Automata Learning with an Incomplete Teacher

ECOOP 2023

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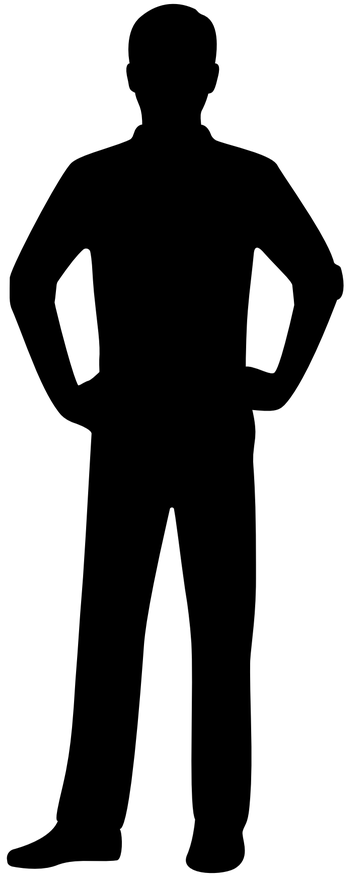
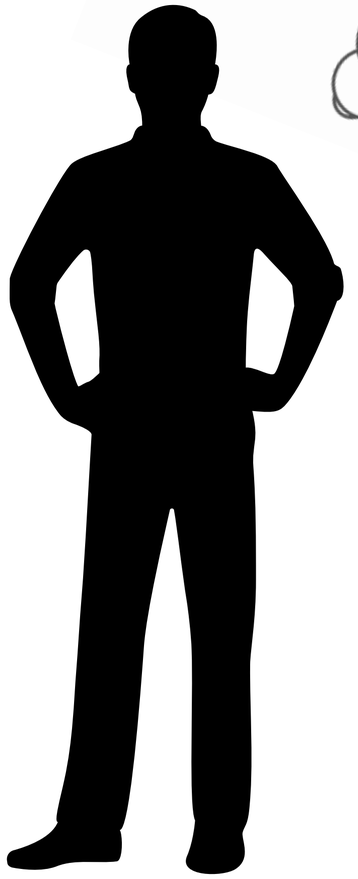
Thomas Wiener *Cornell University*
Alaia Solko-Breslin *University of Pennsylvania*
Caleb Koch *Stanford University*
Nate Foster *Cornell University*
Alexandra Silva *Cornell University*

19 July 2023



Regular

$L \subseteq \{a, b\}^*$



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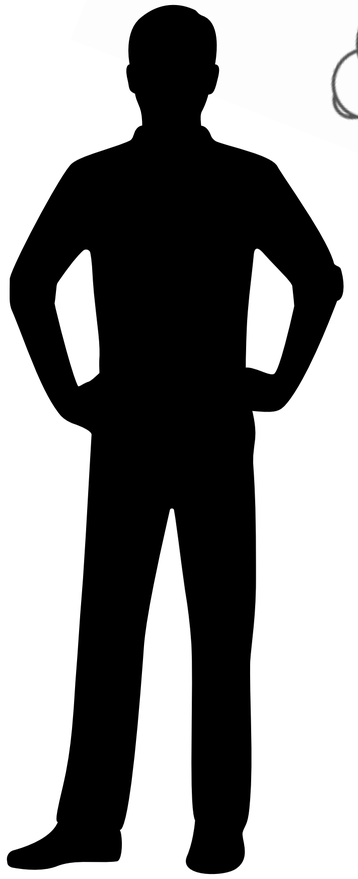
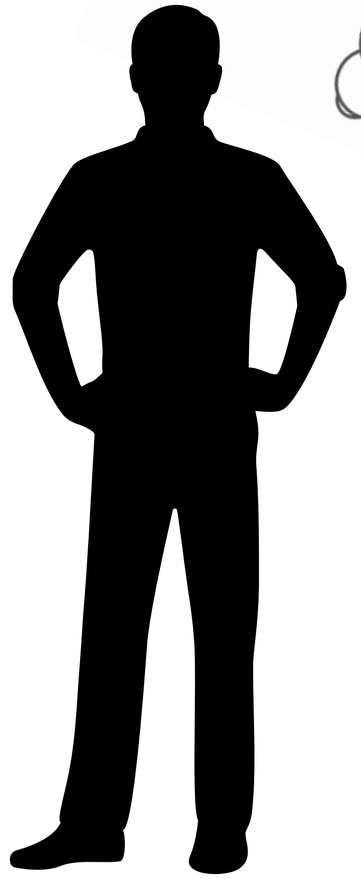


1. You can ask if a given string is in L

Regular

$L \subseteq \{a, b\}^*$

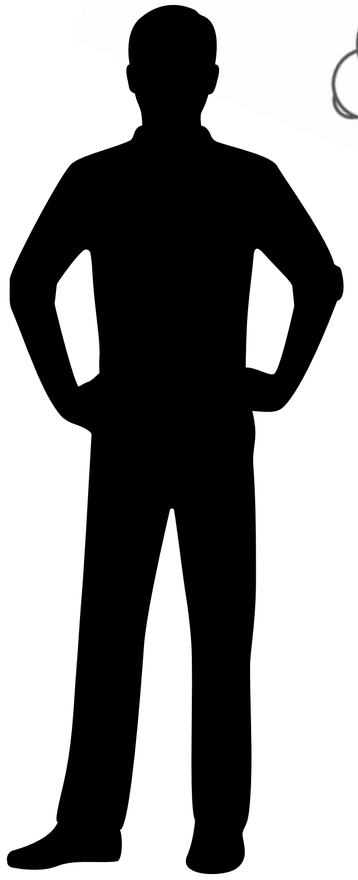


1. You can ask if a given string is in L
2. You can guess a DFA for L

$\varepsilon \in L?$

Regular

$L \subseteq \{a, b\}^*$



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$\varepsilon \in L?$

Yes

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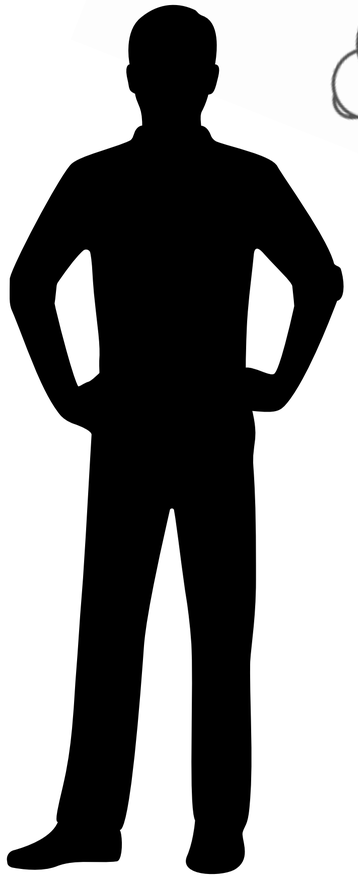

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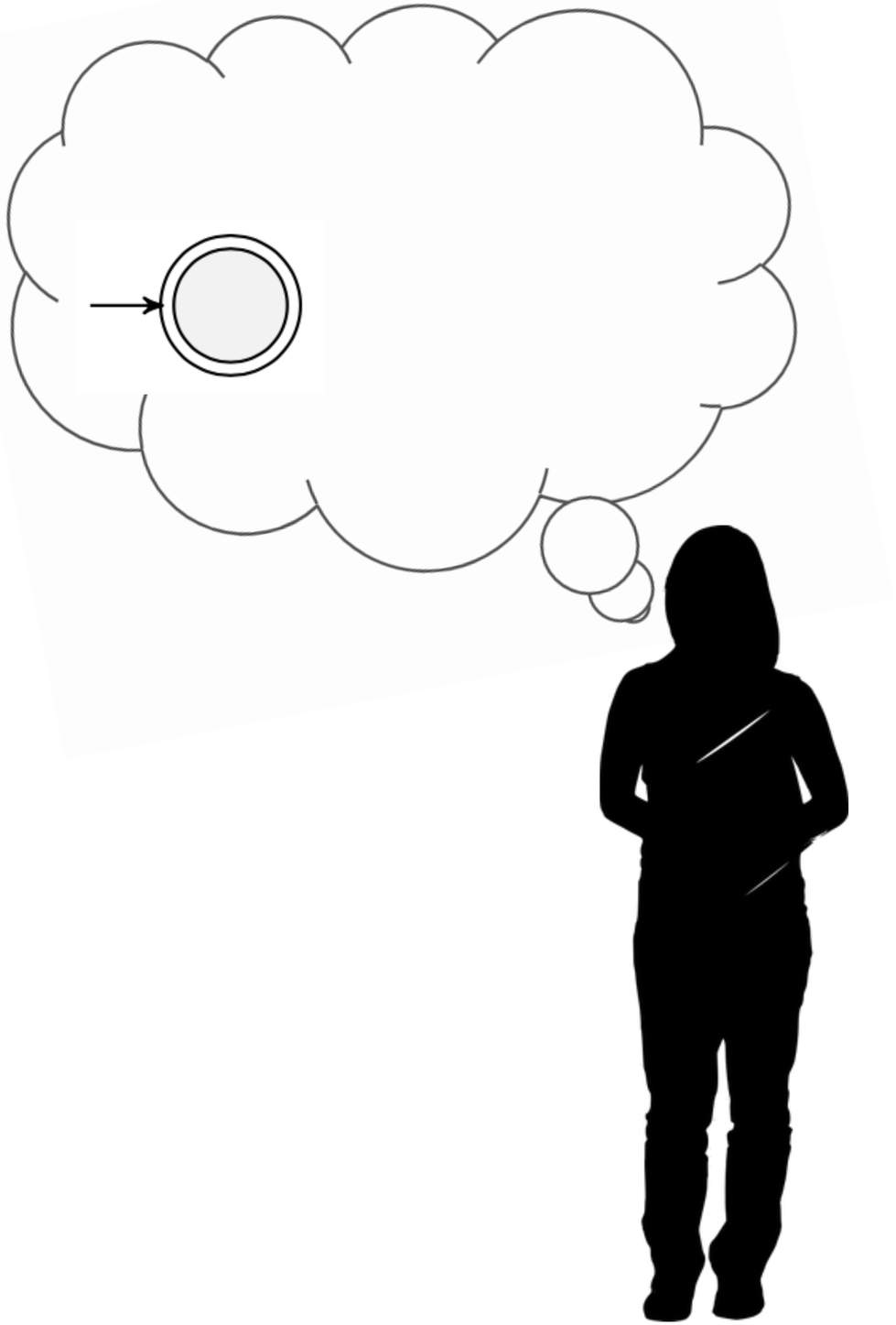
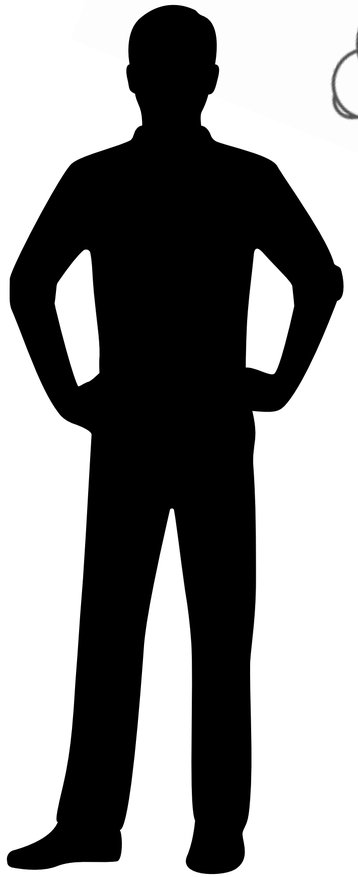


$\varepsilon \in L?$

Yes

Regular

$L \subseteq \{a, b\}^*$



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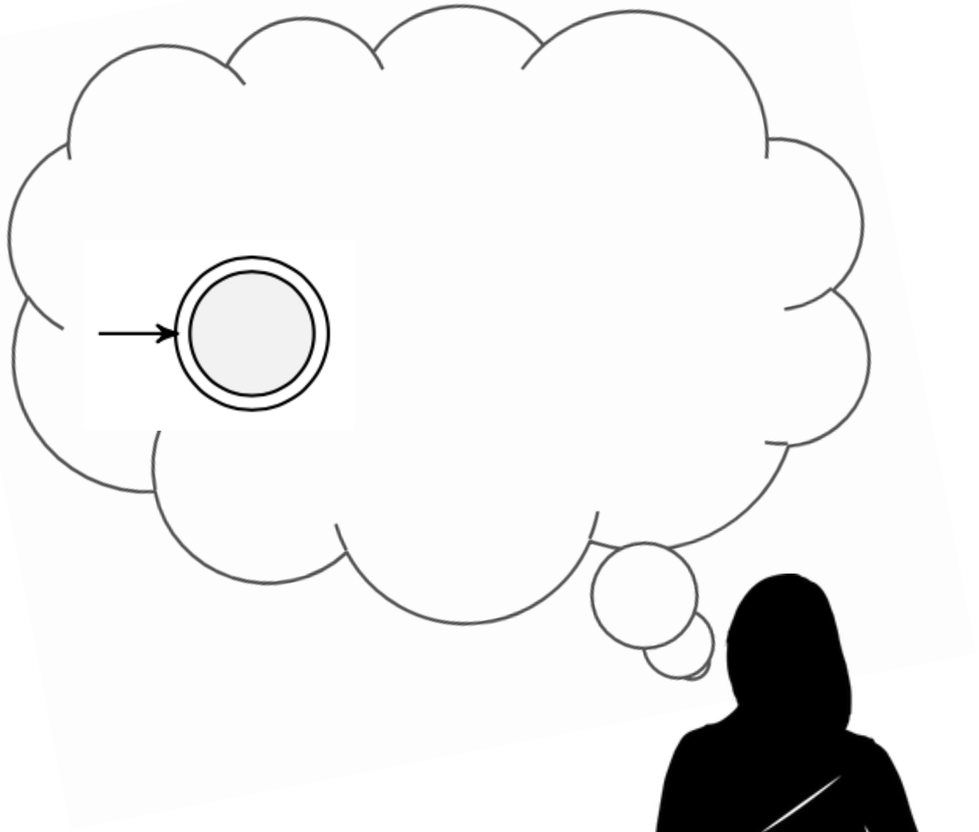

$\varepsilon \in L?$

$a \in L?$

Yes

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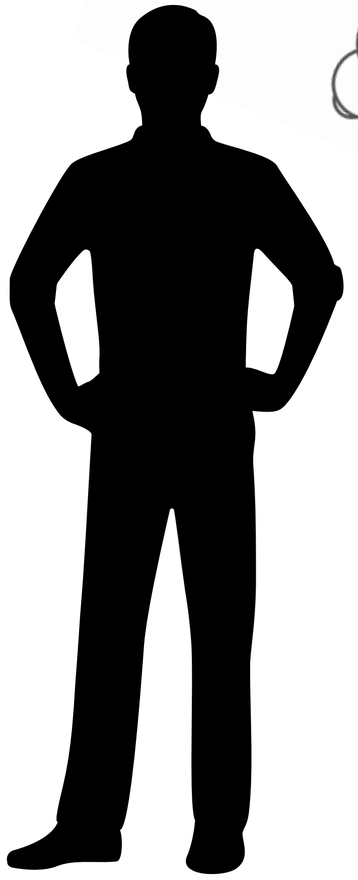

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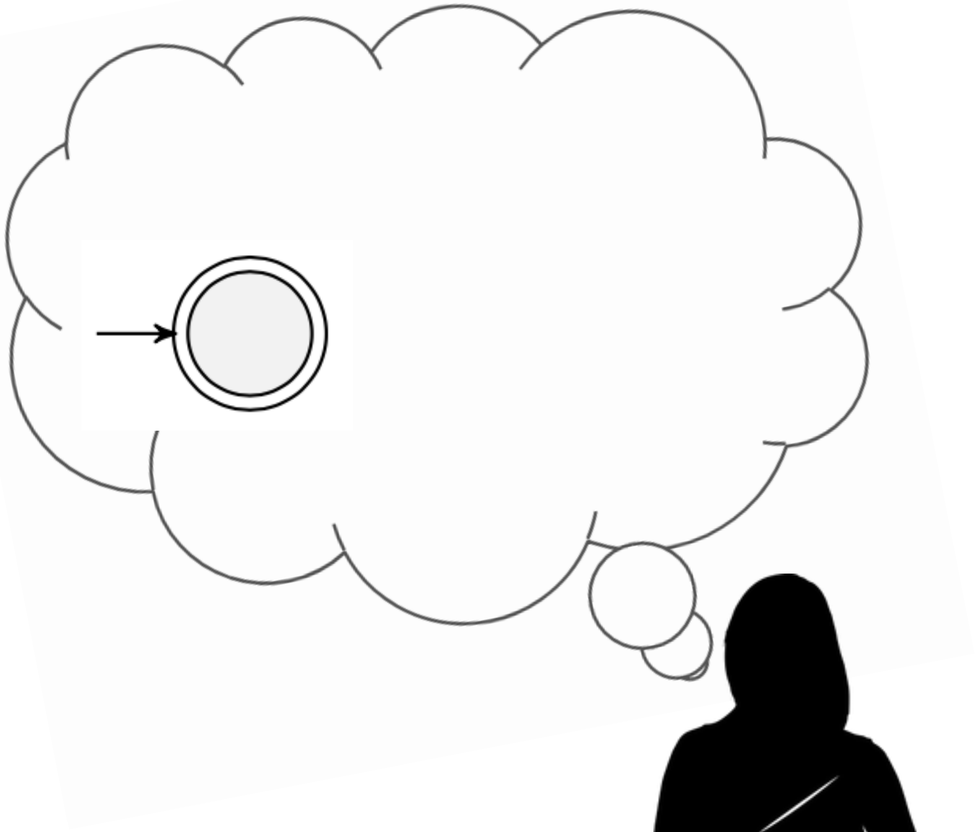

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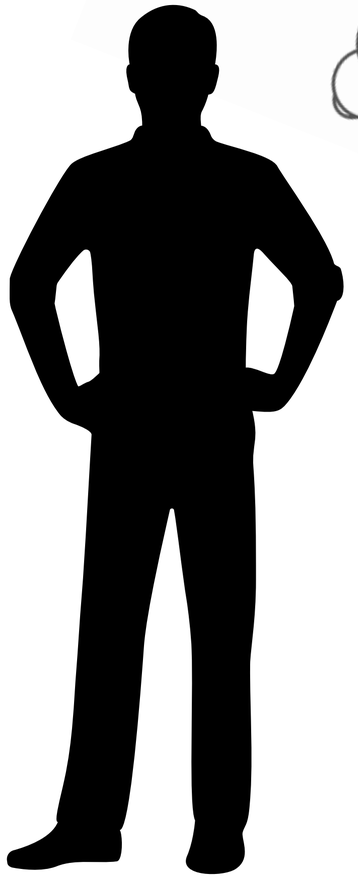

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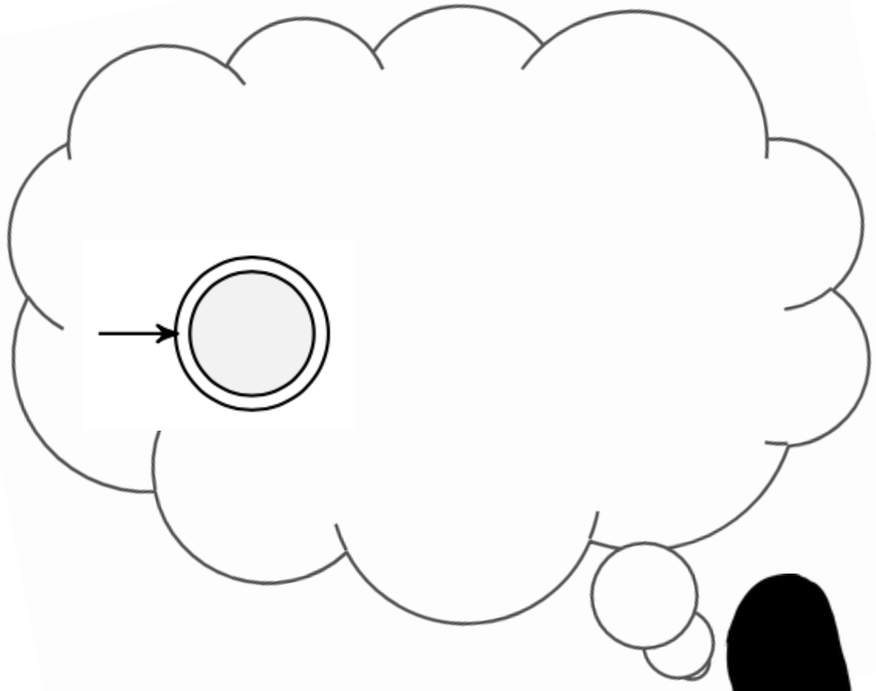

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$b \in L?$

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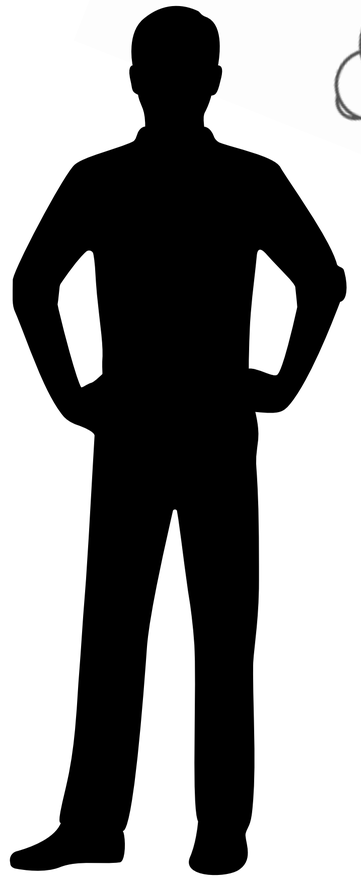

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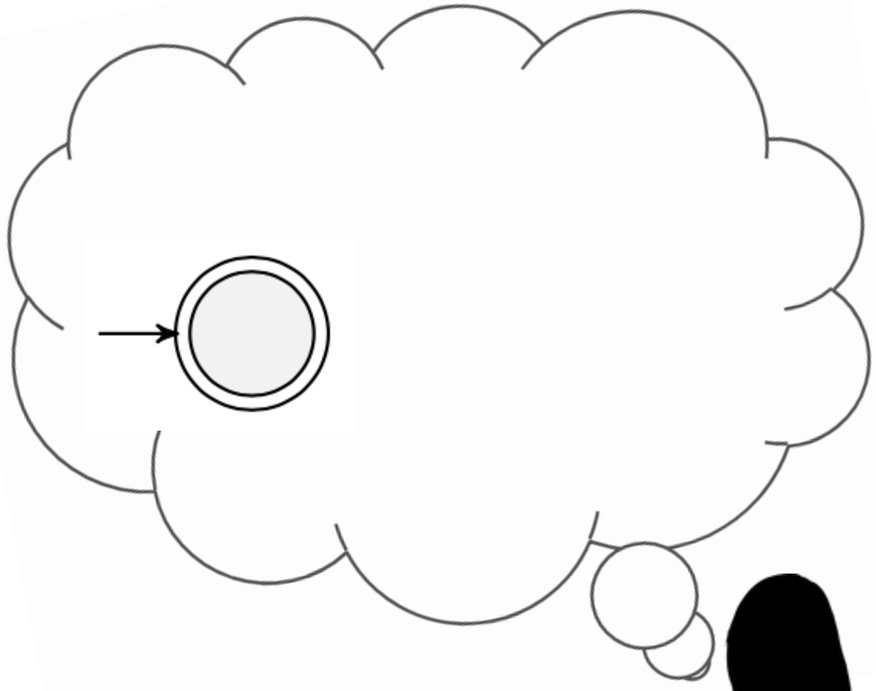

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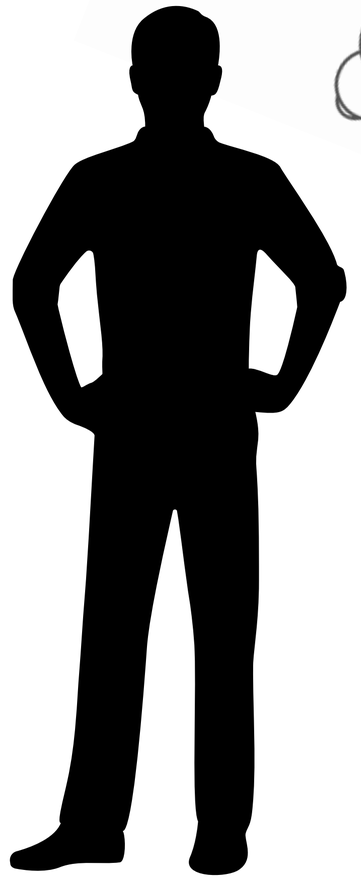

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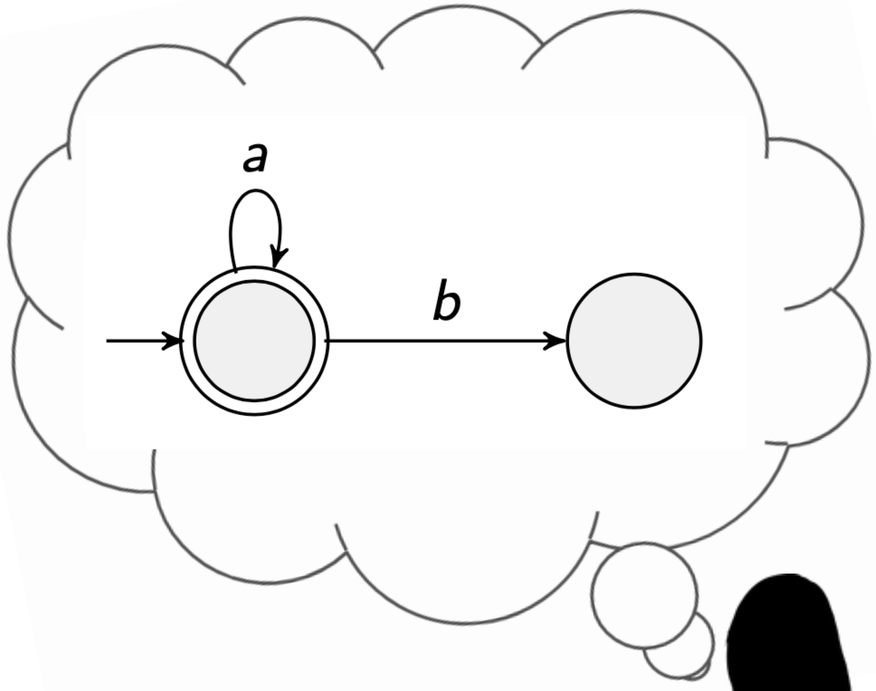

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Regular

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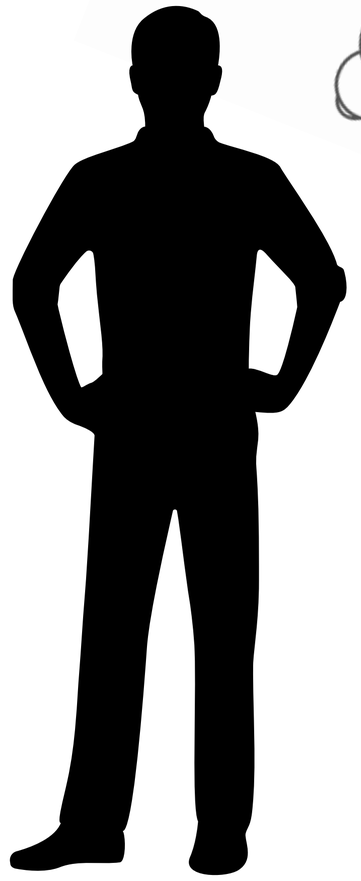

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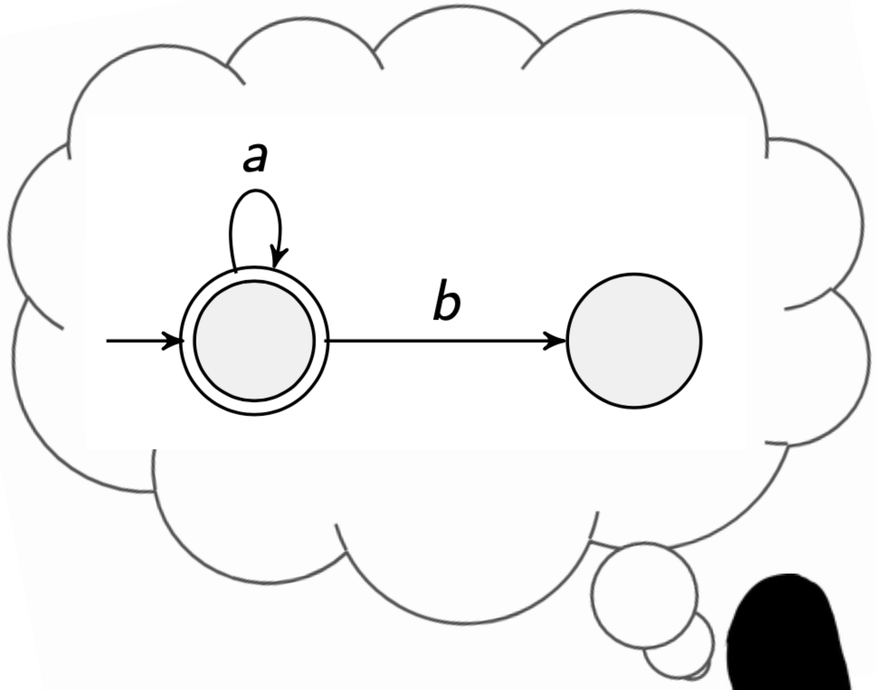

$\varepsilon \in L?$ Yes

$a \in L?$ Yes

$b \in L?$ No

$ba \in L?$

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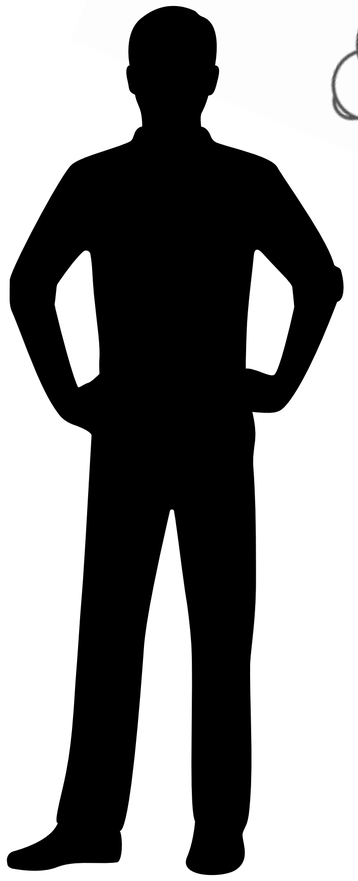

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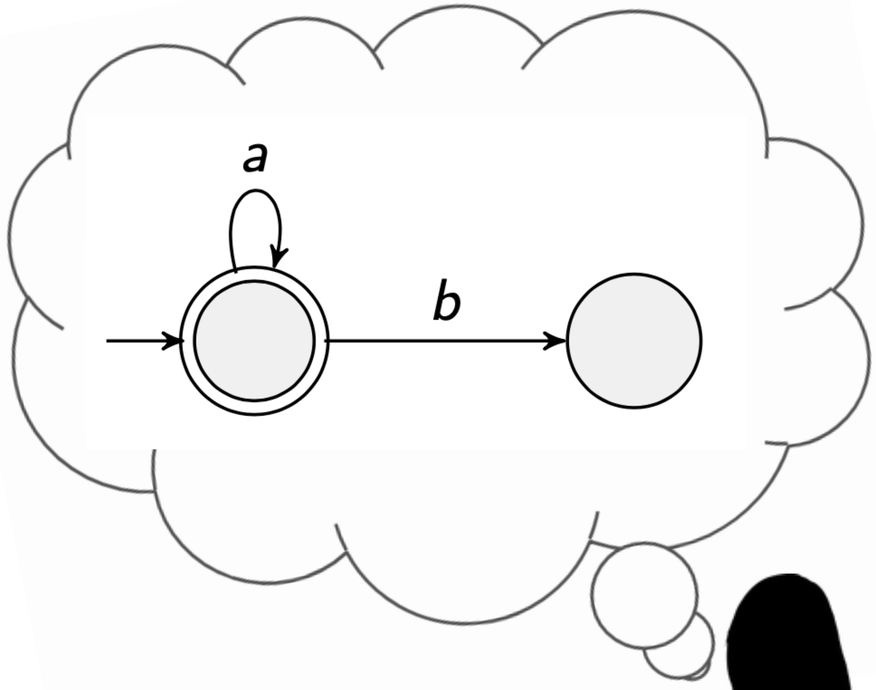

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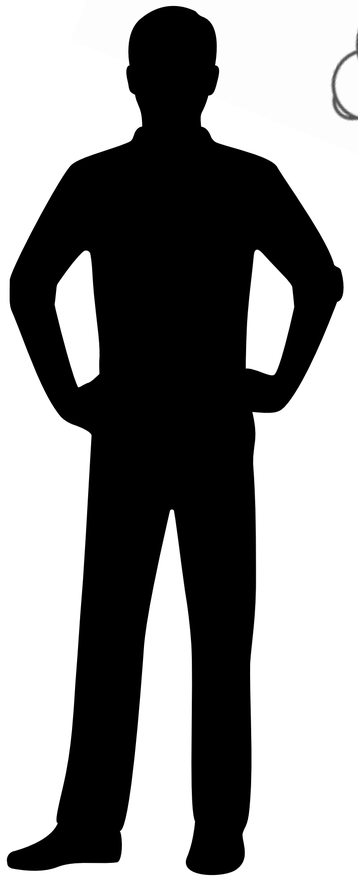

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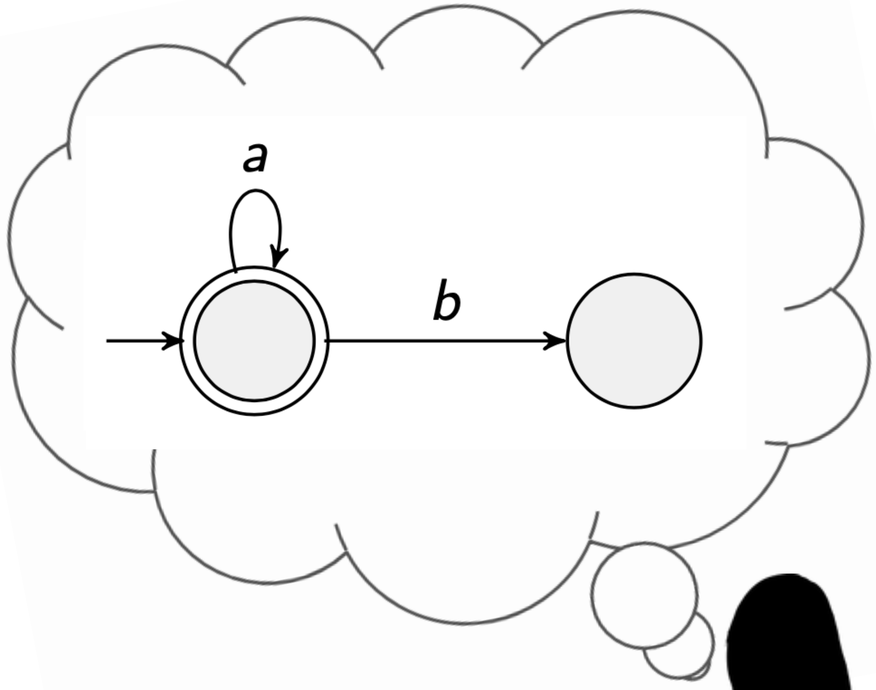

$\varepsilon \in L?$ Yes

$a \in L?$ Yes

$b \in L?$ No

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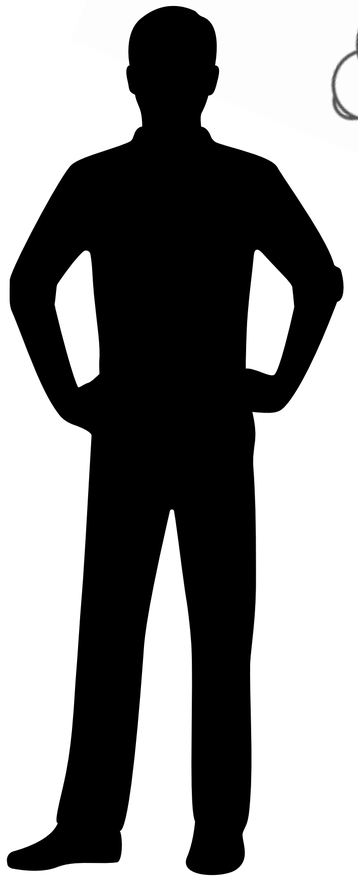

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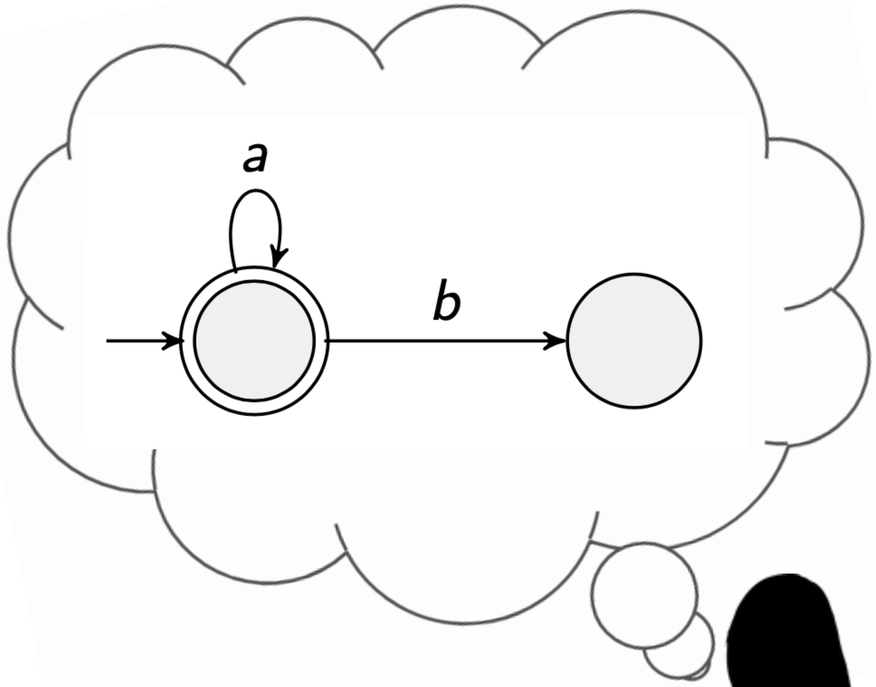

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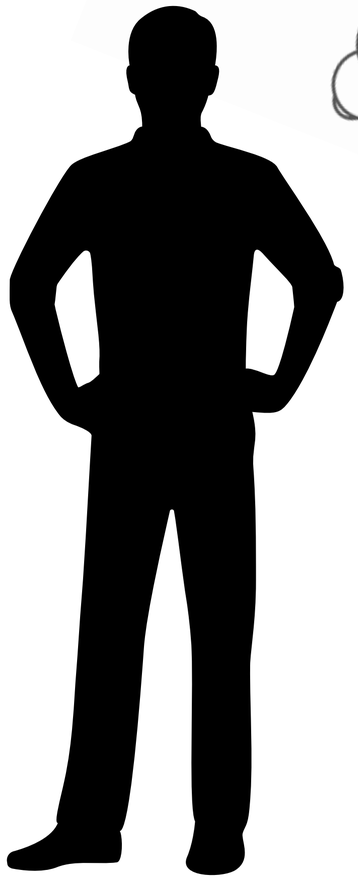

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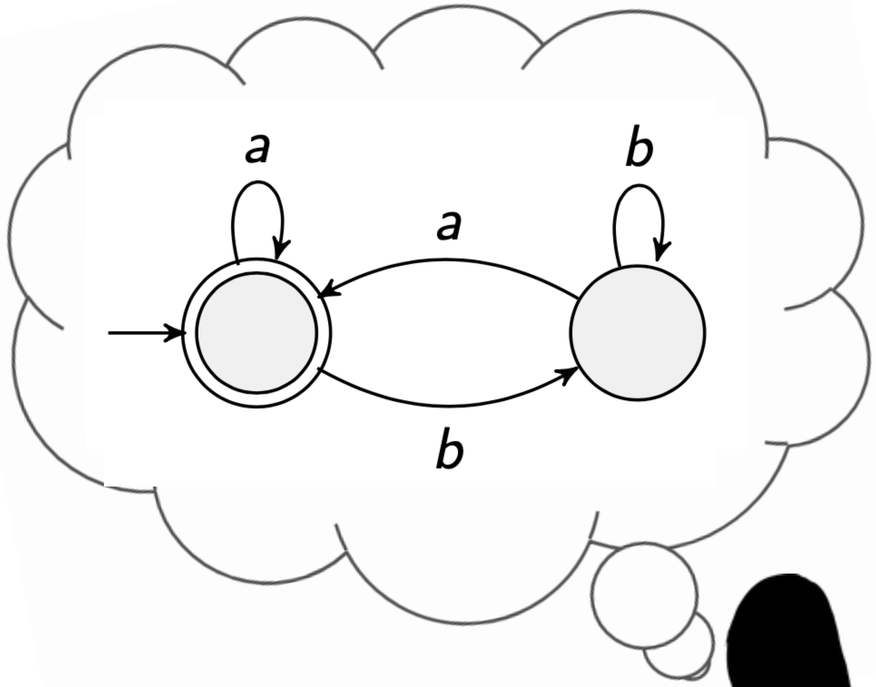

$\varepsilon \in L?$ Yes

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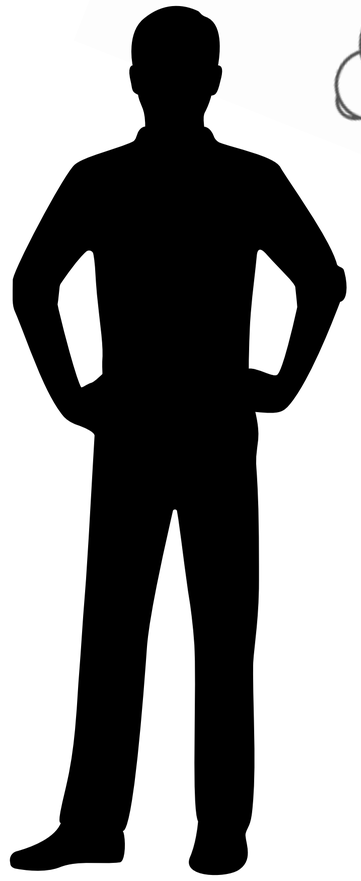
$L \subseteq \{a, b\}^*$



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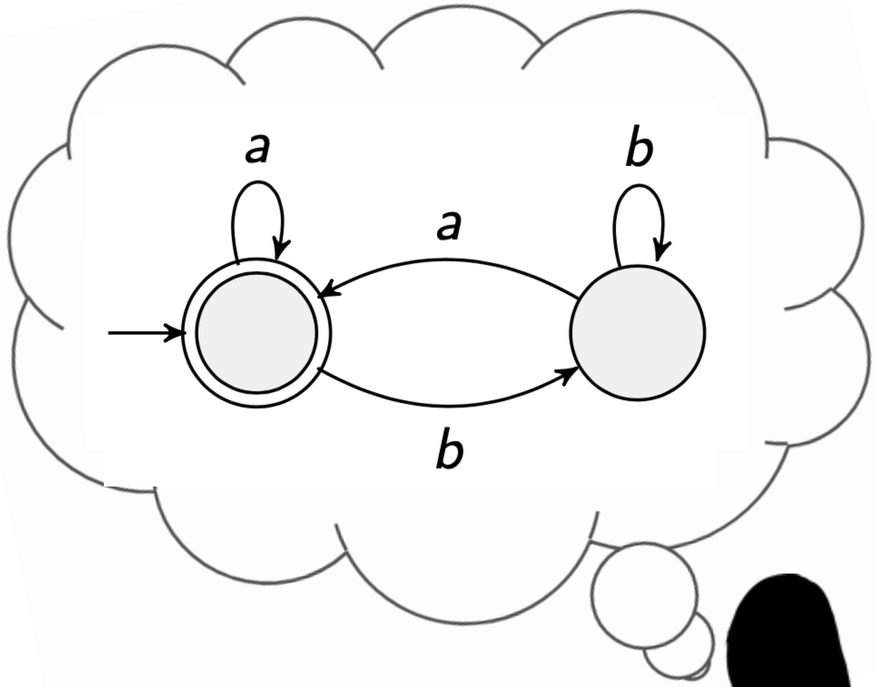

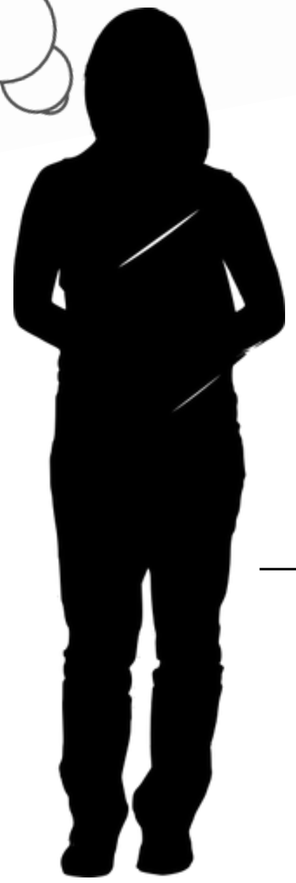

$\varepsilon \in L?$ Yes

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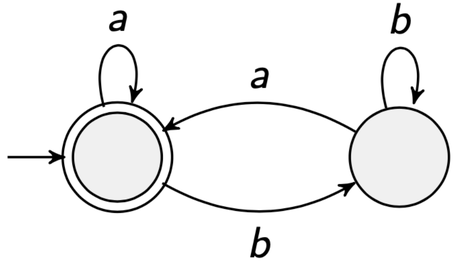
$b \in L?$ No

$ba \in L?$ Yes

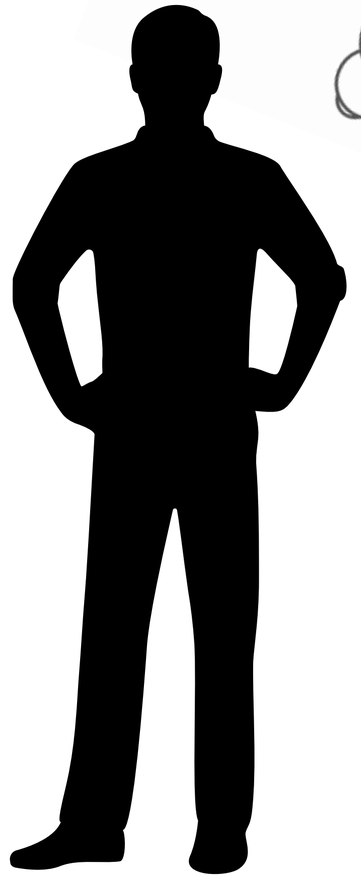
$bb \in L?$ No



?

Regular

$L \subseteq \{a, b\}^*$



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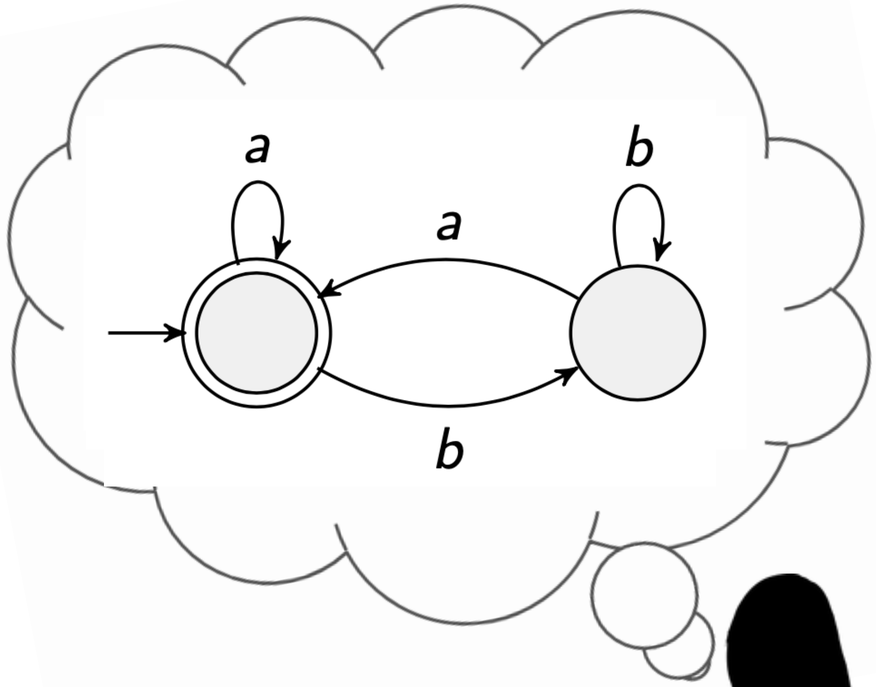
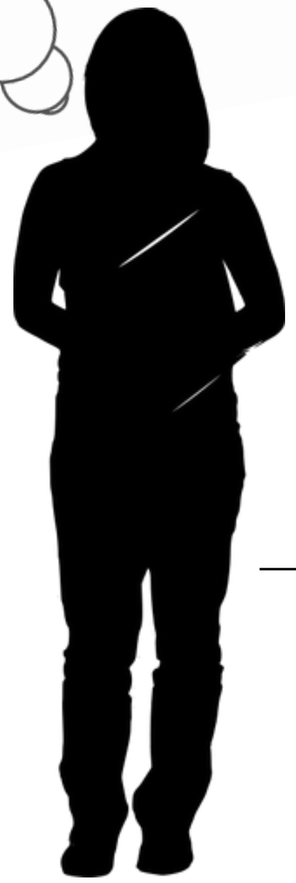




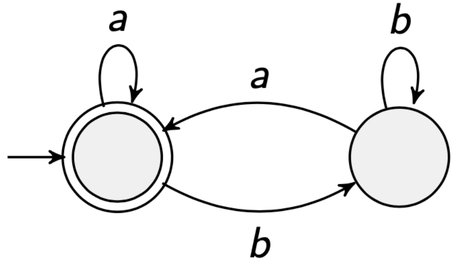
$\varepsilon \in L?$ Yes

$a \in L?$ Yes

$b \in L?$ No

$ba \in L?$ Yes

$bb \in L?$ No

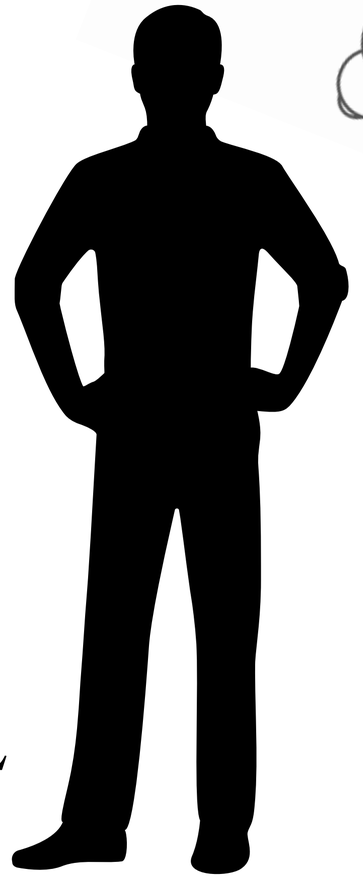


?

No, $bbb \in L$

Regular

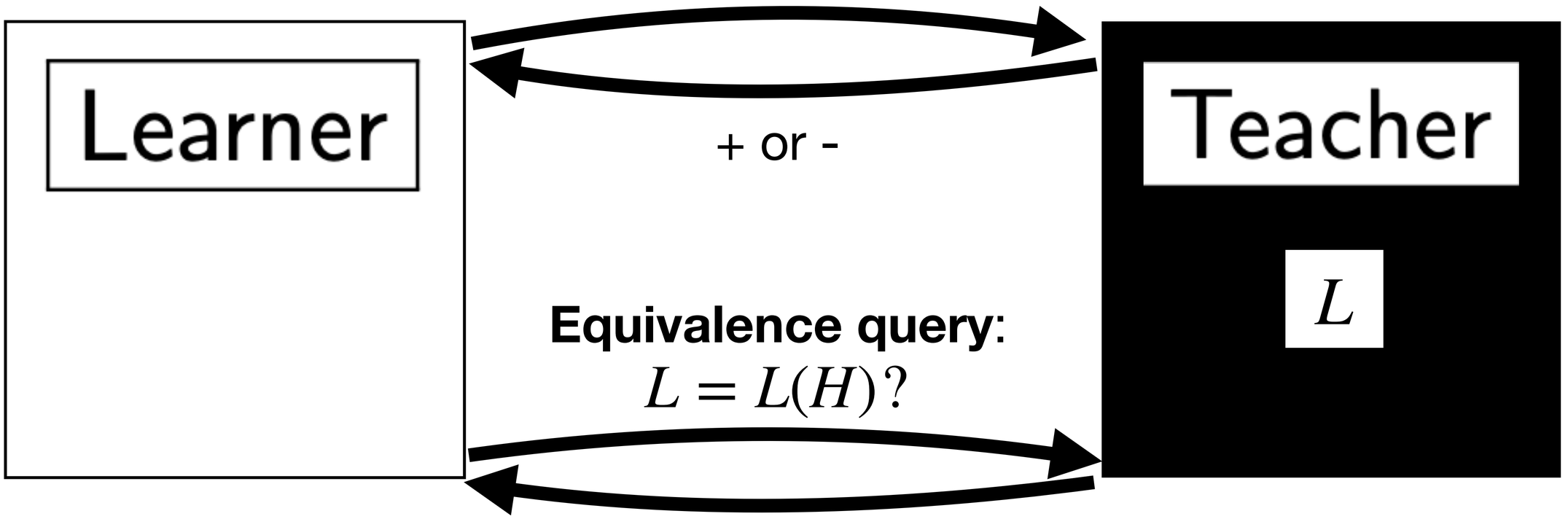
$L \subseteq \{a, b\}^*$



1. You can ask if a given string is in L
2. You can guess a DFA for L

Minimally Adequate Teacher (MAT) Framework

(Angluin, 1987)

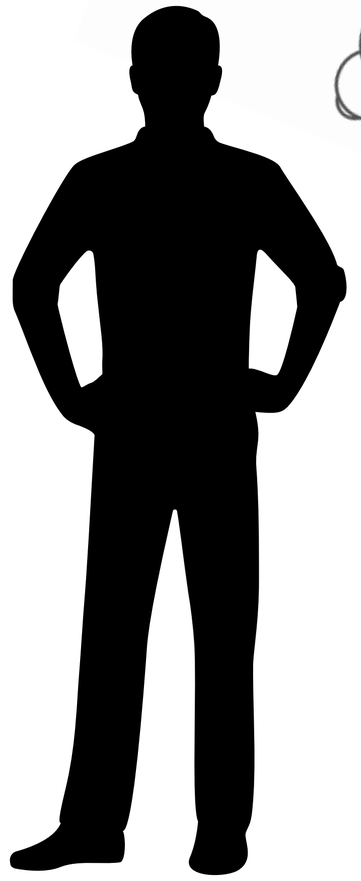


Angluin's $L^\star$

	ε	a
ε	−	+
a	+	+
b	−	+
aa	+	+
ab	+	+

Regular

$L \subseteq \{a, b\}^*$



Angluin's $L^\star$

	ε	a
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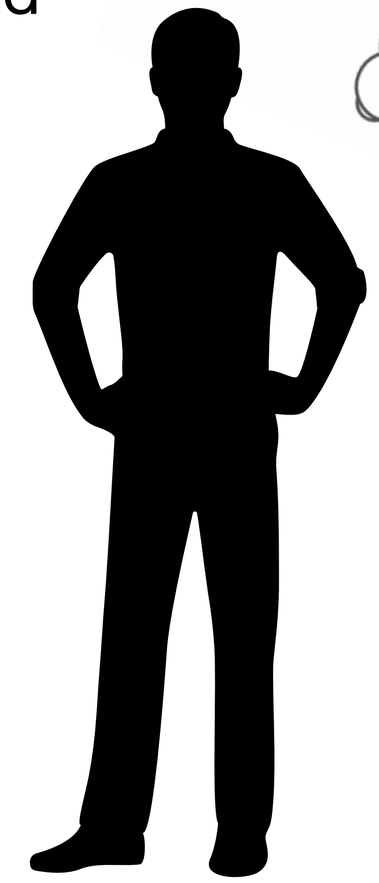
- Uses an *observation table* to guide queries and conjectures

Regular

$L \subseteq \{a, b\}^*$



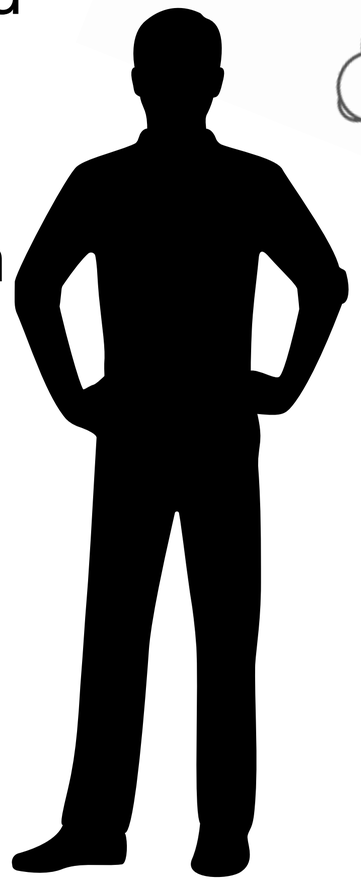
	ε	a
ε	−	+
a	+	+
b	−	+
aa	+	+
ab	+	+

Angluin's $L^\star$

Regular

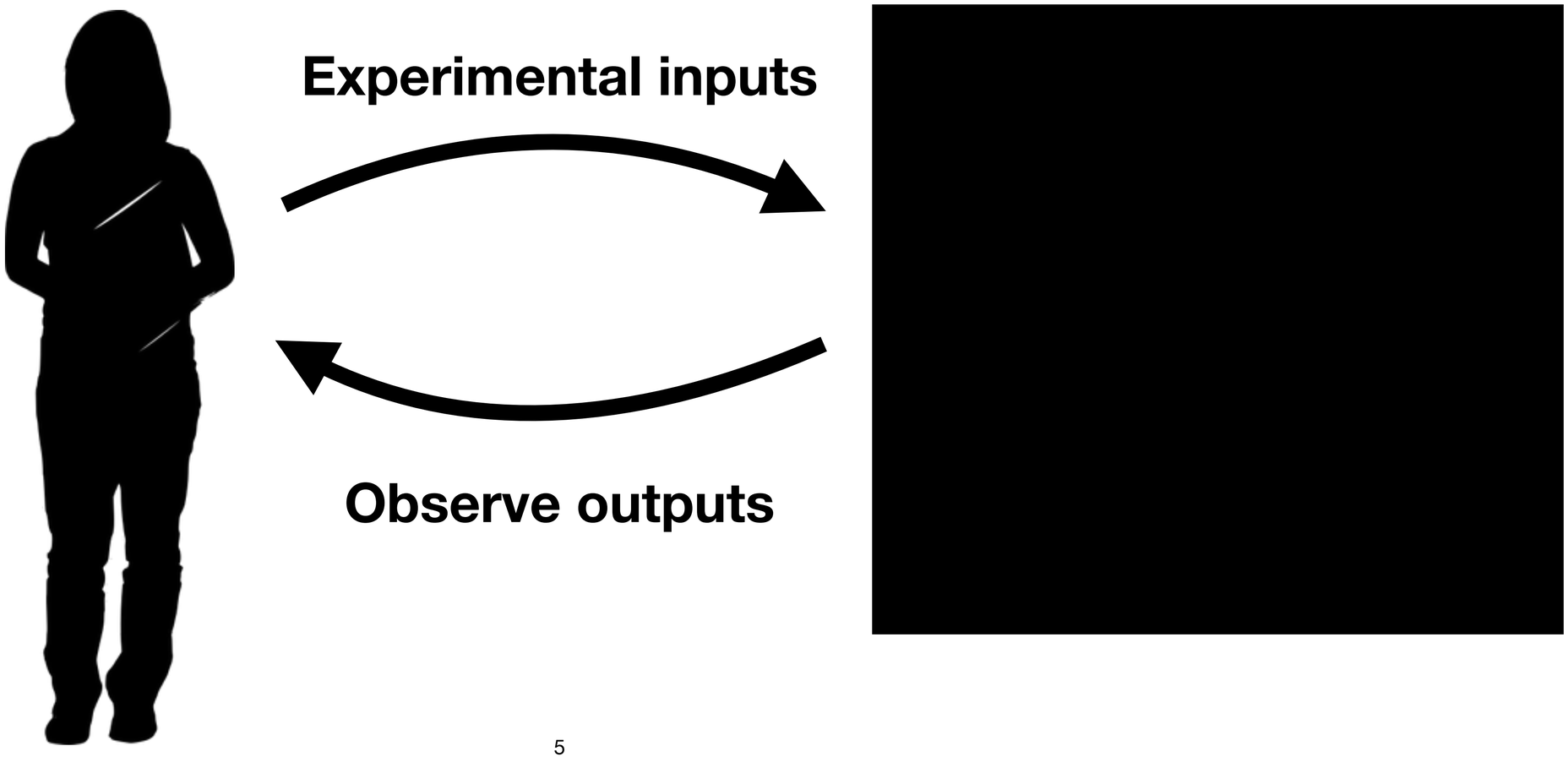
$L \subseteq \{a, b\}^*$

- Uses an *observation table* to guide queries and conjectures
- Guaranteed to learn *minimal* DFA in polynomial queries



Closed-box learning

$L^\star$ in practice



Closed-box learning

$L^\star$ in practice

Experimental inputs

Observe outputs

- TCP
  (Fiterău-Broştean et al, 2014)

Closed-box learning

$L^\star$ in practice

Experimental inputs

Observe outputs

- TCP (Fiterău-Broştean et al, 2014)
- Smartcard Reader (Chalupar et al, 2014)

Closed-box learning

$L^\star$ in practice

Experimental inputs

Observe outputs

- TCP (Fiterău-Broştean et al, 2014)
- Smartcard Reader (Chalupar et al, 2014)
- Java interface specifications (Alur et al, 2005)

Closed-box learning

$L^\star$ in practice

Closed-box learning

$L^\star$ in practice

$$\varepsilon \in L?$$

Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

$a \in L?$

Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

$a \in L?$ No

Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

$a \in L?$ No

$b \in L?$

Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

$a \in L?$ No

$b \in L?$

$ba \in L?$

Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

$a \in L?$ No

$b \in L?$

$ba \in L?$

$bb \in L?$

Closed-box learning

$L^\star$ in practice

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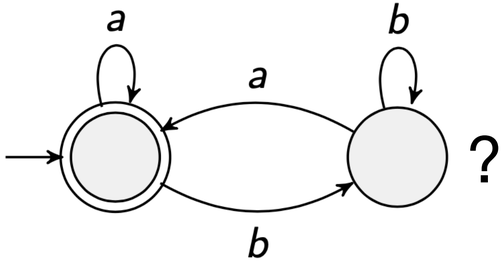


Closed-box learning

$L^\star$ in practice

Challenges:

- System *might not* answer every membership query

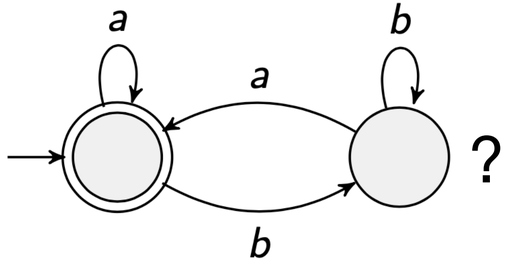
$\varepsilon \in L?$ Yes

$a \in L?$ No

$b \in L?$

$ba \in L?$

$bb \in L?$



Closed-box learning

$L^\star$ in practice

$\varepsilon \in L?$ Yes

$a \in L?$ No

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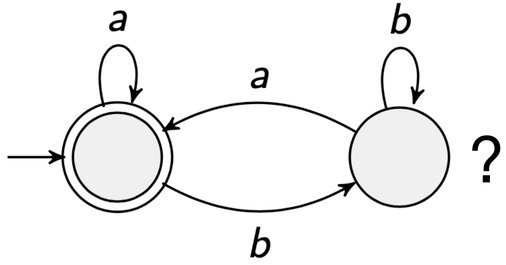
$bb \in L?$

Challenges:

- System *might not* answer every membership query
- System certainly does not answer equivalence query



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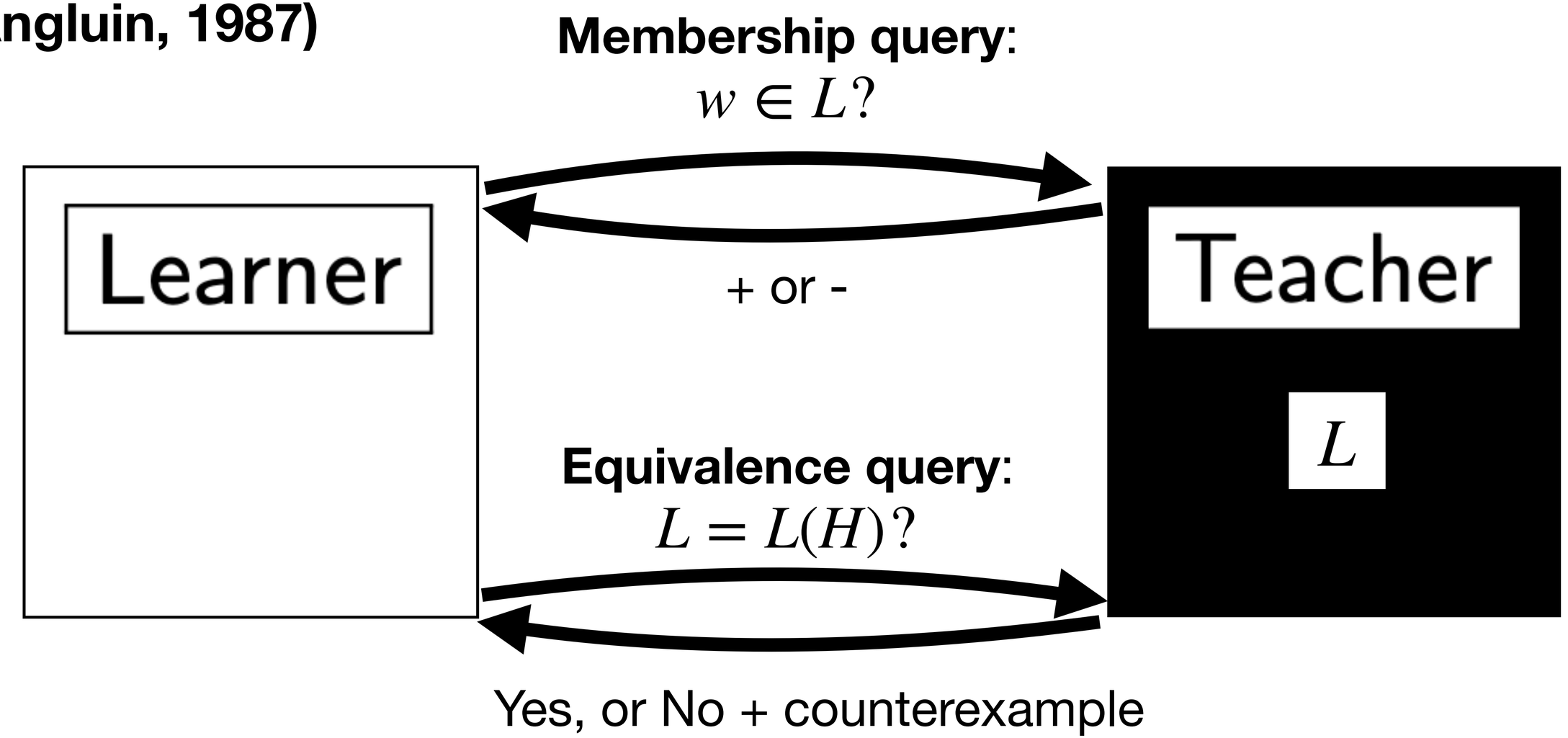
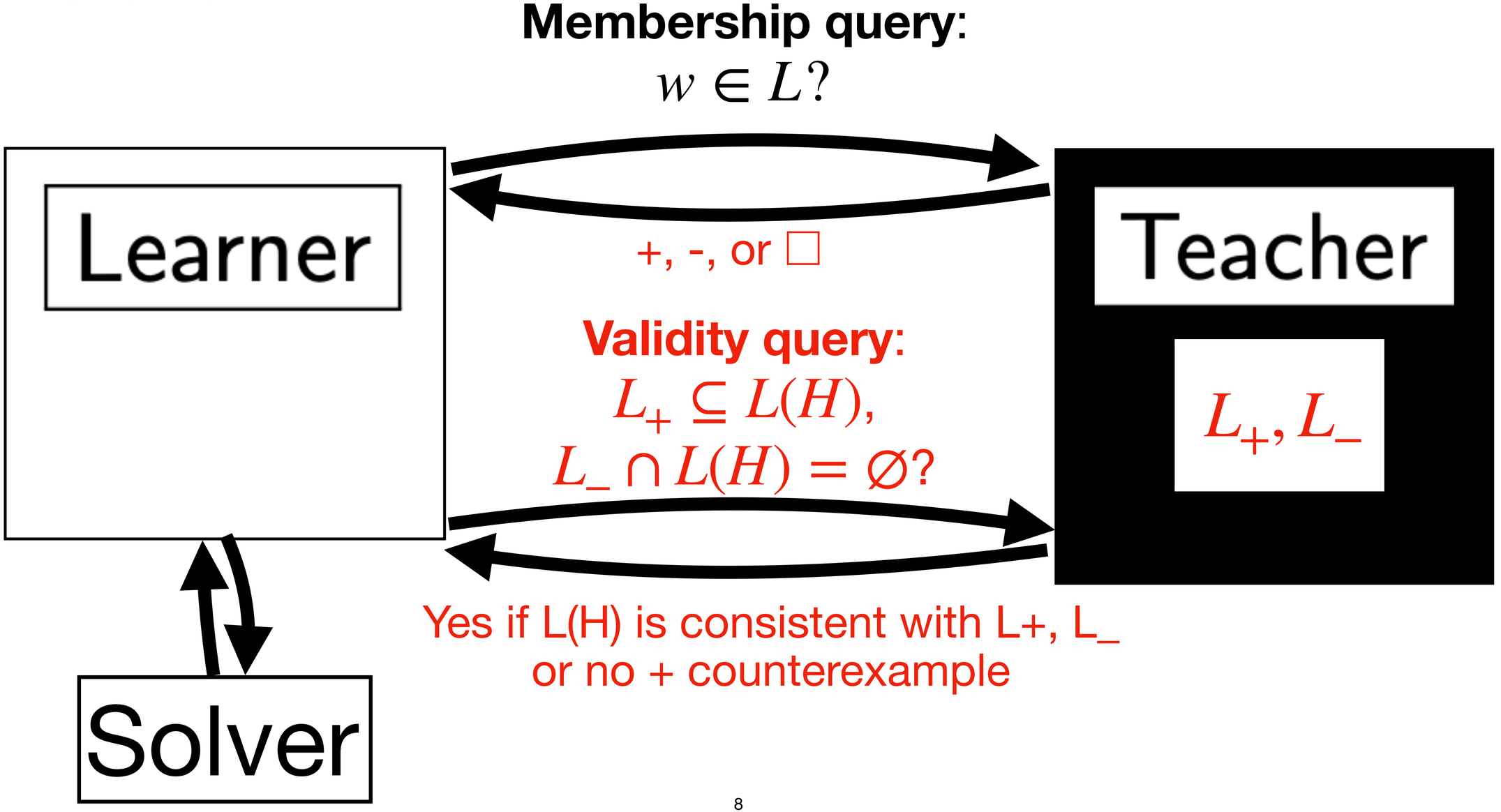
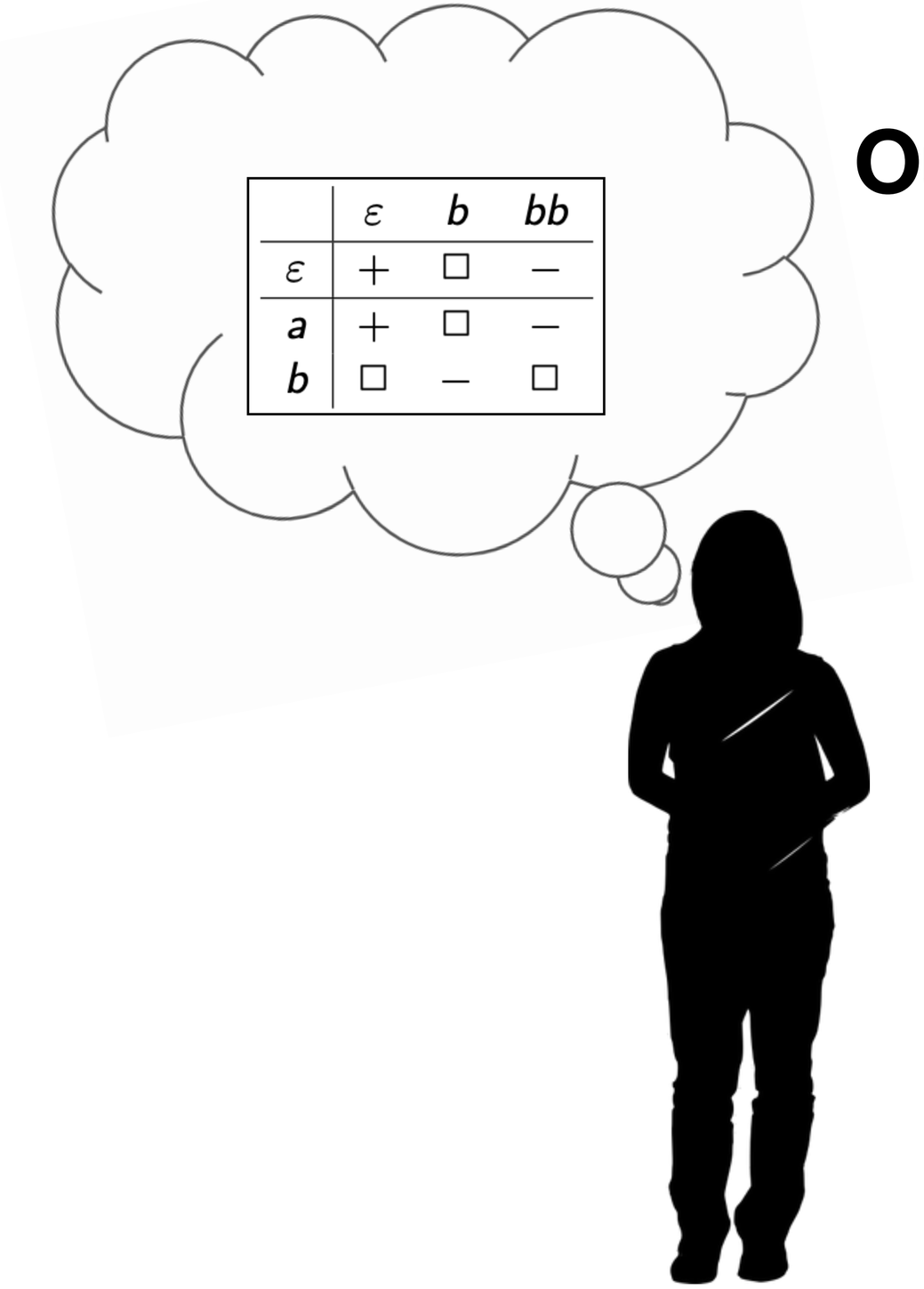


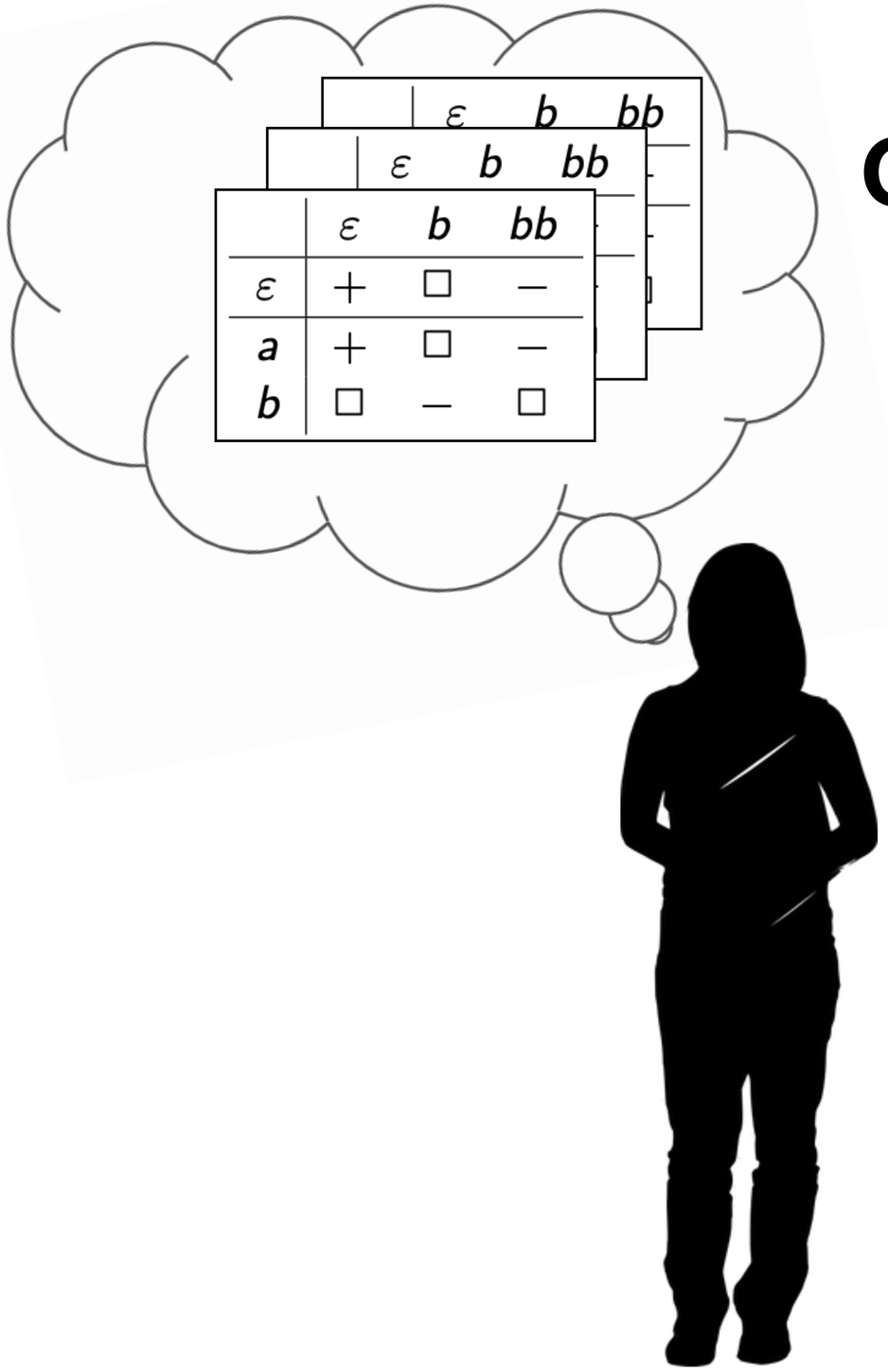
Incomplete Minimally Adequate Teacher (iMAT) Framework (This paper)





Our solution: $L^{\star}_{\square}$

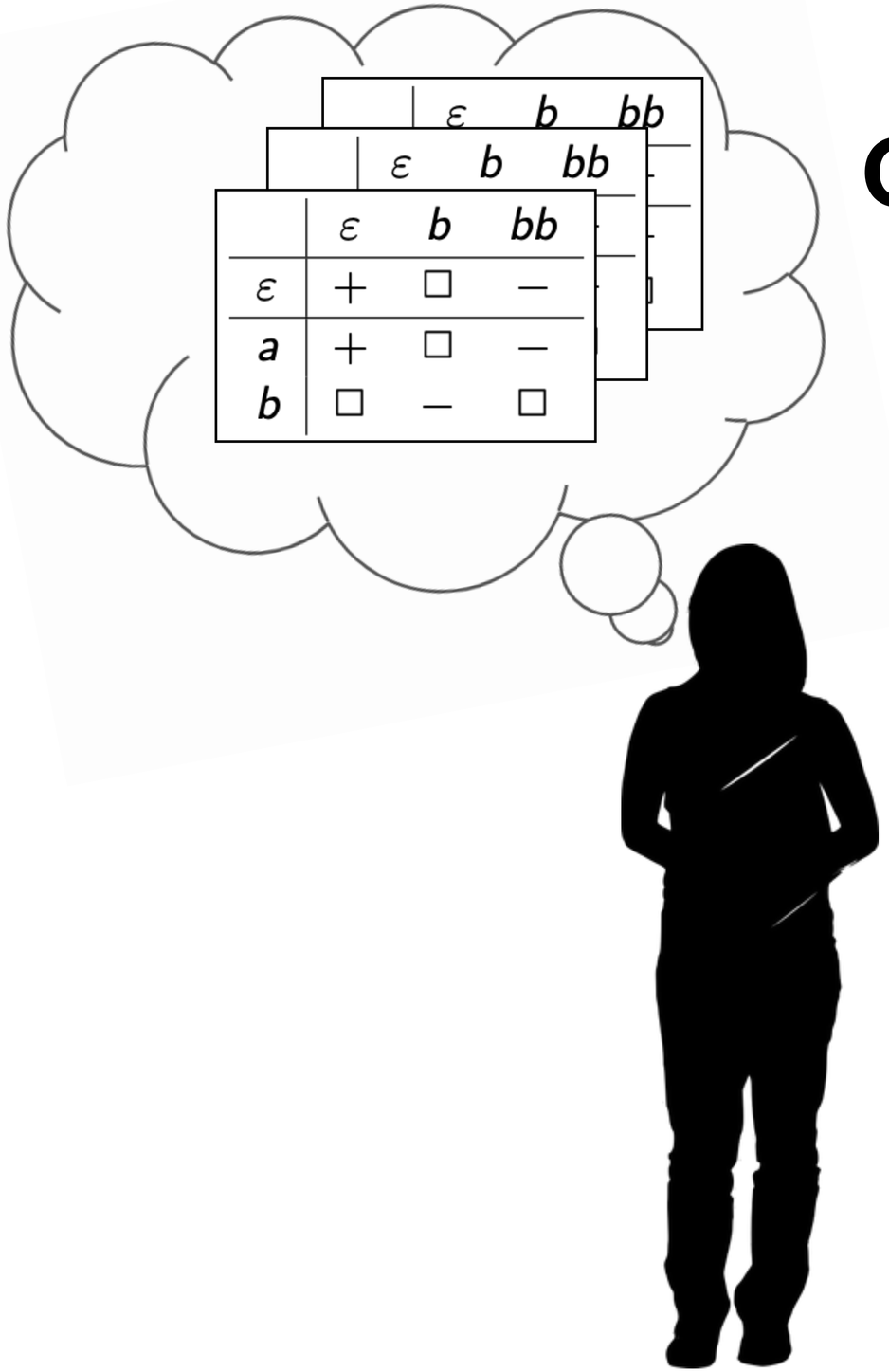
L_+, L_-



Our solution: $L^{\star}_{\square}$

- Uses a worklist of *observation tables with blanks*

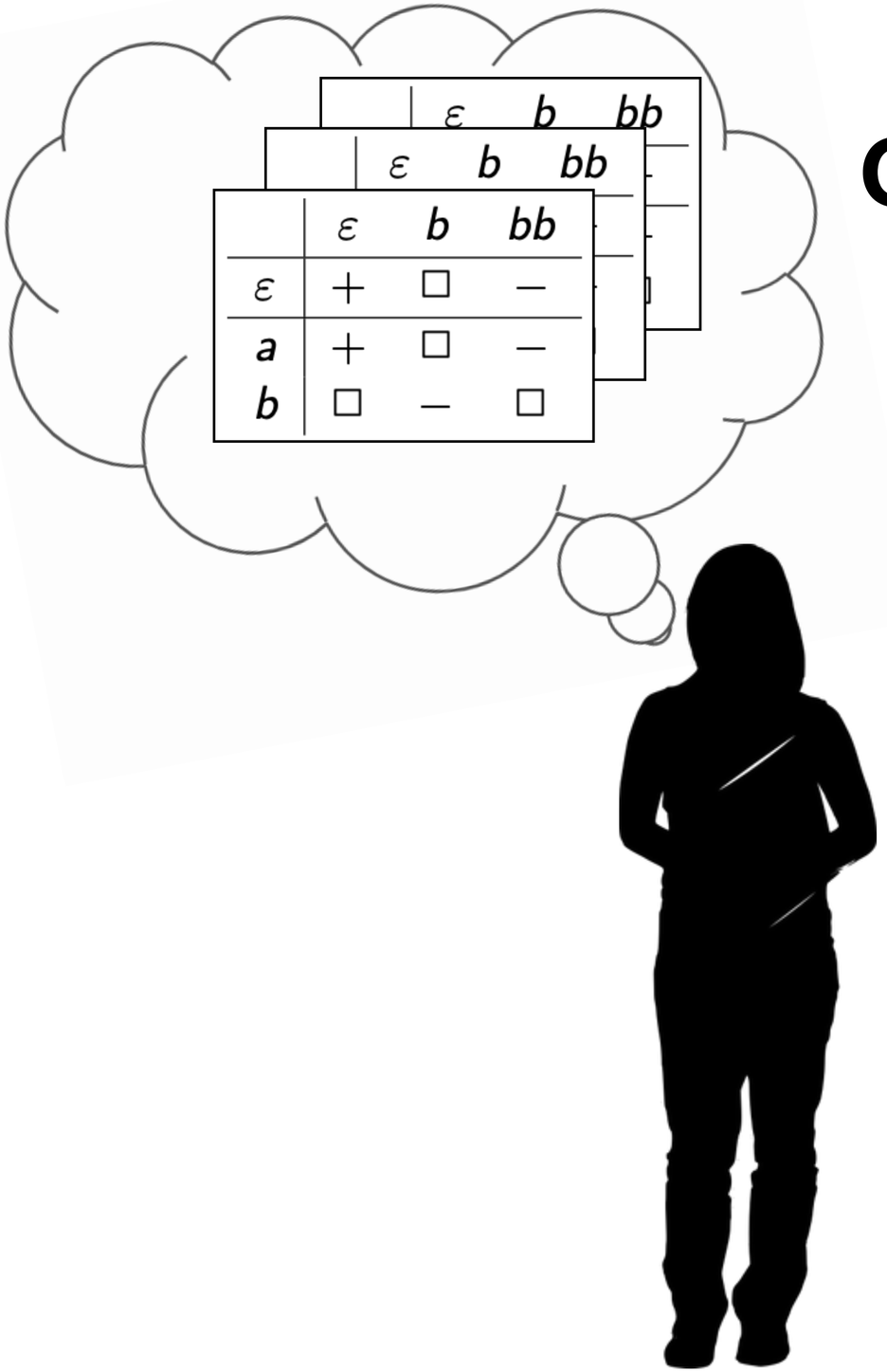
L_+, L_-



Our solution: $L^{\star}_{\square}$

- Uses a worklist of *observation tables with blanks*
- Rely on a *solver* to fill blanks

L_+, L_-



Our solution: $L^{\star}_{\square}$

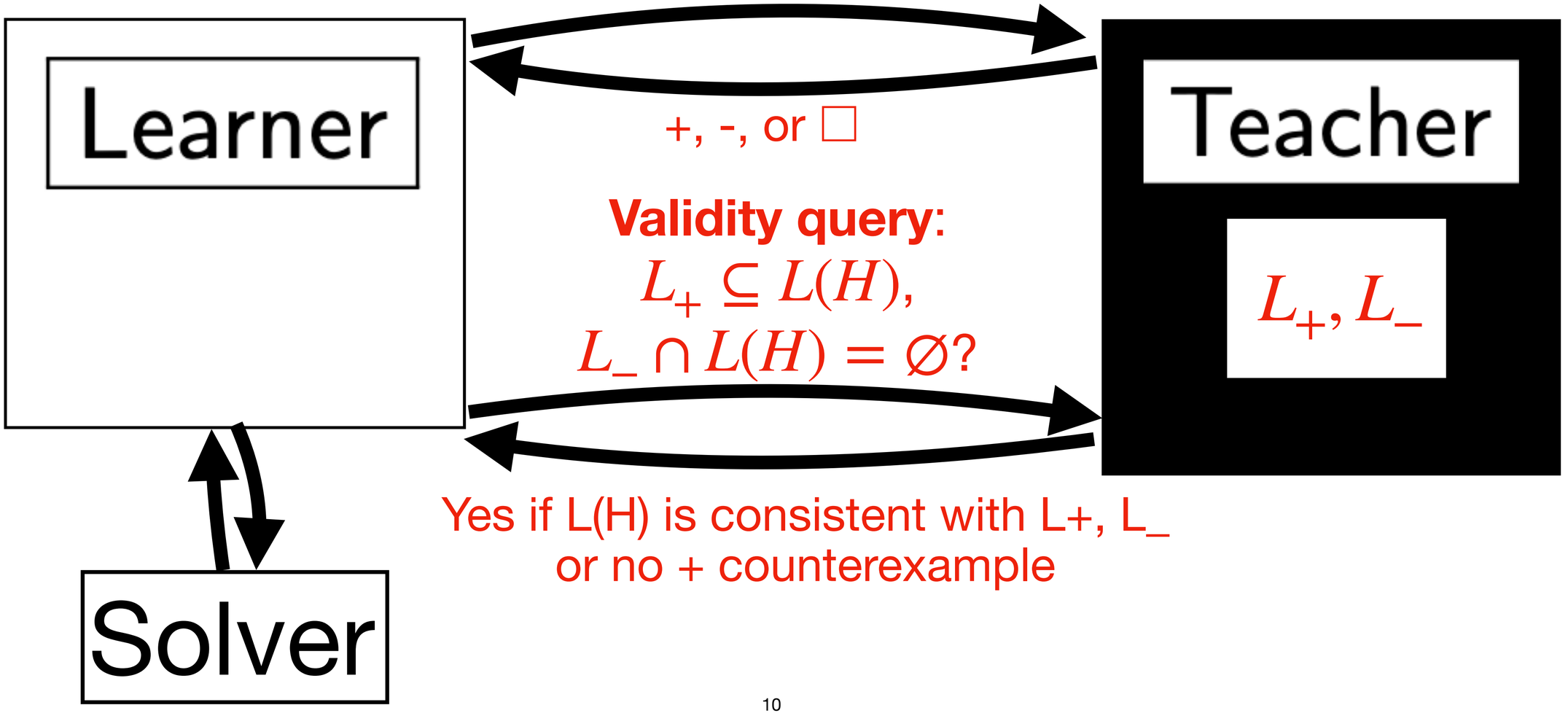
- Uses a worklist of *observation tables with blanks*
- Rely on a *solver* to fill blanks
- Guaranteed to learn *minimum-size* DFA accepting L_+ and rejecting L_-

L_+, L_-

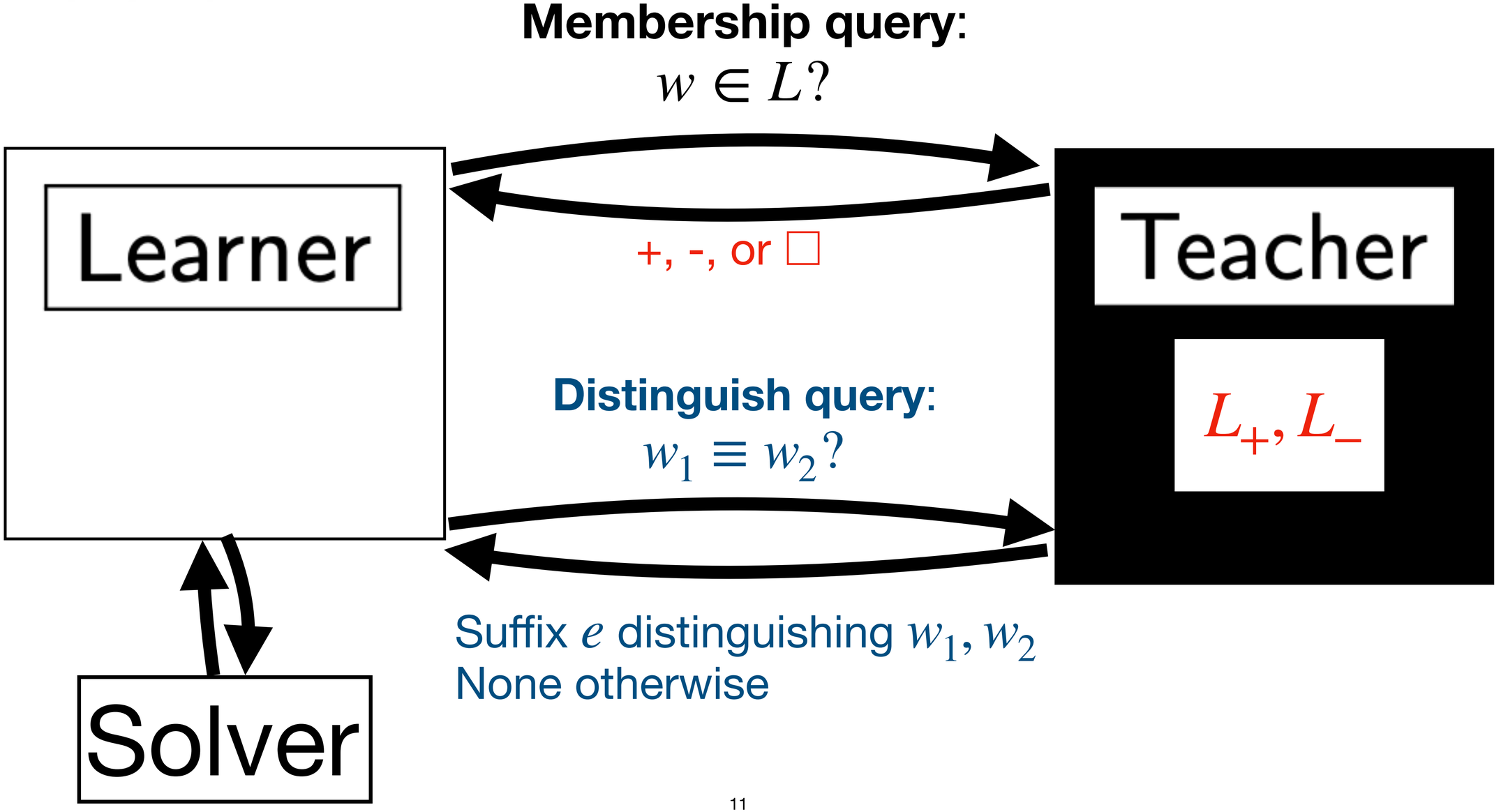
Incomplete Minimally Adequate Teacher (iMAT) Framework (This paper)

Membership query:

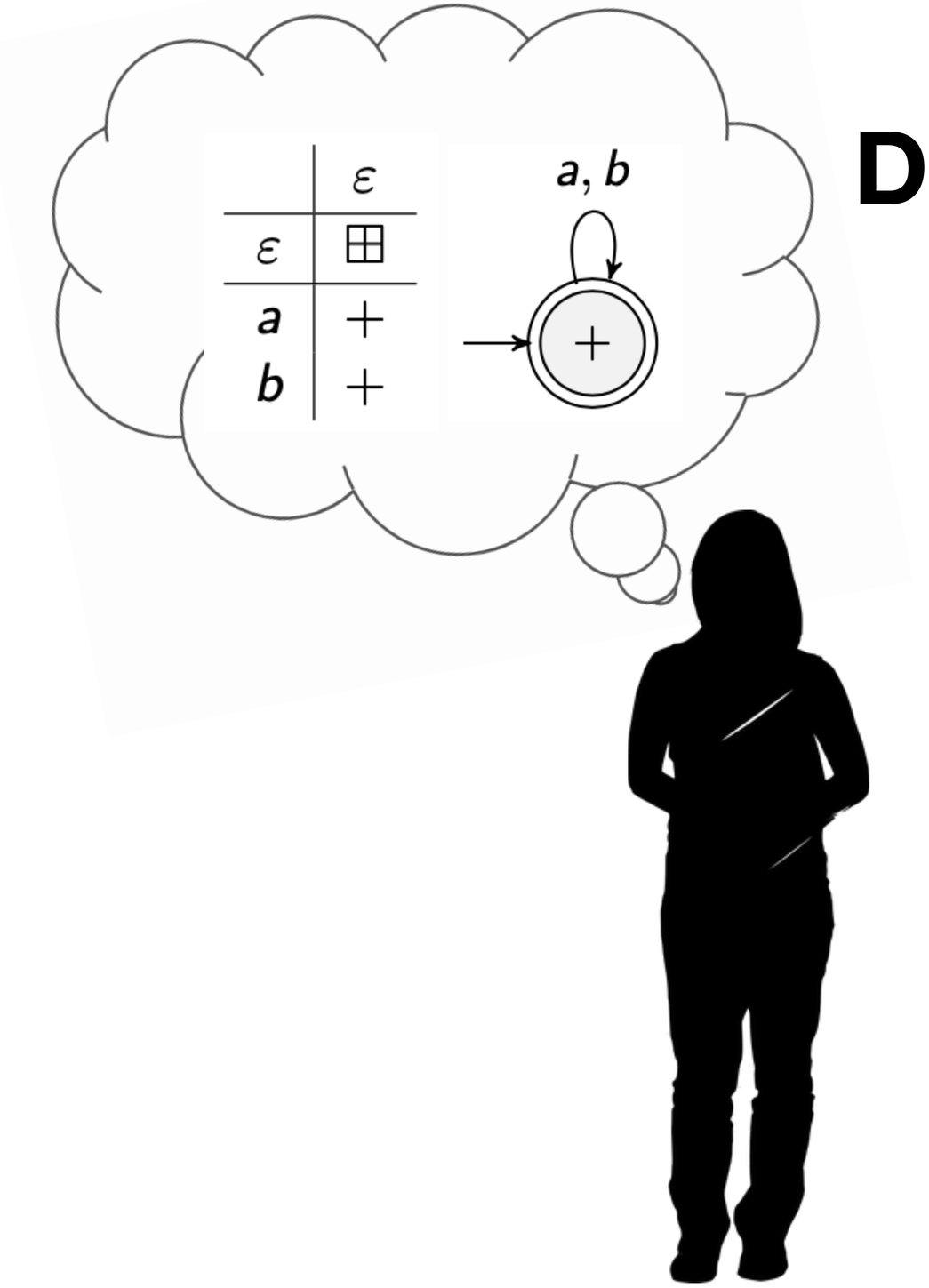
$w \in L?$



Incomplete Minimally Adequate Teacher (iMAT) Framework (This paper)

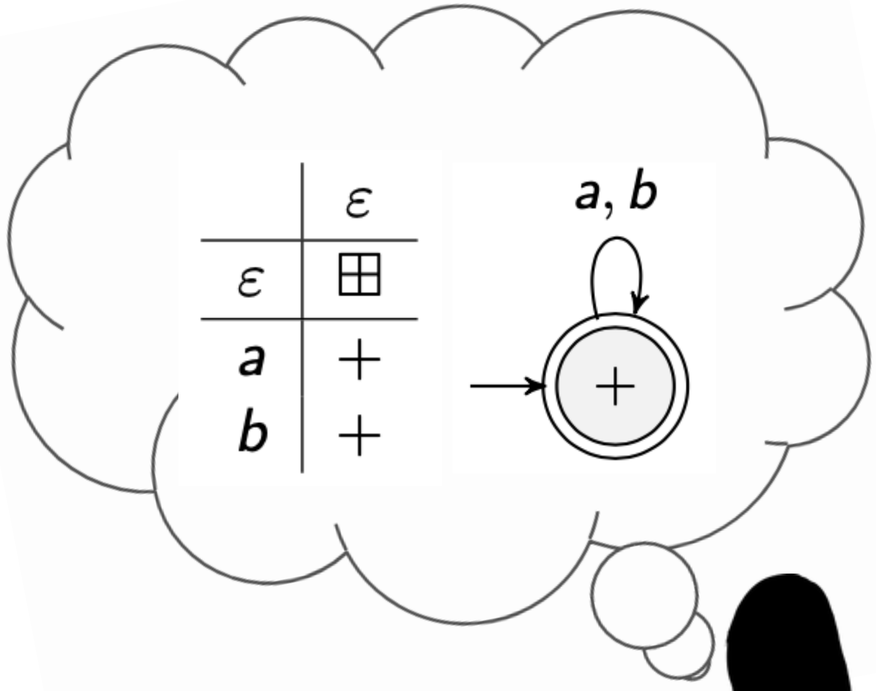


Distinguish query



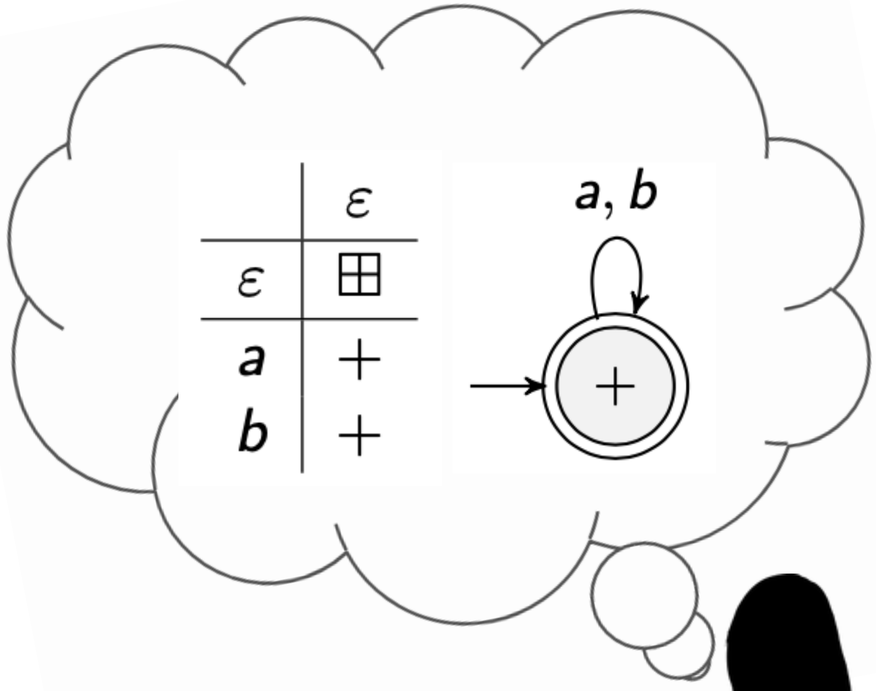
L_+	L_-
a	aa
b	

Distinguish query



Distinguish ε, a?

L_+	L_-
a	aa
b	



Distinguish query

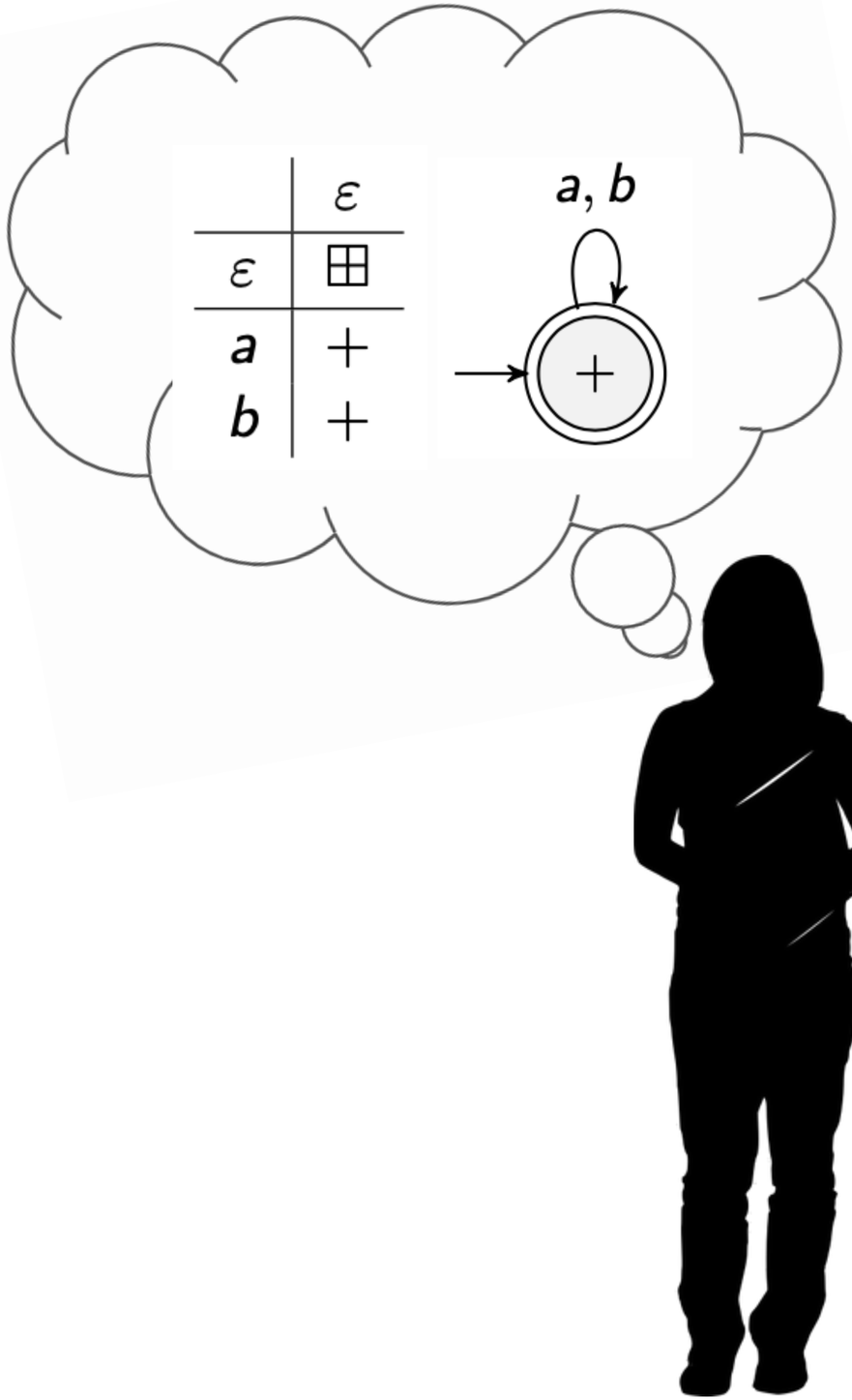
Distinguish ε, a?

Yes: a

$\varepsilon \cdot a \in L_+$

$a \cdot a \in L_-$

L_+	L_-
a	aa
b	



Distinguish query

Distinguish ε, a?

Yes: a

$\varepsilon \cdot a \in L_+$

$a \cdot a \in L_-$

L_+	L_-
a	aa
b	

$L^{\star}_{\square}$ modified to use distinguish is guaranteed to learn minimum size DFA for finite L_+, L_-

Implementation

GitHub link:

- $L^{\star}_{\square}$ is written in OCaml
  - Self contained automata library
  - Library for building automata learning algorithms

- The *solver* is implemented using the Z3 SMT solver
- Optimizations based on unsatisfiable cores and worklist heuristic prioritization

Related Work

- **Leucker and Neider**, ISoLA 2012, “Learning Minimal Deterministic Automata from Inexperienced Teachers”

- **Grinchtein, Leucker, and Piterman**, IJCAR 2006, “Inferring Network Invariants Automatically”

- **Chen, Farzan, Clarke, Tsay, and Wang**, TACAS 2009, “Learning Minimal Separating DFA’s for Compositional Verification"

Q & A

GitHub link:

cornell-pl / nerode-public Public

Q & A

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