Lexical Analysis

Finite Automata

(Part 2 of 2)
PA1, PA1c

- You can submit new rosetta.yada files for PA1, so you can fix errors from PA1c.
Reading Quiz Results

- Average: 2.11 / 4.00 = 53%
- Standard Dev: 1.00
- Goal was 85%
- Particularly troubling was that two-thirds of the class missed “Speedcoding” ...
  - ... which was the name of the assigned reading. You didn't even have to read the paper to get it, you just had to look at the assignment list.
- This gives me no confidence that the majority of students are reading for comprehension.
Cunning Plan

- Regular expressions provide a concise notation for **string patterns**
- Use in lexical analysis requires small extensions
  - To resolve ambiguities
  - To handle errors
- Good algorithms known (next)
  - Require only single pass over the input
  - Few operations per character (table lookup)
One-Slide Summary

- **Finite automata** are formal models of computation that can accept regular languages corresponding to regular expressions.
- **Nondeterministic** finite automata (NFA) feature epsilon transitions and multiple outgoing edges for the same input symbol.
- Regular expressions can be **converted** to NFAs.
- Tools will **generate** DFA-based lexer code for you from regular expressions.
Finite Automata

• Regular expressions = specification
• Finite automata = implementation

• A finite automaton consists of
  - An input alphabet $\Sigma$
  - A set of states $S$
  - A start state $n$
  - A set of accepting states $F \subseteq S$
  - A set of transitions $\text{state} \rightarrow \text{input} \text{ state}$
Finite Automata

- Transition

\[ s_1 \xrightarrow{a} s_2 \]

- Is read

In state \( s_1 \) on input “a” go to state \( s_2 \)

- If end of input (or no transition possible)
  - If in accepting state \( \Rightarrow \) accept
  - Otherwise \( \Rightarrow \) reject
Finite Automata State Graphs

- A state
- The start state
- An accepting state
- A transition
A Simple Example

- A finite automaton that accepts only “1”

![Finite Automaton Diagram]

- A finite automaton accepts a string if we can follow transitions labeled with the characters in the string from the start to some accepting state
Another Simple Example

- A finite automaton accepting any number of 1’s followed by a single 0
- Alphabet $\Sigma = \{0, 1\}$

Check that “1110” is accepted but “110...” is not
And Another Example

• Alphabet $\Sigma = \{0, 1\}$

• What language does this recognize?
And A Fourth Example

- Alphabet still $\Sigma = \{ 0, 1 \}$

- The operation of the automaton is not completely defined by the input
  - On input “11” the automaton could be in either state
Epsilon Moves

• Another kind of transition: $\varepsilon$-moves

[Diagram: A to B with $\varepsilon$]

• Machine can move from state A to state B without reading input
Deterministic and Nondeterministic Automata

- **Deterministic Finite Automata (DFA)**
  - One transition per input per state
  - No $\varepsilon$-moves

- **Nondeterministic Finite Automata (NFA)**
  - Can have multiple transitions for one input in a given state
  - Can have $\varepsilon$-moves

- Finite automata have finite memory
  - Need only to encode the current state
Execution of Finite Automata

• A DFA can take only one path through the state graph
  - Completely determined by input

• NFAs can choose
  - Whether to make $\varepsilon$-moves
  - Which of multiple transitions for a single input to take
Acceptance of NFAs

• An NFA can get into multiple states

Input: 1 0 1

Rule: NFA accepts if it can get in a final state
NFA vs. DFA (1)

• NFAs and DFAs recognize the *same* set of languages (regular languages)
  - They have the same *expressive power*

• DFAs are easier to implement
  - There are no choices to consider
NFA vs. DFA (2)

- For a given language the NFA can be simpler than the DFA

NFA

DFA

- DFA can be *exponentially* larger than NFA
Natural Languages

- This North Germanic language is generally mutually intelligible with Norwegian and Danish, and descends from Old Norse of the Viking Era to a modern speaking population of about 10 million people. The language contains two genders, nouns that are rarely inflected, and a typical subject-verb-object ordering. Its home country is one of the largest music exporters of the modern world, often targeting English-speaking audiences. Bands such as Ace of Base, ABBA and Roxette are examples, with over 420m combined album sales.
Unnatural Languages

- This stack-based structured computer programming language appeared in the 1970's and went on to influence PostScript and RPL. It is typeless and is often used in bootloaders and embedded applications. Example:

  25 10 * 50 +

- Simple C Program:

  ```c
  int floor5(int v) { return (v < 6) ? 5 : (v - 1); }
  ```

- Same program in this Language:

  ```
  : FLOOR5 ( n -- n' ) DUP 6 < IF DROP 5 ELSE 1 - THEN ;
  ```
Regular Expressions to Finite Automata

- High-level sketch

NFA

Regular expressions

Lexical Specification

DFA

Table-driven Implementation of DFA
Regular Expressions to NFA (1)

- For each kind of rexp, define an NFA
  - Notation: NFA for rexp A

- For $\epsilon$

- For input $a$
Regular Expressions to NFA (2)

• For AB

- ![Diagram for AB]

• For A | B

- ![Diagram for A | B]
Regular Expressions to NFA (3)

• For $A^*$

Diagram:

- Start state (ε)
- Transition on ε to state $A$
- Transition on ε from state $A$ to itself
- Final state (ε)

Cartoon comic:

- Calvin and Hobbes discussing destinies controlled by the stars.
- Calvin: "NO, I THINK WE CAN DO WHATEVER WE WANT WITH OUR LIVES."
Example of RegExp -> NFA Conversion

• Consider the regular expression
  \[(1 \mid 0)^* \ 1\]

• The NFA is
Overarching Plan

- Regular expressions
- Lexical Specification
- Table-driven Implementation of DFA

NFA

DFA

Thomas Cole – Evening in Arcady (1843)
NFA to DFA: The Trick

- Simulate the NFA
- Each state of DFA
  - = a non-empty *subset of states* of the NFA
- Start state
  - = the set of NFA states reachable through $\varepsilon$-moves from NFA start state
- Add a transition $S \rightarrow^a S'$ to DFA iff
  - $S'$ is the set of NFA states reachable from the states in $S$ after seeing the input $a$
  - considering $\varepsilon$-moves as well
NFA → DFA Example
NFA → DFA: Remark

- An NFA may be in many states at any time

- How many different states?

- If there are N states, the NFA must be in some subset of those N states

- How many non-empty subsets are there?
  \[ 2^N - 1 = \text{finitely many} \]
Implementation

• A DFA can be implemented by a 2D table $T$
  - One dimension is “states”
  - Other dimension is “input symbols”
  - For every transition $S_i \rightarrow^a S_k$ define $T[i,a] = k$

• DFA “execution”
  - If in state $S_i$ and input $a$, read $T[i,a] = k$ and skip to state $S_k$
  - Very efficient
Table Implementation of a DFA

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>T</td>
<td>U</td>
</tr>
<tr>
<td>T</td>
<td>T</td>
<td>U</td>
</tr>
<tr>
<td>U</td>
<td>T</td>
<td>U</td>
</tr>
</tbody>
</table>
Implementation (Cont.)

- NFA $\rightarrow$ DFA conversion is at the heart of tools such as flex or ocamllex

- But, DFAs can be huge

- In practice, flex-like tools trade off speed for space in the choice of NFA and DFA representations
PA2: Lexical Analysis

• Correctness is job #1.
  - And job #2 and #3!

• Tips on building large systems:
  - Keep it simple
  - Design systems that can be tested
  - Don’t optimize prematurely
  - It is easier to modify a working system than to get a system working
Lexical Analyzer Generator

- Tools like *lex* and *flex* and *ocamllex* will build lexers for you!
- You will use this for PA2

I’ll explain *ocamllex*; others are similar
- See PA2 documentation
Ocamllex “lexer.mll” file

```ocaml
{
   (* raw preamble code
      type declarations, utility functions, etc. *)
}

let re_name_i = re_i

rule normal_tokens = parse
   re_1 { token_1 }
| re_2 { token_2 }
| re_3 { token_3 }

and special_tokens = parse
| re_n { token_n }

```

Example “lexer.mll”

```ml
{
  type token = Tok_Integer of int
             | Tok_Divide

  let digit = ['0' – '9']

  rule initial = parse
    '/'
      { Tok_Divide }
  | digit digit* { let token_string = Lexing.lexeme lexbuf in
                   let token_val = int_of_string token_string in
                   Tok_Integer(token_val) }
  | _          { Printf.printf "Error!\n"; exit 1 }
}
```
Adding Winged Comments

```ocaml
{ type token = Tok_Integer of int (* 123 *)
  | Tok_Divide (* / *)
}
let digit = ['0' - '9']
rule initial = parse
  "//" { eol_comment }
| '/' { Tok_Divide }
| digit digit* { let token_string = Lexing.lexeme lexbuf in
  let token_val = int_of_string token_string in
  Tok_Integer(token_val) }
| _ { Printf.printf "Error!\n";
      exit 1 }

and eol_comment = parse
  '\n' { initial lexbuf }
| _ { eol_comment lexbuf }
```
Using Lexical Analyzer Generators

$ ocamllex lexer.mll
45 states, 1083 transitions, table size 4602 bytes

(* your main.ml file ... *)
let file_input = open_in "file.cl" in
let lexbuf = Lexing.from_channel file_input in
let token = Lexer.initial lexbuf in
match token with
 | Tok_Divide -> printf "Divide Token!\n"
 | Tok_Integer(x) -> printf "Integer Token = %d\n" x
How Big Is PA2?

• The reference “lexer.mll” file is 88 lines
  - Perhaps another 20 lines to keep track of input line numbers
  - Perhaps another 20 lines to open the file and get a list of tokens
  - Then 65 lines to serialize the output
  - I’m sure it’s possible to be smaller!

• Conclusion:
  - This isn’t a code slog, it’s about careful forethought and precision.
Warning!

• You may be tempted to use OCaml for PA2 based on that demo.

• However, you probably want to save OCaml for one of the harder assignments later.
Test Yourself! Exam Practice.

- Are practical parsers and scanners based on deterministic or non-deterministic automata?
- How can regular expressions be used to specify nested constructs?
- How is a two-dimensional *transition table* used in table-driven scanning?
Homework

- PA1 due
- Textbook Reading, CD Reading