4a

Lexical analysis

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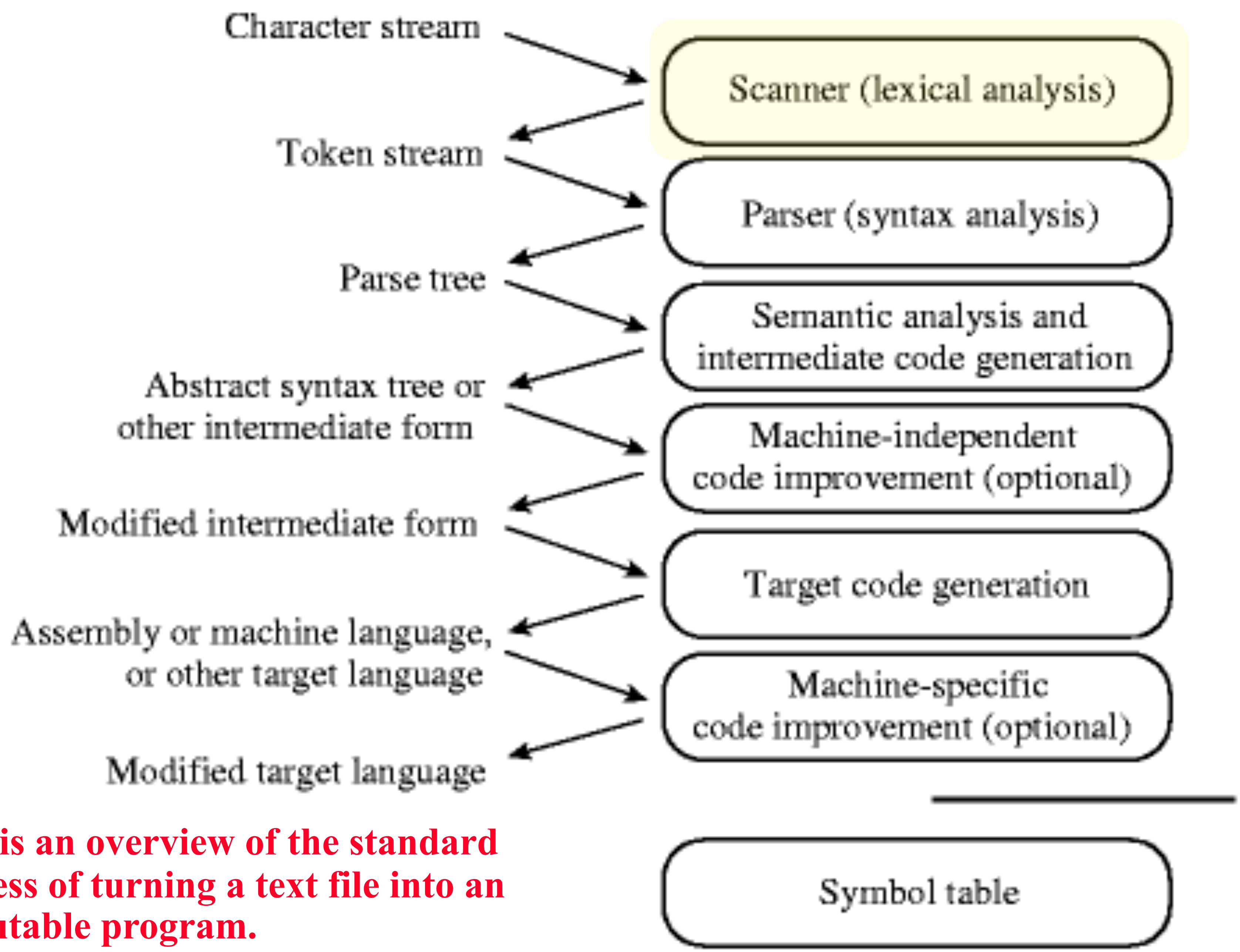
Concepts

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

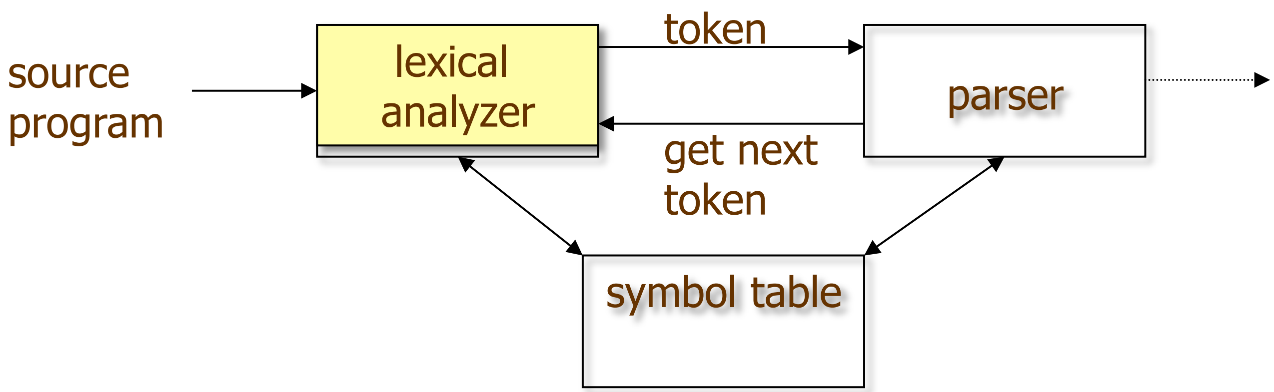


This is an overview of the standard process of turning a text file into an executable program.

Lexical analysis in perspective

LEXICAL ANALYZER: Transforms character stream to token stream

– Also called scanner, lexer, linear analysis



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

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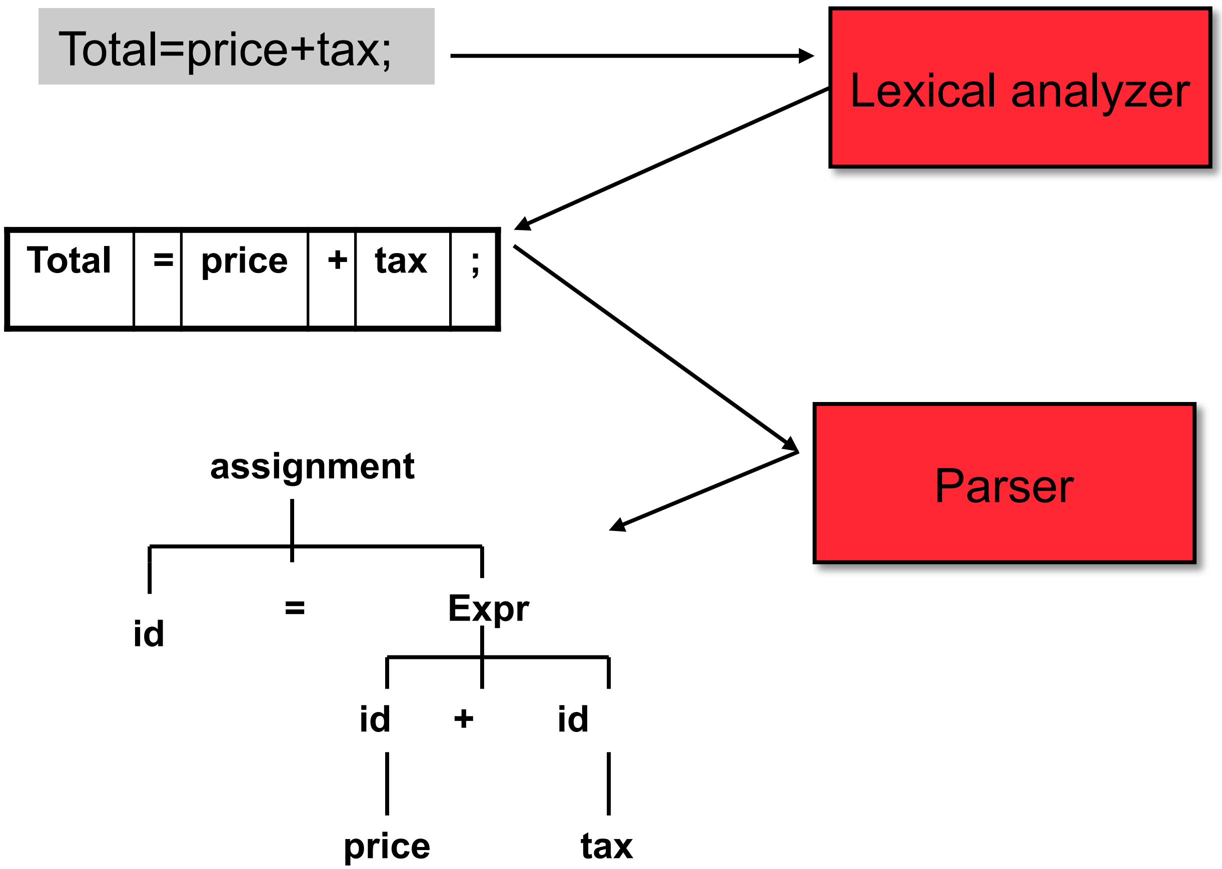
Where we are



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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)*

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

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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, …}

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Regular expression

- Let Σ be an alphabet, *r* 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))*
- It is an inductive definition!
- 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 associatively of the operators (i.e., |, * and “concat”)

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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

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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

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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+

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>

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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

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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 DFAs 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

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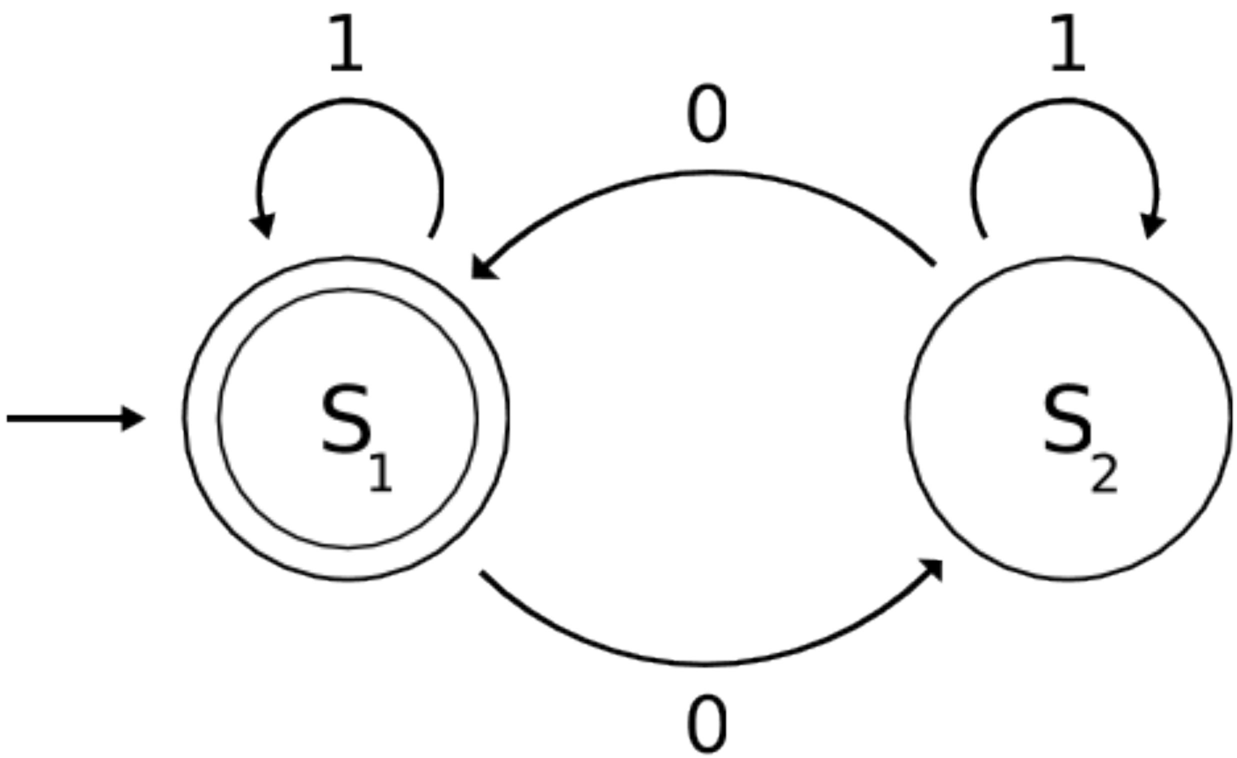
Example

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.



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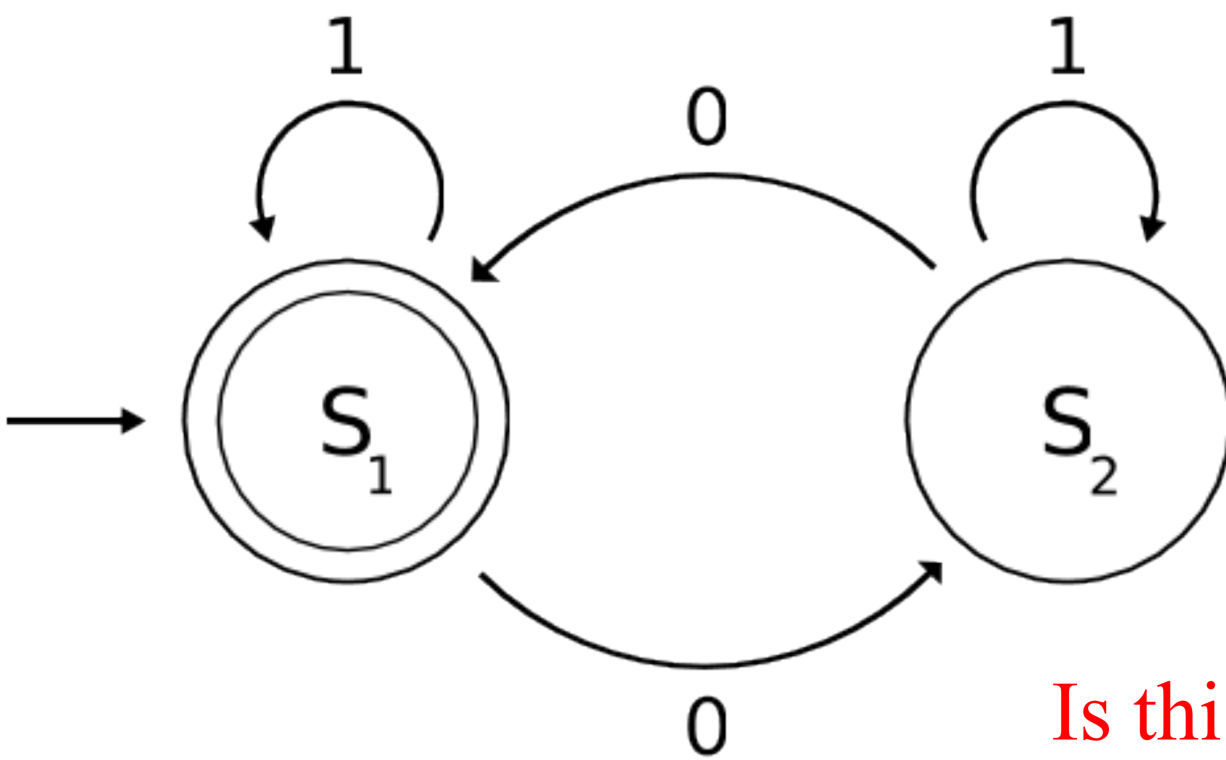
Deterministic finite automaton (DFA)

- 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?

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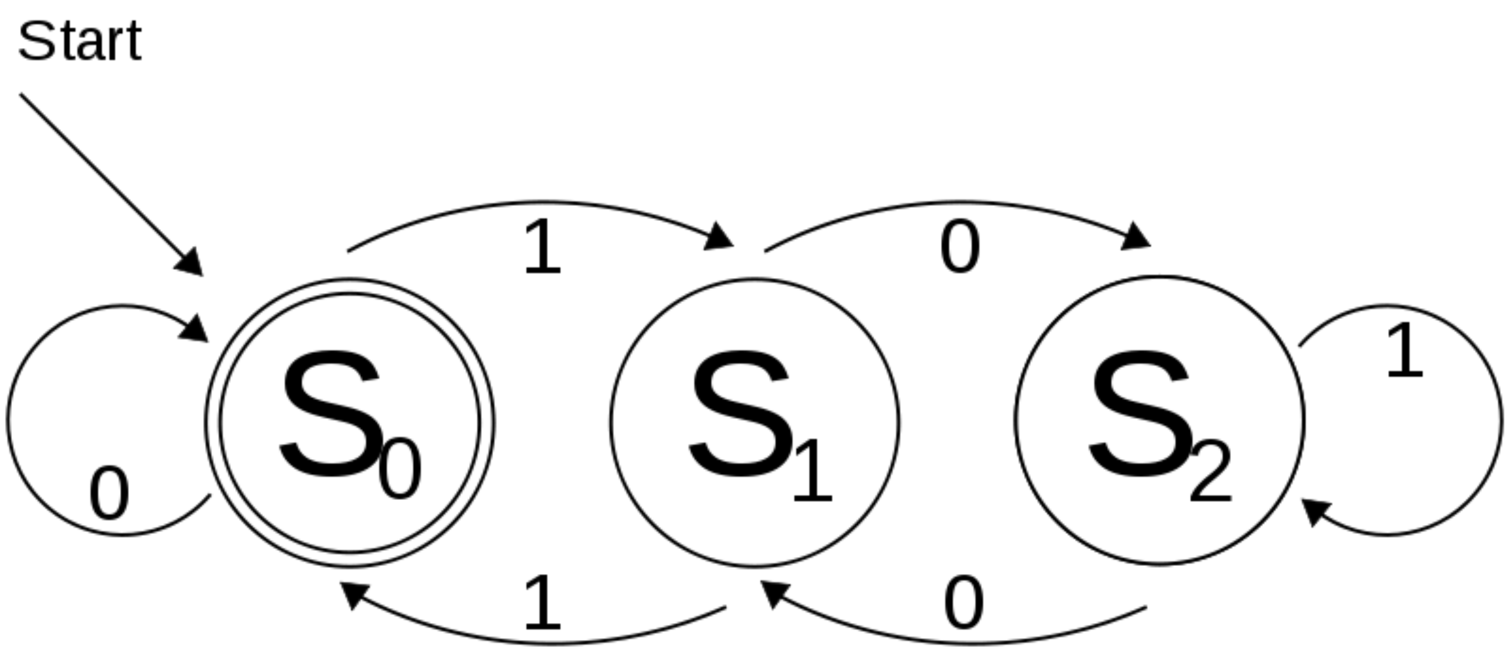
Deterministic finite automaton (DFA)

- 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?

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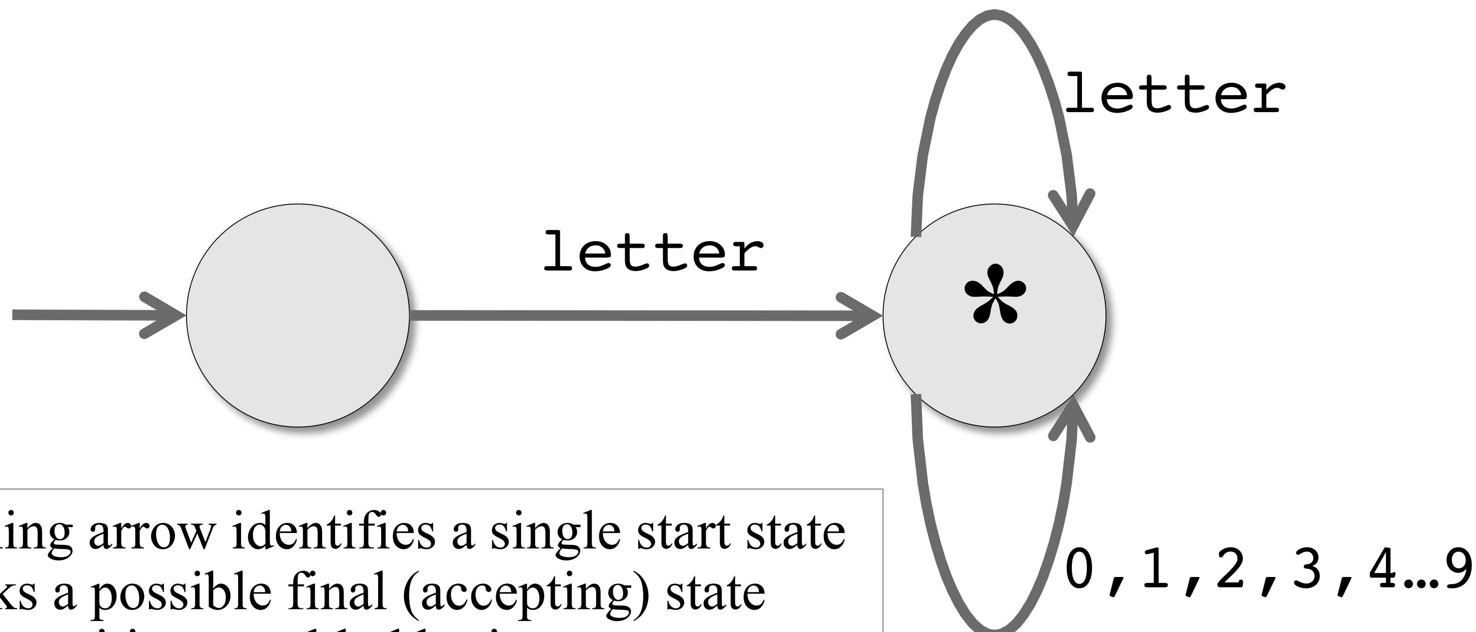
REs can be represented as DFAs

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

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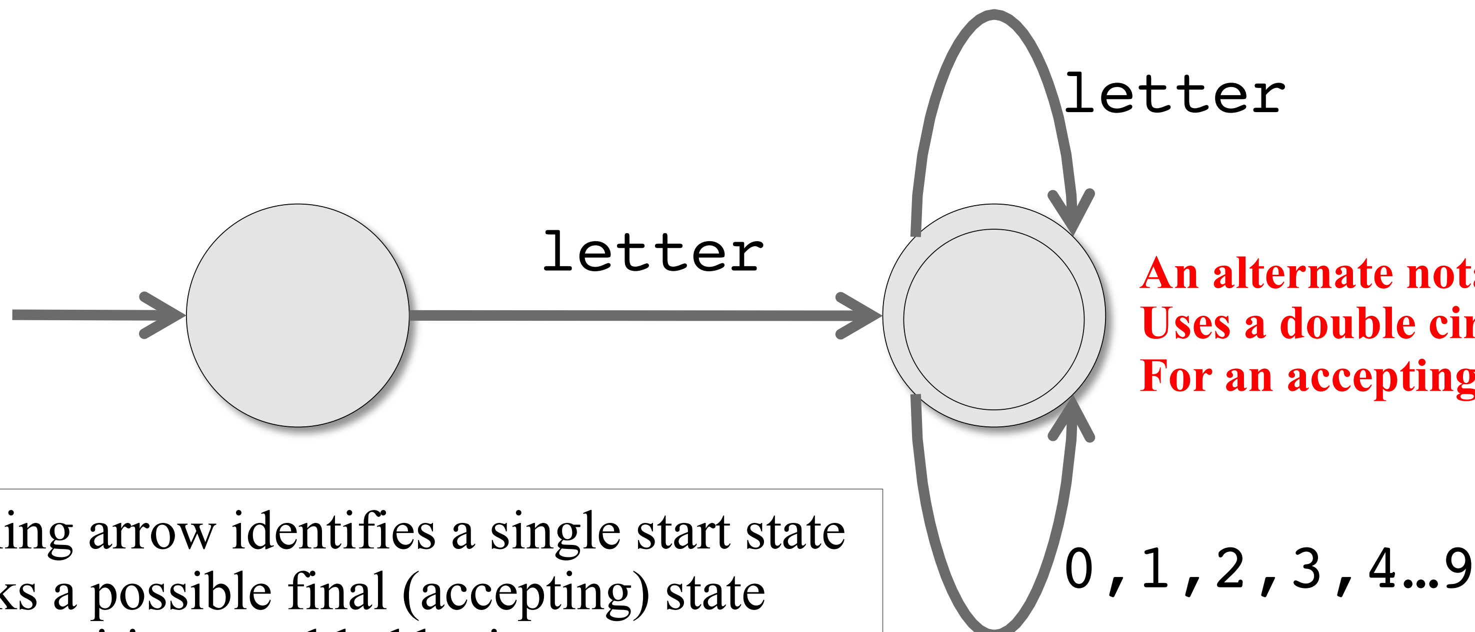
REs can be represented as DFAs

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

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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)

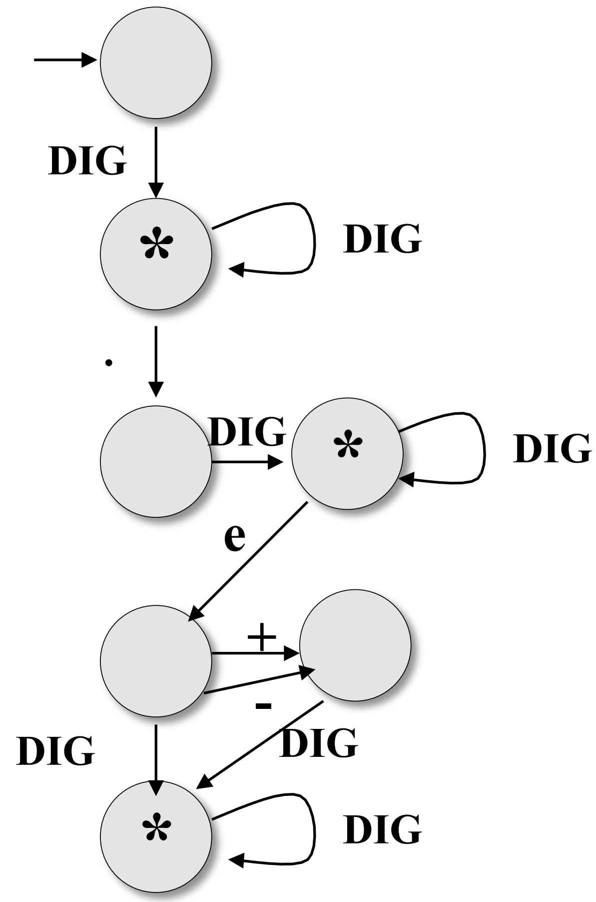
((e (+ | – | ε) *unsignedInt*) | ε)

Note:

– Recursion restricted to leftmost or rightmost position on LHS

– Parentheses used to avoid ambiguity

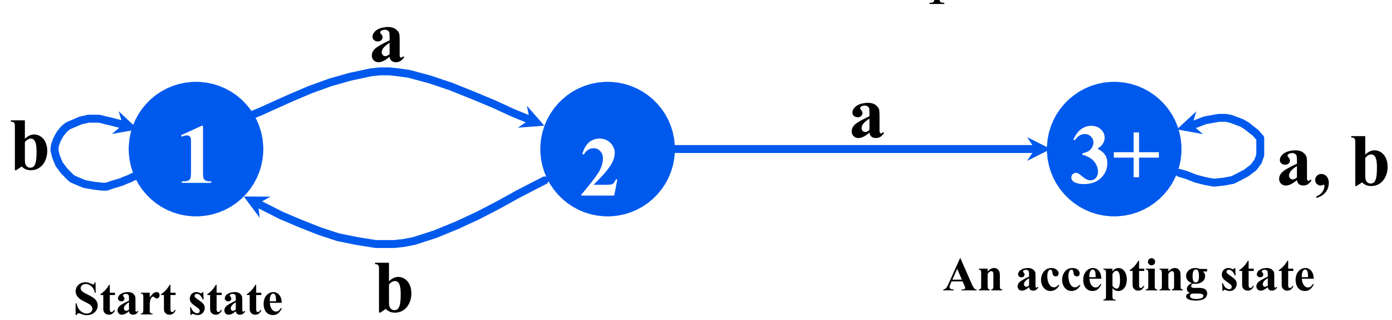
– It's always possible to rewrite by removing epsilons (ε)



- *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	a (*input*)	b (*input*)
1	2	1
2	3	1
3	3	3

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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”);
}
```

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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");
}
```

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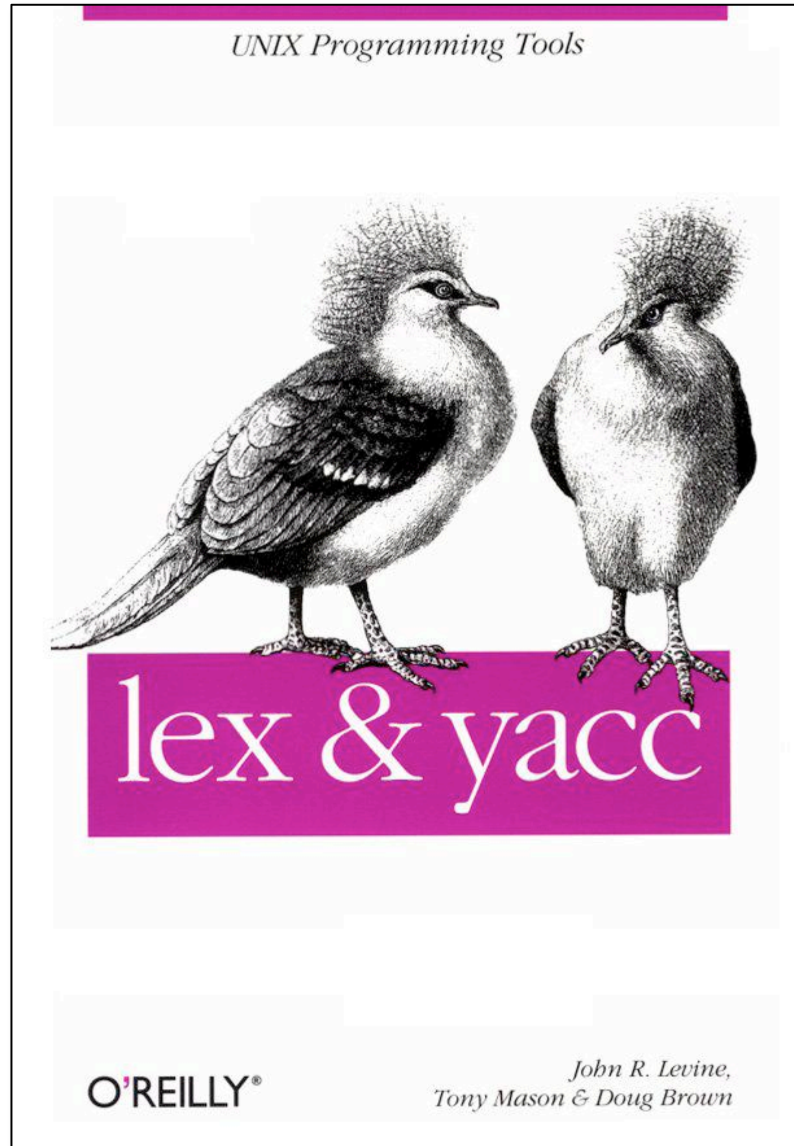
Lex

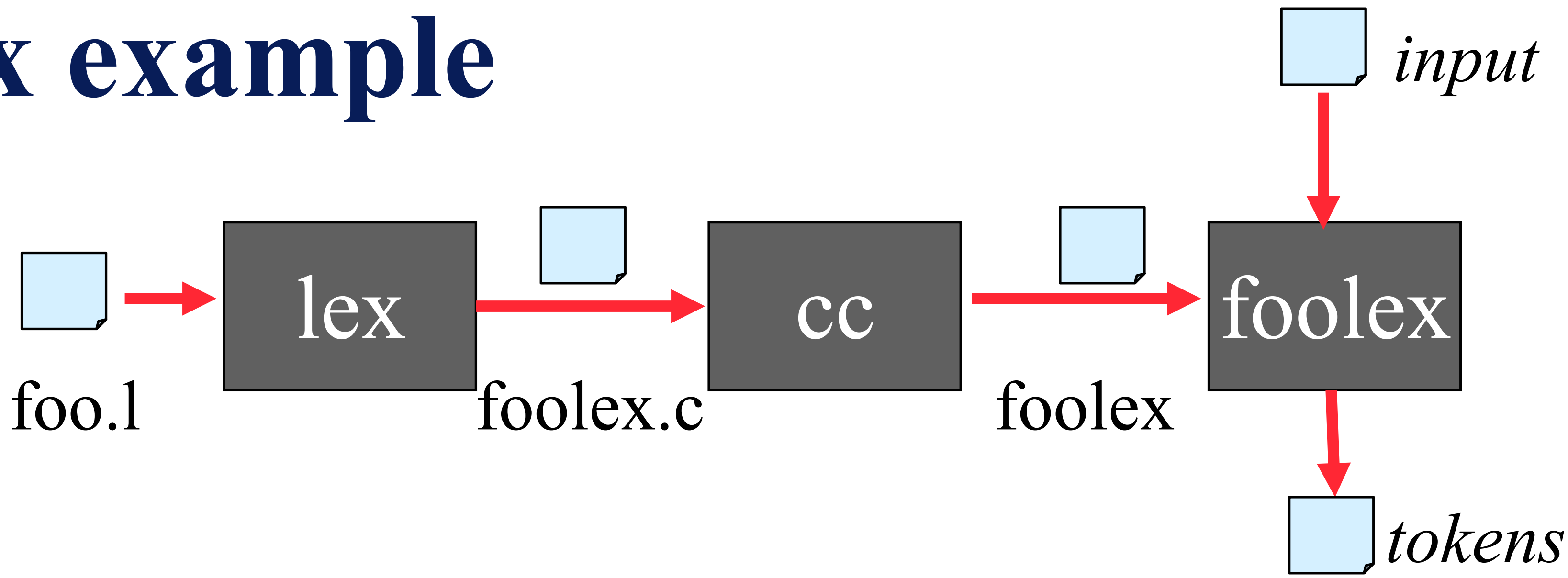
- Lexical analyzer generator
  - It writes a lexical analyzer
- Assumption
  - each token matches a regular expression
- Needs
  - set of regular expressions
  - for each expression an action
- Produces
  - A C program
- Automatically handles many tricky problems
- flex is the gnu version of the venerable 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/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();}
```

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Simplest Example

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

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

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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();}
```

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```
/* 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();}
```

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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

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