CSL 2016

Marseille, France

Coalgebraic learning

Alexandra Silva

UCL ENGINEERING
Change the world

UCL

Automata learning

Automata learning

Active learning

Passive learning

Automata learning

Active learning

Dana Angluin. Learning regular sets from queries and counterexamples. *Inf. Comput.*, 75(2):87–106, 1987.

Automata learning

Active learning

Dana Angluin. Learning regular sets

L* - algorithm

es. *Inf. Comput.*, 75(2):87–106, 1987.

Automata learning

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Dana Angluin. Learning regular sets **L* - algorithm** es. *Inf. Comput.*, 75(2):87–106, 1987.

Deterministic automata — only **simple** regular languages

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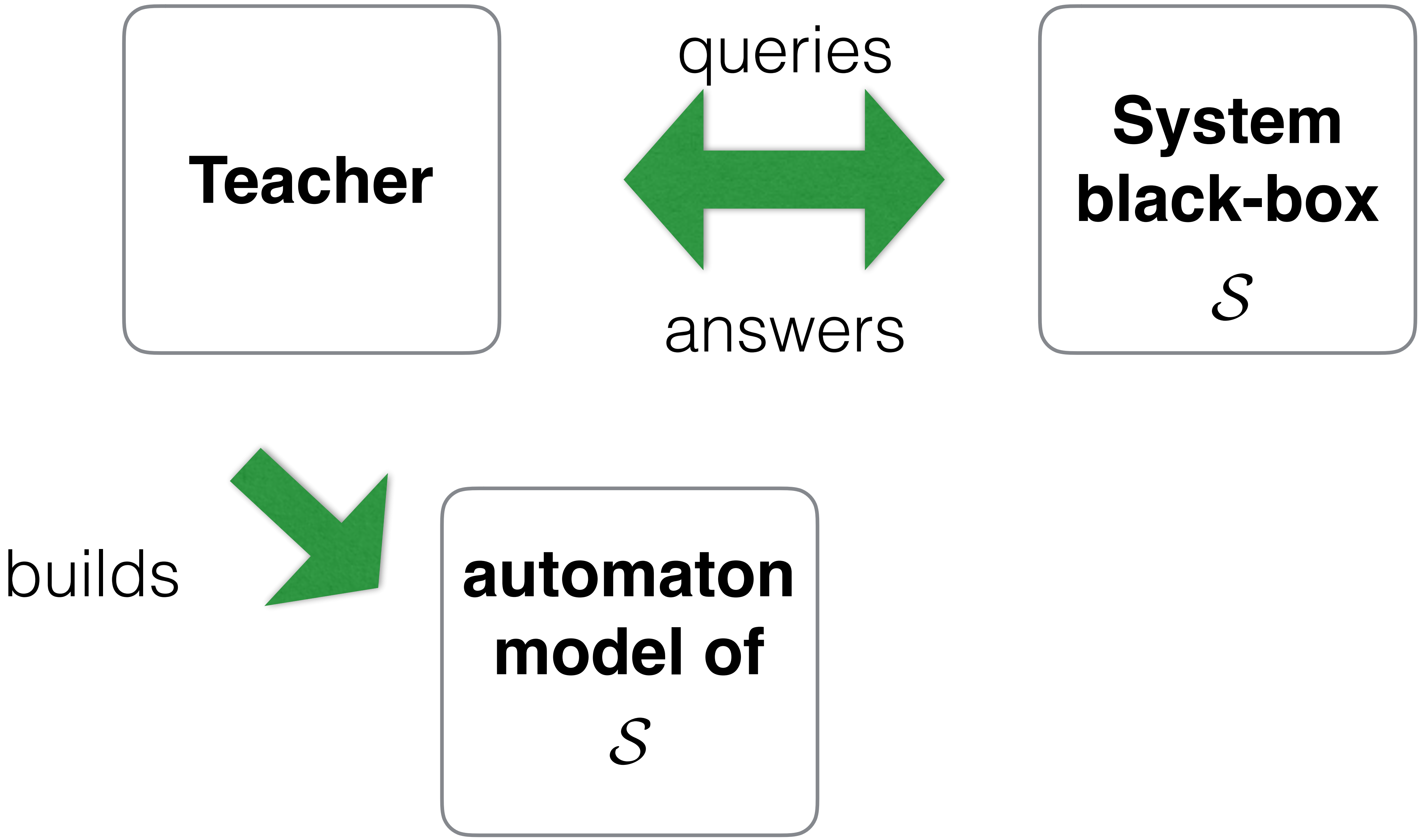
Deterministic automata — only **simple** regular languages

&

L*, by example


Teacher
queries
answers
System black-box
$\mathcal{S}$
builds
automaton model of
$\mathcal{S}$

L*, by example

Teacher queries

Membership queries $w \in \mathcal{L}?$

Equivalence queries $\mathcal{L}(H) = \mathcal{L}?$

Yes :-) *No :-(+ counter-example*

L*, by example

Teacher queries

Membership queries $w \in \mathcal{L}?$

Equivalence queries $\mathcal{L}(H) = \mathcal{L}?$

Yes :-) *No :-(+ counter-example*

Observation table

$$\begin{array}{c|c|ccc} & & \multicolumn{3}{c}{\overbrace{\hphantom{\epsilon \quad a \quad aa}}^{E}} \\ & & \epsilon & a & aa \\ \hline S & \epsilon & 0 & 0 & 1 \\ \hline \cup & a & 0 & 1 & 0 \\ S{\cdot}A & b & 0 & 0 & 0 \end{array}$$

$row\colon S \cup S{\cdot}A \to 2^E$

$row(u)(v) = 1 \iff uv \in \mathcal{L}$

$S, E \subseteq A^\star$

L*, by example

	ϵ	a
ϵ	0	0
a	0	1
aa	1	0
b	0	0
ab	0	0
aaa	0	0
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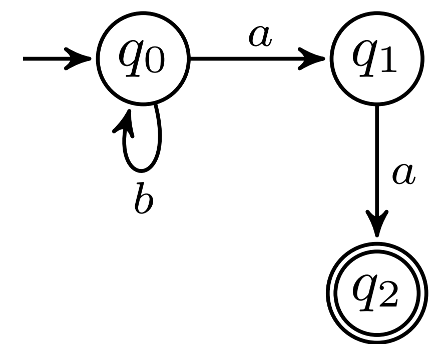
(S, E)



(Q, q_0, F, δ)

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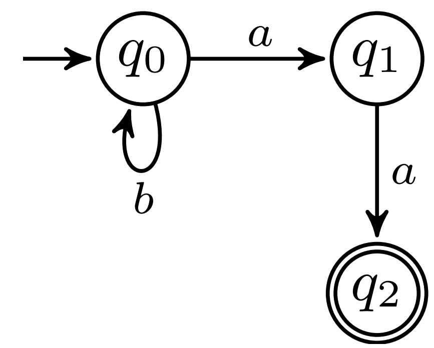

(Q, q_0, F, δ)

- $Q = \{row(s) \mid s \in S\}$ is a finite set of states;
- $F = \{row(s) \mid s \in S, row(s)(\epsilon) = 1\} \subseteq Q$ is the set of final states;
- $q_0 = row(\epsilon)$ is the initial state;
- $\delta \colon Q \times A \to Q$ is the transition function given by $\delta(row(s), a) = row(sa)$.

L*, by example

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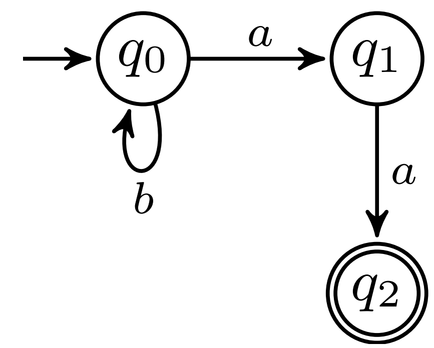

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Why is this well-defined?

Table properties

$$row \colon S \cup S{\cdot}A \to 2^E$$

closed

$$\forall t \in S \cdot A \quad \exists s \in S \qquad row(t) = row(s).$$

consistent

$$\forall s_1, s_2 \text{ s.t. } row(s_1) = row(s_2) \Rightarrow \forall a \in A \quad row(s_1 a) = row(s_2 a).$$

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$row(sa)$ is a state

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choice of $row(s)$ as representative is irrelevant

$\delta(row(s), a) = row(sa)$ well-defined

L*, by example

L* LEARNER

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repeat
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a	0
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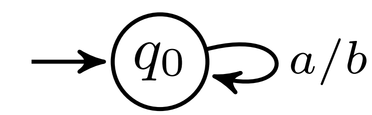
$\mathcal{A}_1 =$ 

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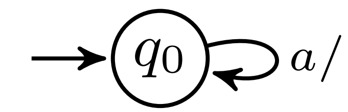

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	ϵ
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$$\mathcal{A}_1 = \begin{tikzcd} {} \arrow[r] & q_0 \arrow[loop right, "a/b"] \end{tikzcd}$$

$$q_0 = row(\epsilon) = \{\epsilon \mapsto 0\}$$

$$t = aa$$

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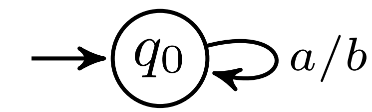
$\mathcal{A}_1 =$ 

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$t = aa$

	ϵ
ϵ	0
a	0
aa	1
b	0
ab	0
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aab	0

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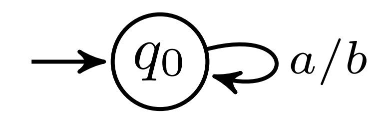
	ϵ
ϵ	0
a	0
b	0

$\mathcal{A}_1 =$ 

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a	0
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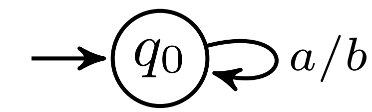
$\mathcal{A}_1 =$ 

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a a

$$\mathcal{L}_n = \{ww \mid w \in A^\star, |w| = n\}$$

$$\mathcal{L}_1 = \{\bar{a}a, \bar{b}b\}$$

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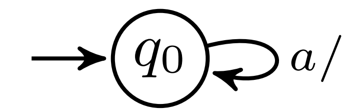
$\mathcal{A}_1 =$ 

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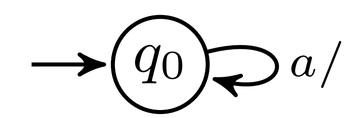
$\mathcal{A}_1 =$ 

$q_0 = row(\epsilon) = \{\epsilon \mapsto 0\}$

$t = aa$

	ϵ
ϵ	0
a	0
aa	1
b	0
ab	0
aaa	0
aab	0

$$\mathcal{L}_n = \{ww \mid w \in A^\star, |w| = n\}$$

$$\mathcal{L}_1 = \{aa, bb\}$$

L*, by example

L* LEARNER

$S, E \leftarrow \{\epsilon\}$
repeat
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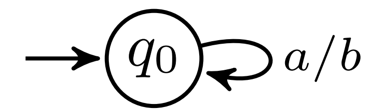
$\mathcal{A}_1 =$ 

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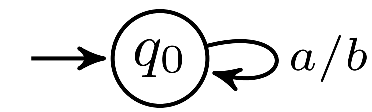
$\mathcal{A}_1 =$ 

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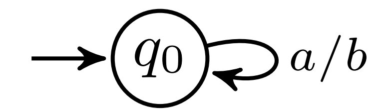
$\mathcal{A}_1 =$ 

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aaa	0
aab	0

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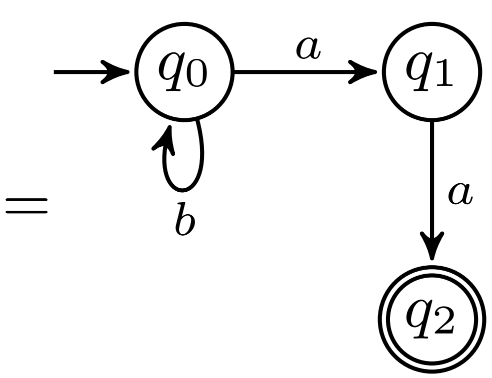
$\mathcal{A}_2 =$ 

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	ϵ
ϵ	0
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b	0

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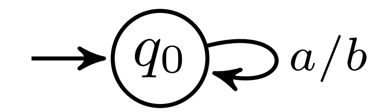

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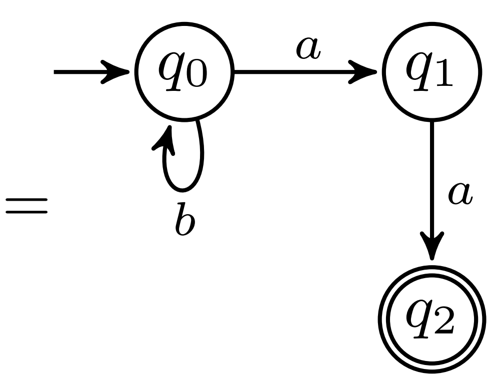

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	ϵ
ϵ	0
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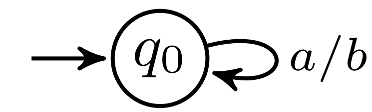

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	ϵ
ϵ	0
a	0
aa	1
b	0
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	ϵ	a
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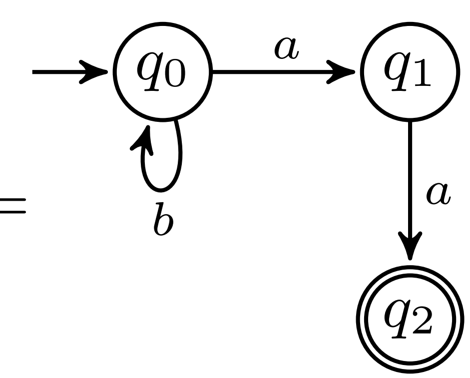
$\mathcal{A}_2 =$



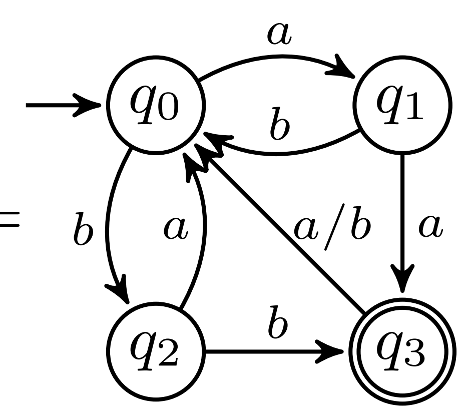
$t = bb$

L*, by example

	ϵ	a
ϵ	0	0
a	0	1
aa	1	0
b	0	0
bb	1	0
ab	0	0
aaa	0	0
aab	0	0
ba	0	0
bba	0	0
bbb	0	0

	ϵ	a	b
ϵ	0	0	0
a	0	1	0
aa	1	0	0
b	0	0	1
bb	1	0	0
ab	0	0	0
aaa	0	0	0
aab	0	0	0
ba	0	0	0
bba	0	0	0
bbb	0	0	0

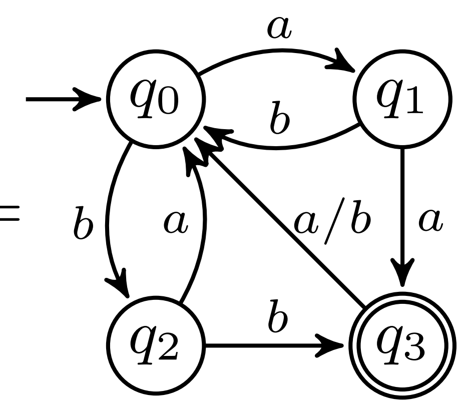
$\mathcal{A}_3 =$



L*, by example

	ϵ	a
ϵ	0	0
a	0	1
aa	1	0
b	0	0
bb	1	0
ab	0	0
aaa	0	0
aab	0	0
ba	0	0
bba	0	0
bbb	0	0

	ϵ	a	b
ϵ	0	0	0
a	0	1	0
aa	1	0	0
b	0	0	1
bb	1	0	0
ab	0	0	0
aaa	0	0	0
aab	0	0	0
ba	0	0	0
bba	0	0	0
bbb	0	0	0

$\mathcal{A}_3 =$ 

$$t = babb$$

L*, by example

	ϵ	a
ϵ	0	0
a	0	1
aa	1	0
b	0	0
bb	1	0
ab	0	0
aaa	0	0
aab	0	0
ba	0	0
bba	0	0
bbb	0	0

	ϵ	a	b
ϵ	0	0	0
a	0	1	0
aa	1	0	0
b	0	0	1
bb	1	0	0
ab	0	0	0
aaa	0	0	0
aab	0	0	0
ba	0	0	0
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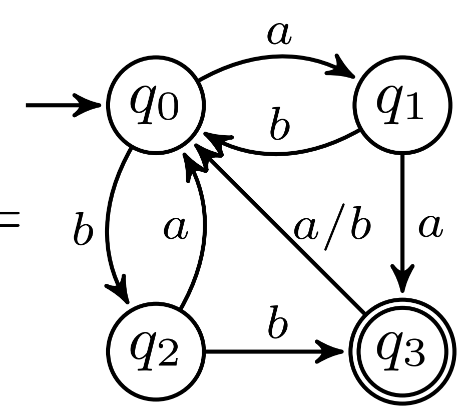
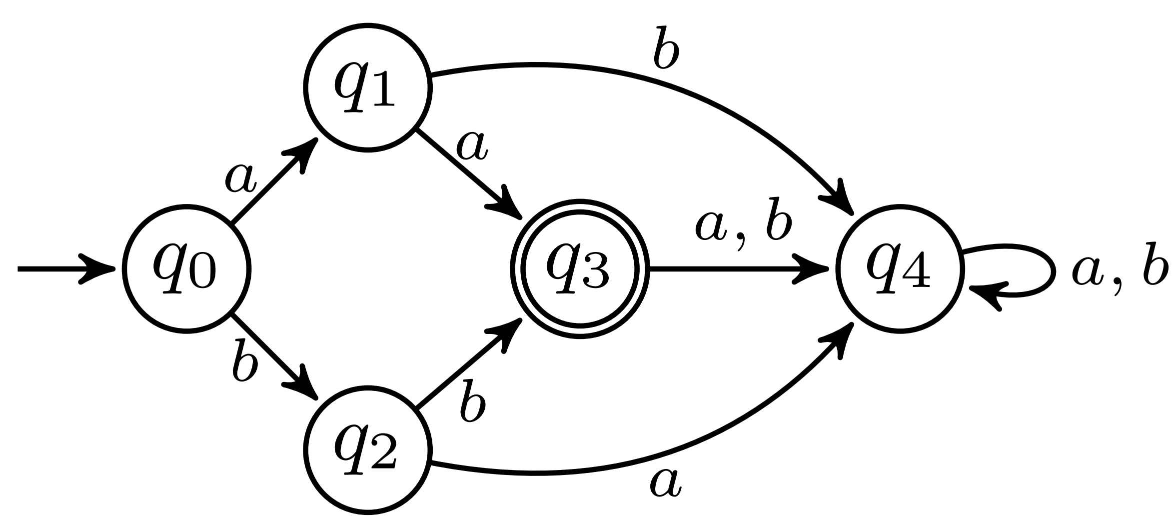
$\mathcal{A}_3 =$ 

$$t = babb$$

$\mathcal{A}_4 =$ 

Automata learning

&

Applications : Security, formal verification, …

Generalisations : Mealy machines, I/O automata, …

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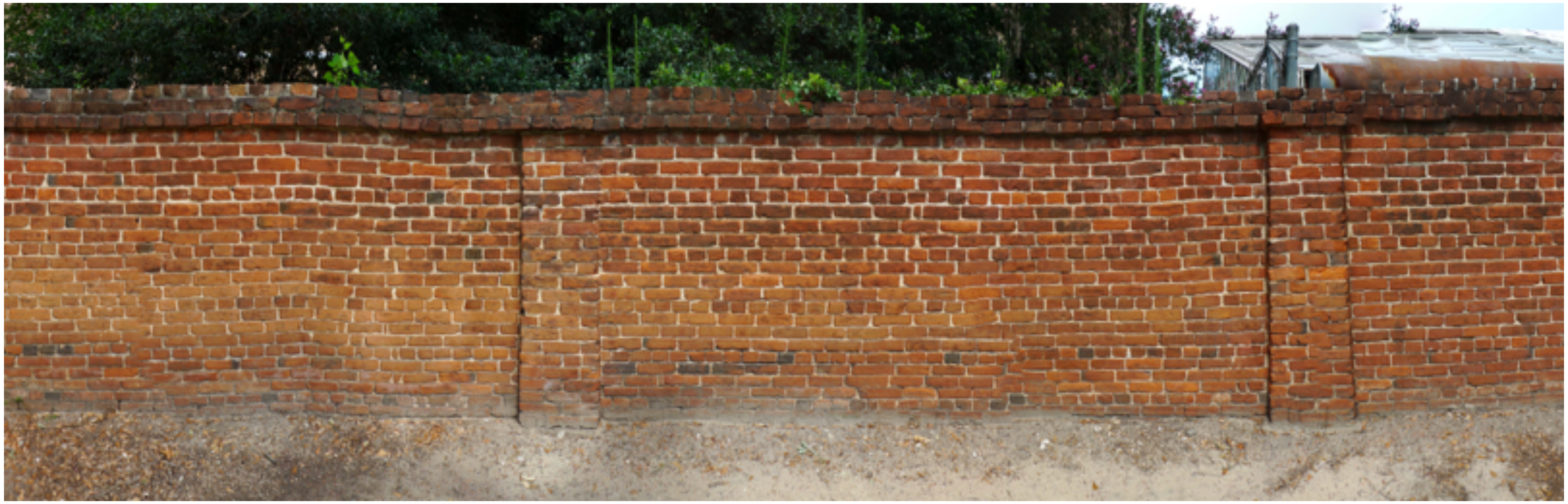

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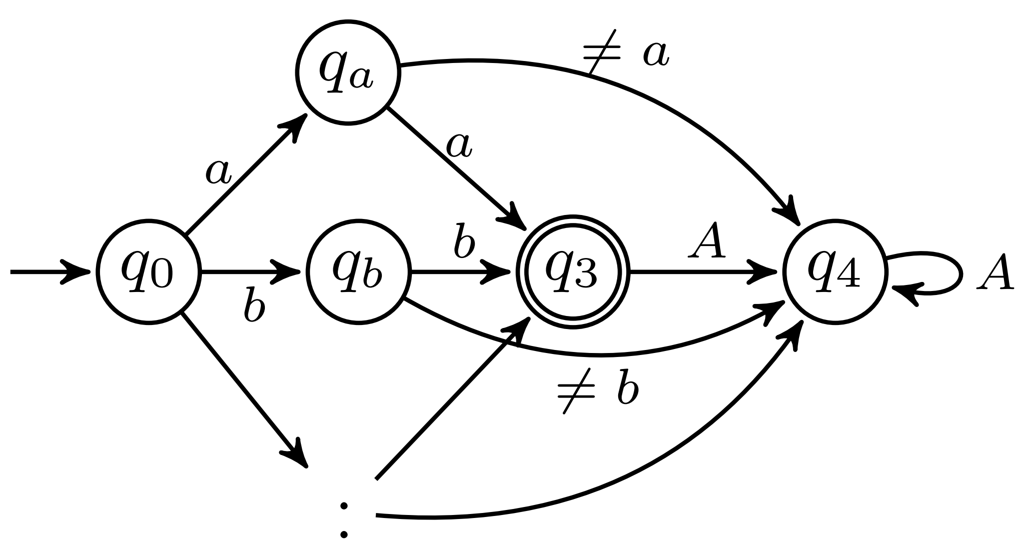
Infinite alphabets

$$\mathcal{L}_n = \{ww \mid w \in A^\star, |w| = n\}$$

$$\mathcal{L}_1 = \{aa, bb\}$$

$\mathcal{A}_5 =$



infinite automaton

Infinite alphabets

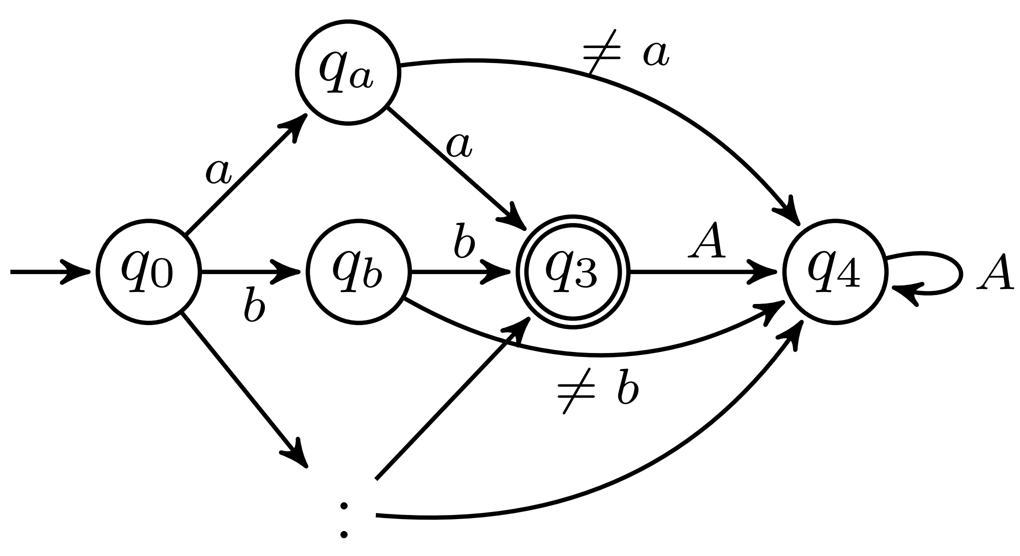
$$\mathcal{L}_n = \{ww \mid w \in A^\star, |w| = n\}$$

A infinite

$$\mathcal{L}_1 = \{aa, bb\}$$

$$\mathcal{L}_1 = \{aa, bb, cc, dd, \ldots\}$$

$\mathcal{A}_5 =$



infinite automaton

Infinite alphabets

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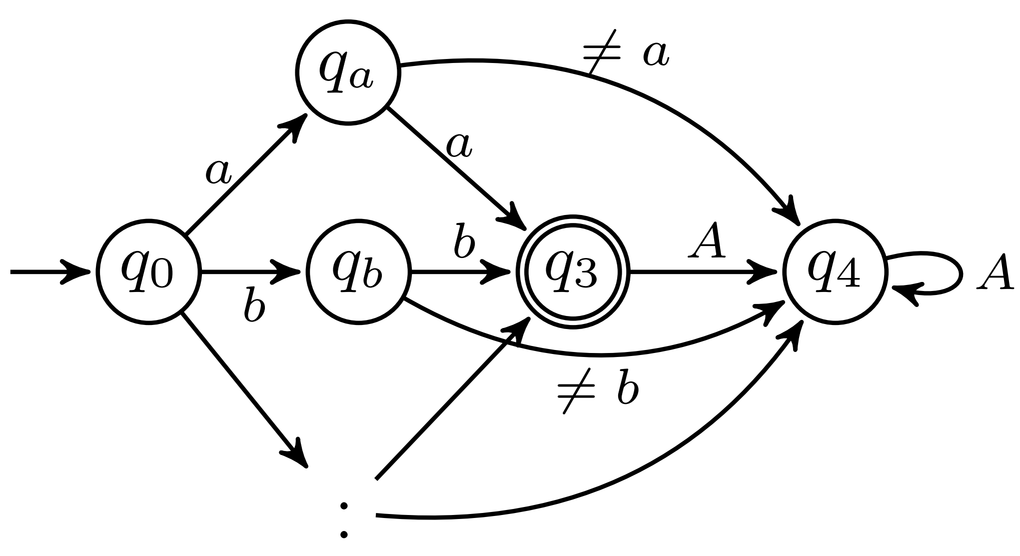
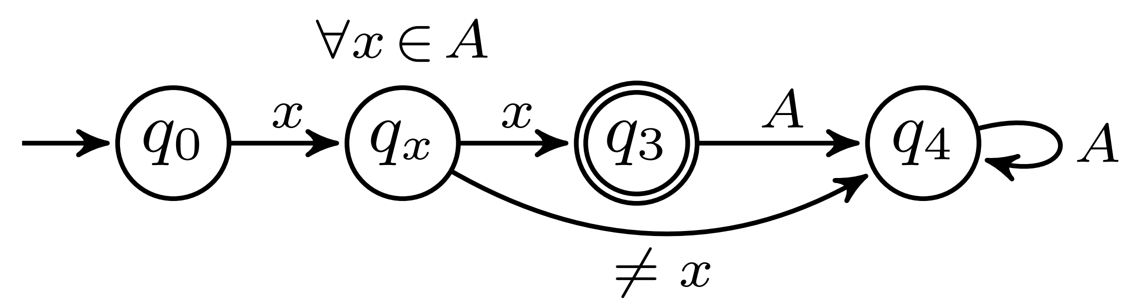
A infinite

$\mathcal{L}_1 = \{\bar{a}a, \bar{b}b\}$

$\mathcal{L}_1 = \{aa, bb, cc, dd, \ldots\}$

$\mathcal{A}_5 =$ 

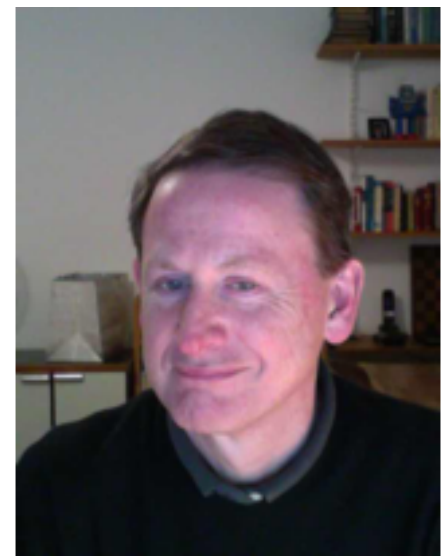


infinite automaton

but with a finite representation

Nominal automata

Nominal sets



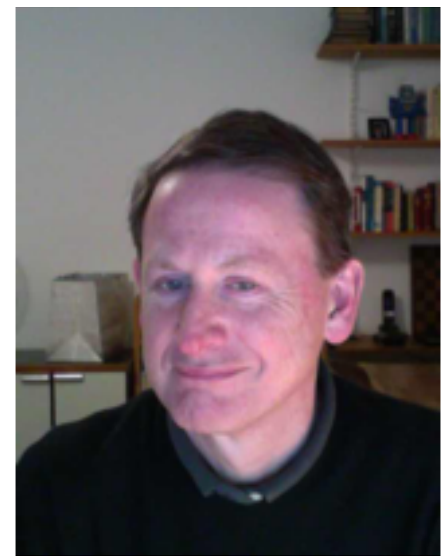
name binding

alpha-equivalence

.....

Nominal automata

Nominal sets



name binding
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.....

Infinite sets

Nominal automata

Nominal sets

name binding

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.....

Infinite sets with symmetries

Nominal automata

Nominal sets

name binding
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Infinite sets with symmetries

Finitely representable

Nominal automata

Nominal sets

name binding
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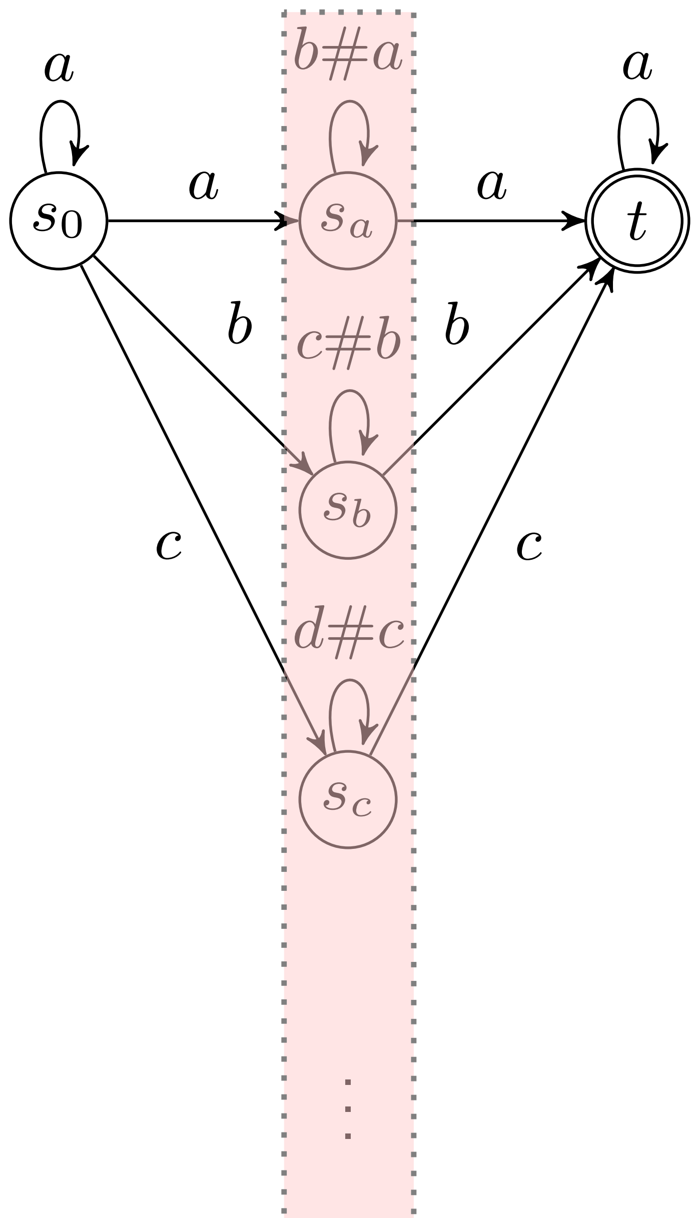
Automata theory
over nominal sets

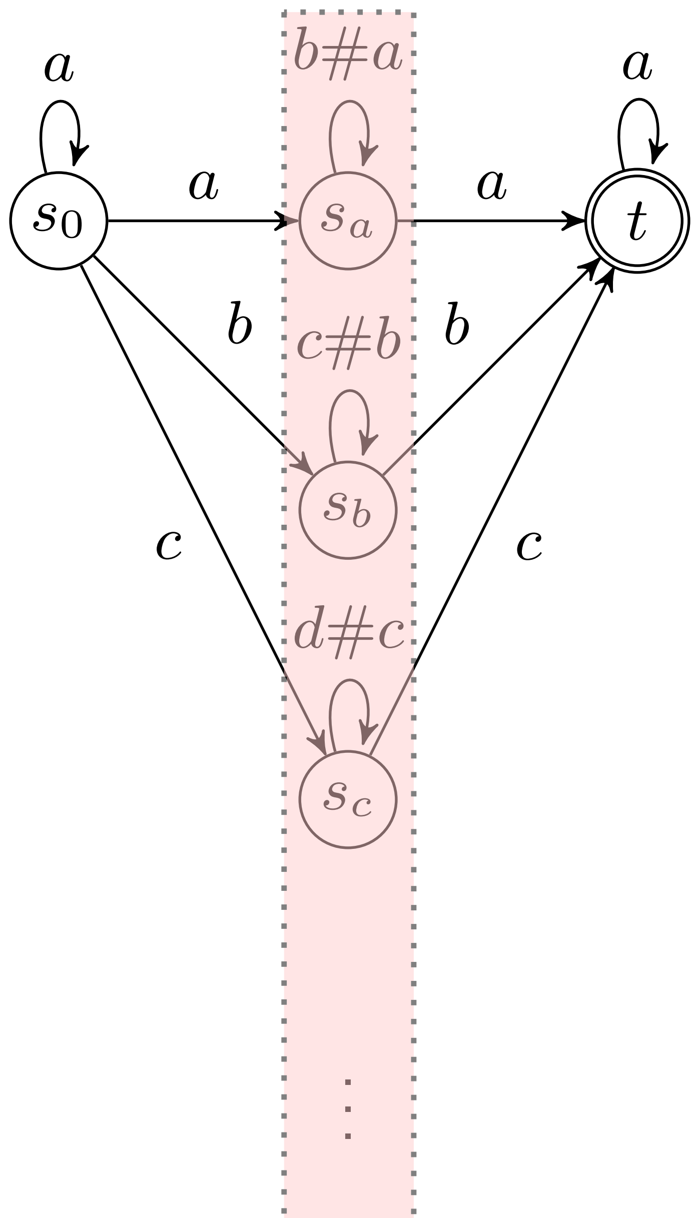
Nominal automata



$\mathbb{A}$ infinite

$\{w \in \mathbb{A}^* \mid \exists a.a \text{ occurs twice in } w\}$

Nominal automata



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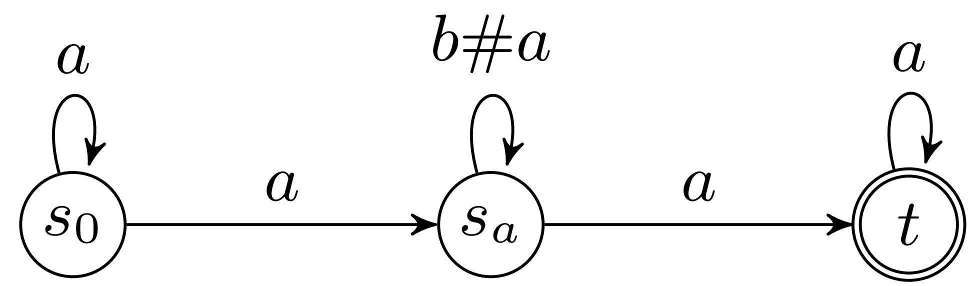


finite representation

Nominal automata

$$\begin{tikzcd} s_0 \arrow[loop above, "a"] \arrow[r, "a"] & s_a \arrow[loop above, "b\#a"] \arrow[r, "a"] & t \arrow[loop above, "a"] \end{tikzcd}$$

finite representation $\quad X = \{s_0\} + \mathbb{A} + \{t\}$

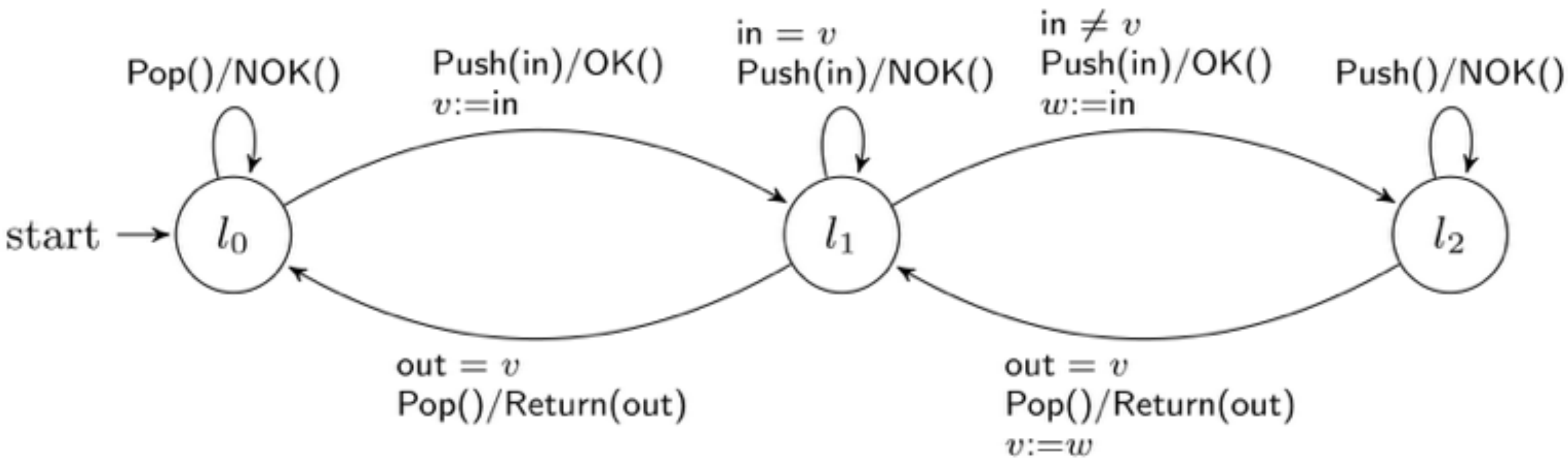
canonical permutations $\quad \pi : \mathbb{A} \to \mathbb{A}$

$$s_a \mapsto s_{\pi a}$$

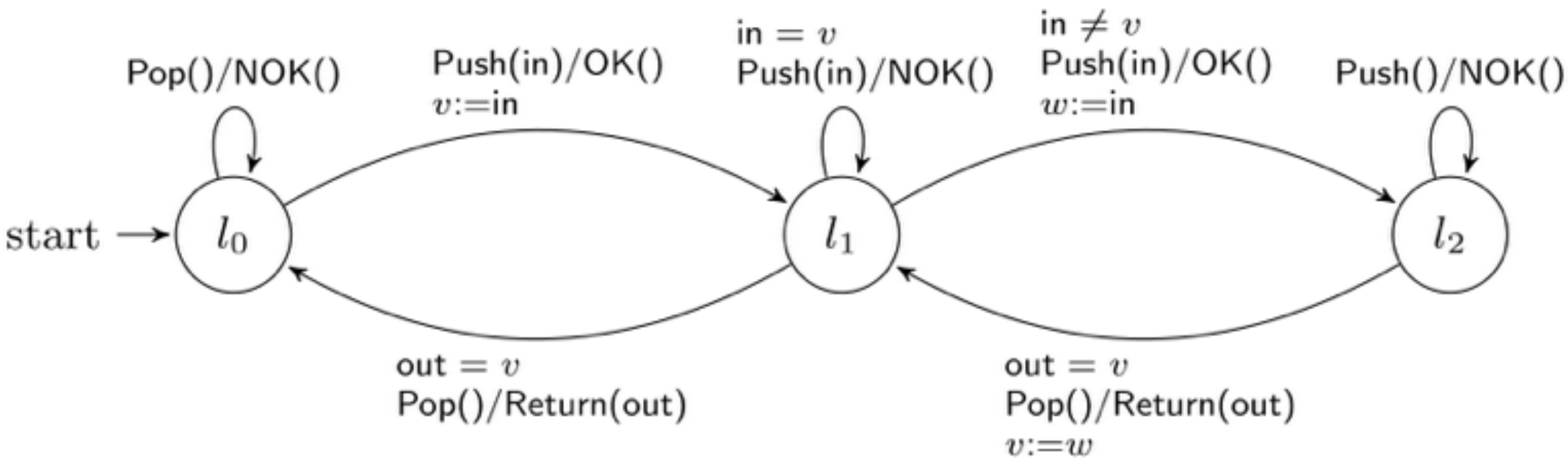
transition closed under permutations
equivariant

$$s_a \xrightarrow{a} t \Rightarrow s_{\pi a} \xrightarrow{\pi a} t$$

Nominal automata

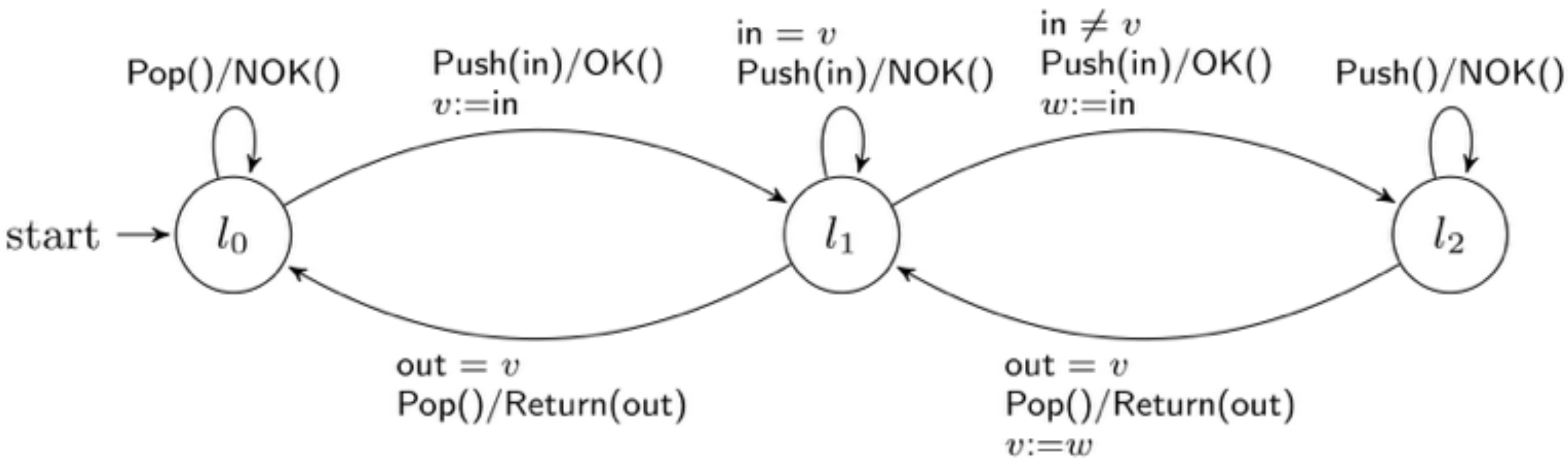


Nominal automata



Better or worse than Nominal automata?

Nominal automata



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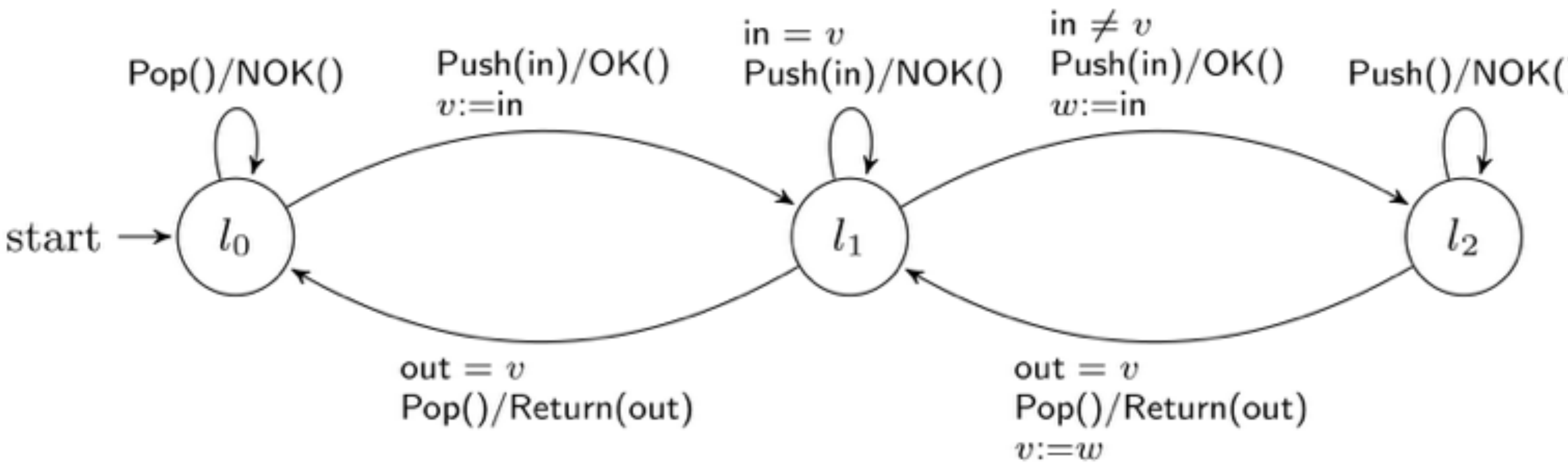
Nominal automata are *just* automata in **Nom**

Nominal automata



Better or worse than Nominal automata?

Nominal automata are *just* automata in **Nom**

$\lambda x.\mathbf{Nom}(x)$ research program

This talk

Learning algorithm for nominal automata

This talk

Learning algorithm for nominal automata

using category theory & coalgebra

This talk

Learning algorithm for nominal automata

using category theory & coalgebra

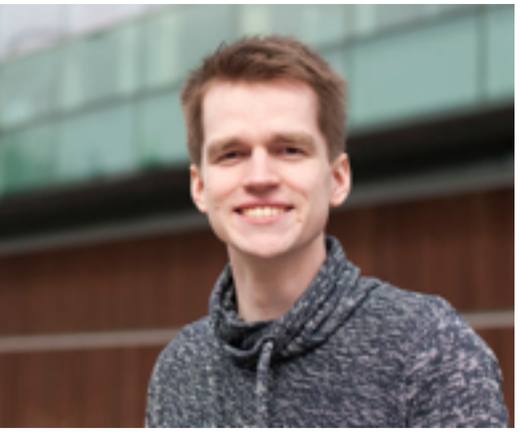
$\boxed{\textit{Angluin meets the Warsaw group}}$

$$(\lambda x.\mathbf{Nom}(x))(L^*)$$

Credits

Joshua Moerman, Matteo Sammartino, Alexandra Silva, Bartek Klin, Michal Szynwelski. **Learning Nominal Automata.**

Bart Jacobs, Alexandra Silva. **Automata Learning: A Categorical Perspective.**





Challenges

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range over infinite sets

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range over infinite sets

finding witnesses potentially requires checking infinite rows

Challenges

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  if (S, E) is not closed
    find $s_1 \in S$, $a \in A$ such that
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    $S \leftarrow S \cup \{s_1 a\}$
  if (S, E) is not consistent
    find $s_1, s_2 \in S$, $a \in A$, and $e \in E$ such that
      $row(s_1) = row(s_2)$ and $\mathcal{L}(s_1 ae) \neq \mathcal{L}(s_2 ae)$
    $E \leftarrow E \cup \{ae\}$
  Make the conjecture $M(S, E)$
  if the Teacher replies **no**, with a counter-example t
    $S \leftarrow S \cup \texttt{prefixes}(t)$
until the Teacher replies **yes** to the conjecture $M(S, E)$.
return $M(S, E)$

range over infinite sets

finding witnesses potentially requires checking infinite rows

t has only finitely many prefixes,

but an infinite S is necessary

Challenges

L* LEARNER

$S, E \leftarrow \{\epsilon\}$
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  while (S, E) is not closed or not consistent
  if (S, E) is not closed
    find $s_1 \in S$, $a \in A$ such that
      $row(s_1 a) \neq row(s)$, for all $s \in S$
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no finite automaton accepts $\mathcal{L}_1$

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(P1) the sets S, S·A and E admit a finite representation up to permutations;
(P2) row is such that row(π(s))(π(e)) = row(s)(e), for all s ∈ S and e ∈ E.
Observation table admits a finite symbolic representation.

Nominal L*

$$
\begin{array}{ll}
6' & S \leftarrow S \cup \texttt{orb}(sa) \\
9' & E \leftarrow E \cup \texttt{orb}(ae) \\
12' & E \leftarrow E \cup \texttt{prefixes}(\texttt{orb}(t))
\end{array}
$$

only 3 lines changed!

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not really… all definitions have to be adapted
to nominal/equivariant.

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only 3 lines changed!

not really… all definitions have to be adapted
to nominal/equivariant.

Correctness, termination, … have to be re-proved!

Nominal L*

not really. pted

Correctnes -proved!

Categorical glasses

(S, E, row) is *closed* if for all $t \in S \cdot A$ there exists an $s \in S$ such that $row(t) = row(s)$.

Categorical glasses

$$
\begin{tikzcd}
S \arrow[r, two heads, "e"] \arrow[drr, bend left, "row"] & \bullet \arrow[dr, tail, "m"] & \\
 & & 2^E \\
S \cdot A \arrow[r, two heads, "e_A"] \arrow[urr, bend right, "row"'] & \bullet \arrow[ur, tail, "m_A"'] \arrow[uu, dotted, "\exists i"] &
\end{tikzcd}
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\end{tikzcd}
\qquad
\begin{tikzcd}
 & \bullet \arrow[r, tail, "m"] \arrow[dd, dotted, two heads, "\exists j"] & 2^E \\
S \arrow[ur, two heads, "e"] \arrow[dr, two heads, "e_\Lambda"'] \arrow[urr, bend left, "row"] \arrow[drr, bend right, "\Lambda(row)"'] & & \\
 & \bullet \arrow[r, tail, "m_\Lambda"'] & (2^E)^A
\end{tikzcd}
$$

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& & (2^E)^A
\end{tikzcd}$$

(S, E, row) is *closed* if for all $t \in S \cdot A$ there exists an $s \in S$ such that

Pretty…. but is it useful?

(S, E, row) is *consistent* if whenever $s_1, s_2 \in S$ are such that $row(s_1) = row(s_2)$, for all $a \in A$, $row(s_1 a) = row(s_2 a)$.

The power of abstraction

Definitions are the *same*

Proof of correctness is the *same*

The power of abstraction

Definitions are the *same*

Proof of correctness is the *same*

$$
\begin{tikzcd}
1 \arrow[d, "\lambda"'] \arrow[dr, "init"] & & 2 \\
A^* \arrow[r, dashed, "r"'] \arrow[d, "c"'] & Q \arrow[r, dashed, "o"'] \arrow[d, "\delta"] \arrow[ur, "final"] & 2^{A*} \arrow[u, "ev_\lambda"'] \arrow[d, "\partial"] \\
(A^*)^A \arrow[r, dashed, "r^A"'] & Q^A \arrow[r, dashed, "o^A"'] & (2^{A*})^A
\end{tikzcd}
$$

The power of abstraction

Learning weighted automata = vector spaces
2014, Jacobs&Silva

Learning NFAs = join semi lattices
2009, Bollig, Habermehl, Kern, Leucker - Angluin-style learning for NFA

Learning product automata = products
Implicitly done by Rivest, Schapire (diversity based learning)

All of these only work for ordinary alphabets

In Nom…

In Nom…

Correctness was easy

Brings almost nothing new to the table

Easy to implement variations
For example, different counter example analysis

Works for any symmetry $Aut(\mathcal{M})$ for any ω-categorical model $\mathcal{M}$
For example homogeneous structures: $(\mathbb{N}, =)$, $(\mathbb{Q}, \leq)$, $(\mathcal{R}, adj)$, …
Needed for products to be orbit-finite

In Nom…

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Implementation was not easy
(Partly because the library for nominal computation was young)

Implementation is not efficient

No concrete communication with teacher yet
(But theoretically possible)

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Abstraction is guidance but there is no free lunch!

Future Work

Implementation

Succinctness

Other symmetries

Verification

Other tools

Conclusions

simple is beautiful.

&

POWERFUL