Active Automata Learning

Formal Methods for Efficient Model Inference

28/11/2024

Motivation of Black-Box Automata Learning

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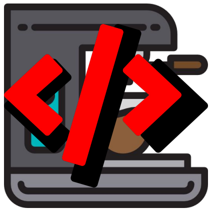

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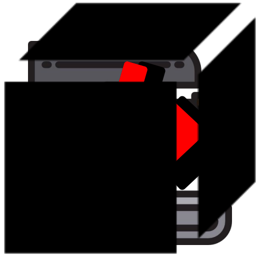

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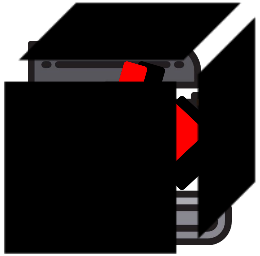

Testing? Verification? Understanding?

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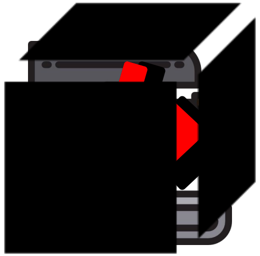
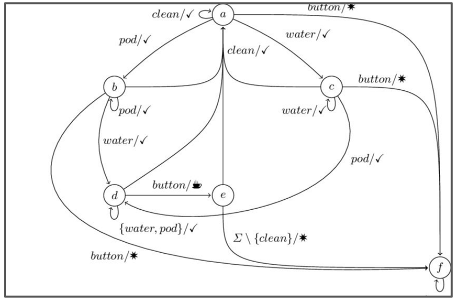
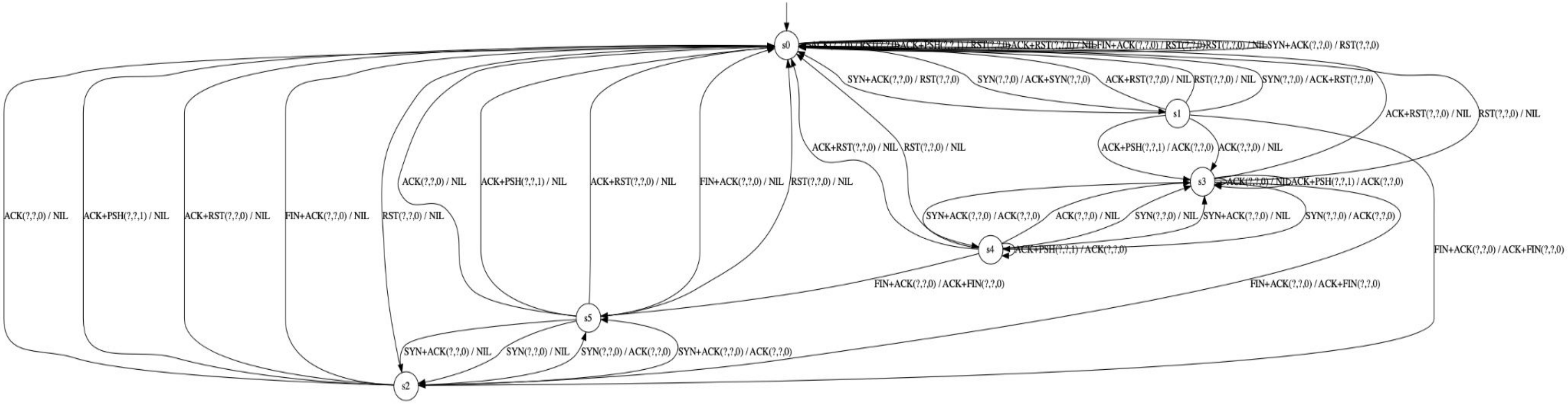


Testing? Verification? Understanding?

Use Automata to
Represent the System
(Explainable and Readable)

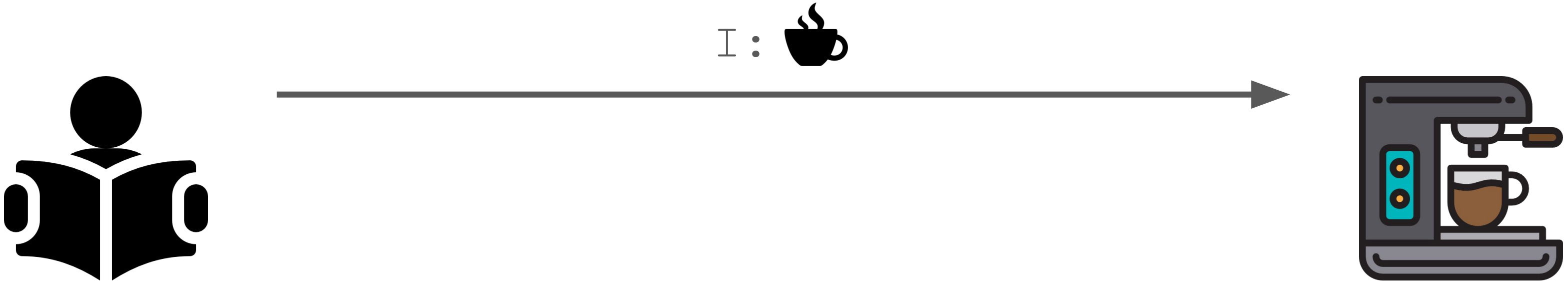


Motivation of Black-Box Automata Learning - Example



A high-level overview

“Learning” Automata



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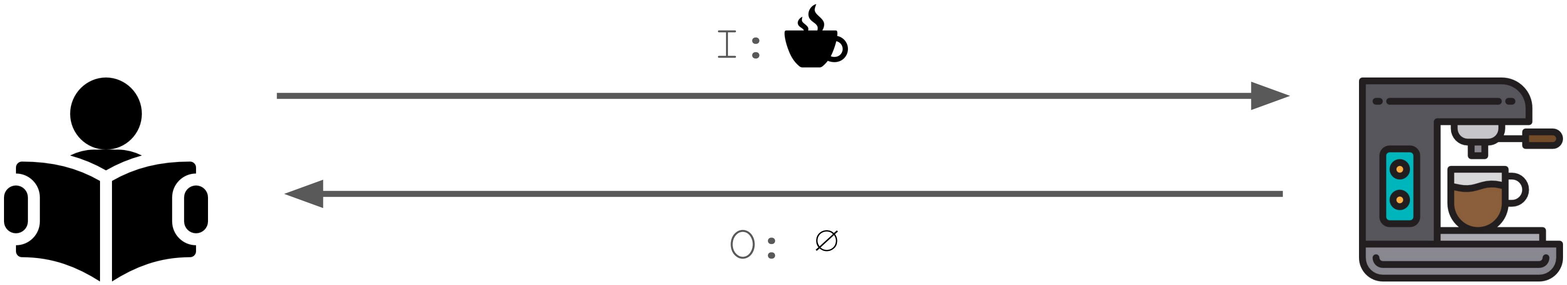

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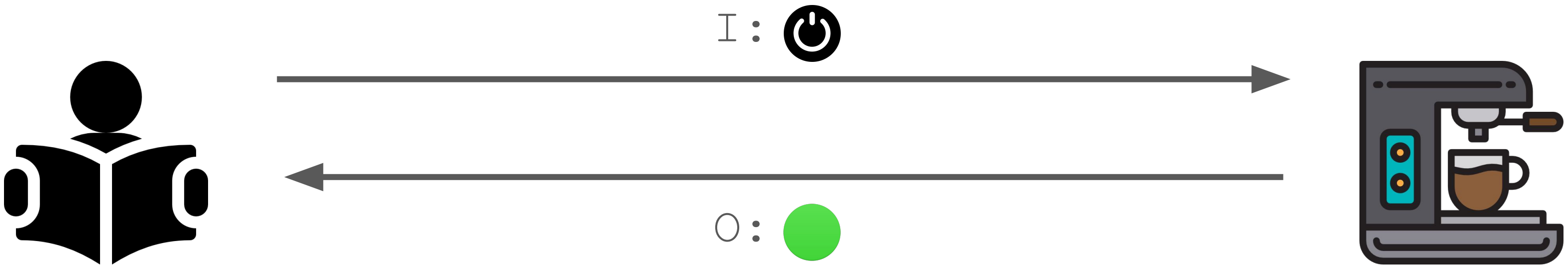

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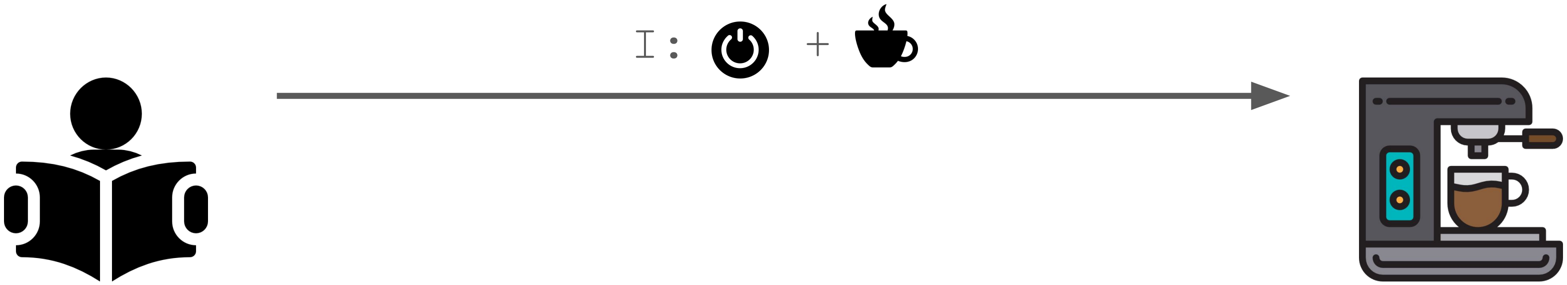

“Learning” Automata

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. . .

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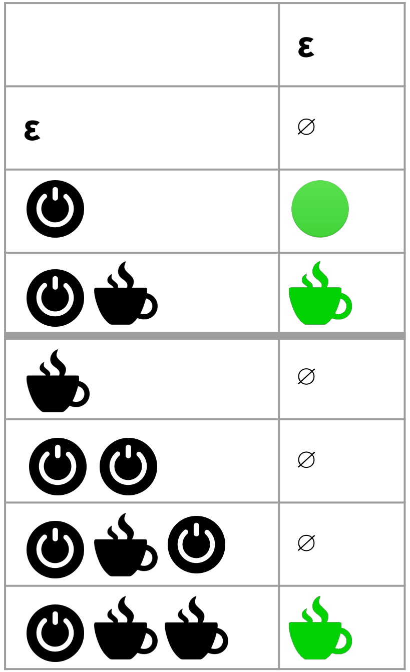

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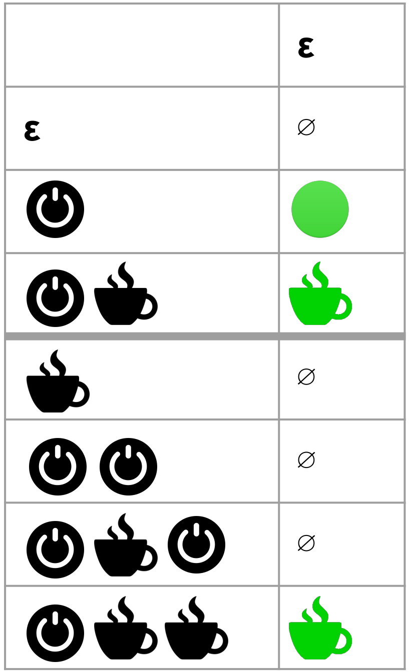

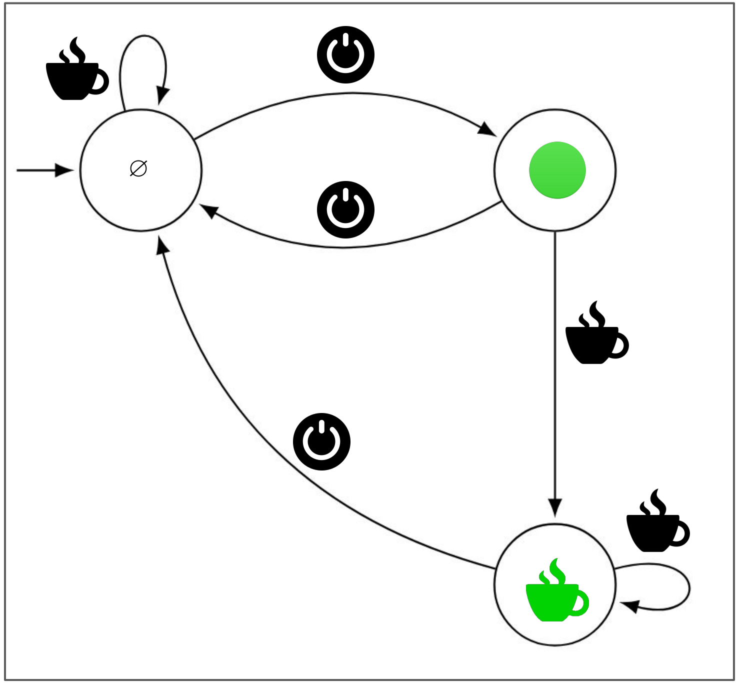

The details

Back to Basics: DFA

A deterministic finite automaton M *is a tuple* $(Q, q_0, \Sigma, \delta, F)$, *where:*

- Q *is a finite set of states*
- $q_0 \in Q$ *is an initial state*
- Σ *is an alphabet*
- $\delta : Q \times \Sigma \to Q$ *is a transition function*
- $F \subseteq Q$ *is a set of final/accepting states*

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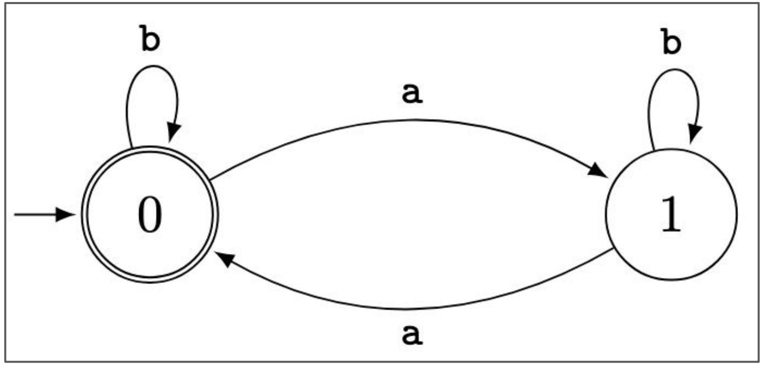

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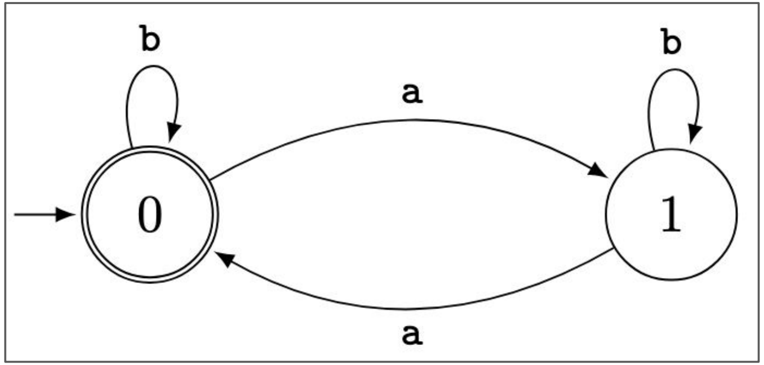
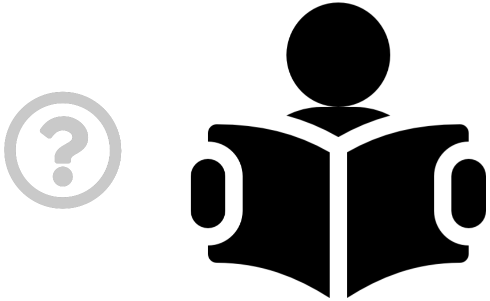
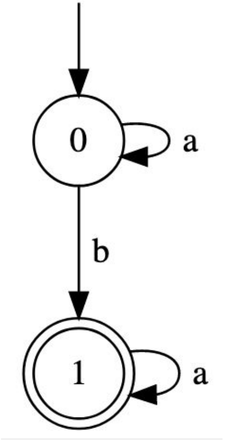


* missing transitions lead to sink state

Basic Framework: Minimally Adequate Teacher (MAT)



Learner

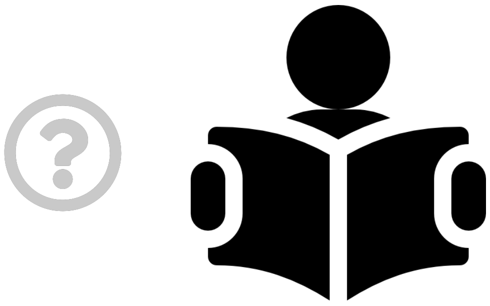


Teacher

Basic Framework: Minimally Adequate Teacher (MAT)

Membership Query

a ?



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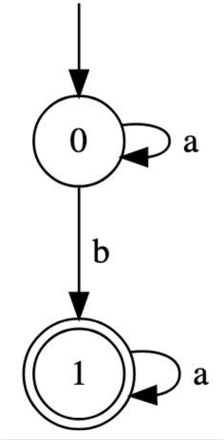

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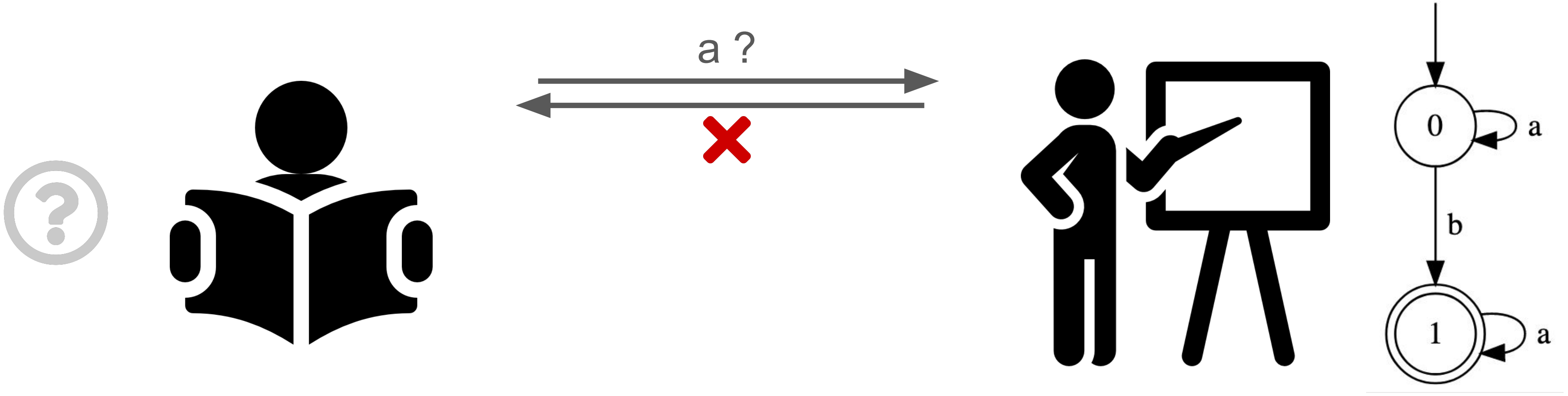

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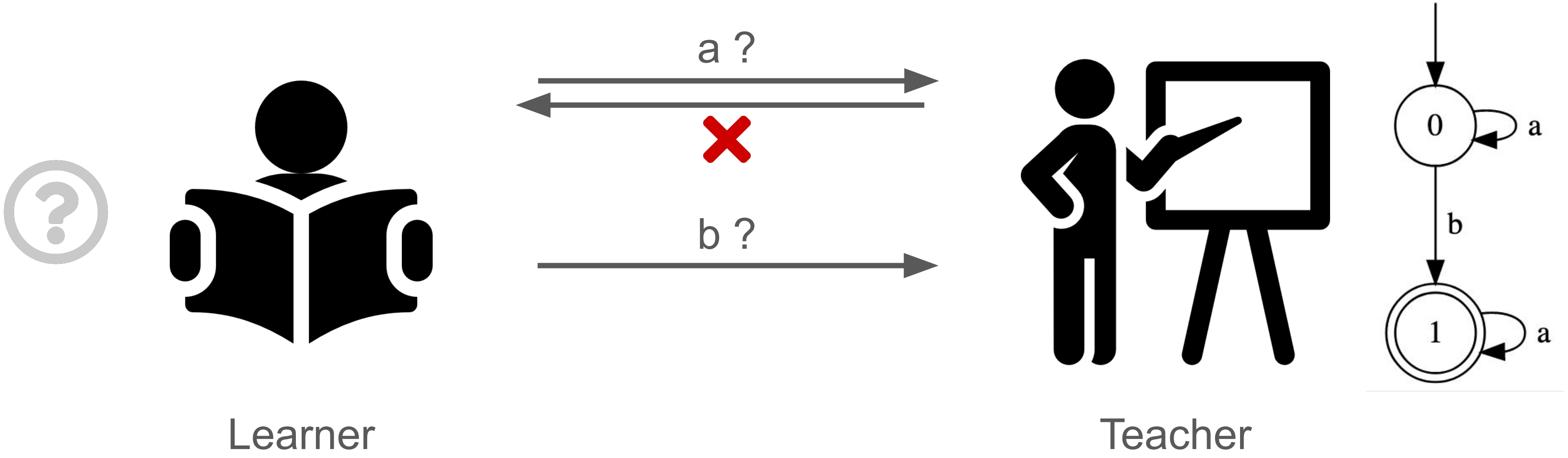

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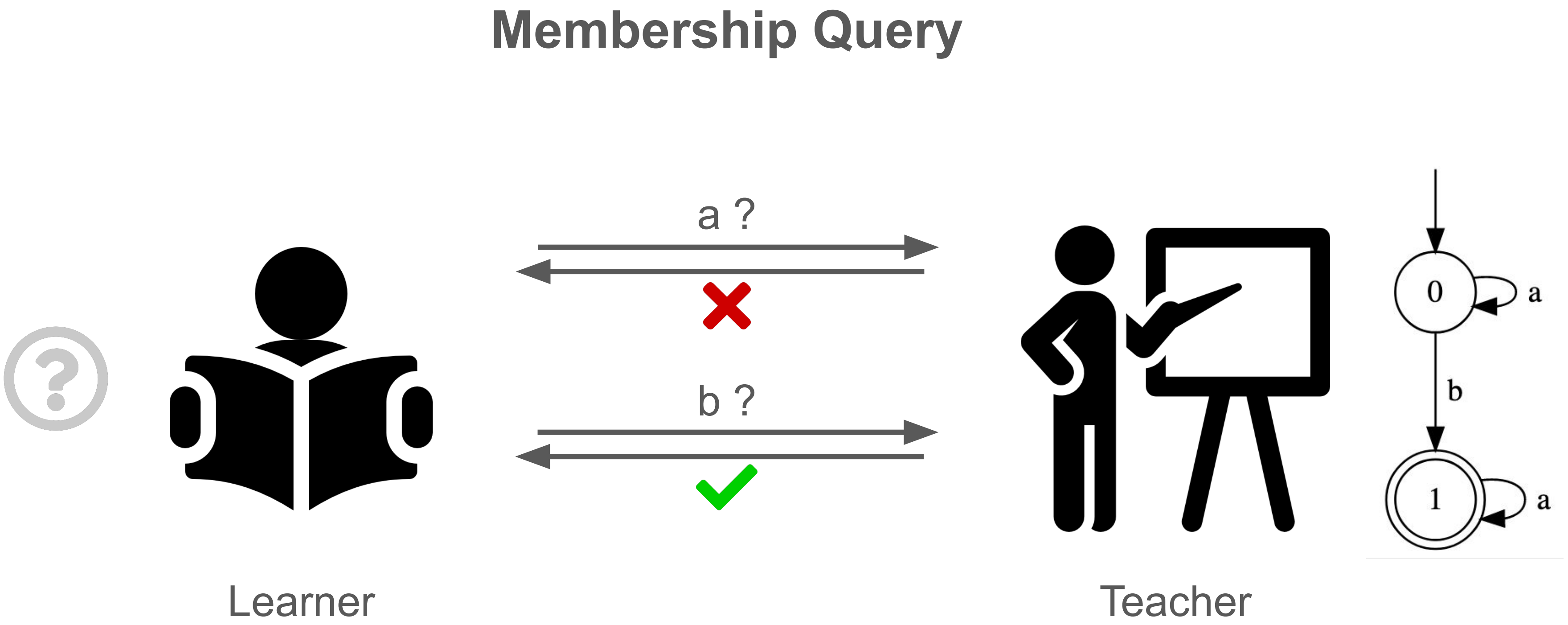

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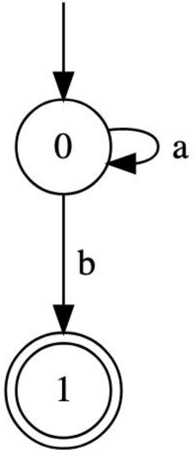
Hypothesis



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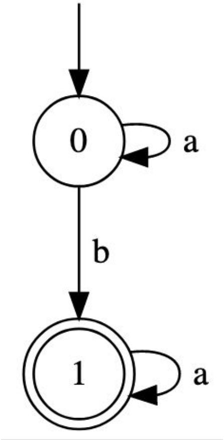

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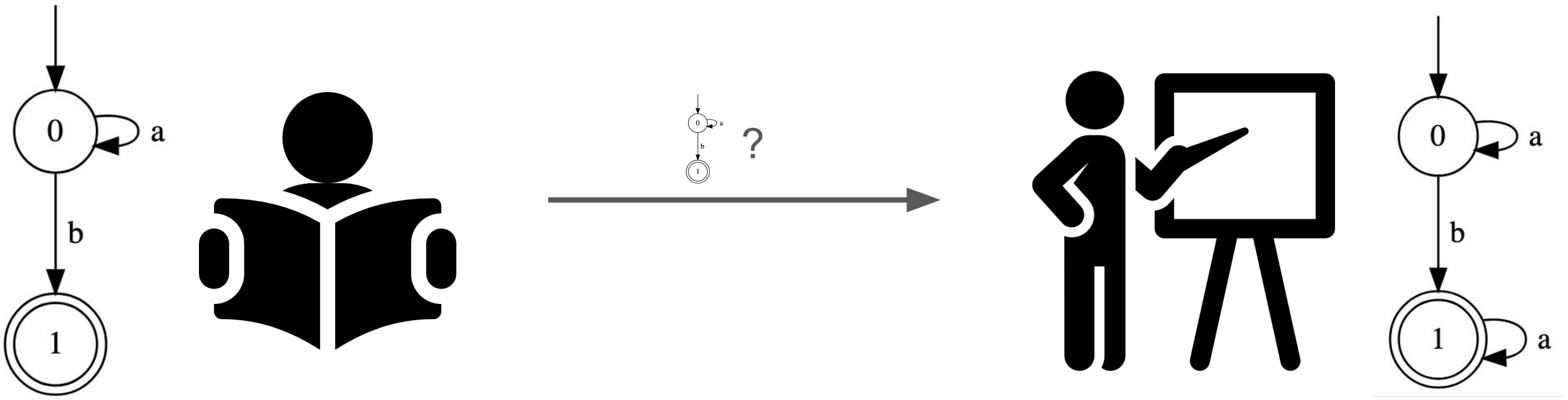
Equivalence Query



Learner

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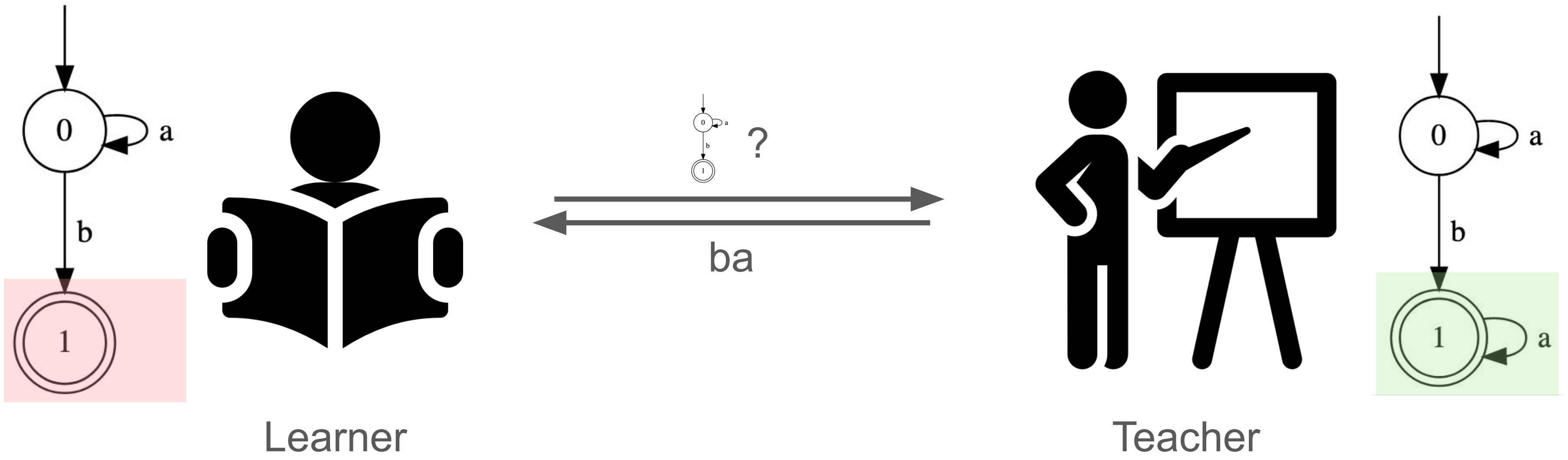
Equivalence Query



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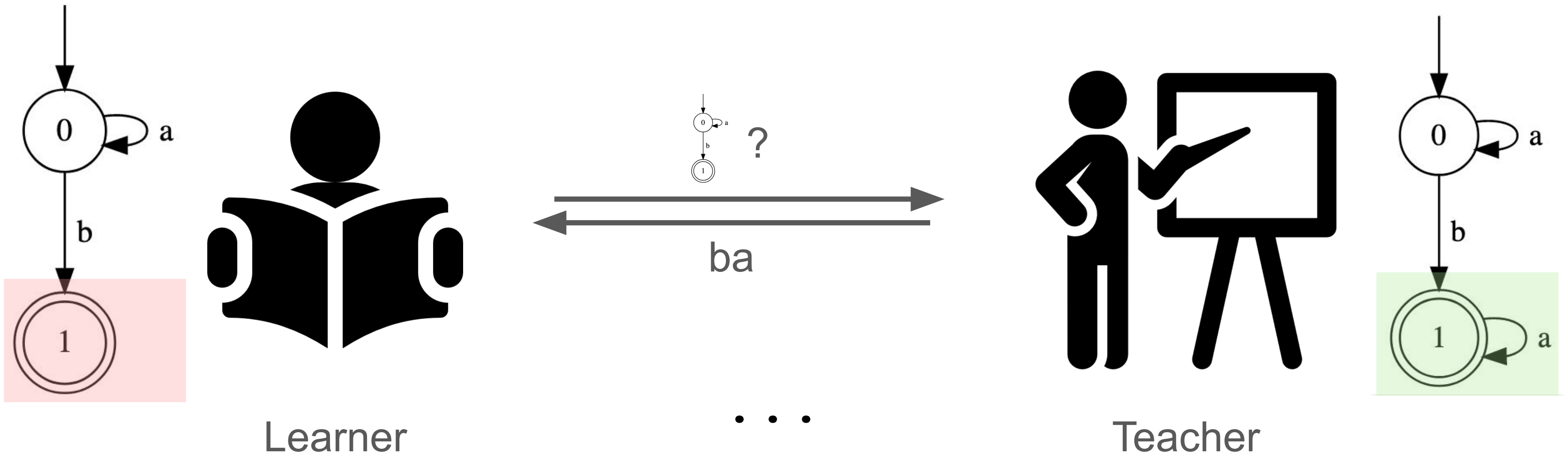
Equivalence Query



MAT: Observation Table

An observation table is a tuple (S, E, T)*, where:*

- S, E *are non-empty finite sets of strings*
- T *is a mapping* $((S \cup S \cdot \Sigma) \cdot E) \to \{\top, \bot\}$

The table structure can be represented visually as:

	E
S	
$S \cdot \Sigma$	

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S	
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		E	
		ε	b
S	ε	1	0
	b	0	0
	bb	0	1
	bbb	1	0
S · Σ	a	1	0
	ba	0	0
	bba	0	1
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	bbbb	0	0

Example. Σ = {a, b}

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	E
S	
$S \cdot \Sigma$	

row(ε) = 1 0
row(b) = 0 0
row(ε) = row(bbb)

	ε	b
ε	1	0
b	0	0
bb	0	1
bbb	1	0
a	1	0
ba	0	0
bba	0	1
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When an observation table is closed and consistent, we can define a minimal DFA where:

$$Q = \{row(s) : s \in S\} \qquad F = \{row(s) : s \in S \wedge T(s) = 1\}$$

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	ε	a
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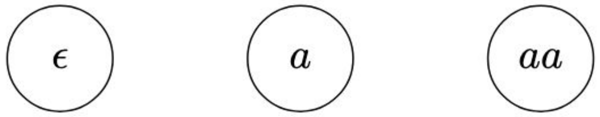

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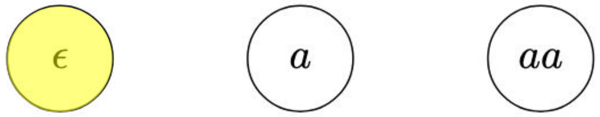

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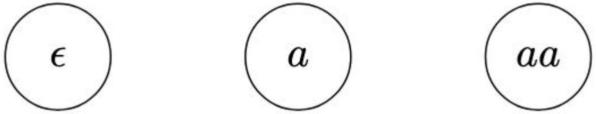

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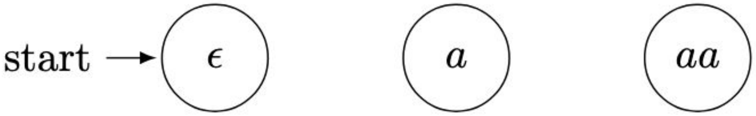

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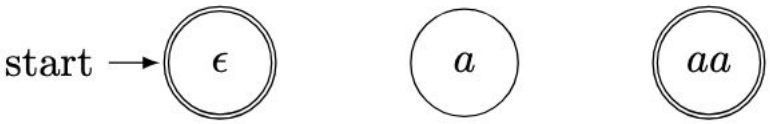

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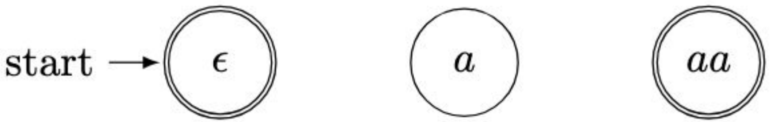

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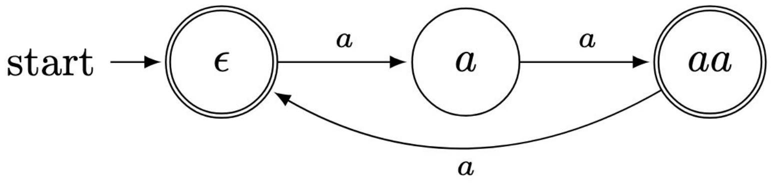

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ε	1	1
b	0	1
a	1	1
ba	0	1
bb	0	0

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The rows in $S \cdot \Sigma$ not in S are added to S and the table is extended.

	ε	a
ε	1	1
b	0	1
a	1	1
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	ε	a
ε	1	1
b	0	1
a	1	1
ba	0	1
bb	0	0

$\longrightarrow$

	ε	a
ε	1	1
b	0	1
bb	0	0
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...		

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	ε	a
ε	1	1
a	1	1
b	1	0
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The $a \in \Sigma$ for which $row(s_1 \cdot a) \neq row(s_2 \cdot a)$ and the $e \in E$ such that $T(s_1 \cdot a \cdot e) \neq T(s_2 \cdot a \cdot e)$ are found, the string $a \cdot e$ is added to E and the table is extended.

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

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

MAT: Observation Table (Consistent)

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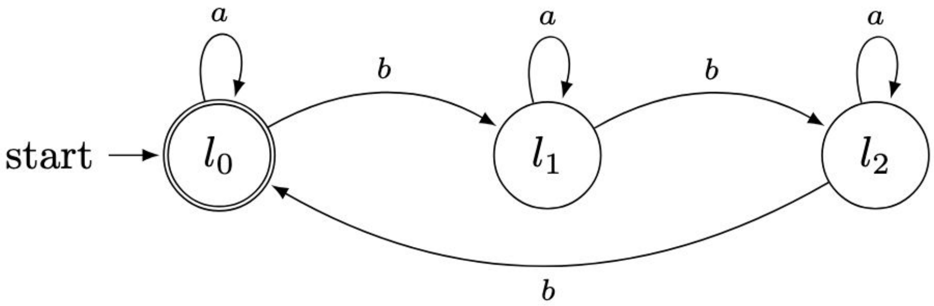
ε	1	1	1
a	1	1	0
b	1	0	0
ba	0	0	0
aa	1	0	1
ab	1	0	0
bb	0	0	0
...			

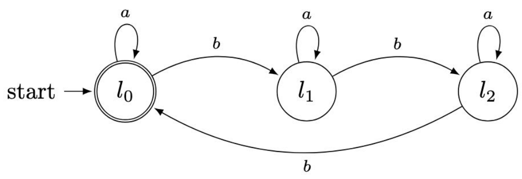
Now a learning example!

MAT: An Example



DFA that accepts strings with a number of b multiple of 3

MAT: An Example



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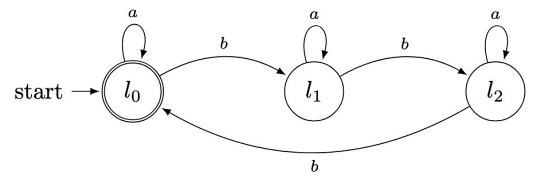
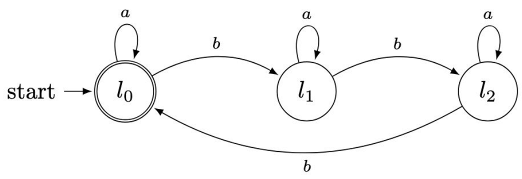


DFA that accepts strings with a number of b multiple of 3

	ε
ε	1
a	1
b	0

Initial table

MAT: An Example



DFA that accepts strings with a number of b multiple of 3

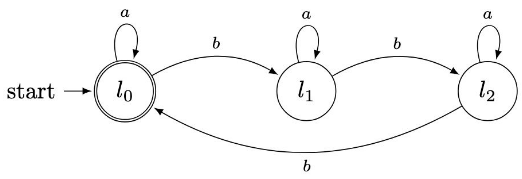
	ε
ε	1
a	1
b	0

Initial table

	ε
ε	1
b	0
a	1
ba	0
bb	0

Closed (and consistent)

MAT: An Example



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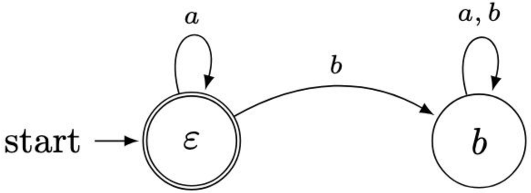
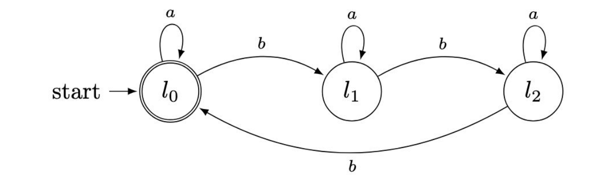


First hypothesis

MAT: An Example



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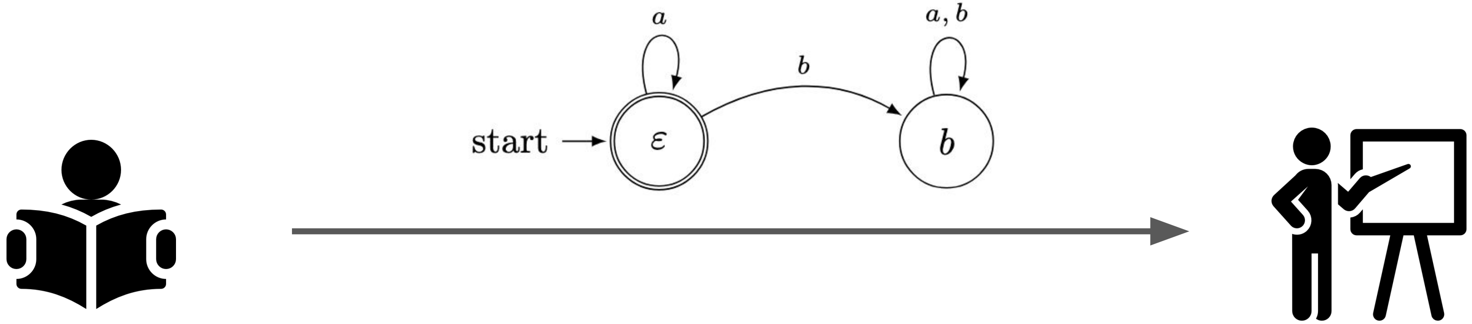
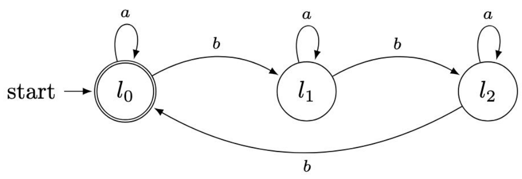


MAT: An Example



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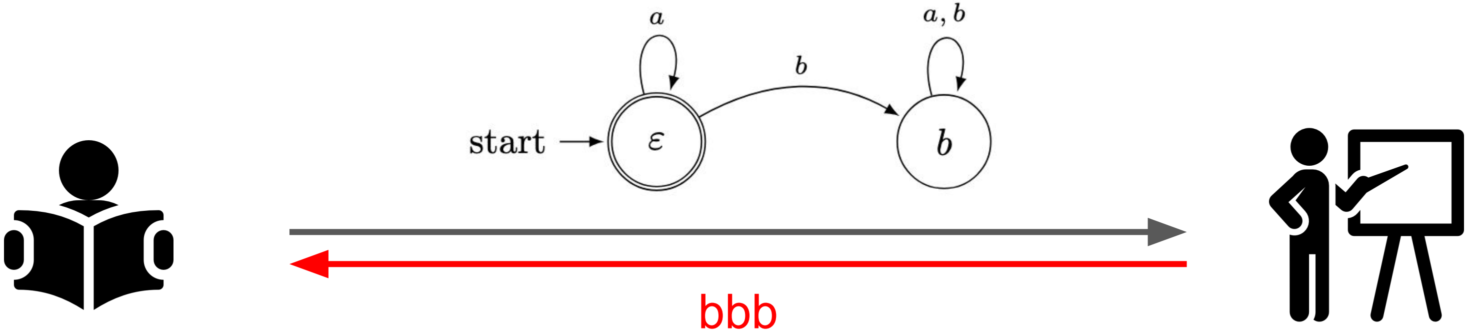

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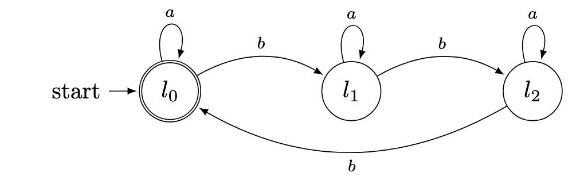

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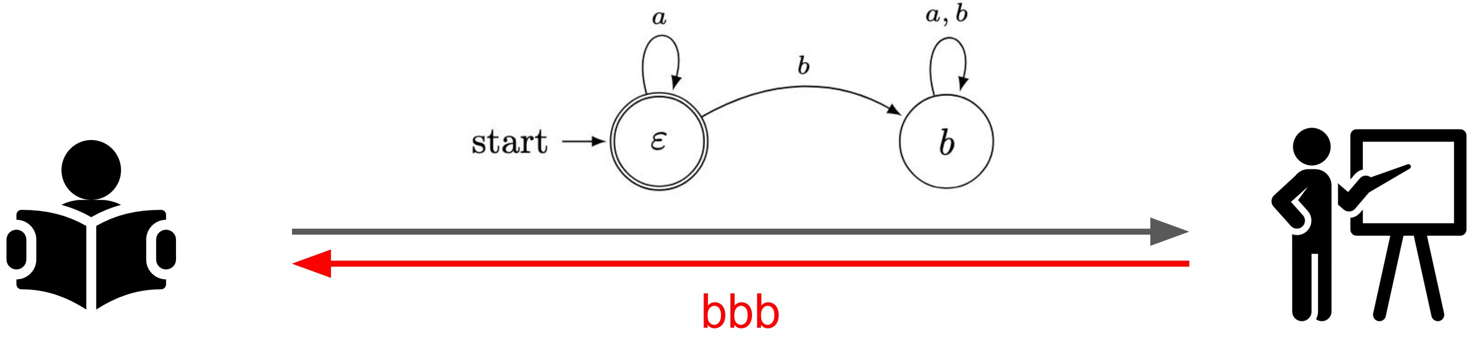
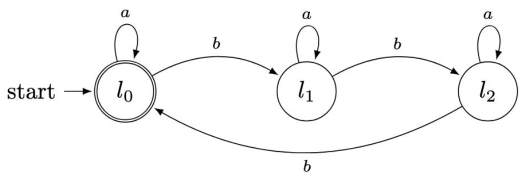


Add counterexample (and all its prefixes) to S

MAT: An Example

	ε
ε	1
b	0
bb	0
bbb	1
a	1
ba	0
bba	0
bbba	1
bbbb	0

Extended with cex

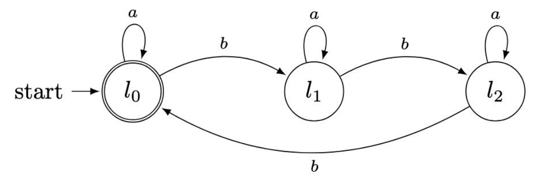


DFA that accepts strings with a number of b multiple of 3

MAT: An Example

	ε
ε	1
b	0
bb	0
bbb	1
a	1
ba	0
bba	0
bbba	1
bbbb	0

Extended with cex



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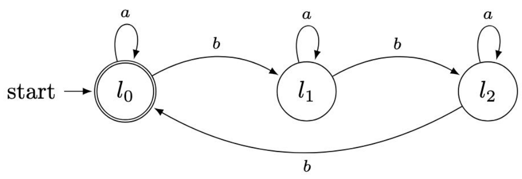

DFA that accepts strings with a number of b multiple of 3

	ε
ε	1
b	0
bb	0
bbb	1
a	1
ba	0
bba	0
bbba	1
bbbb	0

Extended with cex

	ε	b
ε	1	0
b	0	0
bb	0	1
bbb	1	0
a	1	0
ba	0	0
bba	0	1
bbba	1	0
bbbb	0	0

Consistent

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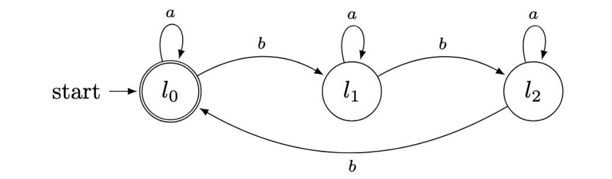

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ε	1
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bb	0
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Extended with cex

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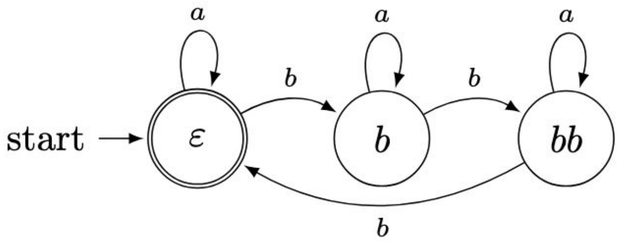
Consistent



Final hypothesis

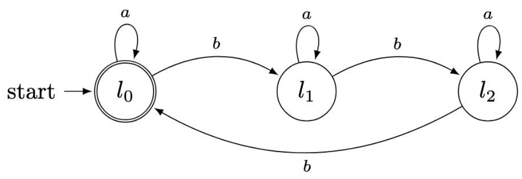
MAT: An Example

	ε
ε	1
b	0
bb	0
bbb	1
a	1
ba	0
bba	0
bbba	1
bbbb	0

Extended with cex

	ε	b
ε	1	0
b	0	0
bb	0	1
bbb	1	0
a	1	0
ba	0	0
bba	0	1
bbba	1	0
bbbb	0	0

Consistent



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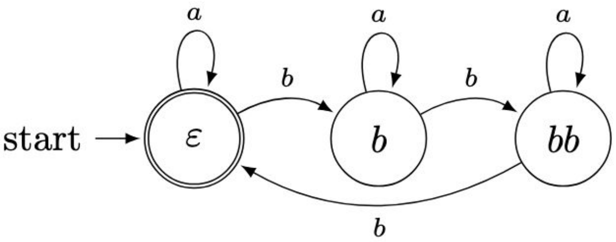

Final hypothesis

MAT: Correctness, Minimality, Termination

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MAT: Alternative to Observation Table

- Classification/Discrimination Tree

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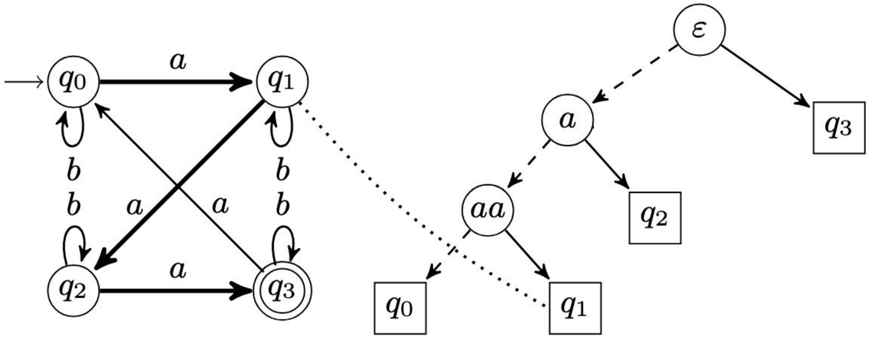

Great! Now some issues…

Problems with MAT In Real-World Environments

Equivalence query?

Teacher vs. System?

Problems with MAT In Real-World Environments

Equivalence query?

Teacher vs. System?

Environment Noise?

Evolving System?

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Conflict

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A ***conflict*** appears when a query's answer formally contradicts a previous query in a way that cannot be expressed by a model of the target class.

Ex.: two different answers for the same query

State of the art: cannot survive conflicts

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In practice: repeating queries so that <u>no conflict</u> reaches the learner

- Exponential growth…
  - Of the number of repeats based on the probability of a conflict reaching the learner
  - Linear increase of noise leads to an exponential increase of the number of repeats

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In practice: repeating queries so that <u>no conflict</u> reaches the learner

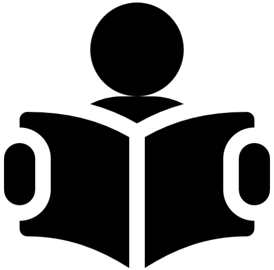
Exponential growth…

Of the number of repeats based on the probability of a conflict reaching the learner

Linear increase of noise leads to an exponential increase of the number of repeats

If only we could allow a few conflicts…

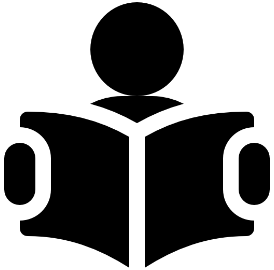
New Framework: C3AL



Learner

Teacher

New Framework: C3AL



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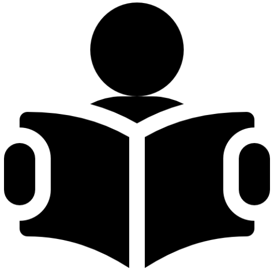

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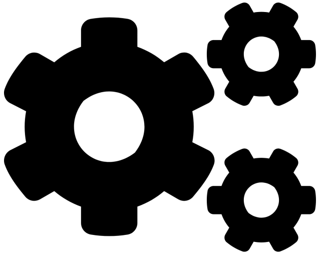
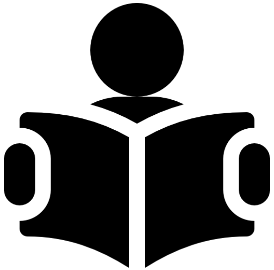
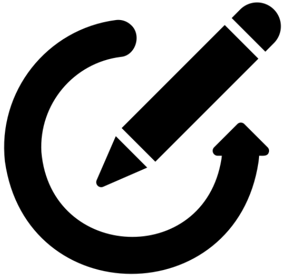


System

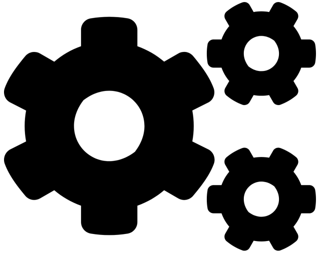
New Framework: C3AL



Learner

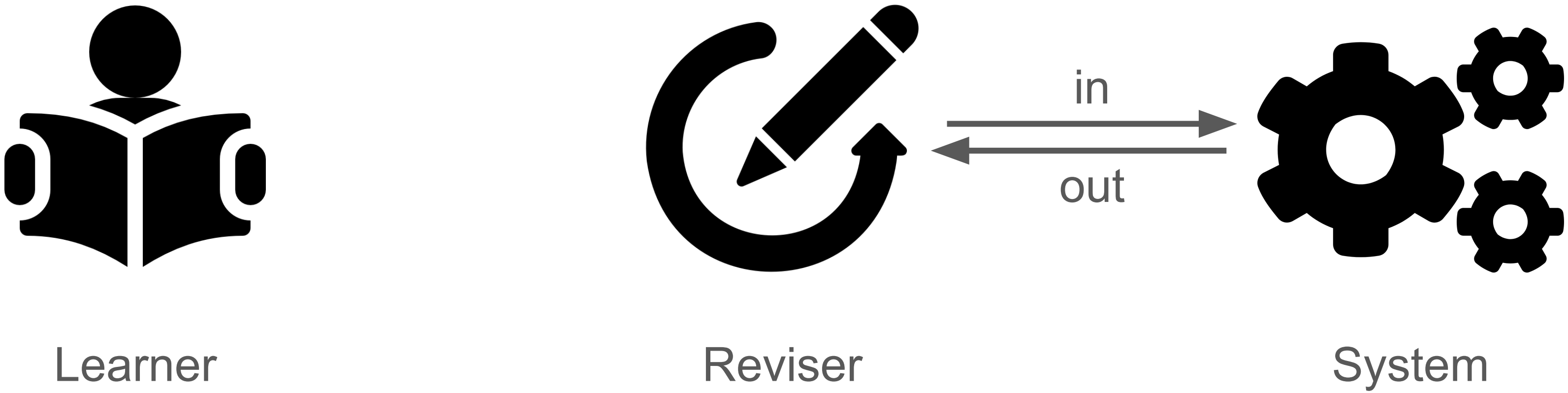


Reviser

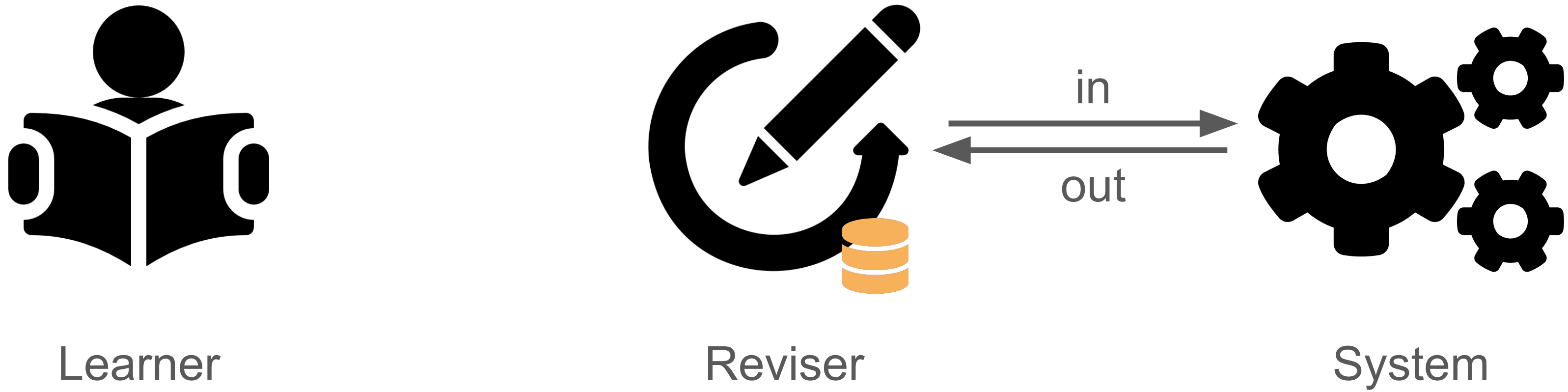


System

New Framework: C3AL



New Framework: C3AL



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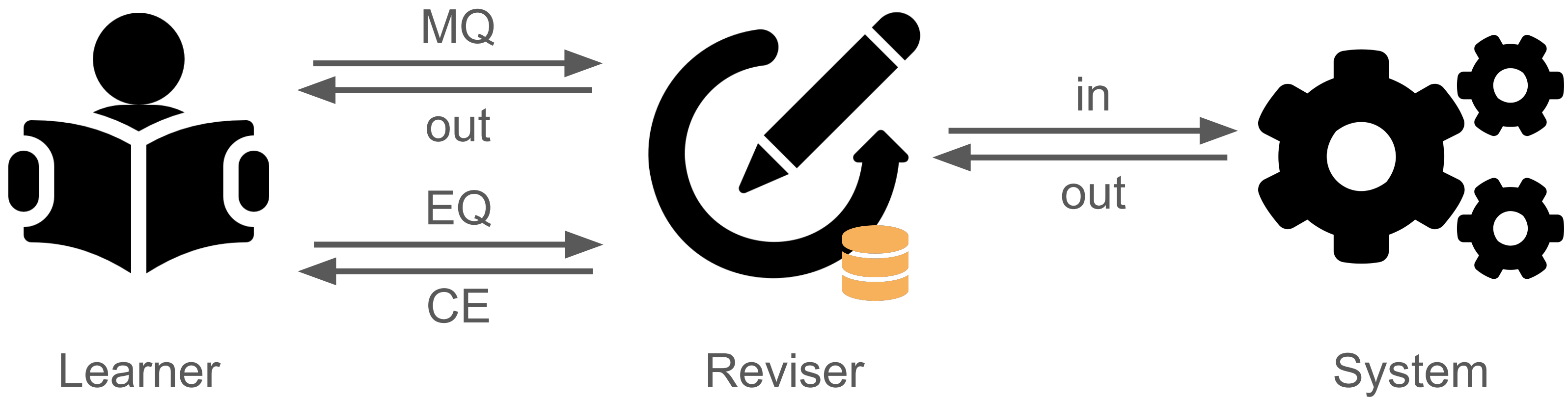

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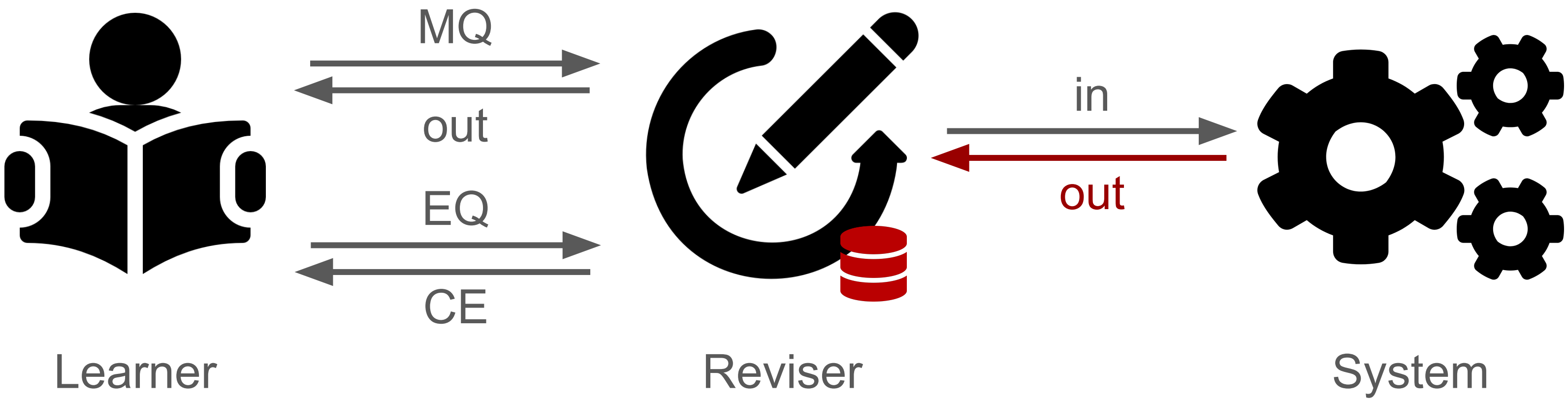

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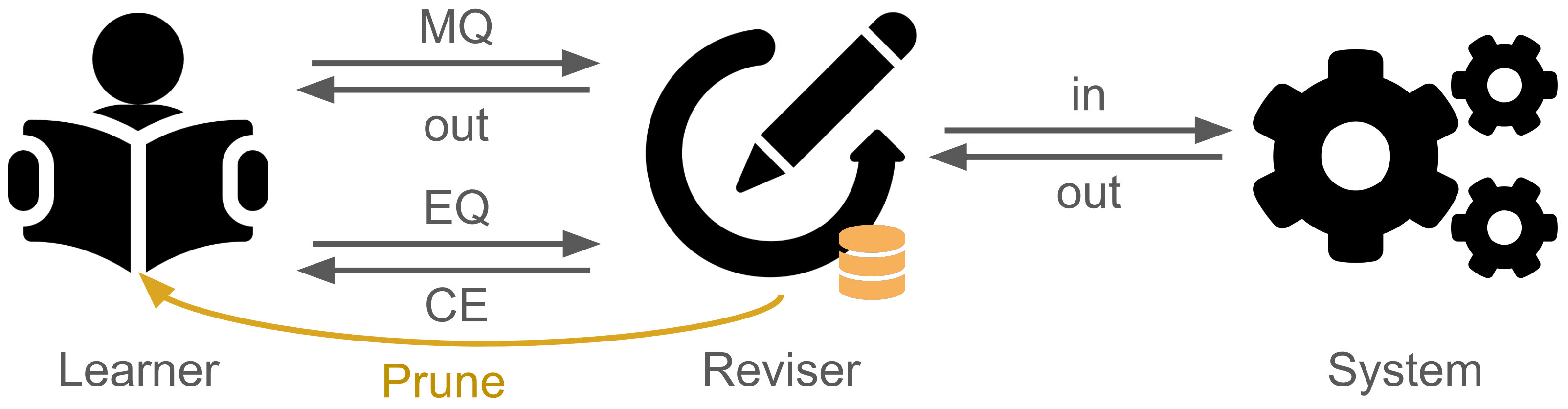

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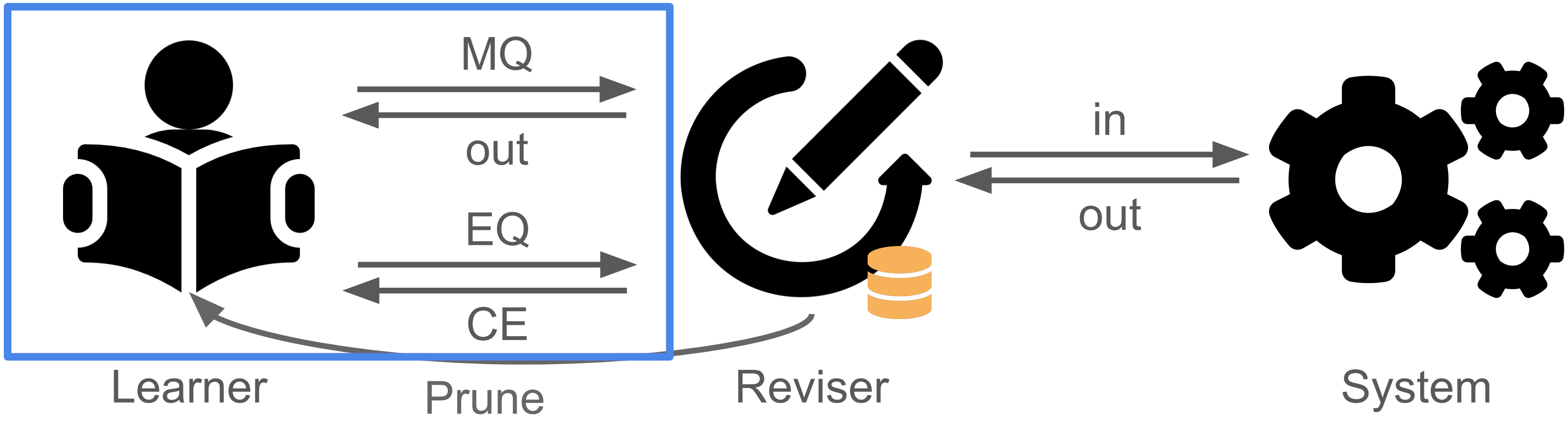

Compatible with state-of-the-art MAT Learners!

Practical Considerations

Reviser Strategy? (conflict management)

Most Recent vs. *Most Frequent* Answer

Practical Considerations

Reviser Strategy? (conflict management)

Most Recent vs. *Most Frequent* Answer

Efficiency of Prune?

No system tests during re-learning, information storage ≠ learning

C3AL vs MAT

C3AL vs MAT

- C3AL <u>more reliable</u> for higher levels of noise and bigger target systems
    - 96% success compared to 80% for MAT
        - noise between 0% and 0.1%
        - between 4 and 66 states
        - alphabet sizes between 7 and 22 input symbols

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        - alphabet sizes between 7 and 22 input symbols
- C3AL provides the <u>most efficient correct model in 70% of the experiments</u>
    - C3AL has on average a 6% reduction in the number of system tests
- We’re now able to learn **large systems that are noisy/evolving !**

LearnLib

https://learnlib.de/pages/tools

Tools

The following projects are listed in alphabetical order.

- **C3AL** (Conflict-Aware Active Automata Learning, link) is an alternative to the MAT framework that treats conflicts (e.g., in noisy environments) as first-class citizens. It is implemented on top of LearnLib and extends previous work on adaptive model learning.

Resources

- Frits Vaandrager. 2017. “Model learning”. https://doi.org/10.1145/2967606
- Dana Angluin. 1987. “Learning regular sets from queries and counterexamples”. https://doi.org/10.1016/0890-5401(87)90052-6
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- M. Isberner , F. Howar, B. Steffen. 2014. “The TTT Algorithm: A Redundancy-Free Approach to Active Automata Learning”. In: Bonakdarpour, B., Smolka, S.A. (eds) Runtime Verification. RV 2014. Lecture Notes in Computer Science, vol 8734. Springer, Cham. https://doi.org/10.1007/978-3-319-11164-3_26
- Tiago Ferreira, Harrison Brewton, Loris D'Antoni, and Alexandra Silva. 2021. “Prognosis: closed-box analysis of network protocol implementations”. In SIGCOMM '21. https://doi.org/10.1145/3452296.3472938
- Tiago Ferreira, Léo Henry, Raquel Fernandes da Silva, Alexandra Silva. 2023. “Conflict-Aware Active Automata Learning”. https://doi.org/10.48550/arXiv.2308.14781

Thank you!