LearnLib Tutorial

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fakultät für informatik
lehrstuhl für programmiersysteme

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Organization

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Outline

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Motivation

Aim of this tutorial ...

- introduce (some of) the theory behind active automata learning
- discuss what are the key challenges when using active automata learning in practice
- motivate the TTT algorithm, which is the only algorithm to properly address the problem of long counterexamples
- give an overview of LearnLib

Outline

High-Level Overview

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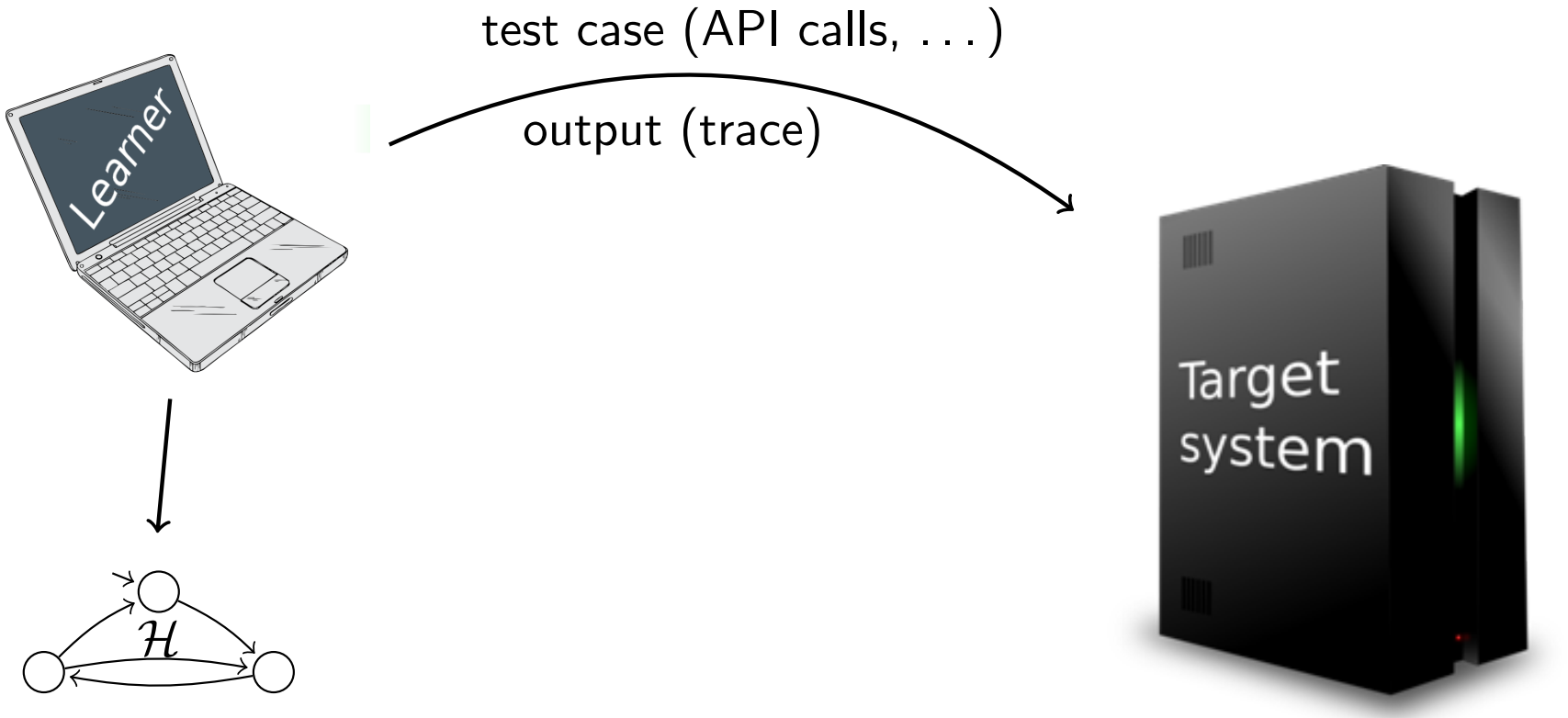
test case (API calls, . . .)

output (trace)

High-Level Overview



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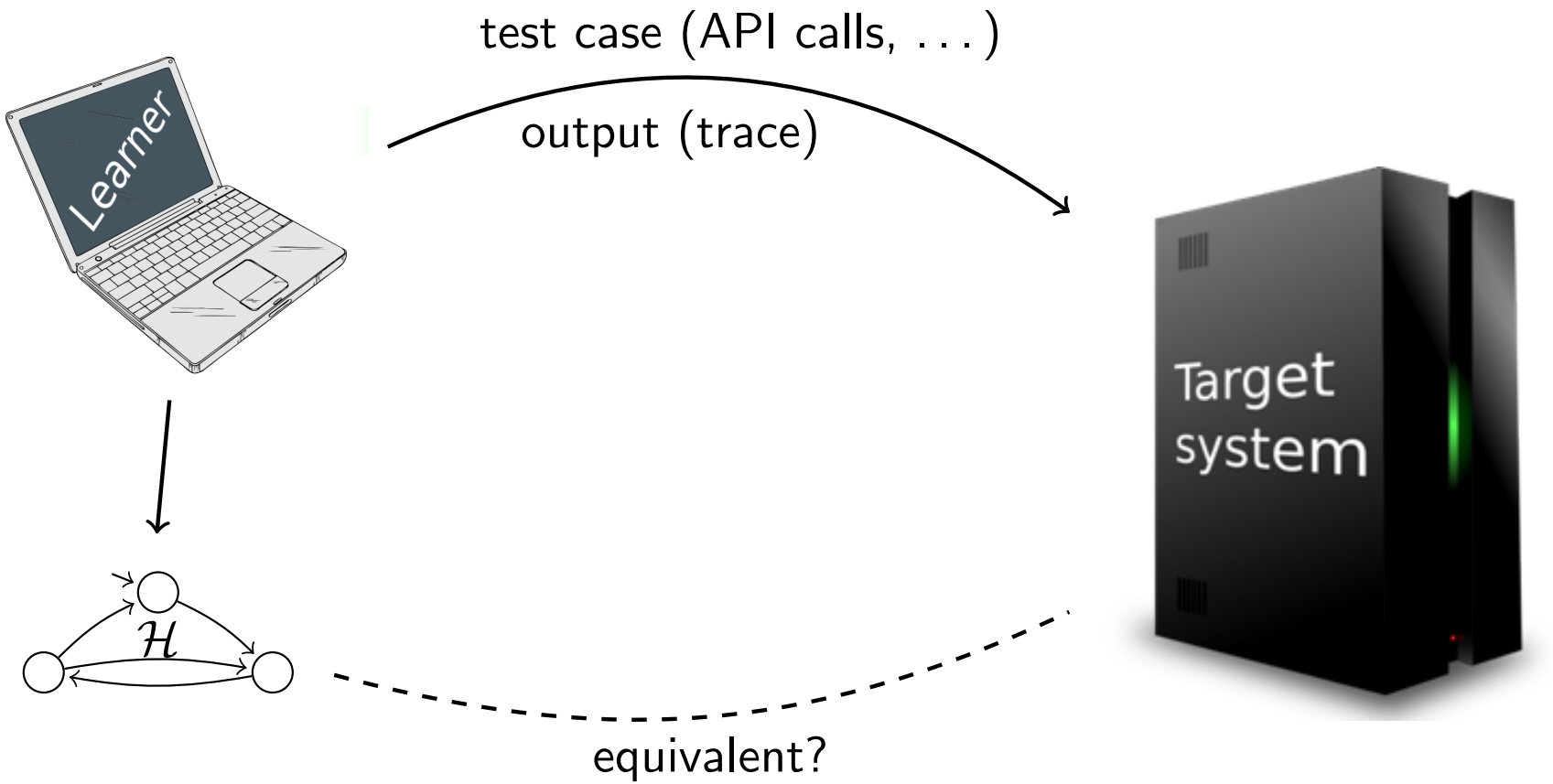

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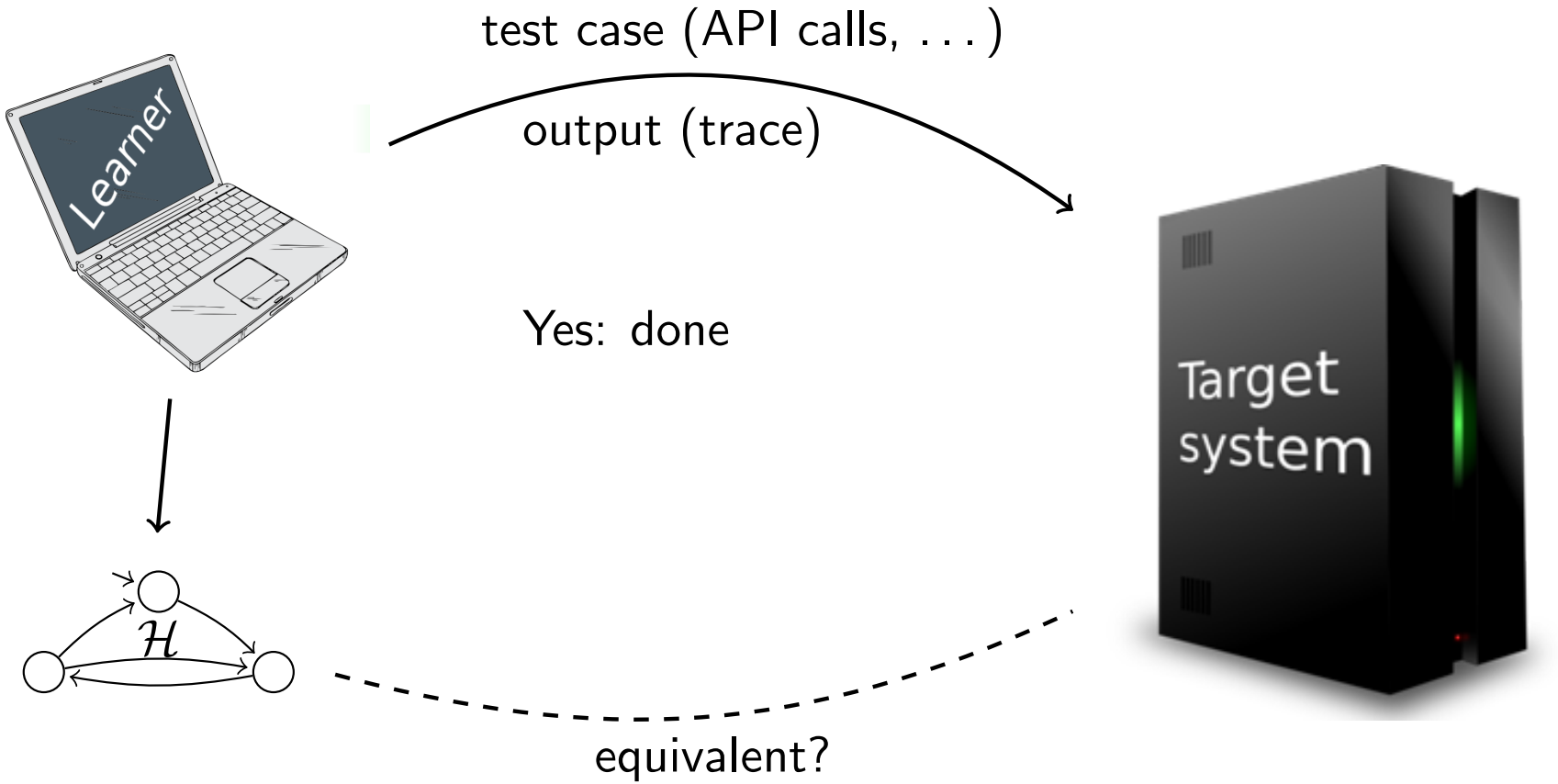

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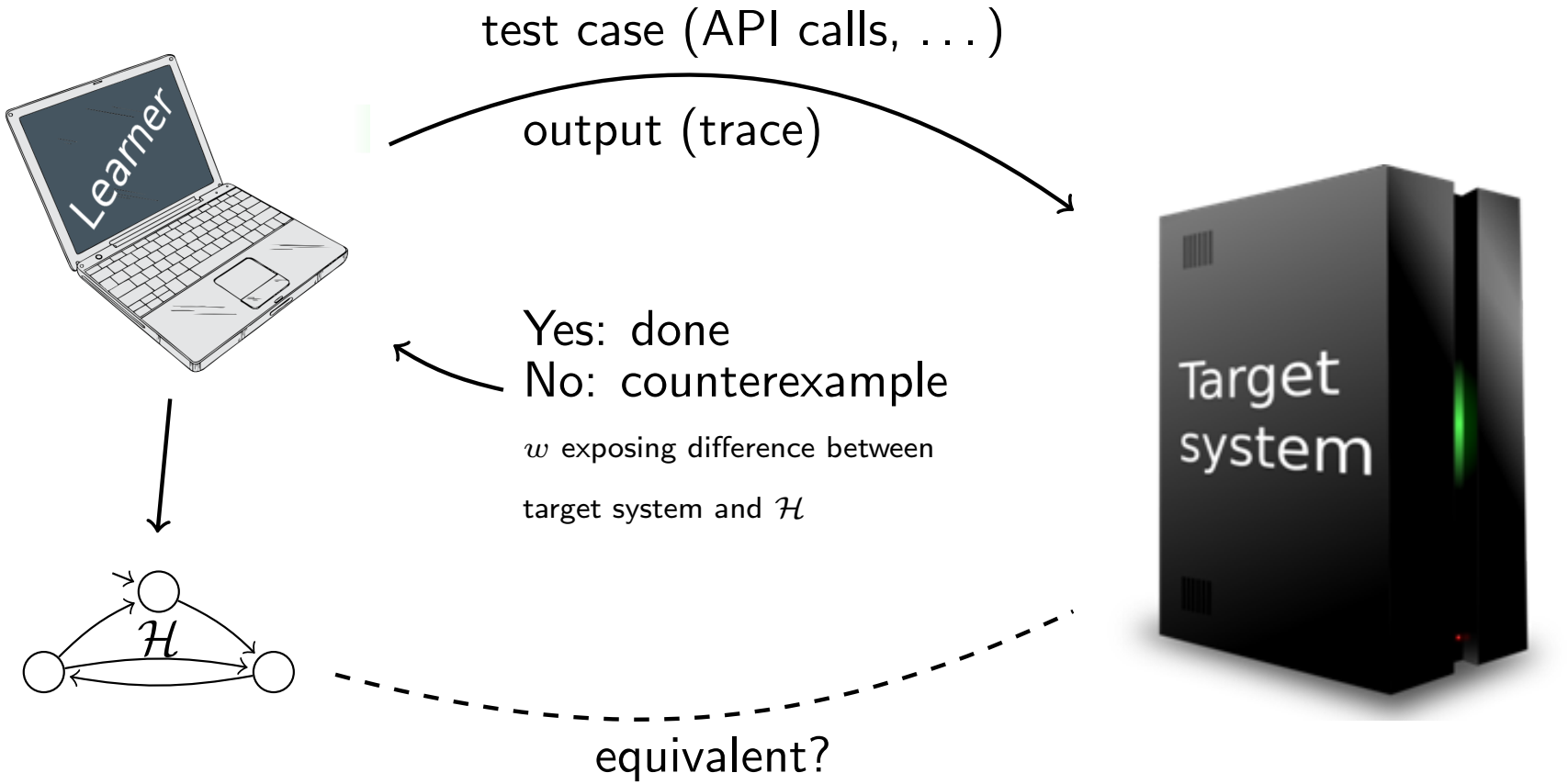

Active Automata Learning

- Active Automata Learning: Construct (behavioral) models of (black-box) systems via testing
  - Typically: finite-state models (DFAs or Mealy machines)
  - "Inverse" of model-based testing: test-based modeling!

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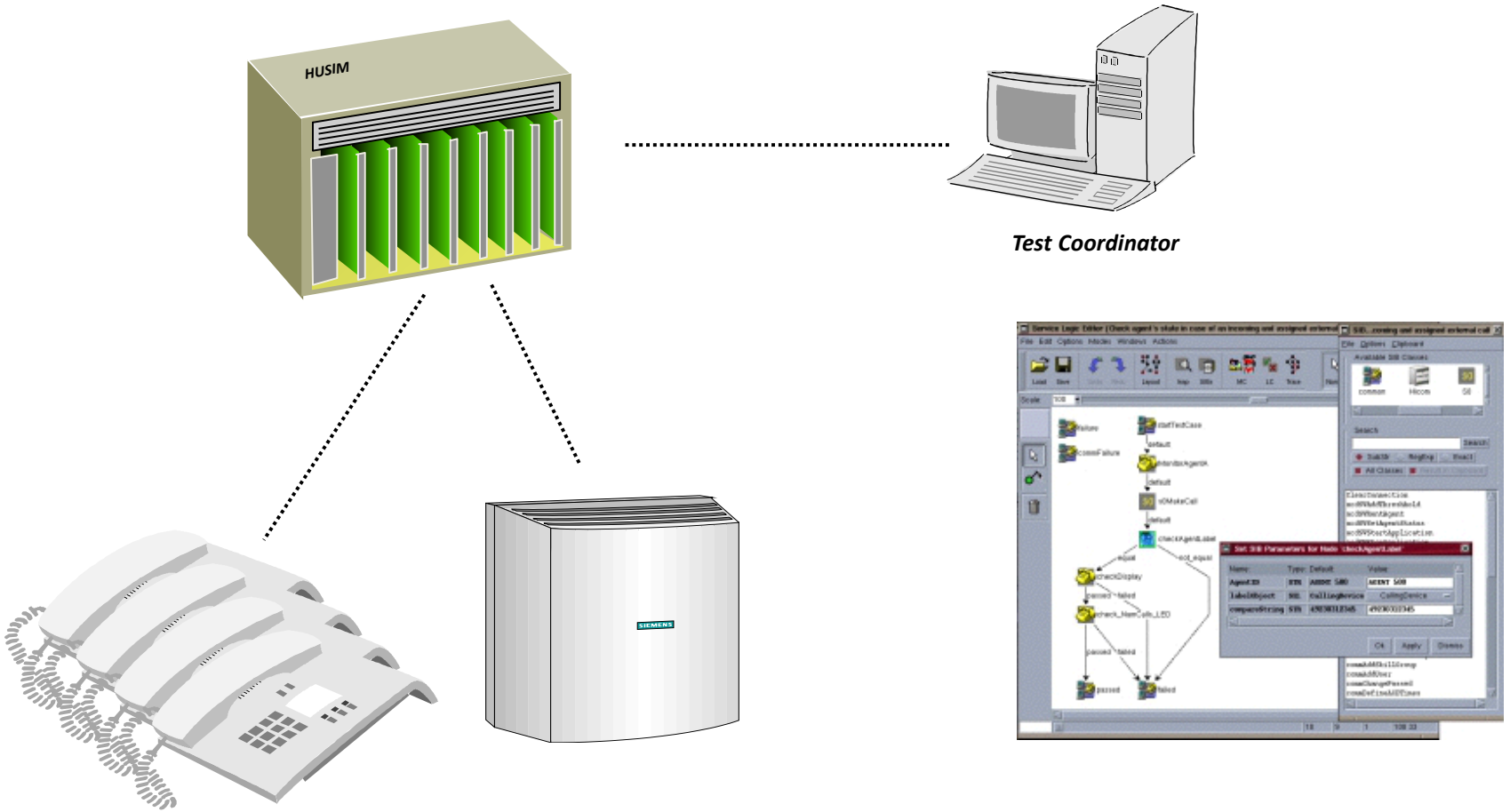
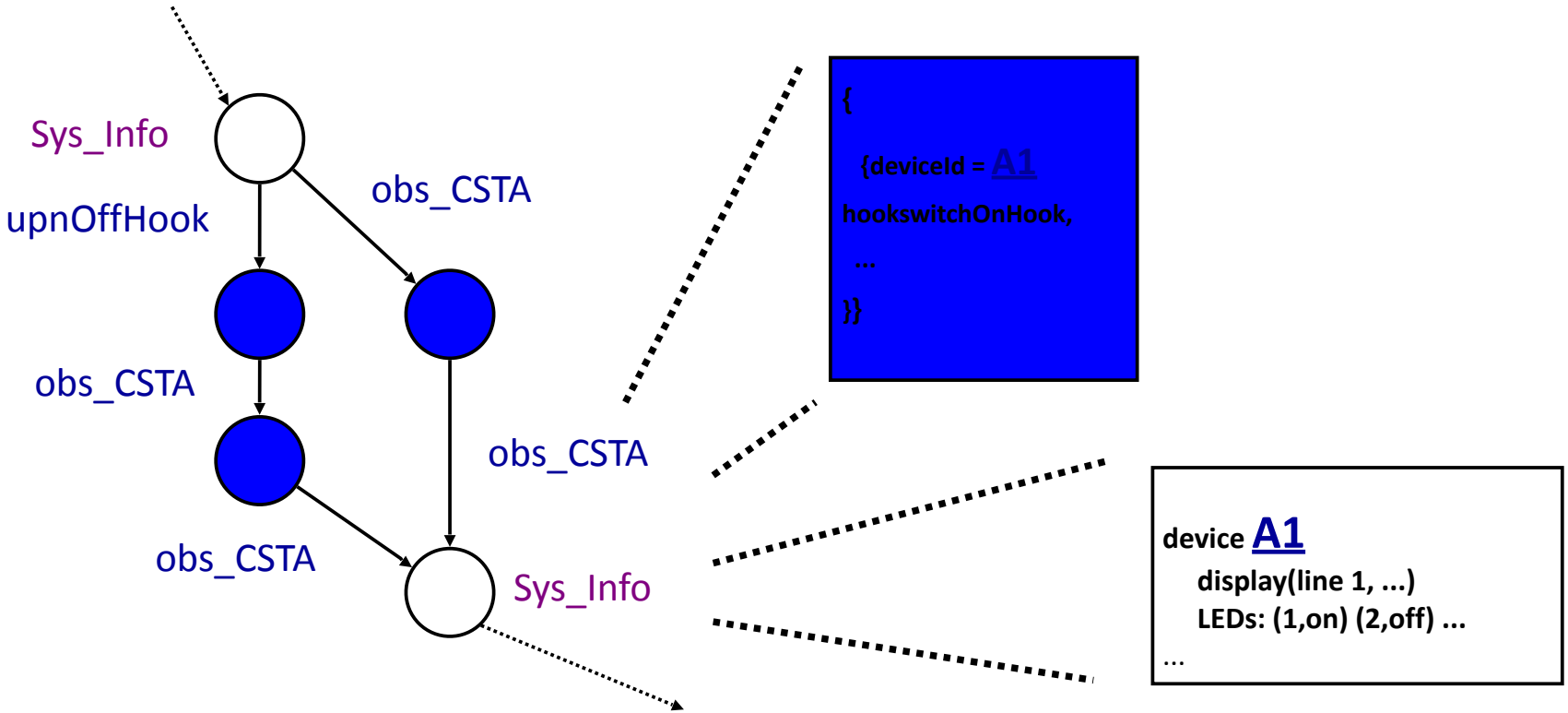
So what is this good for?

Testing Telephony Systems



- Hungar, Magaria, Steffen: Test-Based Model Generation for Legacy Systems (ITC 2003)

Testing Telephony Systems (2)



(small) learned models imposed
major test suite optimizations

Another Application: Learning Models of

Smenk, Moerman, Jansen, Vaandrager: Applying Automata Learning to Embedded Control Software (ICFEM 2015)

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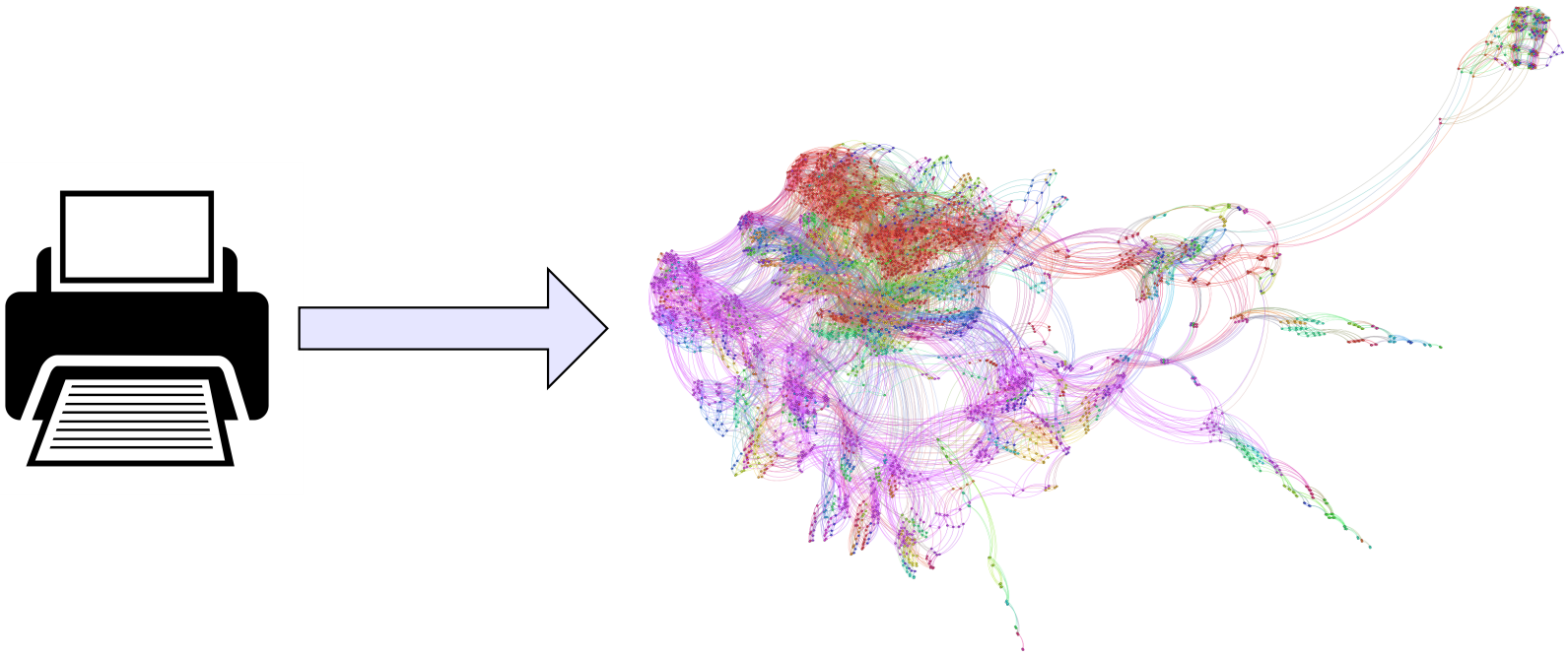

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Lots and Lots of Applications, Actually ...

- Black-box model checking [Peled *et al.*, FORTE'99]
- Test-case generation [Hagerer *et al.*, FASE'02]
- Assume-guarantee style compositional verification [Cobleigh *et al.*, TACAS'03]
- Interface synthesis [Alur *et al.*, POPL'05; Giannakopoulou *et al.*, SAS'12]
- Botnet analysis [Cho *et al.*, CCS'10]
- Connector synthesis [Issarny *et al.*, 2009]
- GUI testing [Choi *et al.*, OOPSLA'13]

Restrictions: System Requirements

What are the restrictions for applying active automata learning?

- Finite input alphabet Σ
- Finite-state ("regular") control structure
- Determinism
- Ability to reset
  - $\Rightarrow$ independence of subsequent membership queries

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Most of the above: matter of choosing the right abstraction!

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What kind of models can be learned?

- Mealy machines [Niese 2003; Shahbaz&Groz 2009]
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- Mealy machines [Niese 2003; Shahbaz&Groz 2009]
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- Classical formulation: DFAs [Angluin 1987]
  - Allows for simpler presentation
  - Adaption to Mealy machines pretty straightforward

Technical Realization: Setup

Assumption: the behavior of the target system is modeled by a DFA $\mathcal{A}$

- Membership Queries ask if a word $w \in \Sigma^*$ is accepted by $\mathcal{A}$
- Notation: $\lambda(w) = 1$ iff w is accepted by $\mathcal{A}$ (otherwise 0) (λ: "output function")

$\Rightarrow$ Membership query $\hat{=}$ λ-evaluation

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- Represent states of $\mathcal{A}$ by words $u \in \Sigma^*$ reaching them
  - Notation: $\mathcal{A}[u] \mathrel{\hat{=}}$ state in $\mathcal{A}$ reached by u
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  - Set $\mathcal{U} \cdot \Sigma$ of "long prefixes"
- States $\mathcal{A}[u]$ and $\mathcal{A}[u']$ are (observably) different iff $\lambda(u \cdot v) \neq \lambda(u' \cdot v)$ for some $v \in \Sigma^*$
  - v called distinguishing suffix (for u and u')
  - challenge: finding distinguishing suffixes (cannot search through the whole of Σ^*)

Realization: Observation Table

Data structure of L* (and similar algorithms): Observation Table

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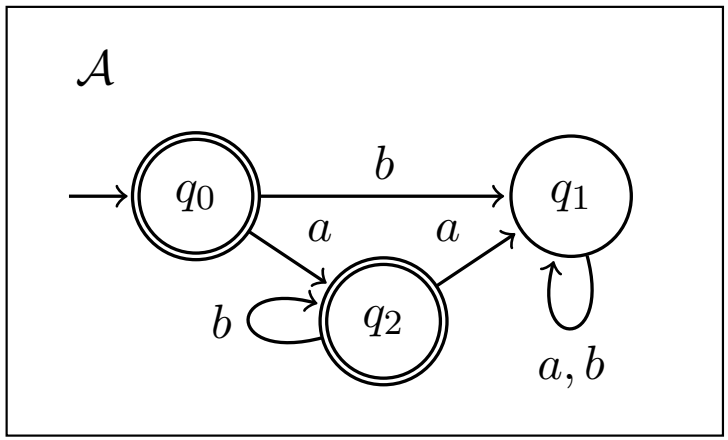

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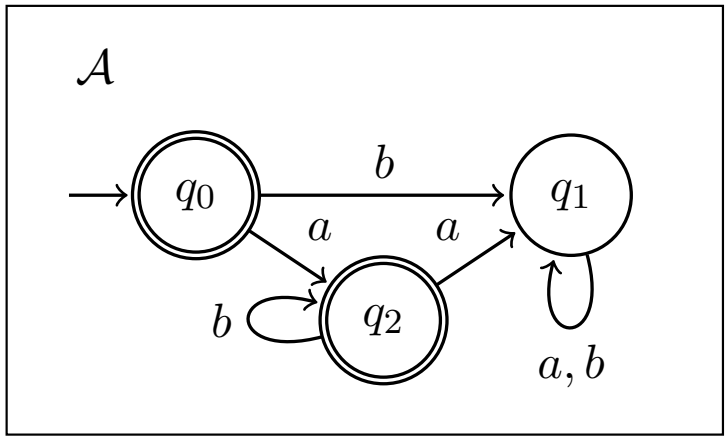

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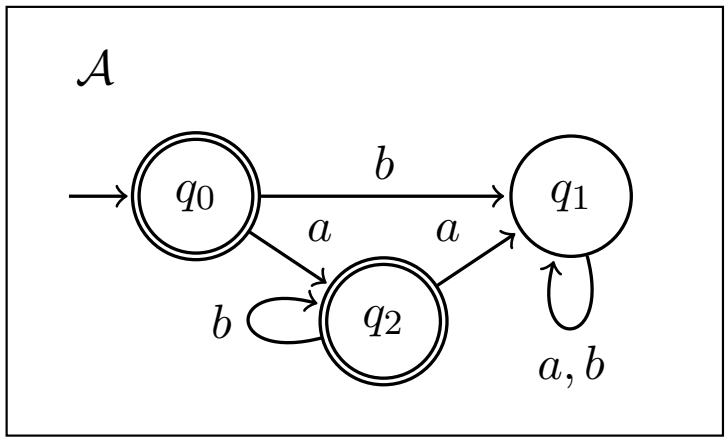

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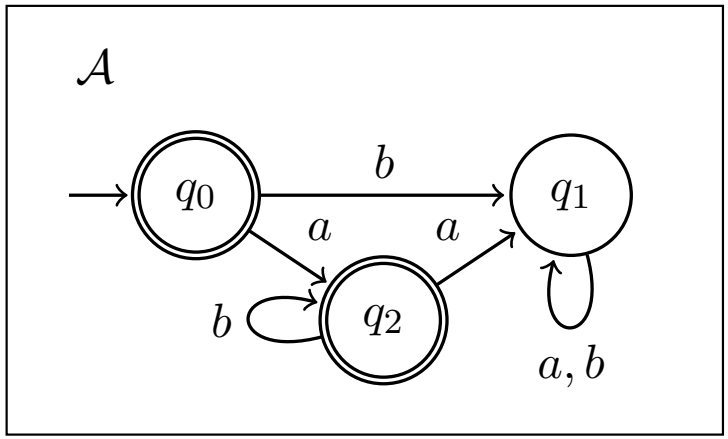

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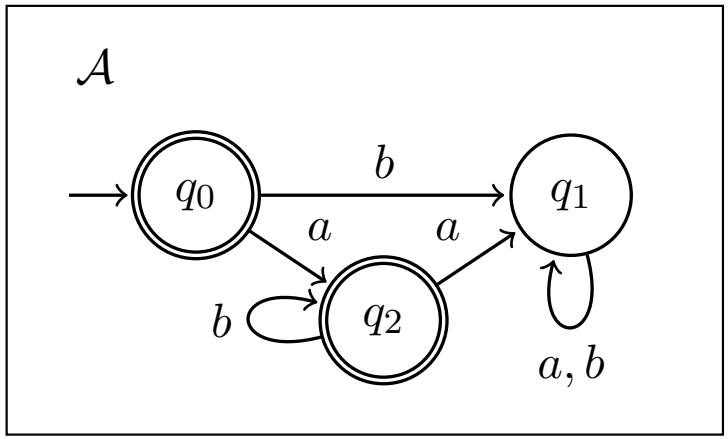

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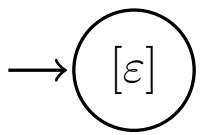
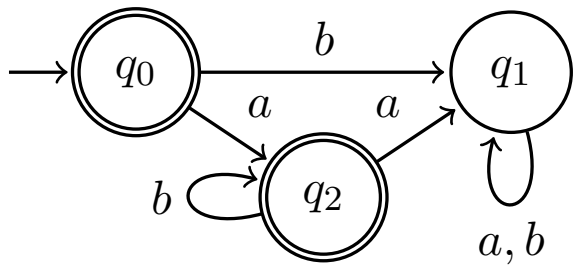


$\mathcal{A}$



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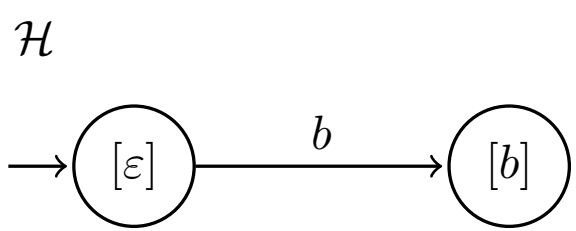

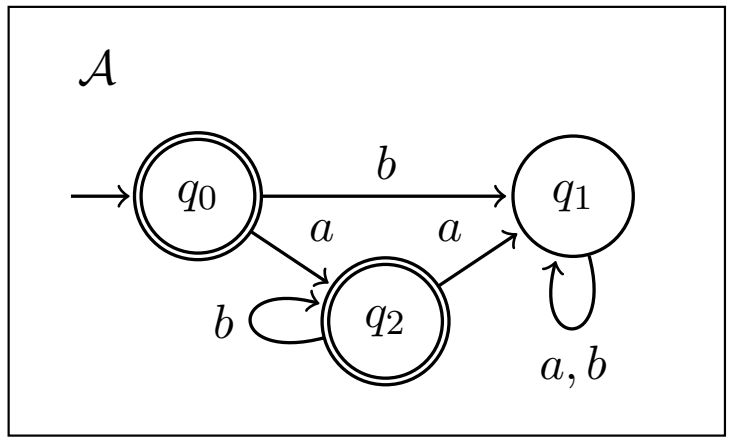

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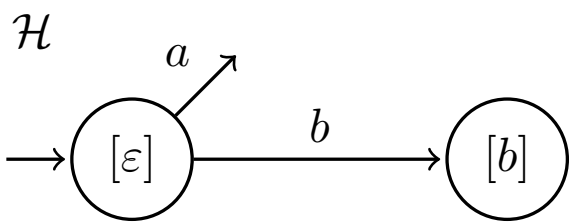

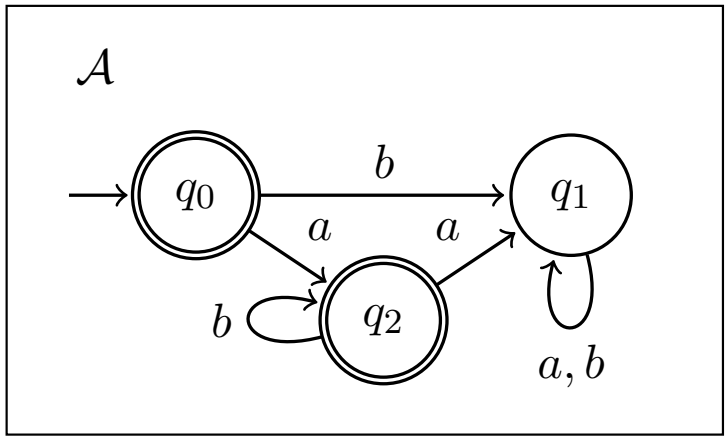

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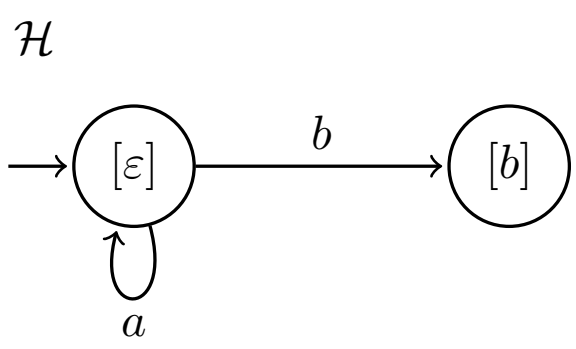

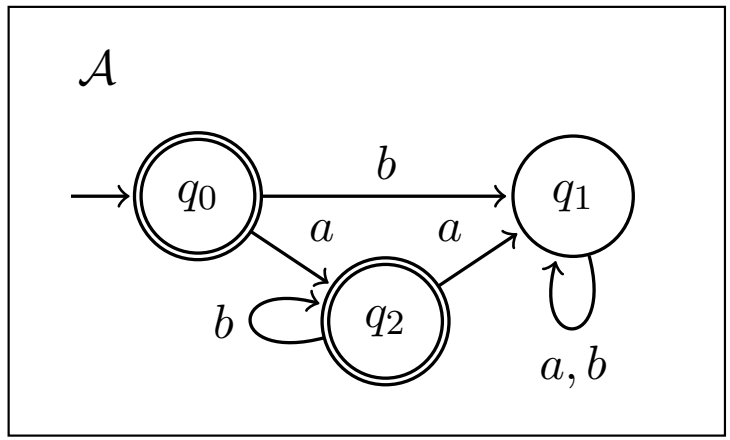

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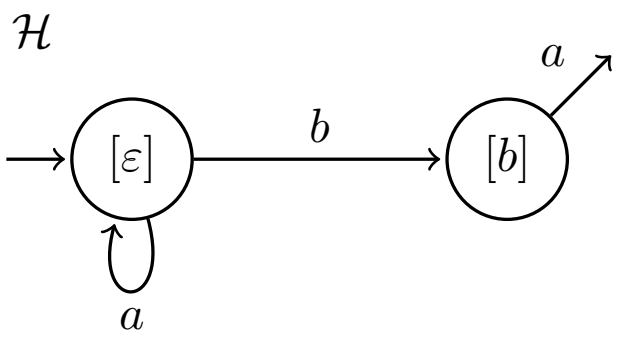

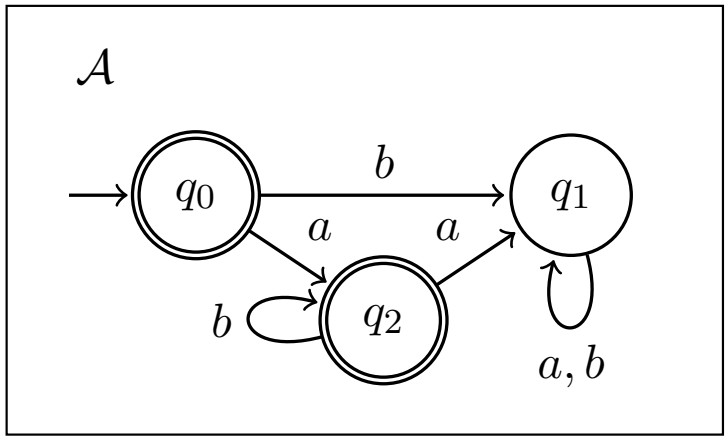

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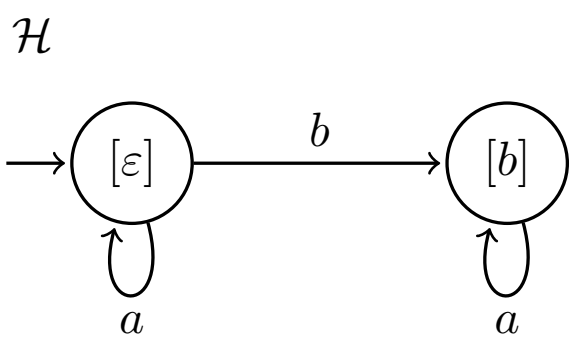

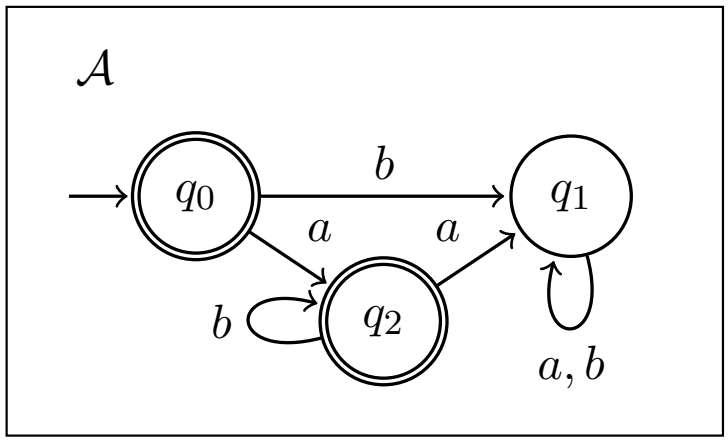

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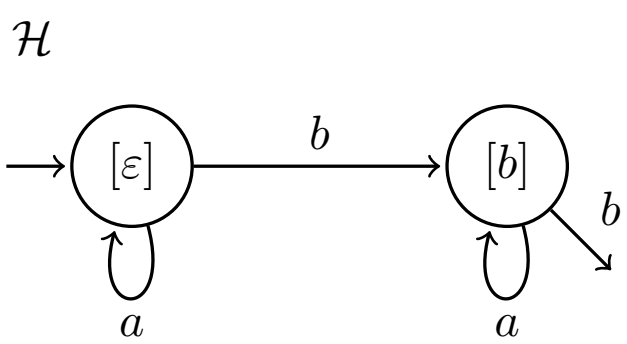

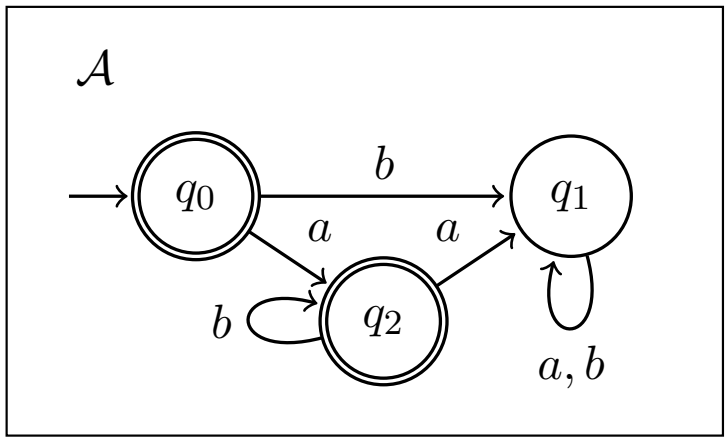

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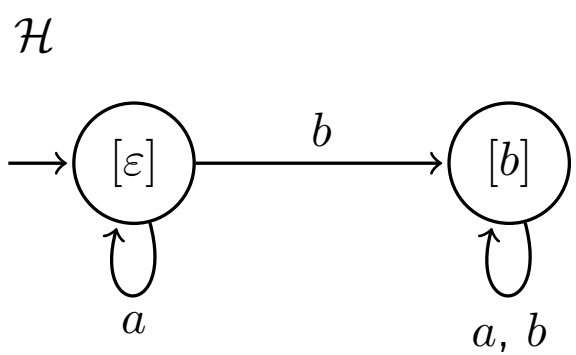

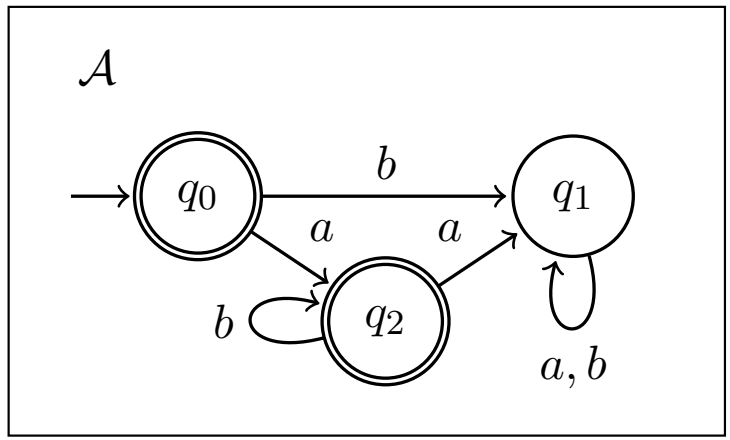

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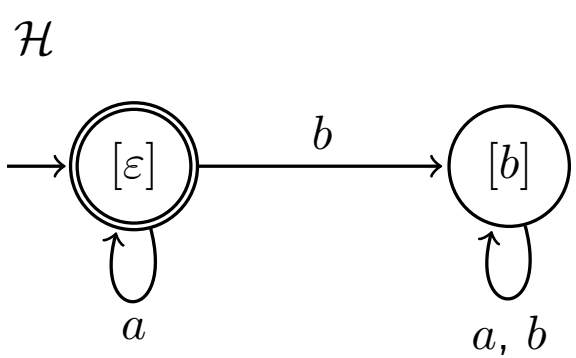

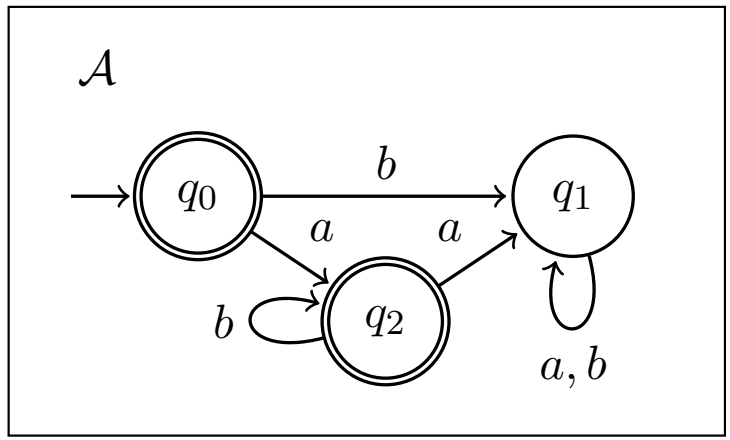

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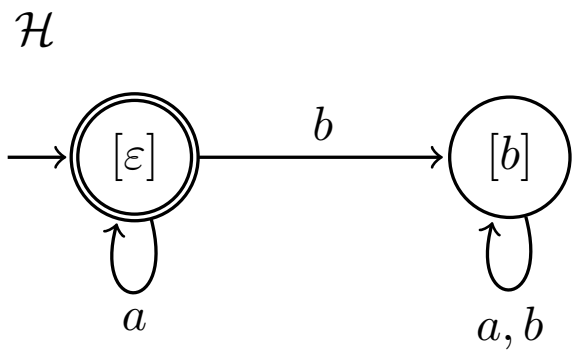
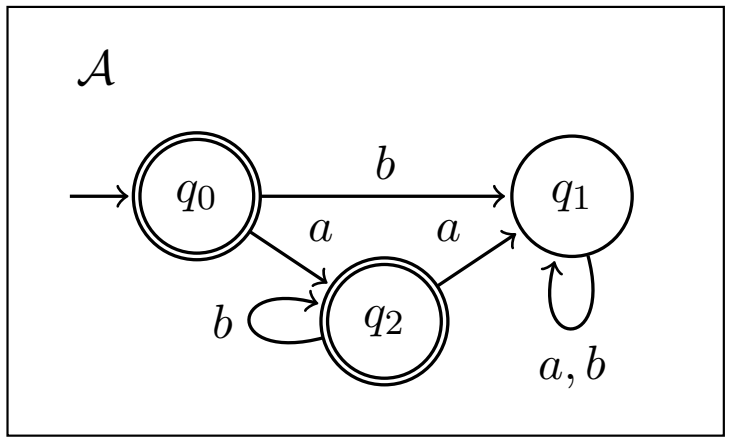
- Cell contents (row u, col. v): $\lambda(u \cdot v)$

Refinement

	ε
ε	1
b	0
a	1
ba	0
bb	0





- $\mathcal{H}$ and $\mathcal{A}$ not equivalent!

Refinement

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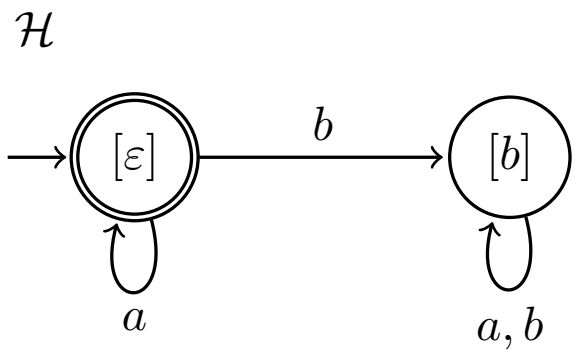
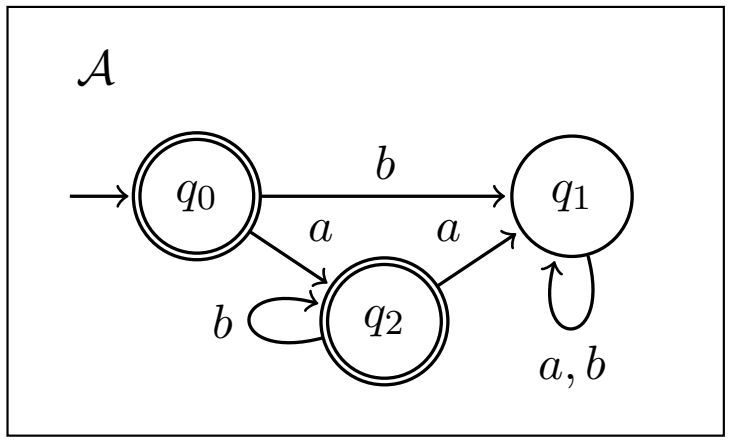
b	0
a	1
ba	0
bb	0





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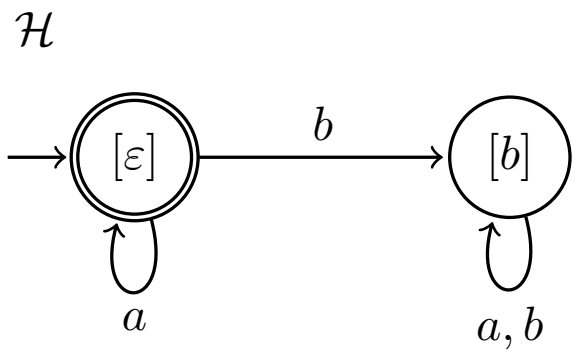

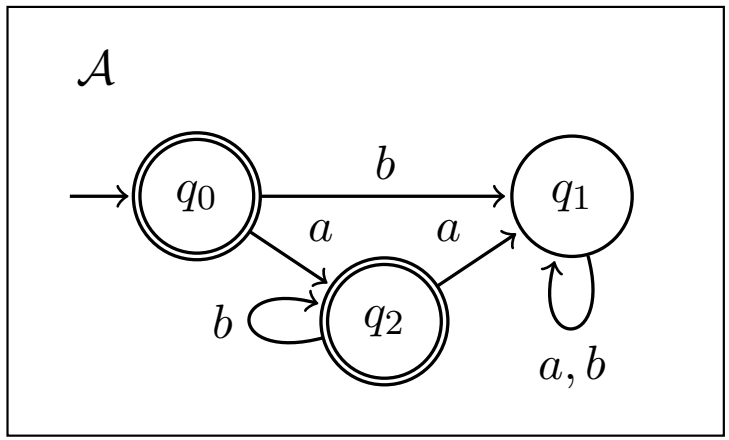

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a	1	
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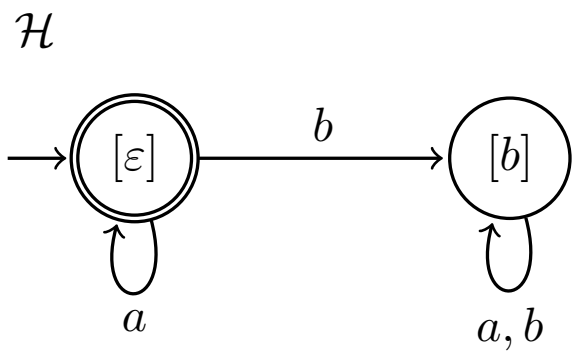
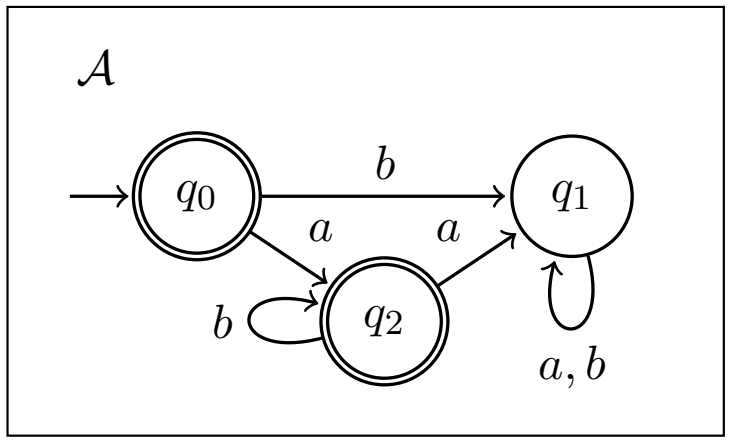
bb	0	





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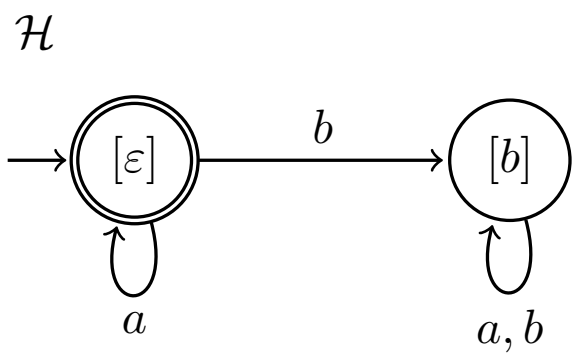

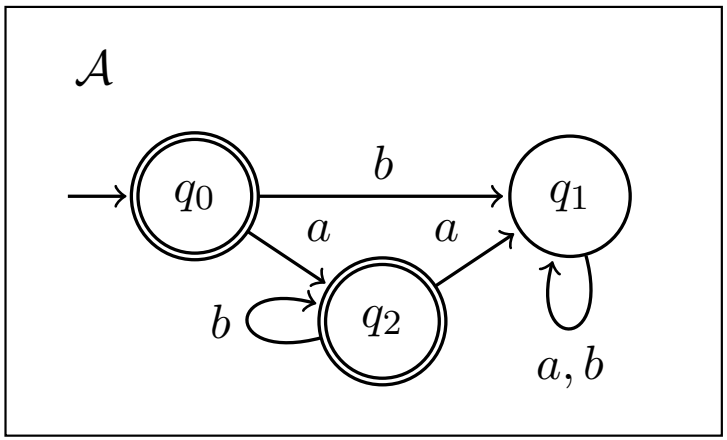

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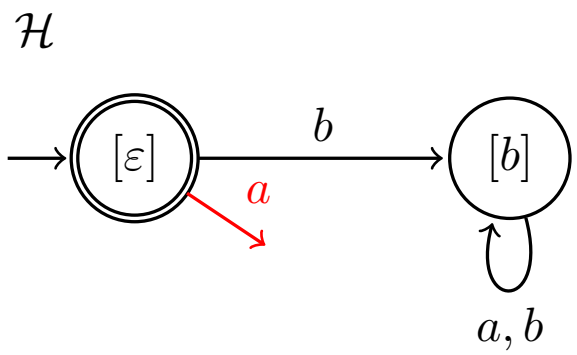

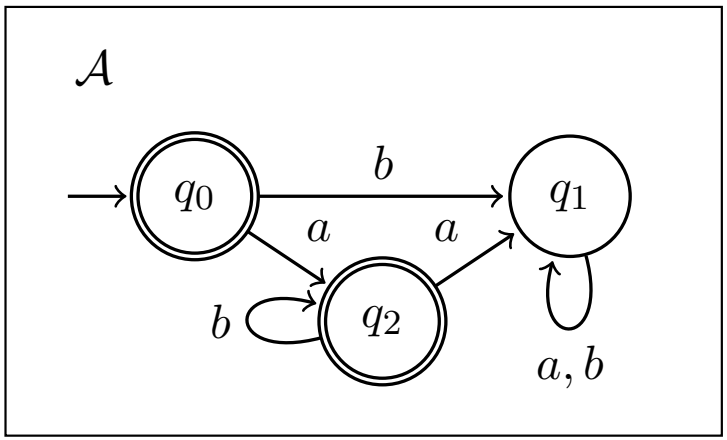

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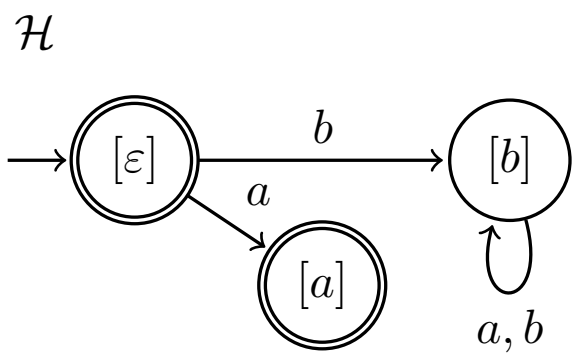

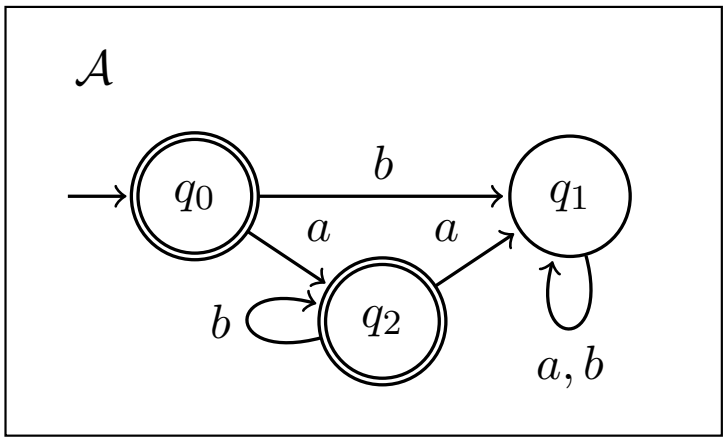

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ε	1	0
b	0	0
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ba	0	0
bb	0	0
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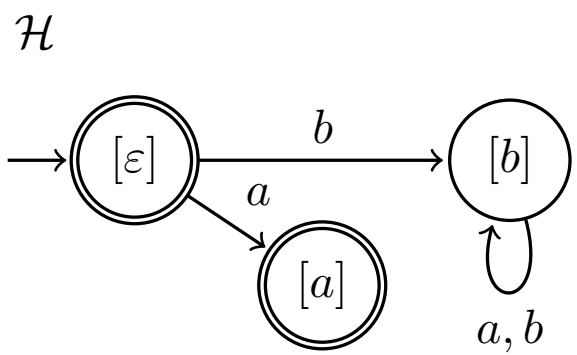

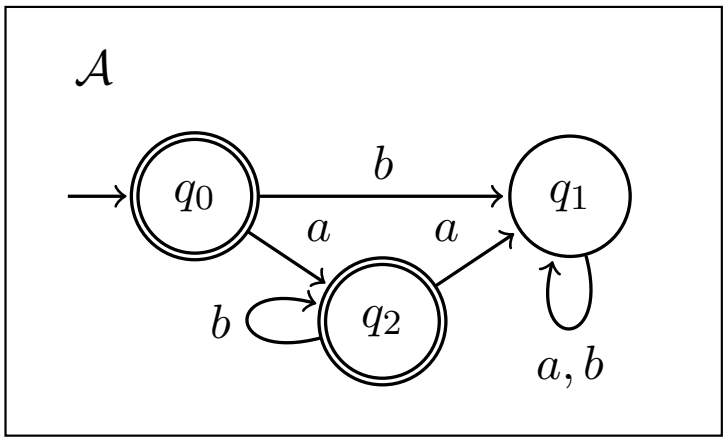

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	ε	b
ε	1	0
b	0	0
a	1	1
ba	0	0
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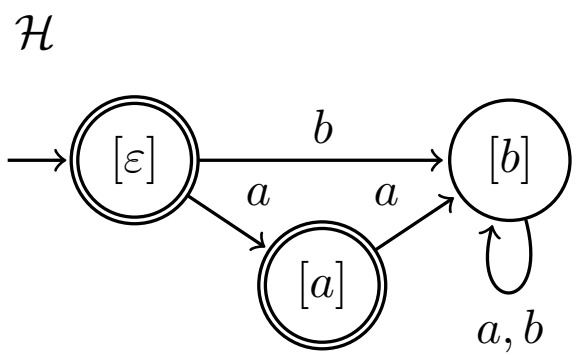
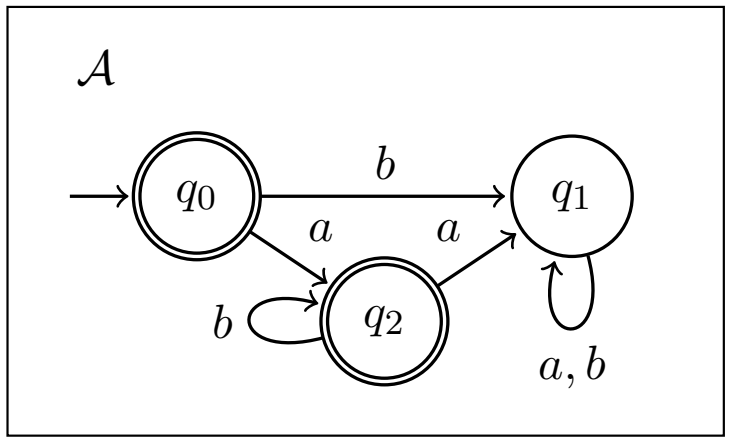
aa	0	0
ab	1	1





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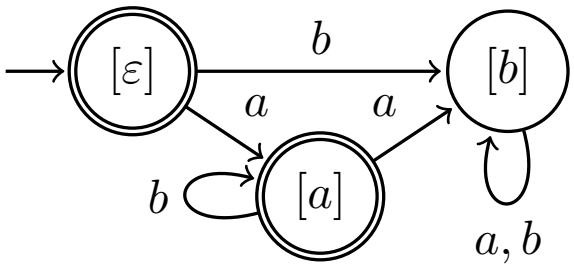
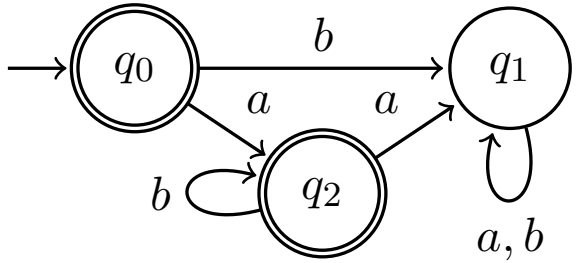
Refinement

	ε	b
ε	1	0
b	0	0
a	1	1
ba	0	0
bb	0	0
aa	0	0
ab	1	1

$\mathcal{H}$



$\mathcal{A}$



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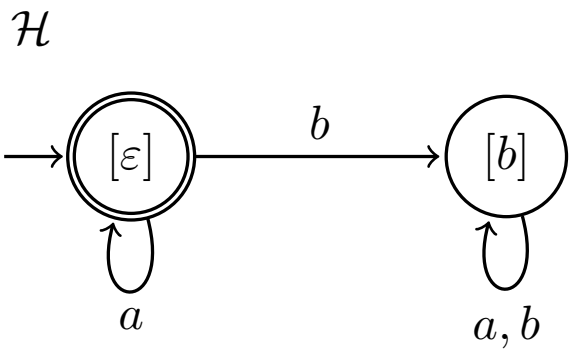
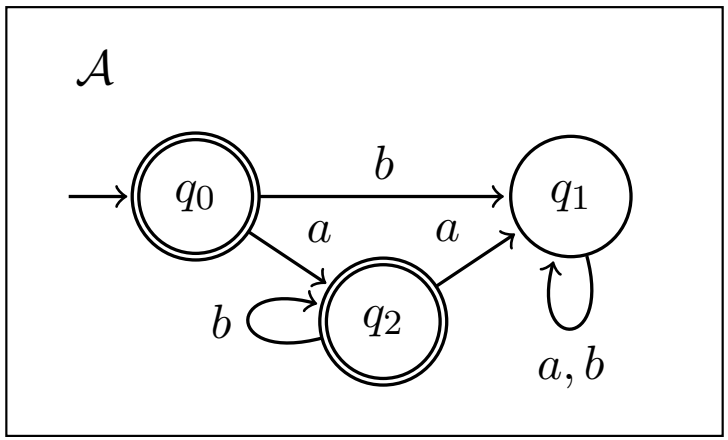
Refinement: Counterexamples

Reminder: original situation





- Previous slide: adding new distinguishing suffix b triggered refinement
- Counterexamples can be used to obtain such a suffix
  - Counterexample: word $w \in \Sigma^*$ s.t. $\lambda_{\mathcal{H}}(w) \neq \lambda(w)$

  $\Rightarrow$ i.e., $\mathcal{H}$ predicts wrong output for w
- Example: $w = ab$. $\lambda(ab) = 1$, $\lambda_{\mathcal{H}}(ab) = 0$

Counterexample Decomposition

Counterexample Decomposition

If w is a counterexample wrt. $\mathcal{H}$, then w has a suffix av s.t. for two access sequences $u, u' \in \mathcal{U}$ such that ua and u' reach the same state in $\mathcal{H}$, we have

$$\lambda(ua \cdot v) \neq \lambda(u' \cdot v).$$

- u' in upper part of table, ua in lower part (since $u \in \mathcal{U}$), contents of both rows are equal

$\Rightarrow$ adding suffix v to table distinguishes ua and u'

$\Rightarrow$ ua gets moved to upper part

Counterexample Decomposition: Visualization

Counterexample Decomposition

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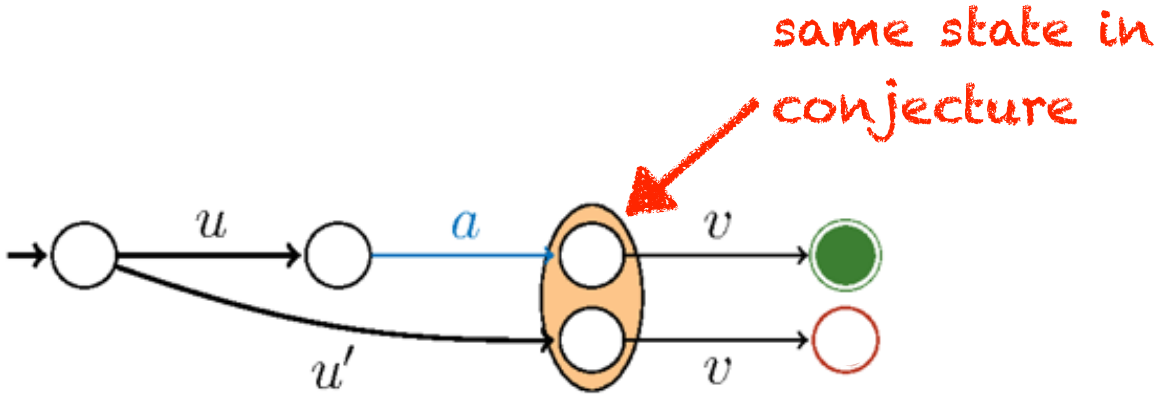

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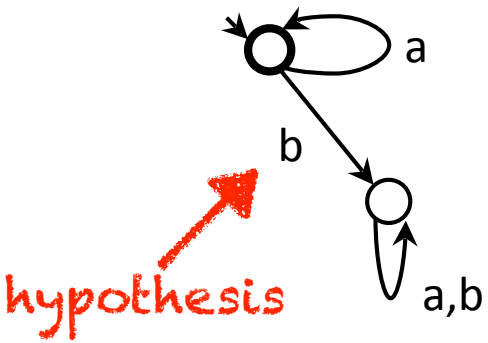
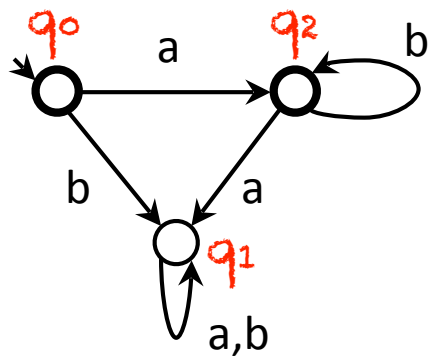


Counterexample: ab



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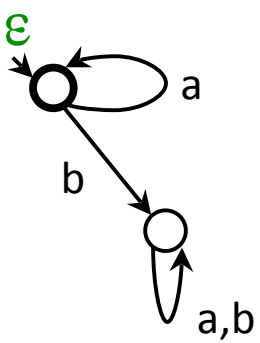

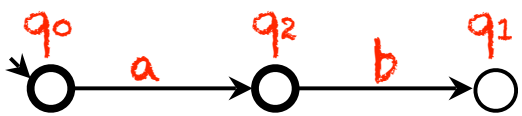

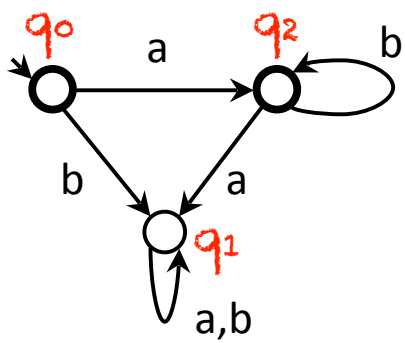

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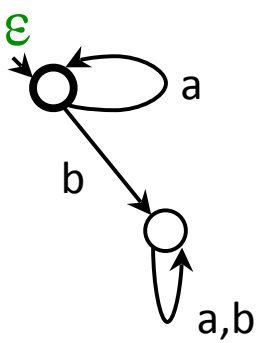

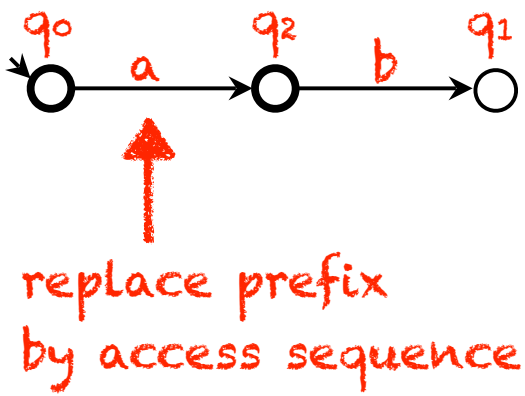

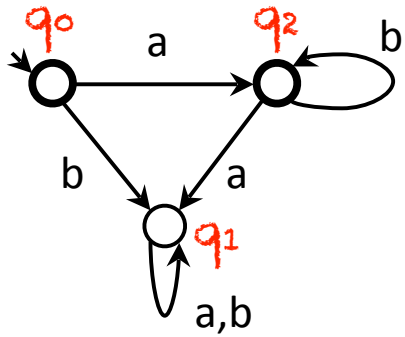

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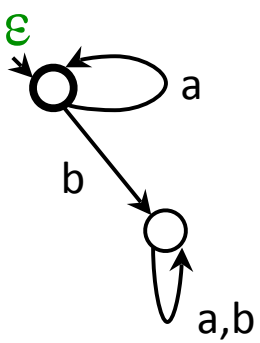

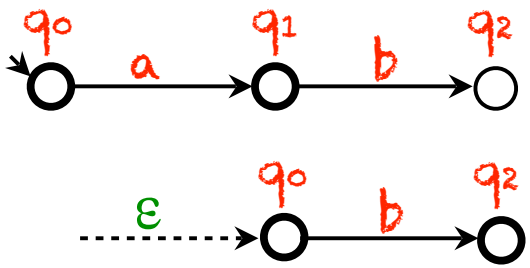

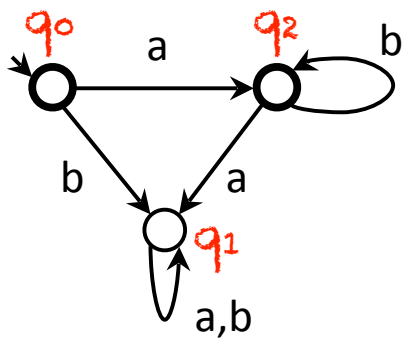

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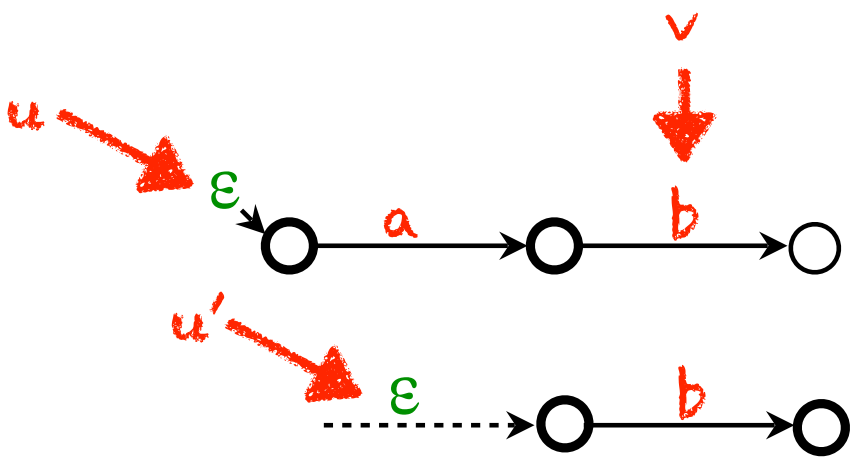

Finding a Decomposition

Counterexample Decomposition

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- Maler&Pnueli (1995): adding all suffixes of counterexample w guarantees that "right" suffix v gets added
  - additional suffixes do not hurt (wrt. refinement)
  - table size ($\hat{=}$ required number of queries/test cases) grows drastically

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  - table size ($\hat{=}$ required number of queries/test cases) grows drastically
- Rivest&Schapire (1993): use binary search to determine v

Binary Search

Notation/terminology:

- (Reminder) $\mathcal{H}[w] \hat{=}$ state in $\mathcal{H}$ reached by $w = w_1 \dots w_m$
- Access sequence of $q \in Q^{\mathcal{H}}$: unique element $u \in \mathcal{U}$ representing state q (furthermore: $\mathcal{H}[u] = q$)
- $\lfloor w \rfloor_{\mathcal{H}} \hat{=}$ access sequence of state $\mathcal{H}[w]$
- $\pi_{\mathcal{H}}(w, i) =_{df} \lfloor w_1 \dots w_i \rfloor_{\mathcal{H}} w_{i+1} \dots w_m$ $(i \in \{0, \dots, m\})$: prefix transformation
  - $\pi_{\mathcal{H}}(w, 0) = w \Rightarrow \lambda(\pi_{\mathcal{H}}(w, 0)) \neq \lambda_{\mathcal{H}}(\pi_{\mathcal{H}}(w, 0))$ (w is a counterexample)
  - $\pi_{\mathcal{H}}(w, m) = \lfloor w \rfloor_{\mathcal{H}} \in \mathcal{U} \Rightarrow \lambda(\pi_{\mathcal{H}}(w, m)) = \lambda_{\mathcal{H}}(\pi_{\mathcal{H}}(w, m))$ ($\lambda(\pi_{\mathcal{H}}(w, m) \cdot \varepsilon)$ determines acceptance of state represented by $\pi_{\mathcal{H}}(w, m) \in \mathcal{U}$)

Binary Search (2)

- $\pi_{\mathcal{H}}(w, i) =_{df} \lfloor w_1 \dots w_i \rfloor_{\mathcal{H}} w_{i+1} \dots w_m$ $(i \in \{0, \dots, m\})$: prefix transformation
  - $\pi_{\mathcal{H}}(w, 0) = w \Rightarrow \lambda(\pi_{\mathcal{H}}(w, 0)) \neq \lambda_{\mathcal{H}}(\pi_{\mathcal{H}}(w, 0))$ (w is a counterexample)
  - $\pi_{\mathcal{H}}(w, m) = \lfloor w \rfloor_{\mathcal{H}} \in \mathcal{U} \Rightarrow \lambda(\pi_{\mathcal{H}}(w, m)) = \lambda_{\mathcal{H}}(\pi_{\mathcal{H}}(w, m))$ ($\lambda(\pi_{\mathcal{H}}(w, m) \cdot \varepsilon)$ determines acceptance of state represented by $\pi_{\mathcal{H}}(w, m) \in \mathcal{U}$)
- Obviously: $\lambda_{\mathcal{H}}$ invariant under prefix transformations (i.e., $\lambda_{\mathcal{H}}(\pi_{\mathcal{H}}(w, i)) = \lambda_{\mathcal{H}}(w)$ for all i)
- Breakpoint: $i \in \{0, \dots, m-1\}$ s.t. $\lambda(\pi_{\mathcal{H}}(w, i)) \neq \lambda(\pi_{\mathcal{H}}(w, i+1))$
  - exists if w is a counterexample

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  - with $u =_{df} \lfloor w_1 \ldots w_i \rfloor_{\mathcal{H}}$, $a =_{df} w_{i+1}$, $v =_{df} w_{i+2} \ldots w_m$:
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Counterexample Decomposition

If w is a counterexample wrt. $\mathcal{H}$, then w has a suffix av s.t. for two access sequences $u, u' \in \mathcal{U}$ such that ua and u' reach the same state in $\mathcal{H}$, we have

$$\lambda(ua \cdot v) \neq \lambda(u' \cdot v).$$

The Cost of Learning

Common measure: query complexity ($\hat{=}$ required number of test cases)

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- Query complexity dominated by size of observation table (1 test case per cell)
  - $kn + 1$ rows
  - 1 suffix added per counterexample $\Rightarrow$ at most n columns

  $\Rightarrow$ size of table in $\mathcal{O}(kn^2)$

The Cost of Learning (2)

Size of observation table: $\mathcal{O}(kn^2)$

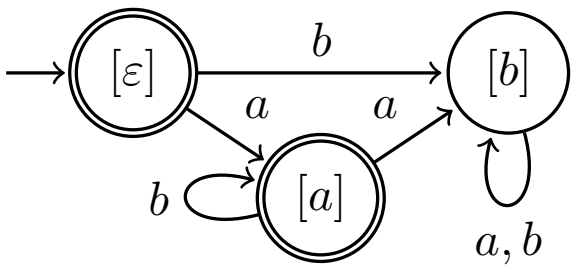
- Plus: counterexample analysis (Rivest&Schapire)
  - Binary search: $\mathcal{O}(\log m)$ queries per counterexample
  - at most $n-1$ counterexamples $\Rightarrow$ total $\mathcal{O}(n \log m)$ queries for counterexample analysis
- Total query complexity: $\mathcal{O}(kn^2 + n \log m)$
- Known lower bound [Balcázar *et al.*, 1997]: $\Omega(kn^2)$

Discrimination Trees

Redundancies in Observation Table

	ε	b
ε	1	0
b	0	0
a	1	1
ba	0	0
bb	0	0
aa	0	0
ab	1	1

$\mathcal{H}$



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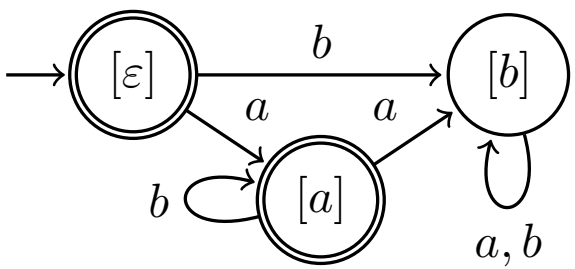

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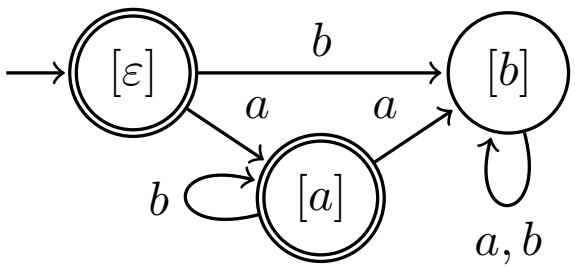

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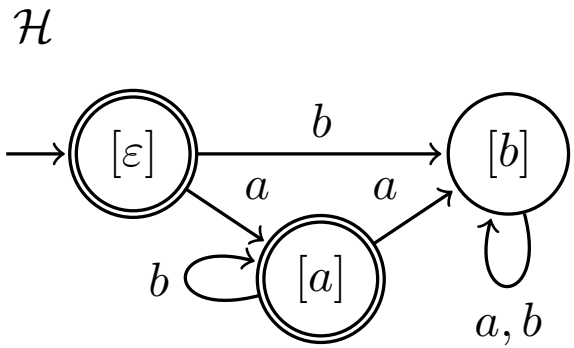

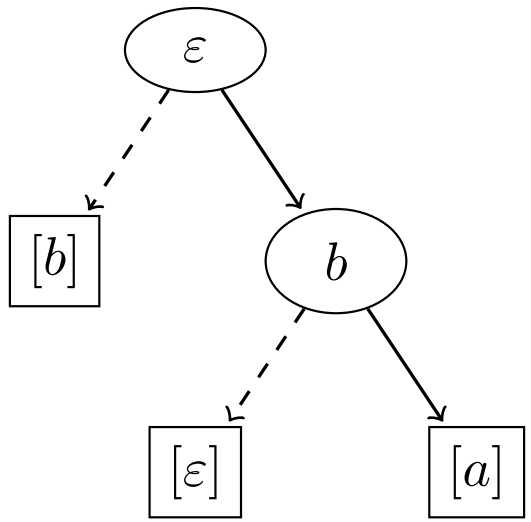

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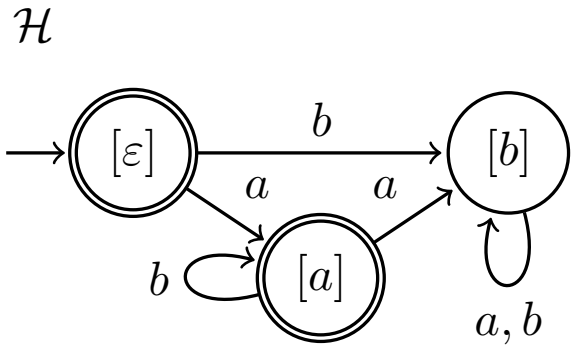
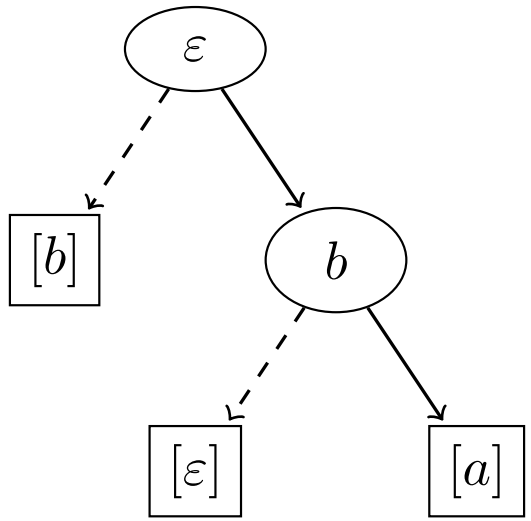
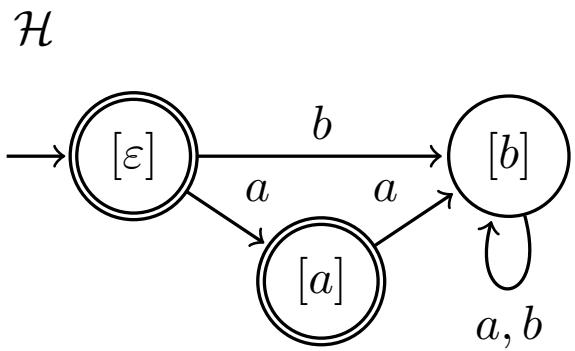
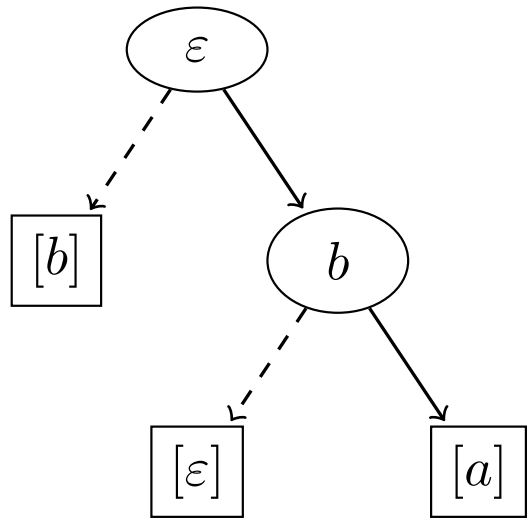




- Value 0 in ε-column sufficient to distinguish $[b]$ from other two states
- Discrimination Tree redundancy-free: exactly one distinguishing suffix for each pair of states (LCA)

Discrimination Trees: Sifting





Determining the target state of the b-transition of state $[a]$:

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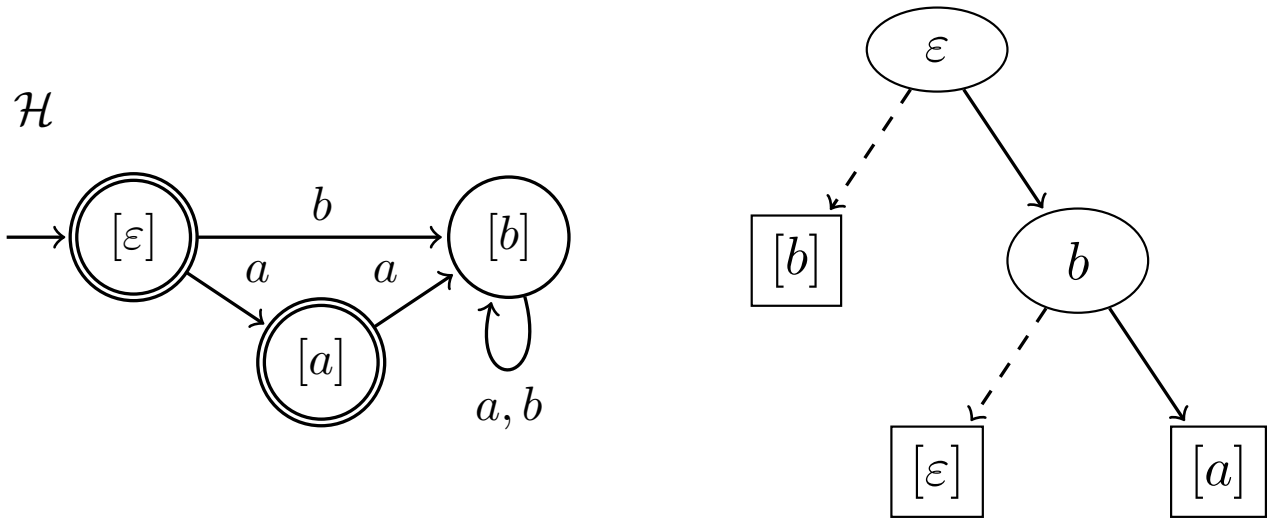

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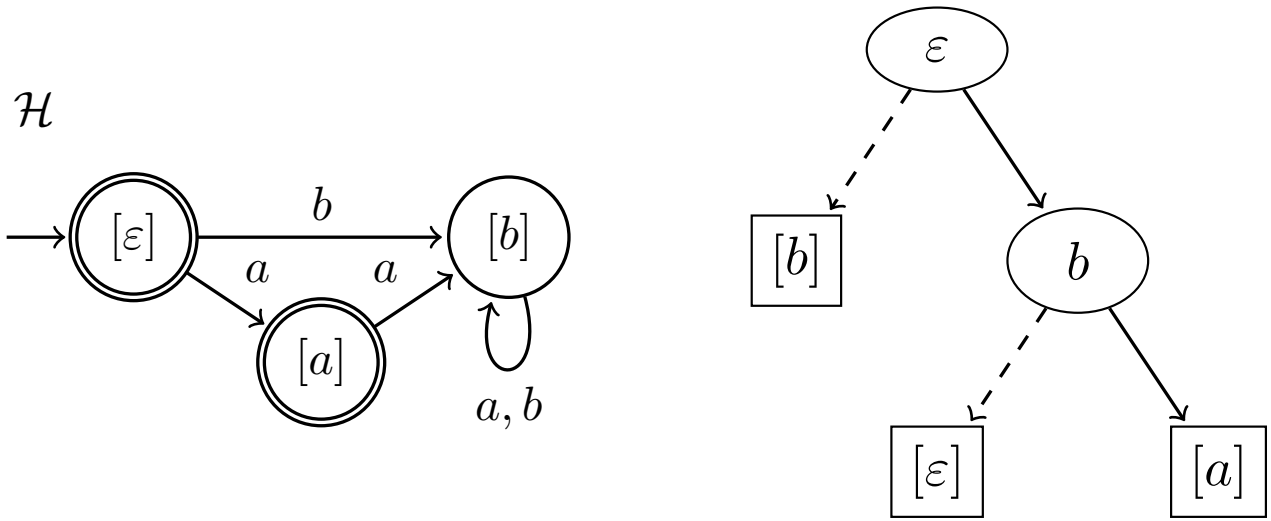

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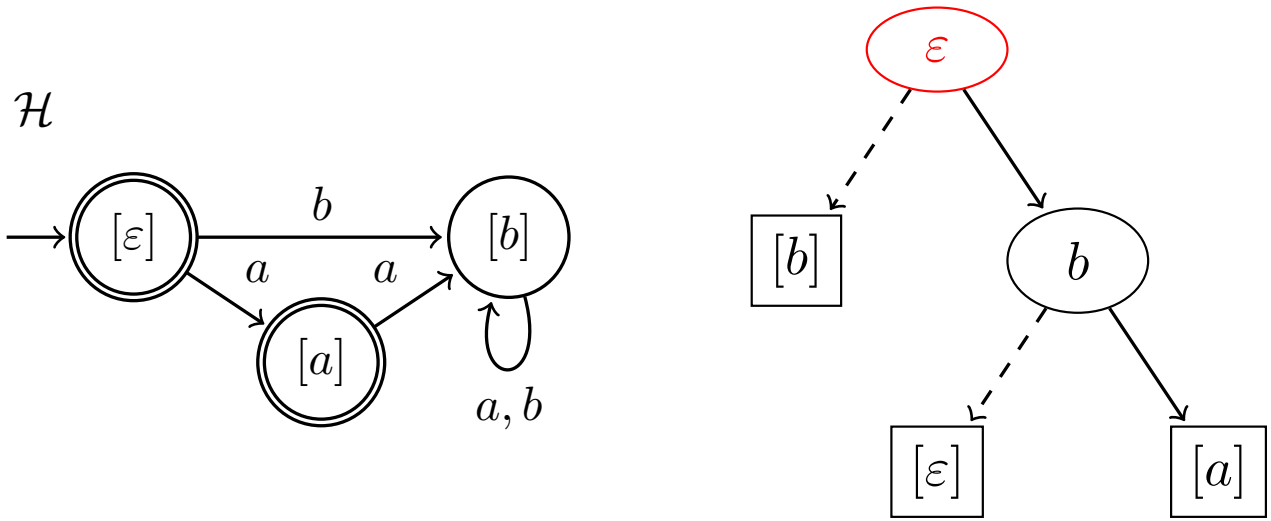

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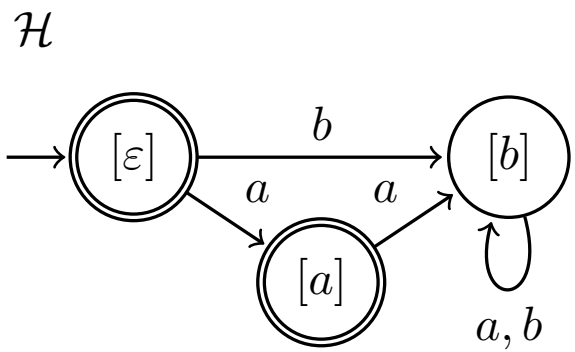

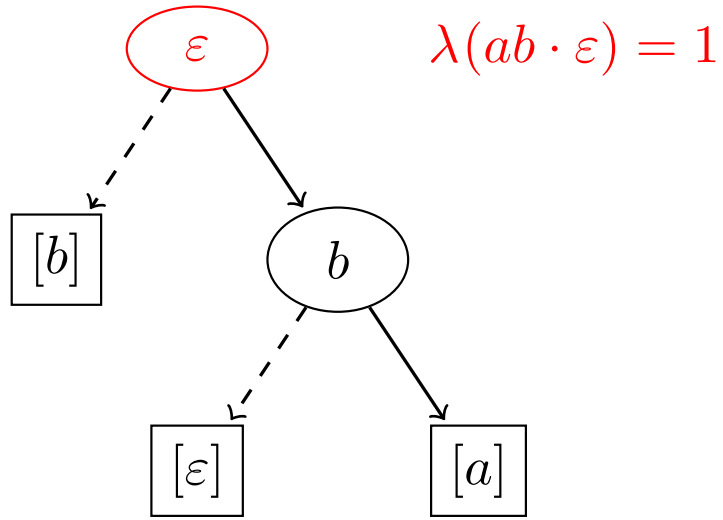

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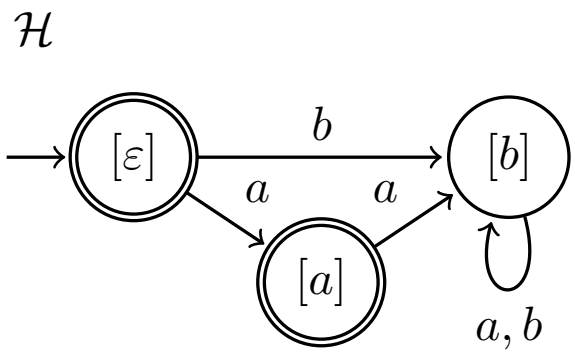

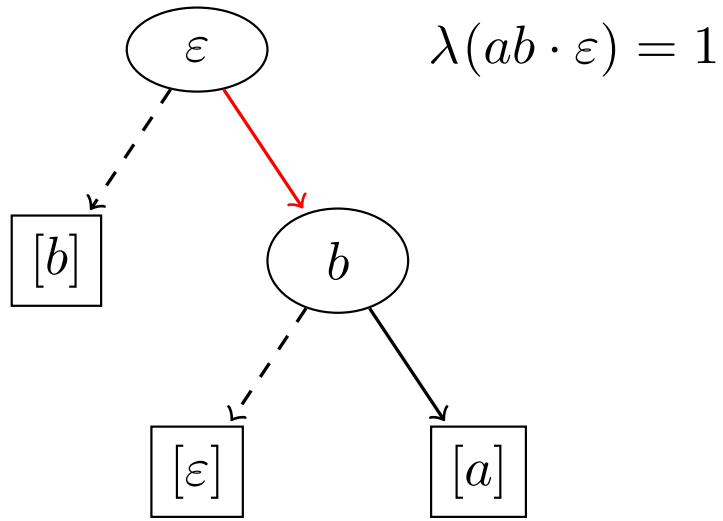

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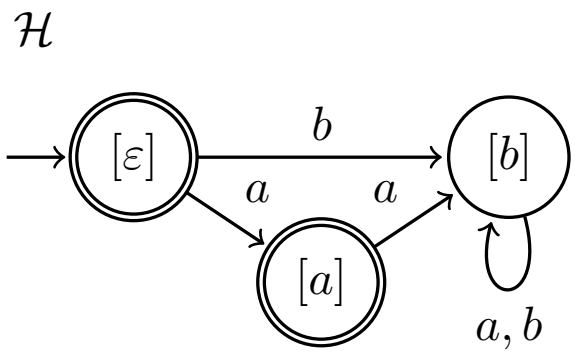

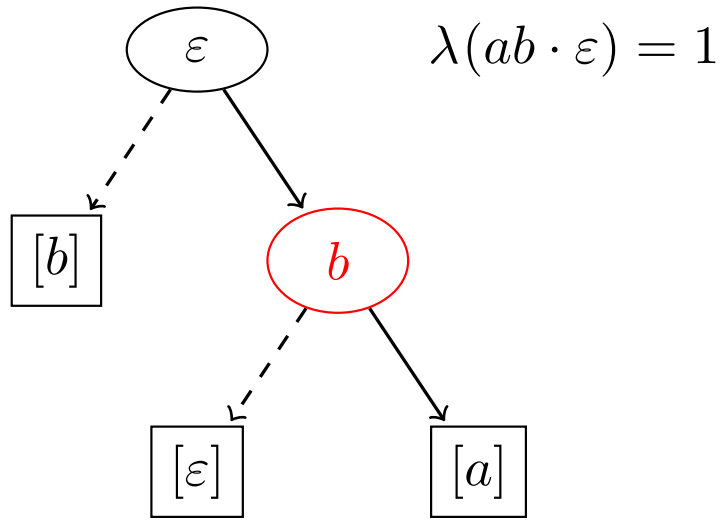

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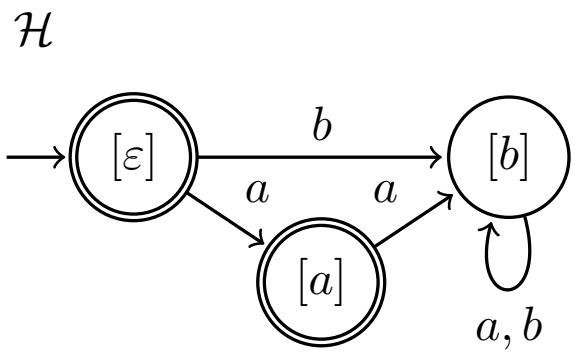

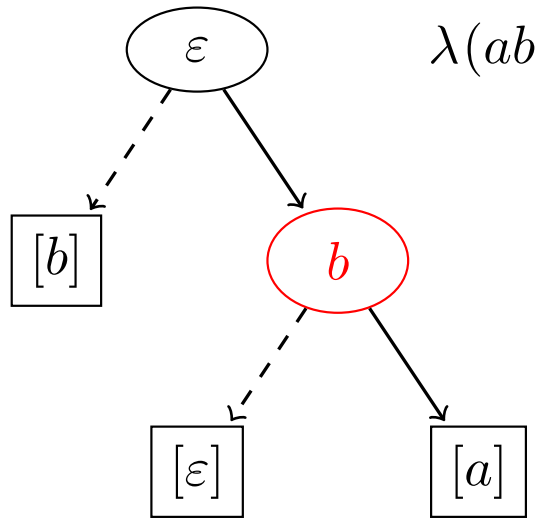

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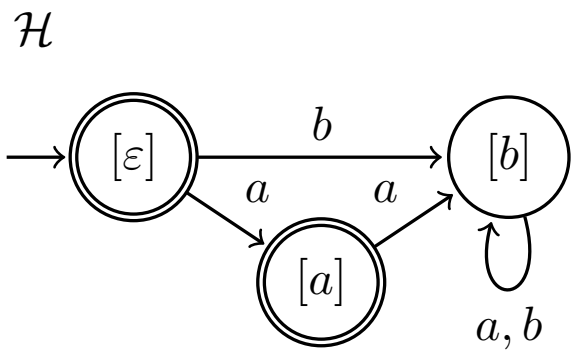

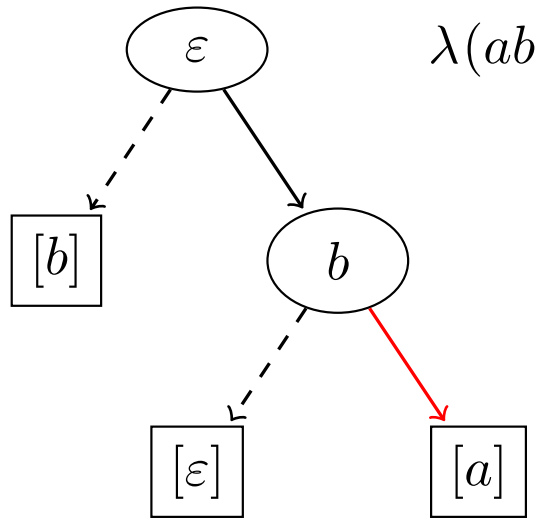

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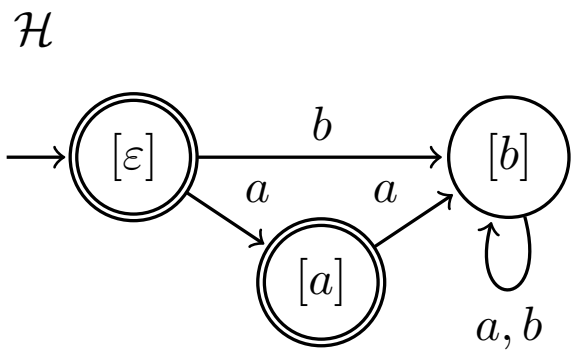

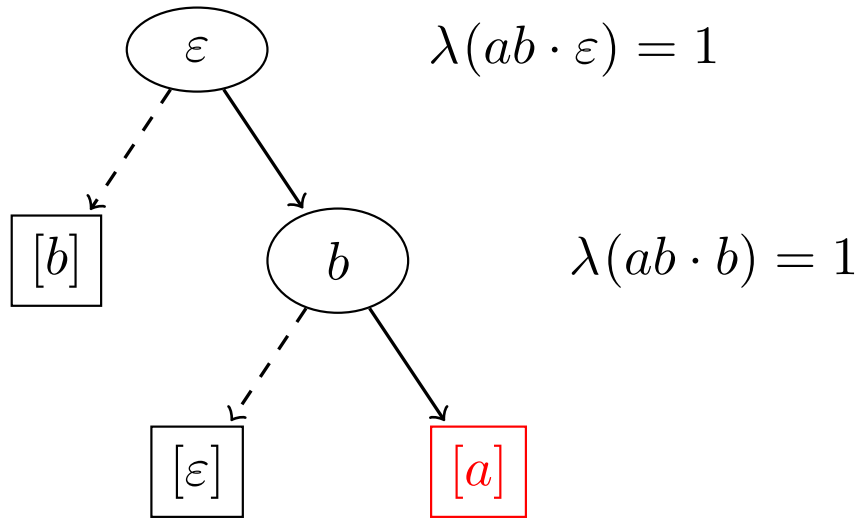

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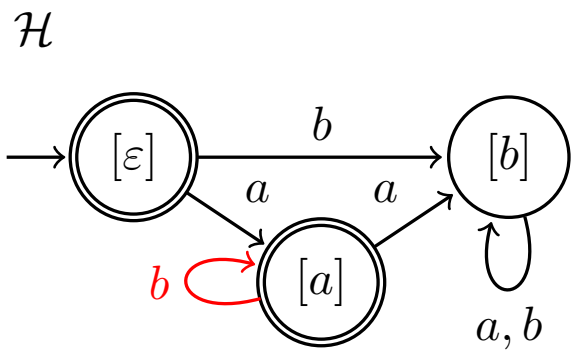

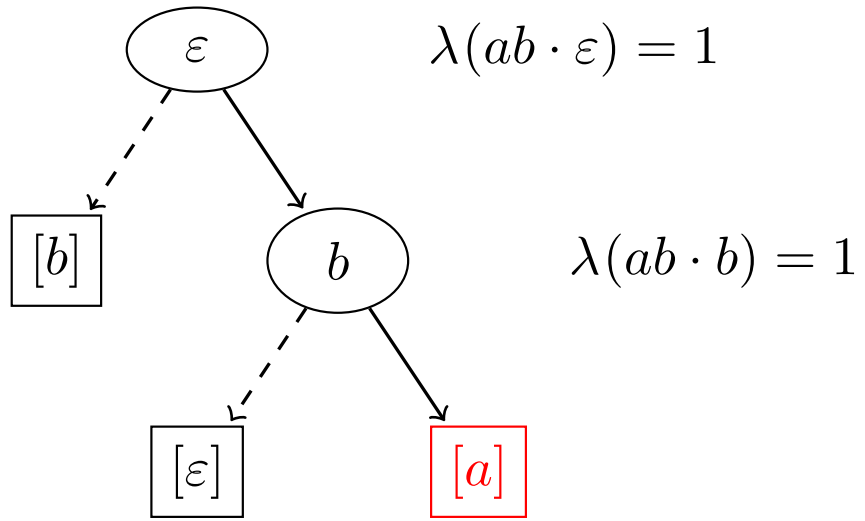

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Discrimination Trees: Refinement

Reminder: Counterexample decomposition yields $u, u' \in \mathcal{U}$, $a \in \Sigma$, $v \in \Sigma^*$

- Observation Table: simply add v to columns
- Does not work for discrimination trees (locality)!

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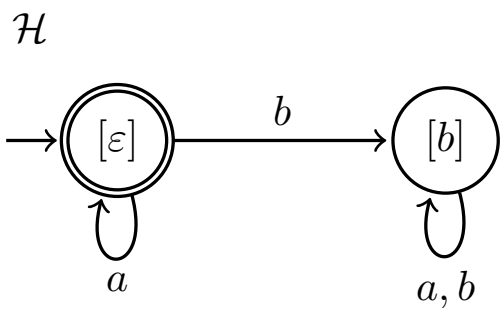

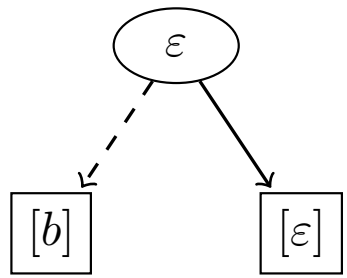

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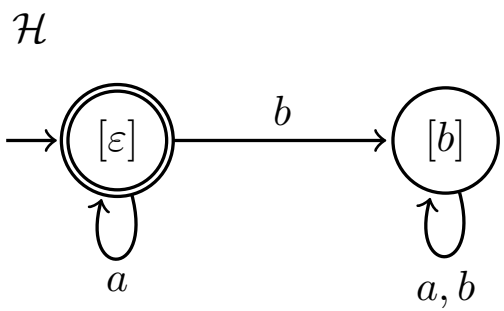

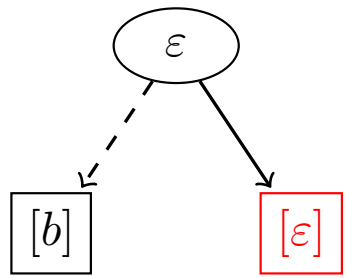

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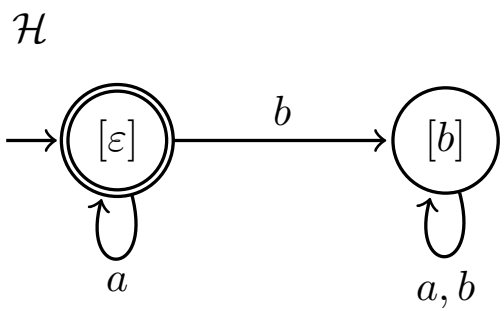

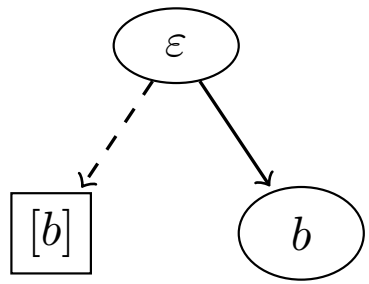

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  - Suffix at new inner node: $v = b$

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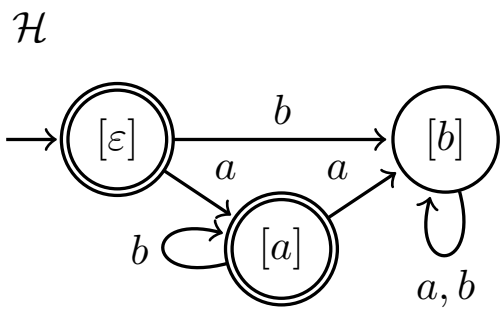
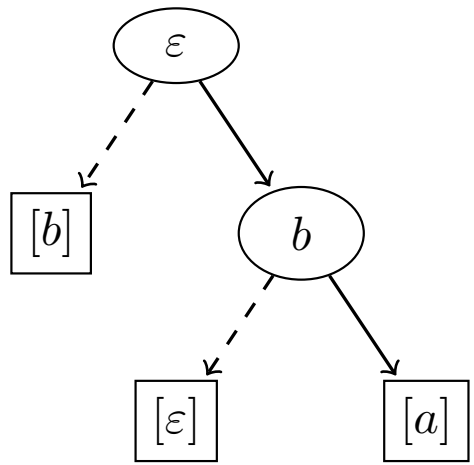
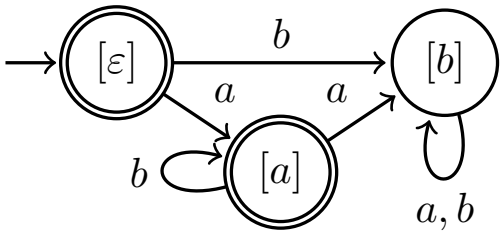




- Refinement: split leaf corresponding to $u' = \varepsilon$
  - Suffix at new inner node: $v = b$
  - New children (leaves): $[u']$ and new state $[ua]$ $(u = \varepsilon)$

Spanning Tree Hypothesis

$\mathcal{H}$



Observation: new states derived from transitions

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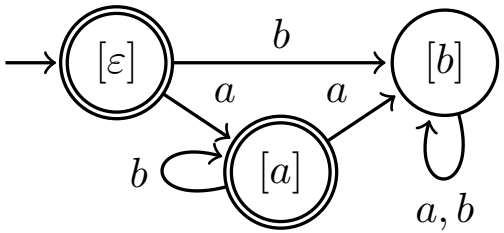

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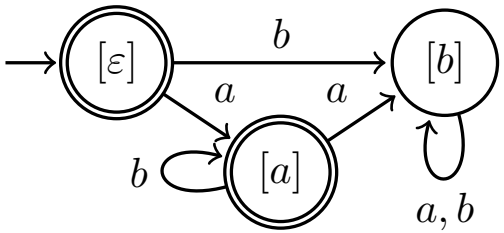

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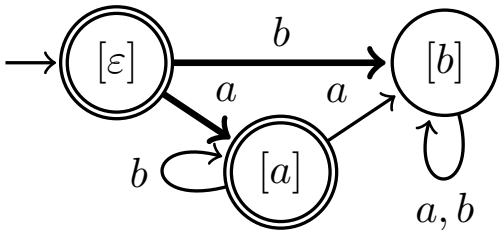

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Observation 2: $\mathcal{U} \setminus \{\varepsilon\}$ are transition access sequences

- $\mathcal{U}$ prefix-closed $\Rightarrow$ transitions in $\mathcal{U} \setminus \{\varepsilon\}$ form spanning tree

$\Rightarrow$ Spanning tree can be used to represent $\mathcal{U}$

Outline

Practical Challenges

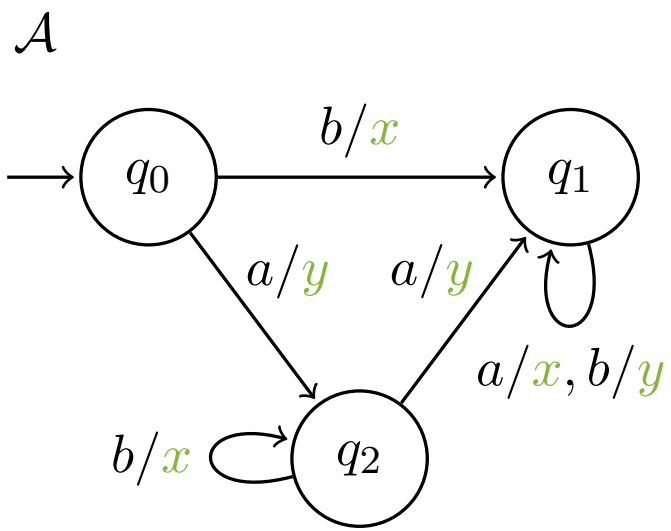
Main practical challenge: Realizing membership and equivalence queries

- Need to fulfill certain criteria: independence, determinism, ...

But first: DFAs not adequate for modeling reactive systems

- Better-suited model: Mealy machines

Mealy machines



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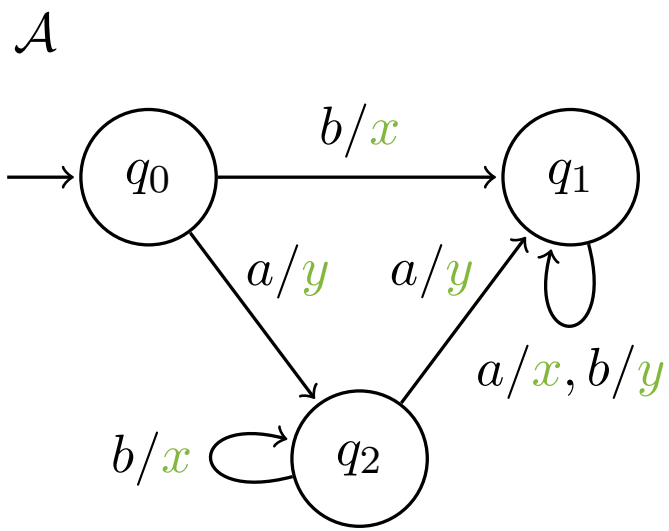

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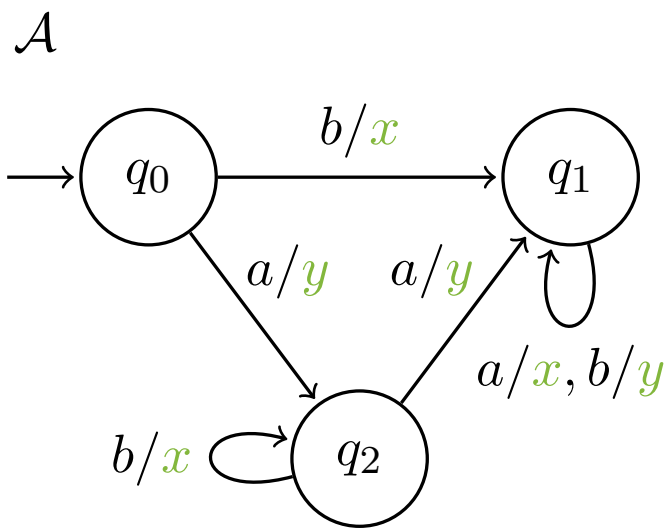

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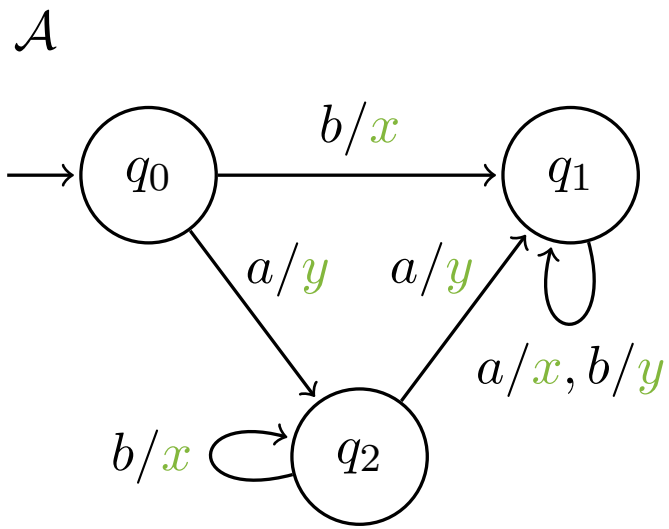

- No accepting/rejecting states, but transition outputs
- Output function: $\lambda : \Sigma^* \to \Omega^*$ (Ω: output alphabet, $\Omega = \{x, y\}$)
- DFA learning can be adapted to Mealy machines in a straightforward way

Realizing Membership Queries

- Membership Queries $\hat{=}$ test cases
- Step 1: define learning alphabet Σ
  - e.g., API calls, communication primitives etc.
- Step 2: define semantics for each symbol

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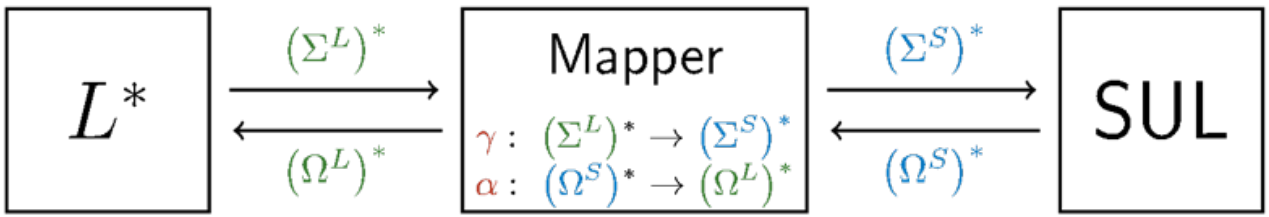
- Data-flow aspects need to be addressed
  - e.g., actions need session id, which is returned upon login etc.

Mapper



- Abstracts from lower-level system details
- Enables finite-state, finite-alphabet models

Realizing Equivalence Queries

Earlier: counterexamples trigger refinement, but how to obtain counterexamples?

- Abstract formulation: equivalence queries

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Realizing Equivalence Queries

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- Abstract formulation: equivalence queries
- Problem: realizing equivalence queries requires detailed knowledge about the system's behavior
  - . . . but obtaining this is the whole point in using learning . . .
- In practice: only approximated equivalence queries are possible
  - i.e., approximate equivalence queries through membership queries

Approximating Equivalence Queries

- Classical approach: conformance testing methods
  - W-method, Wp-method, UIO method etc.
  - relative guarantees (e.g., assuming the target system has at most Δn additional states) at the cost of an exponential number of membership queries

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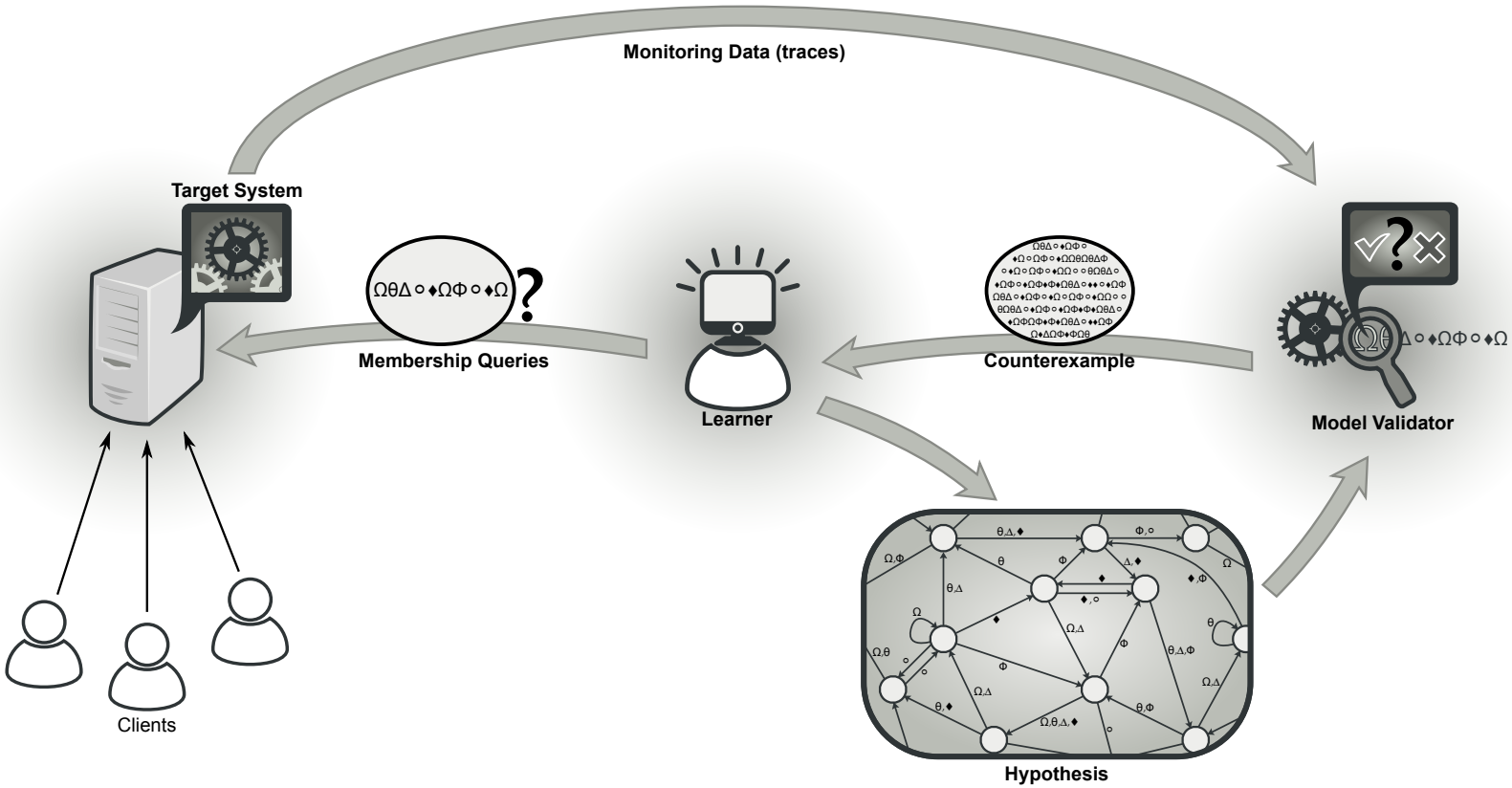
- Often more viable: log-file analysis or monitoring

  $\Rightarrow$ "life-long learning"

Combining Learning and Monitoring



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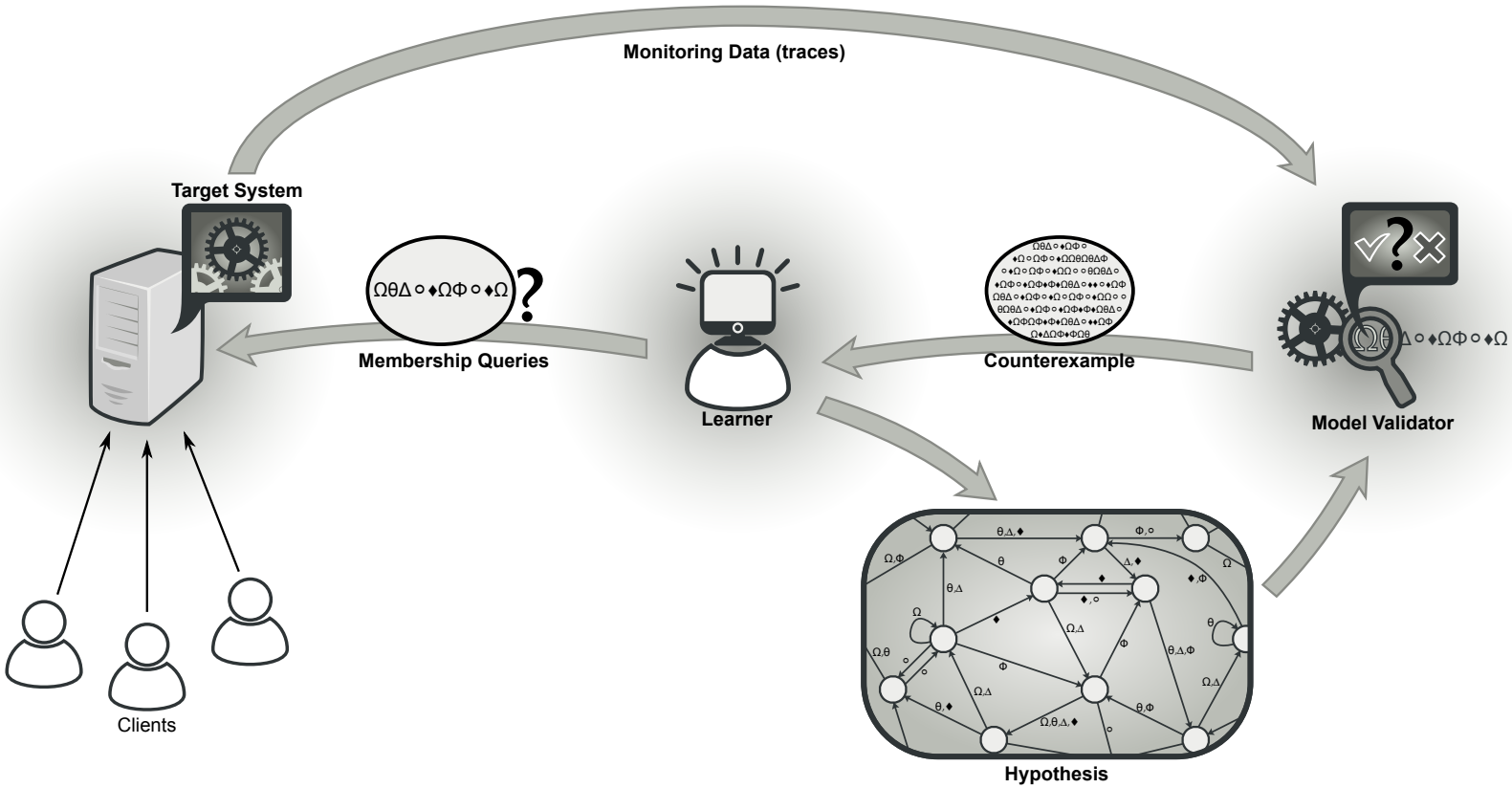
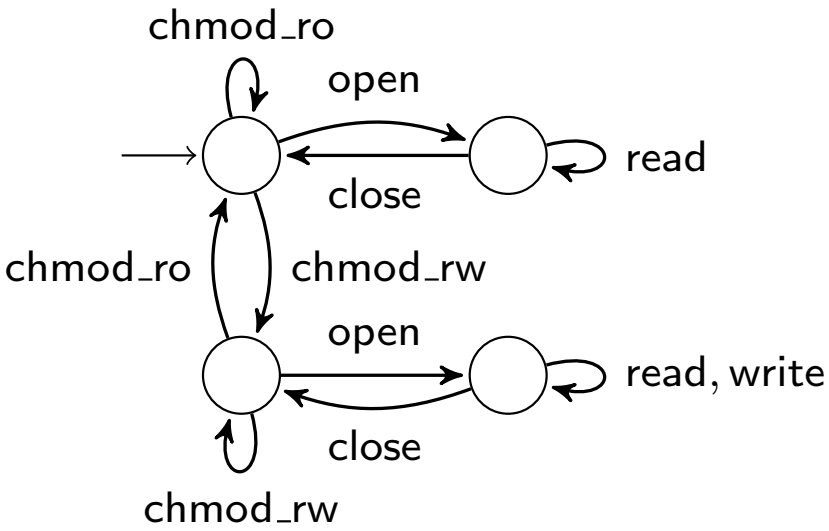


- Executions may run for a long time ⇒ long counterexamples

Counterexamples through Monitoring:



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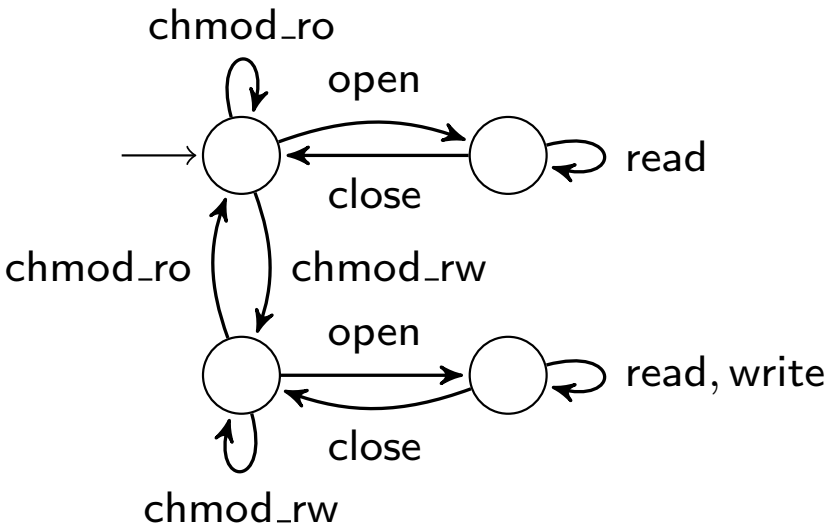

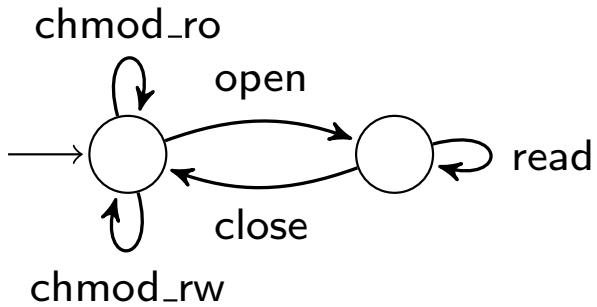

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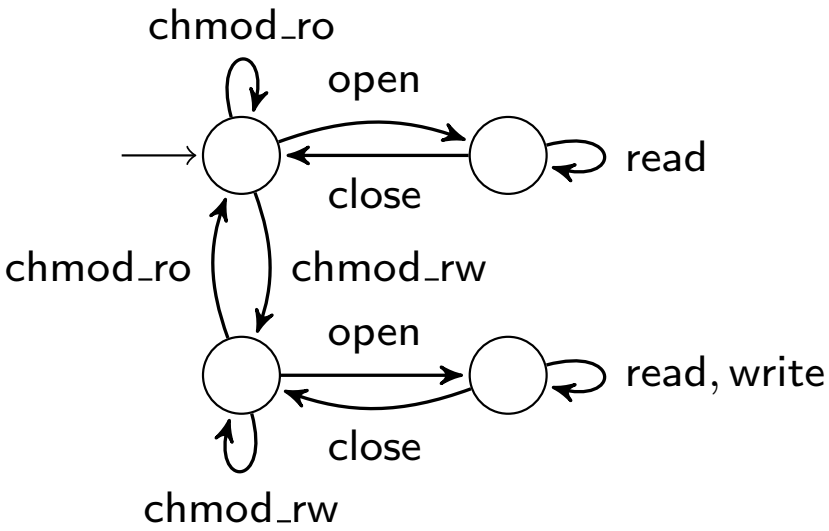
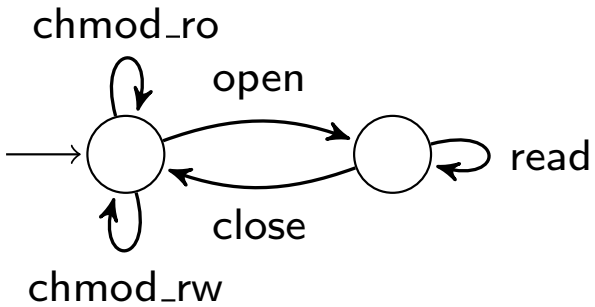
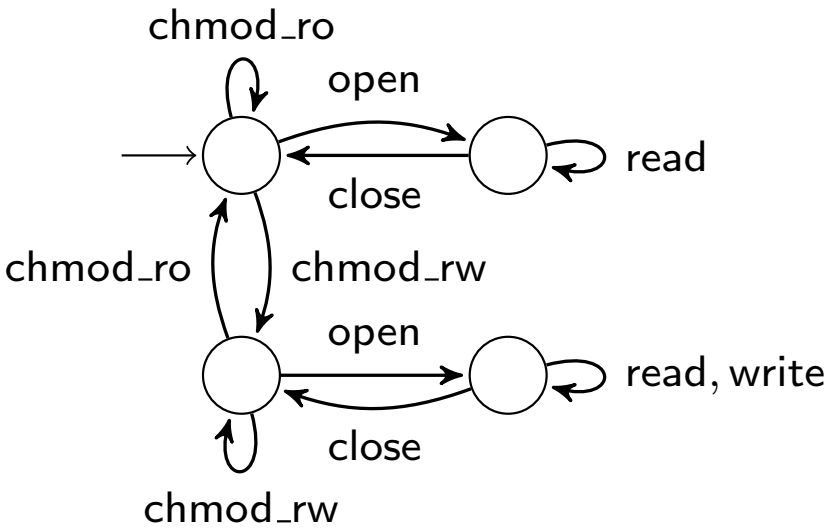
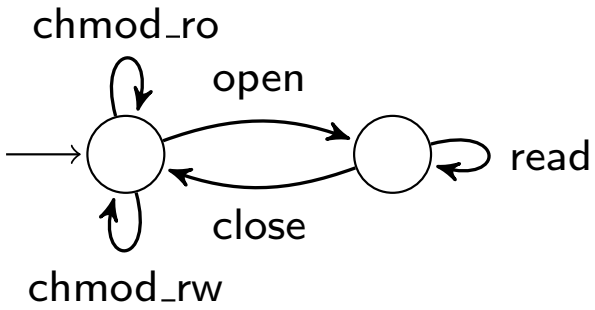




$$\overbrace{\text{open read close open read close chmod\_rw}}^{prefix}\ \underbrace{\text{open read close open read close open write}}_{suffix}$$

Counterexamples through Monitoring:





$$\overbrace{\text{open read close open read close chmod\_rw}}^{prefix}\ \underbrace{\text{open read close open read close open write}}_{suffix}$$

- "Optimal" counterexample chmod_rw open write

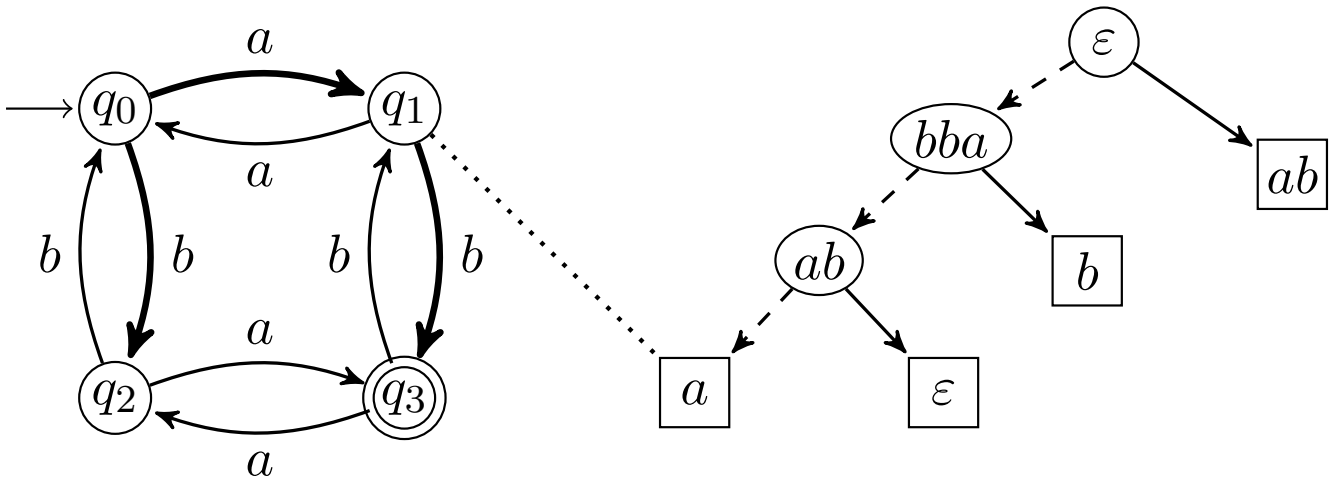
The Problem of Long Counterexamples

- Counterexample decomposition: suffix v extracted from counterexample
- Binary search: no guarantees wrt. length of this suffix (might not even be the shortest such suffix)

$\Rightarrow$ length of suffix v only bounded by m (length of counterexample)

So what is the problem with long suffixes?

The Problem of Long Suffixes



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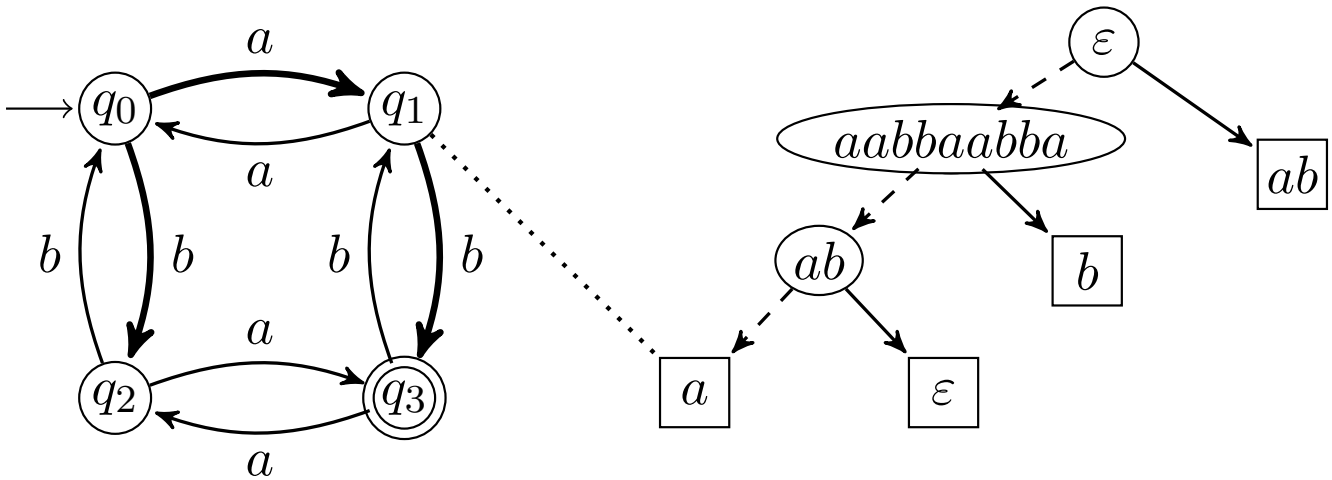

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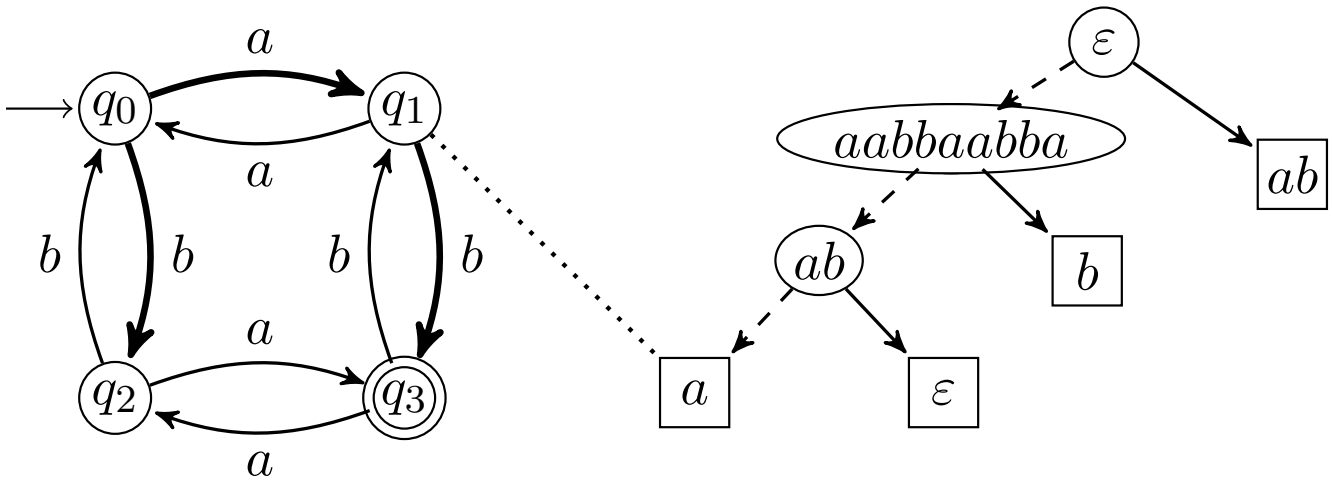
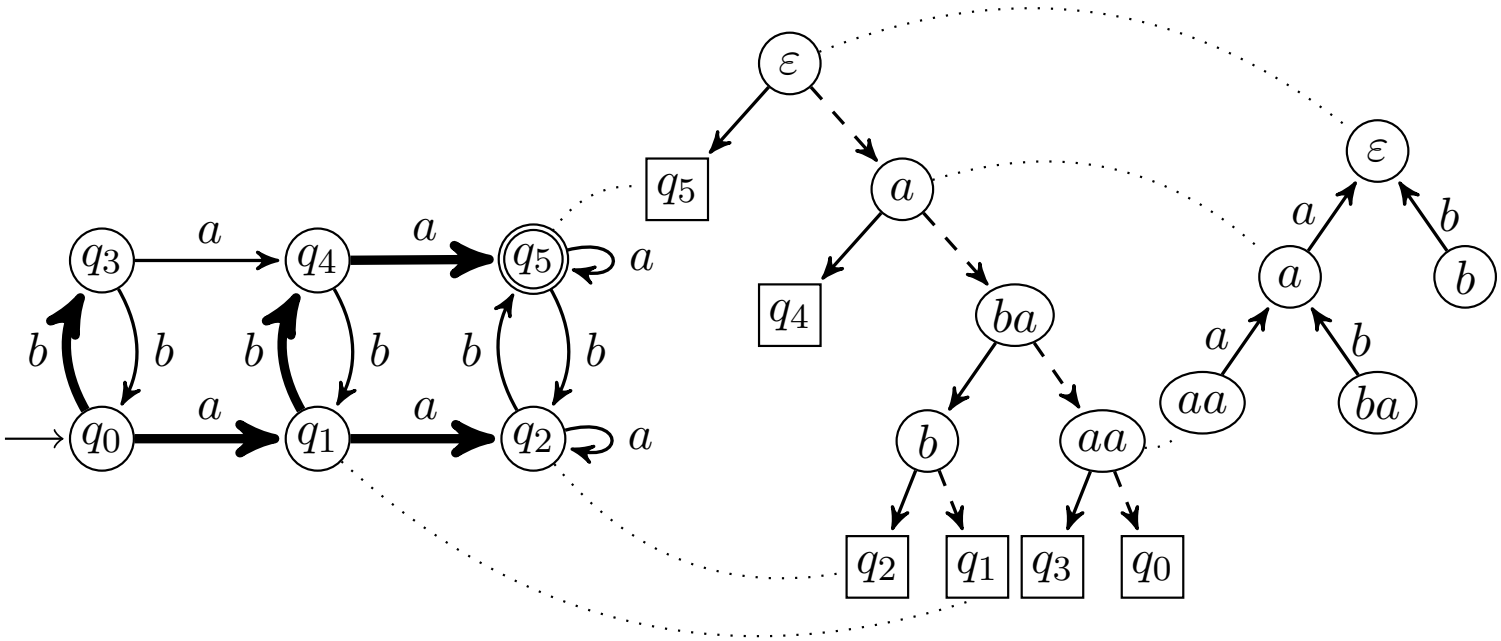


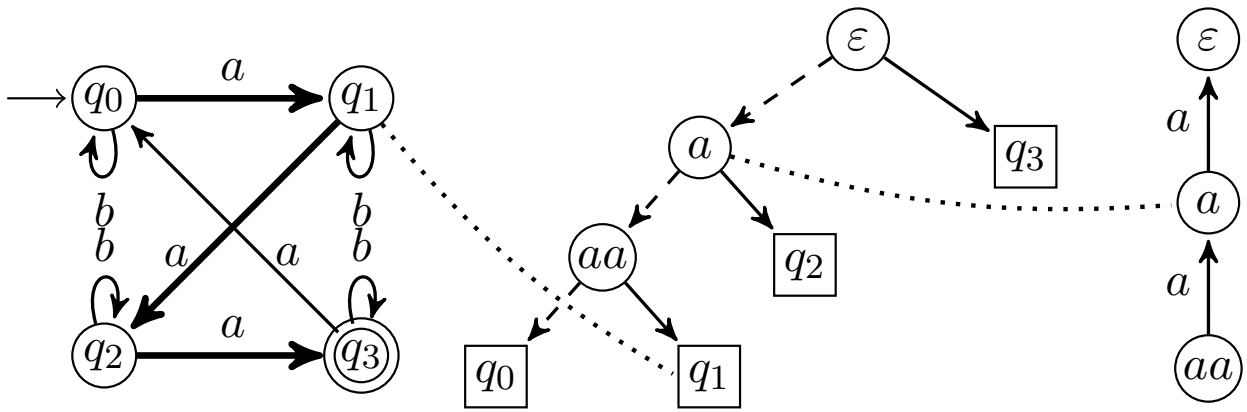
- Consequence: long membership queries
  - $aa\mathit{aabbaabba}, bb\mathit{aabbaabba}, \ldots$
  - Typically: time required for performing membership query linear in its length
- Even worse: impact not "local" but persists throughout entire process

The TTT Algorithm

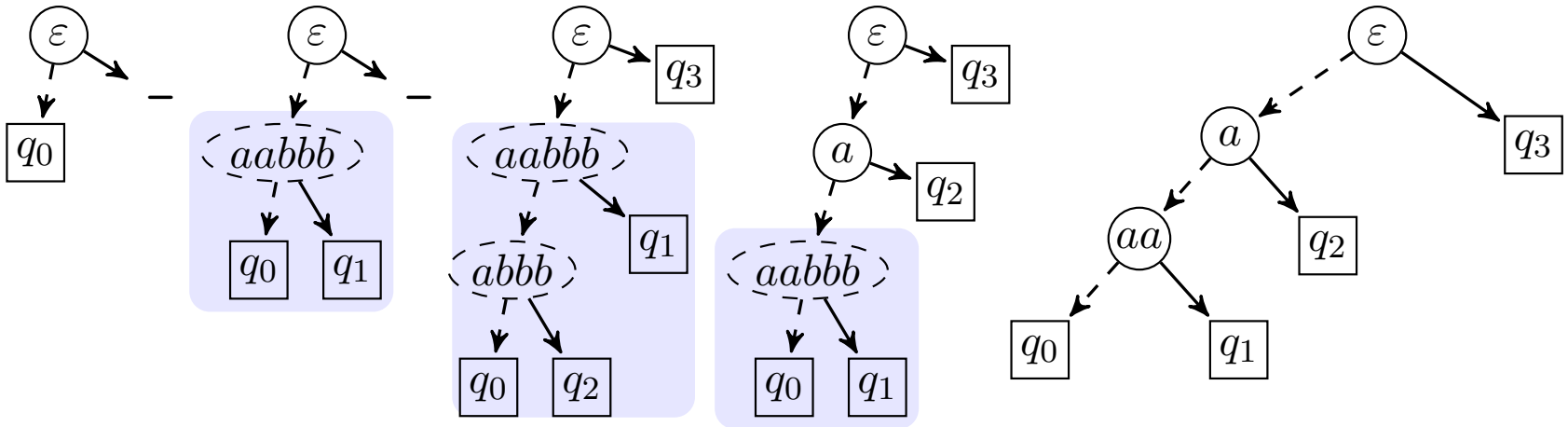


- Idea: "normalize" suffixes to establish suffix-closedness
  - Length of suffixes then bounded by n, organized in Trie
- Spanning **T**ree, Discrimination **T**ree, Suffix **T**rie
  - Linear (optimal) space complexity

TTT – Another Example

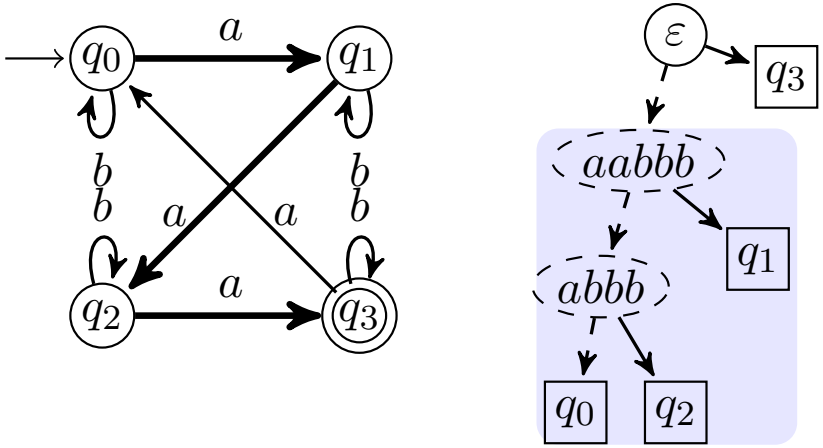


How does it work?



- Main idea: mark new suffixes (i.e., extracted from a counterexample) as temporary
  - Final suffixes only above any temporary suffixes
  - Maximal subtree w/o final suffixes: block
- Finalize temporary suffixes by replacing them with newly constructed ones (preserving suffix closedness)
  - Replace block roots only

Discriminator Finalization – Idea



Find:

- 2 states q, q' in the same block

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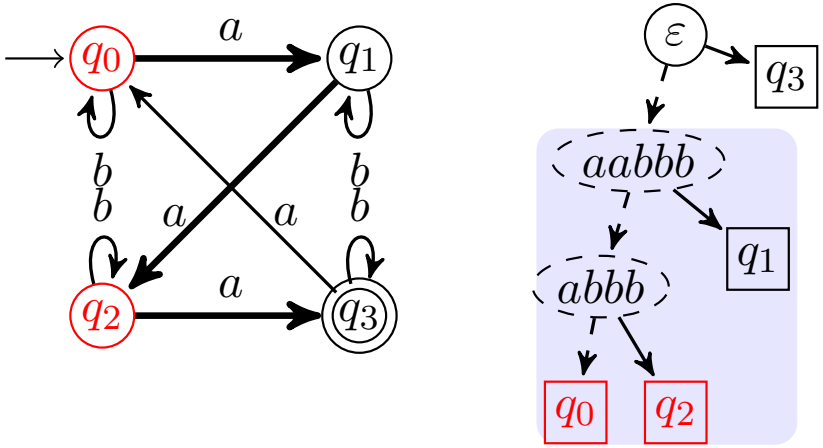

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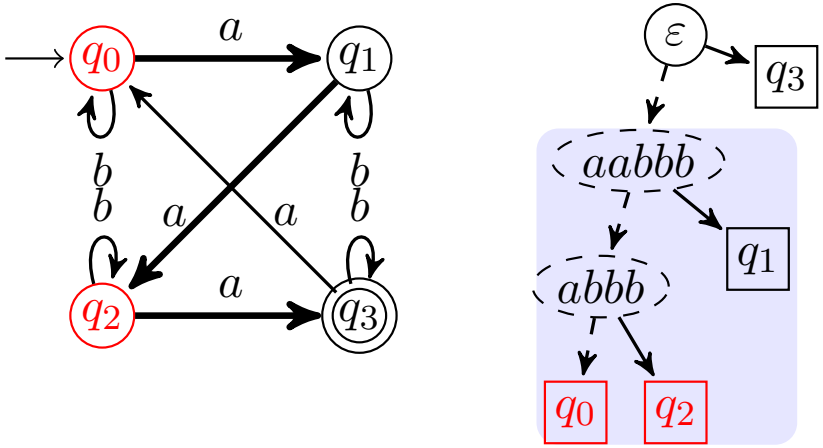

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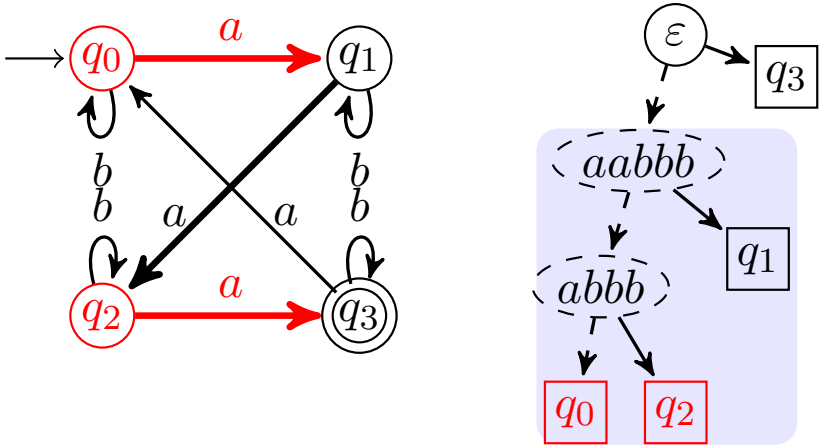

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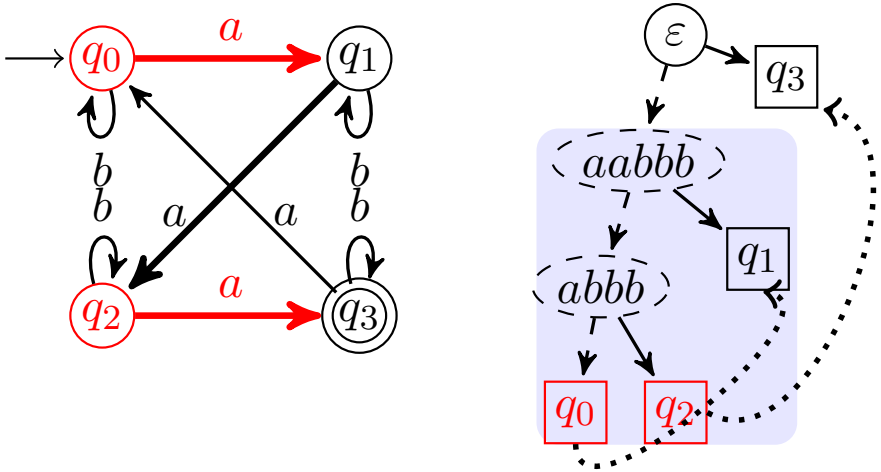

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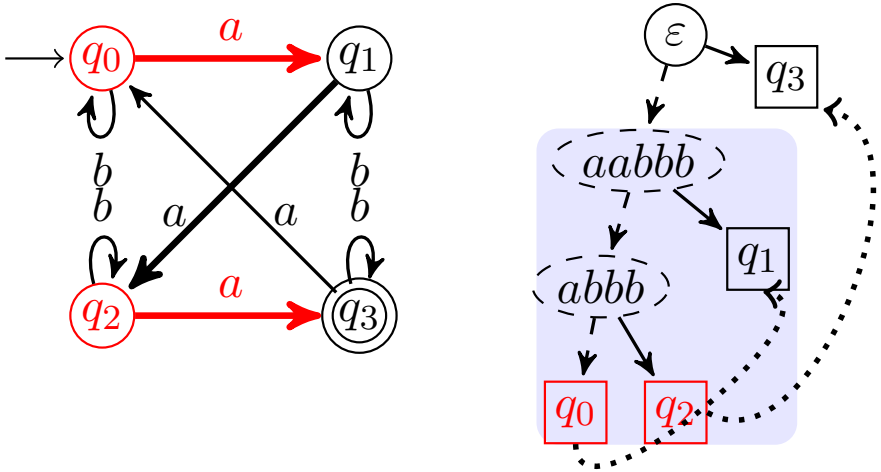

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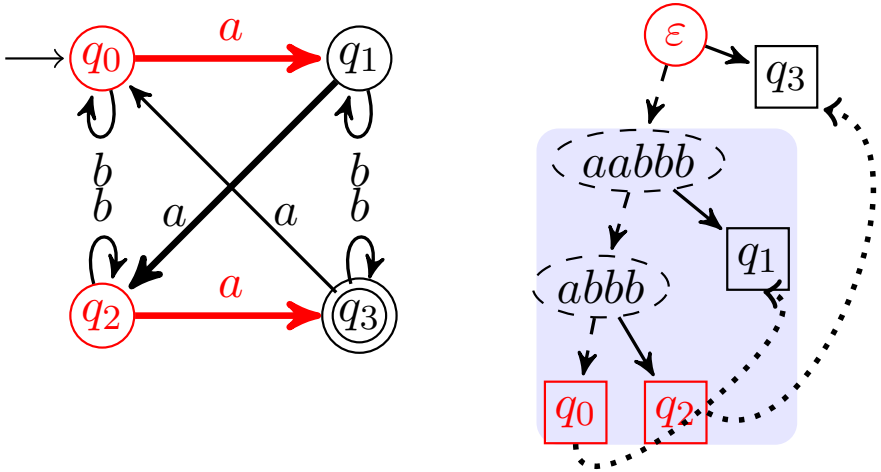

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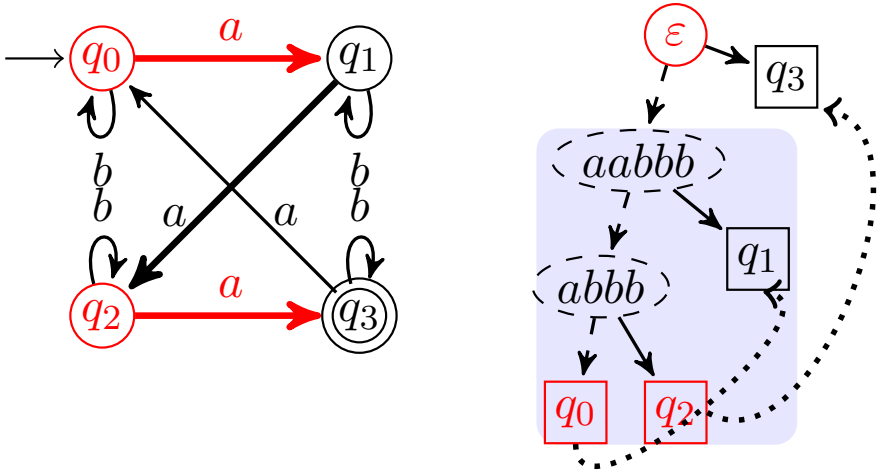

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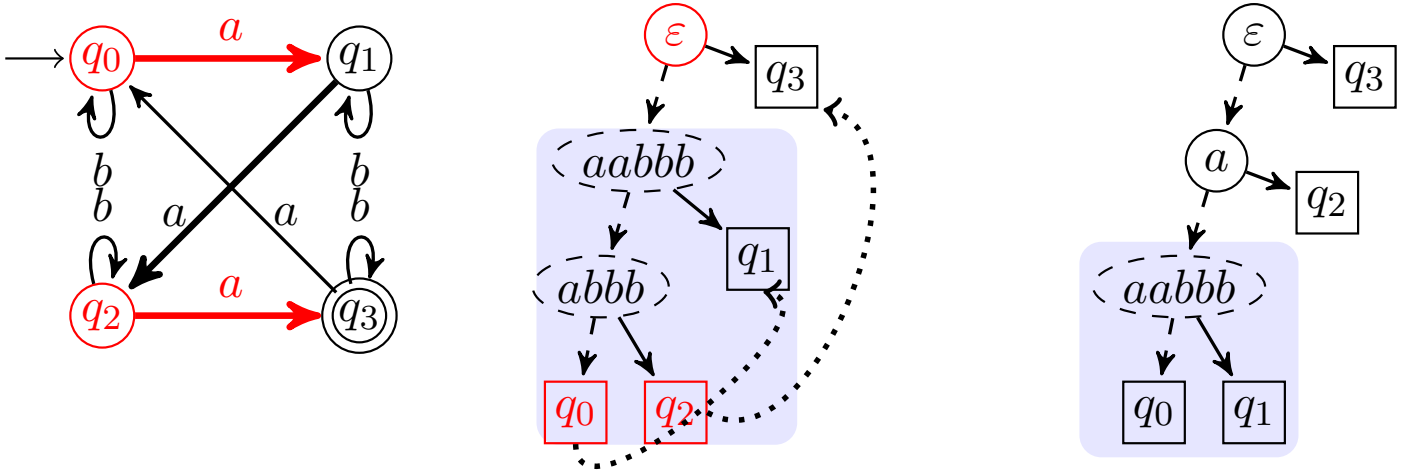

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Discriminator Finalization – Correctness

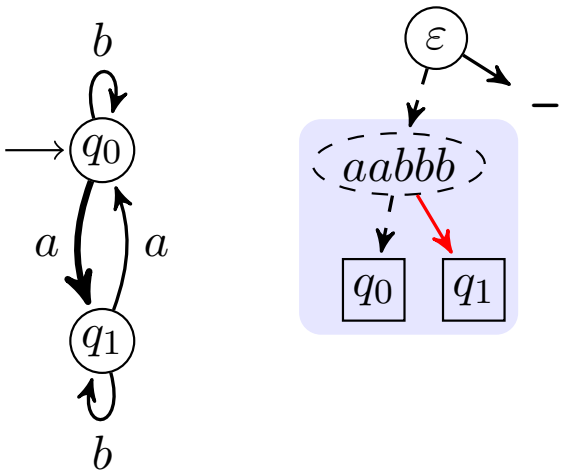
Q: Can we always find such q, q', a?

Discriminator Finalization – Correctness

Q: Can we always find such q, q', a?

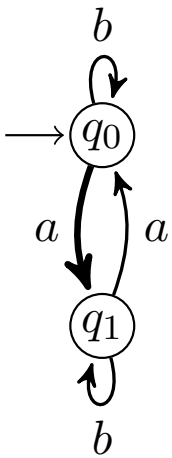
A: Not always - but then our hypothesis is wrong!

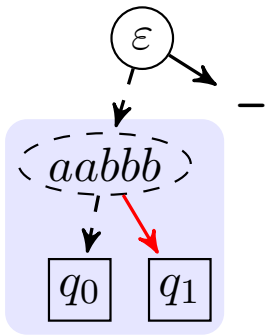
Instable Hypotheses

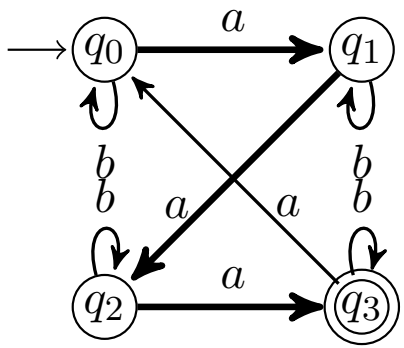


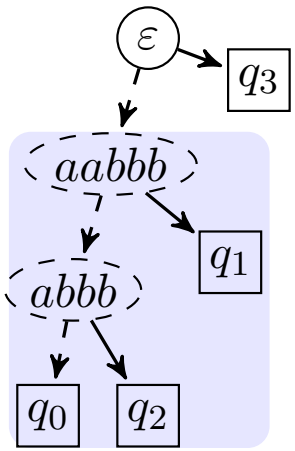
- Hypothesis contradicts correct information $\lambda(a \cdot aabbb) = 1$ (stored in DT)
- Non-canonical hypothesis
- Analyze counterexample $a \cdot aabbb/1$ ...

Instable Hypotheses



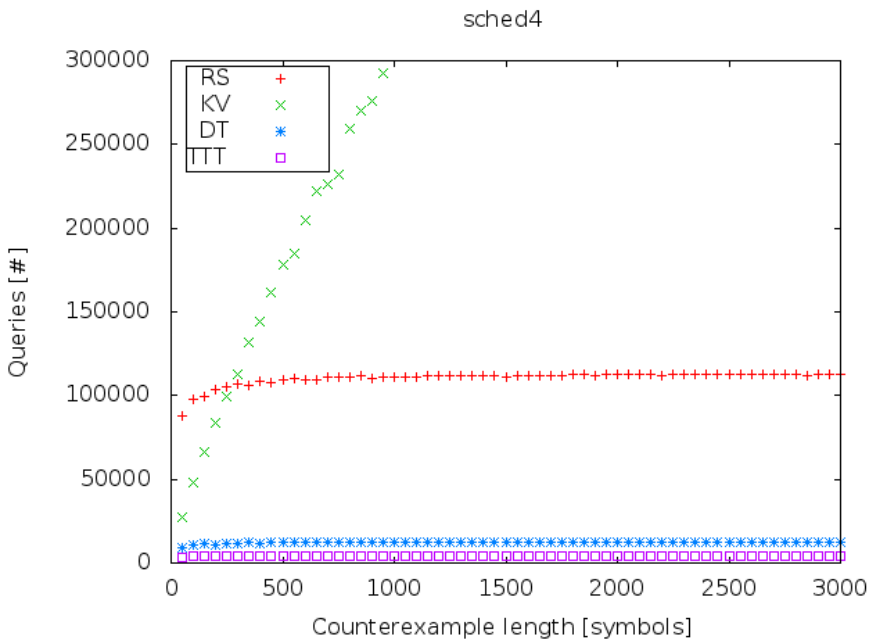


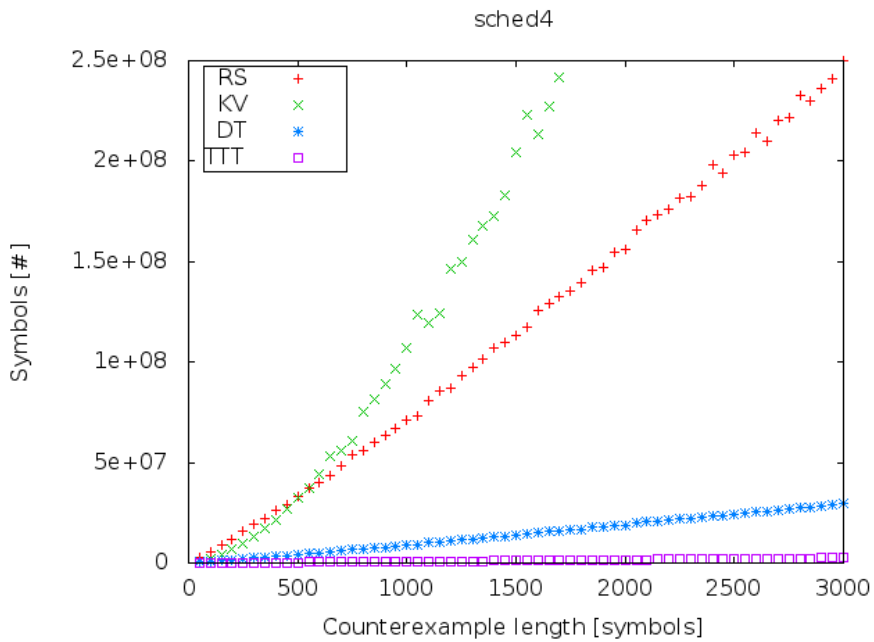




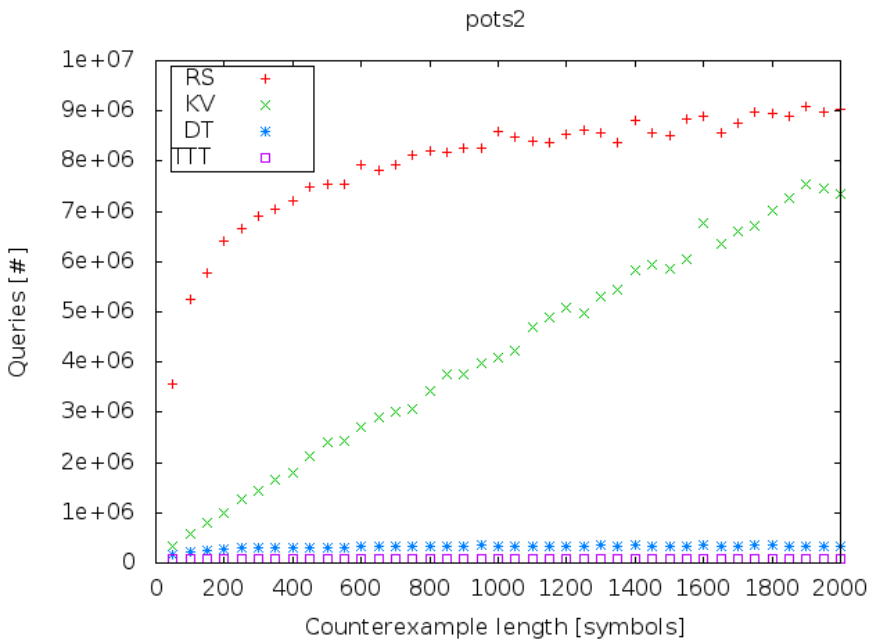
- Hypothesis contradicts correct information $\lambda(a \cdot aabbb) = 1$ (stored in DT)
- Non-canonical hypothesis
- Analyze counterexample $a \cdot aabbb/1$ ...

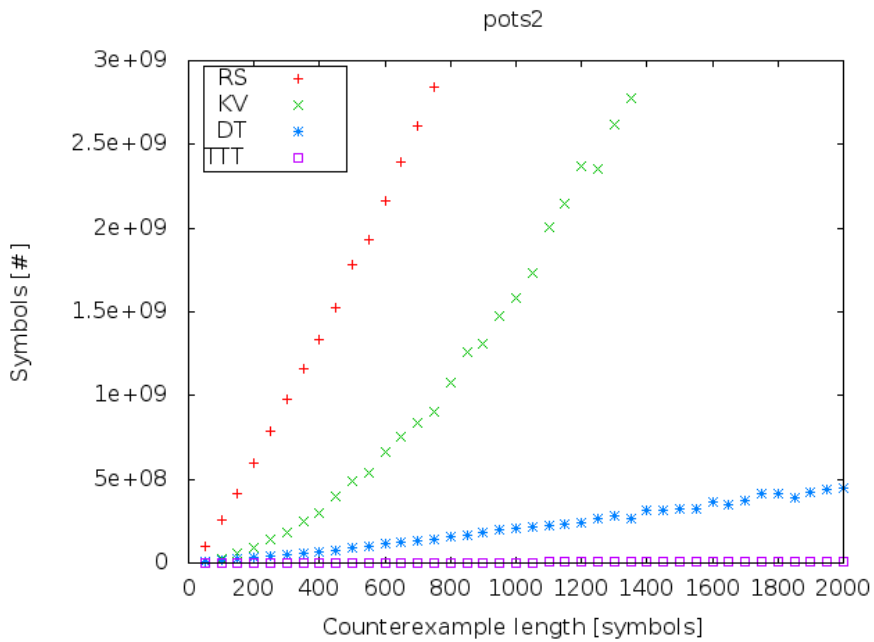
TTT – Some Results (1)





TTT – Some Results (2)





TTT – Some Results (3)

Alg.	RANDOM-10-100 ($\hat{n}/2 \leq \lvert w\rvert \leq 2\hat{n}$)			RANDOM-10-100 ($\lvert w\rvert = 500$)		
L^*	89518 (±31%)	8515147 (±58%)	3 (±0)	104428 (±43%)	25831586 (±44%)	1 (±0)
SUFFIX1BY1	29529 (±12%)	185567 (±19%)	4 (±1)	28817 (±11%)	201714 (±19%)	7 (±1)
RS	28051 (± 7%)	564633 (±59%)	3 (±0)	30286 (±13%)	1691647 (±81%)	1 (±0)
KV	22149 (± 6%)	1017847 (±23%)	12 (±2)	24128 (± 8%)	2370053 (±25%)	27 (±6)
DT	15203 (± 0%)	195958 (±14%)	7 (±1)	16624 (± 5%)	1154253 (±96%)	1 (±1)
TTT	14930 (± 0%)	123742 (± 8%)	8 (±2)	15142 (± 0%)	157407 (±23%)	2 (±1)
Alg.	RANDOM-20-200 ($\hat{n}/2 \leq \lvert w\rvert \leq 2\hat{n}$)			RANDOM-20-200 ($\lvert w\rvert = 500$)		
L^*	181389 (±28%)	16854213 (±53%)	3 (±0)	211490 (±38%)	52334184 (±40%)	1 (±0)
SUFFIX1BY1	59655 (±11%)	333687 (±18%)	4 (±1)	60977 (±12%)	377621 (±20%)	7 (±1)
RS	56158 (± 7%)	906177 (±57%)	2 (±0)	59250 (±10%)	1733102 (±70%)	1 (±0)
KV	36794 (± 3%)	1270735 (±20%)	11 (±2)	37757 (± 4%)	2654647 (±25%)	25 (±6)
DT	31030 (± 0%)	375067 (±13%)	6 (±1)	32987 (± 4%)	1637273 (±73%)	1 (±0)
TTT	30820 (± 0%)	230955 (± 9%)	7 (±1)	31086 (± 0%)	278940 (±15%)	1 (±1)
Alg.	SCHED4 ($\hat{n}/2 \leq \lvert w\rvert \leq 2\hat{n}$)			SCHED4 ($\lvert w\rvert = 500$)		
L^*	68377 (±16%)	3879529 (±27%)	12 (±0)	140906 (±35%)	35758545 (±35%)	2 (±0)
SUFFIX1BY1	46658 (±33%)	2188119 (±39%)	28 (±4)	—†	—	—
RS	11289 (±17%)	388726 (±25%)	36 (±6)	—†	—	—
KV	15921 (± 9%)	735843 (±14%)	71 (±3)	40181 (±15%)	7548726 (±18%)	18 (±2)
DT	4321 (± 8%)	165040 (±20%)	74 (±5)	10647 (± 1%)	3758972 (± 5%)	18 (±2)
TTT	3429 (±11%)	124984 (±37%)	73 (±3)	2449 (± 0%)	77177 (± 6%)	18 (±2)

Outline

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- Website: `http://learnlib.de`
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  - Check out the Wiki for a quick setup guide

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Demo after coffee break