Runtime Verification
From theory to practice and back

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Part I

Regular Expressions

Regular Expressions

- Regular expressions can also be used to write specifications either by giving the wrong or the good behaviour.
- Examples of specifications of wrong behaviour (!e means any event except for e):
  - `(login; (read+write)*; logout)*; (read+write)`
  - `(!approveAccount)*; transfer`
- Examples of specifications of good behaviour (matching prefixes of the regular expression):
  - `(login; (read+write)*; logout)*`
  - `!transfer*; approveAccount; !transfer*; transfer`

Monitoring Regular Expressions

- As with finite state automata, we may want to quantify universally over the target of events:
  - ```
    foreach target (User u)
      (u.login(); u.transfer(..); u.logout())*;
      u.transfer(..)
    ```

- Verification can be done either by:
  - By using the residual algorithm or
  - Transforming into an automaton
    ```

Regular Expressions

RE ::= ? (Any) | 0 (Nothing) | 1 (End)

| a (Proposition)

| !a (All the propositions except a)

| RE + RE (Choice)

| RE ; RE (Sequence)

| RE* (Repetition)

| (RE) (Bracketed expression)

R sions

Matches any event

RE ::= ? (Any) (End)

| a (

Matches the event a

| !a (A

| RE + RE (Ch

| RE ; RE (S

Matches any event but a

| RE* (R

| (RE) (Bracketed expression)

R ons

Matches if nothing happens,
i.e. an empty string

RE ::= ? (Any) | 0 (Nothing) | 1 (End)

| a (Proposition)

| !a (All the prop

| RE + RE (Choice)

| RE ; RE (Sequence)

| RE* (Repetition)

| (RE) (Bracketed expression)

Nothing can match
(like reaching a bad state)

Regular Expressions

RE ::= ? (Any) (End)

| a (P1

| !a (All th positions except a)

| RE + RE (Choice)

| RE ; RE (S

| RE* (Repeti

| (RE) (Bracke

Matches either or

Matches the subsequent behaviour of the two REs

Matches zero or more repetitions of RE

Exercise

- Express properties 2, 5, 6, and 10 of the Financial Transaction System in terms of regular expressions (you can choose whether to specify “matching” or “non matching” expressions

Example

Property 2 - The transaction system must be initialised before any user logs in.

```
property matching {

        (!USER_login)* ; ADMIN_initialise ; ?*

}


property not matching {

        (!ADMIN_initialise)*; USER_login

}
```

More Advanced Example

Property 5 – Once a user is disabled, he or she may not withdraw from an account until being made activate again.

```
property foreach target (UserInfo u) matching {
  ( (!makeDisabled)* ; makeDisabled ; (!withdrawFrom)* ;
        makeActive )*}

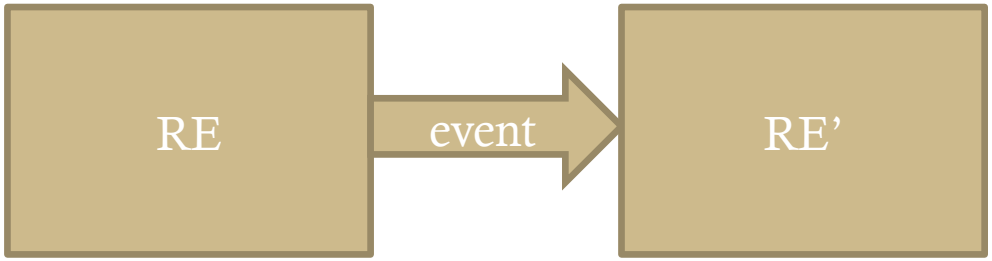
property foreach target (UserInfo u) not matching {
    (?)* ; makeDisabled ; (!makeActive)* ; withdrawFrom
}
```

Part II

Monitoring Regular Expressions using Residuals

Residuals

One way of monitoring REs is by modifying the RE for each observed event



Residuals

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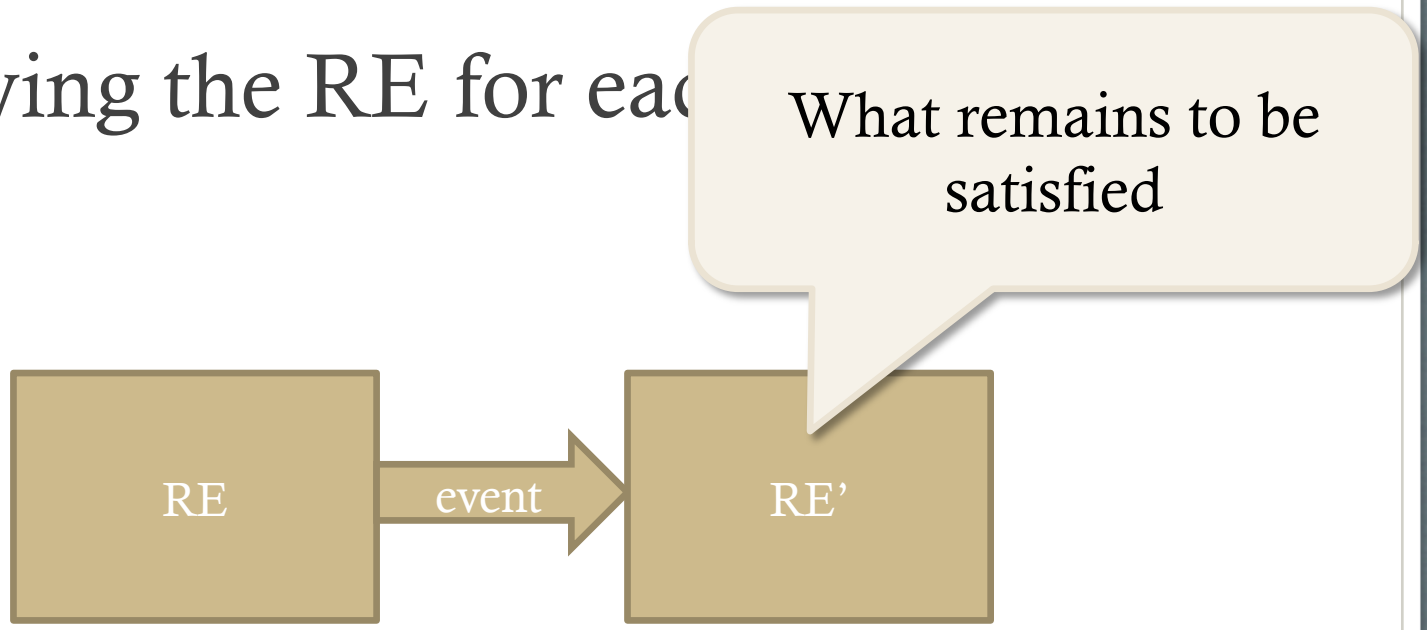
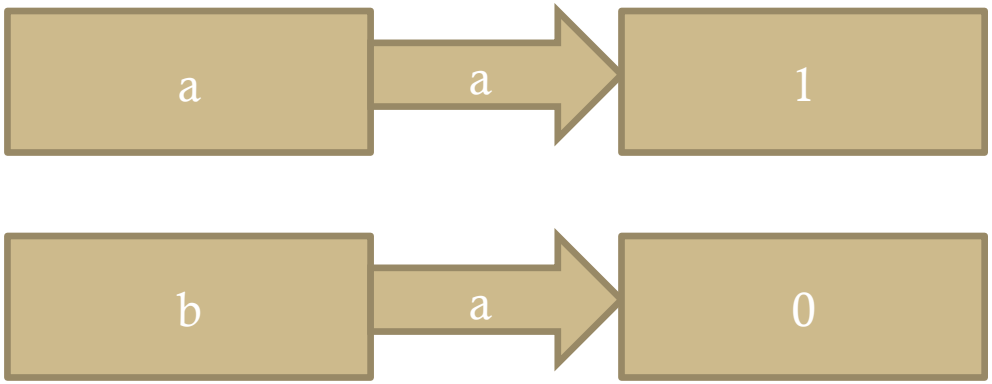
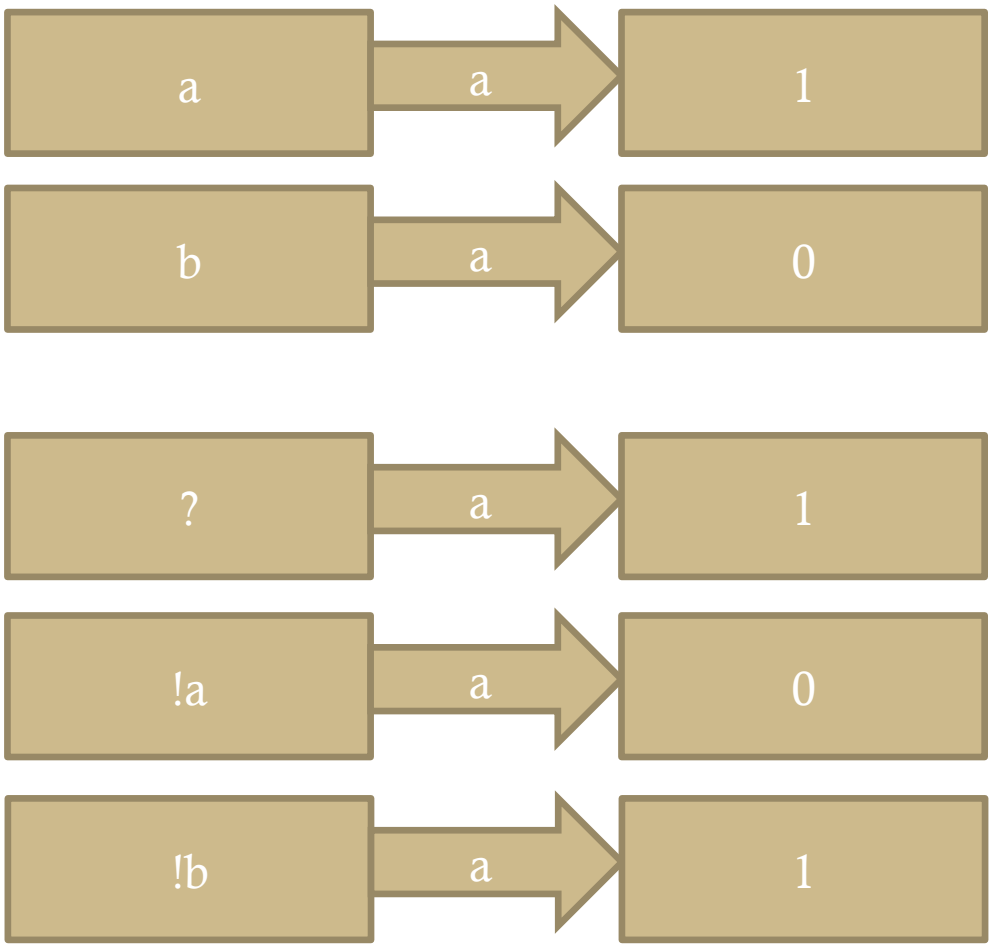


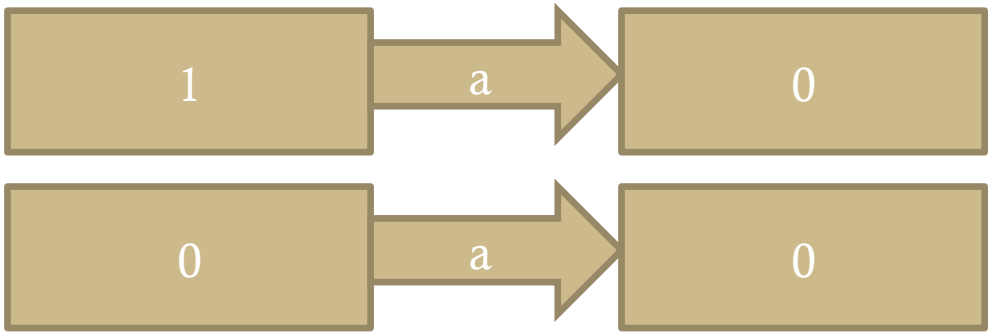
Residuals - Basic



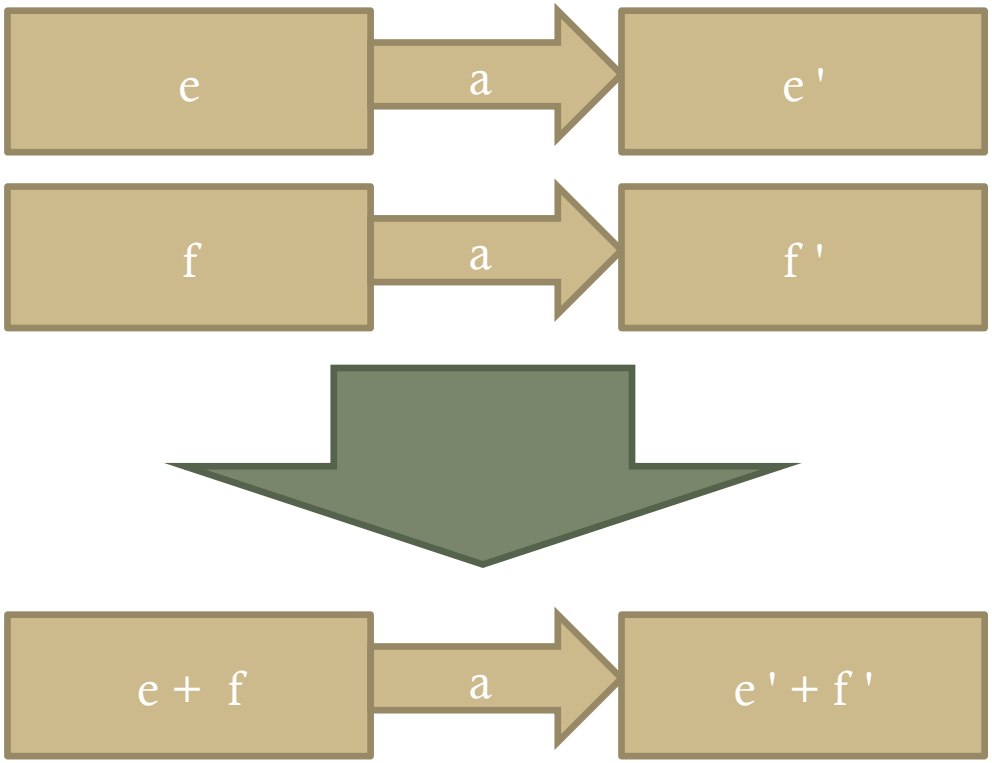
Residuals - Basic



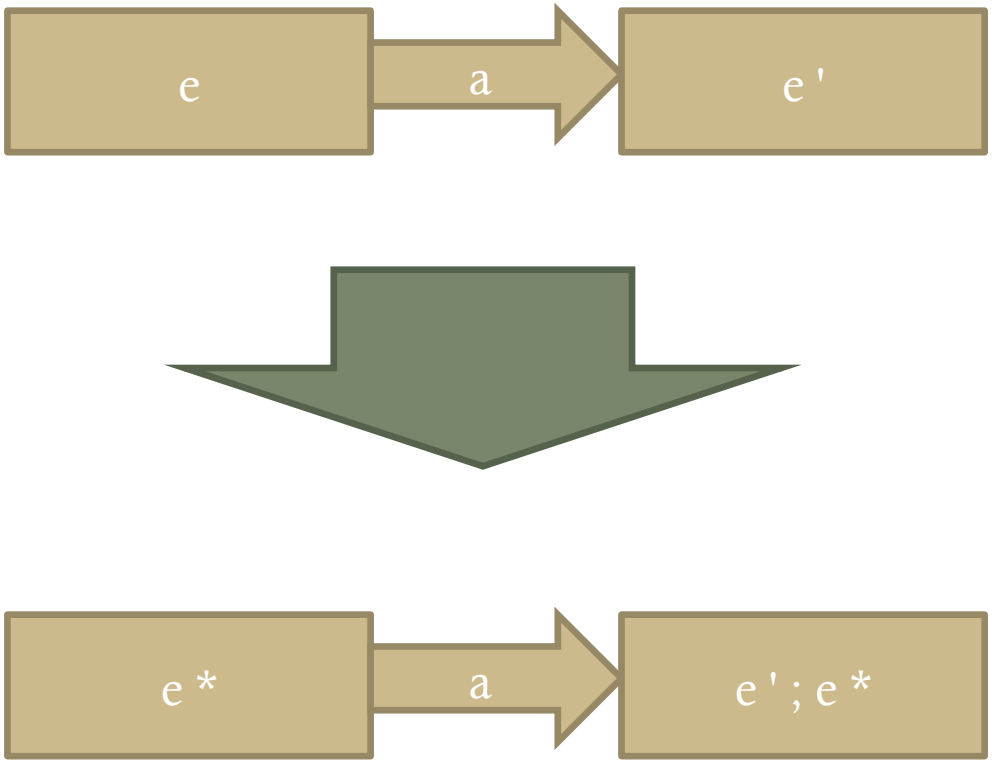
Residuals - Basic



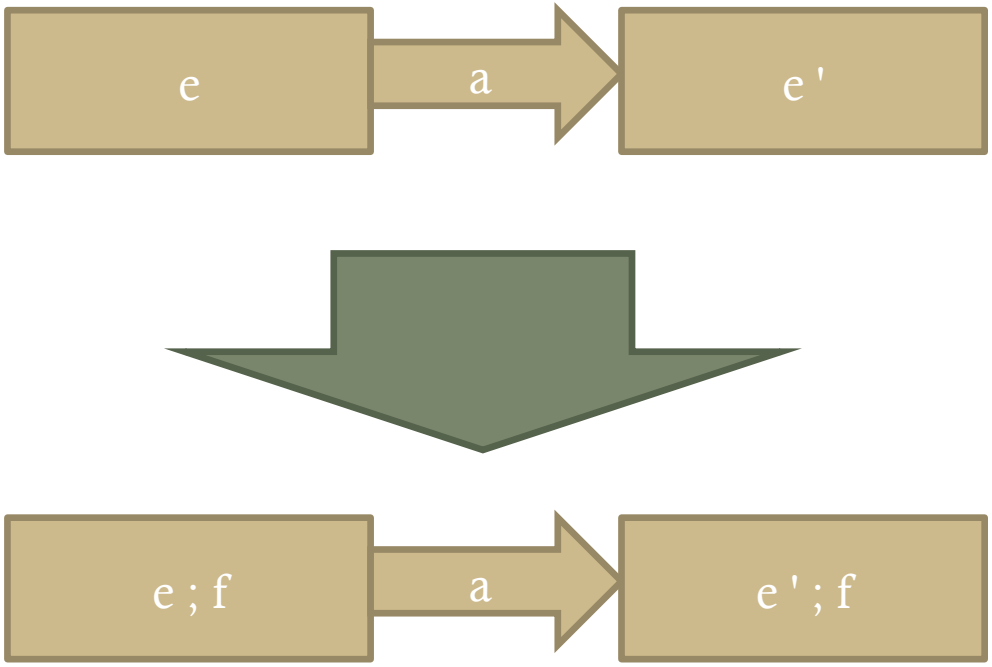
Residuals – Or



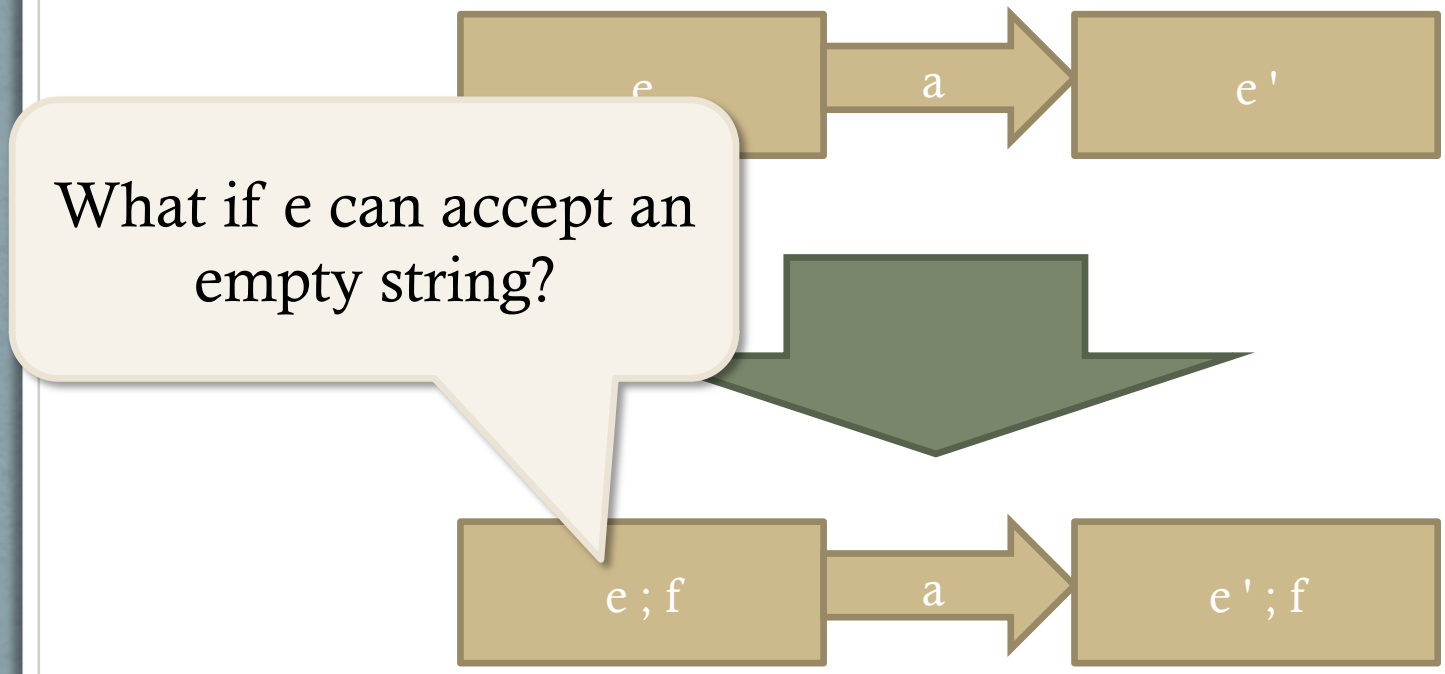
Residuals – Star



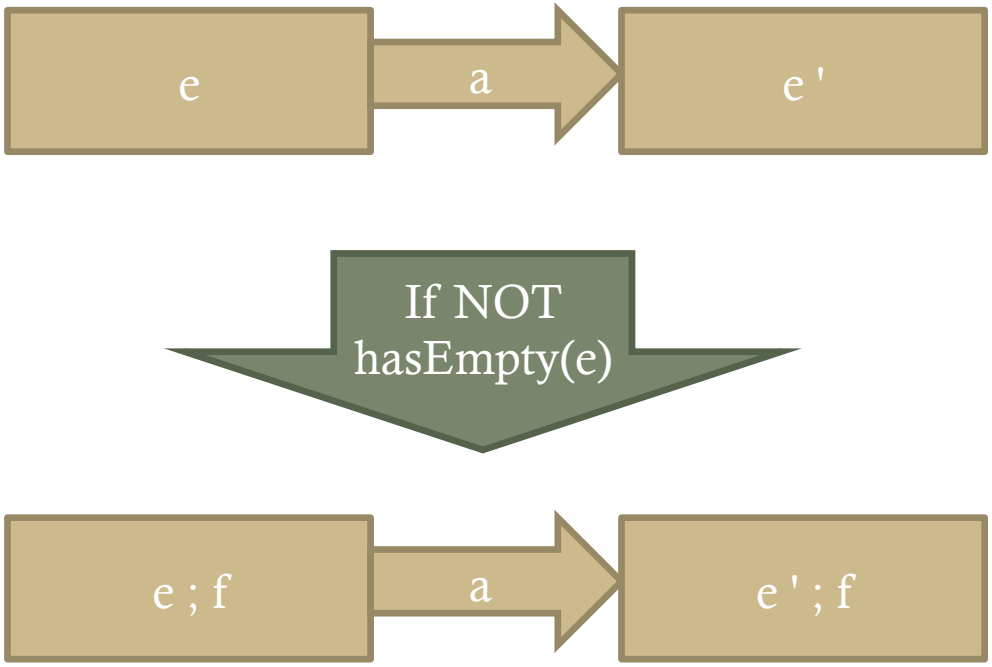
Residuals – Sequence



Residuals – Sequence



Residuals – Sequence



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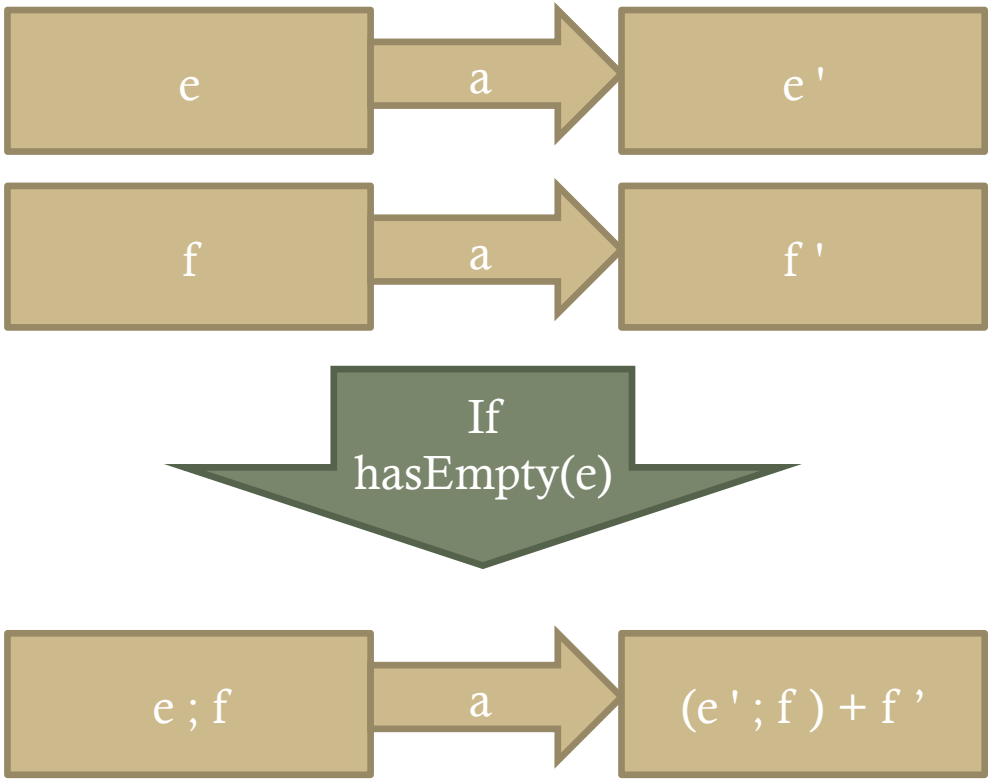


Accepting an Empty String

hasEmpty (?) = false

hasEmpty (0) = false

hasEmpty (1) = true

hasEmpty (a) = false

hasEmpty (!a) = false

hasEmpty (RE1 + RE2) = hasEmpty (RE1) or hasEmpty (RE2)

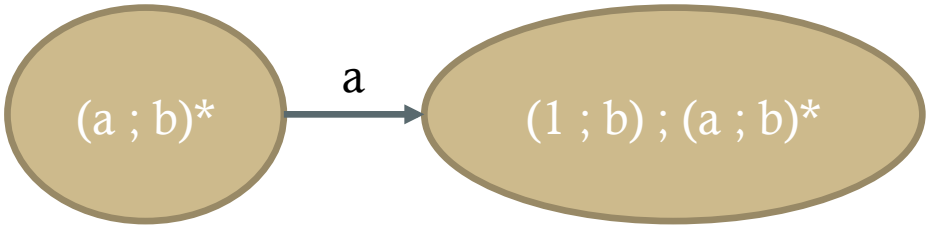
hasEmpty (RE1 ; RE2) = hasEmpty (RE1) and hasEmpty (RE2)

hasEmpty (RE*) = true

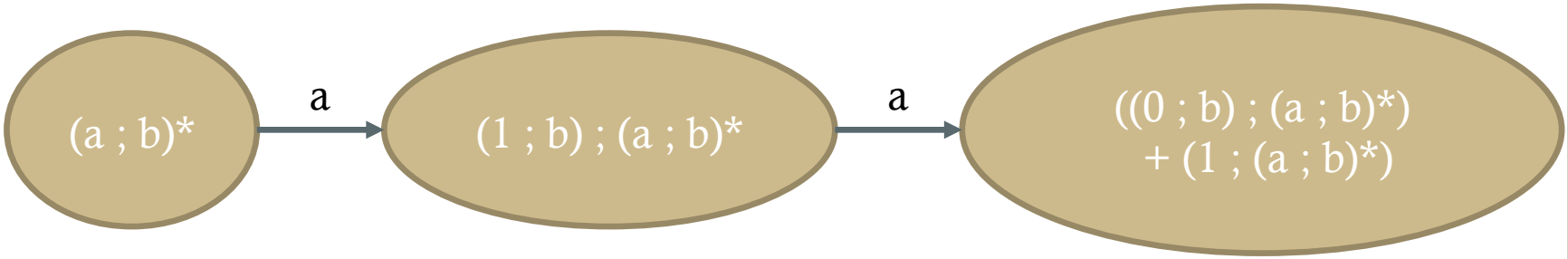
Residuals Example

- Apply residuals on (a ; b)* over the following event sequences:
  1. a, b, a, b
  2. b
  3. a, a
  4. a, b, b

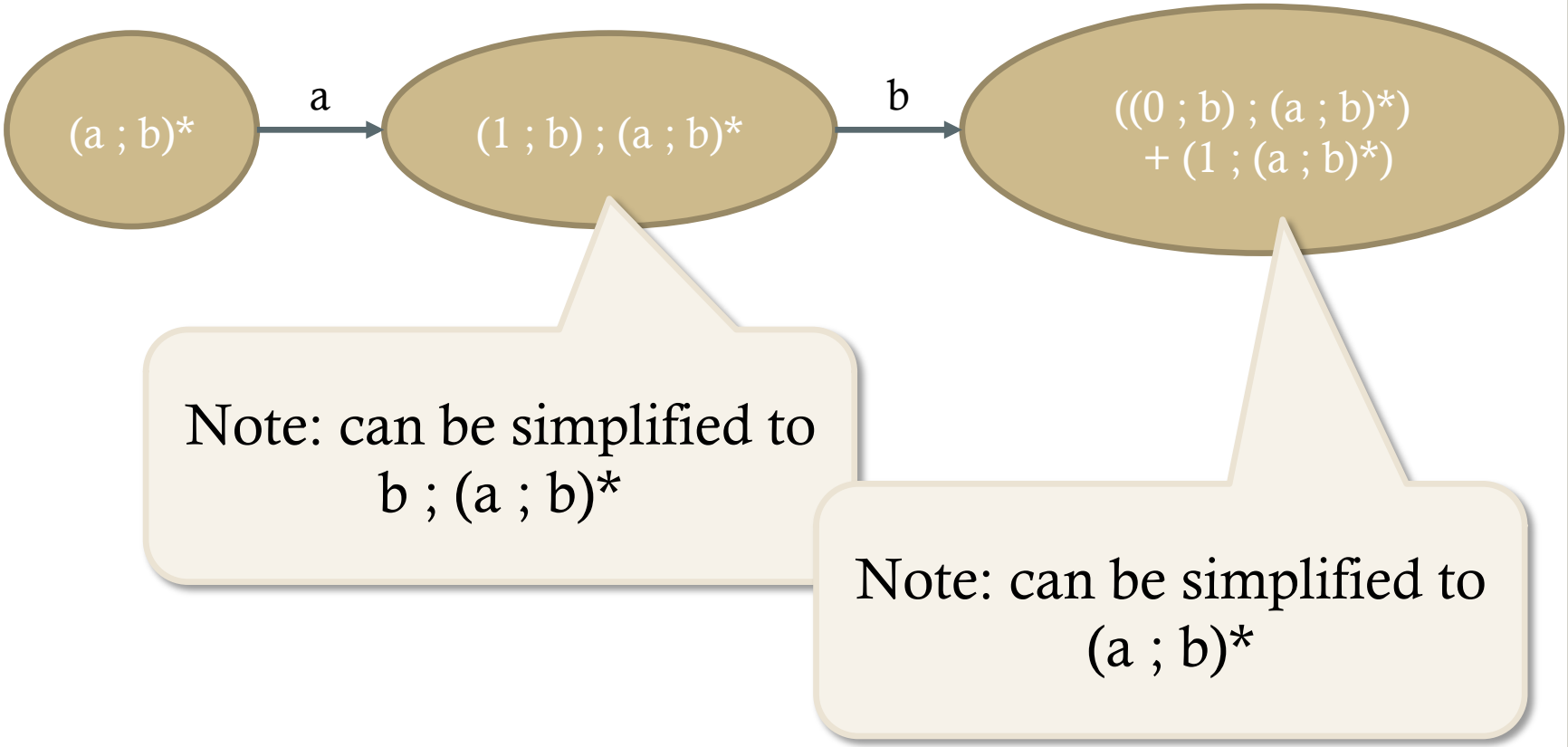
Residuals Example 1



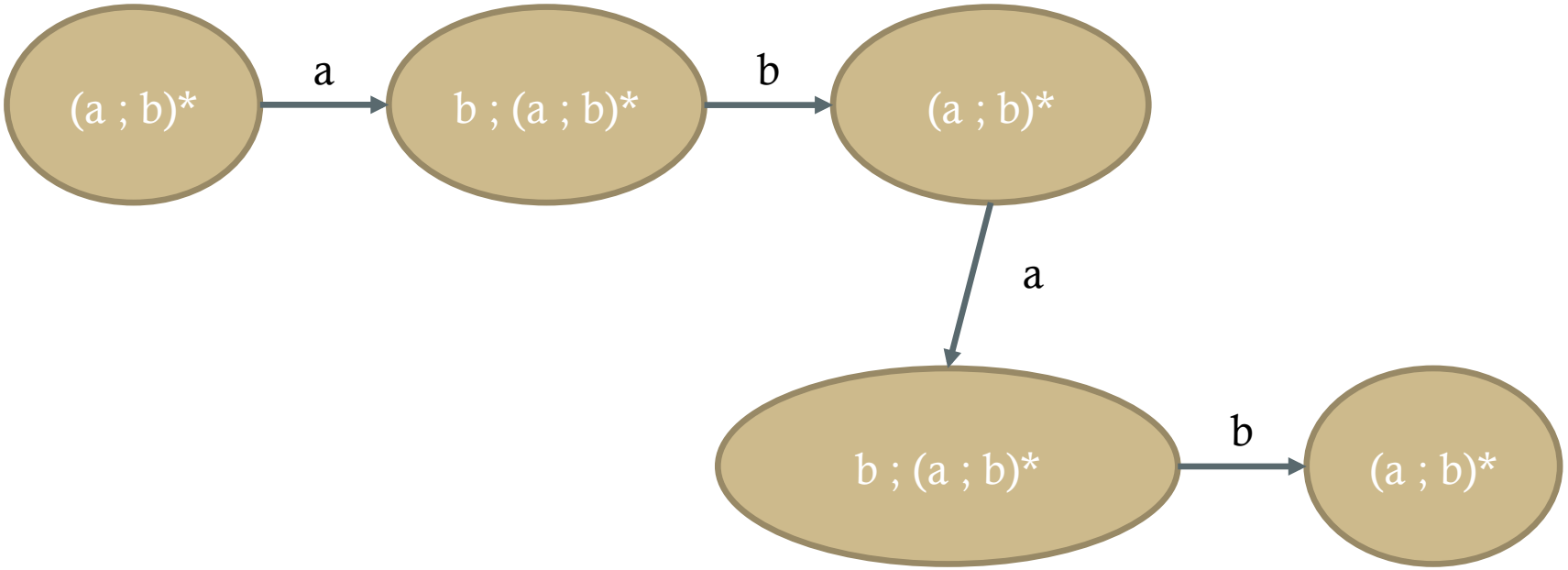
Residuals Example 1



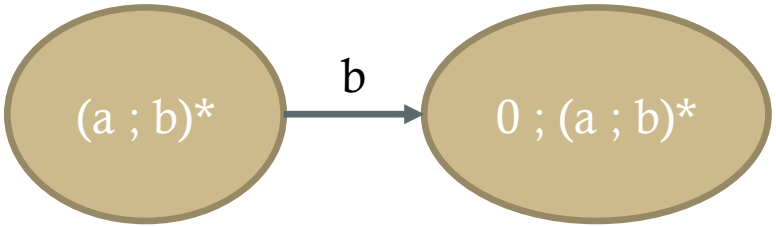
Residuals Example 1



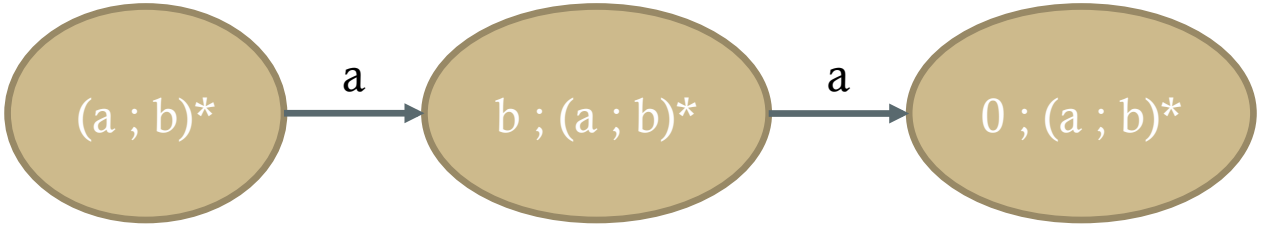
Residuals Example 1



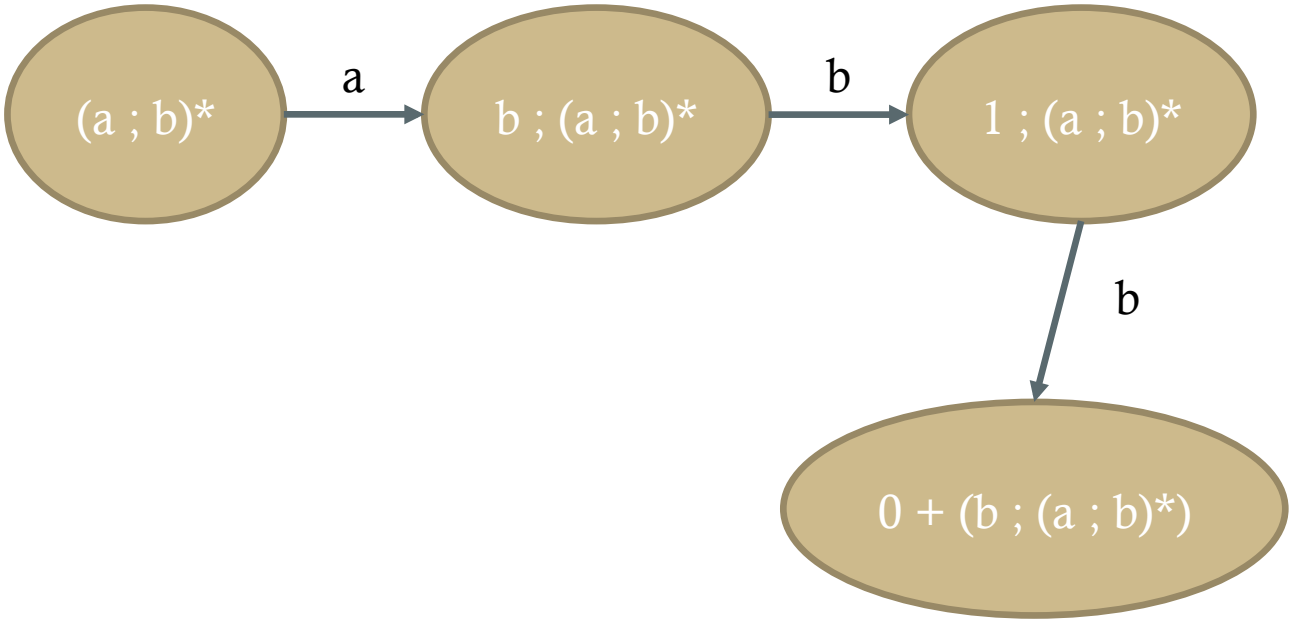
Residuals Example 2



Residuals Example 3



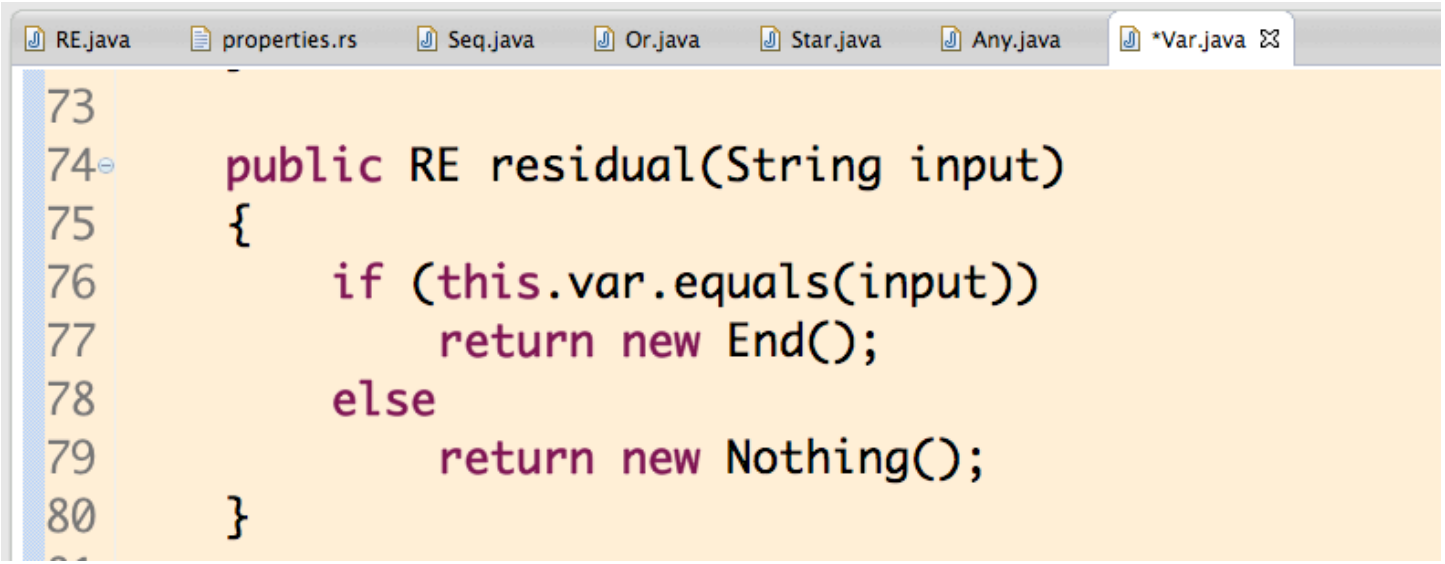
Residuals Example 4



Exercises

- Implement the residual function for all RE classes (i.e. fill in the method for the Or class)

Example


RE.java
properties.rs
Seq.java
Or.java
Star.java
Any.java
*Var.java
73
74 public RE residual(String input)
75 {
76 if (this.var.equals(input))
77 return new End();
78 else
79 return new Nothing();
80 }

Simplifying REs

- If not simplified, REs quickly become long and unreadable with residuals

e.g.: $(0 \; ; ((a + 0) + ?)) + (0 \; ; 1) = 0$

Implemented Simplification Rules

- 1 ; RE = RE
- 0 ; RE = 0
- 0 + RE = RE

Detecting a Violation

- What does it mean to detect a violation?

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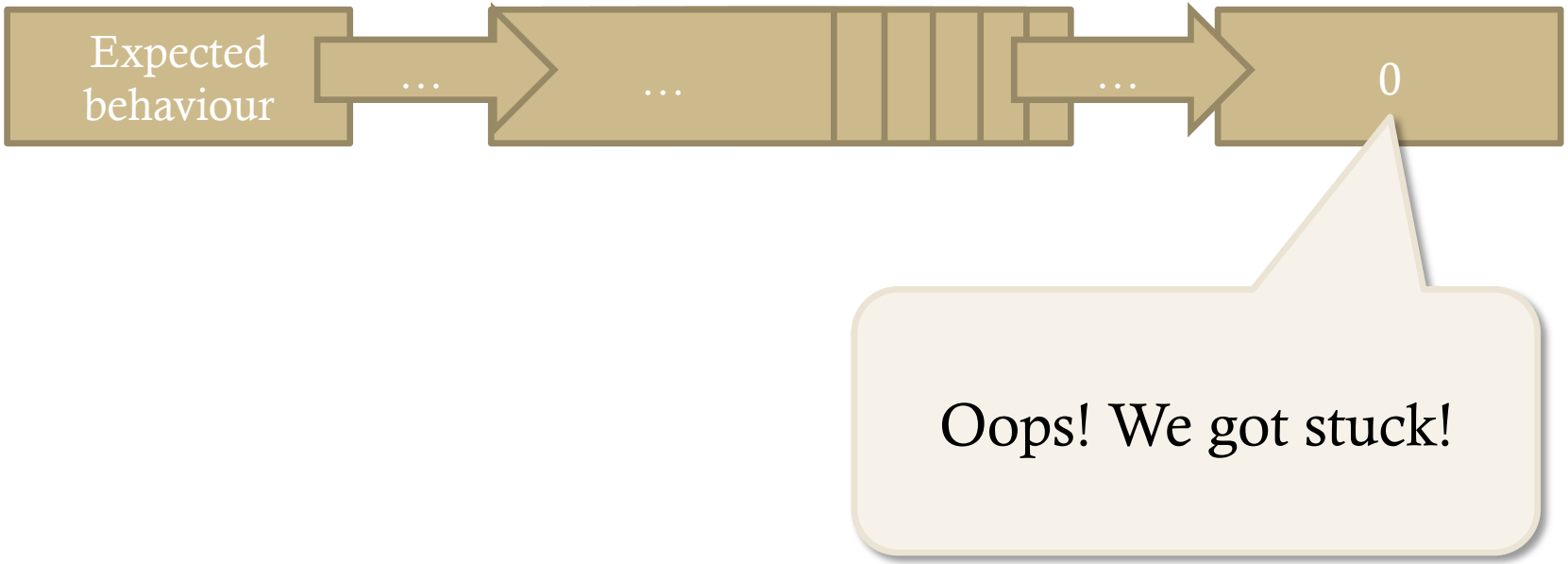
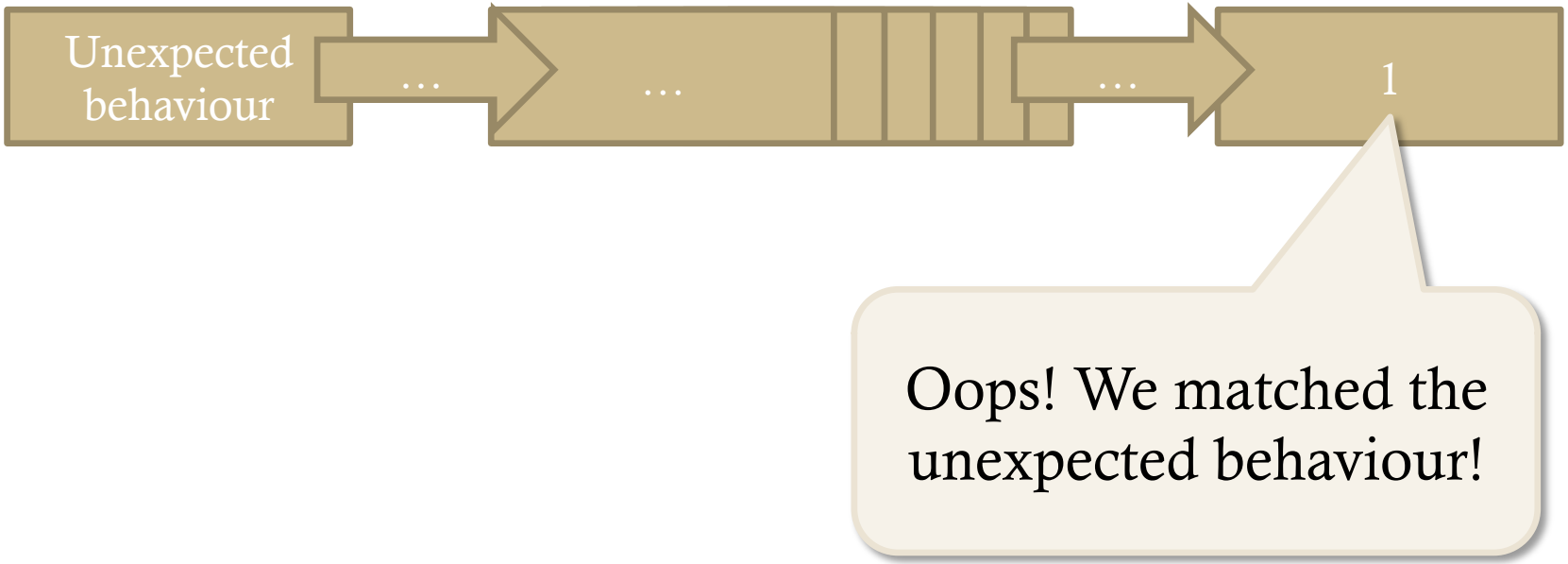


Detecting a Violation

- What does it mean to detect a violation when monitoring for unexpected behaviour?



Part III

(two ways of)

Monitoring Regular Expressions using Automata

Disadvantage of Residuals

- While using residuals it is quite easy to build a monitor…
- … it involves significant overhead at runtime

(imagine how many times the rules would have to be checked for a significantly long regular expression)

Part IIIa

Generating Automata using Residuals

Generating an Automaton 1

- One way of generating an automaton is by applying residuals for any option at runtime and recording the results

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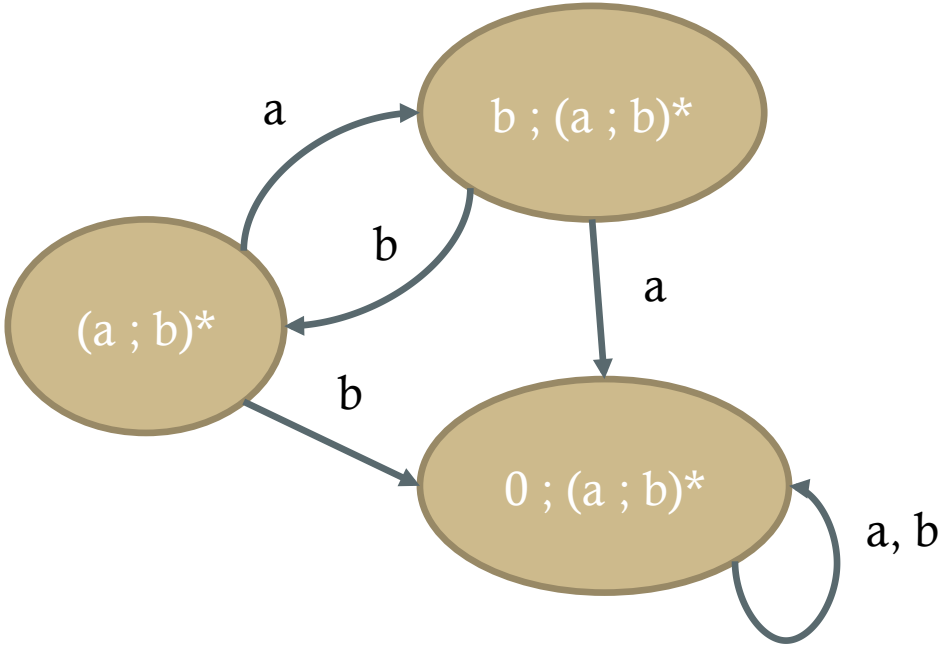

Caveats: REs can grow indefinitely

- 0 + 0 + 0 + 0 + 0 + 0 + 0 … + (a;b)*
- The automaton becomes infinite

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- 0 + 0 + 0 + 0 + 0 + 0 + 0 … + (a;b)*
- The automaton becomes infinite

- Use normal form

RE Normal Form

- A RE is in Normal Form if
  1. All choices are nested on the right-hand side

     e.g.: a + (b + (c + d))
  2. No repeated choices
  3. All choices are ordered (according to some order)

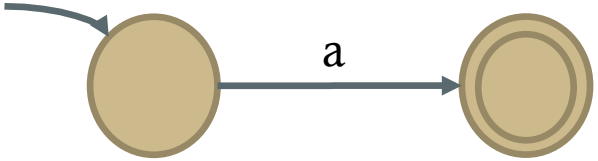
- Note: by associativity, idempotency, and symmetry, any RE can be converted into an RE in normal form

Part IIIb

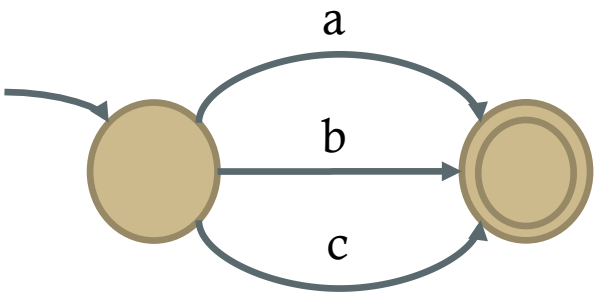
Generating Automata through a 1-to-1 operator mapping

Automata Equivalents

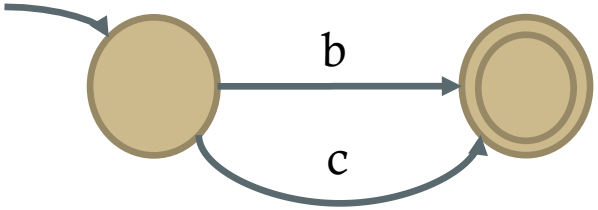
- a



- ?

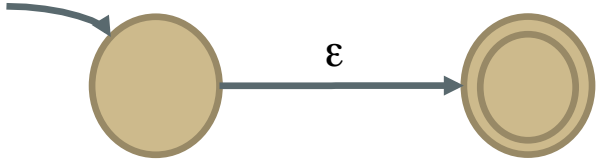


- !a



Automata Equivalents

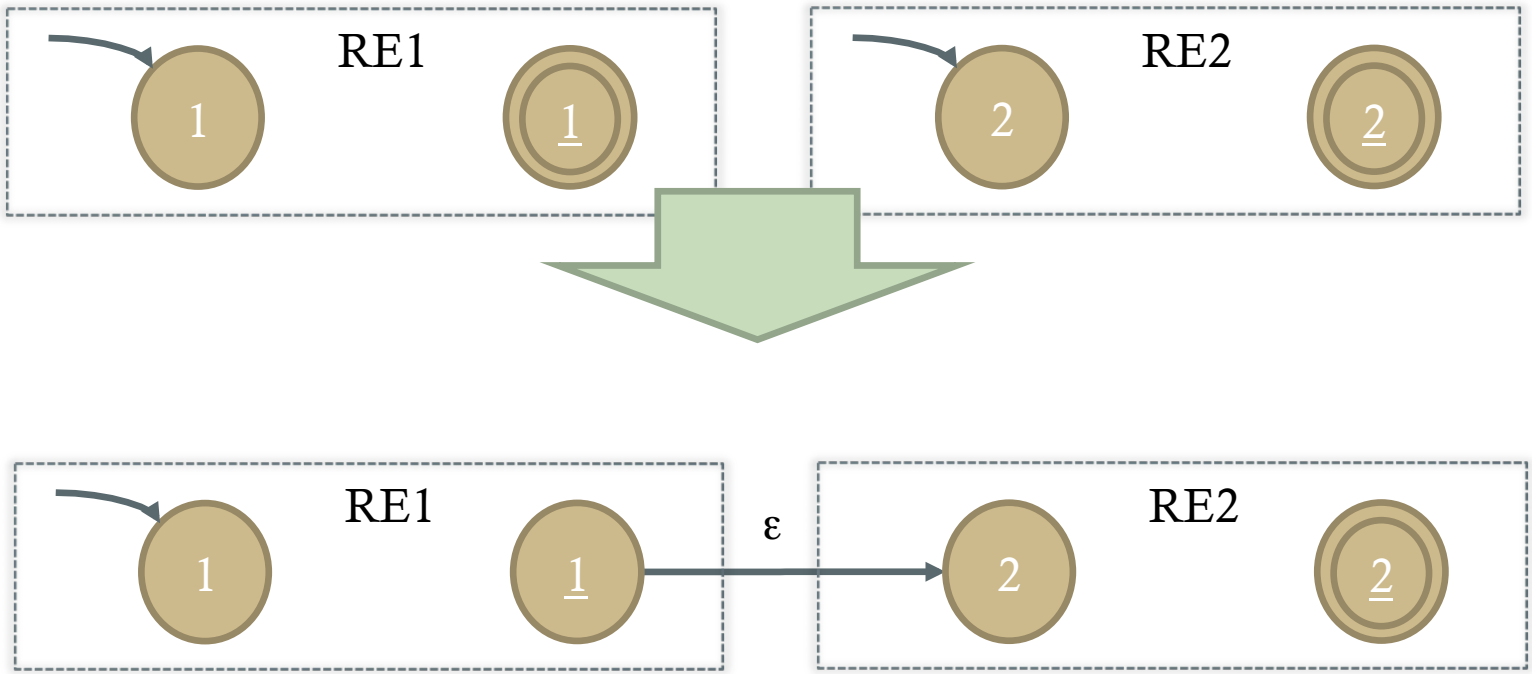
- 1



- 0

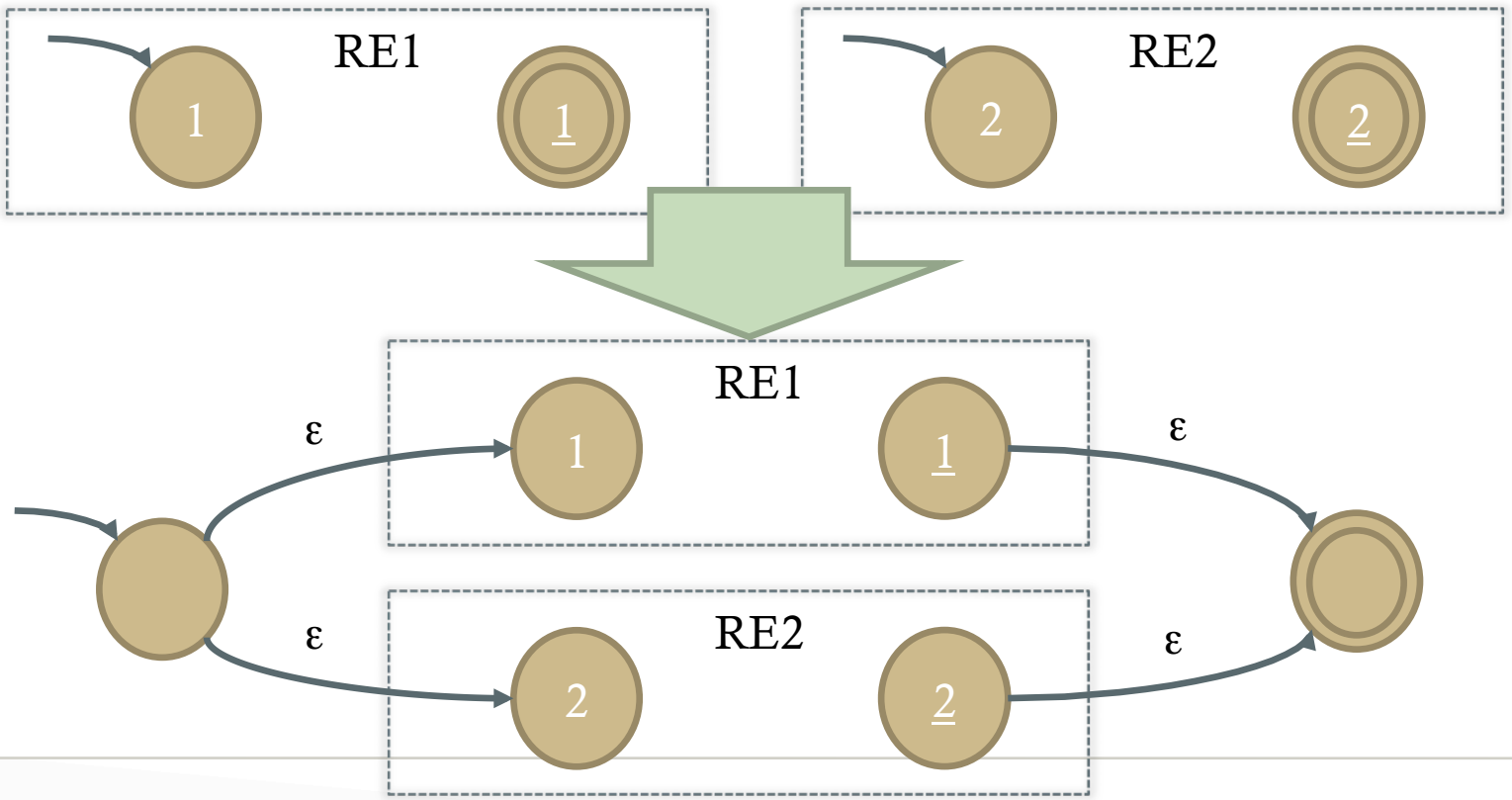
Automata Equivalents

- RE1 ; RE2



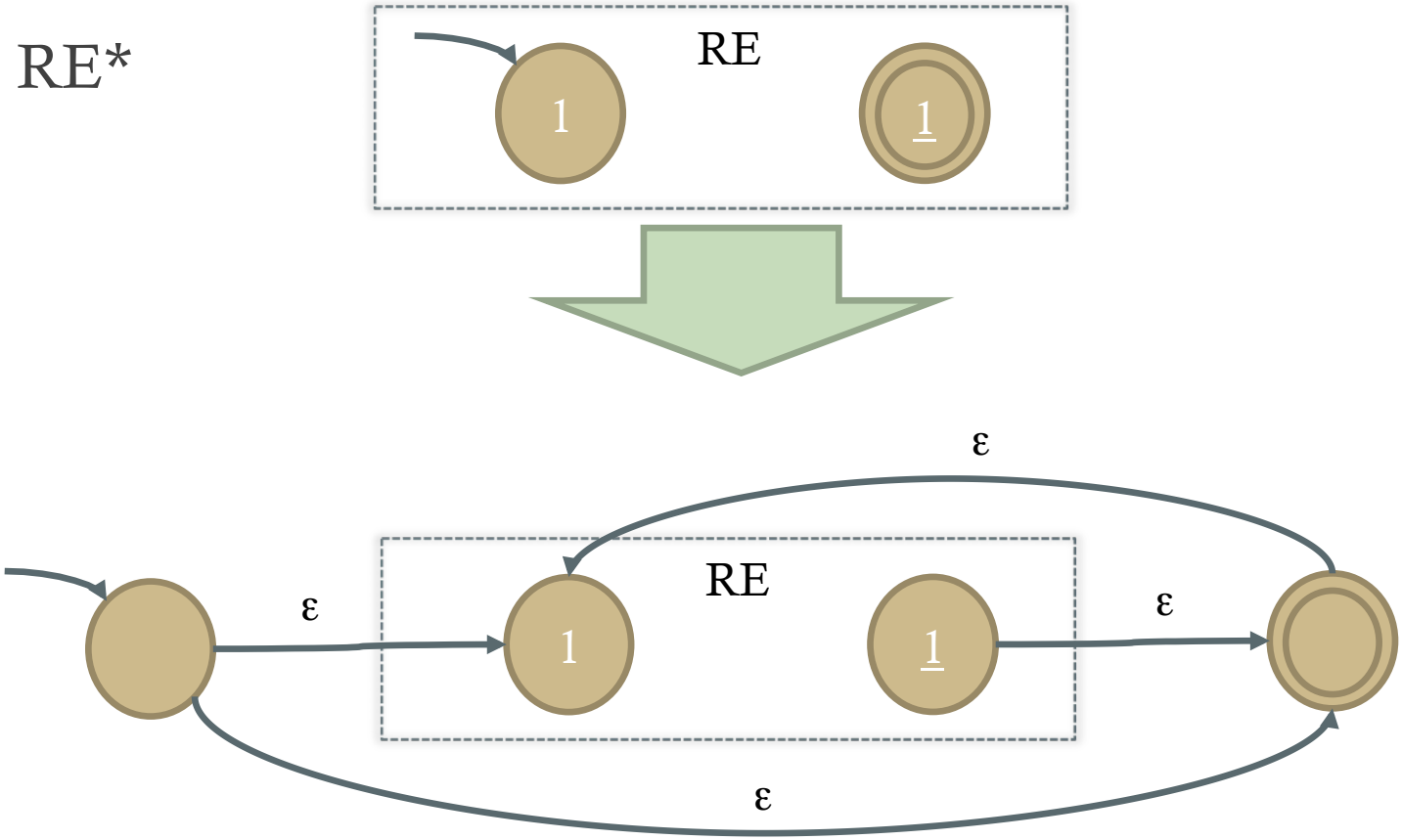
Automata Equivalents

- RE1 + RE2



Automata Equivalents

- RE*

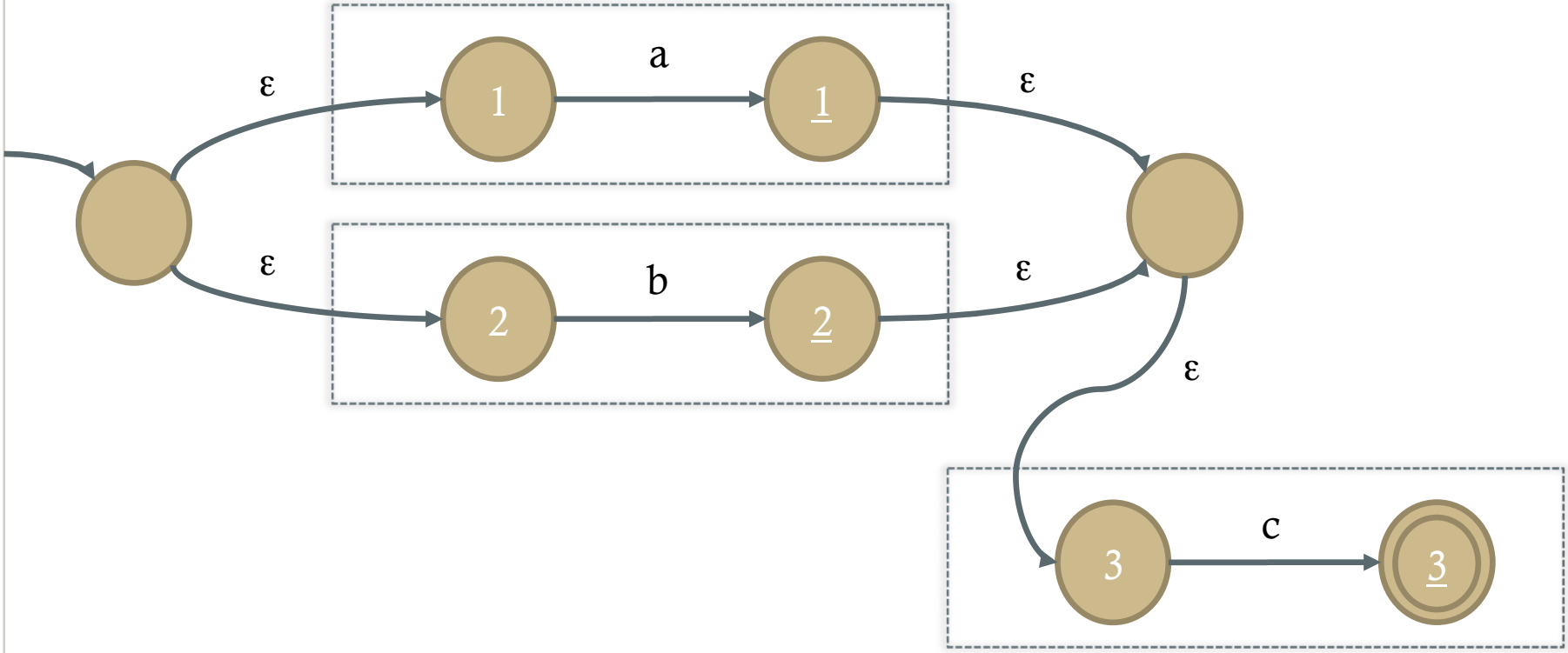


Example

- (a + b) ; c

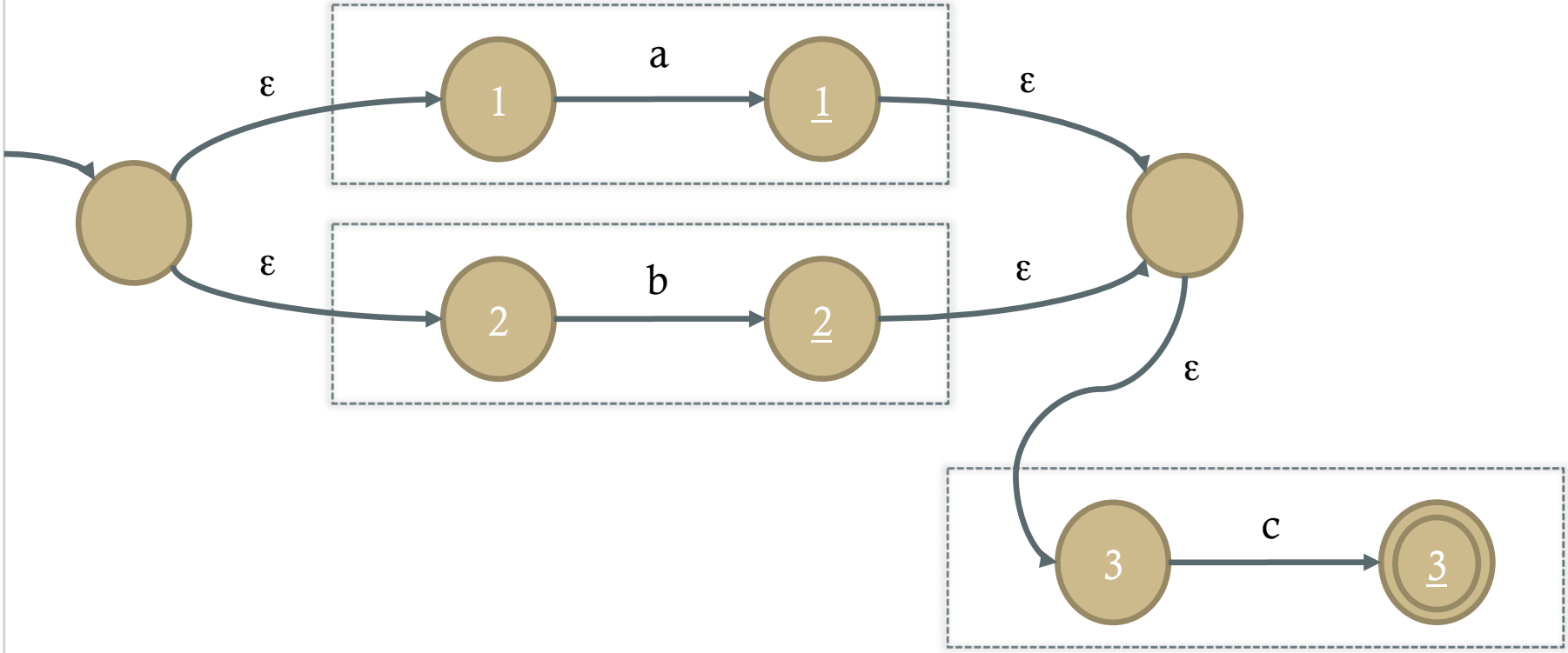
Example

- (a + b) ; c



Problem

- Monitors have to be deterministic!

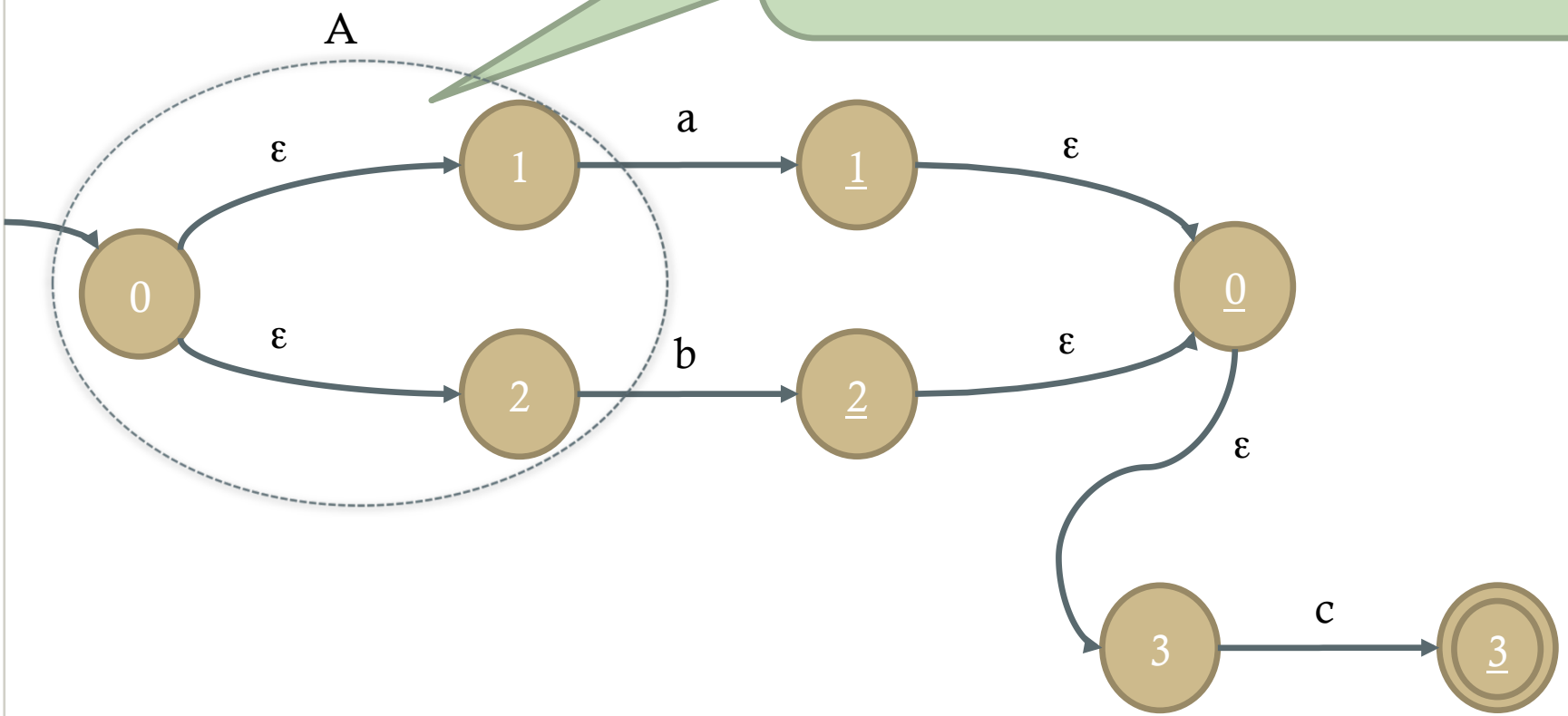


Determinisation in a Nutshell

1. Starting from a given set of states (initially the start states), add **any state reachable from this set on empty strings… call this set A**
2. For each transition leaving any state in A, **combine all possible destinations on each event e** and create a new state B.
3. Restart process from 1. on each B (unless B has already been processed earlier).

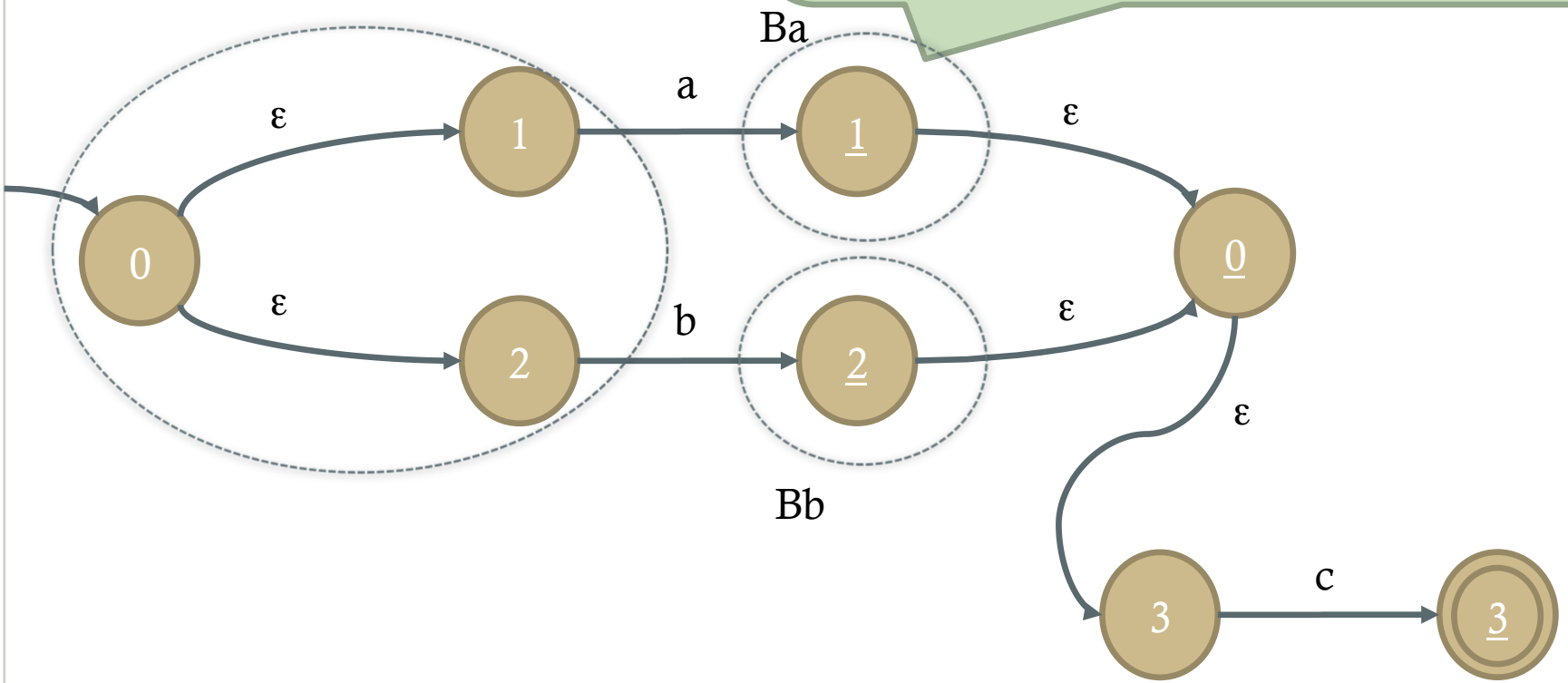
Ex

1. Starting from a given set of states (initially all start states), add **any state reachable from this set on empty strings… call this set A**



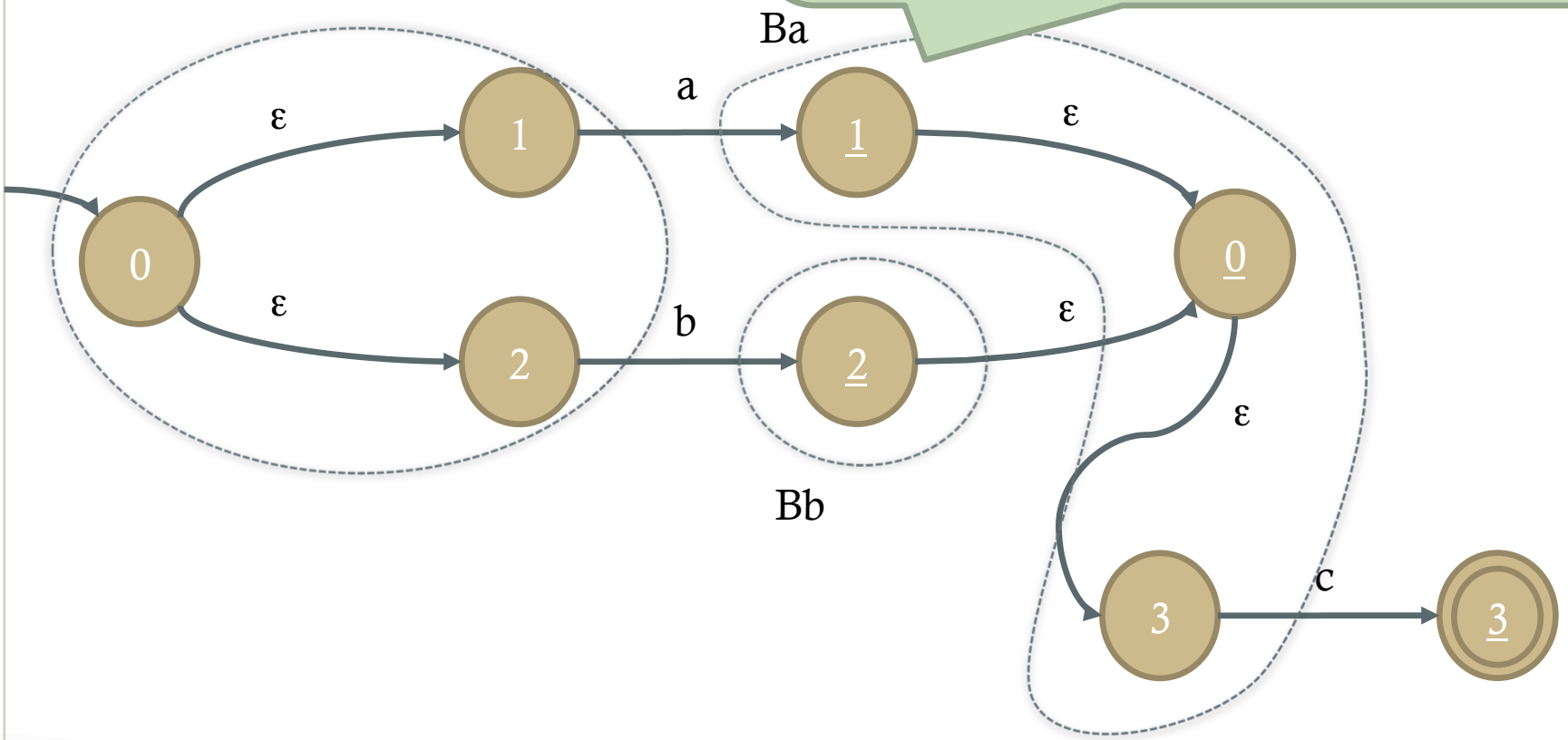
Ex

2. For each transition leaving any state in A, **combine all possible destinations on each event e** and create a new state B.

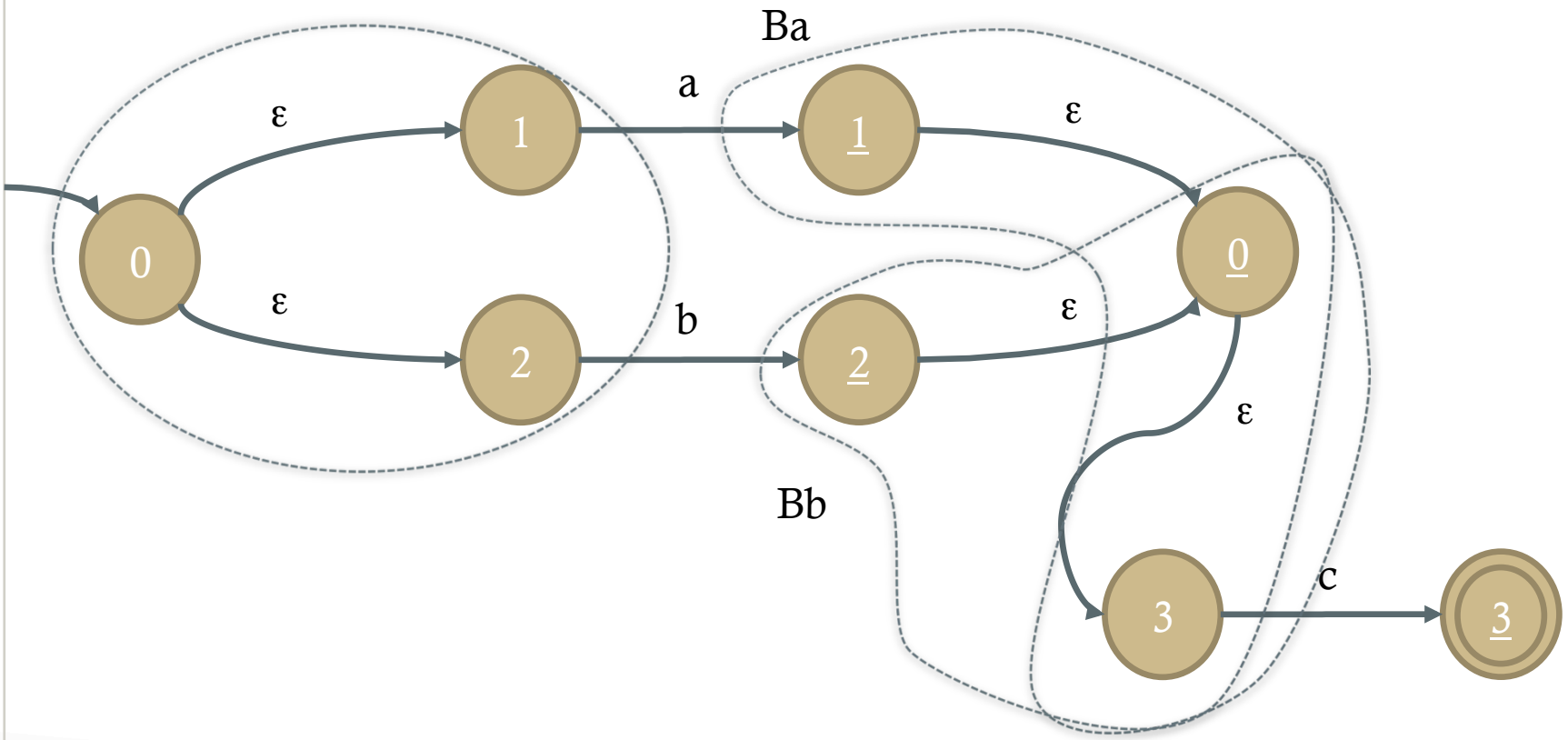


Ex

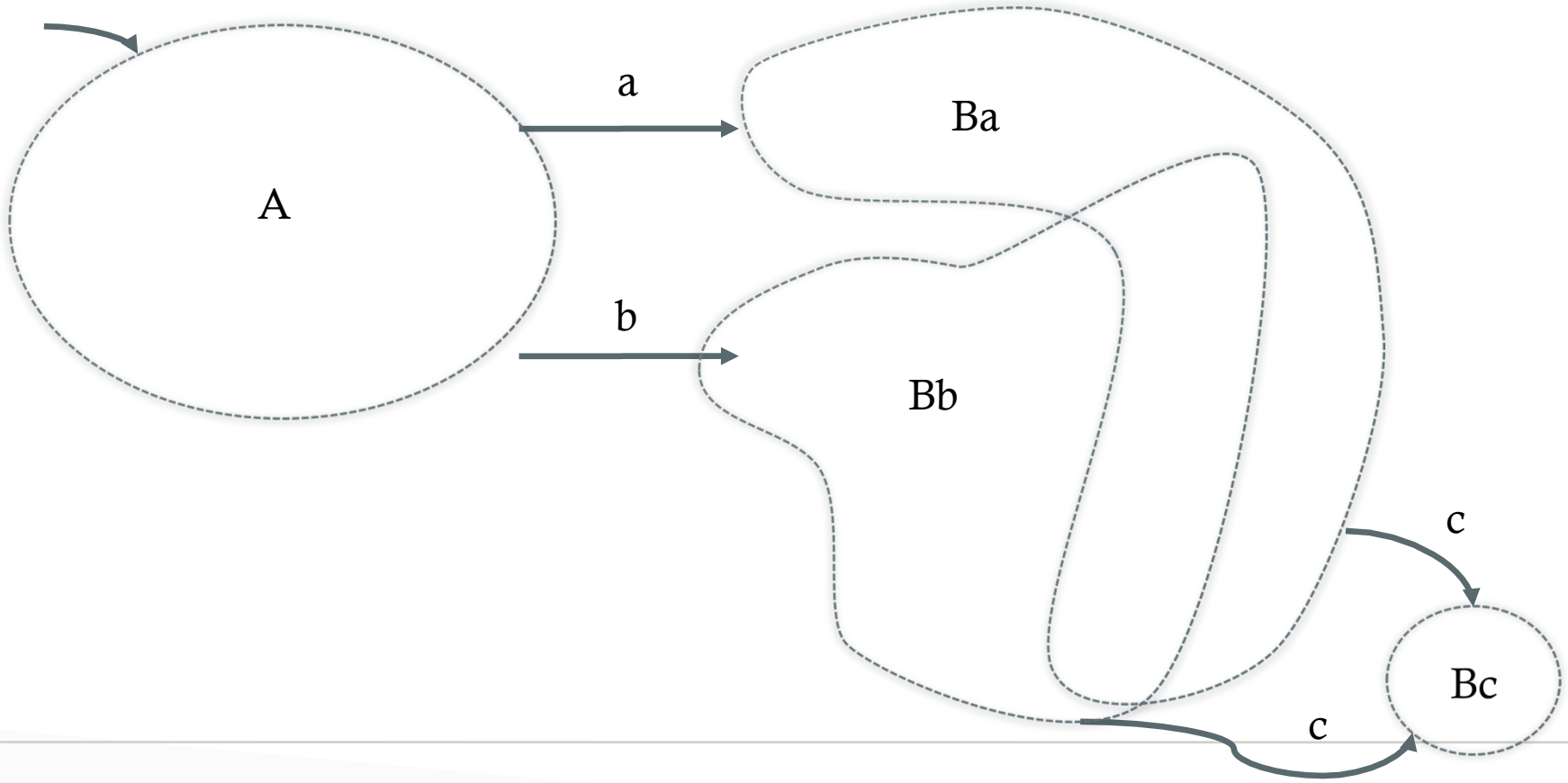
3. Restart process from 1 on each B (unless B has already been processed earlier).



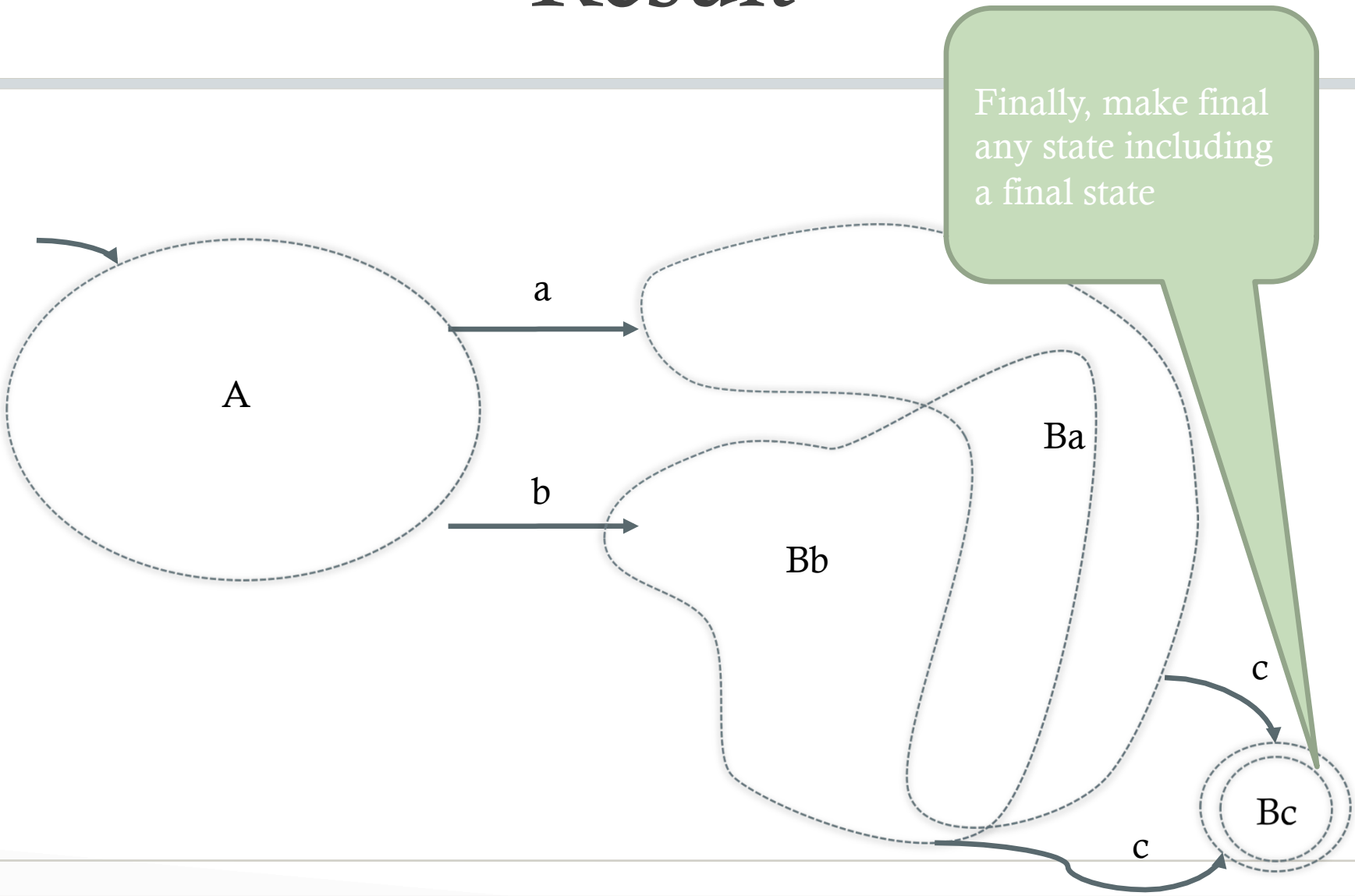
Example



Result



Result


Finally, make final any state including a final state
A
a
b
Ba
Bb
c
Bc
c

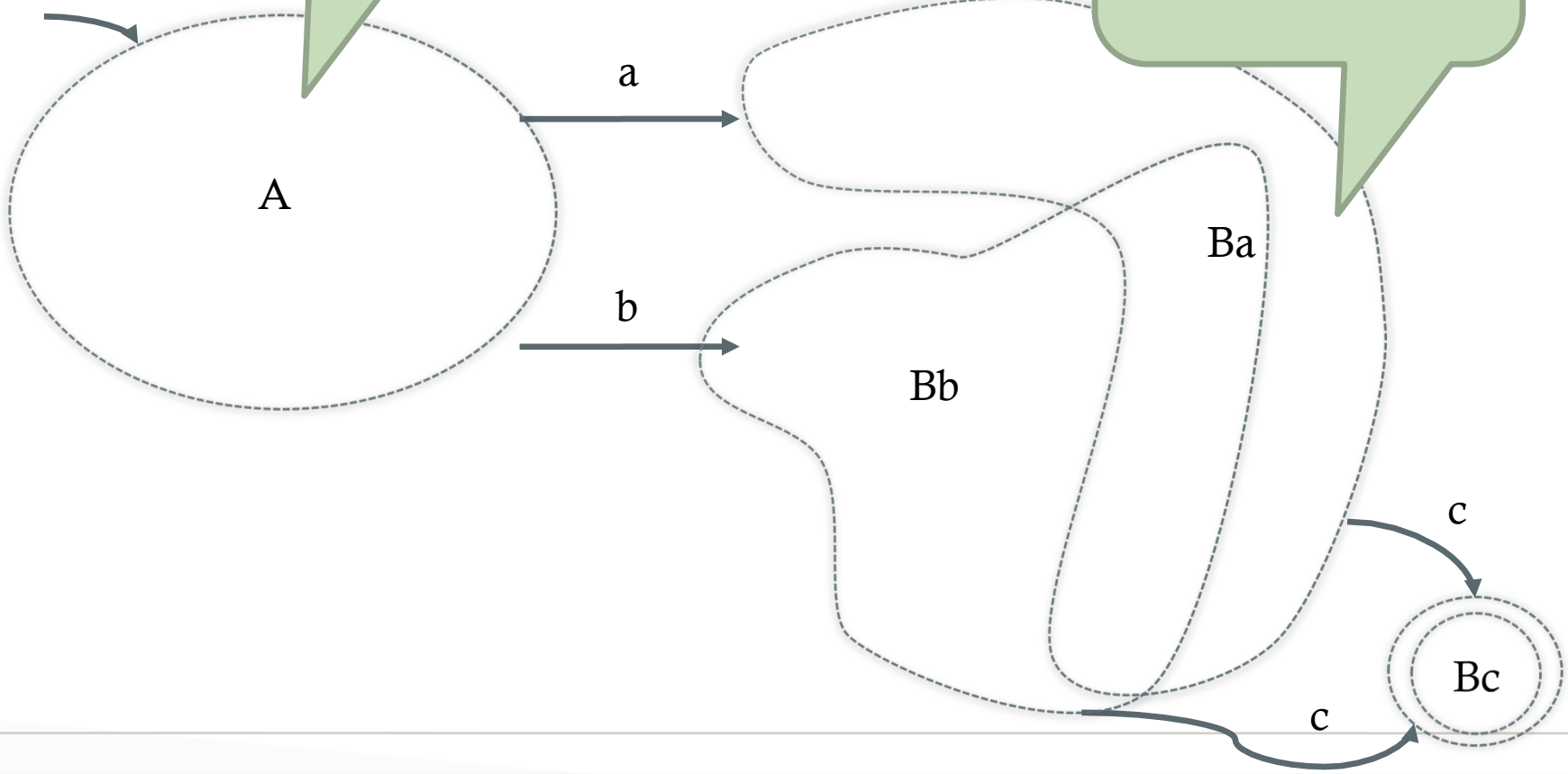
Determinisation

- Good news: the algorithm is provided for your assignment!

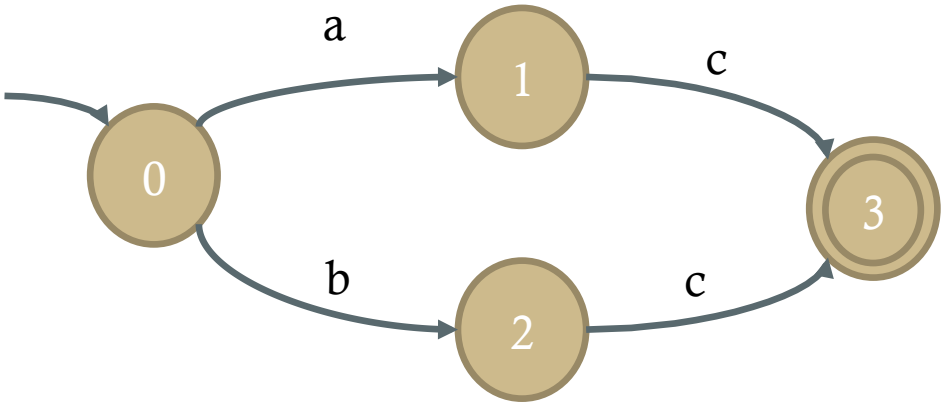
Problem

How should monitor react if observing "**c**" here?

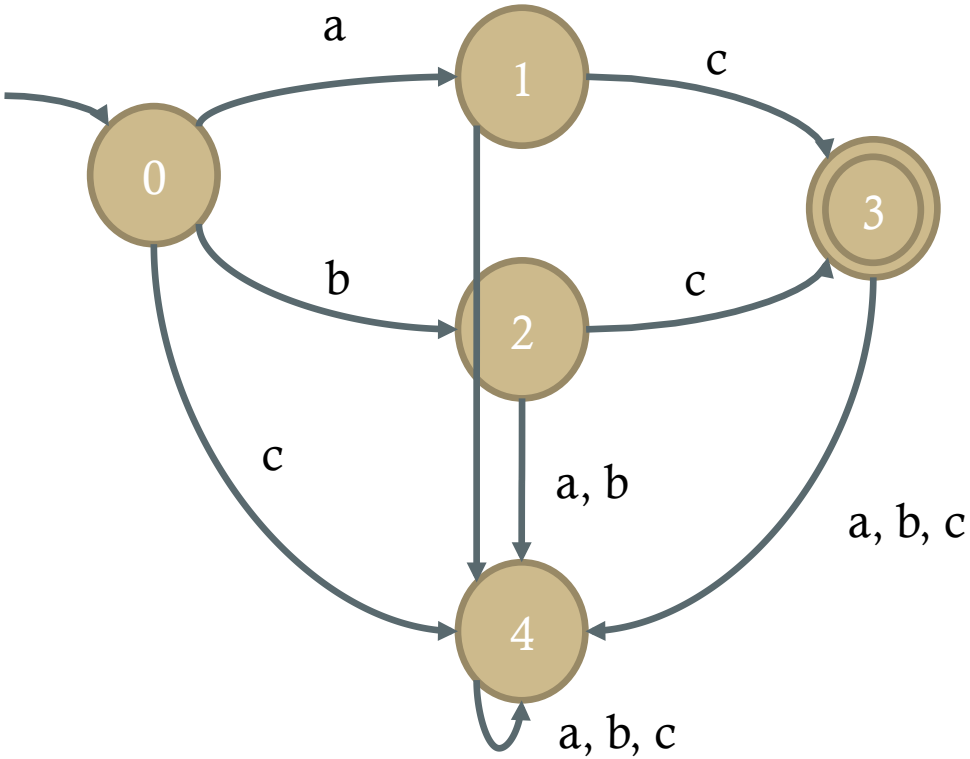
How should monitor react if observing "**a**" here?



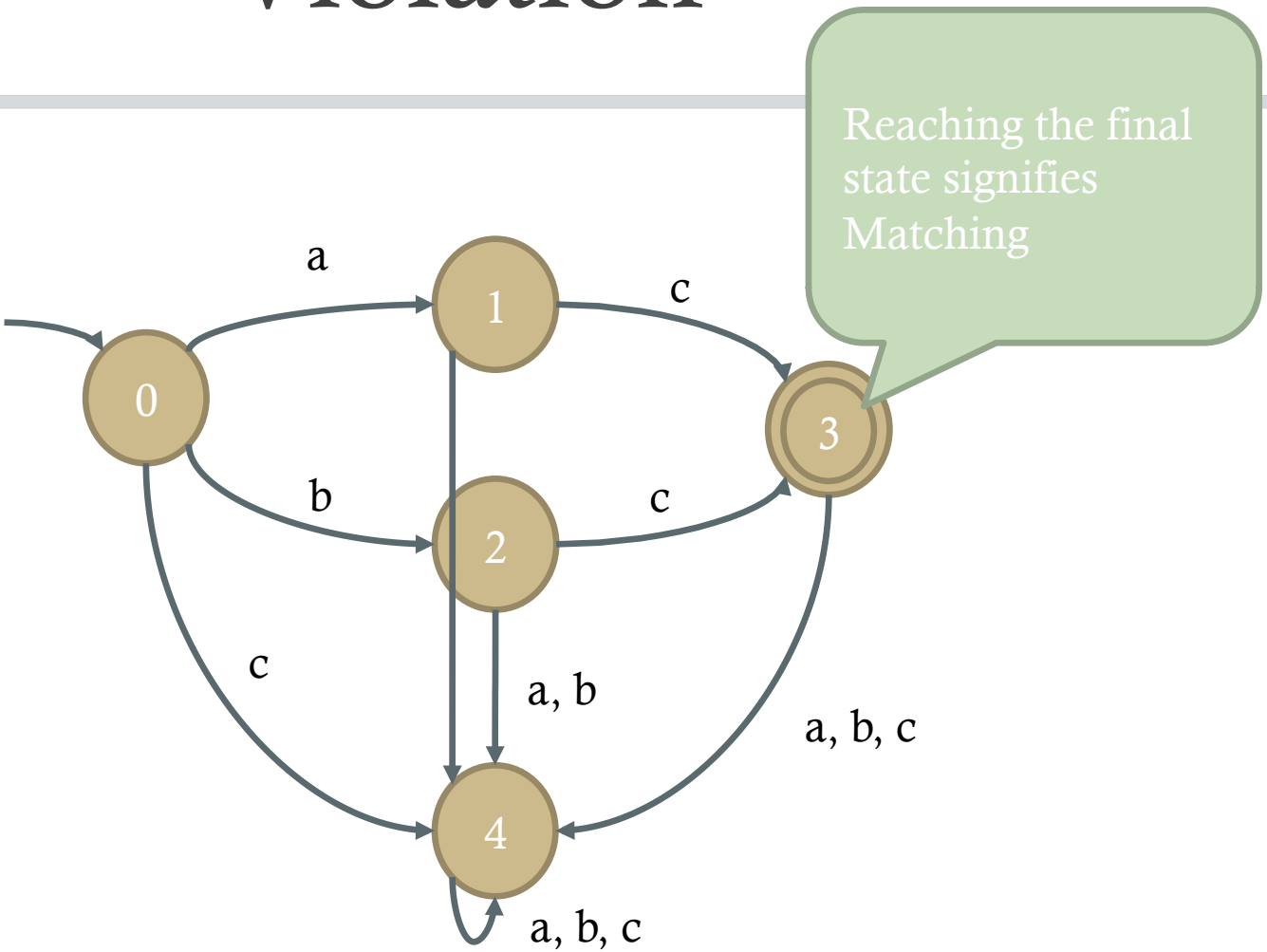
Totality



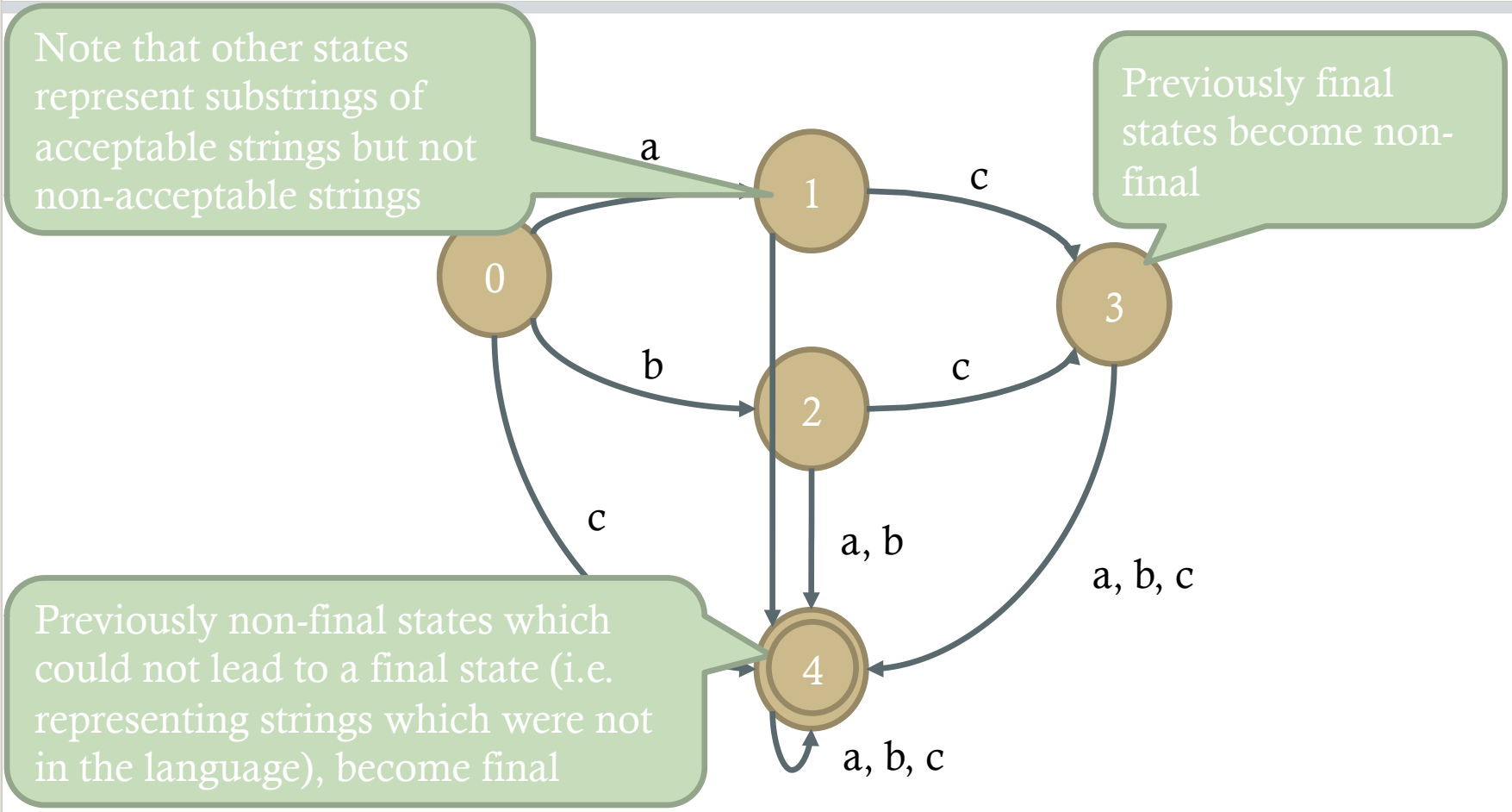
Totality



Violation


Reaching the final state signifies Matching
0
1
2
3
4
a
b
c
c
c
a, b
a, b, c
a, b, c

Complement if you to flag Non-Matching



Exercises

- Fill in the function *sequence()* in class *NFA.java* which connects two automata sequentially together