CMSC 330: Organization of Programming Languages

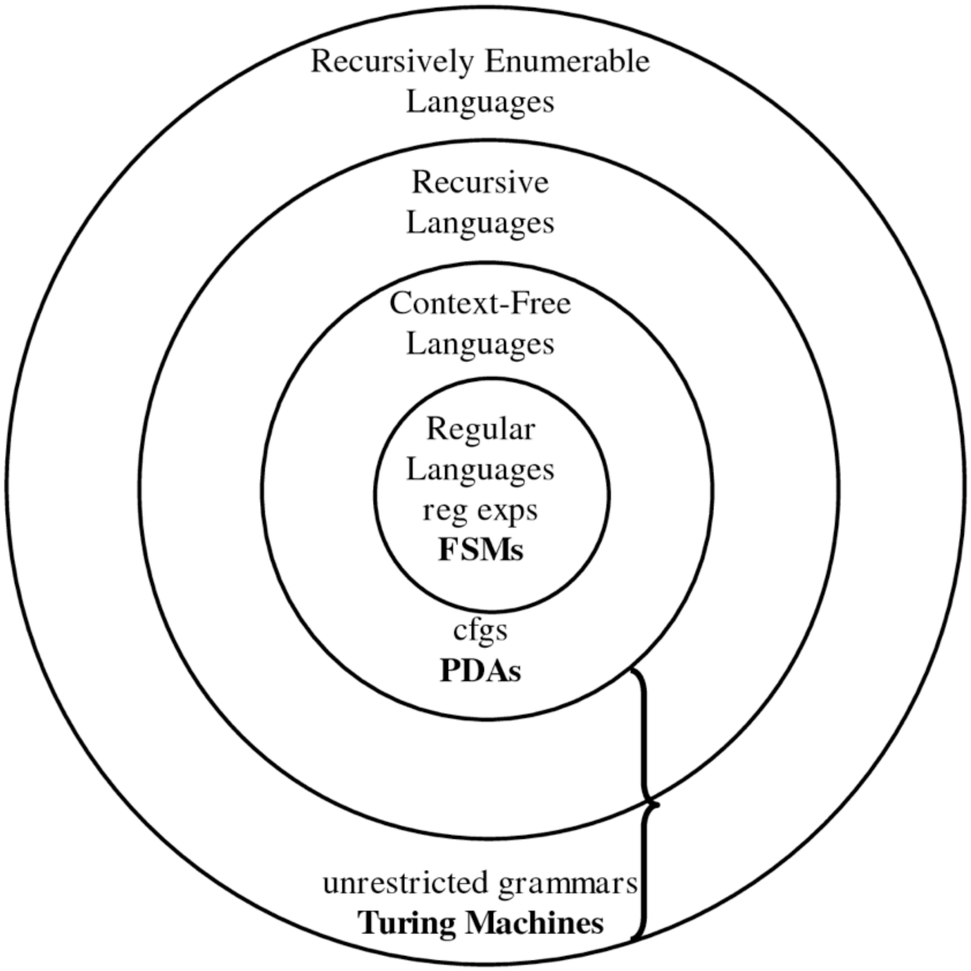
Regular Expressions and Finite Automata

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
  - A great computer science result

Languages and Machines



A Few Questions About REs

- How are REs implemented?
  - Implementing a one-off RE is not so hard
    - How to do it in general?
- What are the basic components of REs?
  - Can implement some features in terms of others
    - E.g., 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
- … next comes the math !

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 over alphabet Σ = {0,1} (binary):
  - 0101
  - 0101110
  - ε

Definition: String concatenation

- String concatenation is indicated by juxtaposition

s_1 = super

s_2 = hero

$s_1 s_2$ = superhero

- Sometimes also written $s_1 \cdot s_2$

- For any string s, we have $s\varepsilon = \varepsilon s = s$
  - You can concatenate strings from different alphabets; then the new alphabet is the union of the originals:
    - If s_1 = super from $\Sigma_1 = \{s,u,p,e,r\}$ and s_2 = hero from $\Sigma_2 = \{h,e,r,o\}$, then $s_1 s_2$ = superhero from $\Sigma_3 = \{e,h,o,p,r,s,u\}$

Definition: Language

- A language L is a set of strings over an alphabet
- Example: All strings of length 1 or 2 over alphabet Σ = {a, b, c} that begin with a
  - L = { a, aa, ab, ac }
- Example: All strings over Σ = {a, b}
  - L = { ε, a, b, aa, bb, ab, ba, aaa, bba, aba, baa, … }
  - Language of all strings written Σ^*
- Example: All strings of length 0 over alphabet Σ
  - L = { s | s $\in \Sigma^*$ and |s| = 0 }

  "the set of strings s such that s is from Σ^* and has length 0"

  = {ε} $\neq \varnothing$

Definition: Language (cont.)

- Example: The set of phone numbers over the alphabet $\Sigma = \{0, 1, 2, 3, 4, 5, 6, 7, 9, (,), -\}$
  - 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 valid Ruby programs
  - Later we'll see how we can specify this language
  - (Regular expressions are useful, but not sufficient)

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
  - $L^* = \{ x \mid x = \varepsilon \text{ or } x \in L \text{ or } x \in LL \text{ or } x \in LLL \text{ or } \ldots\}$

Quiz 1: Which string is **not** in L_3

$L_1 = \{a, ab, c, d, \varepsilon\}$ where $\Sigma = \{a,b,c,d\}$

$L_2 = \{d\}$

$L_3 = L_1L_2$

A. a
B. abd
C. cd
D. d

Quiz 1: Which string is **not** in L_3

$L_1 = \{a, ab, c, d, \varepsilon\}$ where $\Sigma = \{a,b,c,d\}$

$L_2 = \{d\}$

$L_3 = L_1L_2$

A. a
B. abd
C. cd
D. d

Quiz 2: Which string is **not** in L_3

$L_1 = \{a, ab, c, d, \varepsilon\}$ where $\Sigma = \{a,b,c,d\}$

$L_2 = \{d\}$

$L_3 = L_1 \cup L_2$

A. a
B. abd
C. ε
D. d

Quiz 2: Which string is **not** in L_3

$L_1 = \{a, ab, c, d, \varepsilon\}$ where $\Sigma = \{a,b,c,d\}$

$L_2 = \{d\}$

$L_3 = L_1 \cup L_2$

A. a
B. abd
C. ε
D. d

Regular Expressions: Grammar

- Similarly to how we expressed Micro-OCaml we can define a grammar for regular expressions R

$R ::= \varnothing$	The empty language
$\mid \varepsilon$	The empty string
$\mid \sigma$	A symbol from alphabet Σ
$\mid R_1R_2$	The concatenation of two regexps
$\mid R_1 \vert R_2$	The union of two regexps
$\mid R^*$	The Kleene closure of a regexp

Regular Languages

- Regular expressions denote languages. These are the regular languages
  - *aka* regular sets
- Not all languages are regular
  - Examples (without proof):
    - The set of palindromes over Σ
    - $\{a^n b^n \mid n > 0\}$ (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

Semantics: Regular Expressions (1)

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

regular expression	denotes language
$\emptyset$	$\emptyset$
ε	$\{\varepsilon\}$
each symbol $\sigma \in \Sigma$	$\{\sigma\}$

Constants

Semantics: Regular Expressions (2)

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

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

Terminology etc.

- Regexps apply operations to symbols
  - Generates a set of strings (i.e., a language)
    - (Formal definition shortly)
  - Examples
    - a $\rightarrow$ {a}
    - a|b $\rightarrow$ {a} ∪ {b} = {a, b}
    - a* $\rightarrow$ {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

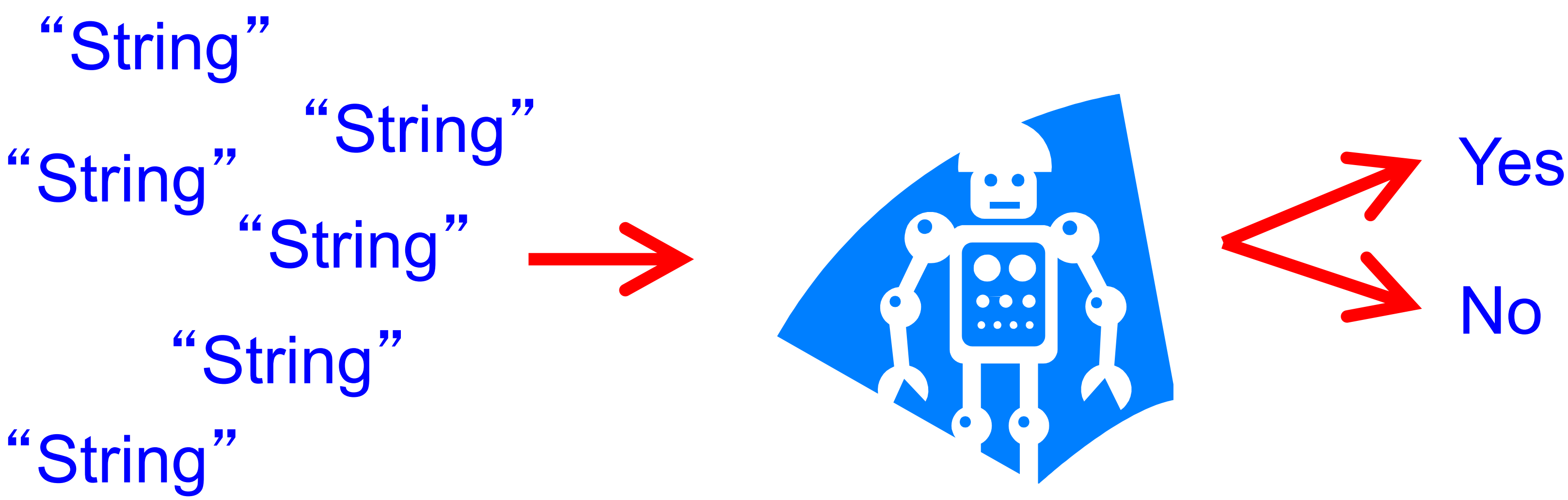
- Order in which operators are applied is:
  - Kleene closure * > concatenation > union |
  - ab|c = (a b) | c → {ab, c}
  - ab* = a (b*) → {a, ab, abb ...}
  - a|b* = a | (b*) → {a, ε, b, bb, bbb ...}
- We use parentheses ( ) to clarify
  - E.g., a(b|c), (ab)*, (a|b)*
  - Using escaped \(if parens are in the alphabet

Ruby Regular Expressions

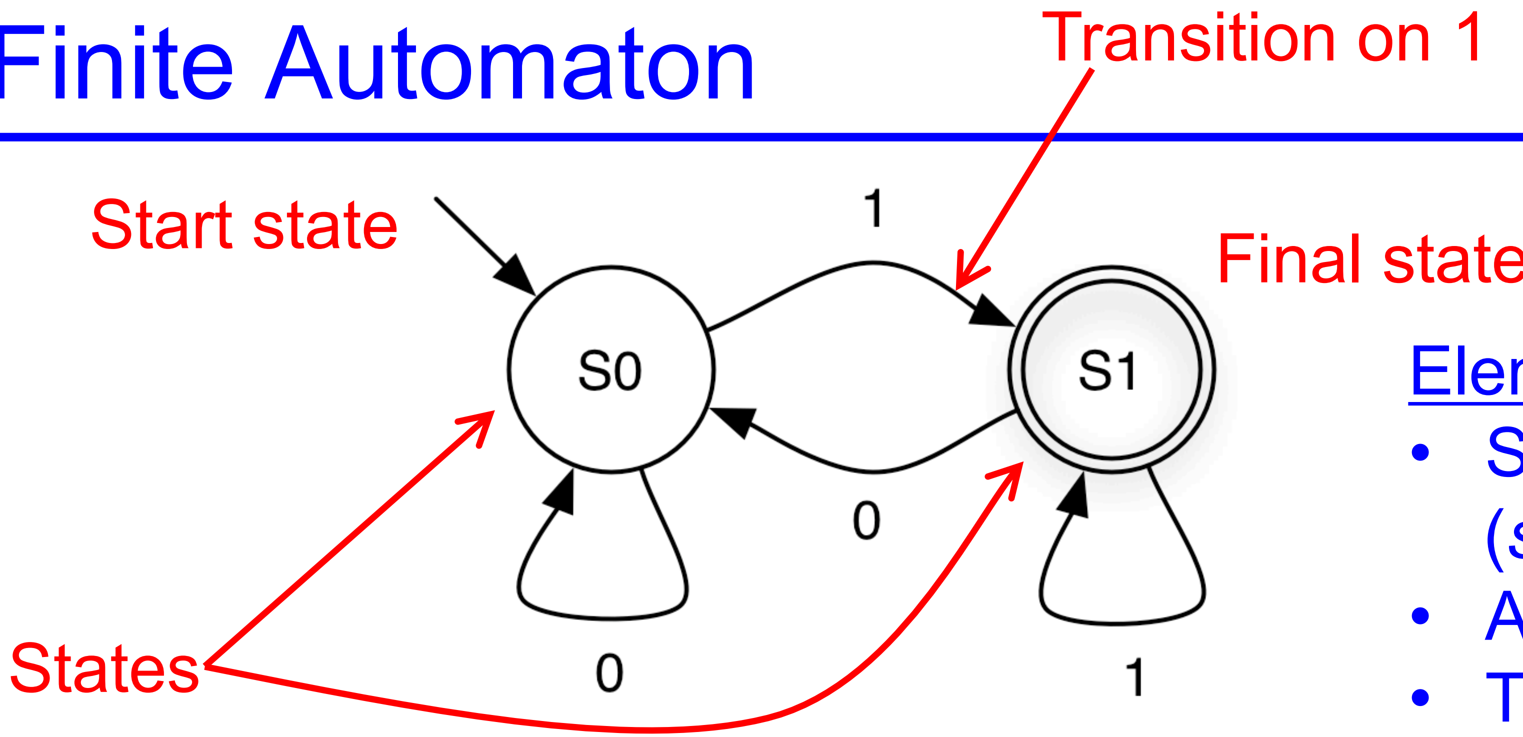
- Almost all of the features we've seen for Ruby REs can be reduced to this formal definition
  - /Ruby/ – concatenation of single-symbol REs
  - /(Ruby|Regular)/ – union
  - /(Ruby)*/ – Kleene closure
  - /(Ruby)+/ – same as (Ruby)(Ruby)*
  - /(Ruby)?/ – same as (ε|(Ruby)) (// is ε)
  - /[a-z]/ – same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

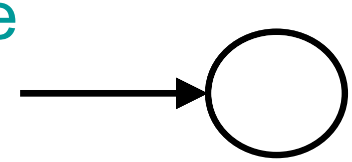


Elements
- States S (*start*, *final*)
- Alphabet Σ
- Transition edges δ

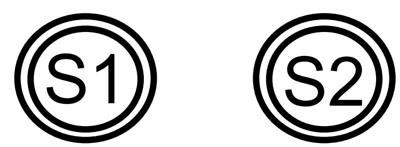
- Machine starts in start or initial state
- Repeat until the end of the string s is reached
  - Scan the next symbol $\sigma \in \Sigma$ of the string s
  - Take transition edge labeled with σ
- String s is accepted if automaton is in final state when end of string s is reached

Finite Automaton: States

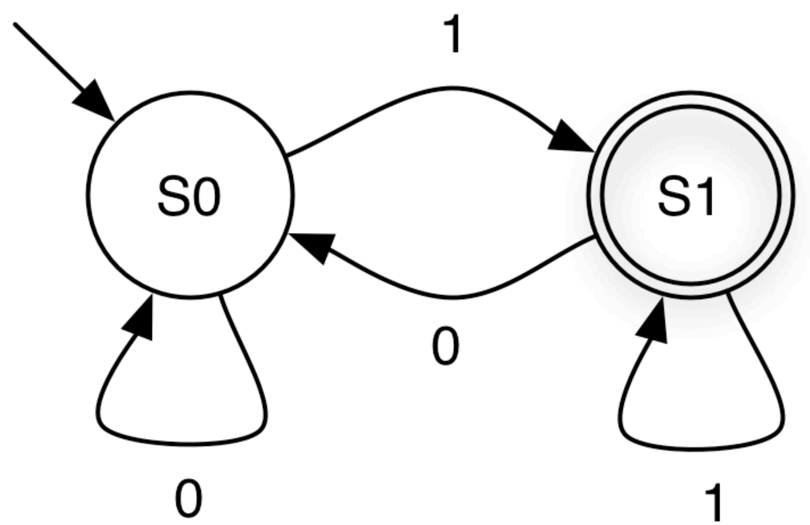
- Start state
  - State with incoming transition from no other state
  - Can have only one start state



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



Finite Automaton: Example 1

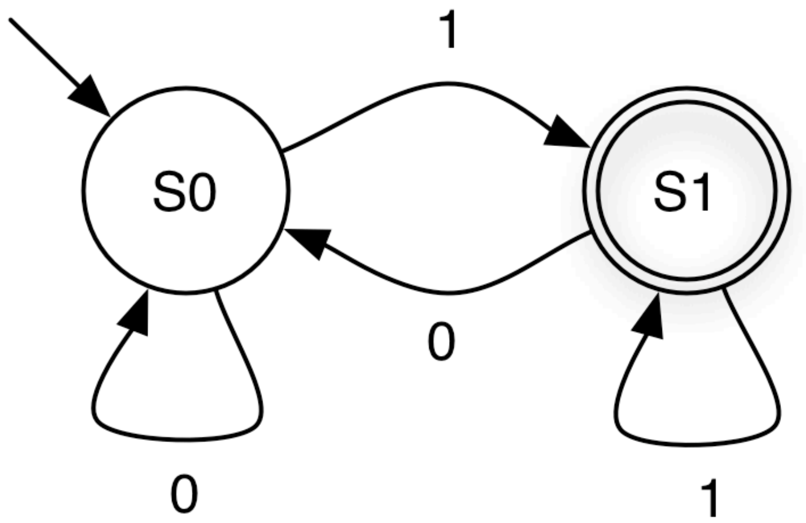


0 0 1 0 1 1

Accepted?

Yes

Finite Automaton: Example 2

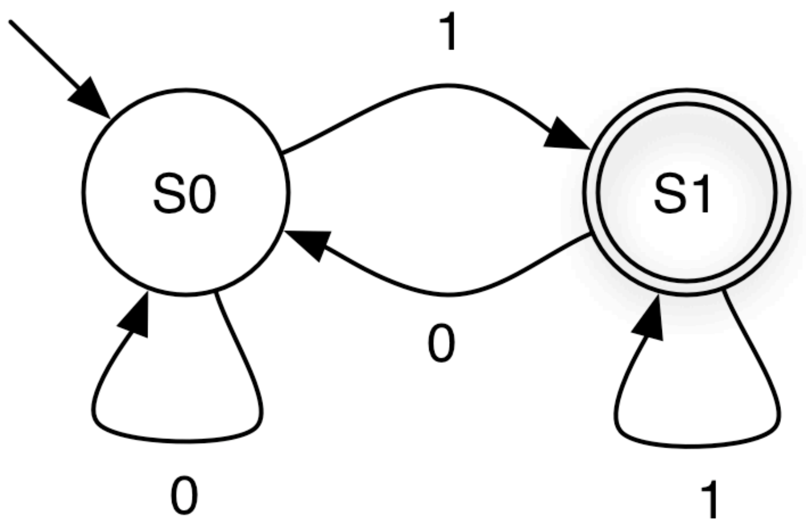


0 0 1 0 1 0

Accepted?

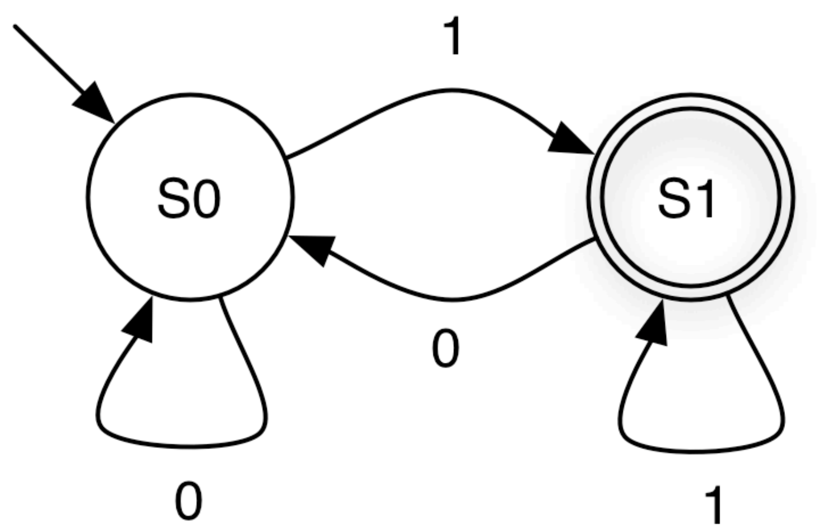
No

Quiz 3: What Language is This?



A. All strings over {0, 1}
B. All strings over {1}
C. All strings over {0, 1} of length 1
D. All strings over {0, 1} that end in 1

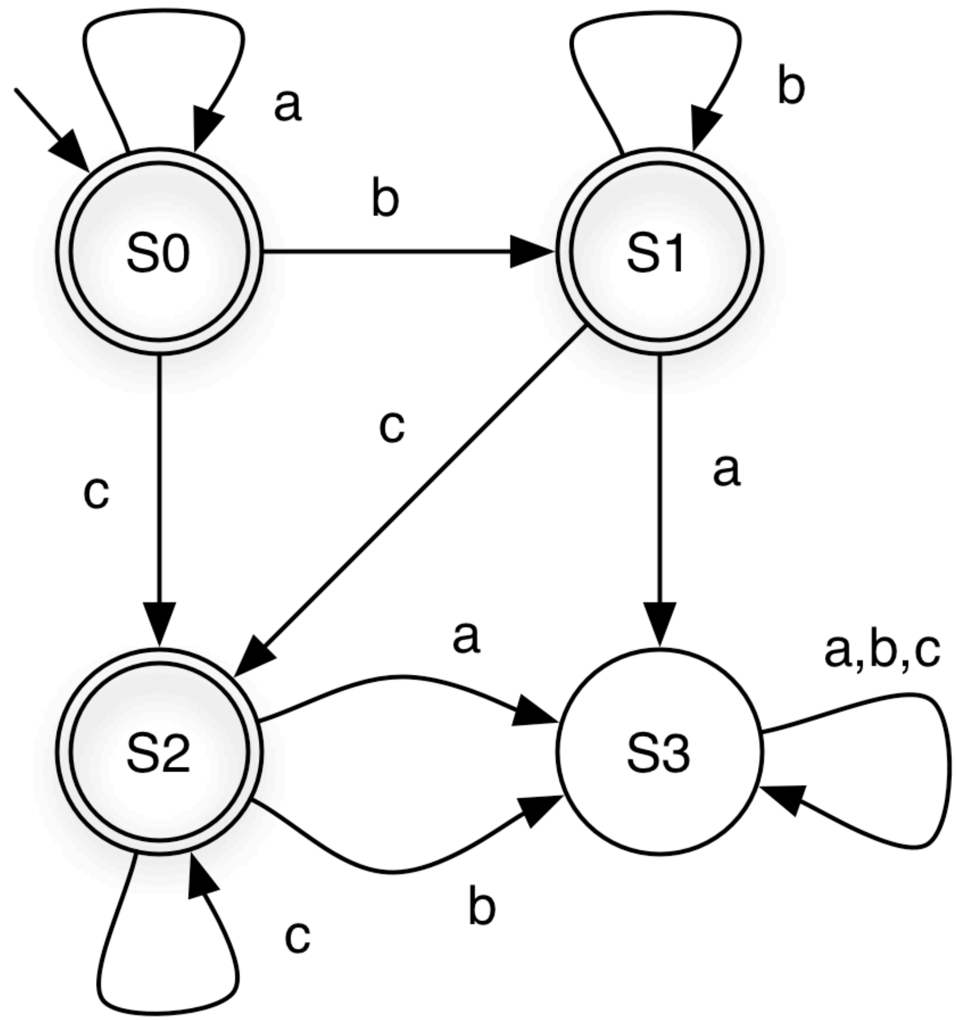
Quiz 3: What Language is This?



A. All strings over {0, 1}
B. All strings over {1}
C. All strings over {0, 1} of length 1
D. All strings over {0, 1} that end in 1

regular expression for this language is (0|1)*1

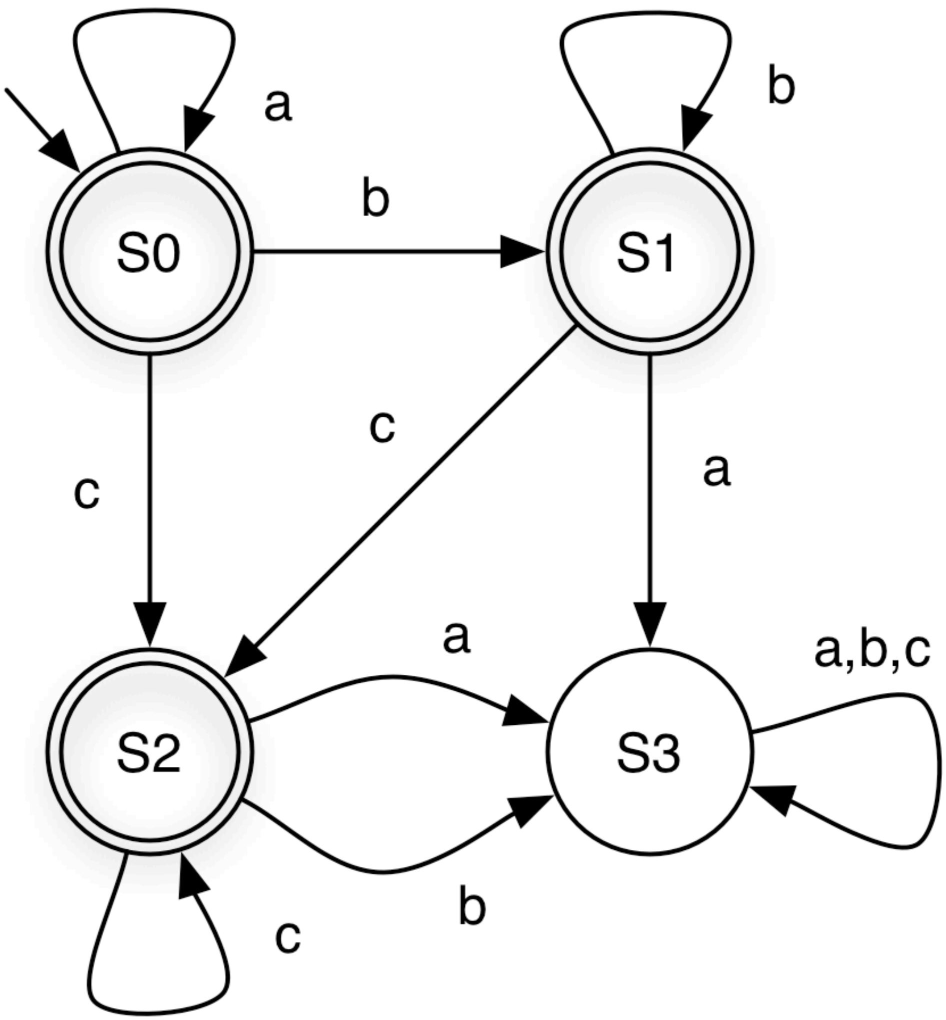
Finite Automaton: Example 3



string	state at end	accepts ?
aabcc		

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

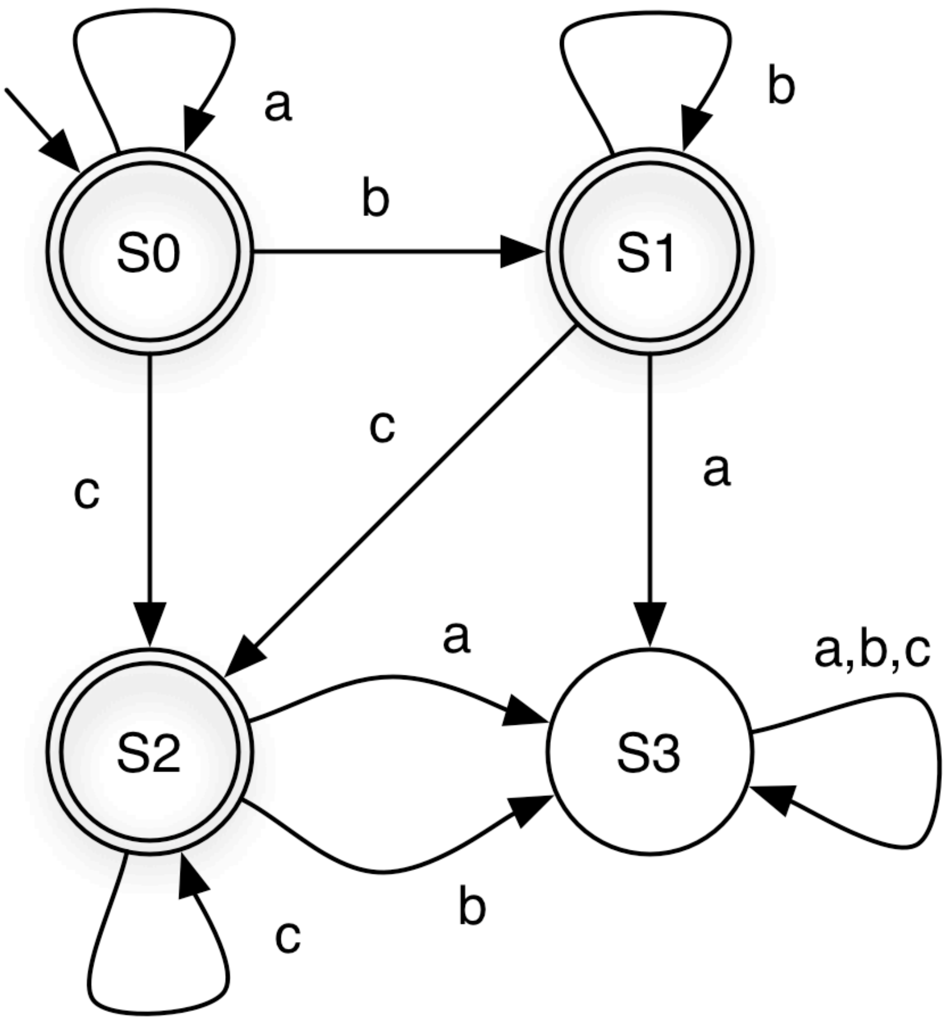
Finite Automaton: Example 3



string	state at end	accepts ?
aabcc	S2	Y

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

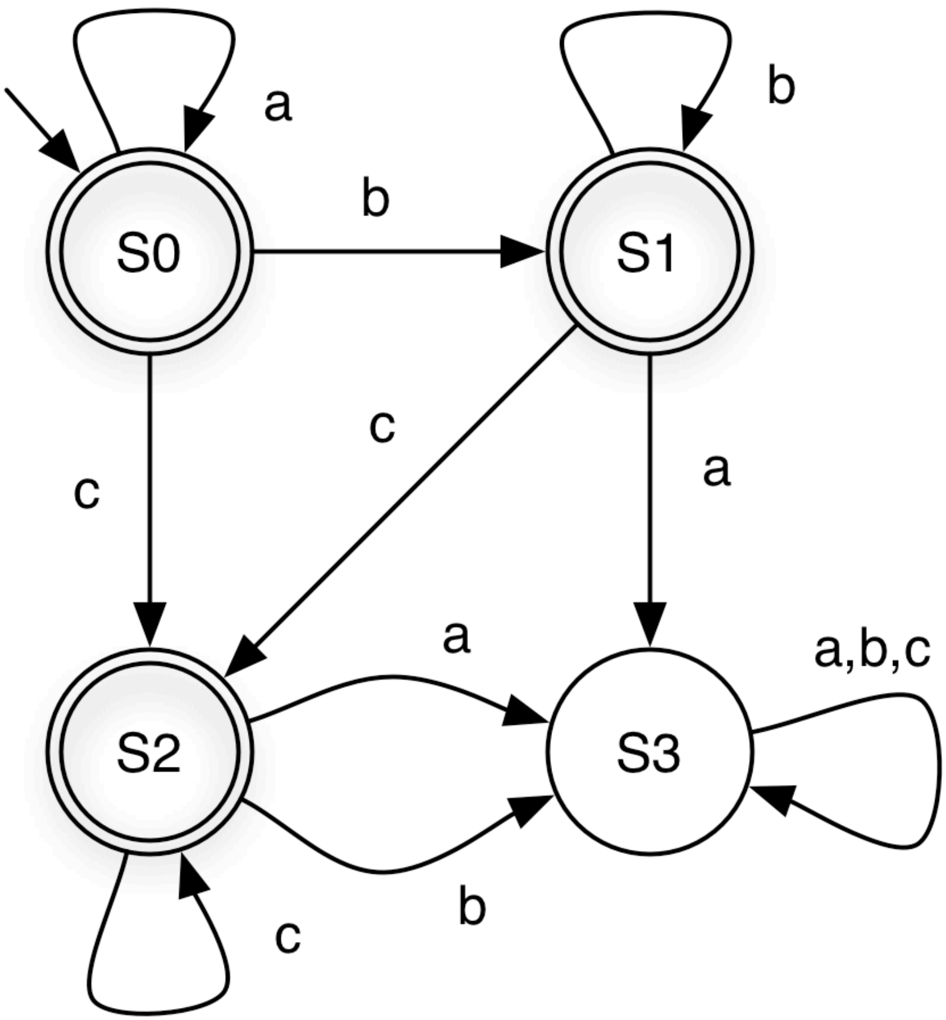
Finite Automaton: Example 3



string	state at end	accepts ?
acca		

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

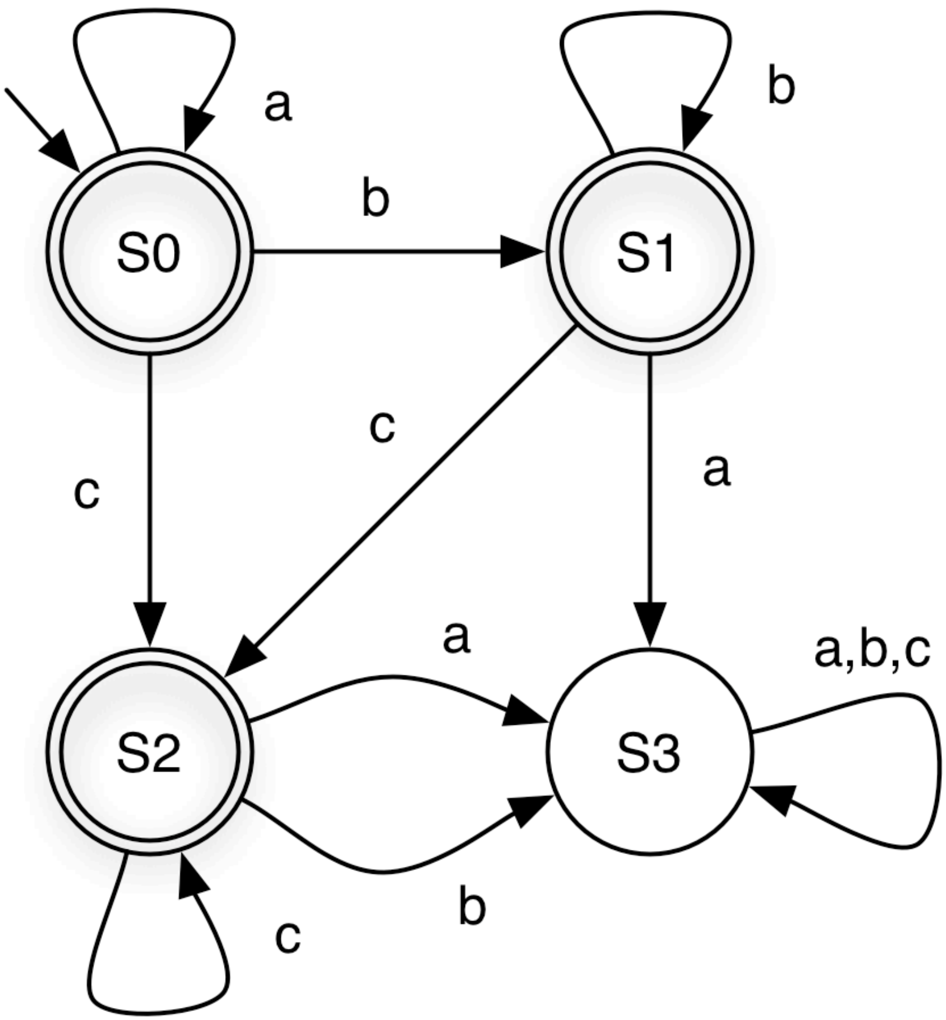
Finite Automaton: Example 3



string	state at end	accepts ?
acca	S3	N

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

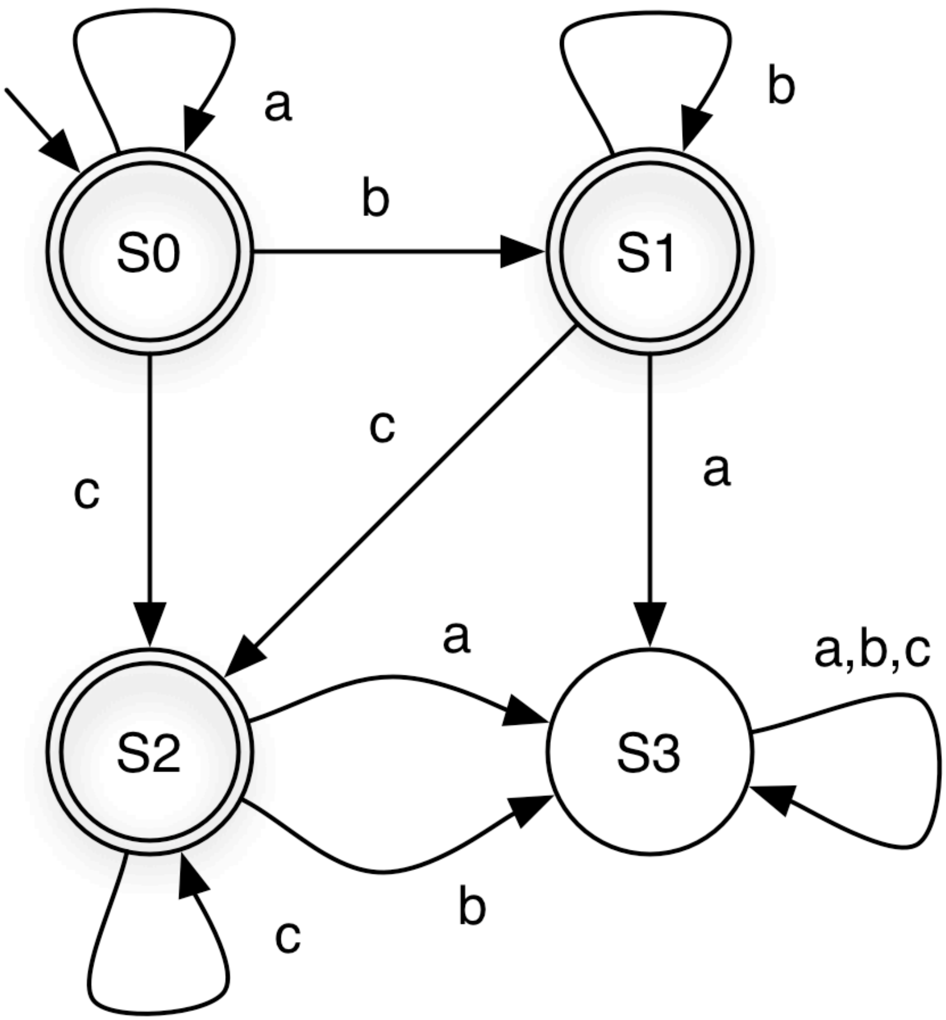
Finite Automaton: Example 3



string	state at end	accepts ?
aacbbb		

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

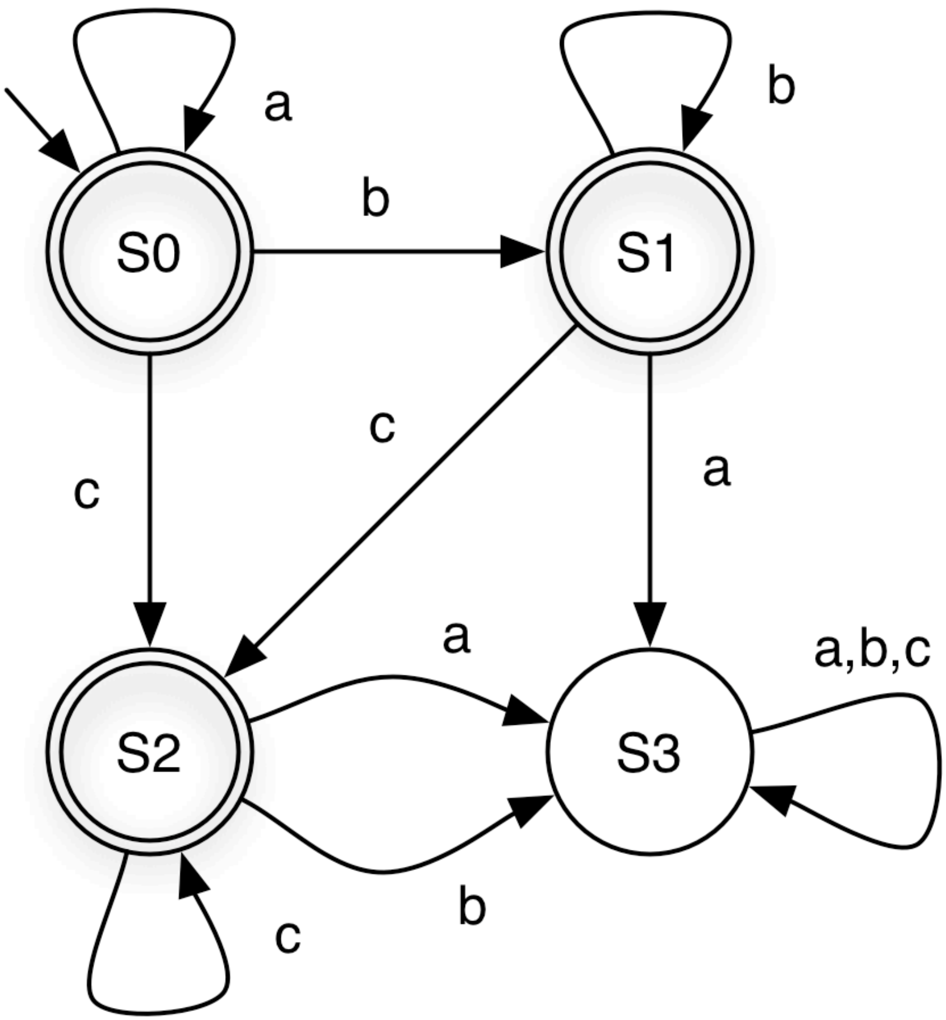
Finite Automaton: Example 3



string	state at end	accepts ?
aacbbb	S3	N

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

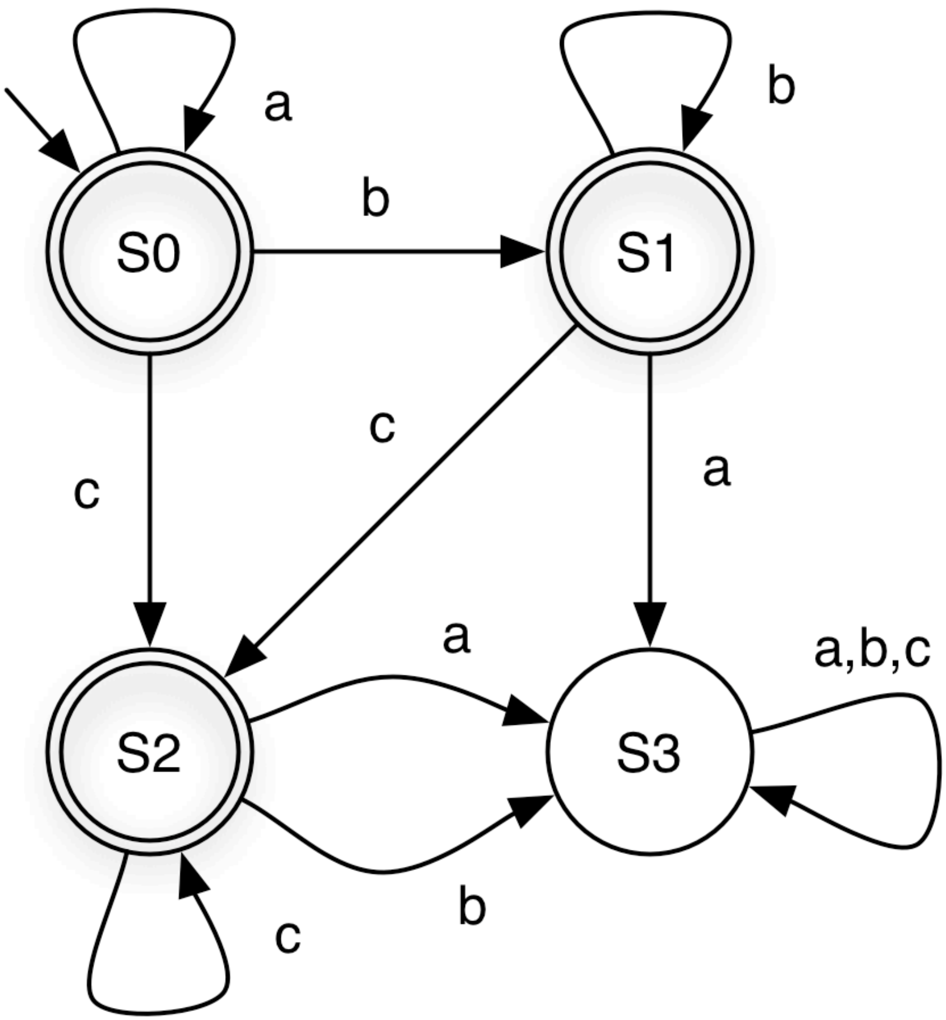
Finite Automaton: Example 3



string	state at end	accepts ?
ε		

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

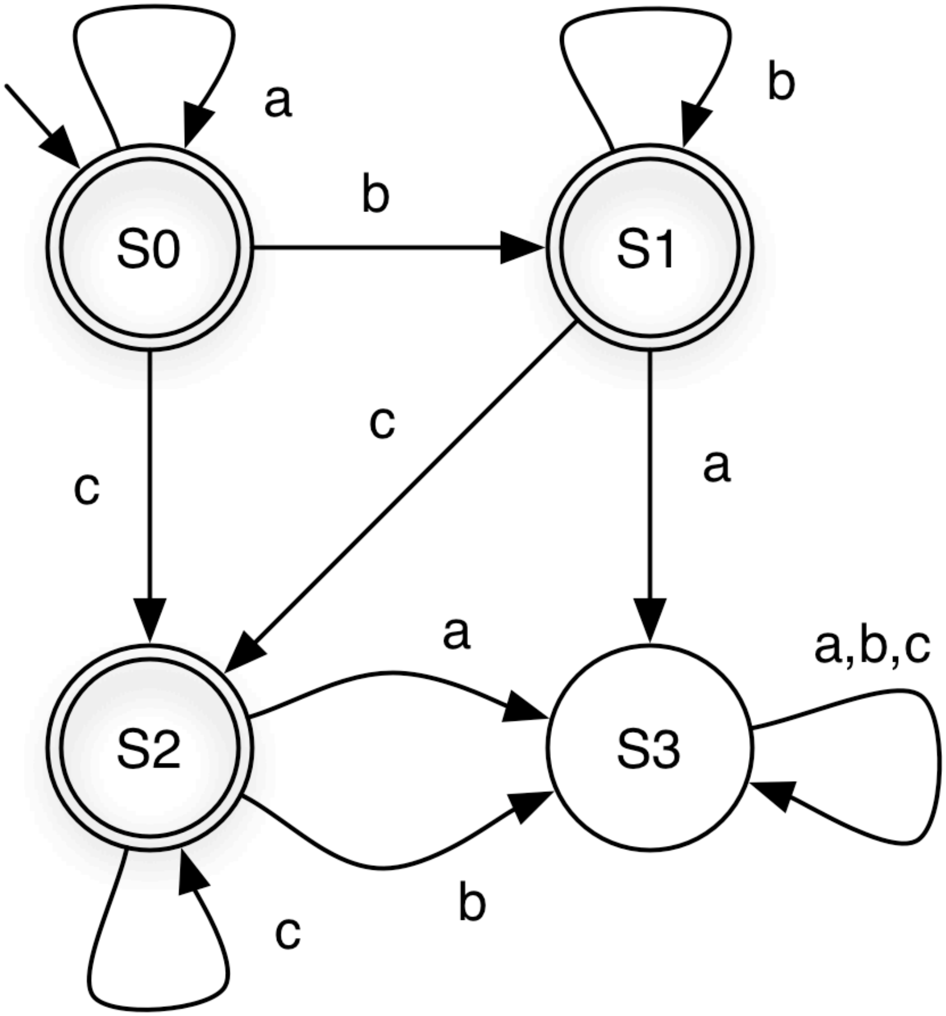
Finite Automaton: Example 3



string	state at end	accepts ?
ε	S0	Y

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

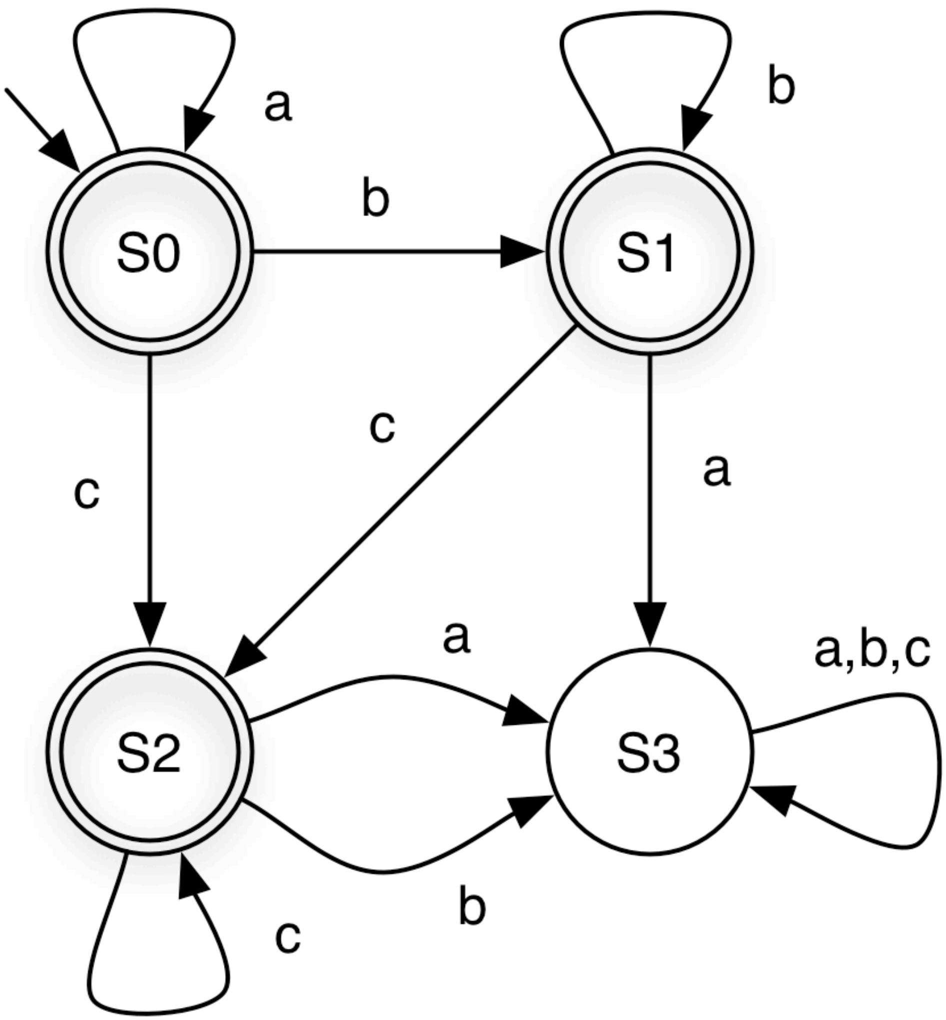
Finite Automaton: Example 3



string	state at end	accepts ?
acba		

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

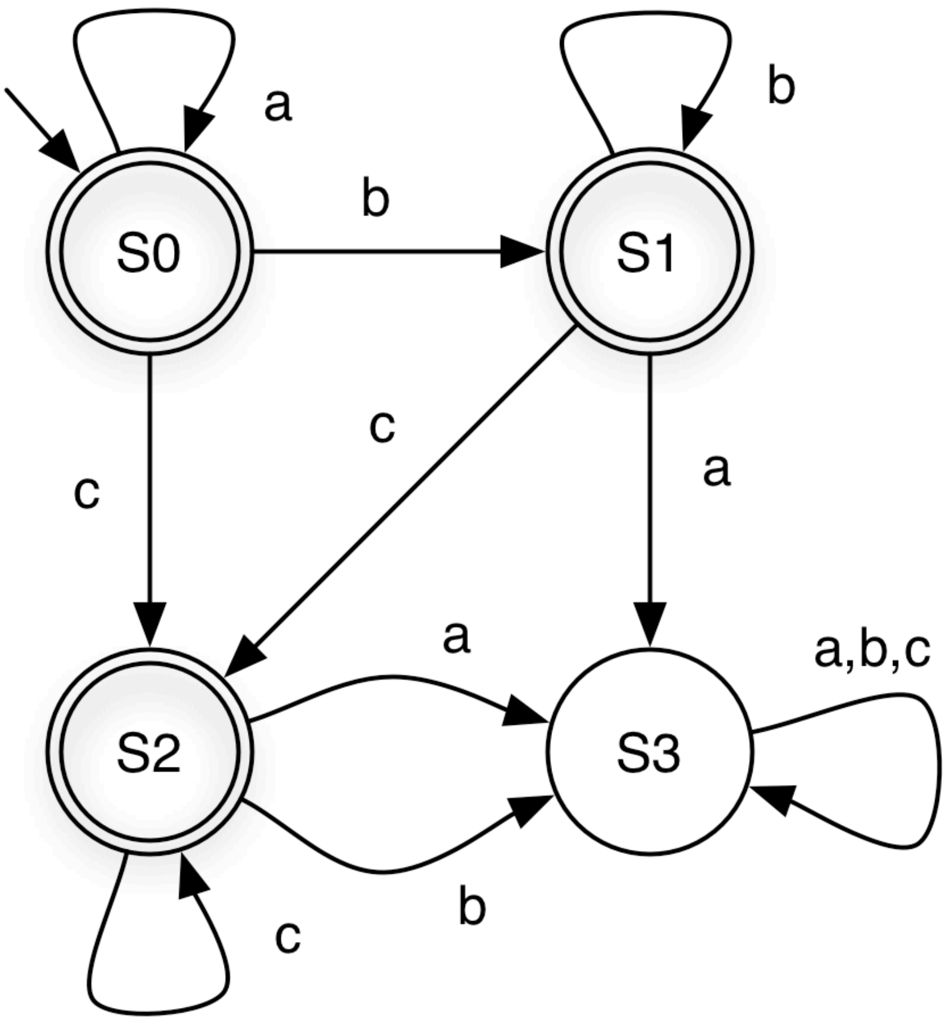
Finite Automaton: Example 3



string	state at end	accepts ?
acba	S3	N

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

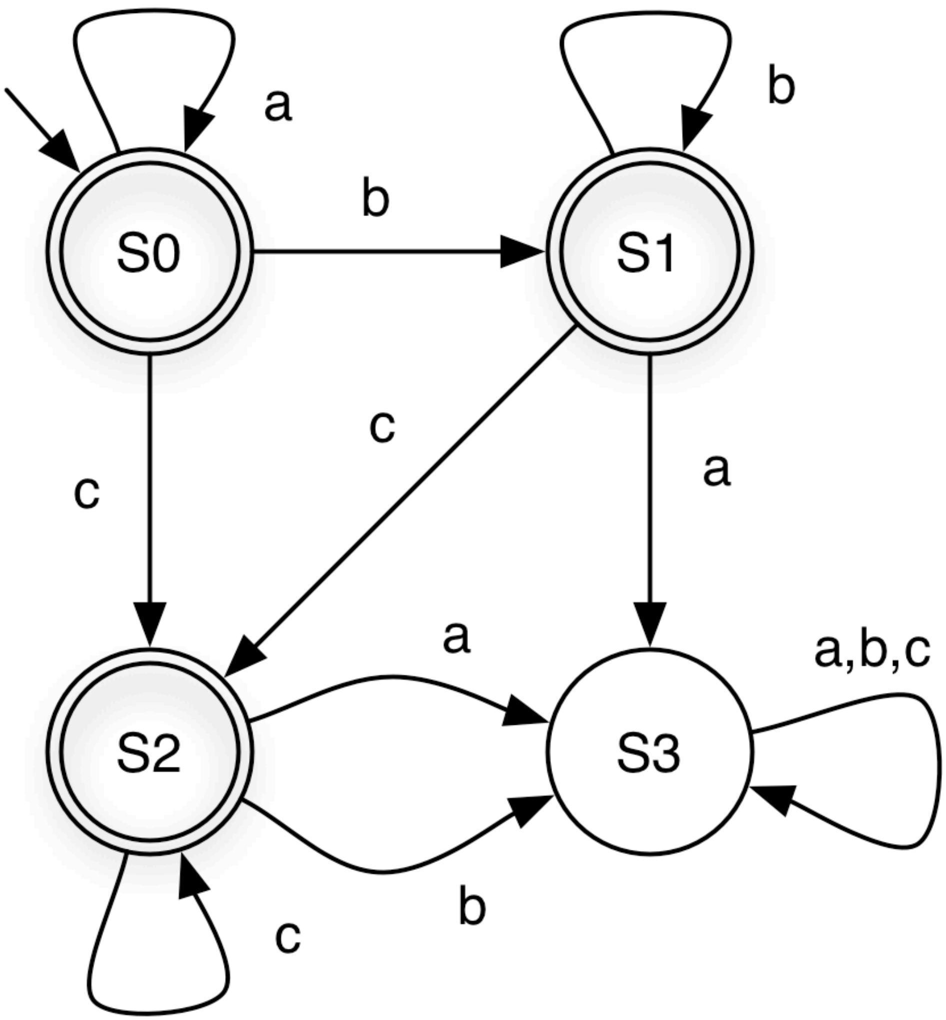
Quiz 4: Which string is **not** accepted?



A. abbbc
B. ccc
C. ε
D. bcca

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

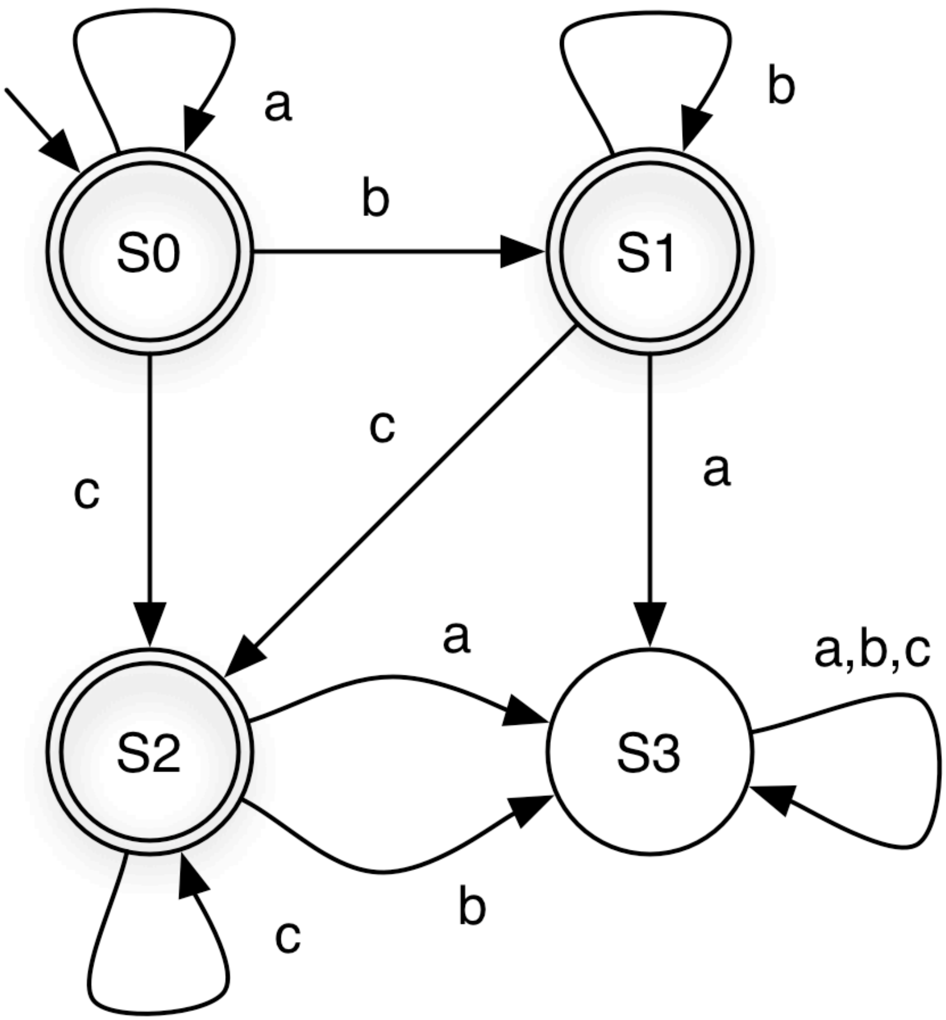
Quiz 4: Which string is **not** accepted?



A. abbbc
B. ccc
C. ε
D. bcca

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

Finite Automaton: Example 3

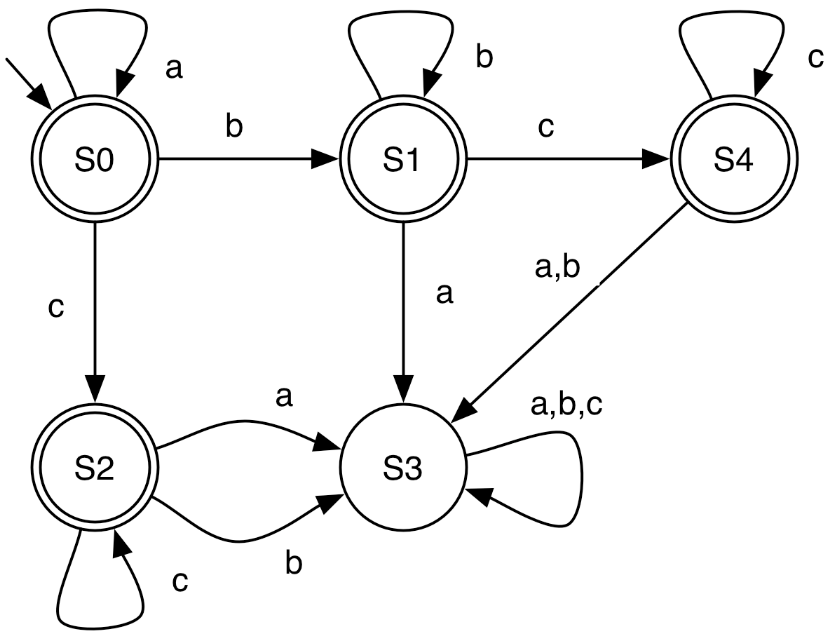


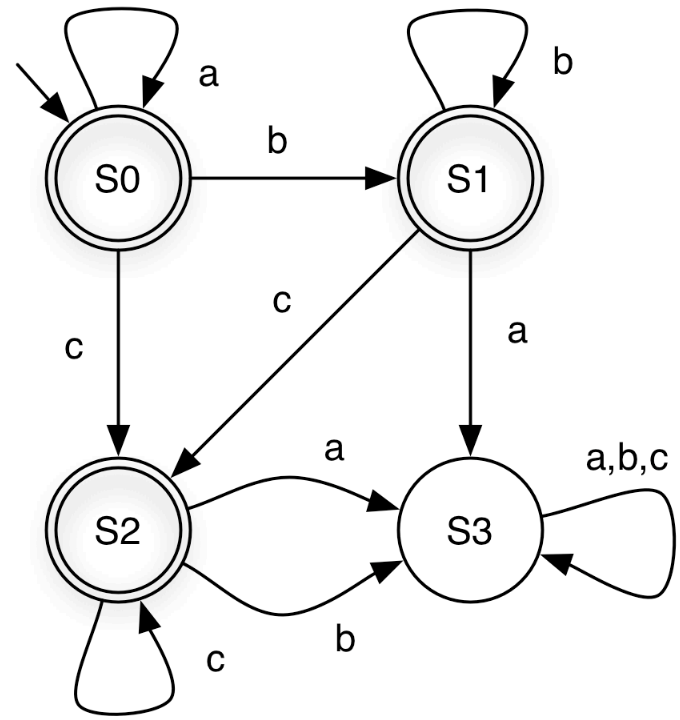
What language does this FA accept?

a*b*c*

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

Finite Automaton: Example 4



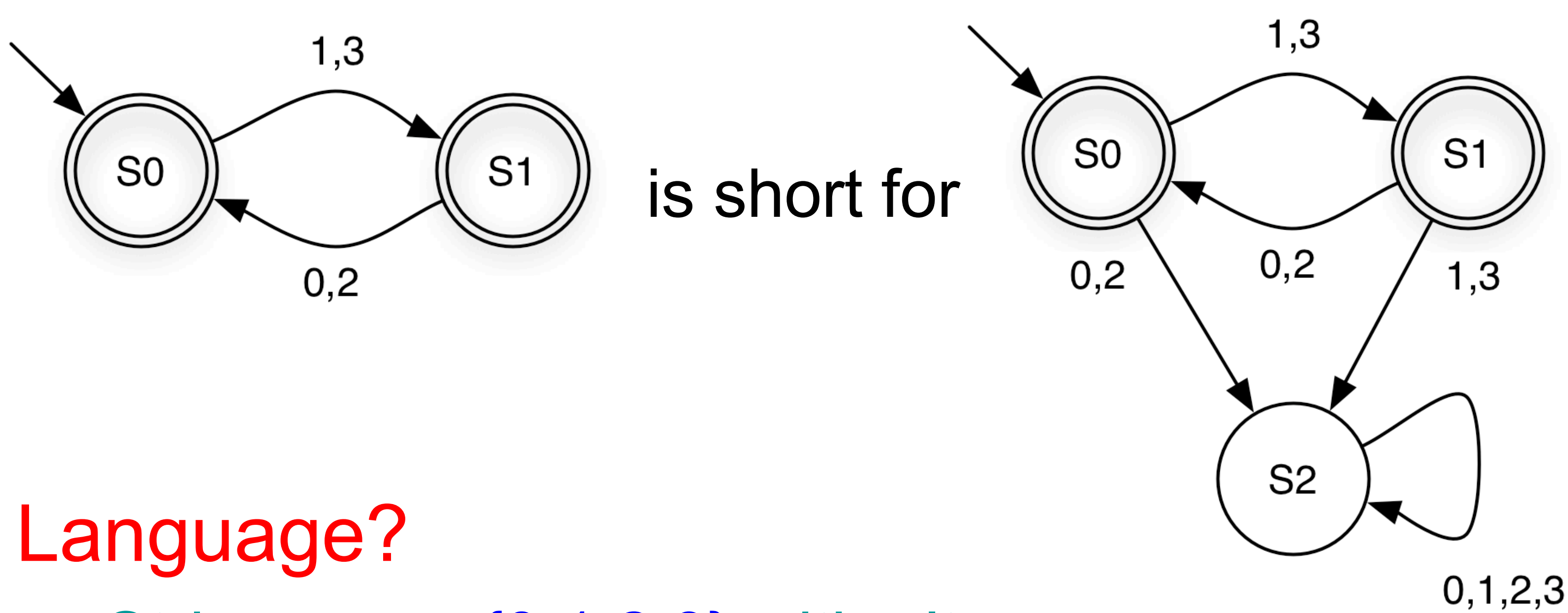


Language?

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

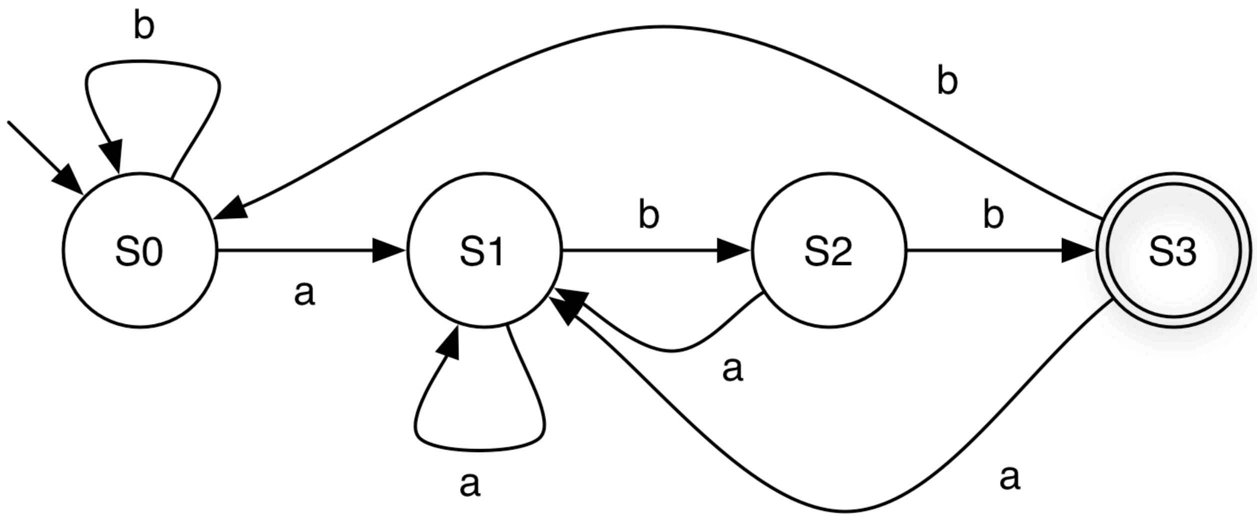
Dead State: Shorthand Notation

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



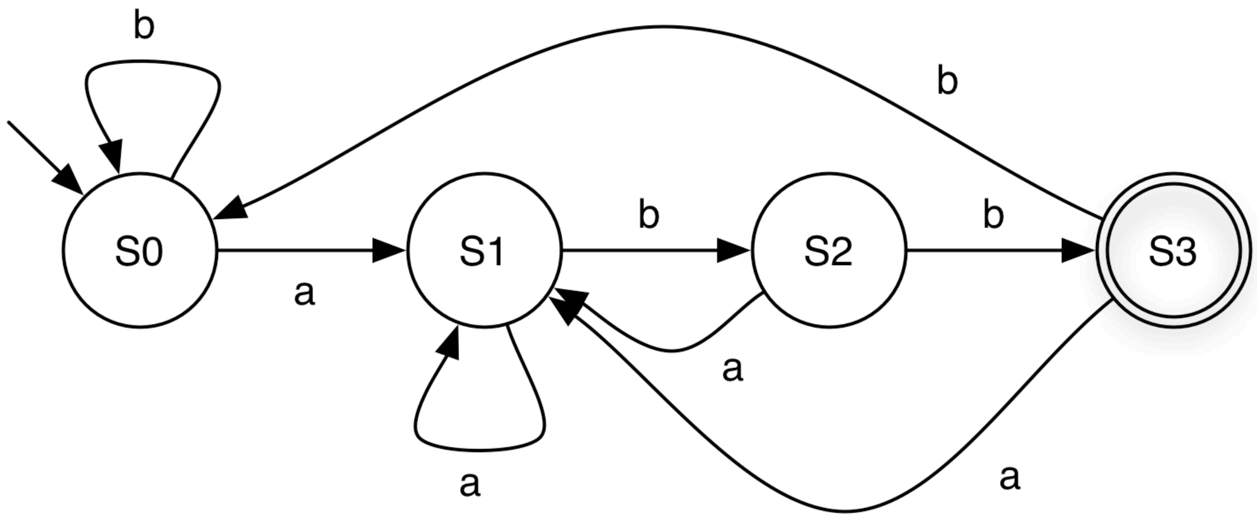
- Language?
  - Strings over {0,1,2,3} with alternating even and odd digits, beginning with odd digit

Finite Automaton: Example 5



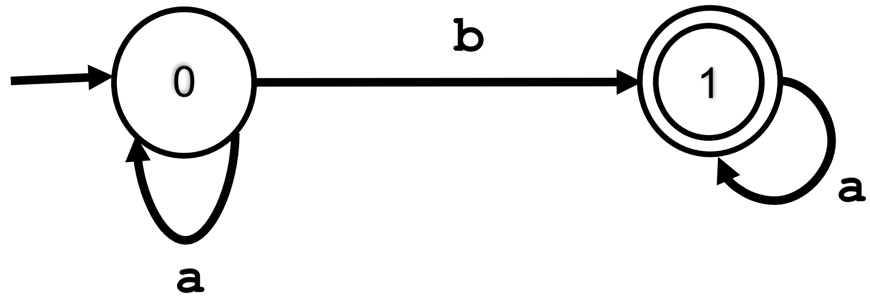
- Description for each state
  - S0 = "Haven't seen anything yet" *OR* "Last symbol seen was a b"
  - S1 = "Last symbol seen was an a"
  - S2 = "Last two symbols seen were ab"
  - S3 = "Last three symbols seen were abb"

Finite Automaton: Example 5



- Language as a regular expression?
  - (a|b)*abb

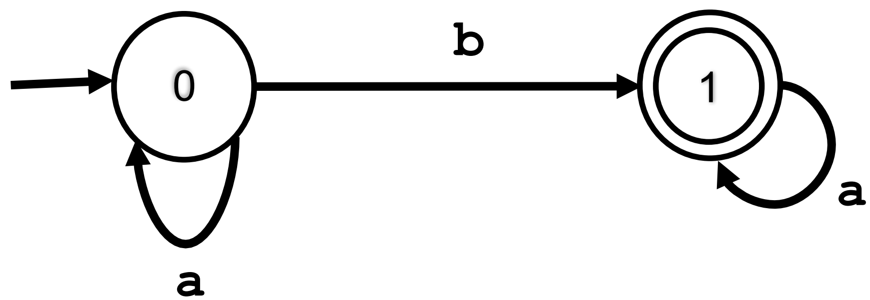
Quiz 5



Over Σ={a,b}, this FA accepts:

A. A string that contains a single b.
B. Zero or more a's, followed by a single b, followed by zero or more a's.
C. Any string in {a,b}.
D. A string that starts with b followed by a's.

Quiz 5



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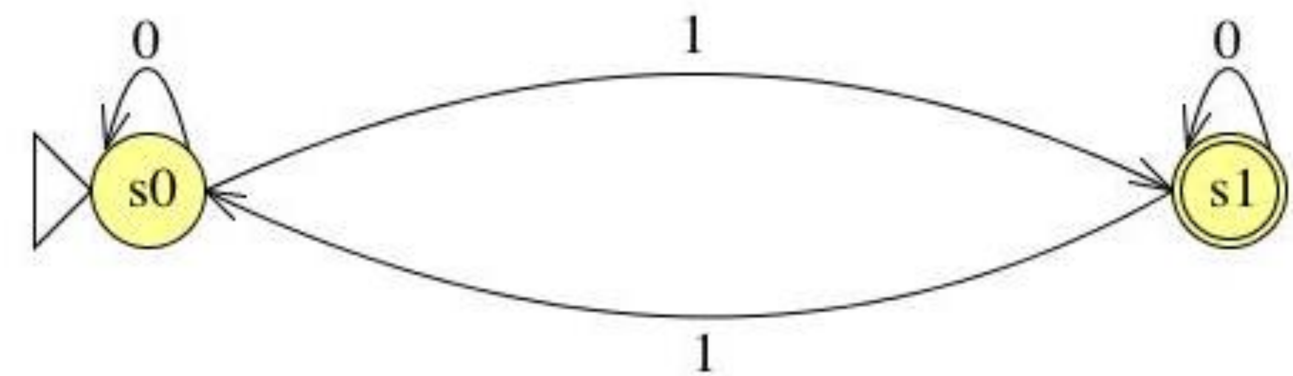
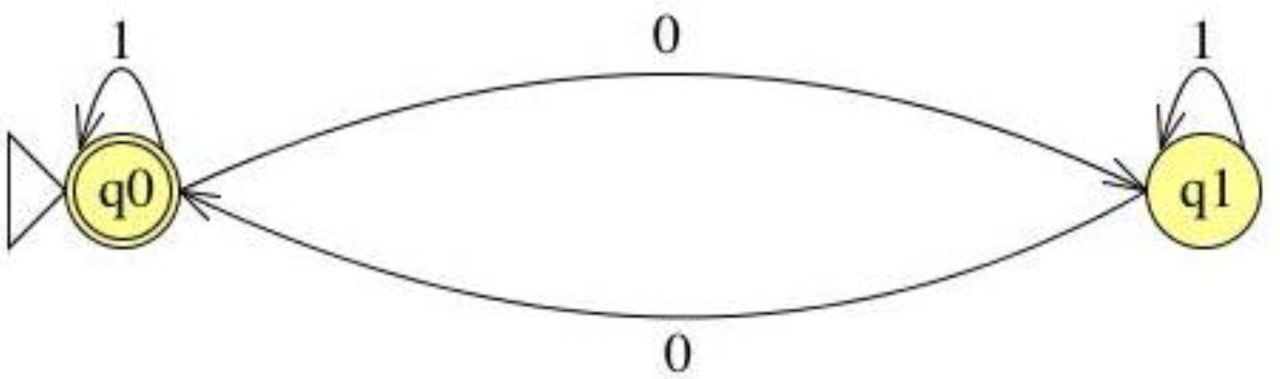
Exercises: Define an FA over Σ = {0,1}

- That accepts strings with an odd number of 1s



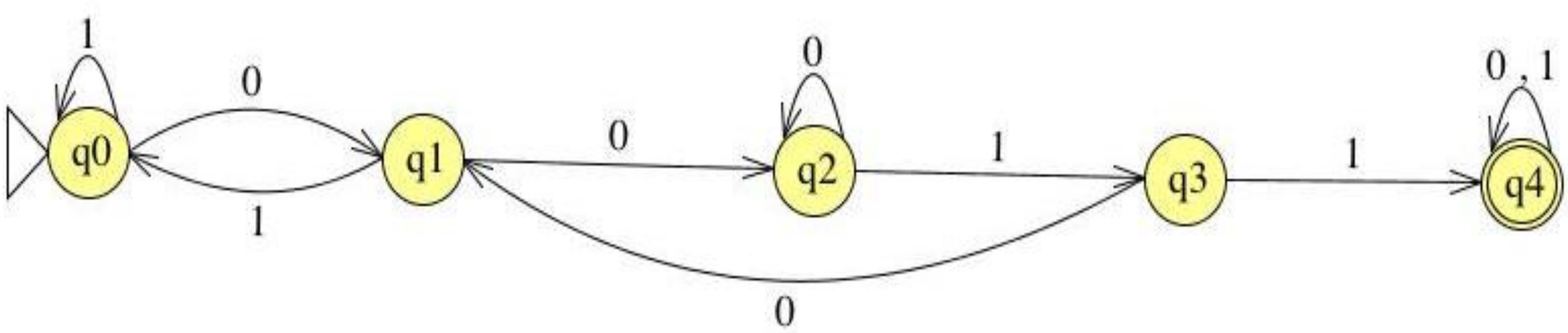
Exercises: Define an FA over Σ = {0,1}

- That accepts strings containing an even number of 0s and any number of 1s



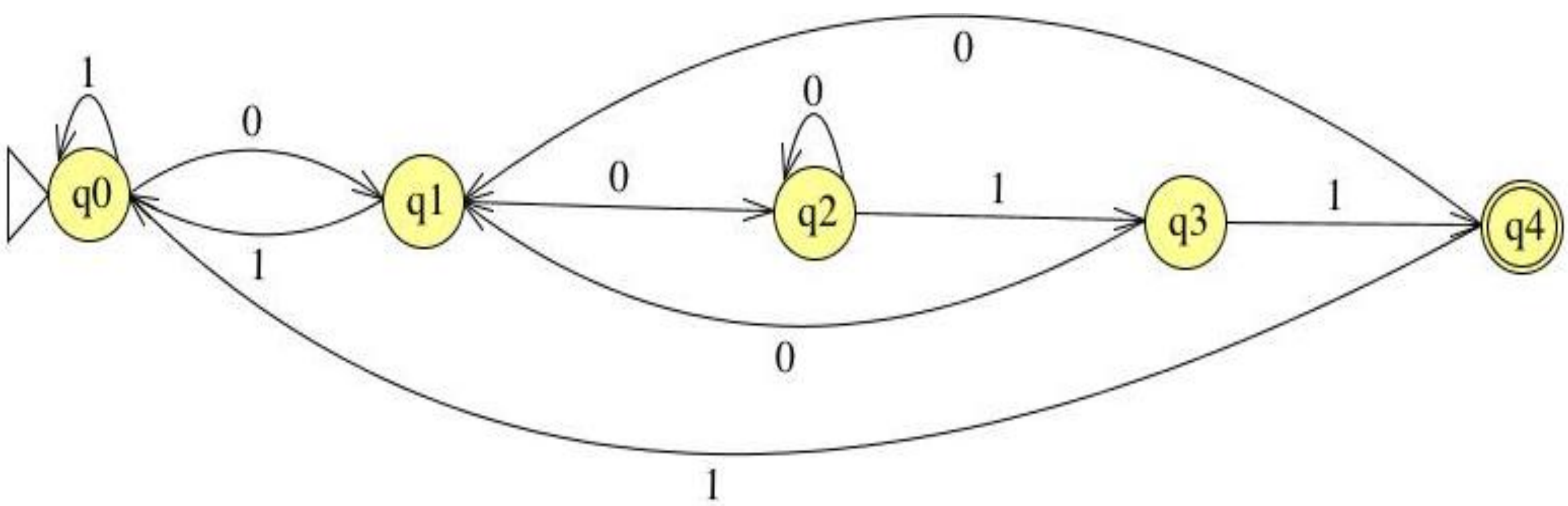
Exercises: Define an FA over Σ = {0,1}

- That accepts strings containing two consecutive 0s followed by two consecutive 1s



Exercises: Define an FA over Σ = {0,1}

- That accepts strings end with two consecutive 0s followed by two consecutive 1s

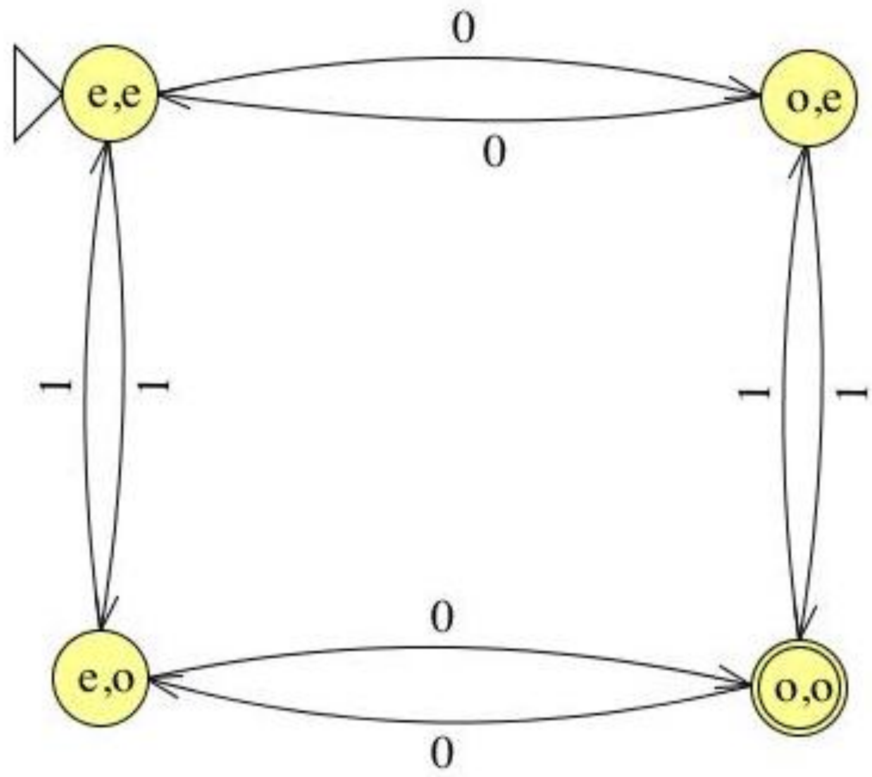


Exercises: Define an FA over Σ = {0,1}

- That accepts strings containing an odd number of 0s and odd number of 1s

4 states:

0s	1s
e	e
o	e
e	o
o	o



Exercises: Define an FA over Σ = {0,1}

- That accepts strings that DO NOT contain odd number of 0s and an odd number of 1s

Flip each state