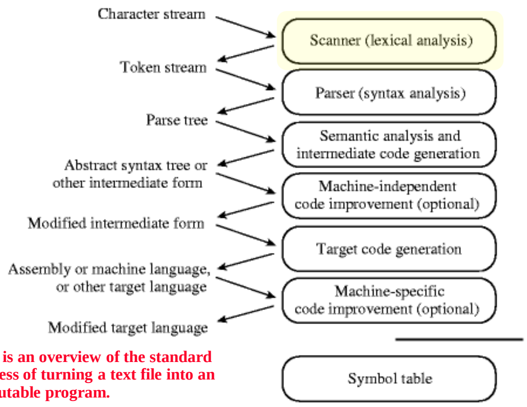
4a

Lexical analysis

Concepts

- Overview of syntax and semantics
- Step one: lexical analysis
  - –Lexical scanning
  - –Regular expressions
  - –DFAs and FSAs
  - –Lex



Character stream

Scanner (lexical analysis)

Token stream

Parser (syntax analysis)

Parse tree

Semantic analysis and intermediate code generation

Abstract syntax tree or other intermediate form

Machine-independent code improvement (optional)

Modified intermediate form

Target code generation

Assembly or machine language, or other target language

Machine-specific code improvement (optional)

Modified target language

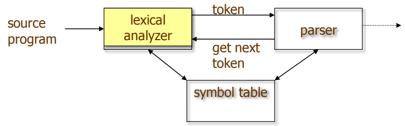
Symbol table

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



source program

lexical analyzer

token

get next token

parser

symbol table

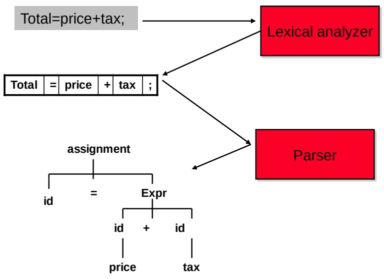
LEXICAL ANALYZER

– 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 Errors

Where we are



Total=price+tax;

Lexical analyzer

Total | = | price | + | tax | ;

Parser

assignment

id = Expr

id + id

price tax

Basic lexical analysis terms

- Token
  - – A classification for a common set of strings
  - – Examples: <identifier>, <number>, <operator>, <open paren>, 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 pattern and is classified by a token
  - – Identifiers: x, count, name, etc…
  - – Integers: -12, 101, 0, …

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 expression (REs)

- Scanners are based on *regular expressions* that define simple patterns
- Simpler and less expressive than BNF
- Examples of a 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)*
- Basic operations are (1) set union, (2) concatenation and (3) Kleene closure
- Plus: parentheses, naming patterns
- No recursion!

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)*

$\boxed{\text{letter}}\ \boxed{\text{(letter | digit) *}}$ concatenation: one pattern followed by another

$\text{letter}\ \ (\boxed{\text{letter | digit}})\ *$ set union: one pattern or another

$\text{letter}\ \ (\text{ letter | digit })\boxed{*}$ Kleene closure: zero or more repetions of a pattern

WHENEVER I LEARN A NEW SKILL I CONCOCT ELABORATE FANTASY SCENARIOS WHERE IT LETS ME SAVE THE DAY.
OH NO! THE KILLER MUST HAVE FOLLOWED HER ON VACATION!
BUT TO FIND THEM WE'D HAVE TO SEARCH THROUGH 200 MB OF EMAILS LOOKING FOR SOMETHING FORMATTED LIKE AN ADDRESS!
IT'S HOPELESS!
EVERYBODY STAND BACK.
I KNOW REGULAR EXPRESSIONS.
PERL!
TAP TAP

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

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 associatively 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^{*}
- So the + operator is just syntactic sugar

Precedence of operators

In interpreting a regular expression

- Parens scope sub-expressions
- * and + have the highest precedence
- Concanenation comes next
- | is lowest.
- All the operators are left associative
- Example
  - (A) | ((B)* (C)) is equivalent to A | B * C
  - What strings does this generate or match?

Either an A or any number of Bs followed by a C

Epsilon

- Sometimes we'd like 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+

Notational shorthand of regular expression

- One or more instance
  - L+ =   L L*
  - L*   =   L+ | ε
  - Examples
    - » digits: digit digit*
    - » digits: digit+
- Zero or one instance
  - L? =   L|ε
  - Examples
    - » Optional_fraction→.digits|ε
    - » optional_fraction→(.digits)?
- Character classes
  - [abc] =   a|b|c
  - [a-z]   =   a|b|c...|z

More syntatic sugar

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

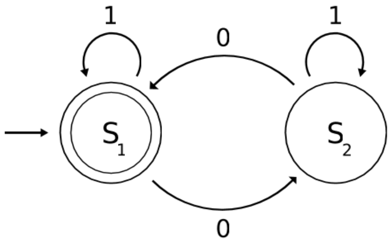
  {read, write, +, -, *, /, :=, 1, 2, …, 10, …, 3.45e-3, …}
- A set of tokens is a *regular set* that can be defined by using a *regular expression*
- For every regular set, there is a *finite automaton* (FA) that can recognize it
  - Aka deterministic *Finite State Machine* (FSM)
  - *i.e.* determine whether a string belongs to the set or not
  - Scanners extract tokens from source code in the same way FAs determine membership

FSM = FA

- Finite state machine and finite automaton are different names for the same concept
- The basic concept is important and useful in almost every aspect of computer science
- The concept provides an abstract way to describe a *process* that
  - Has a finite set of states it can be in
  - Gets a sequence of inputs
  - Each input causes the process to go from its current state to a new state (which might be the same!)
  - If after the input ends, we are in one of a set of accepting state, the input is *accepted* by the FA

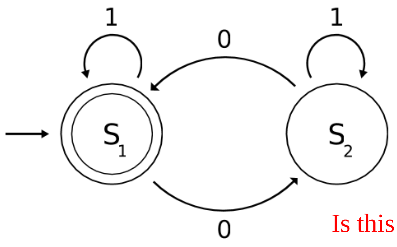
Example

This example shows a FA that determines whether a binary number has an odd or even number of 0's, where S1 is an accepting state.



Deterministic finite automaton (DFA)

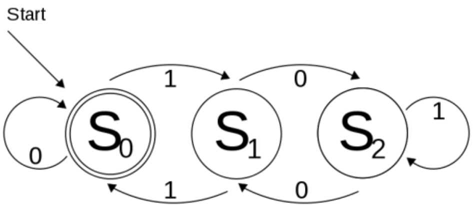
- In a DFA there is only one choice for a given input in every state
- There are no states with two arcs that match the same input that transition to different states



Is this a DFA?

Deterministic finite automaton (DFA)

- If there is an input symbol that matches no arc for the current state, the input is not accepted
- This FA accepts only binary numbers that are multiples of three
- S0 is both the start state and an accept state.

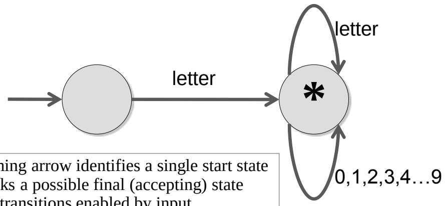


Is this a DFA?

REs can be represented as DFAs

Regular expression for a simple identifier

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

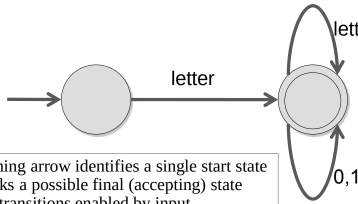


- Incoming arrow identifies a single start state
- * marks a possible final (accepting) state
- State transitions enabled by input
- Arcs represent transitions and are labeled with required input

REs can be represented as DFAs

Regular expression for a simple identifier

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



An alternate notation
Uses a double circle
For an accepting state

- Incoming arrow identifies a single start state
- * marks a possible final (accepting) state
- State transitions enabled by input
- Arcs represent transitions and are labeled with required input

Token Definition Example

Numeric literals in Pascal, e.g.

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

Definition of token *unsignedNum*

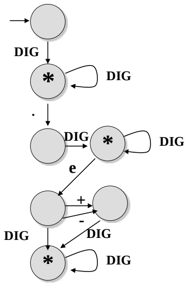
DIG → 0|1|2|3|4|5|6|7|8|9

unsignedInt → *DIG DIG**

unsignedNum →
  unsignedInt
  ((. *unsignedInt*) | ε)
  ((e (+ | – | ε) *unsignedInt*) | ε)

Note:

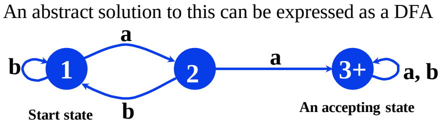
- Recursion restricted to leftmost or rightmost position on LHS
- Parentheses used to avoid ambiguity
- It's always possible to rewrite by removing epsilons (ε)



- *Accepting* states marked with a *
- FAs with epsilons are nondeterministic
- NFAs are harder to implement, use backtracking
- Every NFA can be rewritten as a DFA (gets larger, tho)

Simple Problem

- Write a C 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

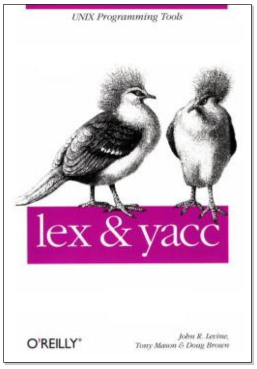
```
#include <stdio.h>
main()
{  enum State {S1, S2, S3};
    enum Label {A, B};
    enum State currentState = S1;
    enum State table[3][2] = {{S2, S1}, {S3, S1}, {S3, S3}};
    int label;
    int c = getchar();
    while (c != EOF) {
         if (c == ‘a’) label = A;
         if (c == ‘b’) label =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

Lex

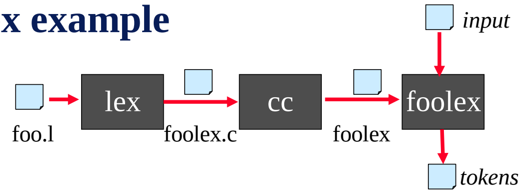
- Lexical analyzer generator
  - It writes a lexical analyzer
- Assumption
  - each token matches a regular expression
- Needs
  - set of regular expressions
  - for each expression an action
- Produces
  - A C program
- Automatically handles many tricky problems
- flex is the gnu version of the venerable 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 access on gl
- See /afs/umbc.edu/users/p/a/park/pub/331/lex

```
% ls -l /afs/umbc.edu/users/p/a/park/pub/331/lex
total 8
drwxr-xr-x 2 park faculty 2048 Sep 27 13:31 aa
drwxr-xr-x 2 park faculty 2048 Sep 27 13:32 defs
drwxr-xr-x 2 park faculty 2048 Sep 27 11:35 footranscanner
drwxr-xr-x 2 park 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