CSE401: Lexing

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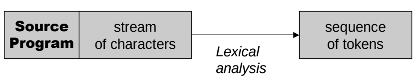
Objectives for today and tomorrow

- Define overall theory and practical structure of lexical analysis
- Briefly recap regular expressions, finite state machines, and their relationship
  - Even briefer recap of the language hierarchy
- Show how to define tokens with regular expressions
- Show how to leverage this style of token definition in implementing a lexer

Lexical analysis (Scanning)



- A token is a group of characters forming basic, atomic chunks of syntax
  - Ex: `17`, `:=`, `3.1415`, `else`, `snork`, …
- The lexer also removes whitespace
  - Whitespace consists of characters between tokens that are ignored
  - Ex: spaces, tabs, newlines, comments
    - – The definition of whitespace varies from language to language

After scanning: syntactic analysis

- The sequence of tokens produced by the scanner is parsed as part of syntactic analysis
- This separation is followed universally
  - Lexing and parsing are theoretically and practically different activities
    - – Character stream to token stream vs. token stream to syntax tree
  - Scanning is time-consuming in many compilers, largely due to handling I/O
    - – By restricting the job of the lexer, a faster implementation is often feasible

Overall approach to scanning

1. Define the tokens for the language using regular expressions
   - Natural representation for tokens
   - But difficult to produce a scanner from REs
2. Convert the regular expressions into non-deterministic finite state automata (NFA)
   - Straightforward conversion
   - Can produce a scanner from NFA, but an inefficient one
3. Convert the NFA into deterministic finite state automata (DFA)
   - Straightforward conversion
4. Convert the DFA into an efficient scanner implementation

Language and automata theory: *a speedy reminder*

- *Alphabet*: a finite set of symbols
- *String*: a finite, possibly empty, sequence of characters in an alphabet
- *Language*: a (possibly empty or infinite) set of strings
- *Grammar*: a finite specification of a language
  - Even if the language is infinite
- *Language automaton*: a machine for accepting a language and rejecting all other strings
  - A language can be specified by many different grammars and automata
  - A grammar or automaton specifies precisely one language

Definitions

- *Lexeme*: a group of characters that form a token
- *Token*: a set of lexemes that match a pattern
  - We'll use regular expressions to define tokens
- A token may have attributes, if the set has more than a single lexeme
  - Ex: integers are a token, but each integer lexeme must also know its value

Regular expressions:
a notation for defining tokens

- The syntax of regular expressions (REs) is defined inductively
- Base cases
  - The empty string (ε)
  - A symbol from the alphabet
- Inductive cases
  - Sequence of two REs: E_1E_2
  - Choice of two REs: $E_1 | E_2$
  - Kleene closure (zero or more occurrences) of an RE: E^*
- Can use parentheses for grouping
- Precedence
  - `*` (highest)
  - sequence
  - `|` (lowest)
- Whitespace is not significant

Notational conveniences:
no additional expressive power

- E^+ means one or more occurrences of `E`
- E^k means `k` occurrences of `E`
- `[E]` means zero or one occurrences of `E` (it's optional)
- `{E}` means E^*
- `not(x)` means any character in the alphabet but `x`
- `not(E)` means any strings in the alphabet but those matching `E`
- $E_1 - E_2$ means any strings matching E_1 except those matching E_2

Naming regular expressions:
simplify RE definitions

- Can assign names to regular expressions
- Can use these names in the definition of another regular expression
- Examples
  - `letter   ::= a | b | … | z`
  - `digit    ::= 0 | 1 | … | 9`
  - `alphanum ::= letter | digit`
- Can eliminate names by macro expansion
- *No recursive definitions are allowed!* **Why?**

Regular expressions for PL/0

```
Program ::= (Token | White)*
Token   ::= Id | Integer | Keyword | Operator | Punct
Punct   ::= ; | : | . | , | ( | )
Keyword ::= module | procedure | begin | end | const
          | var | if | then | while | do | input
          | output | odd | int
Operator::= := | * | / | + | - | = | <> | <= | <
          | >= | >
Integer ::= Digit*
Id      ::= Letter AlphaNum*
AlphaNum::= Letter | Digit
Digit   ::= 0 | … | 9
Letter  ::= a | … | z | A | … | Z
White   ::= <space> | <tab> | <newline>
```


Generate scanner from regular expressions?

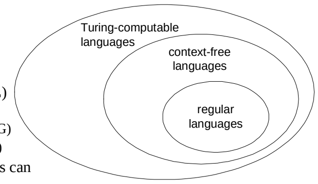
- This would be ideal: REs as input to a scanner generator, and a scanner as output
  - Indeed, some tools can mostly do this
- But it's not straightforward to do this
  - One reason is that there is a lot of non-determinism — choice — that is inherent in regular expressions in general
  - Choice can be implemented using recursion, but it's generally very inefficient
- In any case, these tools go through a process like the one we'll look at

Next steps

- Convert regular expressions to non-deterministic finite state automata (NFA)
- Then convert the NFA to deterministic finite state automata (DFA)
- Then convert DFA into code

Classes of languages

- Regular languages can be specified by
  - regular expressions
  - regular grammars
  - finite-state automata (FSA)
- Context-free languages (CFL) can be specified by
  - context-free grammars (CFG)
  - push-down automata (PDA)
- Turing-computable languages can be specified by
  - arbitrary grammars
  - Turing machines



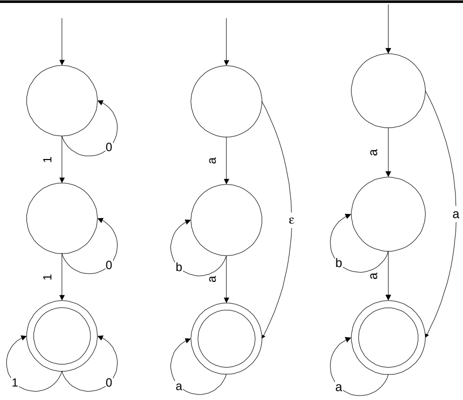
Strict inclusion of these classes of languages

Finite state automata

- A finite set of states
  - One marked as the initial state
  - One or more marked as final states
- A set of transitions from state to state
  - Each transition is marked with a symbol from the alphabet or with ε
- Operate by reading symbols in sequence
  - A transition can be taken if it labeled with the current symbol
  - An ε-transition can be taken at any point, without consuming a symbol
- Accept if done with input and in a final state
- Reject if no transition can be taken or if input is done and not in a final state

DFA vs. NFA

- A deterministic finite state automata (DFA) is one in which there is no choice of which transition to take under any condition
- A non-deterministic finite state automata (NFA) is one in which there is a choice of which transition to take in at least one situation



Plan of attack

- Convert from regular expressions to NFAs because there is an easy construction
  - However, NFAs encode choice, and choice implies recursion, and recursion is slow in a scanner
- Convert from NFAs to DFAs, because there is a well-defined procedure
  - And DFAs lay the foundation for an efficient scanner implementation

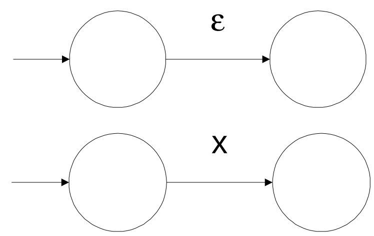
Example: in groups

5 minutes

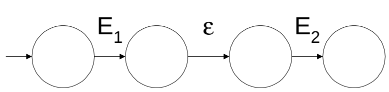
- Consider the language that includes only those binary strings that have odd parity
- For this language, define
  - the alphabet
  - a grammar
  - an automaton

Converting REs to NFAs:

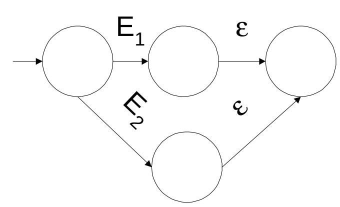
base cases



E_1E_2



$E_1 | E_2$



E^*

?

RE to NFA

- Those rules are sufficient for constructing an equivalent NFA from a regular expression

Time permitting

in groups

- Define a regular expression that recognizes comments of the form
  - `/* … */`
  - Be careful in defining "…"
- Then convert that regular expression to an NFA

Next lecture

- NFA to DFA
- DFA to scanner