Lecture 7: Lexical analyzer generators, lex/flex

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601.428/628 Compilers and Interpreters

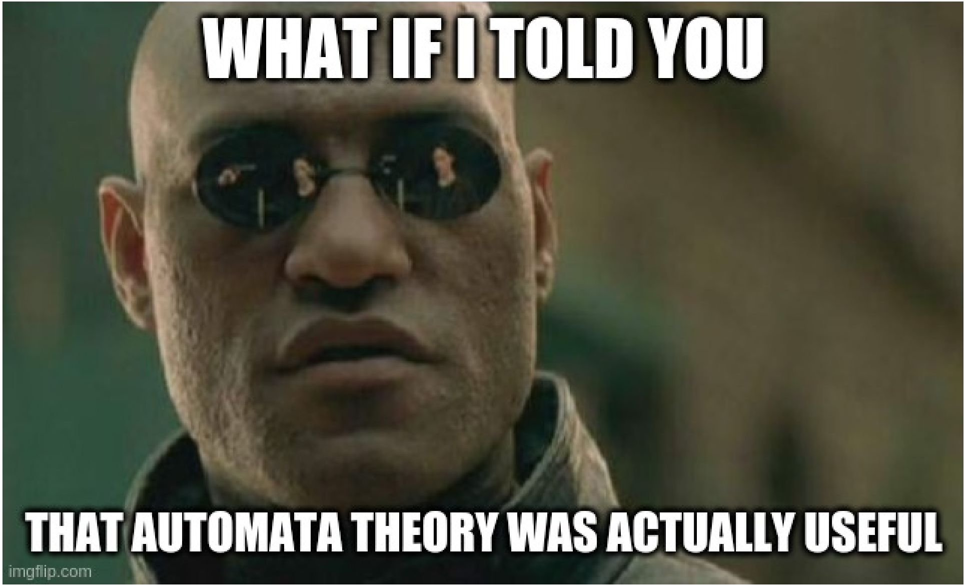
Today

- Regular expressions
- NFAs and DFAs
- lex and flex

Lexical analysis and regular languages

Implementing lexical analyzers

- Lexical analyzers (a.k.a. scanners) break the source text into a sequence of tokens
- We can hand-code these
  - Not terribly difficult, but somewhat tedious
- Is there a better way to implement them?


WHAT IF I TOLD YOU
THAT AUTOMATA THEORY WAS ACTUALLY USEFUL
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Regular languages!

- For any “reasonable” programming language, the lexemes of legal tokens can be described by a *regular language*
- Basic idea:
  - Each kind of token is described by a *regular expression*
  - Regular expressions can be easily converted to *nondeterministic finite automata* (NFAs)
  - The NFA for each kind of token can be combined into a single NFA which recognizes all of the different kinds of tokens
  - The combined NFA can be converted into a *deterministic finite automaton* (DFA)
  - A DFA can be easily converted into an efficient program to recognize tokens

Formal languages, regular languages

- A *formal language* is a set of strings
- A *string* is a sequence of symbols
- *Regular languages* are a particular subset of formal languages
  - Which happen to be useful for describing character patterns of tokens in programming languages
- Each string in a regular language is a string of symbols chosen from an *alphabet*
  - For programming languages, these symbols are text characters appearing in the input source code

Regular expressions

- Regular expressions are one way to specify a *regular language*
- Constructing a regular expression:
  - Sequence of literal symbols: generates a string
  - $\boxed{*}$ operator: means “0 or more”
  - $\boxed{+}$ operator: means “1 or more”
  - $\boxed{|}$ operator: means “or”
  - $\boxed{(}$ and $\boxed{)}$: used for grouping
  - Concatenation: if X and Y are regular expressions, then XY is a regular expression generating all possible strings xy where x is in the language generated by X, and y is in the language generated by Y

Regular expressions

Examples of regular expressions:

Regular expression	Language (set of strings)
a	a
aa	aa
a*	ϵ, a, aa, aaa, ...
aa*	a, aa, aaa, ...
a+	a, aa, aaa, ...
ba+	ba, baa, baaa, ...
(ba)+	ba, baba, bababa, ...
(a|b)	a, b
a|b*	a, ϵ, b, bb, bbb, ...
(a|b)*	ϵ, a, b, aa, ab, ba, bb, ...
aa(ba)*bb	aabb, aababb, aabababb, ...

Insta-quiz!

Which of the following strings is *not* generated by the regular expression $\boxed{(ab)^*|(ba)^*}$?

A. abab

B. bababa

C. abba

D. babab

E. All of the above strings are generated

Extended regular expression syntax

- "Basic" regular expressions are a bit limited
- For example, the regular expression for "lowercase letter" is

  (a|b|c|d|e|f|g|h|i|j|k|l|m|n|o|p|q|r|s|t|u|v|w|x|y|z)
- "Extended" regular expressions can specify *character classes*, e.g.
  - [a-z]
  - [A-Za-z]
  - [0123456789]
  - [0-9]
- Regular expression for C identifiers:

  [A-Za-z_][A-Za-z_0-9]*

NFAs and DFAs

Finite automata

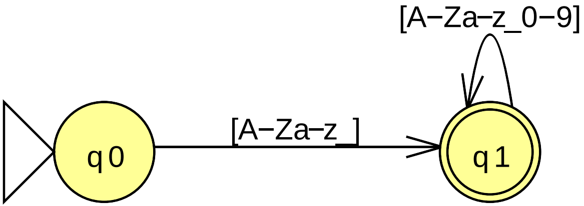
- A *finite automaton* is another way to specify a regular language
- Acts as a *recognizer* for strings in a regular language
  - If it accepts a string, it's in the language
  - If it rejects a string, it's not in the language

Finite automata concepts

- Has *states* and *transitions*
- One state is designated as the *start state*
- At least one state is designated as a *final state*
- Each transition is labeled with one symbol
- Recognition process:
  - Start in start state
  - Following a (non-epsilon) transition consumes one symbol from the candidate string
  - If the current state is a final state when end of string is reached, it's in the language
  - Otherwise, string is not in the language

Finite automata

Finite automaton recognizing C identifiers:



Important: for simplicity, we're labeling transitions with character classes; it's important to understand that this is just a shorthand notation for multiple transitions

- For example, [A-Za-z_] matches 53 characters, so the arrow from q0 to q1 is really 53 distinct transitions

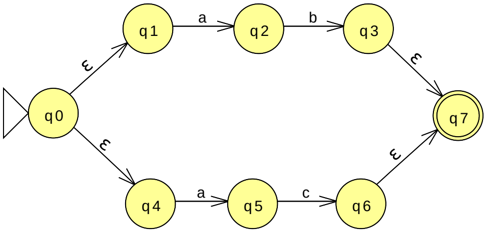
Deterministic finite automata

- The example finite automaton on the previous slide is a *deterministic* finite automaton (DFA)
- "Deterministic" means that
  - In any state, there aren't multiple outgoing transitions (to different "destination" states) labeled with the same symbol, and
  - There aren't any epsilon transitions
- As a DFA processes a candidate string, there is always a single current state

Nondeterministic finite automata

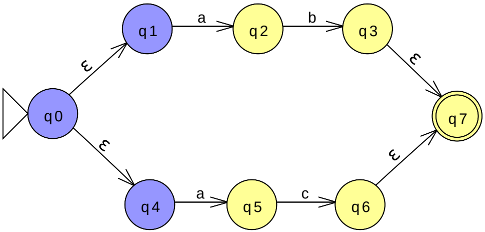
- A *nondeterministic* finite automaton (NFA) has
  - States with multiple outgoing transitions on the same symbol, and/or
  - One or more epsilon transitions
- An epsilon transition does not consume an symbol from the input string
- When an NFA processes a candidate string, it can be in multiple states at the same time
- Candidate string is accepted if, when end of string is reached, current set of states contains any accepting state

Example NFA



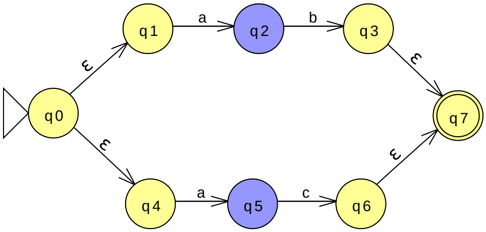
States	Candidate string
	$_\wedge$ab

Example NFA



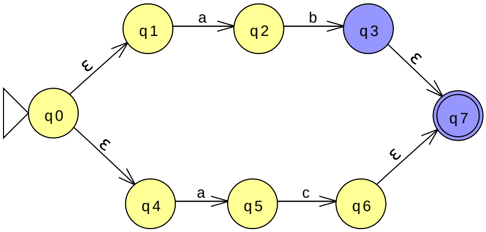
States	Candidate string
{ q0, q1, q4 }	$_\wedge$ab

Example NFA



States	Candidate string
{ q0, q1, q4 }	$_\wedge$ab
{ q2, q5 }	a$_\wedge$b

Example NFA



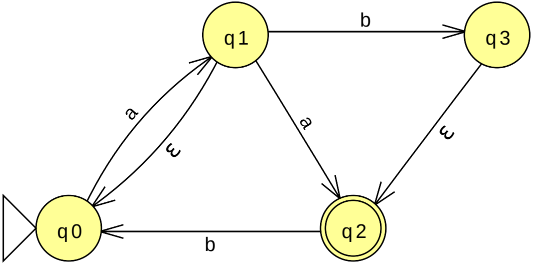
States	Candidate string
{ q0, q1, q4 }	$_\wedge$ab
{ q2, q5 }	a$_\wedge$b
{ q3, q7 }	ab$_\wedge$

When end of string is reached, the current set of states contains a final state (q7), so the string is accepted

Insta-quiz!

What set of states is reached when the NFA on the right recognizes the string $\boxed{\text{aab}}$?

A. { q0 }
B. { q0, q3 }
C. { q1, q3 }
D. { q0, q2, q3 }
E. None of the above



Eliminating nondeterminism

- Nondeterminism can always be eliminated!
- I.e., for any NFA, we can create a DFA that recognizes the same language
  - NFA with n states could yield a DFA with 2^n states, but that's not likely to occur in practice
- Basic idea: simulate behavior of all possible inputs to the NFA, map each reachable set of NFA states to a corresponding DFA state
- We'll show an example of how this works soon

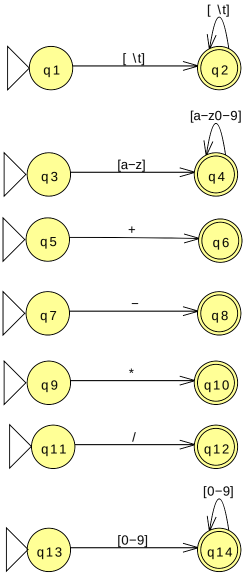
Example language

Regular expressions for tokens in a simple programming language:

Token kind	Regular expression	Note
Whitespace	[␣\t]+	Not a token per se, but does need to be recognized by the lexer
Identifier	[a-z][a-z0-9]*	
Addition	\+	Literal plus symbol, not "1 or more"
Subtraction	-	
Multiplication	*	Literal asterisk
Division	/	
Number	[0-9]+	

Example language: per-token FAs

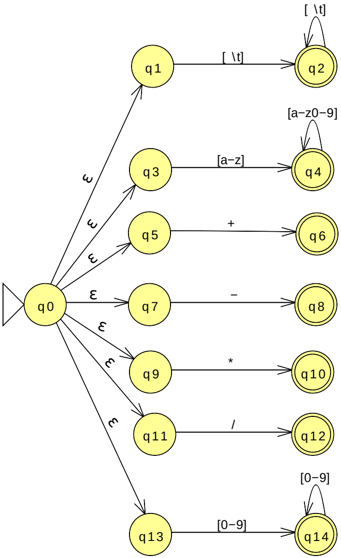
Translate each regular expression into a DFA (this can be automated)



Example language: unified NFA

Combine individual token FAs into a single NFA

NFA recognizes union of all lexemes (for all kinds of tokens)

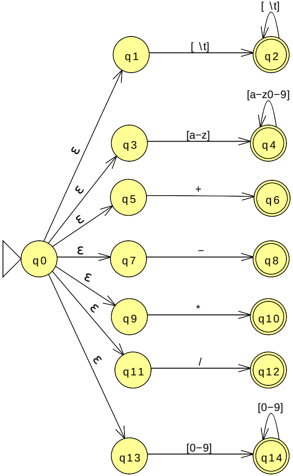


Example language: conversion to DFA

- Now, let's convert the unified NFA into a DFA
- For each reachable set of states in NFA, create corresponding state in DFA
- Add transitions to DFA corresponding to transitions between reachable NFA state sets
- See textbook for full algorithm

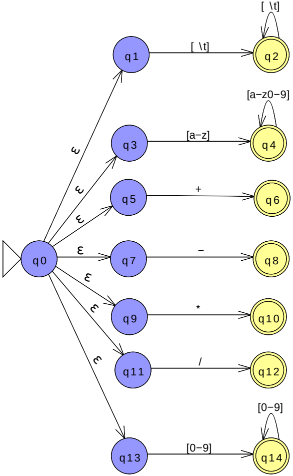
NFA to DFA conversion

NFA states	DFA state



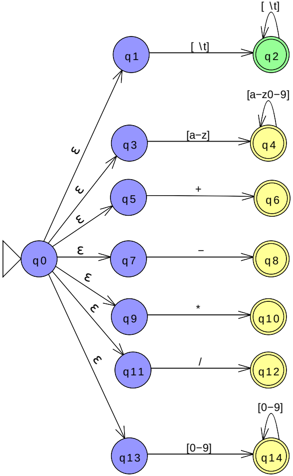
NFA to DFA conversion

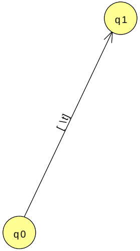
NFA states	DFA state
{ 0,1,3,5,7,9,11,13 }	0



NFA to DFA conversion

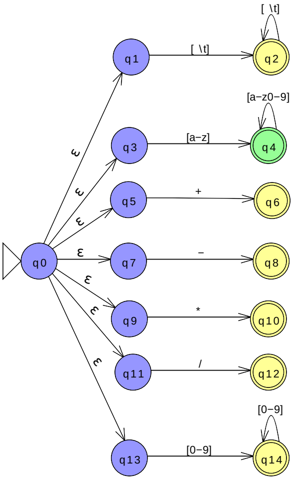
NFA states	DFA state
{ 0,1,3,5,7,9,11,13 }	0
{ 2 }	1

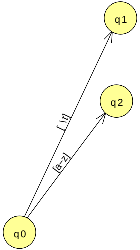




NFA to DFA conversion

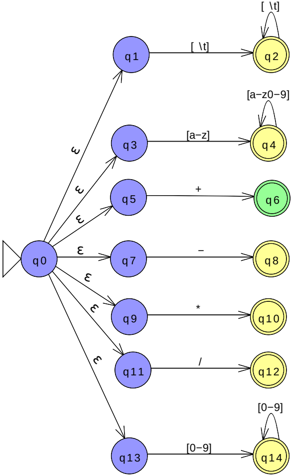
NFA states	DFA state
{ 0,1,3,5,7,9,11,13 }	0
{ 2 }	1
{ 4 }	2

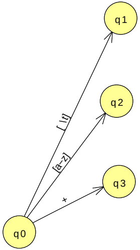




NFA to DFA conversion

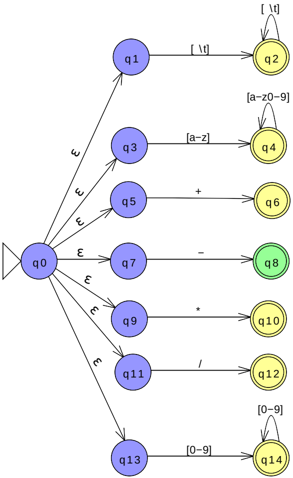
NFA states	DFA state
{ 0,1,3,5,7,9,11,13 }	0
{ 2 }	1
{ 4 }	2
{ 6 }	3

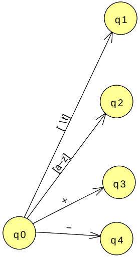




NFA to DFA conversion

NFA states	DFA state
{ 0,1,3,5,7,9,11,13 }	0
{ 2 }	1
{ 4 }	2
{ 6 }	3
{ 8 }	4





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NFA states	DFA state
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{ 2 }	1
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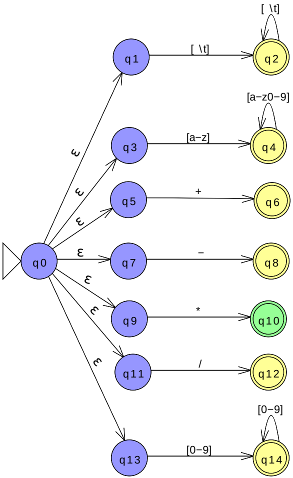
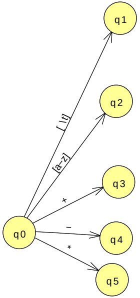
{ 8 }	4
{ 10 }	5





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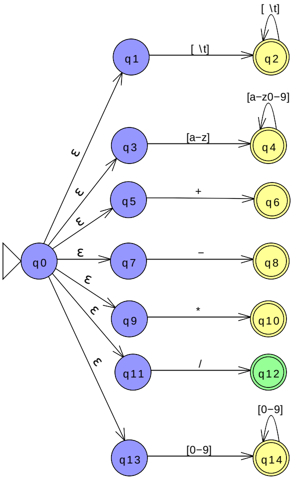
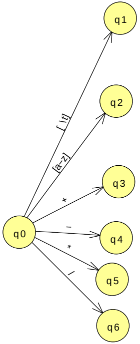
{ 12 }	6





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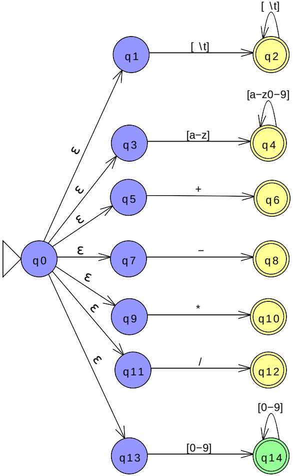
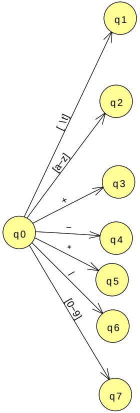
{ 14 }	7





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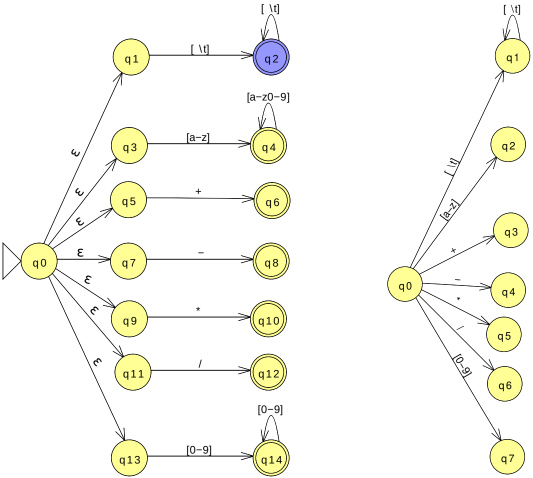

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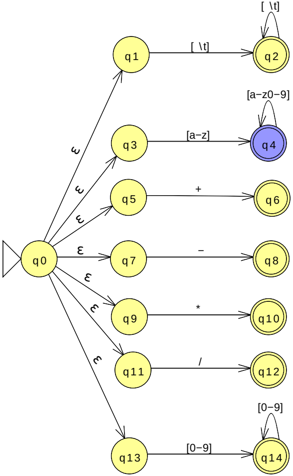

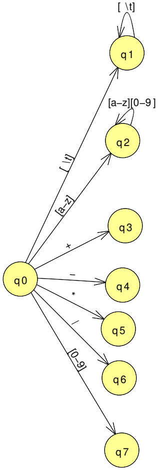

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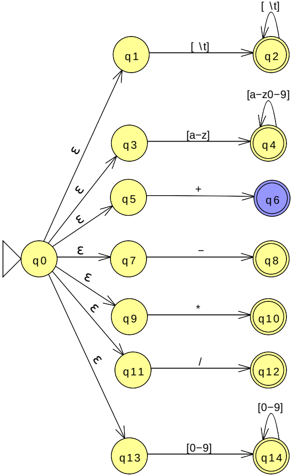

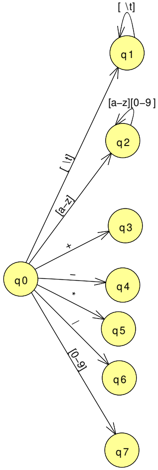

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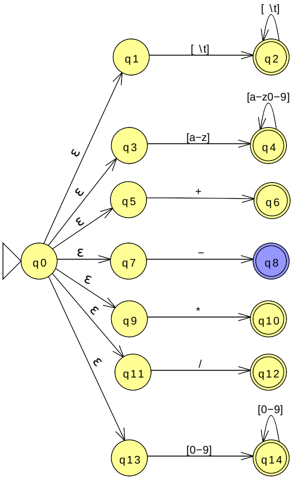

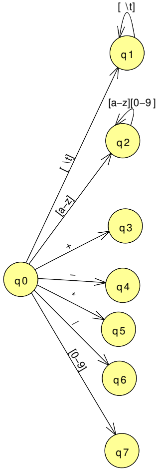

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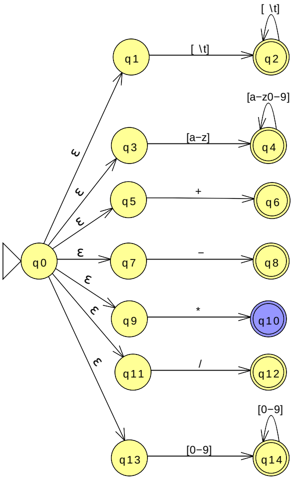

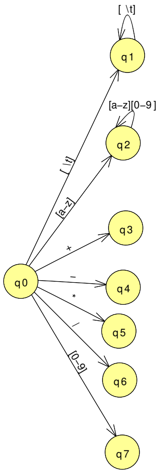

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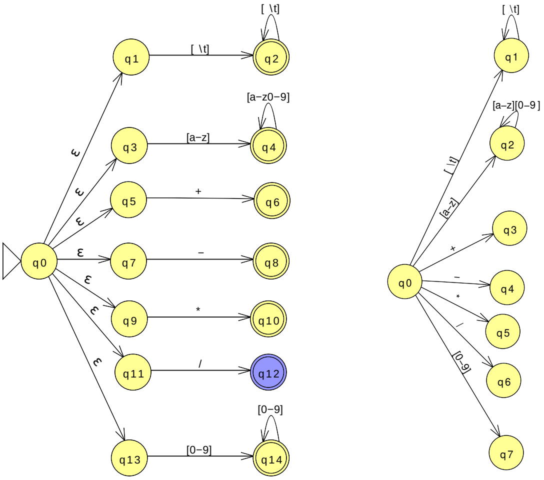

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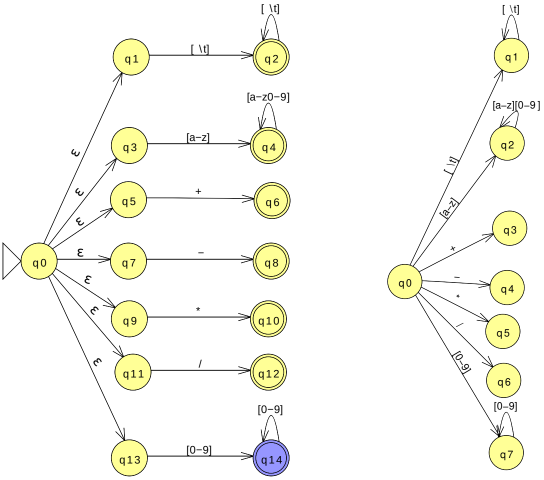

NFA to DFA conversion

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{ 2 }	1
{ 4 }	2
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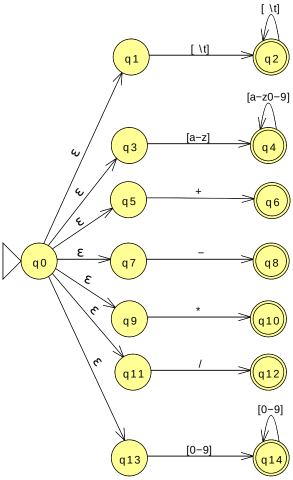
{ 14 }	7

Final steps:

- Make q0 of DFA the start state
- Each NFA state set containing a final state has its corresponding DFA state marked as final



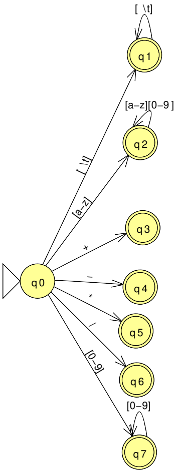


Table-driven recognition

Any DFA can be represented as a table indicating, for each DFA state, which transitions to other DFA states exist

Given a table, it's trivial to create a program to recognize the language

Basic idea: repeatedly

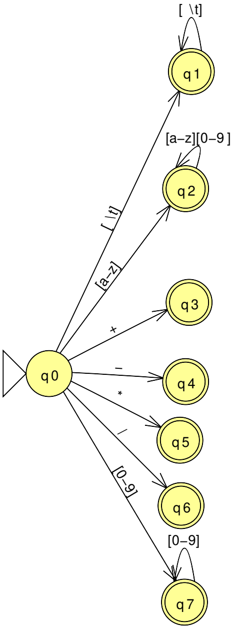
- Read an input character
- See if there is a transition to another state

When we reach EOF, or if there's no transition available, see if we're in a final state

- Which one we're in tells us what kind of token we've recognized

DFA transition table

State	[\t]	[a-z]	+	-	*	/	[0-9]
0	1	2	3	4	5	6	7
1	1	–	–	–	–	–	–
2	–	2	–	–	–	–	2
3	–	–	–	–	–	–	–
4	–	–	–	–	–	–	–
5	–	–	–	–	–	–	–
6	–	–	–	–	–	–	–
7	–	–	–	–	–	–	7



Some details

A few issues required to make this work:

- NFA to DFA conversion algorithm doesn't guarantee a *minimal DFA*
  - Can use DFA minimization algorithm
- A final DFA state could correspond to multiple NFA final states
  - For example, keywords are generally matched by the same regular expression pattern as identifiers
  - For example, if a keyword is recognized, the NFA will also be in the final state for identifiers
  - Solution is to prioritize kinds of tokens
    - E.g., keywords take priority over identifiers

Can we put this into practice?

Is this a basis for implementing practical lexical analyzers?

It would be very time-consuming to build NFAs and DFAs by hand. For example, the notation “[a-z]” is really 26 different characters requiring 26 different FA transitions, 26 columns in the DFA table, etc.

But, could we automate this process?

lex and flex

lex and flex

lex and flex are *lexical analyzer generators*

- lex: developed at AT&T Bell Labs, distributed with Unix, not really used any more
- flex: modern open-source replacement for lex

They automate the process we've just covered

And, they're surprisingly easy to use

flex lexer specification

```
%{
C preamble (includes, definitions, global vars)
%}

flex options

%%

patterns and actions

%%

C functions
```

Example flex program

```
%{
#include <stdio.h>

enum TokenKind {
  TOK_IDENTIFIER = 1,
  TOK_PLUS,
  TOK_MINUS,
  TOK_TIMES,
  TOK_DIVIDE,
  TOK_NUMBER,
};
%}

%option noyywrap

%%

[ \t\n]+          { /* whitespace, ignore */ }
[a-z][a-z0-9]*    { return TOK_IDENTIFIER; }
"+"               { return TOK_PLUS; }
"-"               { return TOK_MINUS; }
"*"               { return TOK_TIMES; }
"/"               { return TOK_DIVIDE; }
[0-9]+            { return TOK_NUMBER; }

%%
```

```
int main(void) {
  yyin = stdin;
  int kind;
  while ((kind = yylex()) != 0) {
    printf("%d:%s\n", kind, yytext);
  }
  return 0;
}
```

Source code in `lexdemo.zip` linked from course website

Running the example program

User input in **bold**:

```
$ ./lexdemo
foo + bar * 42
1:foo
2:+
1:bar
4:*
6:42
```

How flex programs work

Basic idea:

- Sequence of *patterns* and *actions*
- When a pattern is recognized, the corresponding action is executed
  - If input matches multiple patterns, the pattern appearing earliest takes priority
- Action can return control to parser, or continue recognizing more input
  - If action has a `return` statement, it indicates to the parser what kind of token was recognized

yylex() function

The `yylex()` function reads input until both

- A pattern is matched, and
- The pattern's action executes a `return`

The value returned by the action is the return value of `yylex()`

Returns 0 when end of input is reached

- Token kind values should thus be non-zero

yyin, yytext

`yyin`: A `FILE*` variable from which input will be read

`yytext`: This is a (nul terminated) C character string containing the lexeme of the recognized pattern

yylval

A variable of the union type `YYSTYPE` (usually declared by the parser)

Members of this union allow different grammar symbols to have different kinds of values associated with them

- Lexer actions can assign to one of the fields
- We'll see how this works when we cover yacc/bison