CS412/413

Introduction to
Compilers and Translators
Spring '01

Lecture 3: Automating lexical analysis

Outline

- Handouts (2)
- Regexp example
- Scanner inner loop
- DFAs
- NFAs
- RE-NFA conversion
- NFA-DFA conversion

Extended regular expression syntax

If R_1, R_2 are legal regular expressions, so are:

a	for any ordinary symbol **a**
R_1R_2	(concatenation)
$R_1\|R_2$	(or)
R_1*	(Kleene star: 0 or more concats)
$R_1?$	(0 or 1)
R_1+	(1 or more)
(R_1)	(no effect: grouping)
[**abc**...]	(any of the listed)

Lexer generator

- Reads in list of regular expressions $R_1,\ldots R_n$, one per token, with attached actions

```
-?[1-9][0-9]*   { return new Token(Tokens.IntConst,
                                   Integer.parseInt(yytext()) }
```

- Generates scanning code that decides:
  1. whether the input is lexically well-formed
  2. what is the corresponding token sequence
- Observation: Problem 1 is equivalent to deciding whether the input is in the language of the regular expression $(R_1|\ldots|R_n)*$
- Goal: how can we efficiently test membership in L(R) for arbitrary R?

Regular expression matching

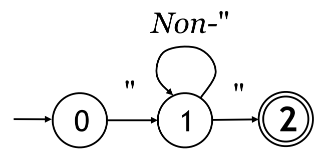
- Sketch of an efficient implementation:
  - start in some initial state
  - look at each input character in sequence, update scanner state accordingly
  - if state at end of input is an *accepting state*, the input string matches the RE
- For tokenizing, only need a finite amount of state: (*deterministic*) *finite automaton* (DFA) or *finite state machine*
- State of automaton = single integer

Finite Automata "[^"]*"

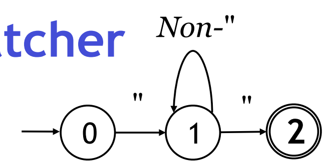
- Automaton (DFA) can be represented as
  - A *transition table*

	"	*Non-"*
0	1	Error
1	2	1
2	Error	Error

  - A graph



A regexp matcher



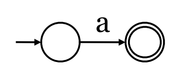

```
boolean accept_state[NSTATES] = { ... };
int trans_table[NSTATES][NCHARS] = { ... };
int state = 0;

while (state != ERROR_STATE) {
   c = input.read();
   if (c < 0) break;
   state = table[state][c];
}
return accept_state[state];
```

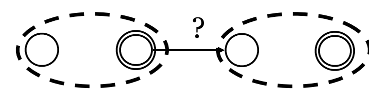

RE → Finite automaton?

- Can we build a finite automaton for every regular expression?
- Strategy: consider every possible kind of regular expression (define by induction on size of regular expression)

a



R_1R_2



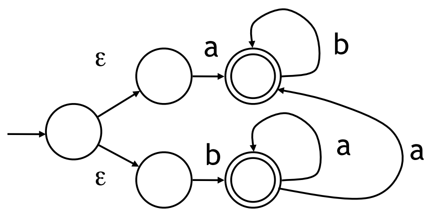
$R_1 | R_2$?

Definition: NFA

- Non-deterministic finite automaton has:
  - set of states; start state; accepting state(s)
  - arrows connecting states labeled by input symbols, or ε (which does not consume input)
  - two arrows leaving a state may have same label

Example:

regexp?

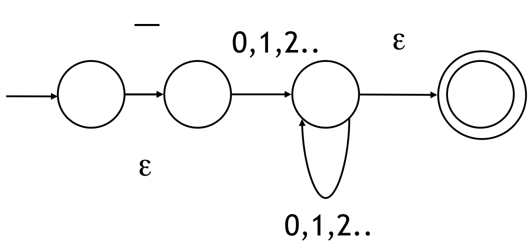


DFA vs NFA

- DFA: action of automaton on each input symbol is fully determined
  - obvious table-driven implementation
- NFA:
  - automaton may have choice on each step
  - automaton accepts a string if there is *any way* to make choices to arrive at accepting state / every path from start state to an accept state is a string accepted by automaton
  - not obvious how to implement efficiently!

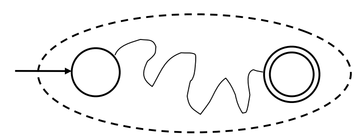
RE ⇒ NFA intuition

-?[0-9]+ (**-**|ε) **[0-9][0-9]***

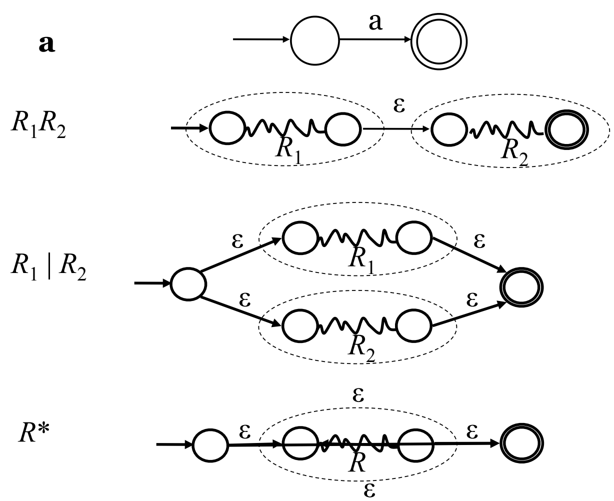


NFA construction

- NFA only needs one stop state (why?)
- Canonical NFA:



Inductive Construction



Executing NFA

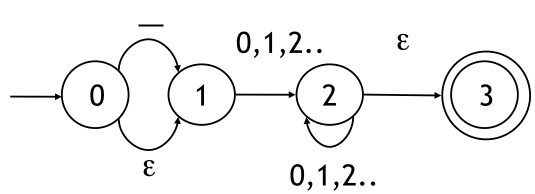
- Problem: how to execute NFA efficiently?

"strings accepted are those for which there is some corresponding path from start state to an accept state"

- Conclusion: search all paths in graph consistent with the string
- Idea: search paths in parallel
  - Keep track of subset of NFA states that search could be in after seeing string prefix
  - "Multiple fingers" pointing to graph

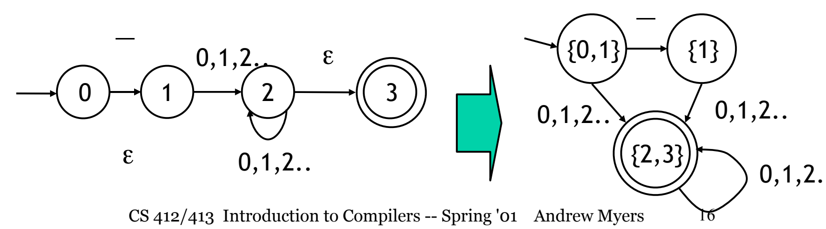
Example

- Input string: -23
- NFA states:
  {0,1}
  {1}
  {2, 3}
  {2, 3}



NFA-DFA conversion

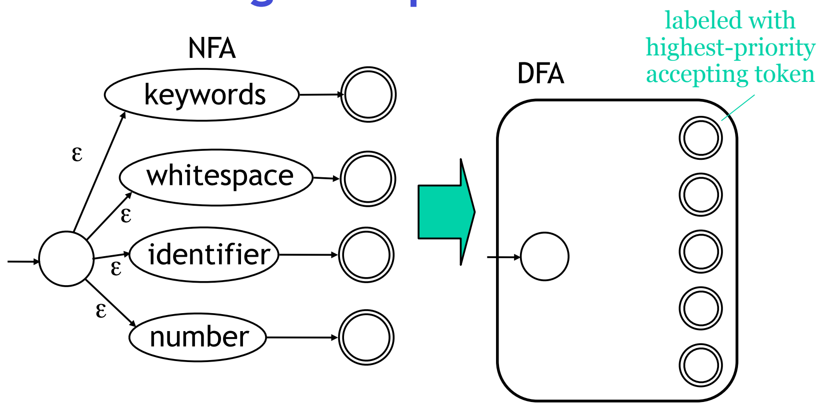
- Can convert NFA directly to DFA by same approach
- Create one DFA for each distinct subset of NFA states that could arise
- States: {0,1}, {1}, **{2, 3}**



DFA minimization

- DFA construction can produce large DFA with many states
- Lexer generators perform additional phase of *DFA minimization* to reduce to minimum possible size (see Dragon Book for details)

Handling multiple token REs



Longest-match rule: on "error" in DFA, output token (invoke action) from last reached accept state.

Summary

- Lexical analyzer converts text stream to tokens
- Regular expressions define tokens precisely
- Regular expressions (+priority order) converted to a fast table-driven scanner by converting them to NFAs, then to DFAs
- Result: shorter, easily maintained code
  - NFA-DFA conversion handles "overlapping" tokens that can be hard to code, maintain
  - usually as or more efficient than hand-written code
- Lexer generators available off-the-shelf
- Usable for all kinds of input parsing tasks
- Read chapters 1-2 from Appel