CMSC 330: Organization of Programming Languages

Regular Expressions and Finite Automata

How do regular expressions work?

- What we've learned
  - What regular expressions are
  - What they can express, and cannot
  - Programming with them
- What's next: how they work
  - Mixture of a very practical tool (string matching with REs) and some nice theory
  - A great computer science result

A Few Questions About REs

- How are REs implemented?
  - Implementing a one-off RE is not so hard
    - How to do it in general?
  - We'll see how to build a structure to parse REs
- What are the basic components of REs?
  - Can implement some features in terms of others
    - E.g., we saw that e+ is the same as ee*
- What does a regular expression represent?
  - Just a set of strings
    - This observation provides insight on how we go about our implementation

Definition: Alphabet

- An alphabet is a finite set of symbols
  - Usually denoted Σ
- Example alphabets:
  - Binary: $\Sigma = \{0,1\}$
  - Decimal: $\Sigma = \{0,1,2,3,4,5,6,7,8,9\}$
  - Alphanumeric: $\Sigma = \{0\text{-}9, a\text{-}z, A\text{-}Z\}$

Definition: String

- A string is a finite sequence of symbols from Σ
  - ε is the empty string ("" in Ruby)
  - |s| is the length of string s
    - |Hello| = 5, |ε| = 0
  - Note
    - Ø is the empty set (with 0 elements)
    - Ø ≠ { ε } ≠ ε
- Example strings:
  - 0101 ∈ Σ = {0,1} (binary)
  - 0101 ∈ Σ = decimal
  - 0101 ∈ Σ = alphanumeric

Definition: String concatenation

- String concatenation is indicated by juxtaposition
  - If s_1 = super and s_2 = hero, then s_1s_2 = superhero
  - Sometimes also written $s_1 \cdot s_2$
  - For any string s, we have sε = εs = s
  - You can concatenate strings from different alphabets; then the new alphabet is the union of the originals:
    - If s_1 = super ∈ Σ_1 = {s,u,p,e,r} and s_2 = hero ∈ Σ_2 = {h,e,r,o}, then s_1s_2 = superhero ∈ Σ_3 = {e,h,o,p,r,s,u}

Definition: Language

- A language L is a set of strings over an alphabet
- Example: The set of phone numbers over the alphabet Σ = {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, (,), -}
  - Give an example element of this language `(123) 456-7890`
  - Are all strings over the alphabet in the language? `No`
  - Is there a Ruby regular expression for this language?

```
/\(\d{3,3}\) \d{3,3}-\d{4,4}/
```

- Example: The set of all strings over Σ
  - Often written Σ*

Definition: Language (cont.)

- Example: The set of strings of length 0 over the alphabet Σ = {a, b, c}
  - L = { s | s ∊ Σ* and |s| = 0} = {ε} ≠ Ø
- Example: The set of all valid Ruby programs
  - Is there a Ruby regular expression for this language?

No. Matching (an arbitrary number of) brackets so that they are balanced is impossible using REs { { { … } } }

- REs represent languages, but not all of them
  - The languages represented by regular expressions are called, appropriately, the regular languages

Definition: Regular Expressions

- Given an alphabet Σ, the regular expressions over Σ are defined inductively as

regular expression	denotes language
∅	∅
ε	{ε}
each element σ ∈ Σ	{σ}

Constants

Definition: Regular Expressions (cont.)

- Let A and B be regular expressions denoting languages L_A and L_B, respectively

regular expression	denotes language
AB	$L_A L_B$
(A|B)	$L_A \cup L_B$
A*	$L_A{}^*$

Operations

- There are no other regular expressions over Σ

Operations on Languages

- Let Σ be an alphabet and let L, L_1, L_2 be languages over Σ
- Concatenation L_1L_2 is defined as
  - $L_1L_2 = \{ xy \mid x \in L_1 \text{ and } y \in L_2\}$
- Union is defined as
  - $L_1 \cup L_2 = \{ x \mid x \in L_1 \text{ or } x \in L_2\}$
- Kleene closure is defined as
  - $L^* = \{ x \mid x = \varepsilon \text{ or } x \in L \text{ or } x \in LL \text{ or } x \in LLL \text{ or } \ldots\}$

Regular Expressions Denote Languages

- By applying operations on constants
  - Generates a set of strings (i.e., a language)
  - Examples
    - a → {"a"}
    - a|b → {"a"} ∪ {"b"} = {"a", "b"}
    - a* → {ε} ∪ {"a"} ∪ {"aa"} ∪ … = {ε,"a", "aa", … }
- If s ∈ language generated by a RE r, we say that r accepts, describes, or recognizes string s

Precedence

- Order in which operators are applied
  - In arithmetic
    - Multiplication × > addition +
    - 2 × 3 + 4 = (2 × 3) + 4 = 10
  - In regular expressions
    - Kleene closure * > concatenation > union |
    - ab|c = (a b) | c = {“ab”, “c”}
    - ab* = a (b*) = {“a”, “ab”, “abb”…}
    - a|b* = a | (b*) = {“a”, “”, “b”, “bb”, “bbb”…}
  - Can change order using parentheses ( )
    - E.g., a(b|c), (ab)*, (a|b)*

Regular Languages

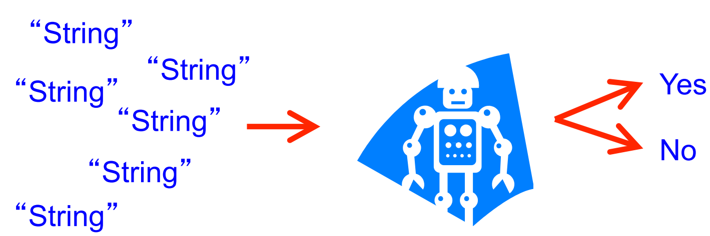
- The languages that can be described using regular expressions are the regular languages or regular sets
- Not all languages are regular
  - Examples (without proof):
    - The set of palindromes over Σ
      - reads the same backward or forward
    - $\{a^n b^n \mid n > 0\}$ (a^n = sequence of n a’s)
- Almost all programming languages are not regular
  - But aspects of them sometimes are (e.g., identifiers)
  - Regular expressions are commonly used in parsing tools

Ruby Regular Expressions

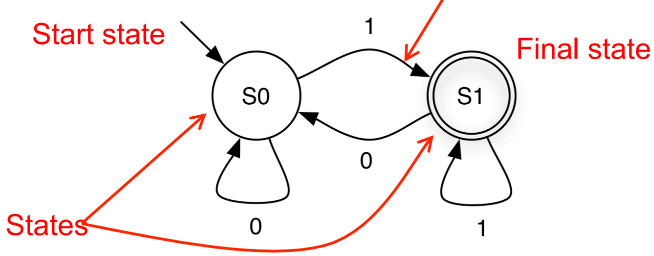
- Almost all of the features we’ve seen for Ruby REs can be reduced to this formal definition
  - /Ruby/ – concatenation of single-character REs
  - /(Ruby|Regular)/ – union
  - /(Ruby)*/ – Kleene closure
  - /(Ruby)+/ – same as (Ruby)(Ruby)*
  - /(Ruby)?/ – same as (ε|(Ruby)) (// is ε)
  - /[a-z]/ – same as (a|b|c|...|z)
  - / [^0-9]/ – same as (a|b|c|...) for a,b,c,... ∈ Σ - {0..9}
  - ^, $ – correspond to extra characters in alphabet

Implementing Regular Expressions

- We can implement a regular expression by turning it into a finite automaton
  - A “machine” for recognizing a regular language



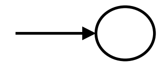
Finite Automata



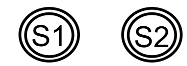
- Machine starts in start or initial state
- Repeat until the end of the string is reached
  - Scan the next symbol s of the string
  - Take transition edge labeled with s
- String is accepted if automaton is in final state when end of string reached

Finite Automata: States

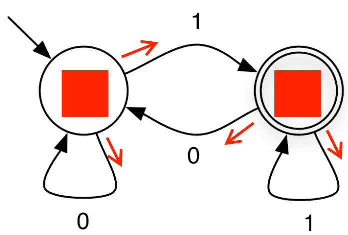
- Start state
  - State with incoming transition from no other state
  - Can have only 1 start state



- Final states
  - States with double circle
  - Can have 0 or more final states
  - Any state, including the start state, can be final



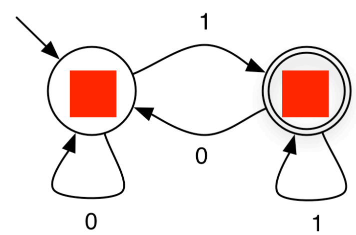
Finite Automaton: Example 1



0 0 1 0 1 1

accepted

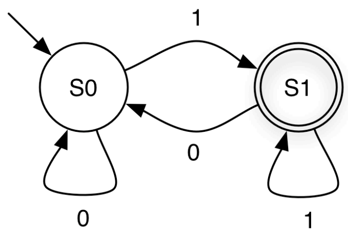
Finite Automaton: Example 2



0 0 1 0 1 0

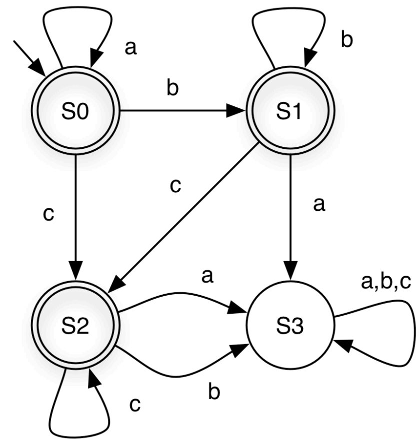
not accepted

What Language is This?



- All strings over {0, 1} that end in 1
- What is a regular expression for this language?
  (0|1)*1

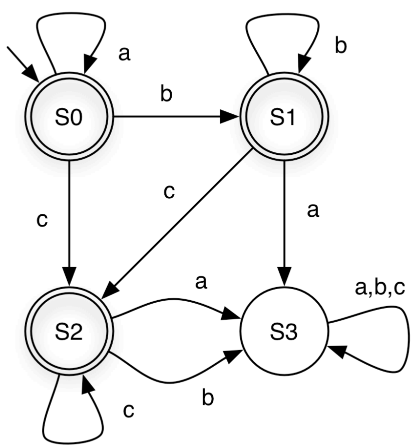
Finite Automaton: Example 3



string	state at end	accepts ?
aabcc	S2	Y
acc	S2	Y
bbc	S2	Y
aabbb	S1	Y
aa	S0	Y
ε	S0	Y
acba	S3	N

(a,b,c notation shorthand for three self loops)

Finite Automaton: Example 3 (cont.)



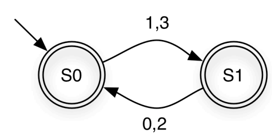
What language does this FA accept?

a*b*c*

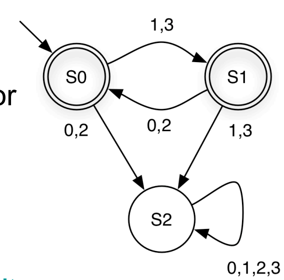
S3 is a dead state – a nonfinal state with no transition to another state

Dead State: Shorthand Notation

- If a transition is omitted, assume it goes to a dead state that is not shown

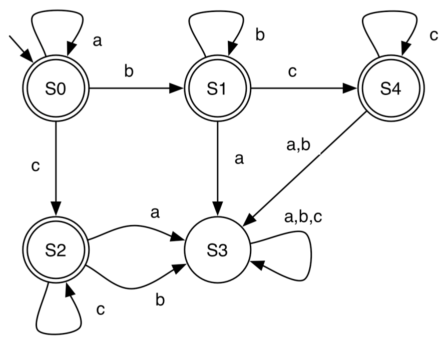


is short for



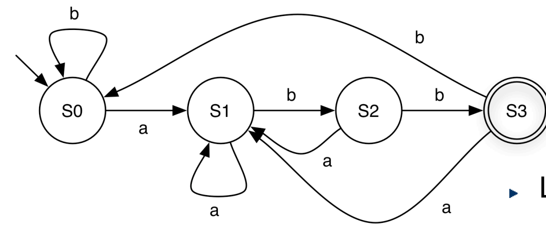
- Language?
  - Strings over {0,1,2,3} with alternating even and odd digits, beginning with odd digit

Finite Automaton: Example 4



a*b*c* again, so DFAs are not unique

Finite Automaton: Example 5



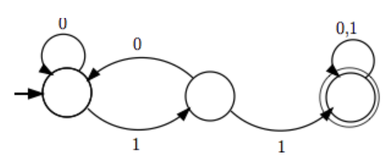
- Language?
  - (a|b)*abb
- Description for each state
  - S0 = "Haven't seen anything yet" OR "seen zero or more b's" OR "Last symbol seen was a b"
  - S1 = "Last symbol seen was an a"
  - S2 = "Last two symbols seen were ab"
  - S3 = "Last three symbols seen were abb"

The Questions (for next time)

- Are FAs equivalent to regular expressions?
  - Every FA can be translated into an RE
  - Every RE can be translated into an FA
  - Yes!
- How can we generate an FA for a given RE?
  - If we can do this, we can implement RE matching
- How can we optimize an FA?
  - Many FAs can implement the same language
  - Some might be more efficient than others

Practice

Give the English descriptions and the DFA or regular expression of the following languages:

- ((0|1)(0|1)(0|1)(0|1)(0|1))*
  - All strings with length a multiple of 5
- (01)*|(10)*|(01)*0|(10)*1
  - All alternating binary strings
- 

  All binary strings containing the substring "11"

Practice

- Give the regular expressions and finite automata for the following languages
  - You and your neighbors' names
  - All protein-coding DNA strings (including only ATCG and appearing in multiples of 3)
  - All binary strings containing an even length substring of all 1's
  - All binary strings containing exactly two 1's
  - All binary strings that start and end with the same number

Review

- Languages
  - Sets of strings
  - Operations on languages
- Regular expressions
  - Constants
  - Operators
  - Precedence
- Finite automata
  - States
  - Transitions
  - Accept strings