One-clock deterministic timed automata are efficiently identifiable in the limit

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LATA 2009

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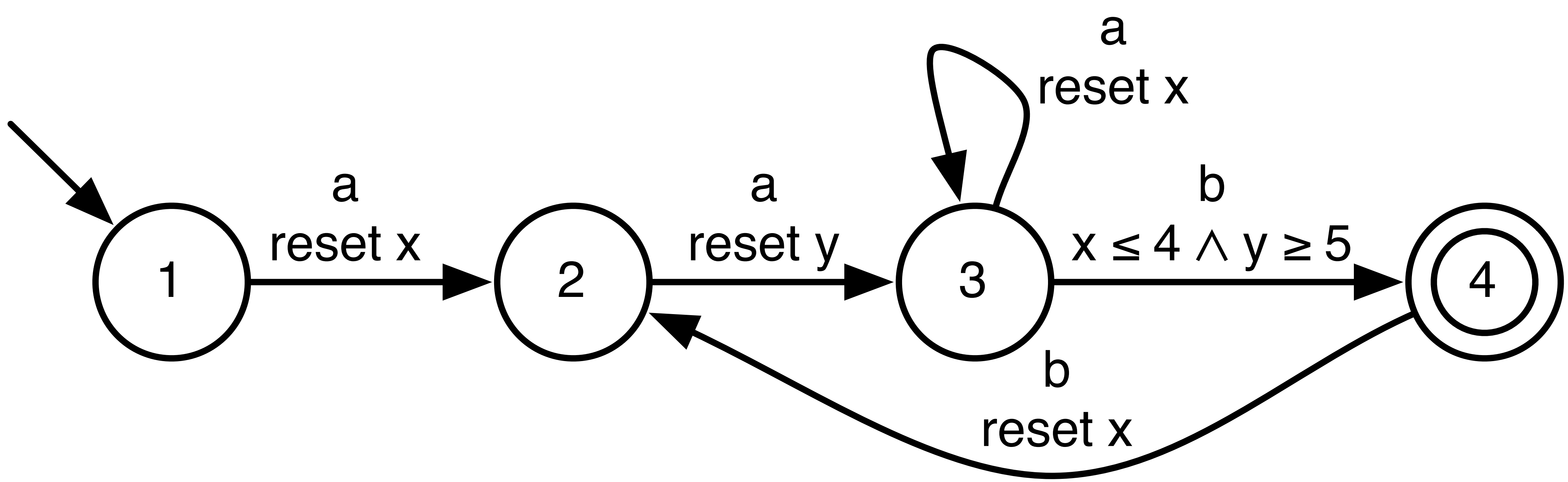
Overview

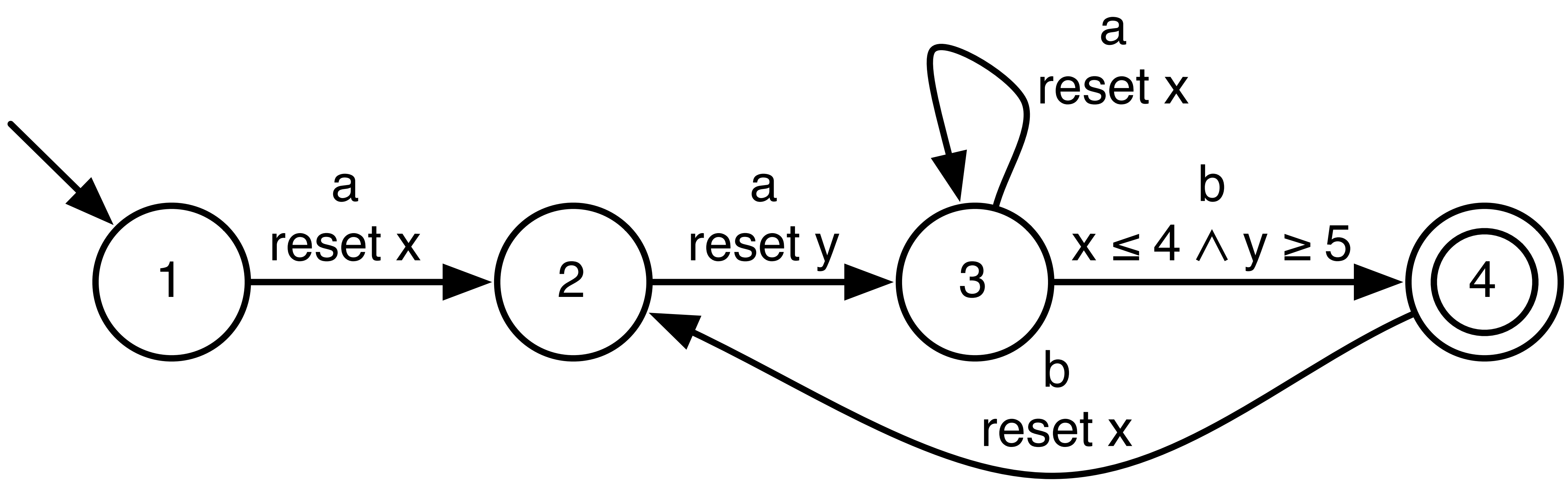
- Deterministic timed automata (DTAs)
- Why learn DTAs?
- Efficient identification in the limit
- DTAs are not efficiently identifiable
- Learning DTAs with a single clock efficiently
- Conclusions and future work

DTAs



Monday, April 6, 2009

DTAs



accepts: (a, 1)(a, 2)(a, 3)(b, 4) rejects: (a, 1)(a, 2)(a, 1)(b, 2)

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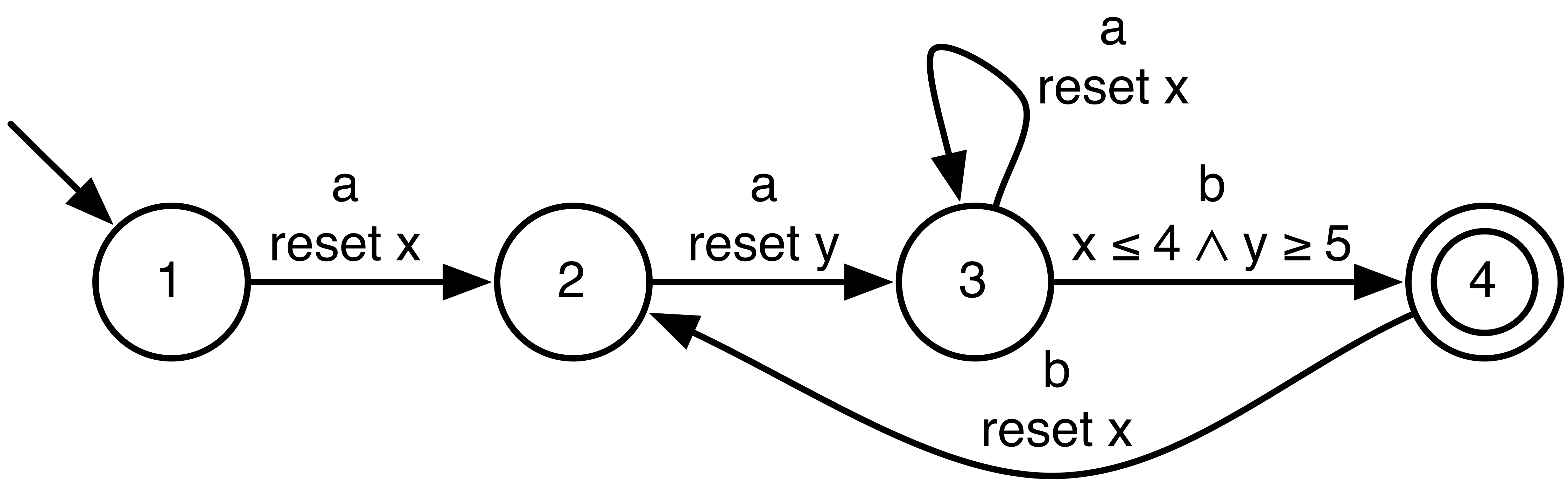
DTAs



rejects: (a, t)(a, t')(b, t'') for any t, t', t''
because x is reset before y in such a path

DTAs

- A deterministic timed automaton (DTA):
  - A deterministic finite state automaton (DFA)
  - A set of clocks X
  - A clock guard (constraint) g for every transition d
  - A set of clock resets R for every transition d
- Timed properties:
  - All clocks increase their values synchronously
  - A clock value can be reset to 0
  - A transition can fire if its clock guard is satisfied

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Why learn DTAs?

- DTAs:
  - Use an explicit time representation (using numbers)
  - Are intuitive models for many real-time systems
  - Are used to model and verify reactive systems
- In practice it is often difficult to construct DTAs by hand, but data is easy to obtain:
  - We want to identify them from data

Why learn DTAs?

- Any timed system can also be represented using an implicit time representation, using DFAs or HMMs
  - Exponential blowup of the models and the data required for learning
  - Inefficient in the size of the timed data and the timed model
- We want to learn DTAs directly from timed data
  - Is it possible to do so efficiently?

Applications

- Learning truck driver behavior
- Identifying process models
- Inferring models for ship movement
- Model based testing
- ...
  - Anywhere where representing time explicitly results in a large reduction in model size

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Identification in the limit

- Identification in the limit views learning of languages and models as a continuous process:
  - Data is observed
  - This data is used to modify the current model
- Identification is successful if from some point on, the model does not change anymore, and if it is correct
- Identification is efficient if this point can occur after observing a polynomial amount of data, and if the model is computed using a polynomial time algorithm

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Efficient Identification

- A language class C is efficiently identifiable in the limit if:
  - there exists a polynomial time algorithm that can identify any language L from C
  - this algorithm is guaranteed to identify the correct language L_t when the input data contains a polynomial characteristic set:
    - a subset of size polynomial in the size of the smallest representation (automaton) A such that $L(A) = L_t$

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Polynomial Distinguishability

- If C is efficiently identifiable in the limit (from polynomial time and data), then an automaton class C_a for C is polynomially distinguishable
- A class of automata C_a is polynomially distinguishable if:
  - for any two automata A and A' in C_a, there exists a string in the symmetric difference of L(A) and L(A') of size polynomial in |A| + |A'|

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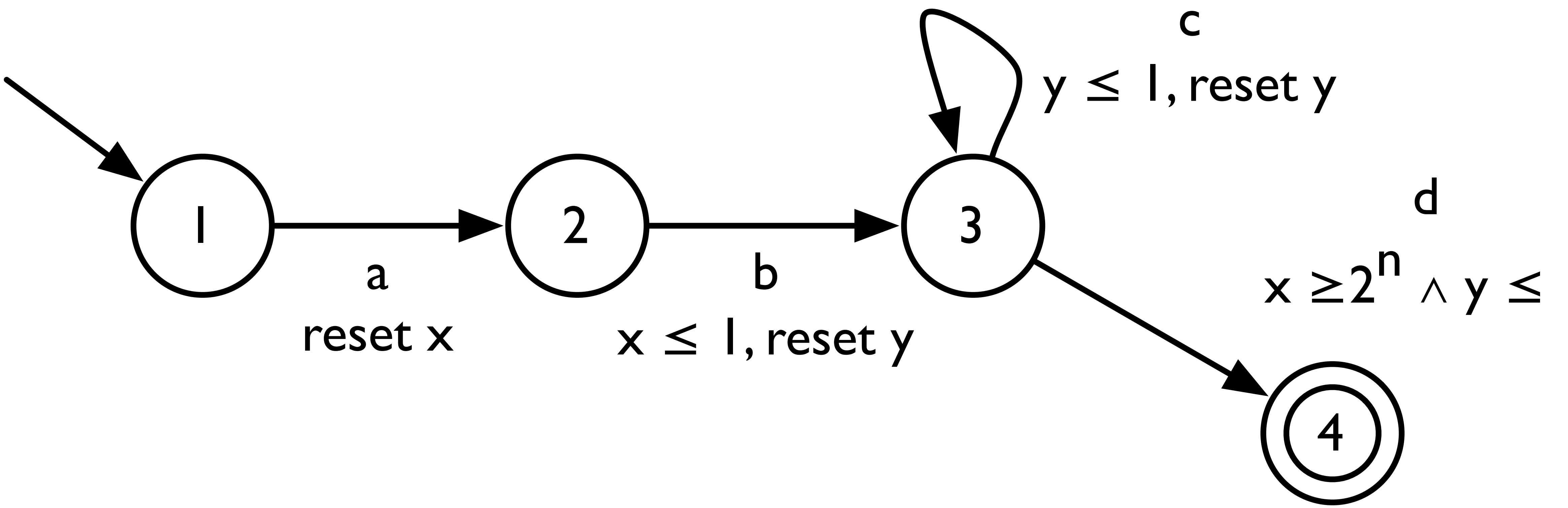
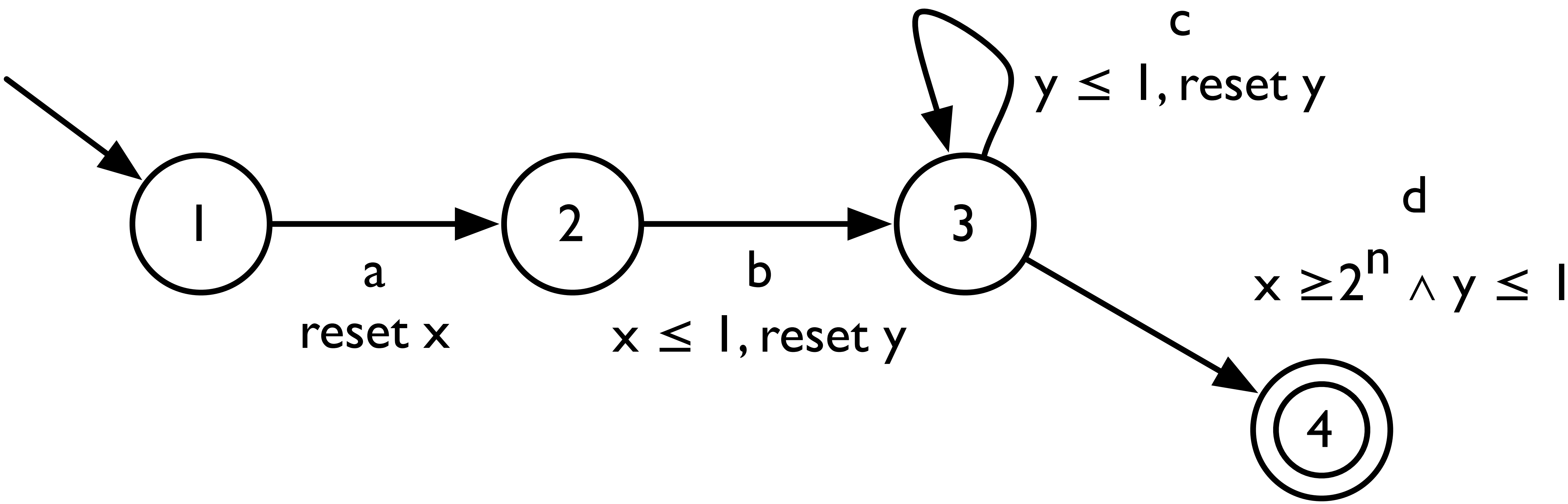
DTAs are not pol. dist.



This DTA requires a timed string of exponential length in order to end in state 4

DTAs are not pol. dist.



accepts only (a, t)(b, t')(c, t_1)...(c, t_m)(d, t'') where:

all t', t'', t_1, ..., $t_m \leq 1$ and $\sum t_1, \ldots, t_m \geq 2^n$,

hence, it has to hold that: $m \geq 2^n$

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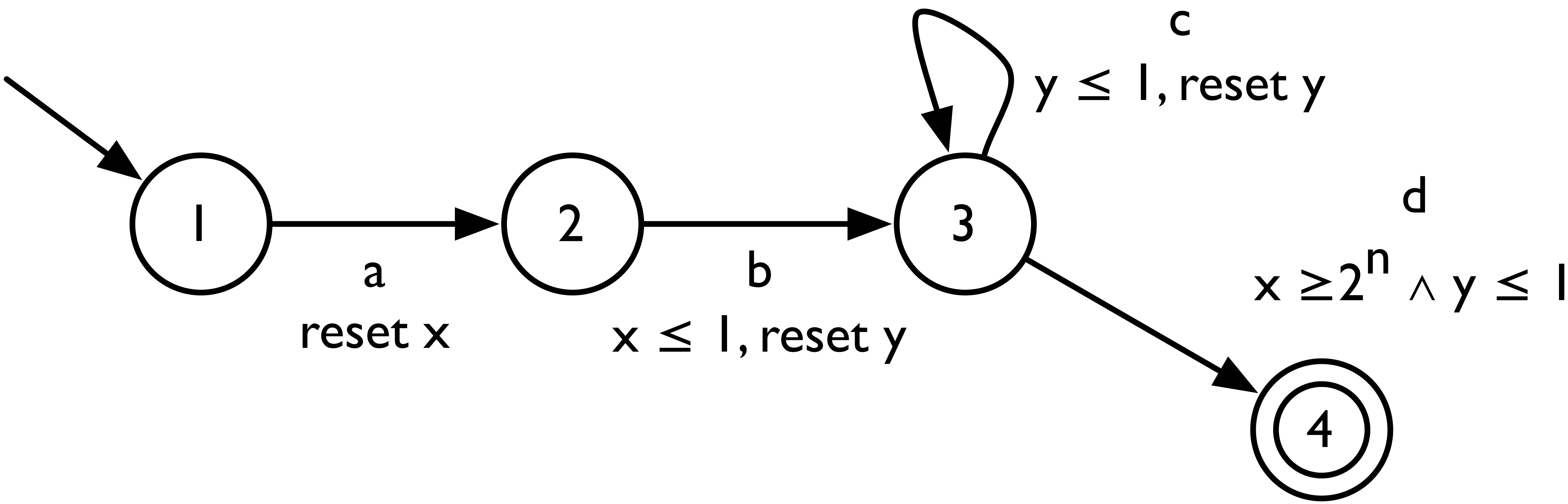
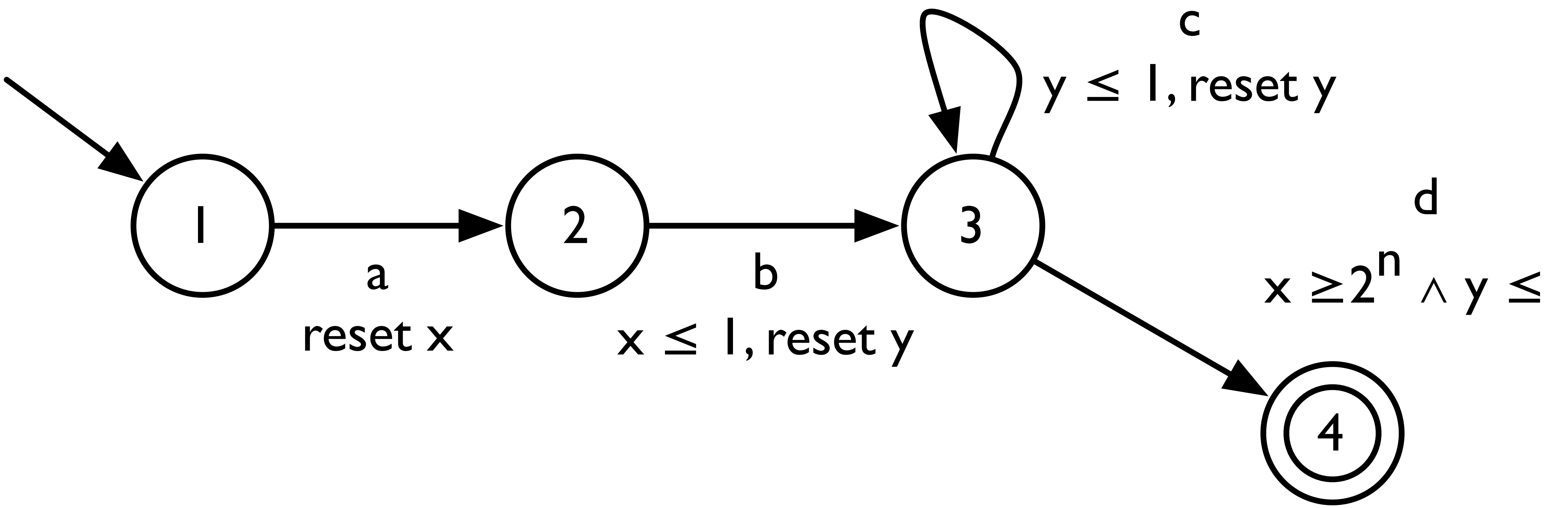
DTAs are not pol. dist.



We cannot polynomially bound the size of the shortest string that distinguishes these DTAs (for different n) from a DTA accepting the empty language

2-DTAs are not pol. dist.



These DTAs only require 2 clocks!

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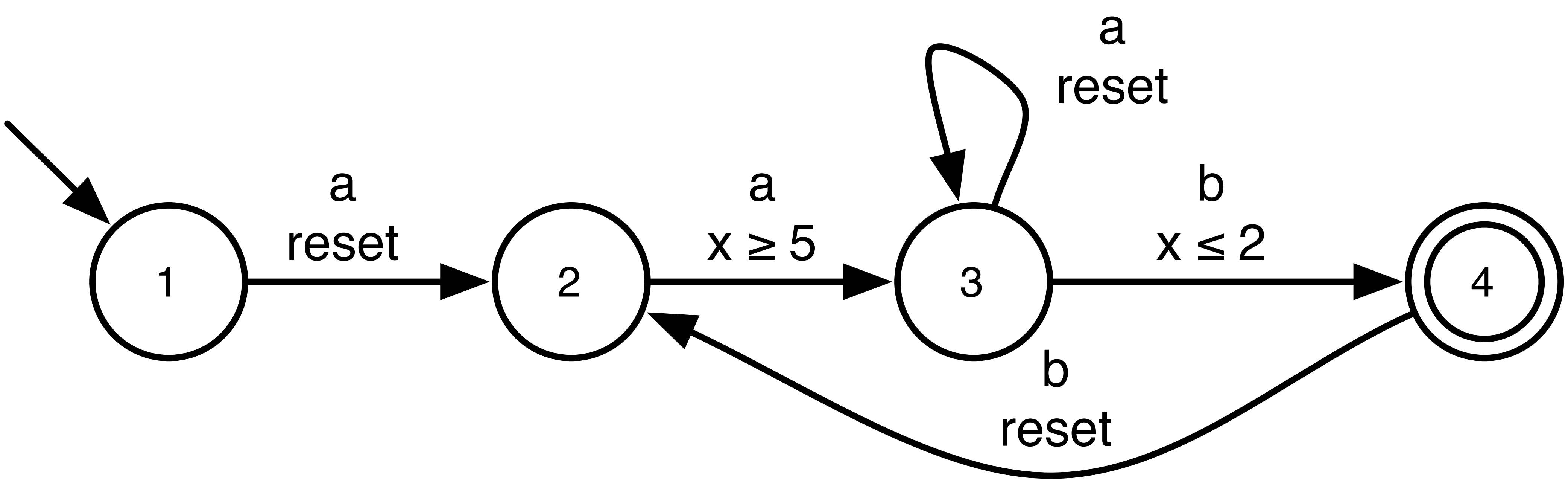
1-DTAs

- An 1-DTA is a DTA with one clock x
- The DTAs we used to prove the non-polynomial distinguishability of DTAs require at least two clocks
- 1-DTAs are polynomially distinguishable! (ICGI 2008)
- Are they efficiently identifiable?

1-DTAs



rejects: (a, t)(a, t')(b, t'') for any t, t', t''
because x is greater than 5
the first time it enters state 3

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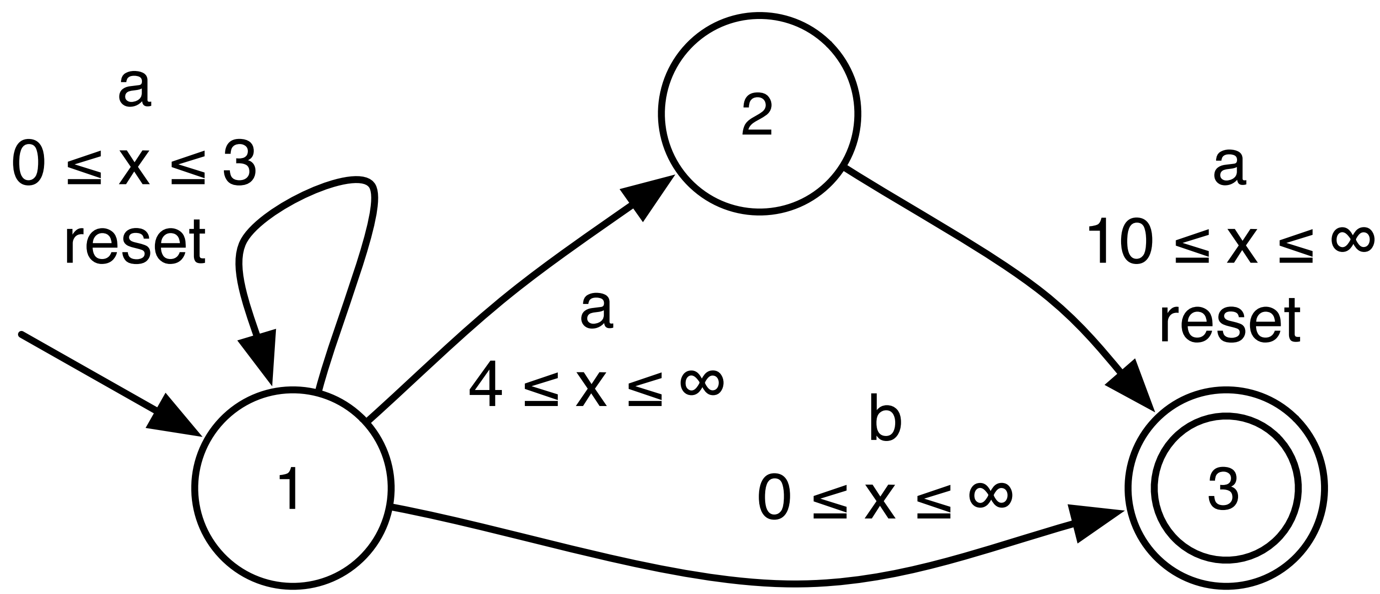
Learning 1-DTAs

- Based on RPNI, an algorithm for learning DFA
- Learn 1-DTA one transition <q, q', a, r, g> at a time:
  - The source state q
  - The target state q'
  - The transition label a
  - The cock reset r
  - The clock guard g

Learning Example



$S_+ \supseteq$ {(a,4)(a,6); (a,5)(b,6); (b,3)(a,2); (a,4)(a,1)(a,3); (a,4)(a,2)(a,2)(b,3)}

$S_- \supseteq$ {(a,3)(a,10); (a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)}

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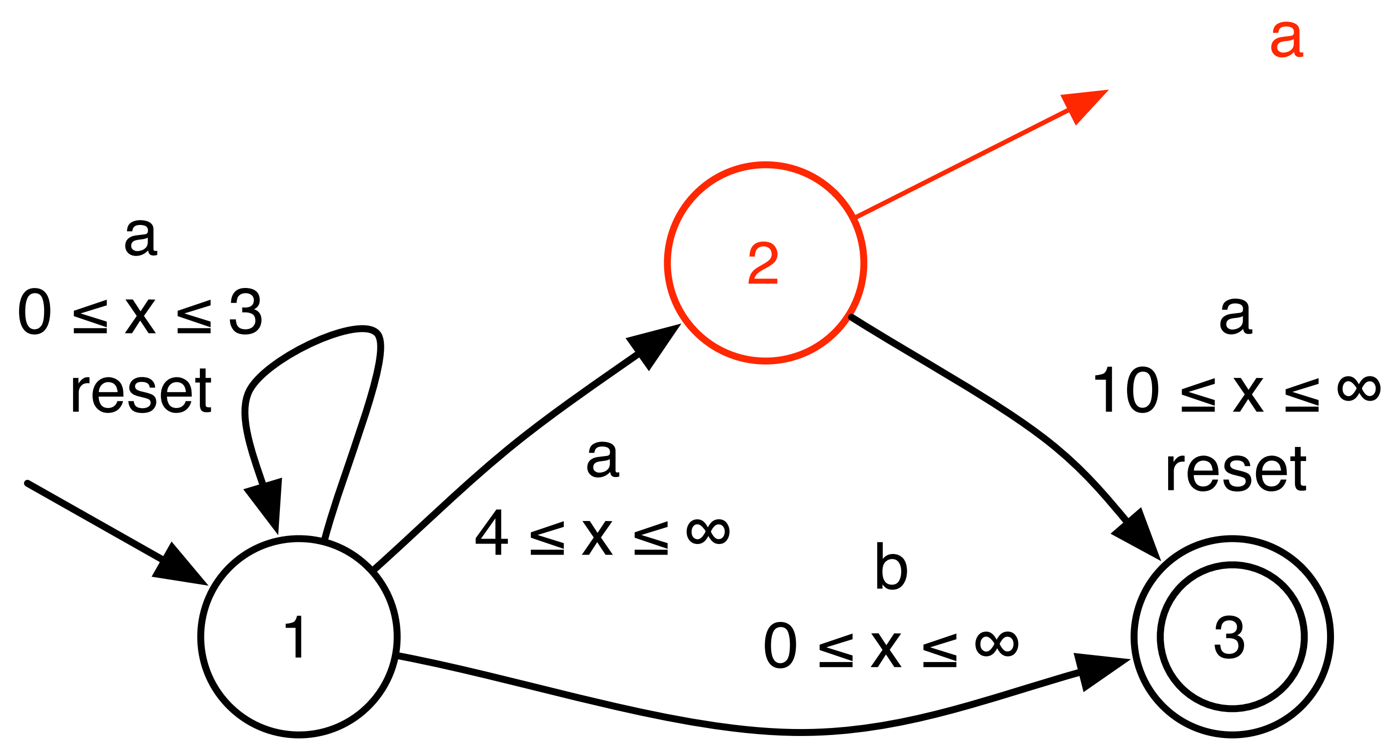
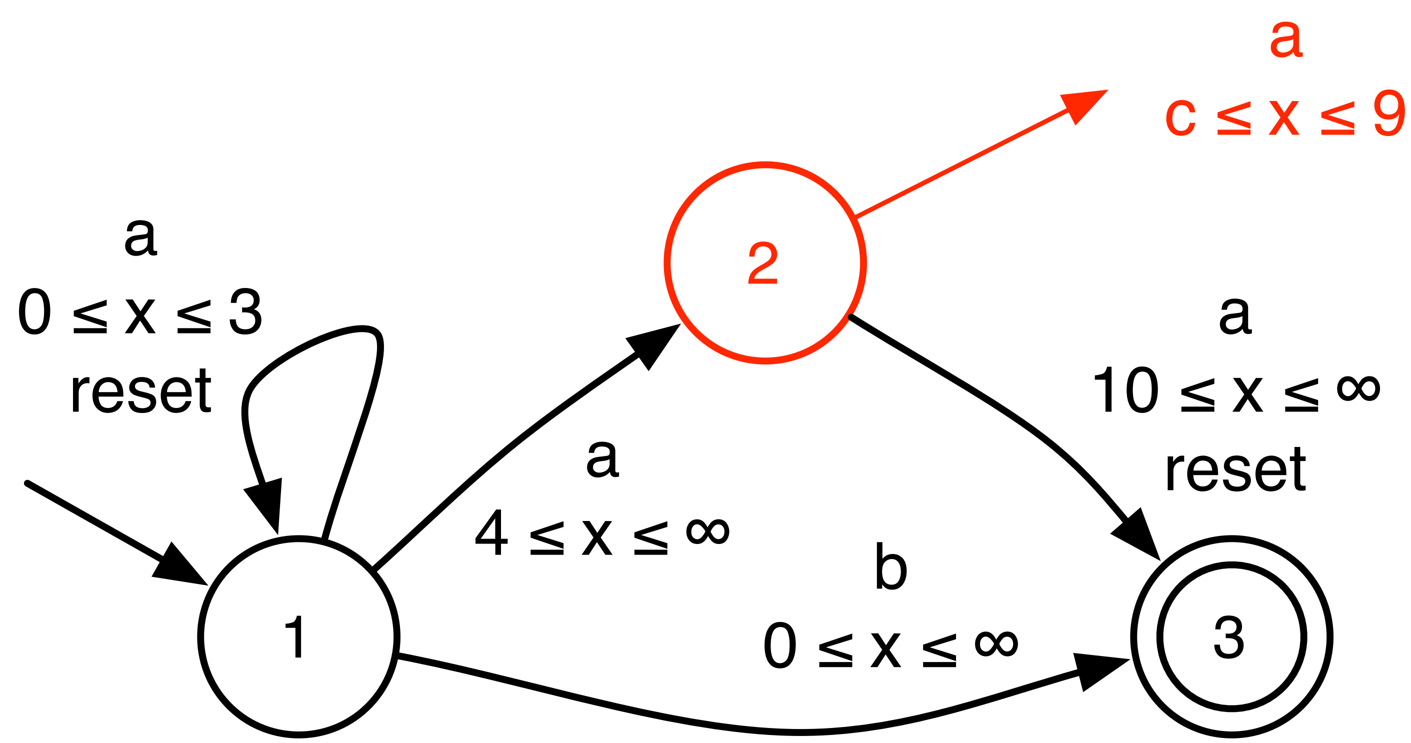
Learning Example



Choose the source state and transition label: smallest number first and alphabetic order

Identify a transition for state 2, with label a

Learning Example



Choose the maximum upper bound for g, in this case 9

Use the data set to determine the smallest consistent lower bound c

$g = c \leq x \leq 9$

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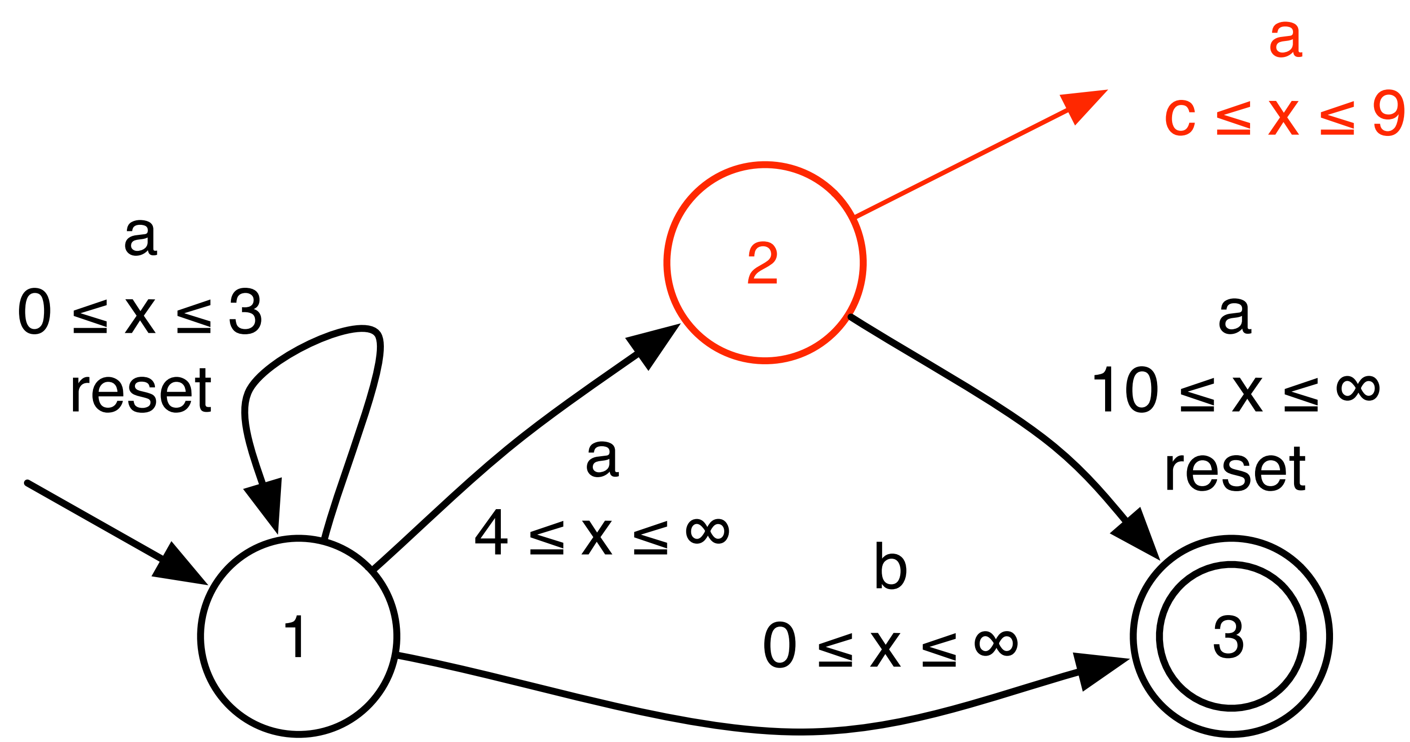
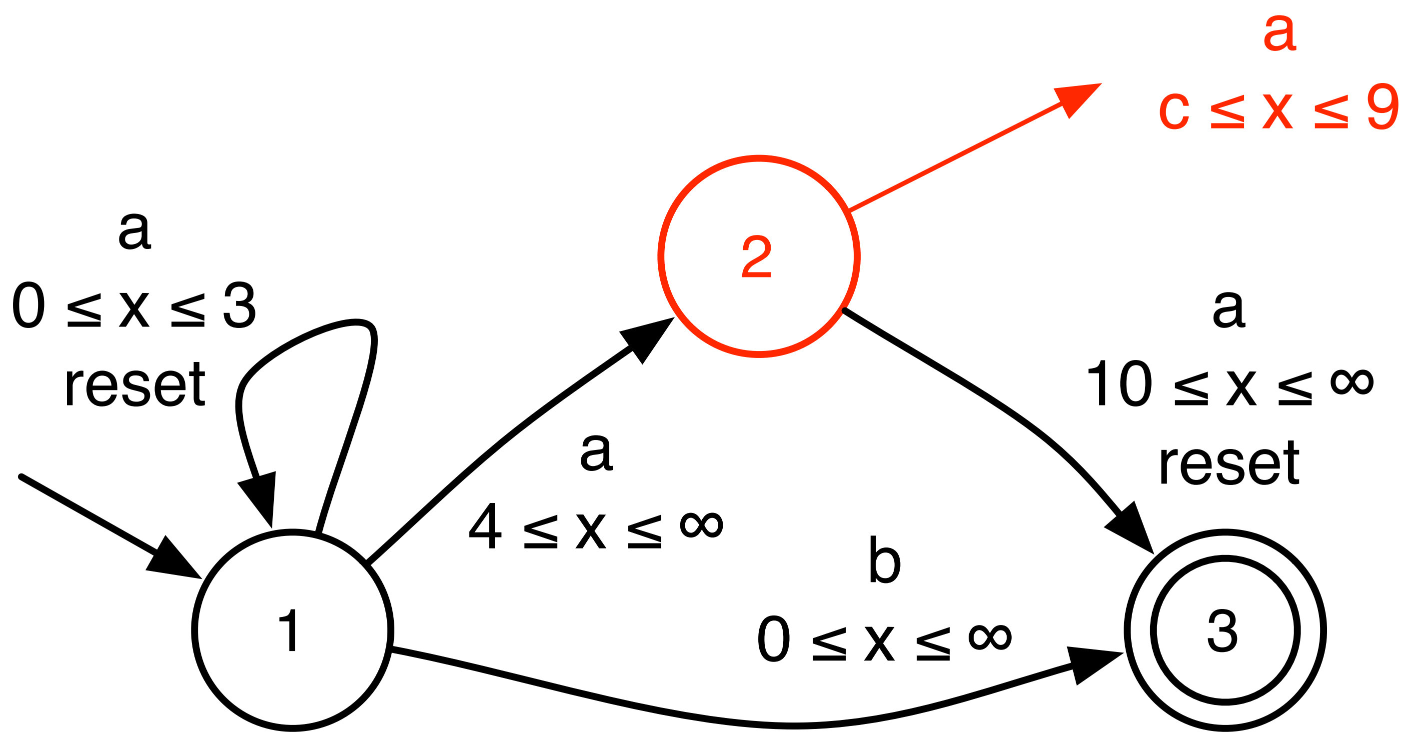
Learning Example



The smallest reachable lower bound is 4

$4 \leq c \leq 9$

Learning Example

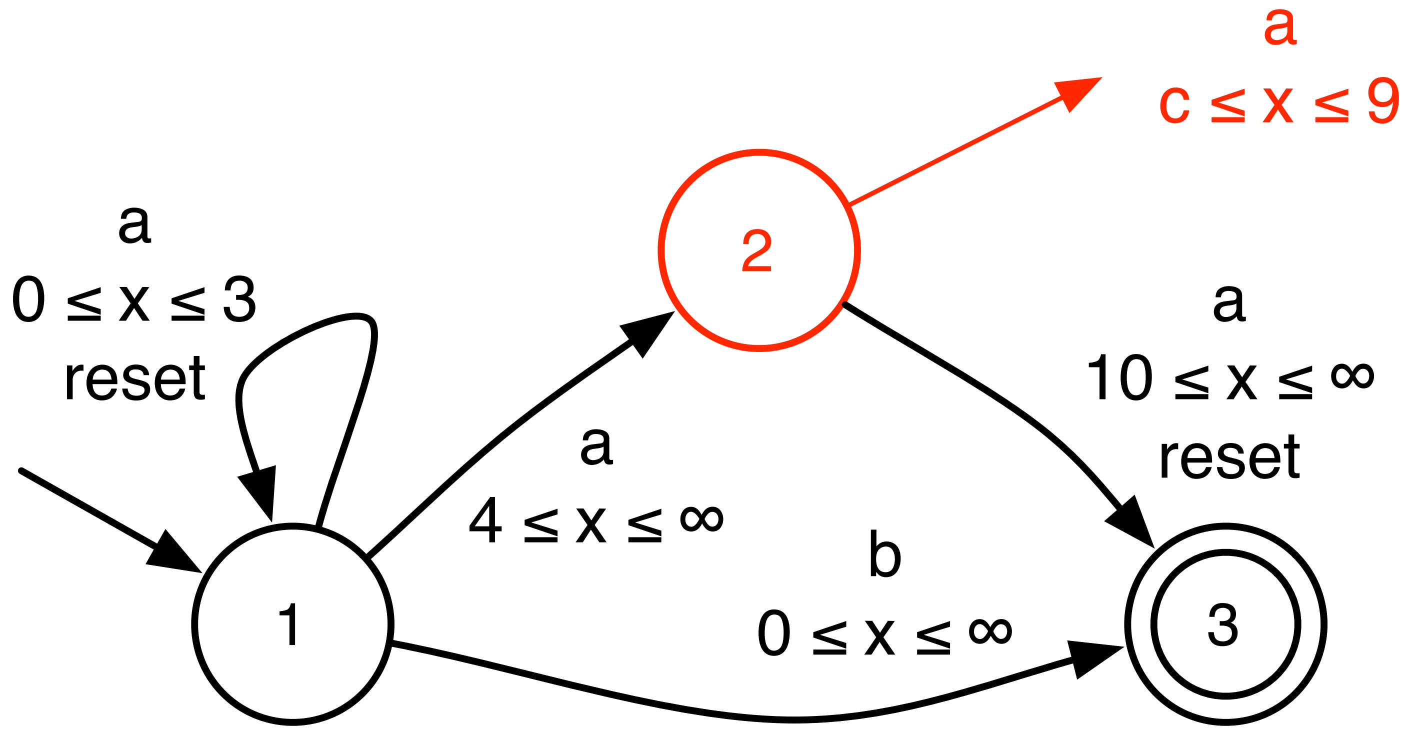


$S_+ \supseteq$ {(a,4)(a,1)(a,3); (a,4)(a,2)(a,2)(b,3)}

$S_- \supseteq$ {(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)}

will potentially use the transition

Learning Example

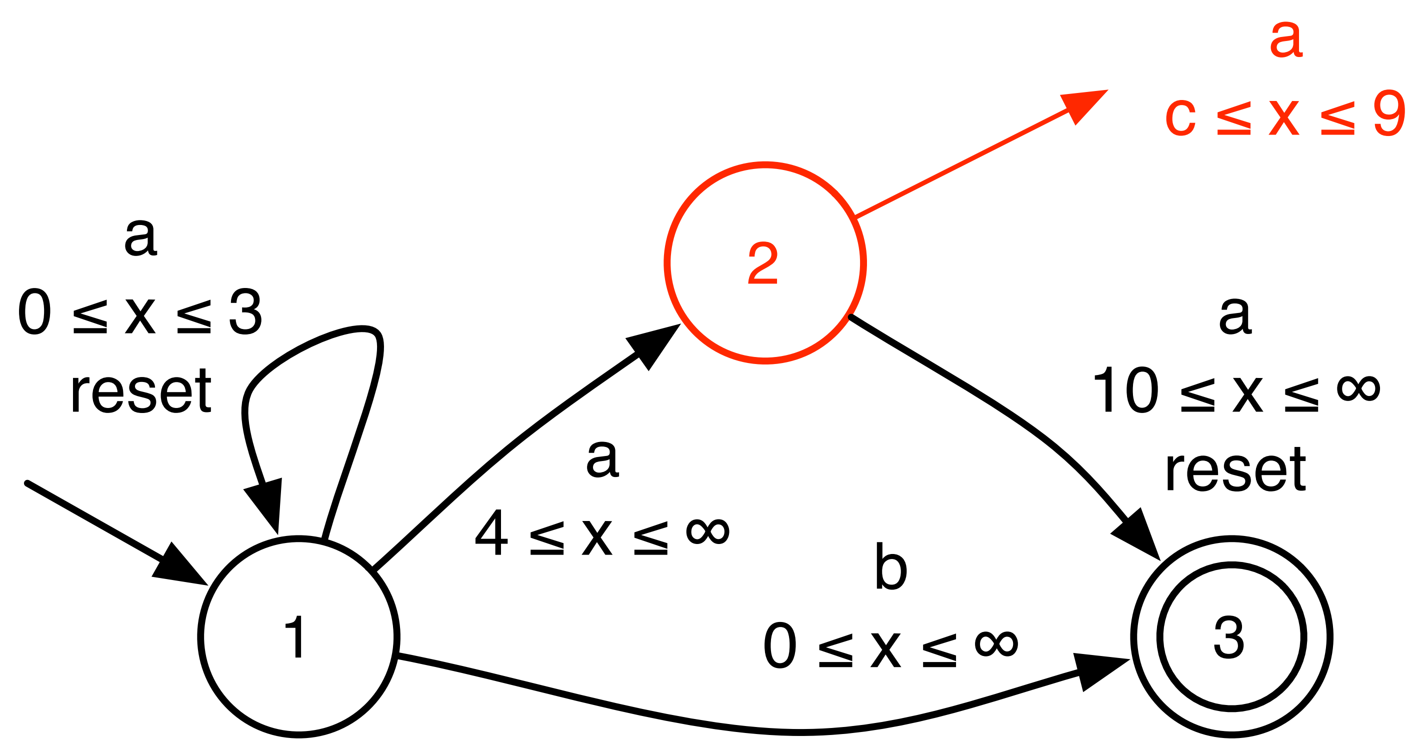


$S_+ \supseteq \{(a,4)(a,1)(a,3); (a,4)(a,2)(a,2)(b,3)\}$

$S_- \supseteq \{(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)\}$

$c \in \{4, 5, 6, 7, 8, 9\}$

Learning Example



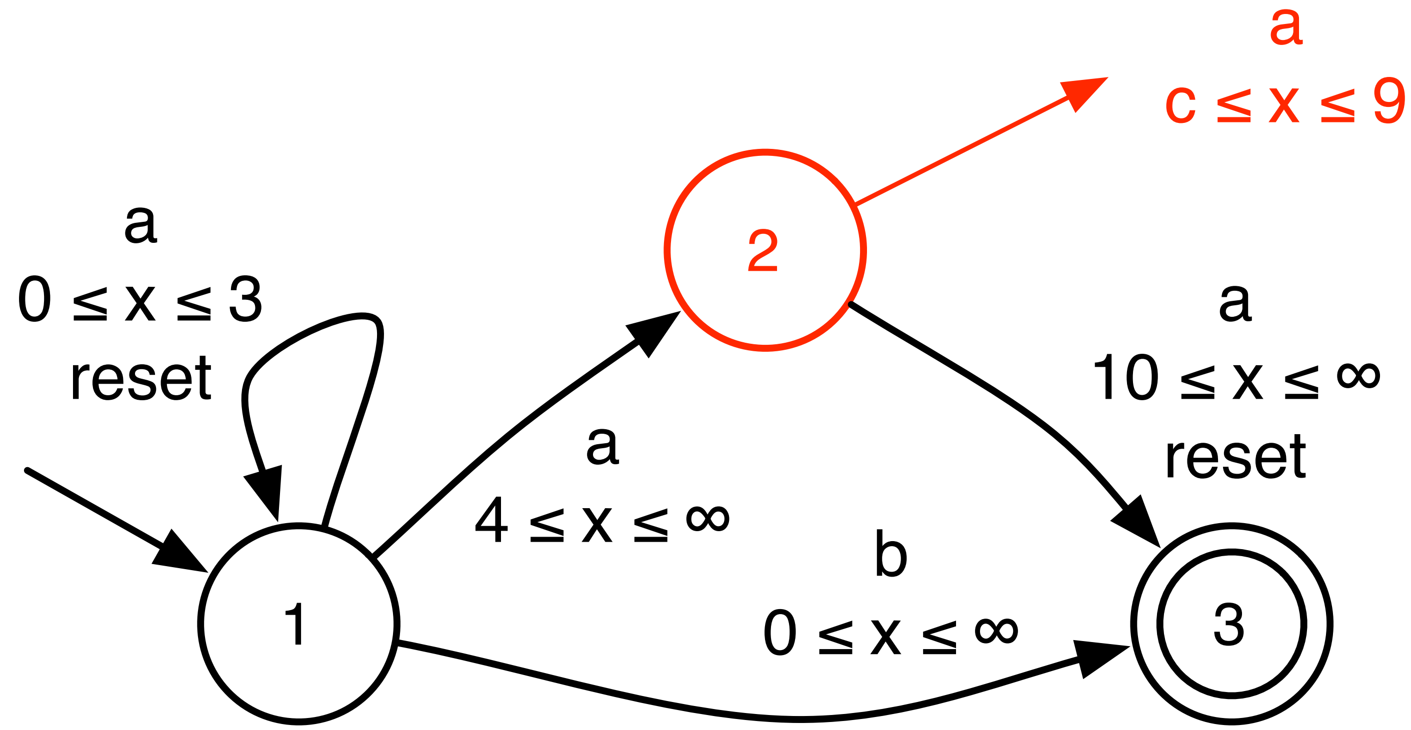
$S_+ \supseteq$ {(a,4)(a,1)(a,3); (a,4)(a,2)(a,2)(b,3)}

$S_- \supseteq$ {(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)}

inconsistency

$c \in \{4, 5, 6, 7, 8, 9\}$

Learning Example

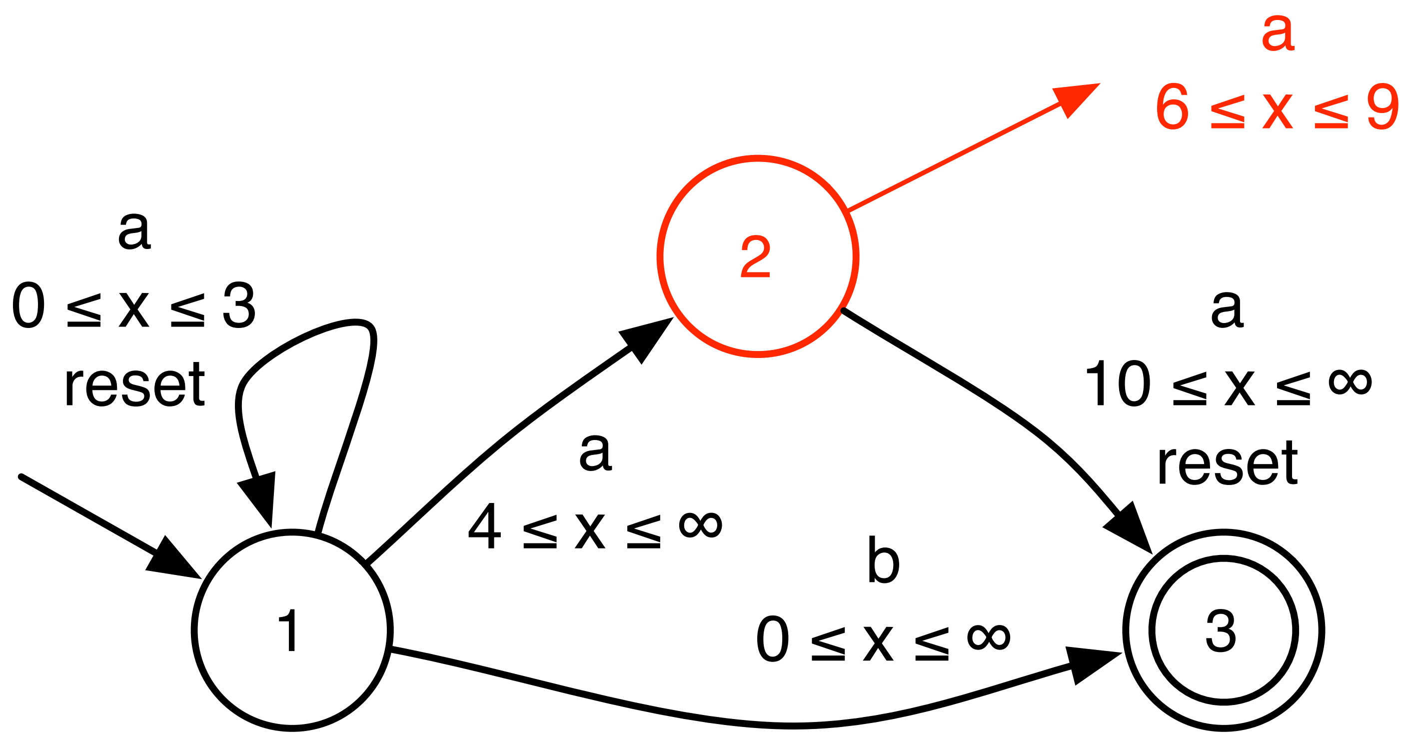


$S_+ \supseteq \{(a,4)(a,2)(a,2)(b,3)\}$

$S_- \supseteq \{(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)\}$

$c \in \{6, 7, 8, 9\}$

Learning Example



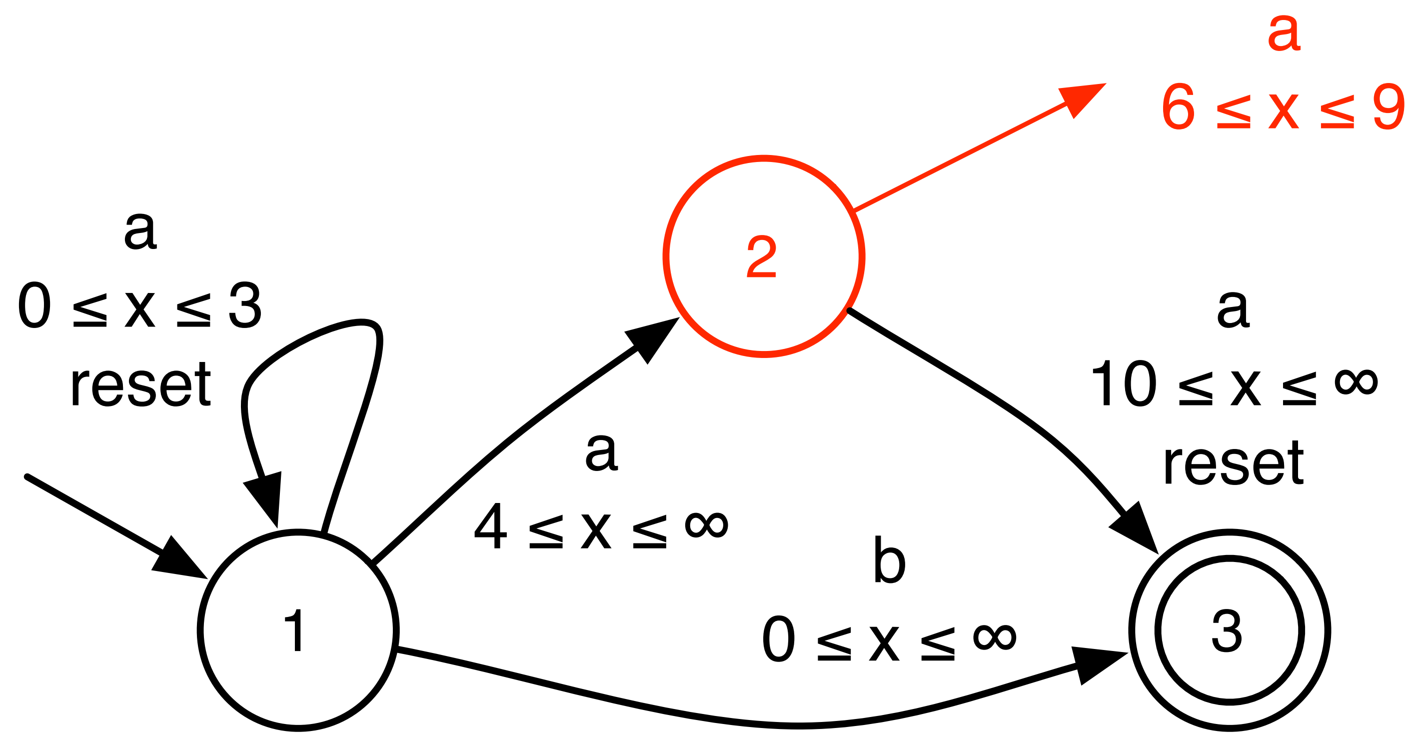
$S_{+} \supseteq \{(a,4)(a,2)(a,2)(b,3)\}$

$S_{-} \supseteq \{(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)\}$

no inconsistency

$c \in \{6, 7, 8, 9\} \rightarrow c = 6$

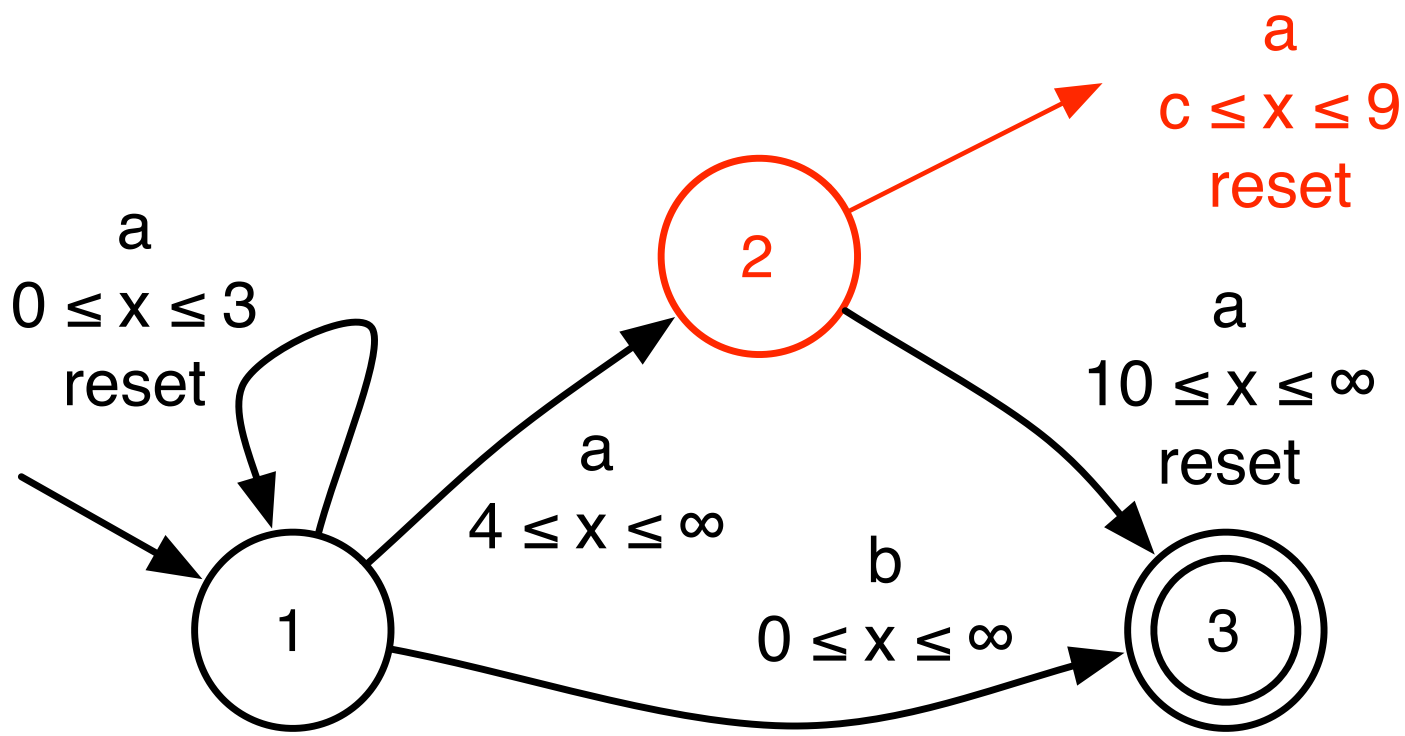
Learning Example



The identified guard is $g = 6 \leq x \leq 9$
if the clock is not reset

Perform the same algorithm for identifying g if the clock is reset

Learning Example



$S_+ \supseteq \{(a,4)(a,1)(a,3); (a,4)(a,2)(a,2)(b,3)\}$

$S_- \supseteq \{(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)\}$

$c \in \{4, 5, 6, 7, 8, 9\}$

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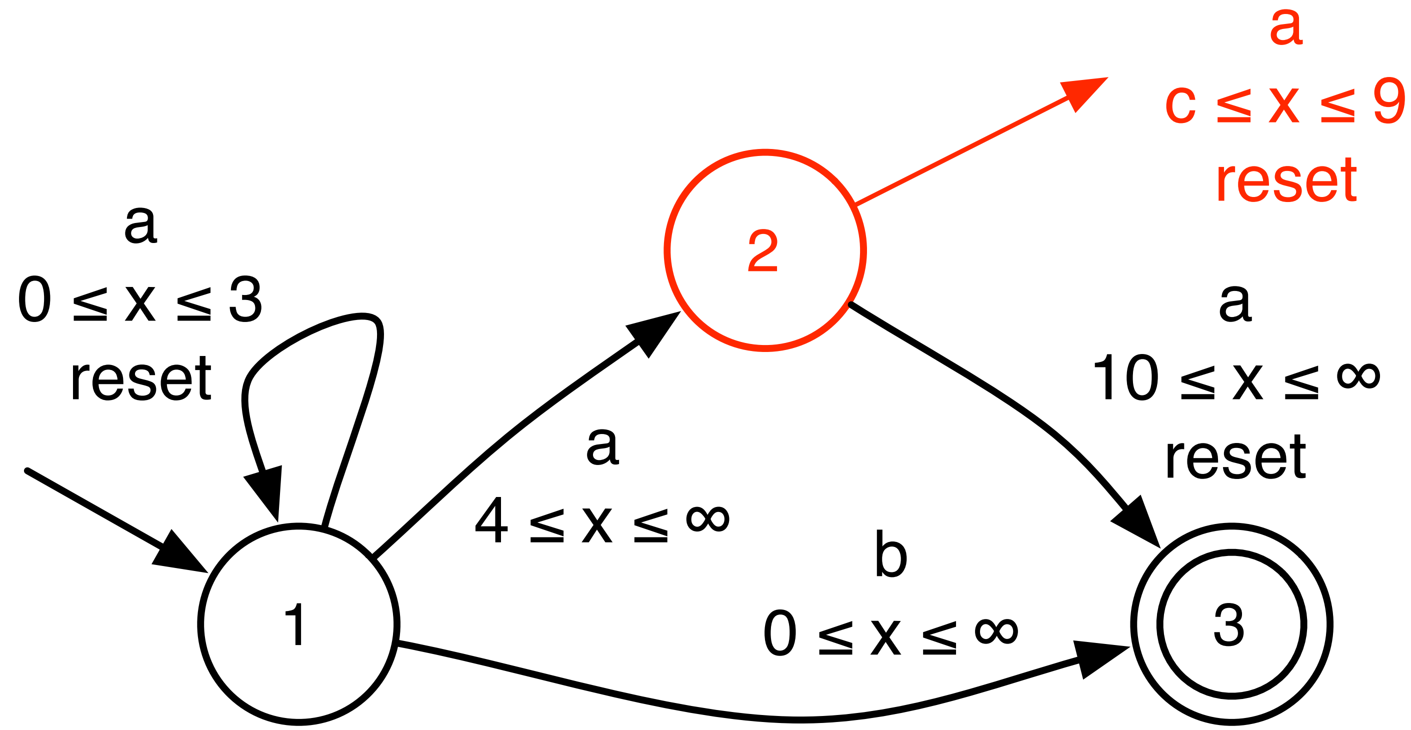
Learning Example



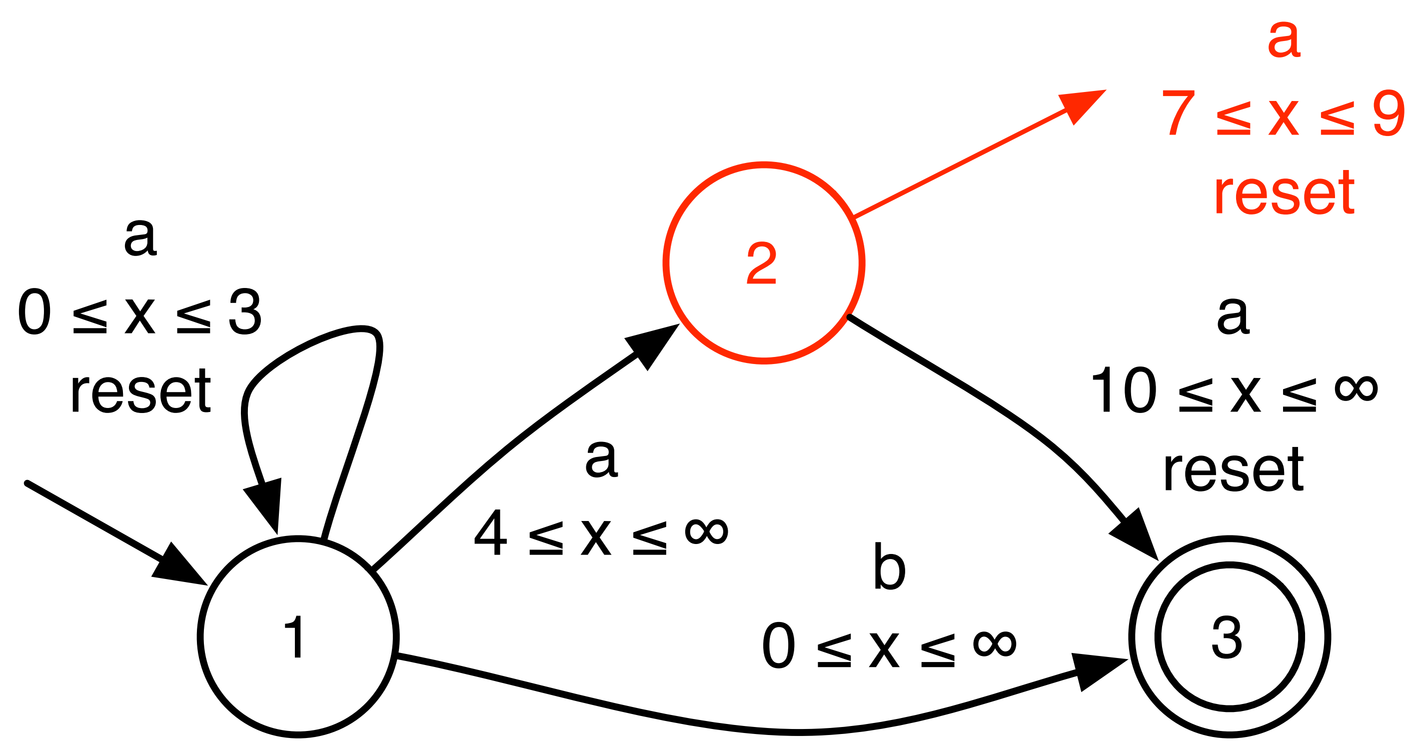
$S_+ \supseteq$ {(a,4)(a,1)(a,3); (a,4)(a,2)(a,2)(b,3)}

$S_- \supseteq$ {(a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)}

inconsistency if the clock is reset

c ∈ {4, 5, 6, 7, 8, 9}

Learning Example



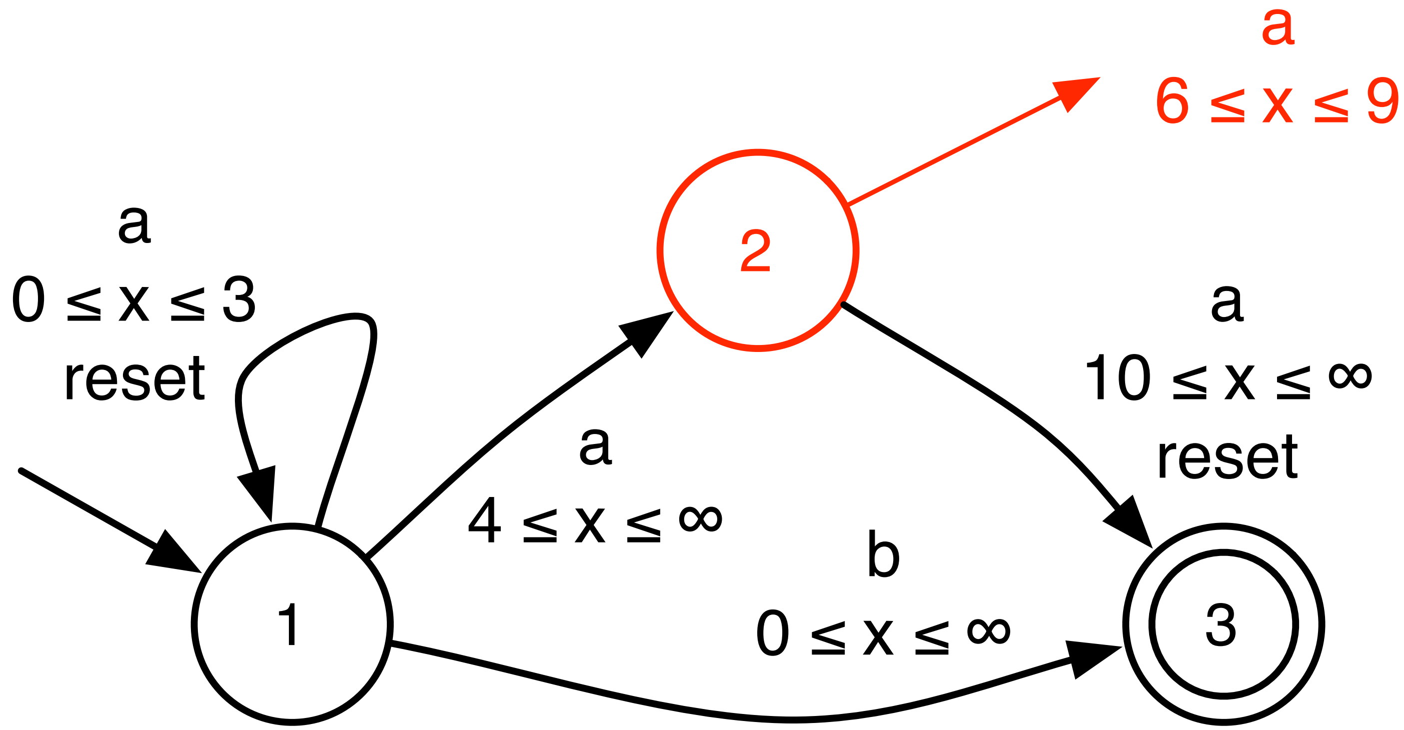
$S_+ \supseteq \{\}$

$S_- \supseteq \{(a,4)(a,3)(a,2)(b,3); (a,5)(a,3)\}$

no inconsistency if the clock is reset

$c \in \{7, 8, 9\} \rightarrow c = 7$

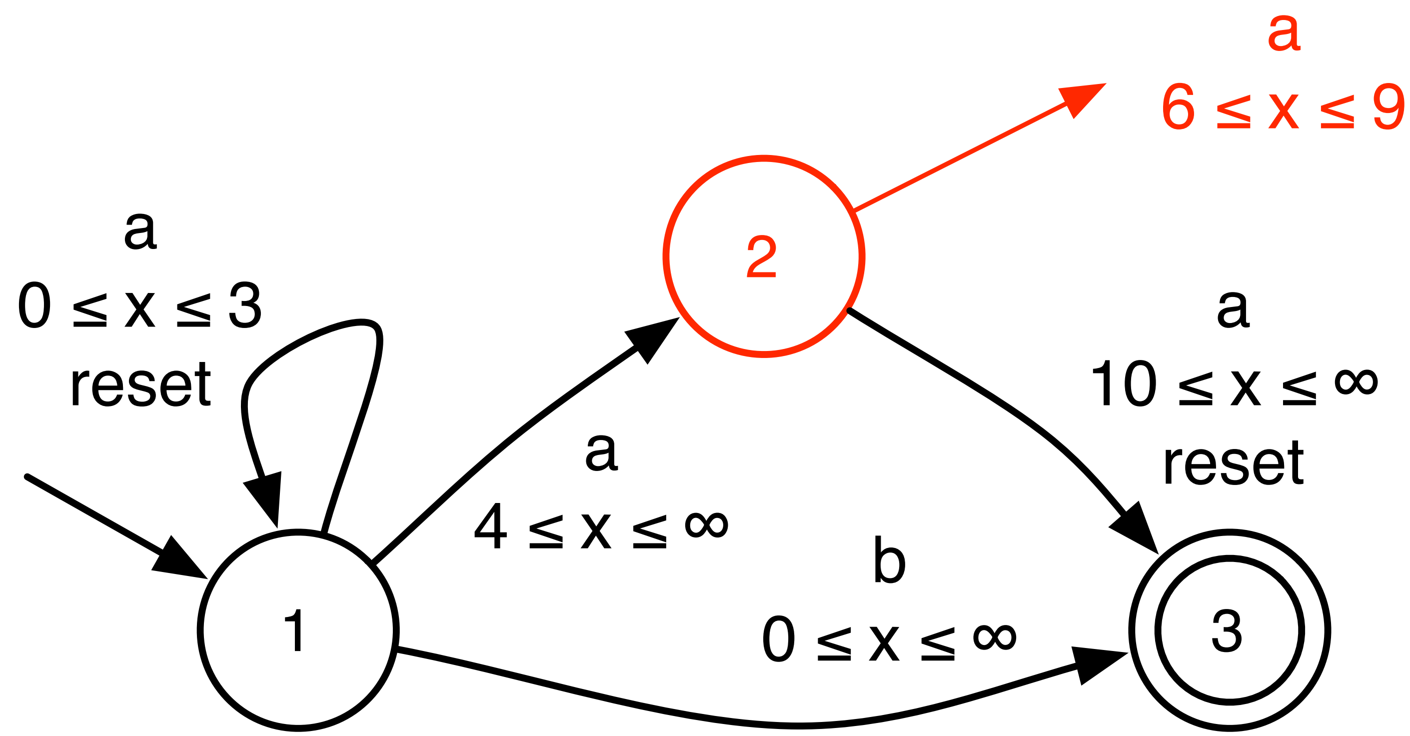
Learning Example



The identified guard is $g = 7 \leq x \leq 9$
if the clock is reset

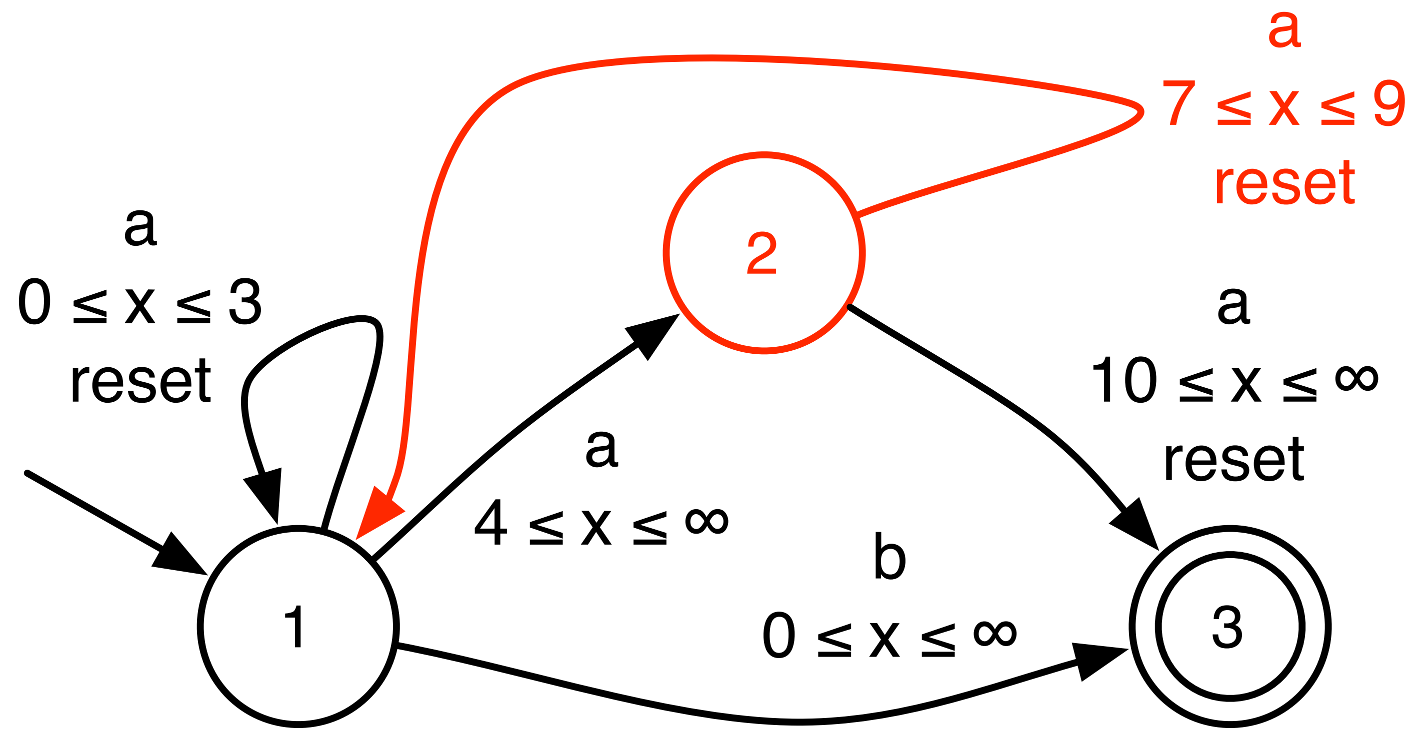
Choose the smallest lower bound:
$g = 6 \leq x \leq 9$ and the clock is not reset

Learning Example



Choose the first consistent target state
(identical to RPNI)

Learning Example



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$S_- \supseteq$ {(a,3)(a,10); (a,4)(a,2)(a,2); (a,4)(a,3)(a,2)(b,3); (a,5)(a,3)}

no inconsistency if q' = 1

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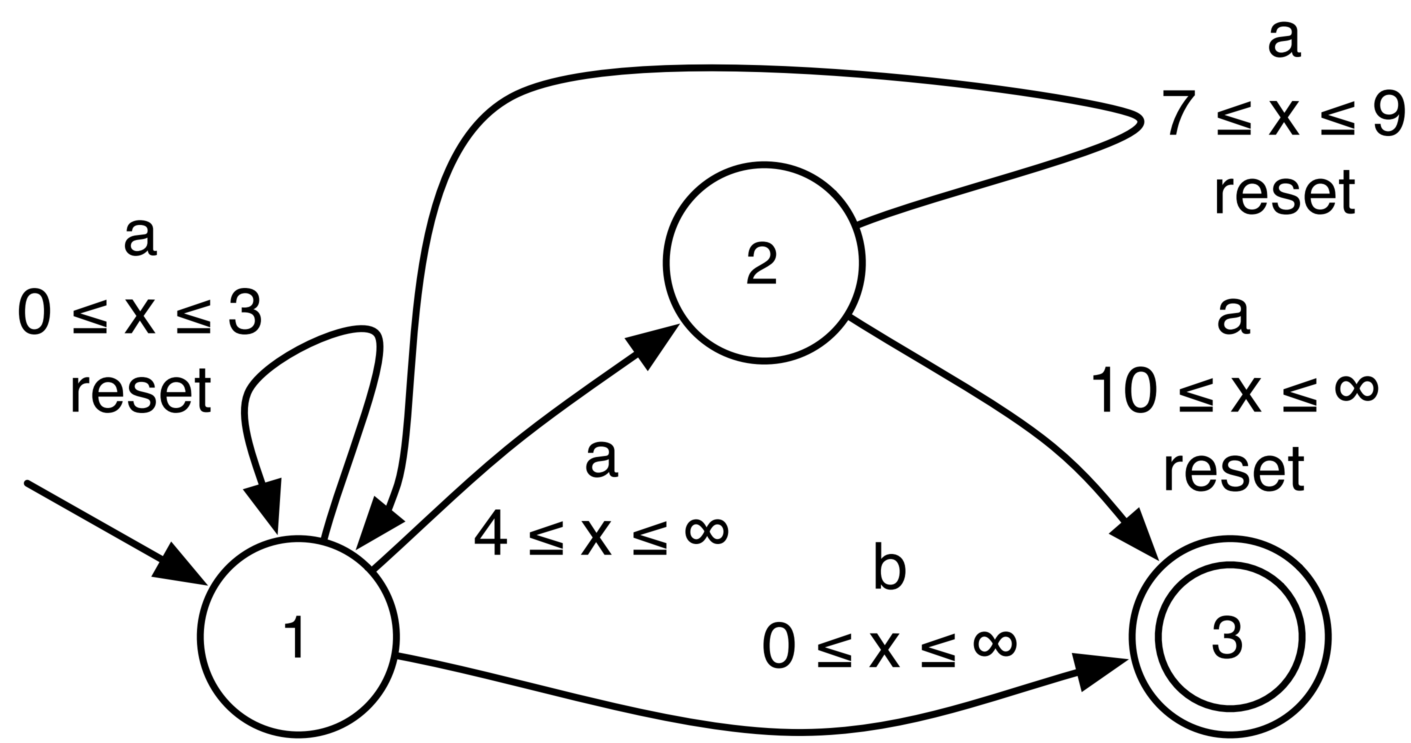
Learning Example



We identify:

<q = 2, q' = 1, s = a, r = false, g = 6 ≤ x ≤ 9>

and iterate

Learning 1-DTAs

- Identify transitions in a fixed order
- Use data to determine the smallest consistent clock guard and clock reset
- Use data to determine the first consistent target state, like RPNI
- Iterate until no new transitions can be identified

Properties

- The algorithm is polynomial time because:
  - Identifying a single transition takes polynomial time
  - Every transition is fired by at least one string
- Identifying a 1-DTA requires polynomial data because:
  - Inconsistent pairs exist for every incorrect decision
  - 1-DTAs are polynomially distinguishable, hence:
    - The inconsistent pairs are of polynomial length
    - Reaching all possible behaviors of a 1-DTA requires a polynomial number of transitions

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Learning 1-DTAs

- Theorem:
  - 1-DTAs are efficiently identifiable in the limit

Conclusions

- DTAs are an intuitive representation for real-time systems
- They are more compact (efficient) than DFA or HMM representations of the same systems
- Unfortunately, DTAs can in general not be identified efficiently
- 1-DTAs are efficiently identifiable in the limit, and still a lot more compact than DFAs or HMMs

Future work

- Find classes of DTAs with multiple clocks that are polynomially distinguishable
- Determine whether DTA learning algorithms exist that identify DTAs efficiently in the size of the smallest 1-DTA representation
- See whether this algorithm and the theorems are useful in other settings, such as model checking or system testing
- Write an evidence driven variation of this algorithm and test it on real data

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