CS412/413

Introduction to Compilers
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Lecture 4: Lexical Analyzers
02 Feb 04

Outline

- DFA state minimization
- Lexical analyzers
- Automating lexical analysis
- Jlex lexical analyzer generator

Finite Automata

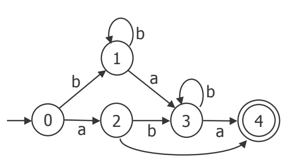
- Finite automata:
  - States, transitions between states
  - Initial state, set of final states
- DFA = deterministic
  - Each transition consumes an input character
  - Each transition is uniquely determined by the input character
- NFA = non-deterministic
  - There may be ε-transitions, which do not consume input characters
  - There may be multiple transitions from the same state on the same input character

From Regexp to DFA

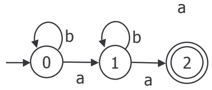
- Two steps:
  - Convert the regular expression to an NFA
  - Convert the resulting NFA to a DFA
- The generated DFAs may have a large number of states
- State Minimization = optimization which converts a DFA to another DFA which recognizes the same language and has a minimum number of states

State Minimization

- Example:
  - DFA1:



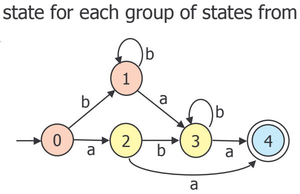
  - DFA2:



  - Both DFAs accept: b*ab*a

State Minimization

- Idea: find groups of equivalent states
  - all transitions from states in one group G_1 go to states in the same group G_2
  - construct the minimized DFA such that there is one state for each group of states from the initial DFA



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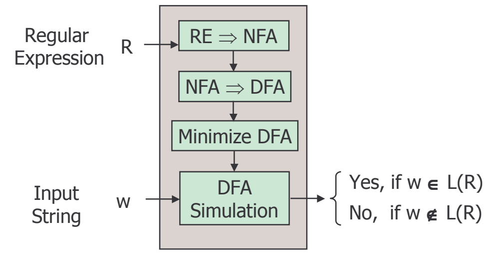
DFA Minimization (Hopcroft)

Step 1: Construct a partition P of the set of states having two groups:
F = the set of final (accepting) states
S-F = set of non-final states

Step 2:
Repeat Let $P = G_1 \cup \ldots \cup G_n$ the current partition
Partition each goup G_i into subgroups:
Two states s and t are in the same subgroup if, for each symbol **a** there are transitions $s \to s'$ and $t \to t'$ and s', t' belong to the same group G_j
Combine all the computed subgroups into a new partition P'
Until P = P'

Step3: Construct a DFA with one state for each group of states in the final partition P

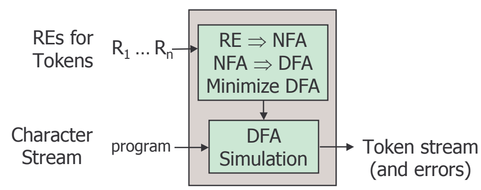
Optimized Acceptor



Lexical Analyzers vs Acceptors

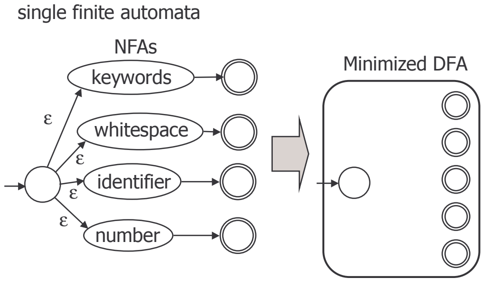
- Lexical analyzers use the same mechanism, but they:
  - Have multiple RE descriptions for multiple tokens
  - Return a sequence of matching tokens at the output (or an error)
  - Always return the longest matching token
  - For multiple longest matching tokens use rule priorities

Lexical Analyzers



Handling Multiple REs

- Combine the NFAs of all the regular expressions into a single finite automata

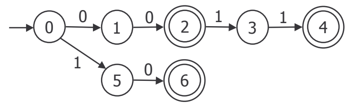


Lexical Analyzers

- Token stream at the output
  - Associate tokens with final states
  - Output the corresponding token when reaching a final state
- Longest match
  - When in a final state, look if there is a further transition; otherwise return the token for the current final state
- Rule priority
  - Same longest matching token when there is a final state corresponding to multiple tokens
  - Associate that final state to the token with the highest priority

Issue

- JLex tries to find the longest matching sequence
- Problem: what if the lexer goes past a final state of a shorter token, but then doesn't find any other longer matching token later?
- Consider R = 00 | 10 | 0011 and input: 0010

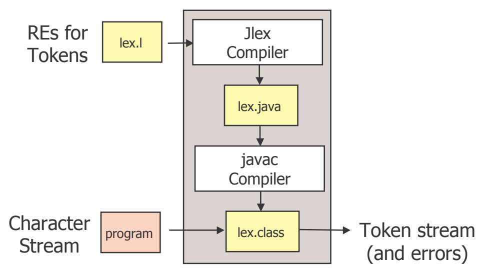


- We reach state 3 with no transition on input 0!
- Solution: record the last accepting state

Automating Lexical Analysis

- All of the lexical analysis process can be automated !
  - RE → NFA → DFA → Minimized DFA
  - Minimized DFA → Lexical Analyzer (DFA Simulation Program)
- We only need to specify:
  - Regular expressions for the tokens
  - Rule priorities for multiple longest match cases

Lexical Analyzer Generators



Jlex Specification File

- Jlex = Lexical analyzer generator
  - written in Java
  - generates a Java lexical analyzer
- Has three parts:
  - Preamble, which contains package/import declarations
  - Definitions, which contains regular expression abbreviations
  - Regular expressions and actions, which contains:
    - the list of regular expressions for all the tokens
    - Corresponding actions for each token (Java code to be executed when the token is returned)

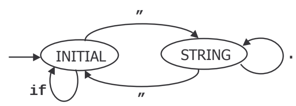
Example Specification File

```
Package Parse;
Import Error.LexicalError;
%%
digits = 0|[1-9][0-9]*
letter = [A-Za-z]
identifier = {letter}({letter}|[0-9_])*
whitespace = [\ \t\n\r]+
%%
{whitespace} {/* discard */}
{digits}      { return new
                  Token(INT, Integer.valueOf(yytext()); }
"if"          { return new Token(IF, null); }
"while"       { return new Token(WHILE, null); }
{identifier}  { return new Token(ID, yytext()); }
.             { ErrorMsg.error("illegal character"); }
```


Start States

- Mechanism which specifies in which state to start the execution of the DFA
- Define states in the second section
  - %state STATE
- Use states as prefixes of regular expressions in the third section:
  - <STATE> regex {action}
- Set current state in the actions
  - yybegin(STATE)
- There is a pre-defined initial state: YYINITIAL

Example




```
%state STRING
%%
<YYINITIAL> "if"     { return new Token(IF, null); }
<YYINITIAL> "\""     { yybegin(STRING); }
<STRING>    "\""     { yybegin(YYINITIAL); }
<STRING>     .       { }
```


Start States and REs

- The use of states allow the lexer to recognize more than regular expressions (or DFAs)
  - Reason: the lexer can jump across different states in the semantic actions using yybegin(STATE)
- Example: nested comments
  - Increment a global variable on open parentheses and decrement it on close parentheses
  - When the variable gets to zero, jump to YYINITIAL
  - The global variable essentially models an infinite number of states!

Conclusion

- Regular expressions: concise way of specifying tokens
- Can convert RE to NFA, then to DFA, then to minimized DFA
- Use the minimized DFA to recognize tokens in the input stream
- Automate the process using lexical analyzer generators
  - Write regular expression descriptions of tokens
  - Automatically get a lexical analyzer program which identifies tokens from an input stream of characters