: letter (letter | digit)*

letter (letter | digit) *

concatenation: one pattern followed by another

letter (letter | digit) *

set union: one pattern or another

letter (letter | digit) *

Kleene closure: zero or more repetions of a pattern

Regular expressions are extremely useful in many applications. Mastering them will serve you well.

Formal language operations

Operation	Notation	Definition	Example L={a, b} M={0,1}
union of L and M	L ∪ M	L ∪ M = {s | s is in L or s is in M}	{a, b, 0, 1}
concatenation of L and M	LM	LM = {st | s is in L and t is in M}	{a0, a1, b0, b1}
Kleene closure of L	L*	L* denotes zero or more concatenations of L	All the strings consists of "a" and "b", plus the empty string. {ε, a, b, aa, bb, ab, ba, aaa, …}
positive closure	L+	L+ denotes "one or more concatenations of " L	All the strings consists of "a" and "b". {a, b, aa, bb, ab, ba, aaa, …}

Regular expression

- Let Σ be an alphabet and *r* be a regular expression. Then L(*r*) is the language that is characterized by the rules of *r*
- Definition of regular expression
  - ε is a regular expression that denotes the language {ε}
  - If a is in Σ, a is a regular expression that denotes {a}
  - Let r & s be regular expressions with languages L(r) & L(s)
    - » (r) | (s) is a regular expression → L(r) ∪ L(s)
    - » (r)(s) is a regular expression →L(r) L(s)
    - » (r)* is a regular expression → (L(r))*
- A regular language is a language that can be defined by a regular expression

Regular expression example revisited

- Examples of regular expression

```
Letter:  a|b|c|...|z|A|B|C...|Z
Digit: 0|1|2|3|4|5|6|7|8|9
Identifier: letter (letter | digit)*
```

- Q: why it is an regular expression?
  – Because it only uses the operations of union, concatenation and Kleene closure
- Being able to name patterns is just syntactic sugar
- Using parentheses to group things is just syntactic sugar provided we specify the precedence and associativity of the operators (i.e., |, * and "concat")

Another common operator: +

- The + operator is commonly used to mean "one or more repetitions" of a pattern
- For example, letter^+ means one or more letters
- We can always do without this, e.g.

  letter^+ is equivalent to letter letter^*

Precedence of operators

- * and + have the highest precedence;
- Concatenation comes next;
- | is lowest.
- All the operators are left associative.
- Example
  - (a) | ((b)*(c)) is equivalent to a|b*c
  - What strings does this RE generate or match?

Epsilon

- Sometimes we need a token that represents nothing
- This makes a regular expression matching more complex, but can be useful
- We use the lower case Greek letter epsilon, ε, for this special token
- Example:

  digit: 0|1|2|3|4|5|6|7|8|9|0

  sign: +|-|ε

  int: sign digit

Properties of regular expressions

We can easily determine some basic properties of the operators involved in building regular expressions

<table>
<tr><th>Property</th><th>Description</th></tr>
<tr><td>r|s = s|r</td><td>| is commutative</td></tr>
<tr><td>r|(s|t) = (r|s)|t</td><td>| is associative</td></tr>
<tr><td>(rs)t=r(st)</td><td>Concatenation is associative</td></tr>
<tr><td>r(s|t)=rs | rt
(s|t)r=sr | tr</td><td>Concatenation distributes over |</td></tr>
<tr><td>… …</td><td></td></tr>
</table>

Notational shorthand of regular expression

- One or more instance – the + operator
  - L+ = L L*
  - L* = L+ | ε
  - Examples
    - » digits: digit digit*
    - » digits: digit+

More syntatic sugar

- Zero or one instance – the ? operator
  - L? = L|ε
  - Examples
    - » Optional_fraction→.digits|ε
    - » optional_fraction→(.digits)?
- Character classes – the [] operators
  - [abc] = a|b|c
  - [a-z] = a|b|c...|z

Regular grammar and regular expression

- They are equivalent
  - Every regular expression can be expressed by regular grammar
  - Every regular grammar can be expressed by regular expression
- Example
  - An identifier must begin with a letter and can be followed by arbitrary number of letters and digits.

Regular expression	**Regular grammar**
ID: LETTER (LETTER | DIGIT)*	ID → LETTER ID_REST ID_REST → LETTER ID_REST | DIGIT ID_REST | EMPTY

Formal definition of tokens

- A set of tokens is a set of strings over an alphabet

  {read, write, +, -, *, /, :=, 1, 2, …, 10, …, 3.45e-3, …}

- A set of tokens is a *regular set* that can be defined by using a *regular expression*
- For every regular set, there is a *deterministic finite automaton* (DFA) that can recognize it
  - Aka deterministic *Finite State Machine* (FSM)
  - *i.e.* determine whether a string belongs to the set or not
  - Scanners extract tokens from source code in the same way DFAs determine membership

Token Definition Example

- Numeric literals in Pascal, e.g.

  1, 123, 3.1415, 10e-3, 3.14e4

- Definition of token *unsignedNum*

  DIG → 0|1|2|3|4|5|6|7|8|9

  unsignedInt → *DIG DIG**

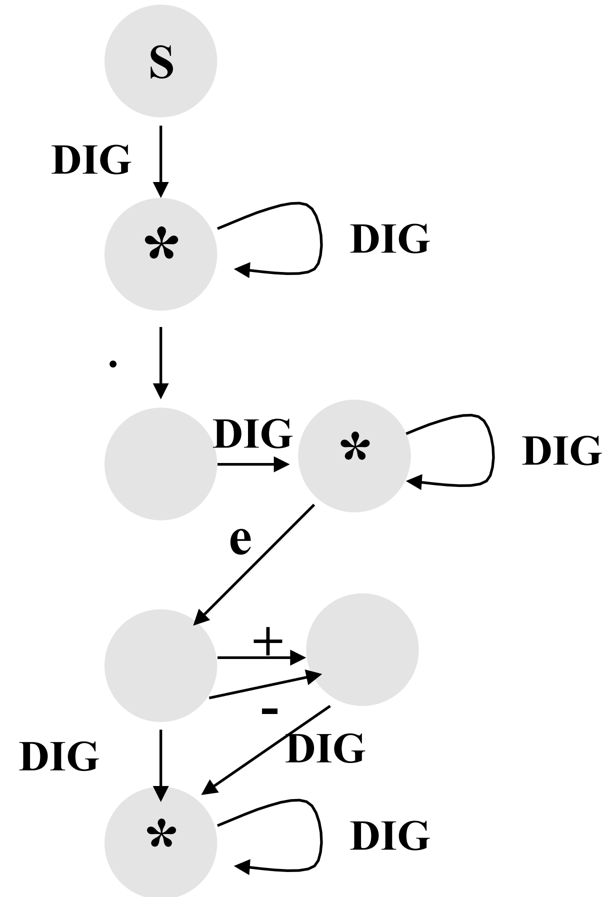
  unsignedNum →

  unsignedInt

  ((. *unsignedInt*) | ε)

  ((e (+ | – | ε) *unsignedInt*) | ε)

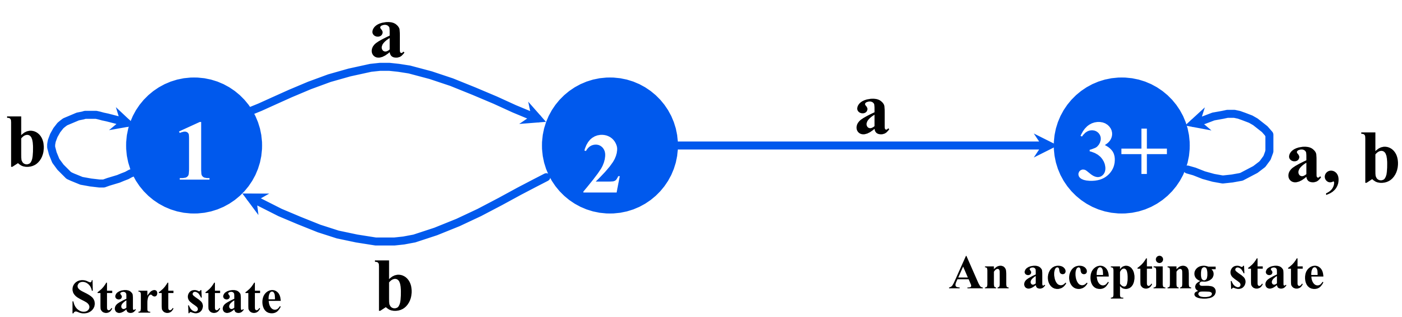
- Notes:
  - Recursion restricted to leftmost or rightmost position on LHS
  - Parentheses used to avoid ambiguity
  - It's always possible to rewrite removing epsilons (ε)



- **FAs with epsilons are nondeterministic.**
- **NFAs are much harder to implement (use backtracking)**
- **Every NFA can be rewritten as a DFA (gets larger, though)**

Simple Problem

- Write a program which reads in a character string, consisting of a's and b's, one character at a time. If the string contains a double aa, then print string *accepted* else print string *rejected*.
- An abstract solution to this can be expressed as a DFA



The state transitions of a DFA can be encoded as a table which specifies the new state for a given current state and input

current state \ *input*	a	b
1	2	1
2	3	1
3	3	3

one approach in C

```
#include <stdio.h>
main()
{   enum State {S1, S2, S3};
    enum State currentState = S1;
    int c = getchar();
    while (c != EOF) {
        switch(currentState) {
          case S1:  if (c == ‘a’) currentState = S2;
                    if (c == ‘b’) currentState = S1;
                    break;
          case S2:  if (c == ‘a’) currentState = S3;
                    if (c == ‘b’) currentState = S1;
                    break;
          case S3:  break;
         }
         c = getchar();
     }
     if (currentState == S3) printf(“string accepted\n”);
     else printf(“string rejected\n”);
}
```

using a table simplifies the program

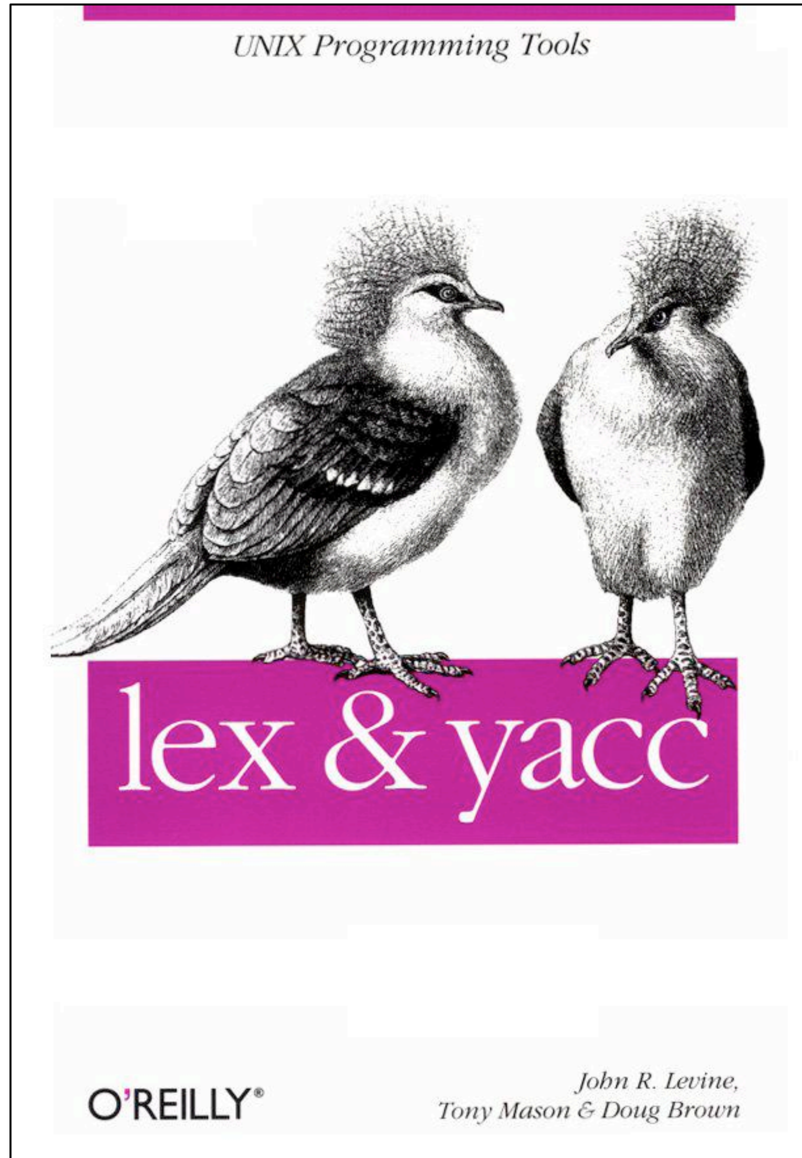
```
#include <stdio.h>
main()
{  enum State {S1, S2, S3};
   enum Label {A, B};
   enum State currentState = S1;
   enum State table[3][2] = {{S2, S1}, {S3, S1}, {S3, S3}};
   int label;
   int c = getchar();
   while (c != EOF) {
        if (c == ‘a’) label = A;
        if (c == ‘b’) label = B;
        currentState = table[currentState][label];
        c = getchar();
    }
   if (currentState == S3) printf(“string accepted\n”);
   else printf(“string rejected\n”);
}
```

Lex

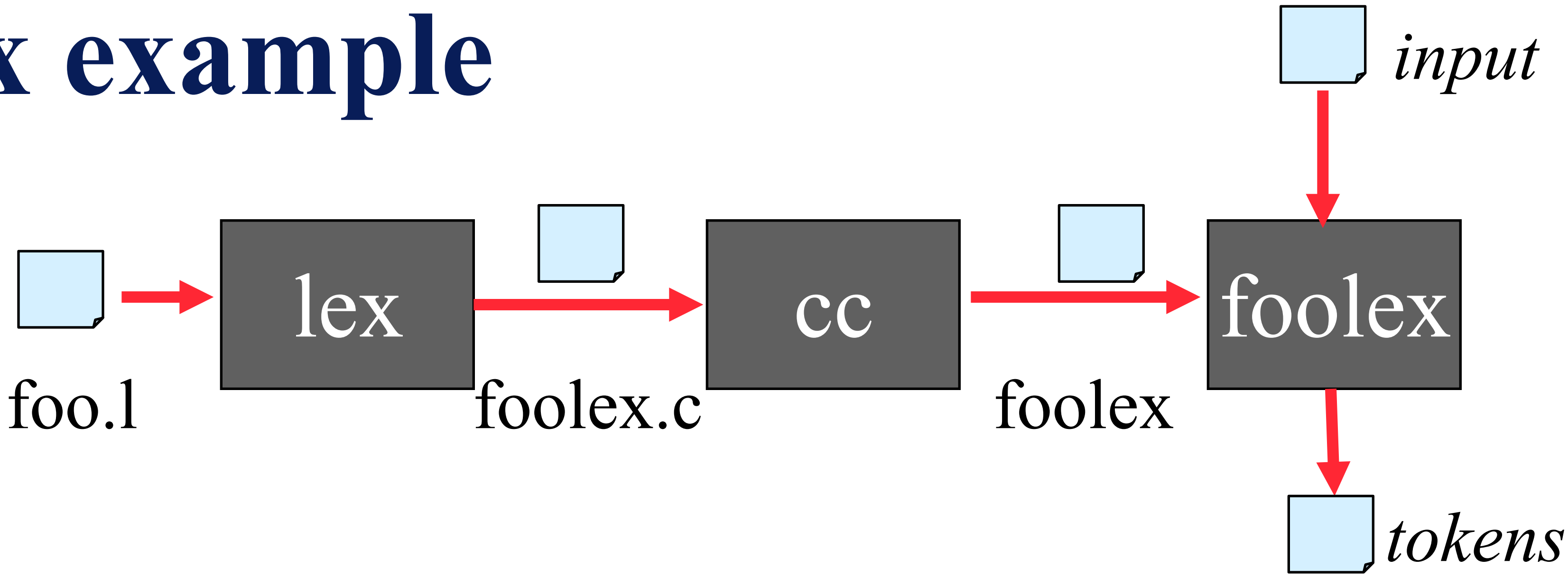
- Lexical analyzer generator
  - It writes a lexical analyzer
- Assumption
  - each token matches a regular expression
- Needs
  - set of regular expressions
  - for each expression an action
- Produces
  - A C program
- Automatically handles many tricky problems
- flex is the gnu version of the venerable unix tool lex.
  - Produces highly optimized code

Scanner Generators

- E.g. lex, flex
- These programs take a table as their input and return a program (*i.e.* a scanner) that can extract tokens from a stream of characters
- A very useful programming utility, especially when coupled with a *parser generator* (e.g., yacc)
- standard in Unix



Lex example




```
> flex -ofoolex.c foo.l
> cc -ofoolex foolex.c -lfl
```

```
>more input
begin
  if size>10
    then size * -3.1415
end
```

```
> foolex < input
Keyword: begin
Keyword: if
Identifier: size
Operator: >
Integer: 10 (10)
Keyword: then
Identifier: size
Operator: *
Operator: -
Float: 3.1415 (3.1415)
Keyword: end
```

Examples

- The examples to follow can be accessed on gl
- See /afs/umbc.edu/users/f/i/finin/pub/lex

```
% ls -l /afs/umbc.edu/users/f/i/finin/pub/lex
total 8
drwxr-xr-x 2 finin faculty 2048 Sep 27 13:31 aa
drwxr-xr-x 2 finin faculty 2048 Sep 27 13:32 defs
drwxr-xr-x 2 finin faculty 2048 Sep 27 11:35 footranscanner
drwxr-xr-x 2 finin faculty 2048 Sep 27 11:34 simplescanner
```

A Lex Program

```
... definitions ...
%%
... rules ...
%%
... subroutines ...
```

```
DIG [0-9]
ID [a-z][a-z0-9]*
%%
{DIG}+              printf("Integer\n”);
{DIG}+"."{DIG}*     printf("Float\n”);
{ID}                printf("Identifier\n”);
[ \t\n]+            /* skip whitespace */
.                   printf(“Huh?\n");
%%
main(){yylex();}
```


Simplest Example

```
%%
.|\n        ECHO;
%%
main()
{
   yylex();
}
```

- No definitions
- One rule
- Minimal wrapper
- Echoes input

Strings containing aa

```
%%
(a|b)*aa(a|b)*      {printf("Accept %s\n", yytext);}

[a|b]+              {printf("Reject %s\n", yytext);}

.|\n                ECHO;
%%
main() {yylex();}
```

Rules

- Each has a rule has a *pattern* and an *action*
- Patterns are regular expression
- Only one action is performed
  - The action corresponding to the pattern matched is performed
  - If several patterns match the input, the one corresponding to the **longest** sequence is chosen
  - Among the rules whose patterns match the same number of characters, the rule given first is preferred

Definitions

- The definitions block allows you to name a RE
- If the name appears in curly braces in a rule, the RE will be substituted

```
DIG [0-9]

%%

{DIG}+              printf("int: %s\n", yytext);
{DIG}+"."{DIG}*     printf("float: %s\n", yytext);
.                   /* skip anything else */

%%

main(){yylex();}
```



```
/* scanner for a toy Pascal-like language */
%{
#include <math.h> /* needed for call to atof() */
%}
DIG [0-9]
ID    [a-z][a-z0-9]*
%%
{DIG}+                printf("Integer: %s (%d)\n", yytext, atoi(yytext));
{DIG}+"."{DIG}* printf("Float: %s (%g)\n", yytext, atof(yytext));
if|then|begin|end     printf("Keyword: %s\n",yytext);
{ID}                  printf("Identifier: %s\n",yytext);
"+"|"-"|"*"|"/"       printf("Operator: %s\n",yytext);
"{"[^}\n]*"}"         /* skip one-line comments */
[ \t\n]+              /* skip whitespace */
.                     printf("Unrecognized: %s\n",yytext);
%%
main(){yylex();}
```

Flex's RE syntax

x character 'x'

. any character except newline

[xyz] *character class*, in this case, matches either an 'x', a 'y', or a 'z'

[abj-oZ] *character class* with a range in it; matches 'a', 'b', any letter from 'j' through 'o', or 'Z'

[^A-Z] *negated character class*, i.e., any character but those in the class, e.g. any character except an uppercase letter.

[^A-Z\n] any character EXCEPT an uppercase letter or a newline

r* zero or more r's, where r is any regular expression

r+ one or more r's

r? zero or one r's (i.e., an optional r)

{name} expansion of the "name" definition

"[xy]\"foo" the literal string: '[xy]"foo' (note escaped ")

x if x is an 'a', 'b', 'f', 'n', 'r', 't', or 'v', then the ANSI-C interpretation of \x. Otherwise, a literal 'x' (e.g., escape)

rs RE r followed by RE s (e.g., concatenation)

r|s either an r or an s

<<EOF>> end-of-file