Categorical **A**utomata **L**earning **F**ramework

calf-project.org

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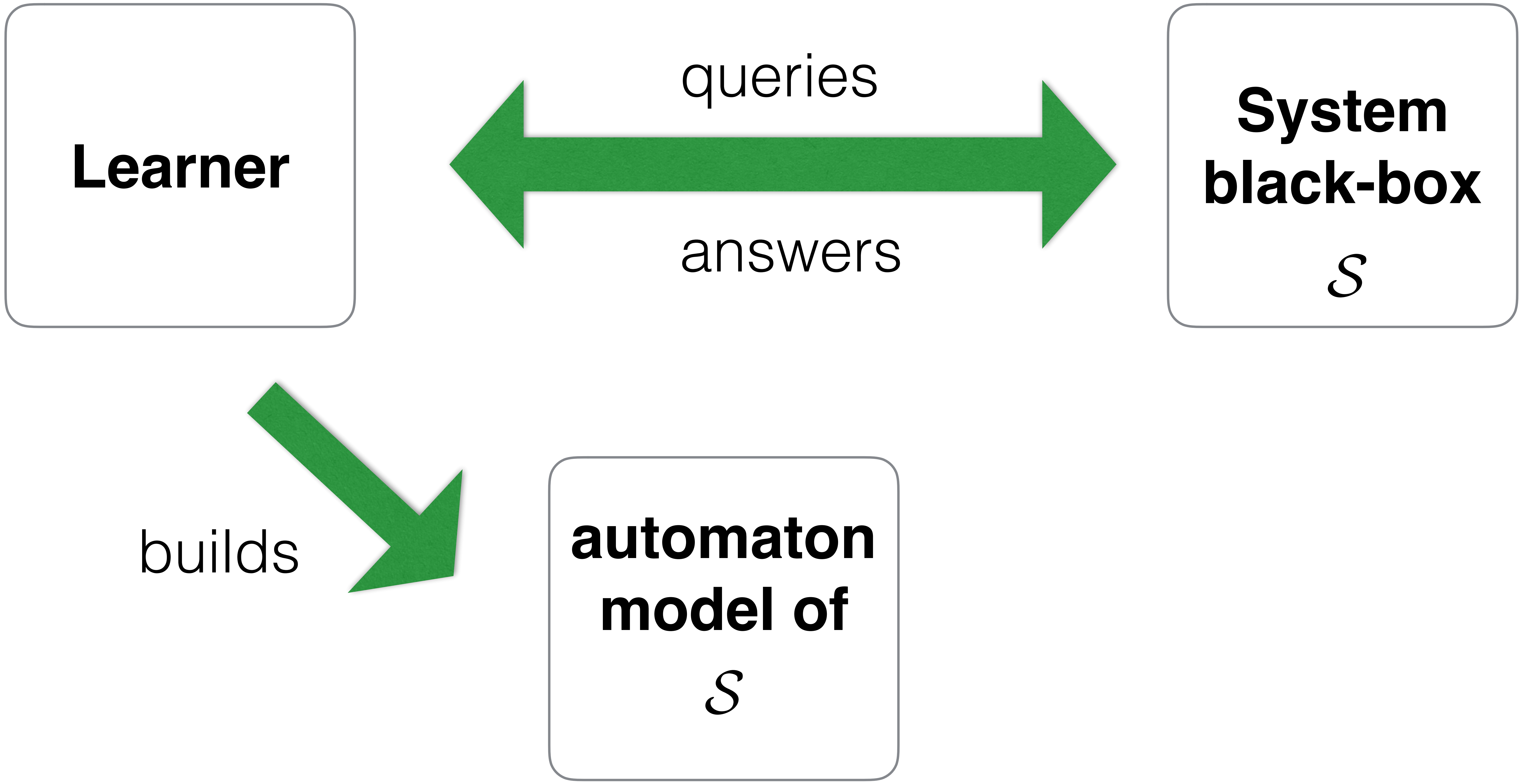
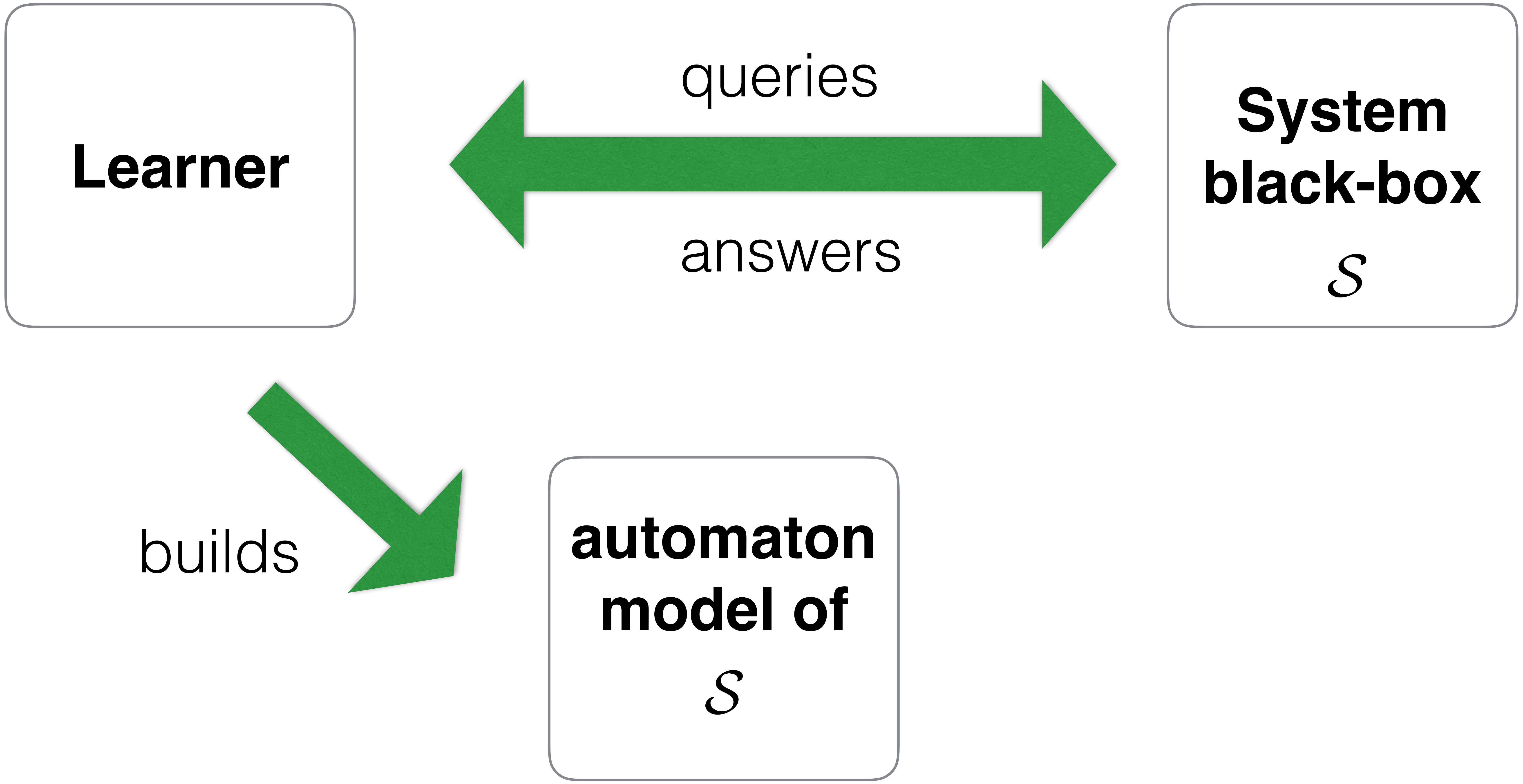
ENS Lyon

Automata learning



Automata learning



No formal specification available? **Learn it!**

L* algorithm (D.Angluin '87)

Finite alphabet of system's actions A

set of system behaviors is a **regular language** $\mathcal{L} \subseteq A^\star$

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Learner

Teacher

$\mathcal{L}$

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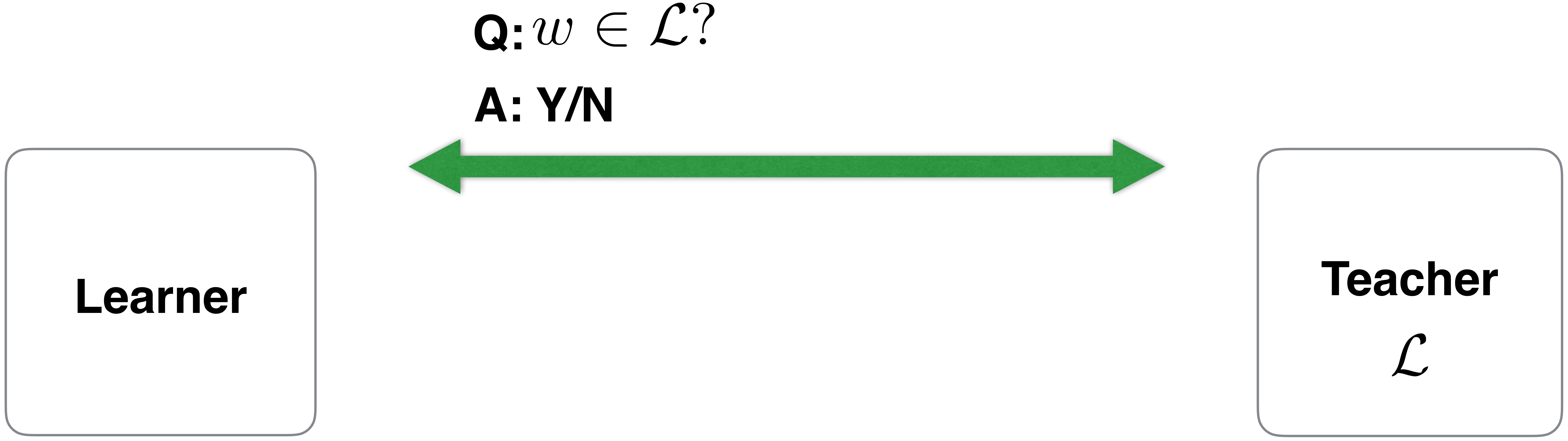

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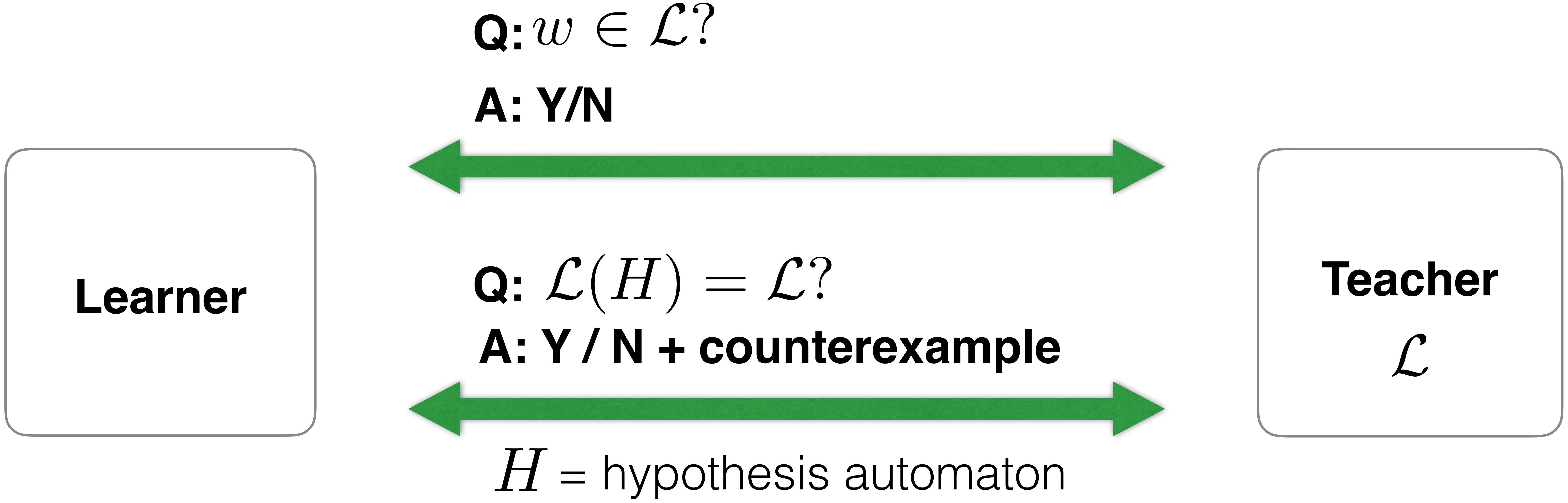

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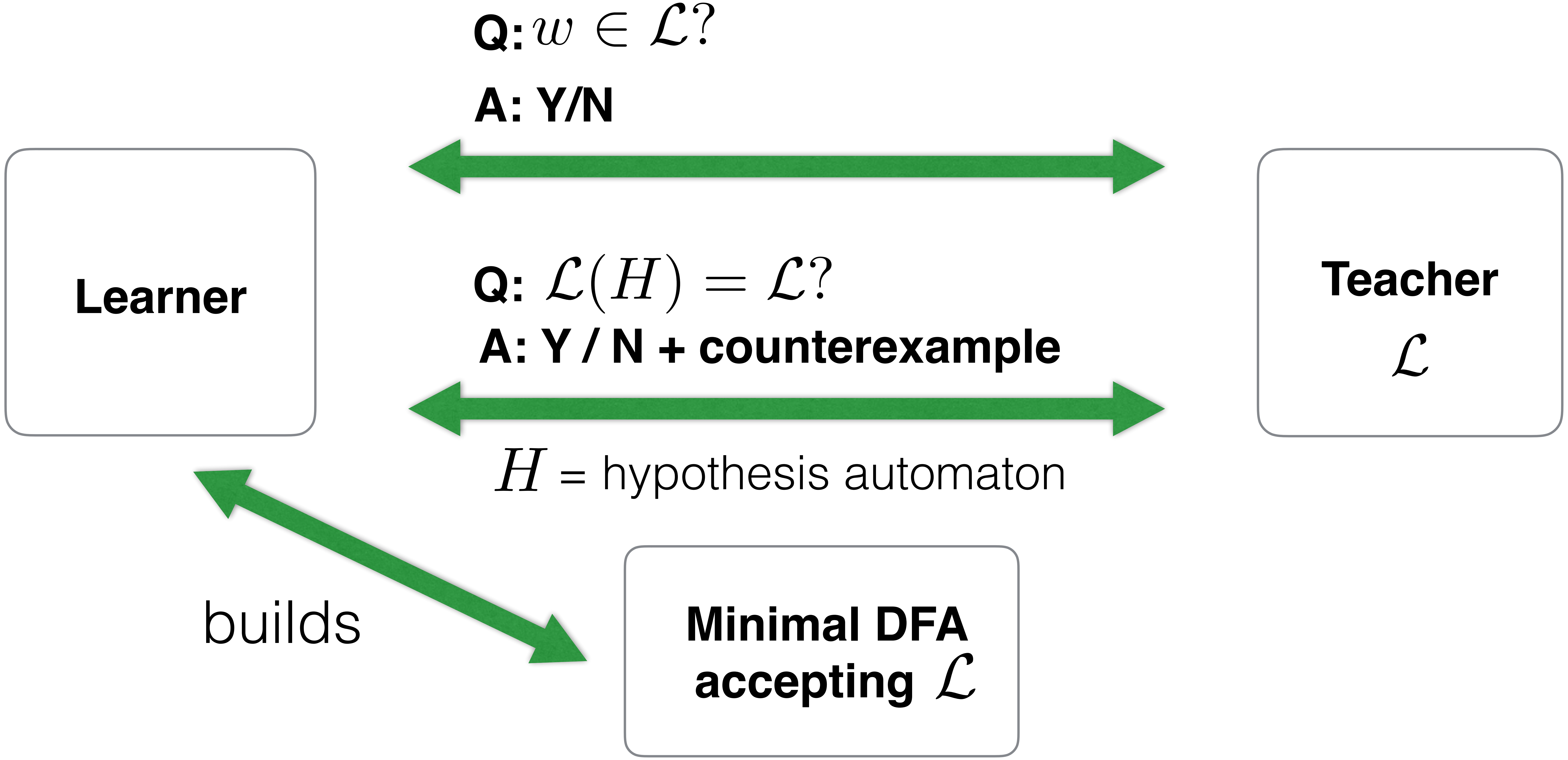

A zoo of automata

Probabilistic

Weighted

Alternating

Universal

Non-deterministic

Register

Mealy Machines

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Correctness proofs

involved and hard to check

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Category theory comes to the rescue!

Algorithms

Correctness proofs

involved and hard to check

Category Theory

Conceptual tools

Correctness proof(s)

Guidelines new algorithms

Unveil connections

Category Theory

Conceptual tools

Correctness proof(s)

Guidelines new algorithms

Unveil connections

No free lunch!

Automata

$$X \to 2 \times X^A$$

DFA

Automata

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$$X \to \mathbb{R} \times (\mathbb{R}^X)^A$$

WFA

Automata

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DFA

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WFA

$$X \to FTX$$

Algebraic properties

Transition structure

$$X \to FTX$$

$$X \to 2 \times X^A$$

DFA

$$X \to \mathbb{R} \times (\mathbb{R}^X)^A$$

WFA

$$X \to FTX$$

$$X \to 2 \times X^A$$

DFA

$$2^{A^*}$$

$$X \to \mathbb{R} \times (\mathbb{R}^X)^A$$

WFA

$$\mathbb{R}^{A^*}$$

Vector space

acceptance

$$X \to FTX$$

$$X \to 2 \times X^A$$

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DFA

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Vector space

Language equivalence

equivalence

Weighted language equivalence **or** bisimilarity

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Weighted language equivalence **or** bisimilarity

Proof methods for equivalence

Up-to techniques

Algebraic structure → Better Proof Techniques

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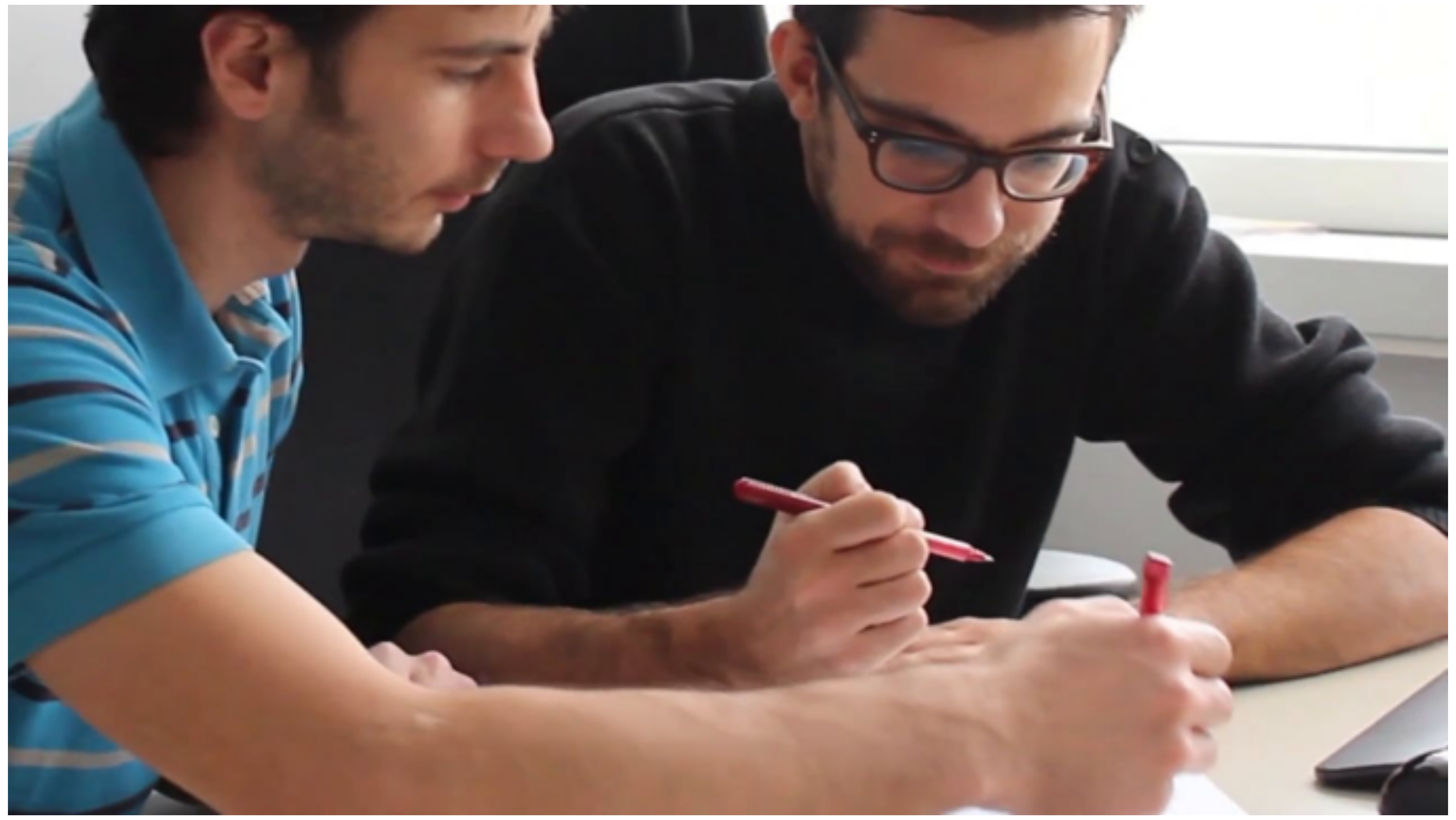
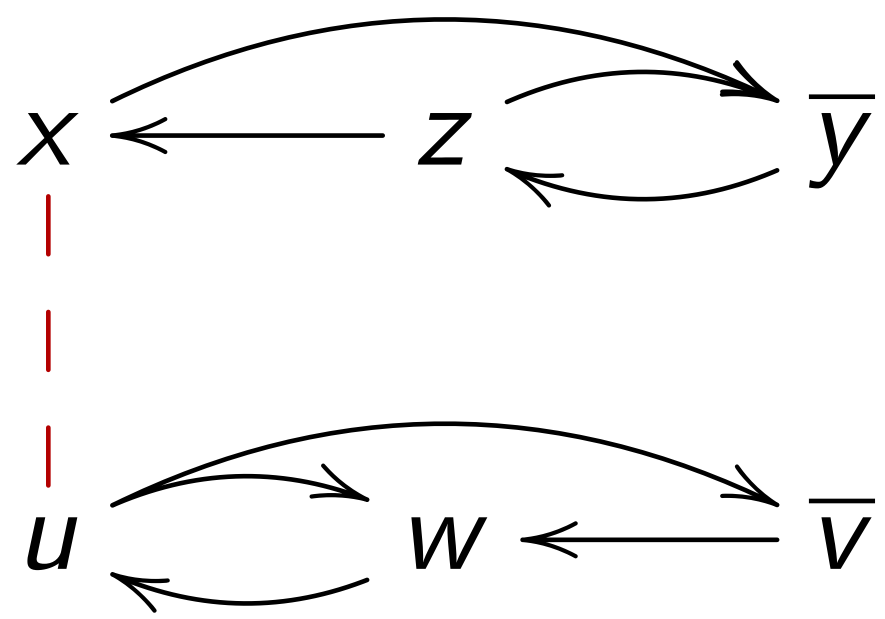
Algebraic structure → Better Proof Techniques



HKC algorithm - Bonchi and Pous 2014

Example



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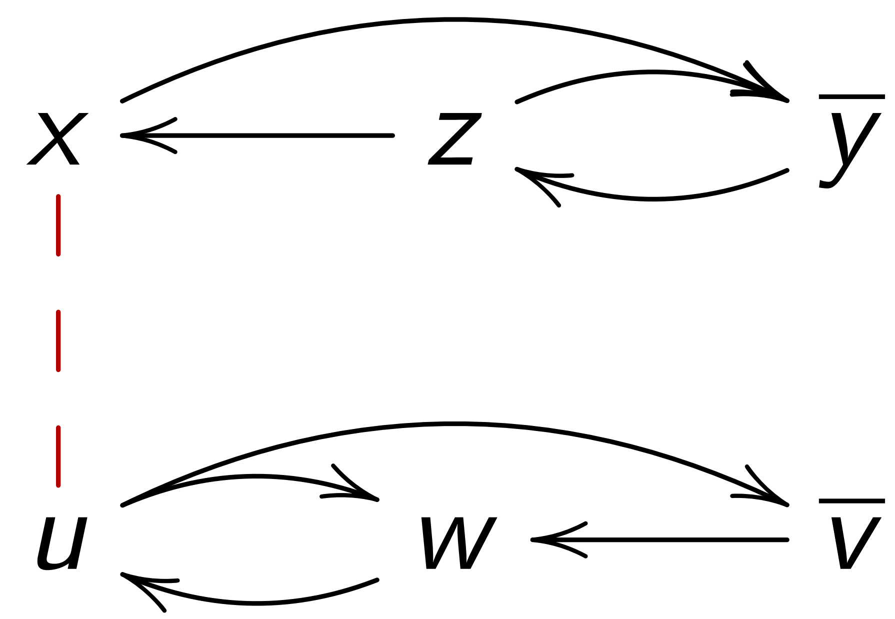
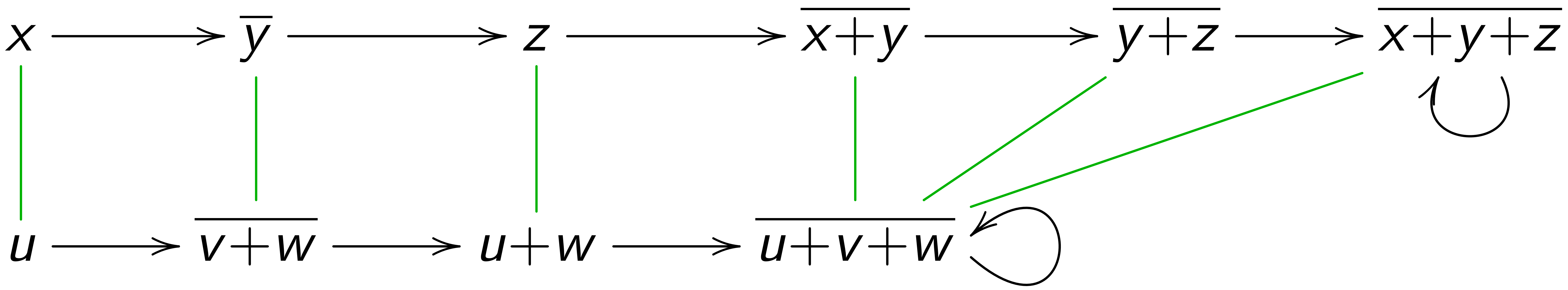


Build a bisimulation using
powerset construction on the fly



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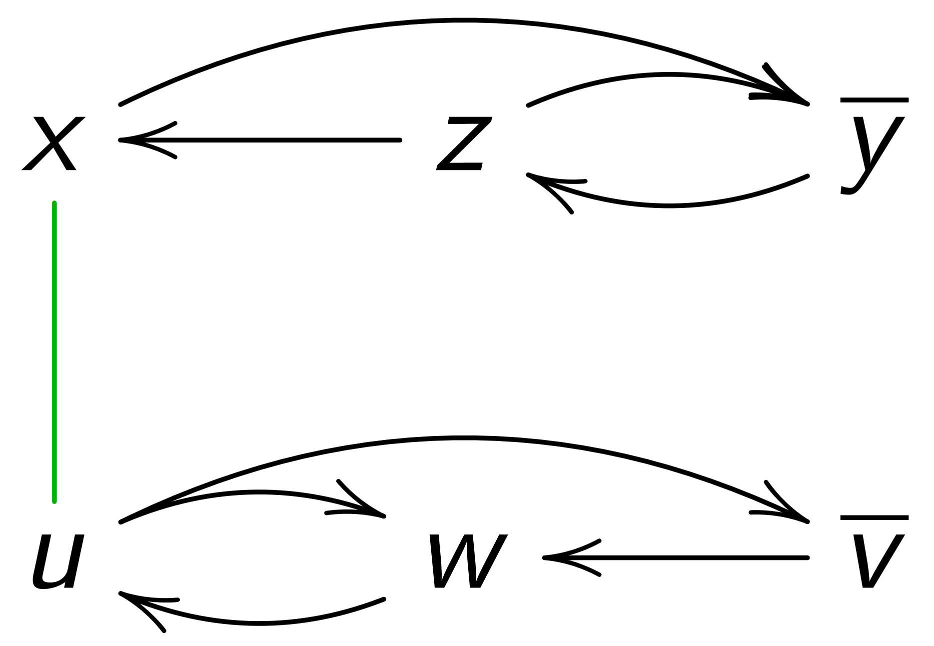
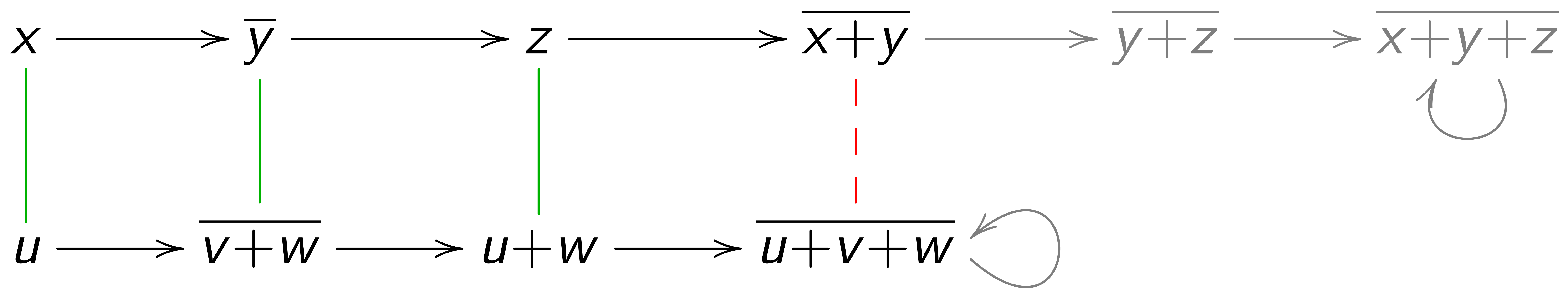
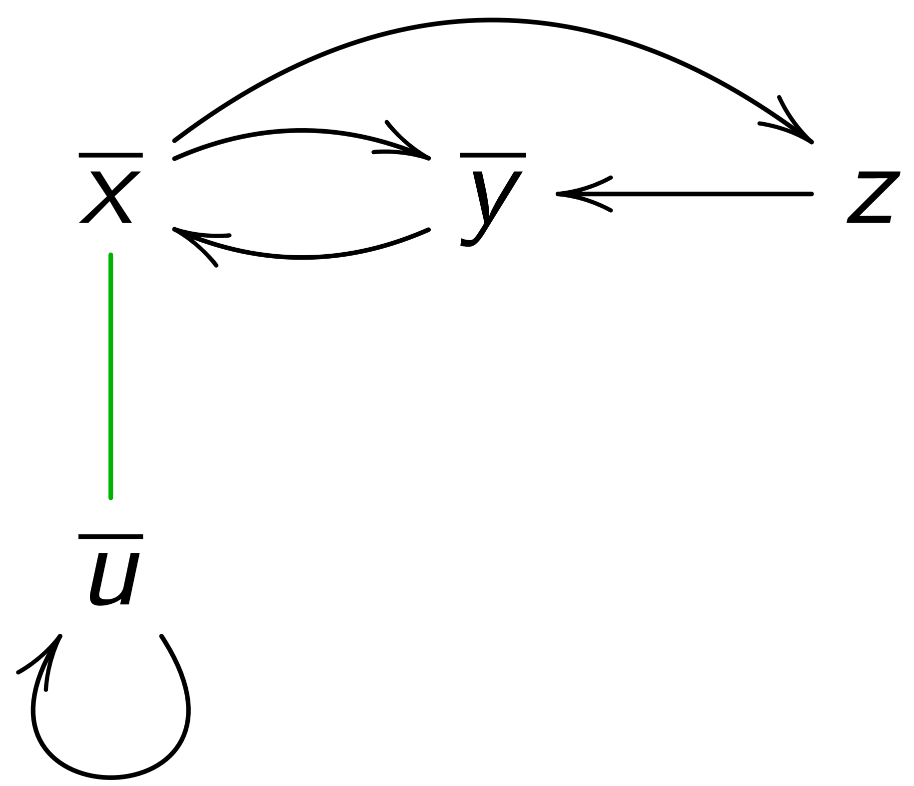


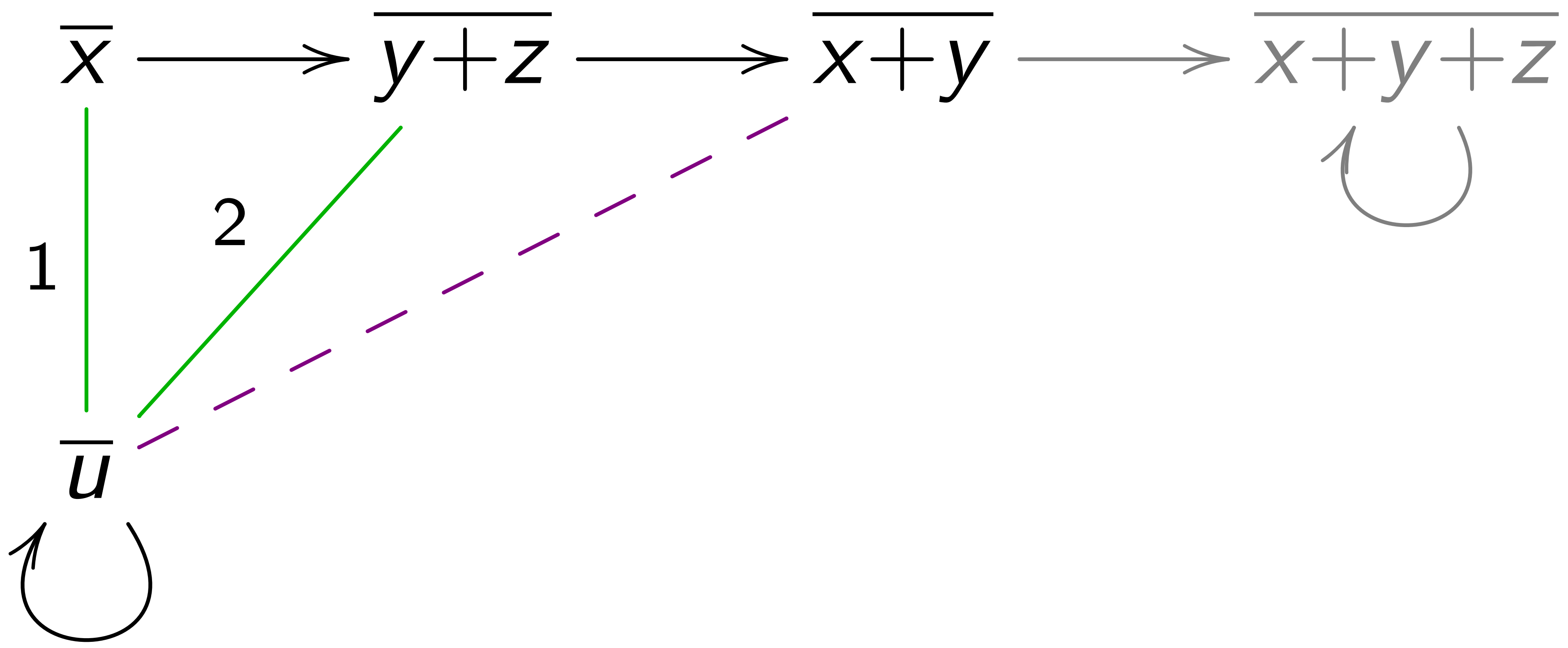
$$
\begin{array}{rl}
 & (x,\ u) \\
+ & (y,\ v+w) \\
\hline
= & (x+y,\ u+v+w)
\end{array}
$$



using bisimulations up to union

Another example





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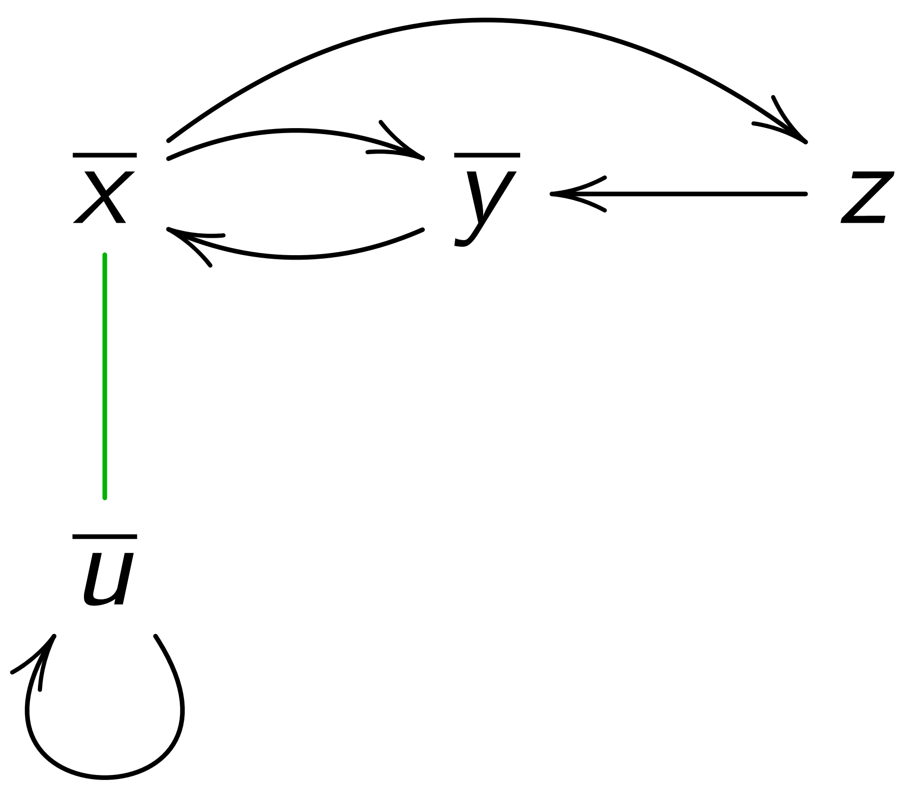
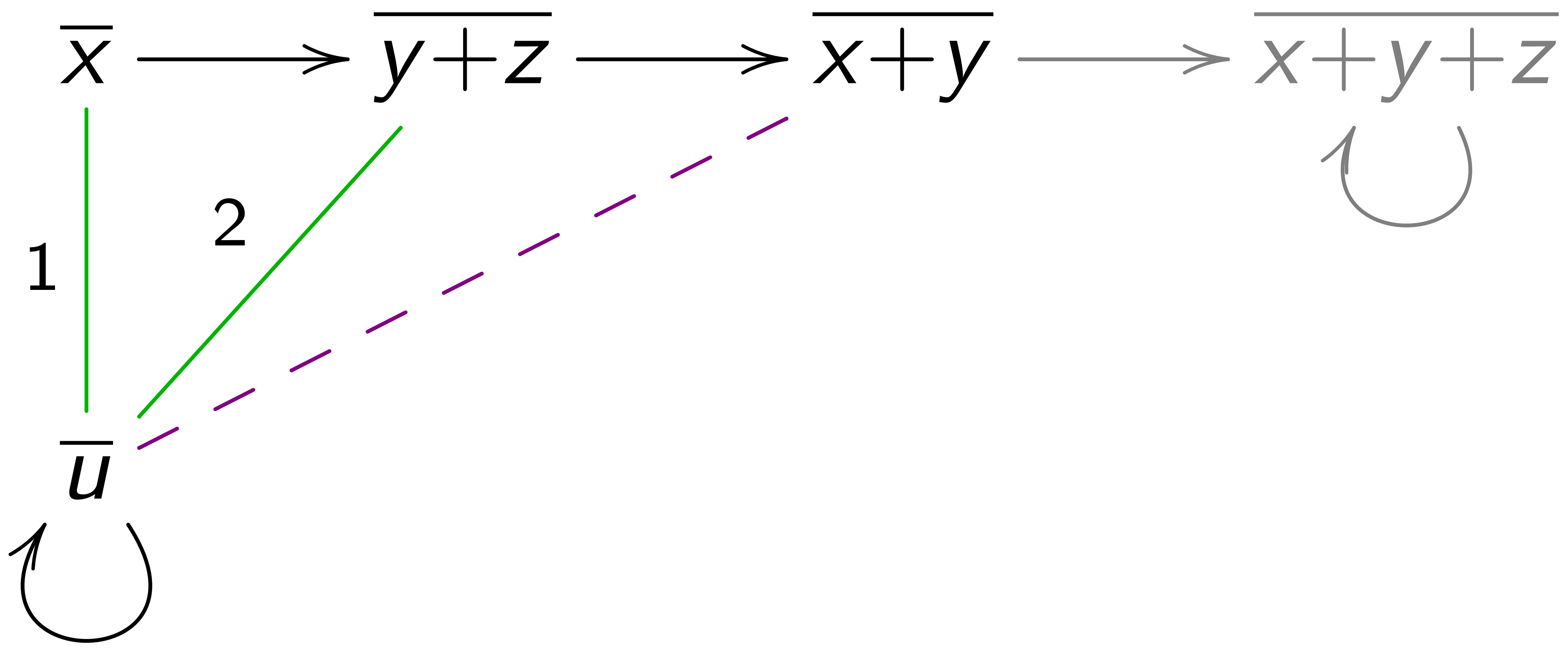
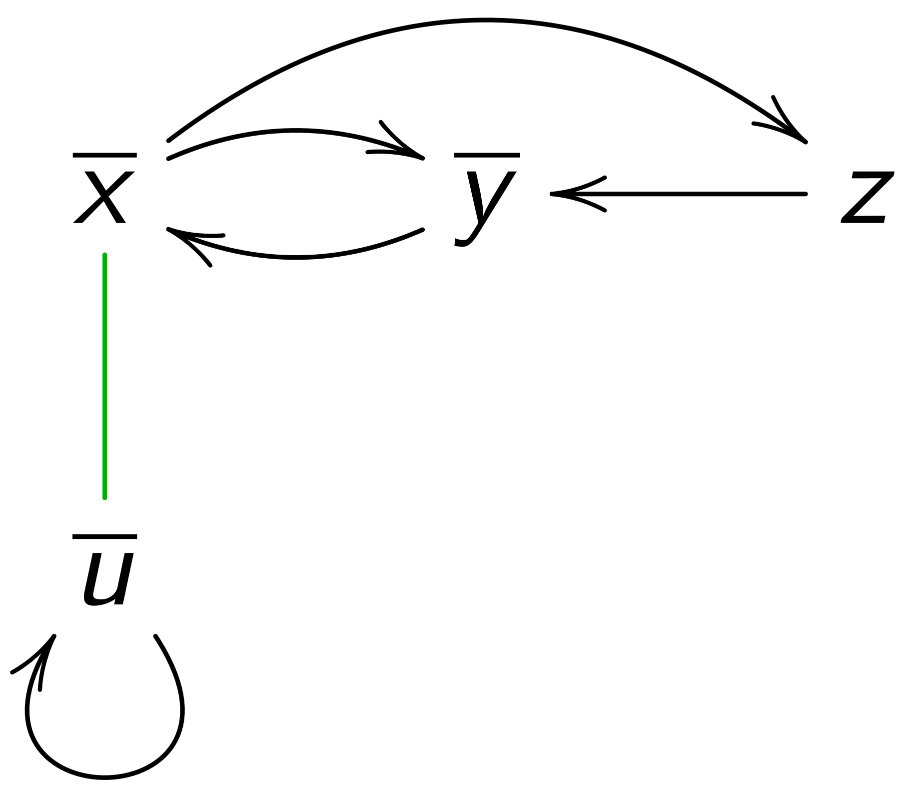
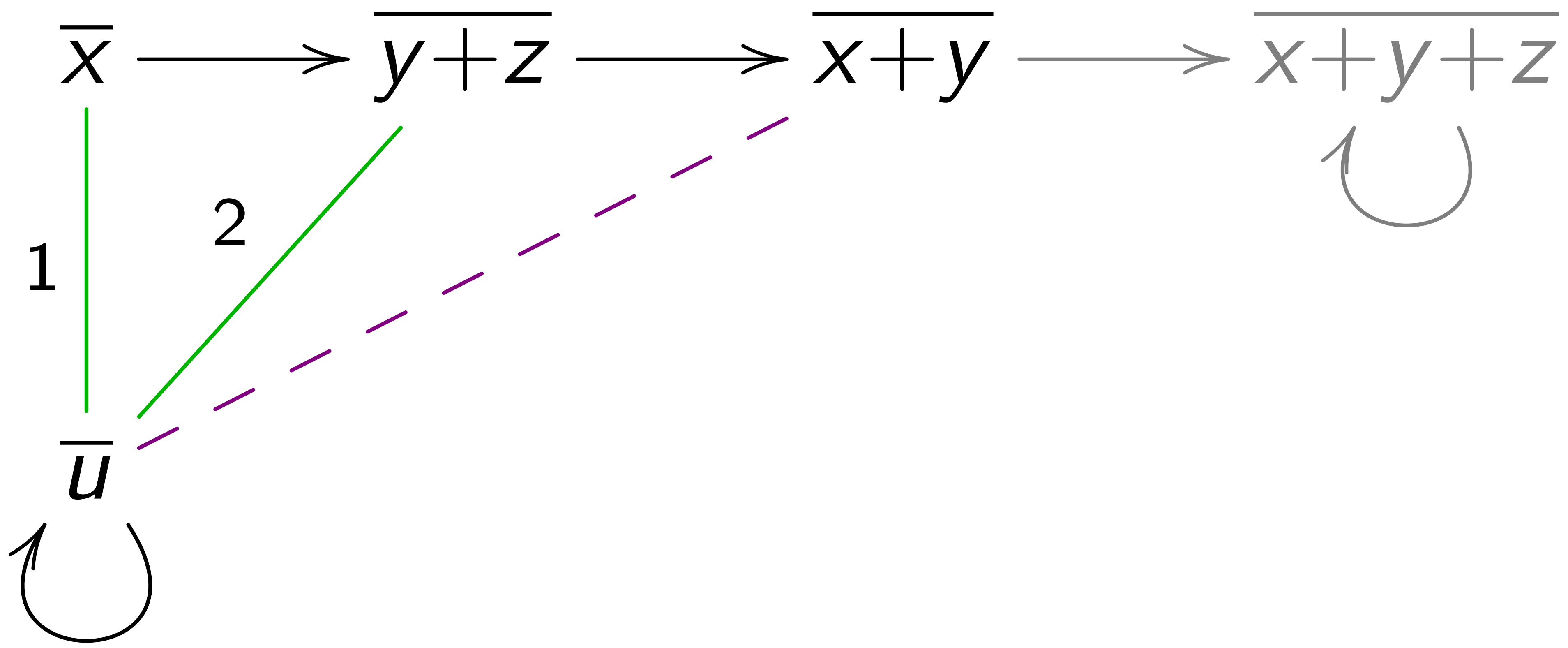




$$
\begin{aligned}
x+y &= u+y && (1)\\
&= y+z+y && (2)\\
&= y+z &&\\
&= u && (2)
\end{aligned}
$$

Another example





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Bisimulations up-to **congruence**

HKC algorithm of Bonchi&Pous

More examples

Up-To Techniques for Weighted Systems. (TACAS '17)

Filippo Bonchi, Barbara König, Sebastian Küpper

The Power of Convex Algebras (CONCUR' 17)

Filippo Bonchi, Alexandra Silva, Ana Sokolova

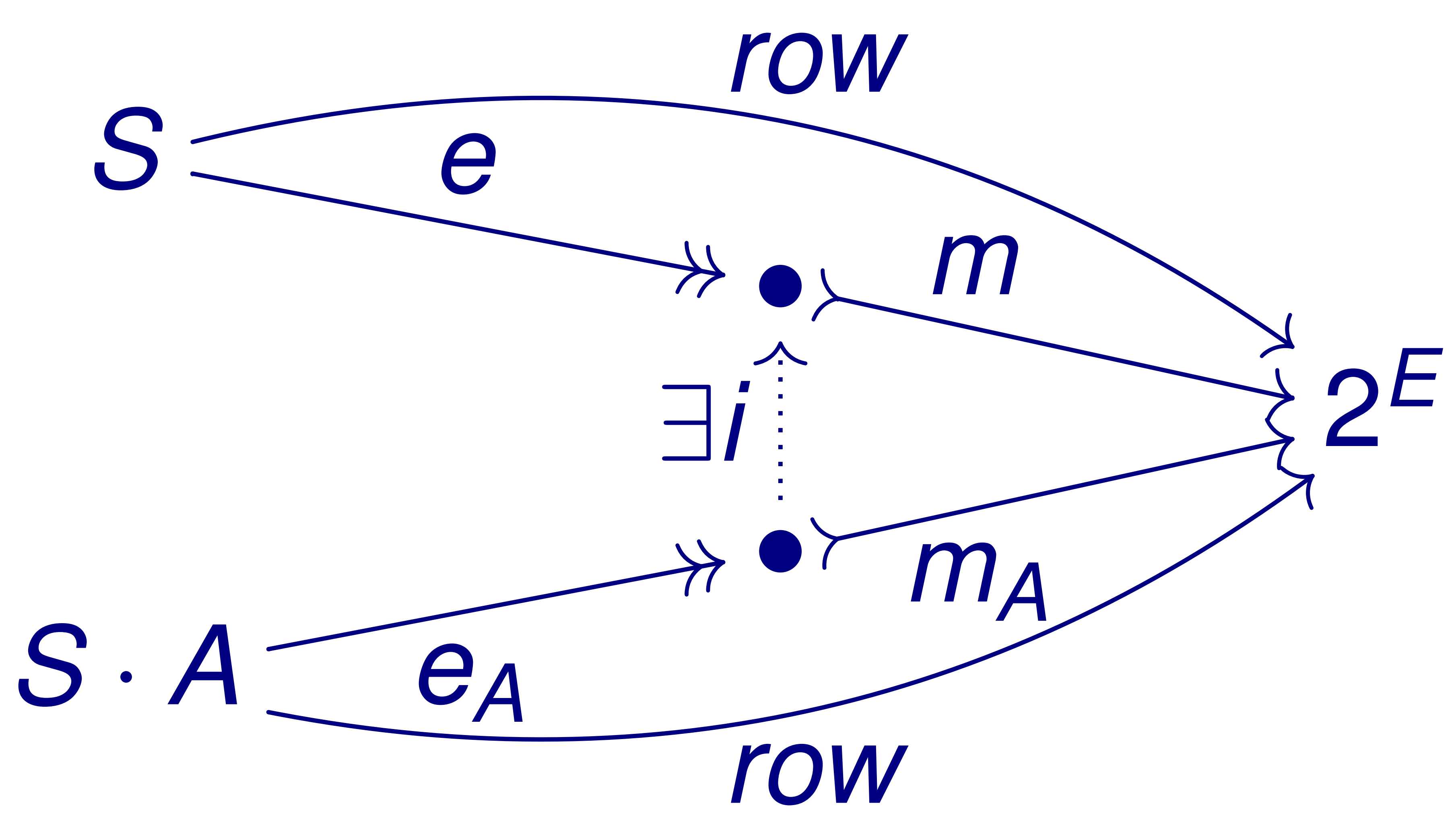
Coinduction up-to in a fibrational setting (CSL-LICS 2014)

Filippo Bonchi, Daniela Petrisan, Damien Pous, Jurriaan Rot

Category Theory in learning

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

Category Theory in learning



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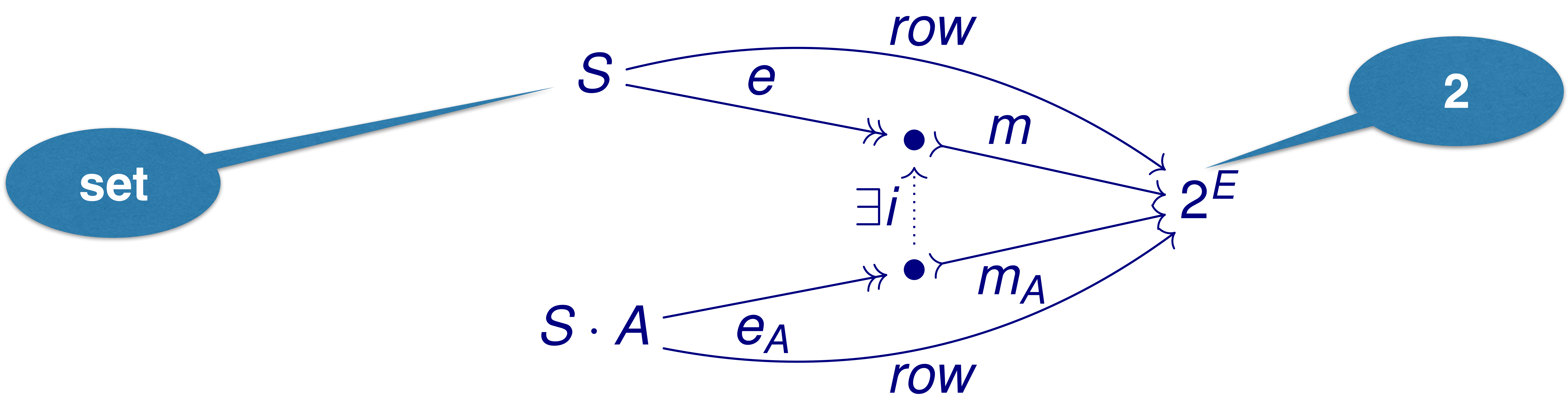

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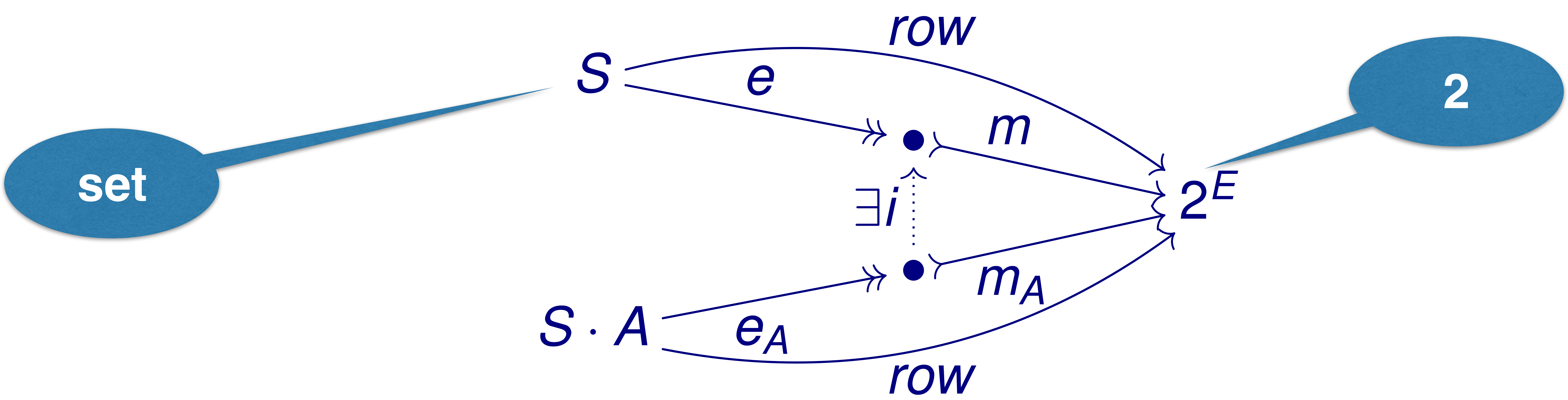

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Can we develop L* for infinite (nominal) sets?

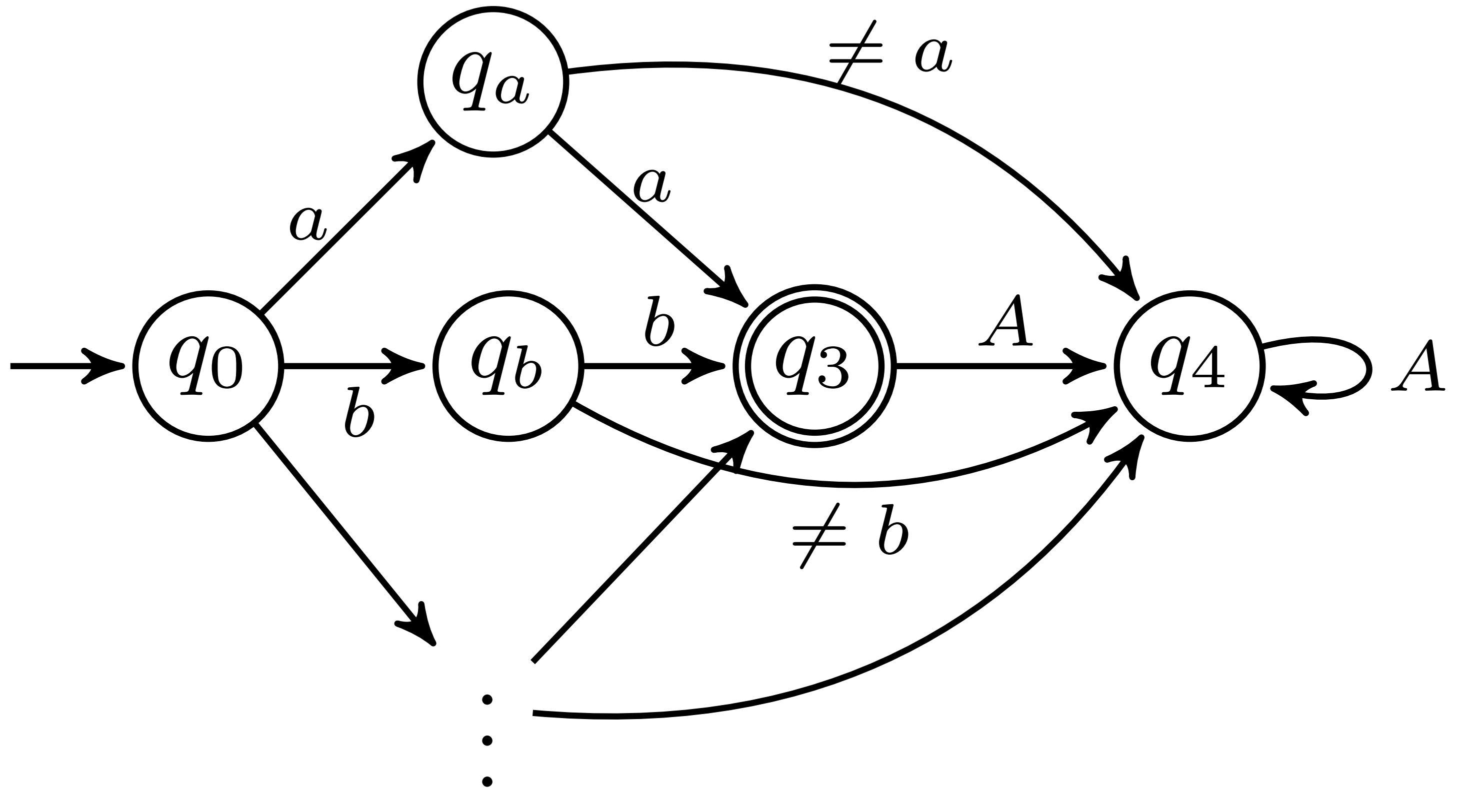
Infinite alphabets

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

A infinite

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

$\mathcal{A}_5 =$



infinite automaton

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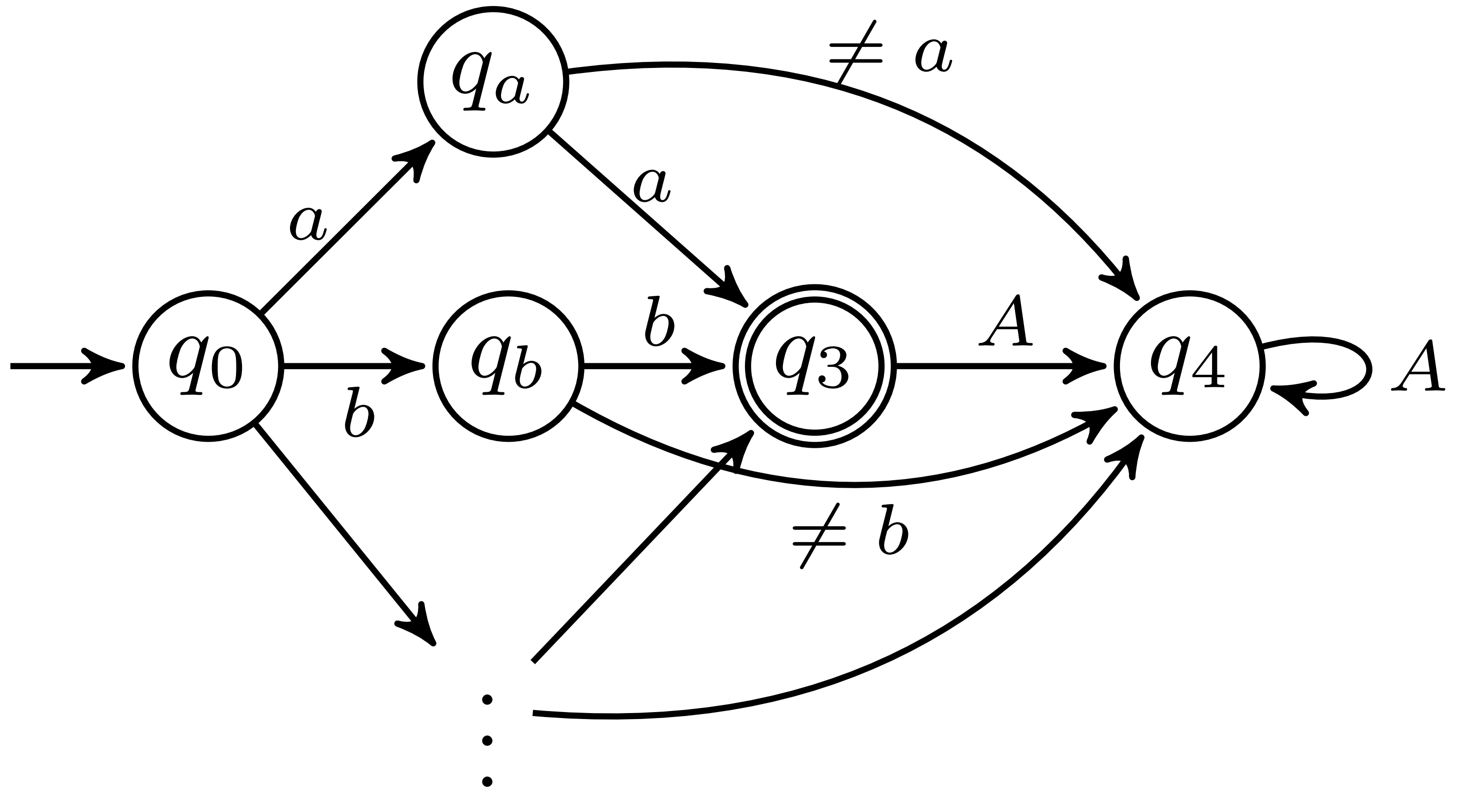

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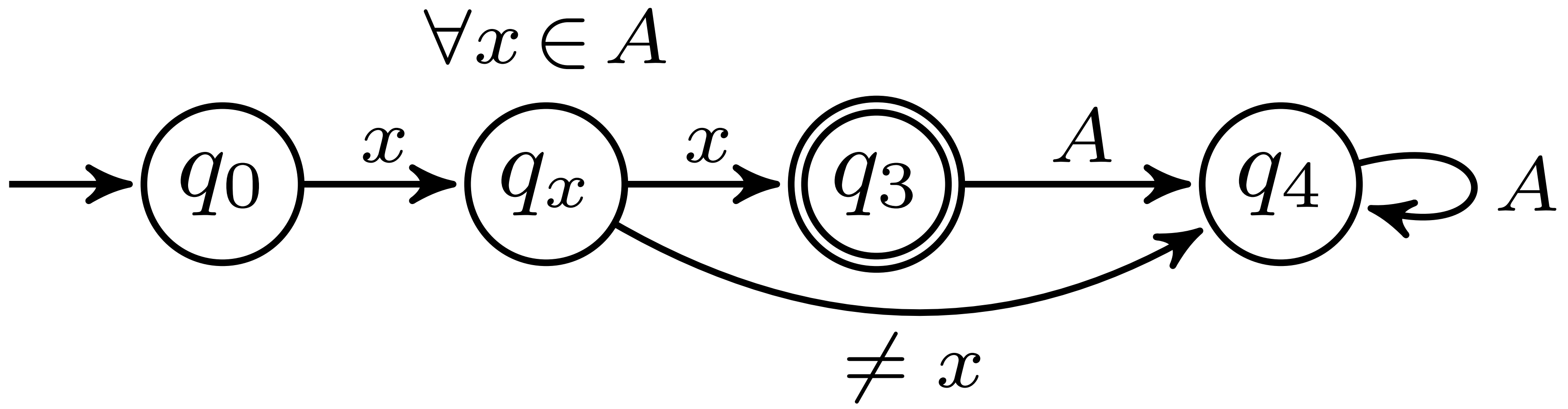

but with a finite representation

Nominal automata

Nominal sets

name binding
alpha-equivalence
…..

Nominal automata

Nominal sets

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Infinite sets

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Infinite sets with symmetries → Finitely representable

Nominal automata

Nominal sets

name binding
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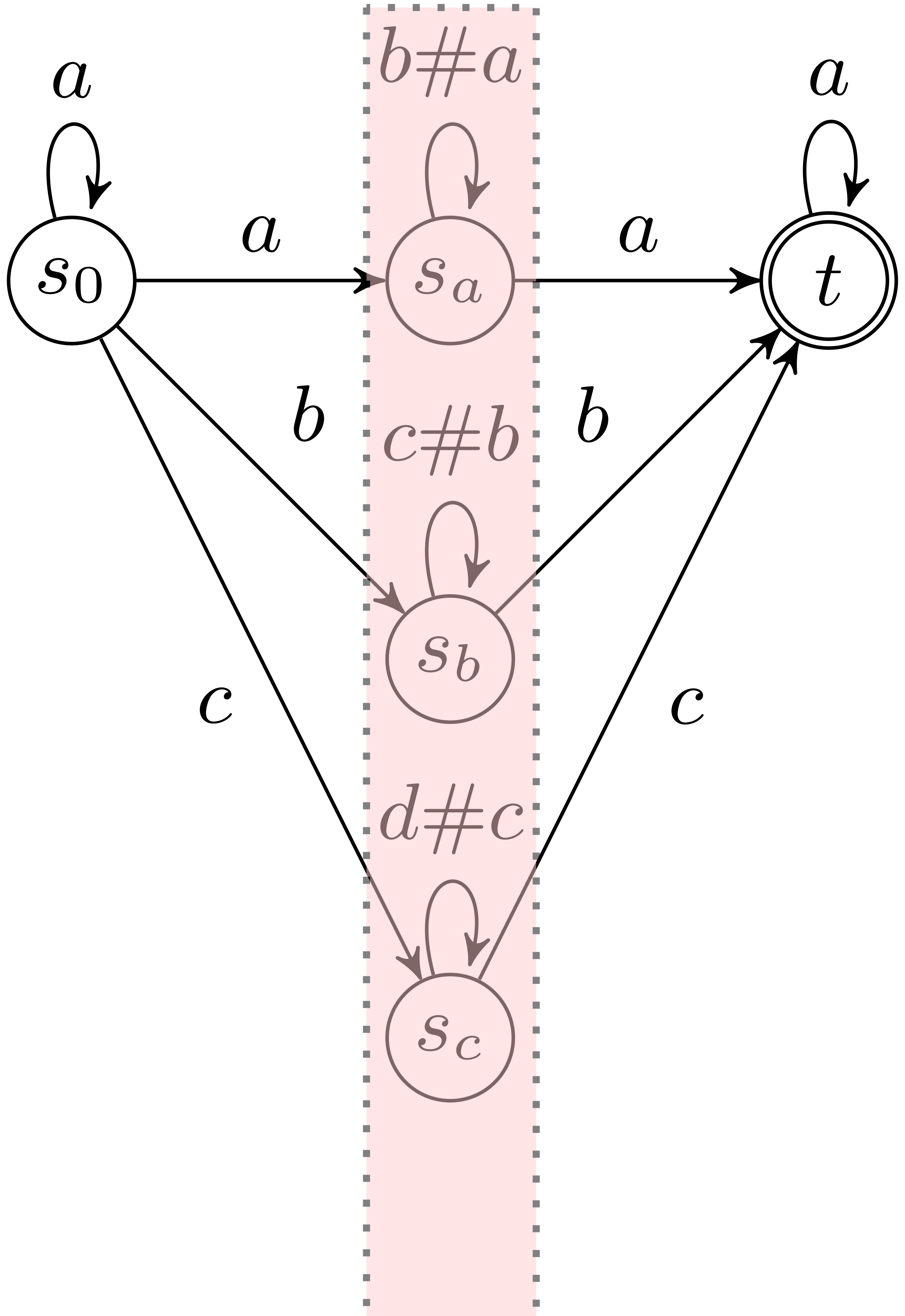
.....

Infinite sets with symmetries → Finitely representable

Automata theory
over nominal sets

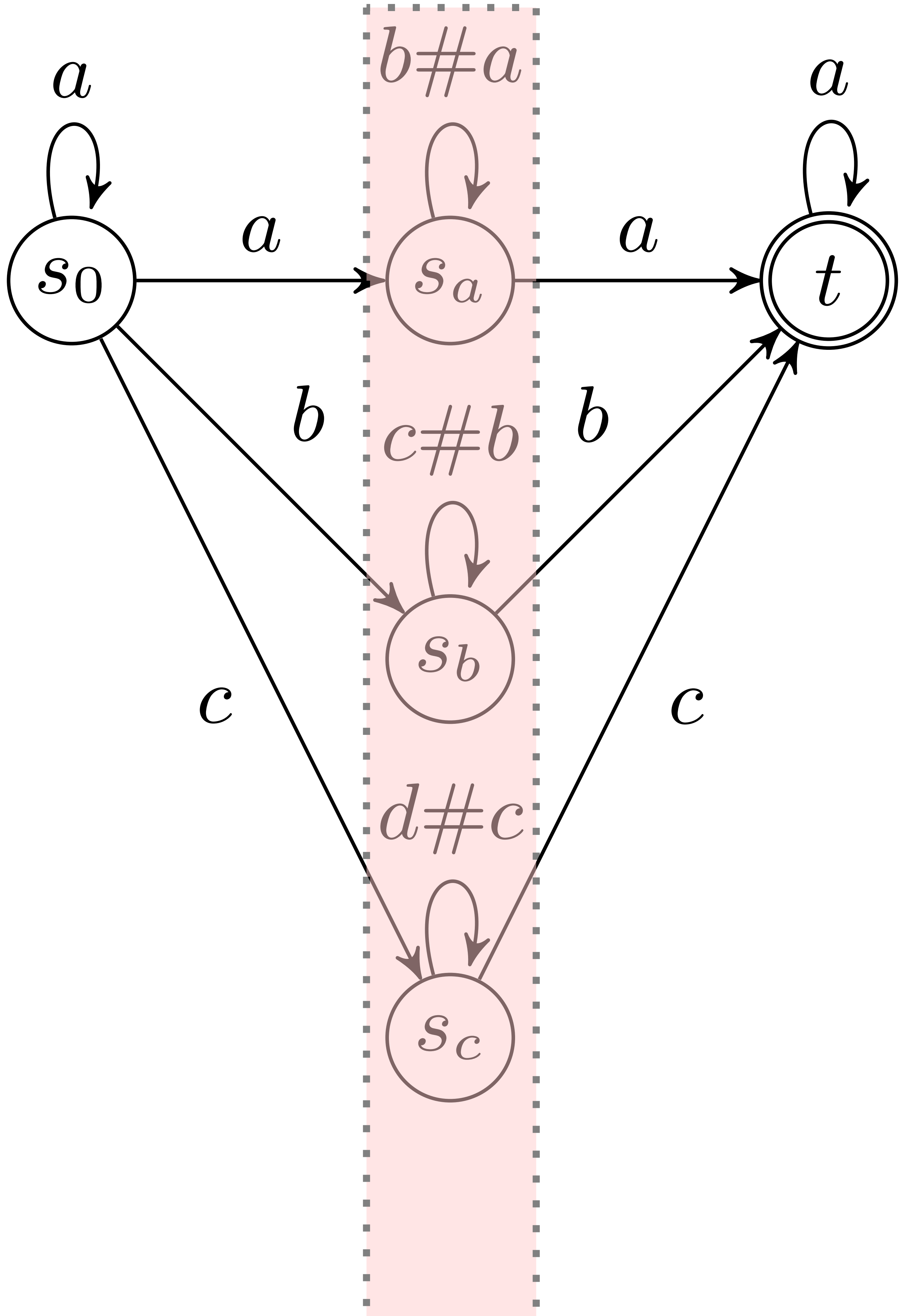
Nominal automata



$\mathbb{A}$ infinite

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

Nominal automata



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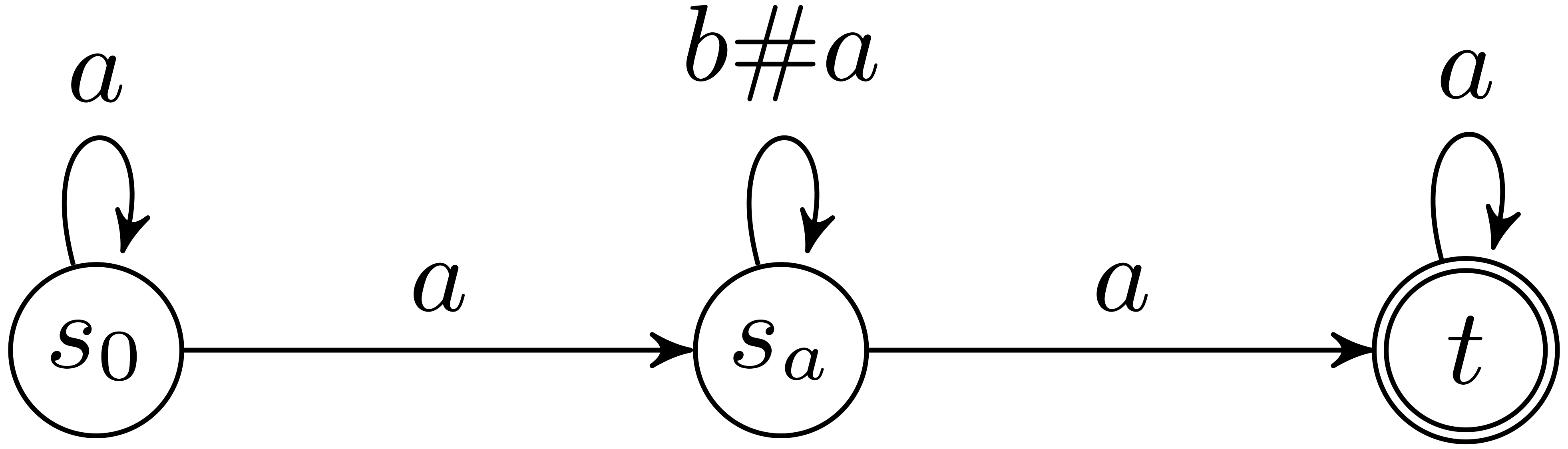
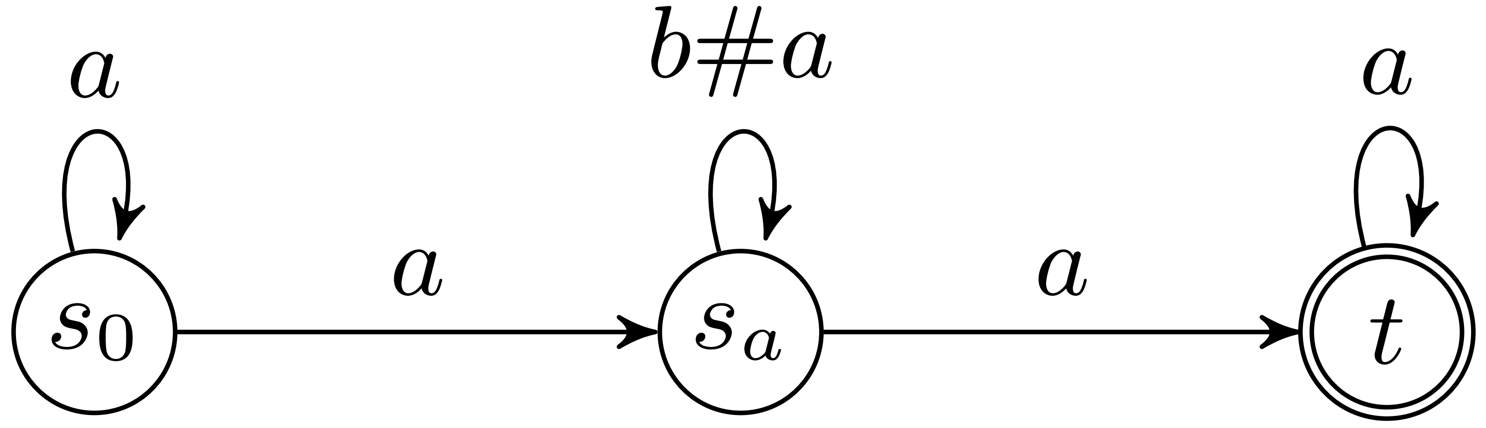


finite representation

Nominal automata



finite representation

$$X = \{s_0\} + \mathbb{A} + \{t\}$$

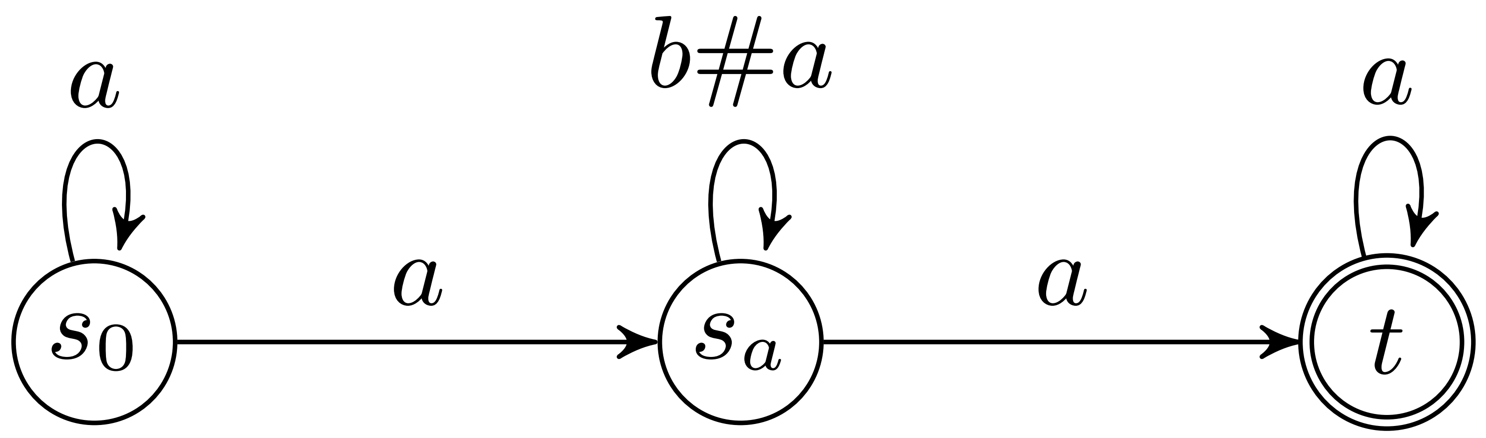
canonical permutations

$$\pi : \mathbb{A} \to \mathbb{A}$$
$$s_a \mapsto s_{\pi a}$$

transition closed under permutations
equivariant

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

Nominal automata



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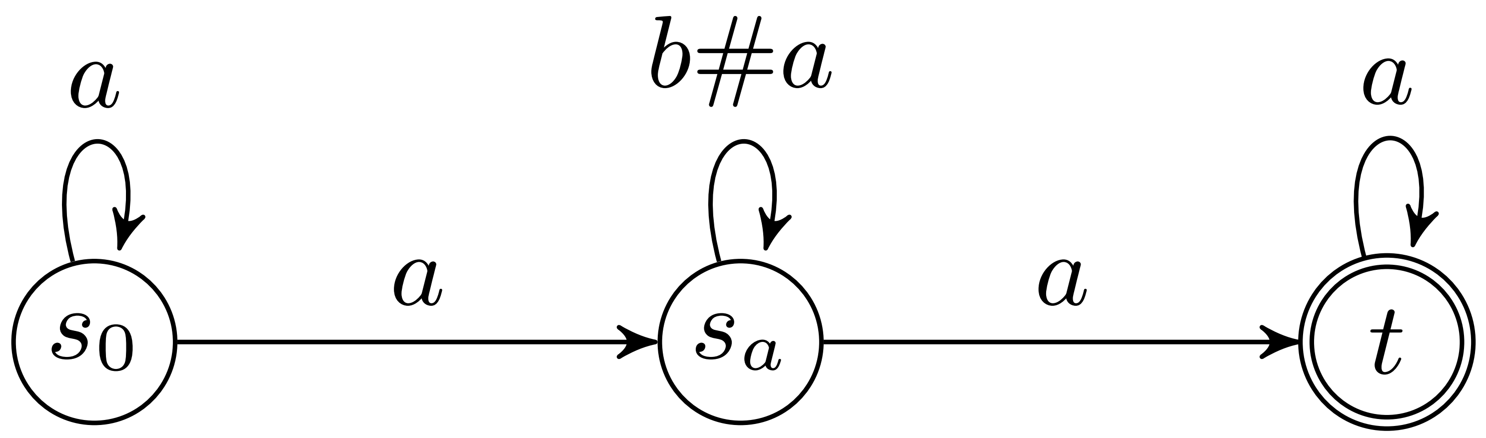
equivariant

algebraic structure

Nominal automata



$$X \to 2 \times X^A$$

DFA in Nom

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Challenges

L* LEARNER

$S, E \leftarrow \{\epsilon\}$
repeat
  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
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    $S \leftarrow S \cup \{s_1 a\}$
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  Make the conjecture $M(S, E)$
  if the Teacher replies **no**, with a counter-example t
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range over infinite sets

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range over infinite sets

finding witnesses potentially requires checking infinite rows

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no finite automaton accepts $\mathcal{L}_1$

Challenges

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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
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Categorical glasses

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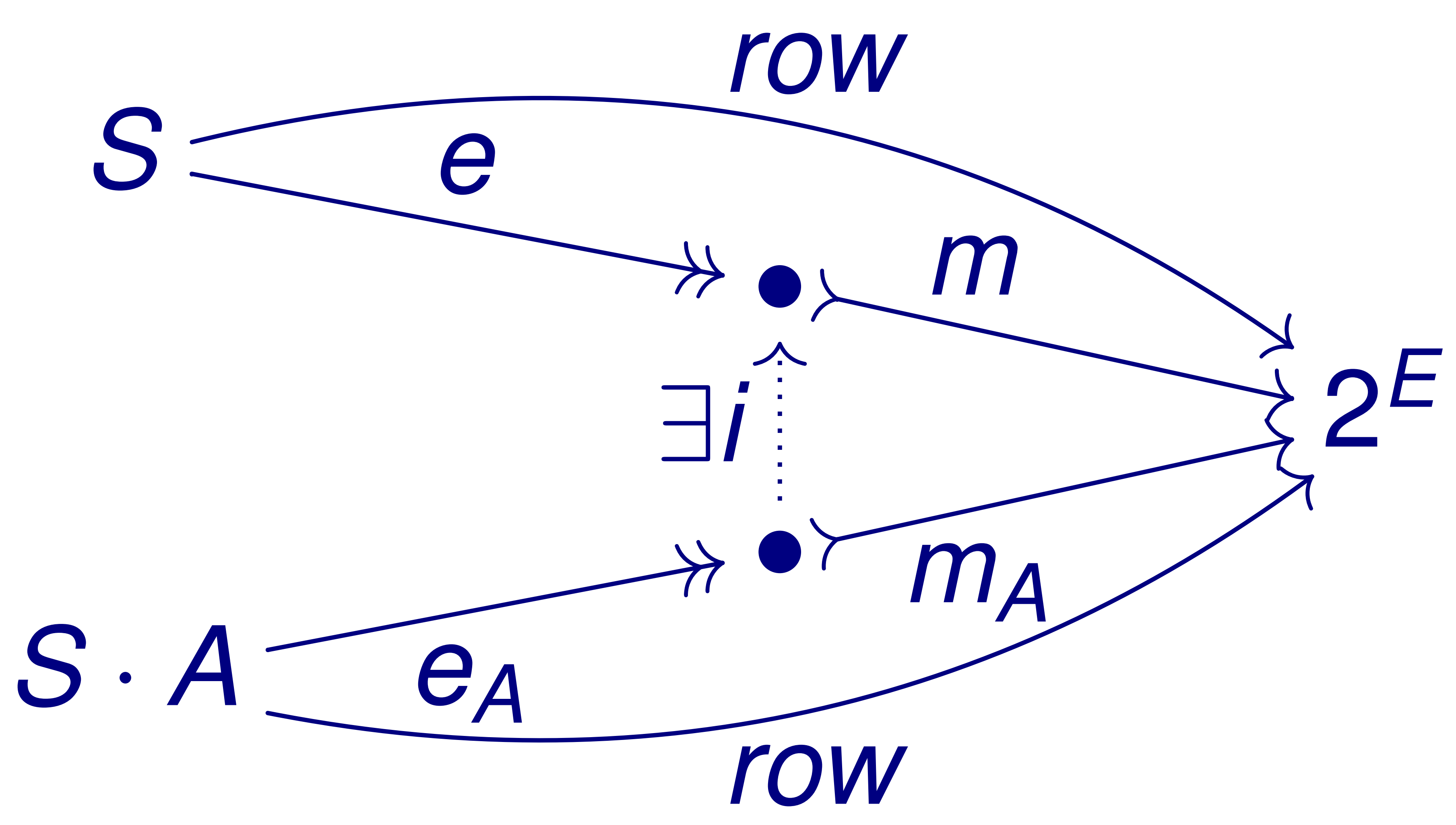

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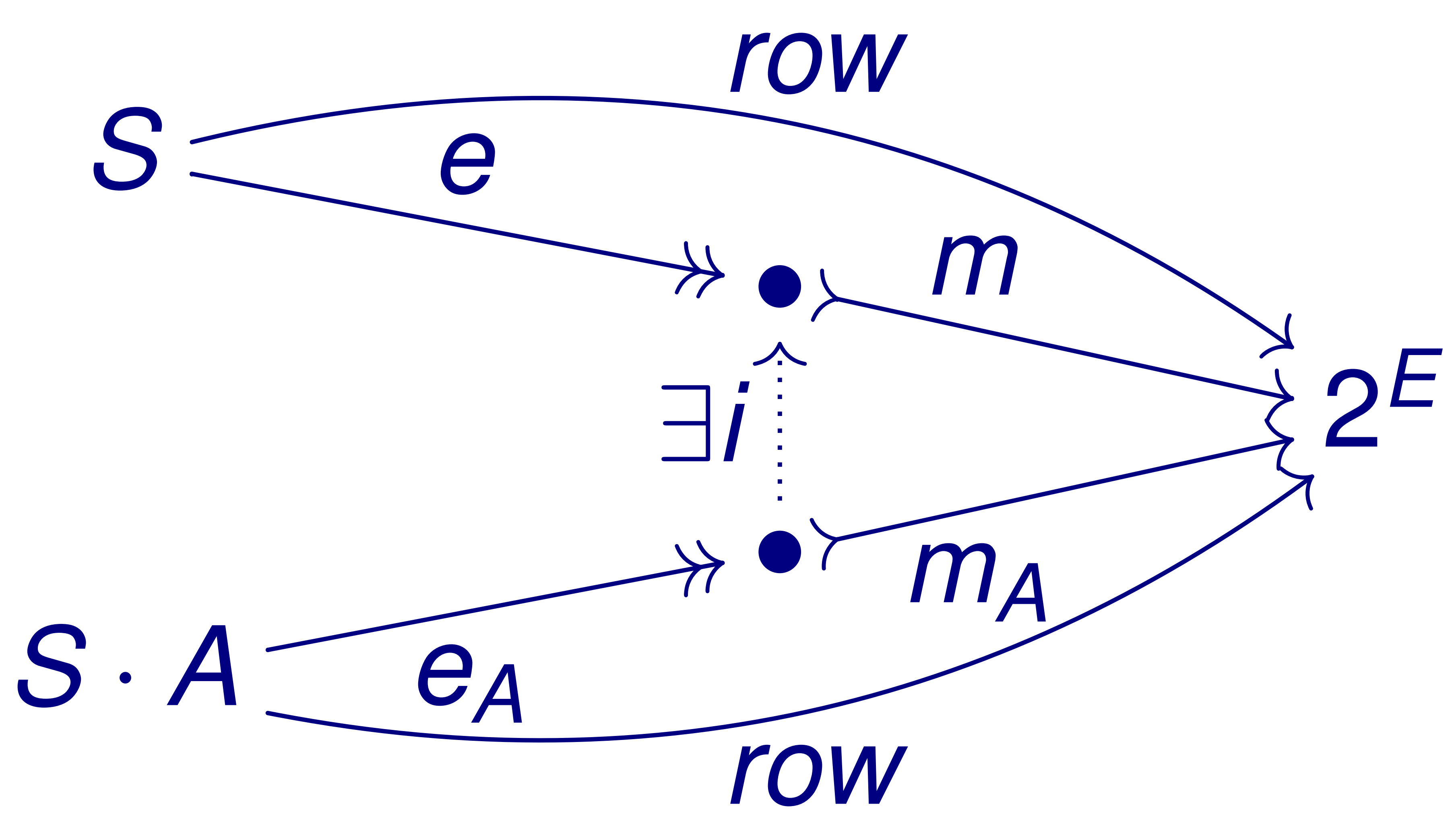

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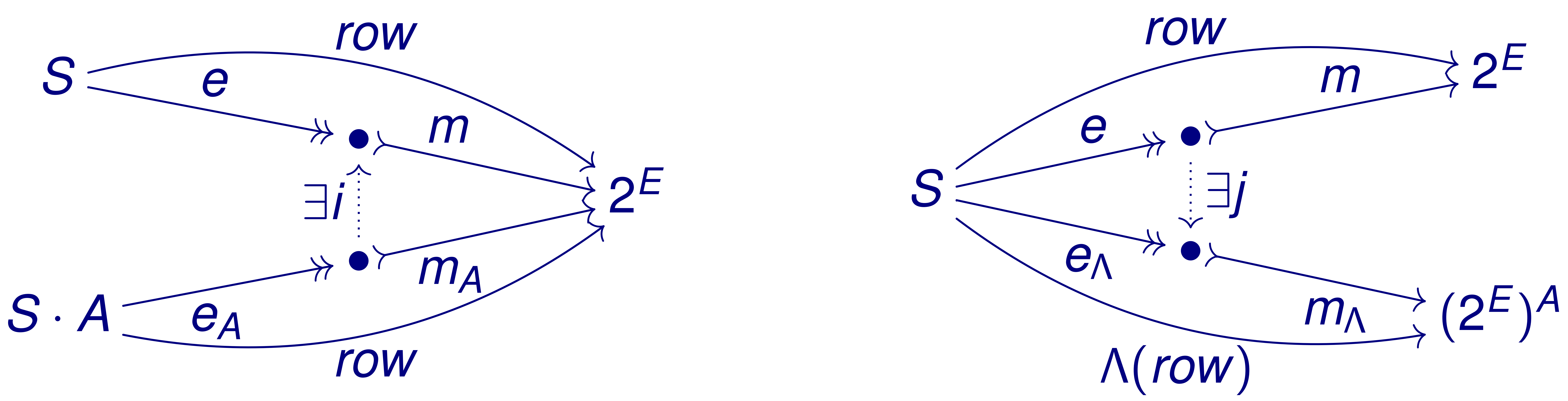
(S, E, row) is *consistent* if whenever $s_1, s_2 \in S$ are such that $row(s_1) = row(s_2)$, for all $a \in A$, $row(s_1 a) = row(s_2 a)$.

Categorical glasses



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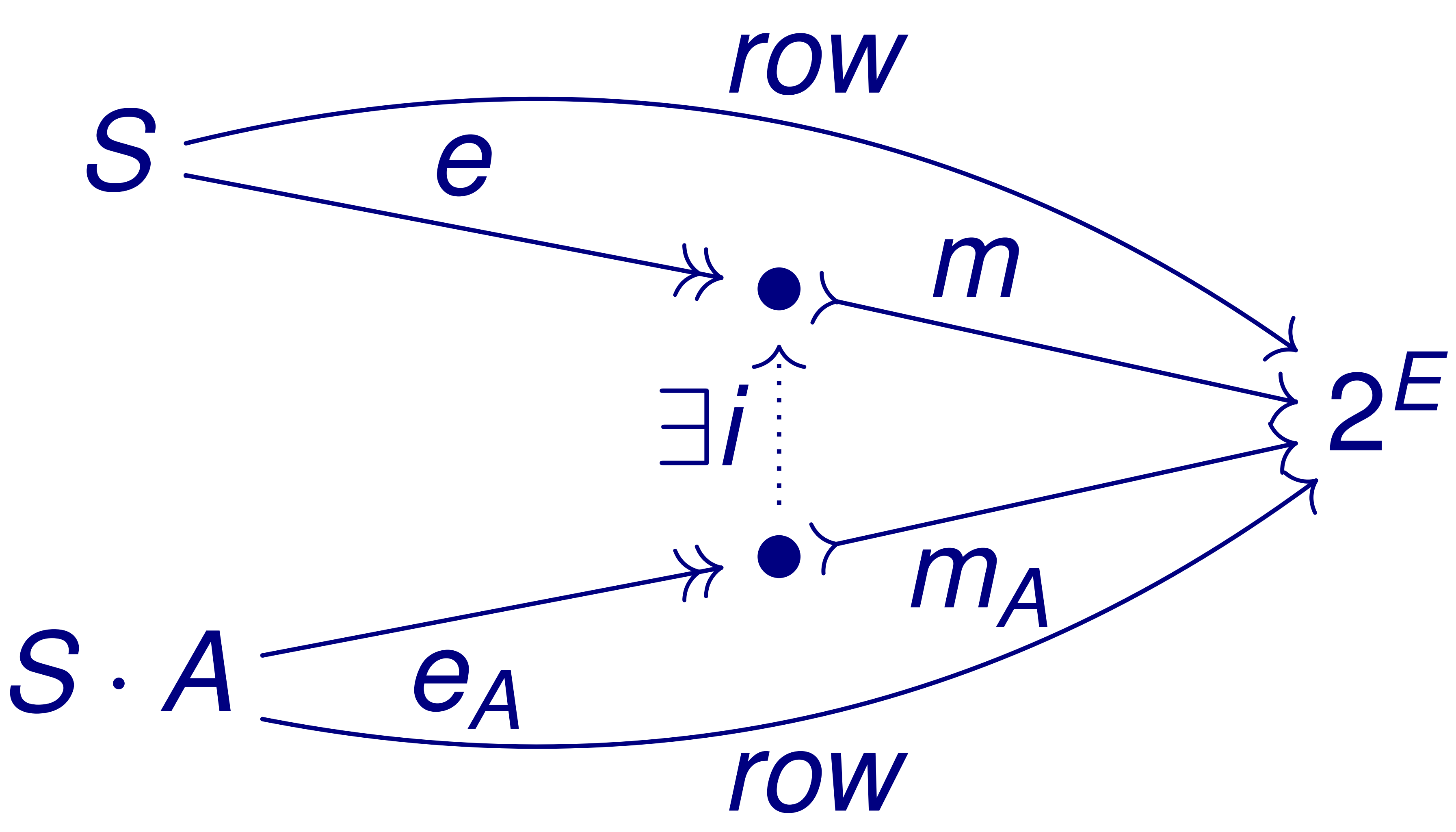

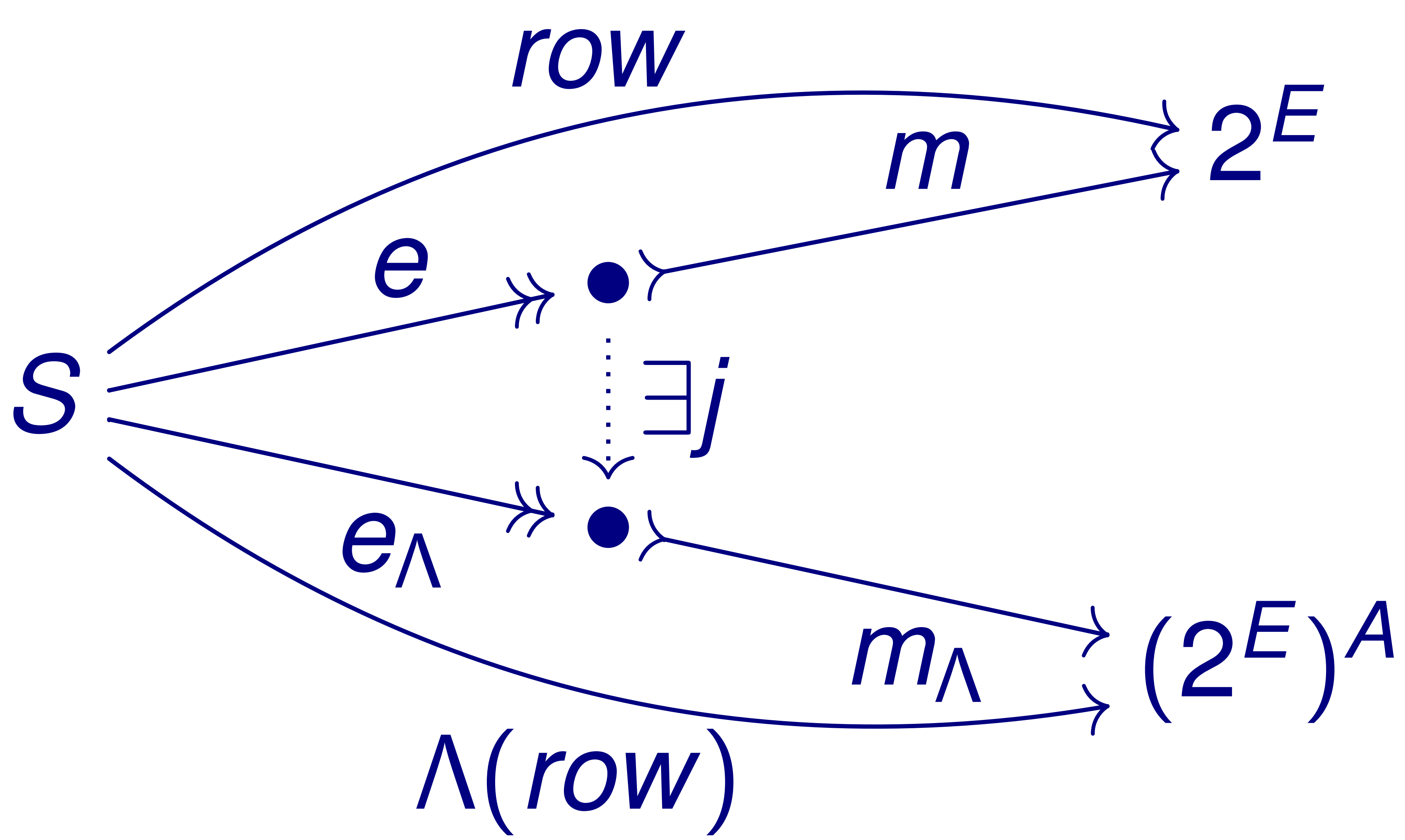

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Pretty.... but is it useful?

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The power of abstraction

$$X \to 2 \times X^A$$

DFA in Nom

Definitions are the *same*

Proof of correctness is the *same*

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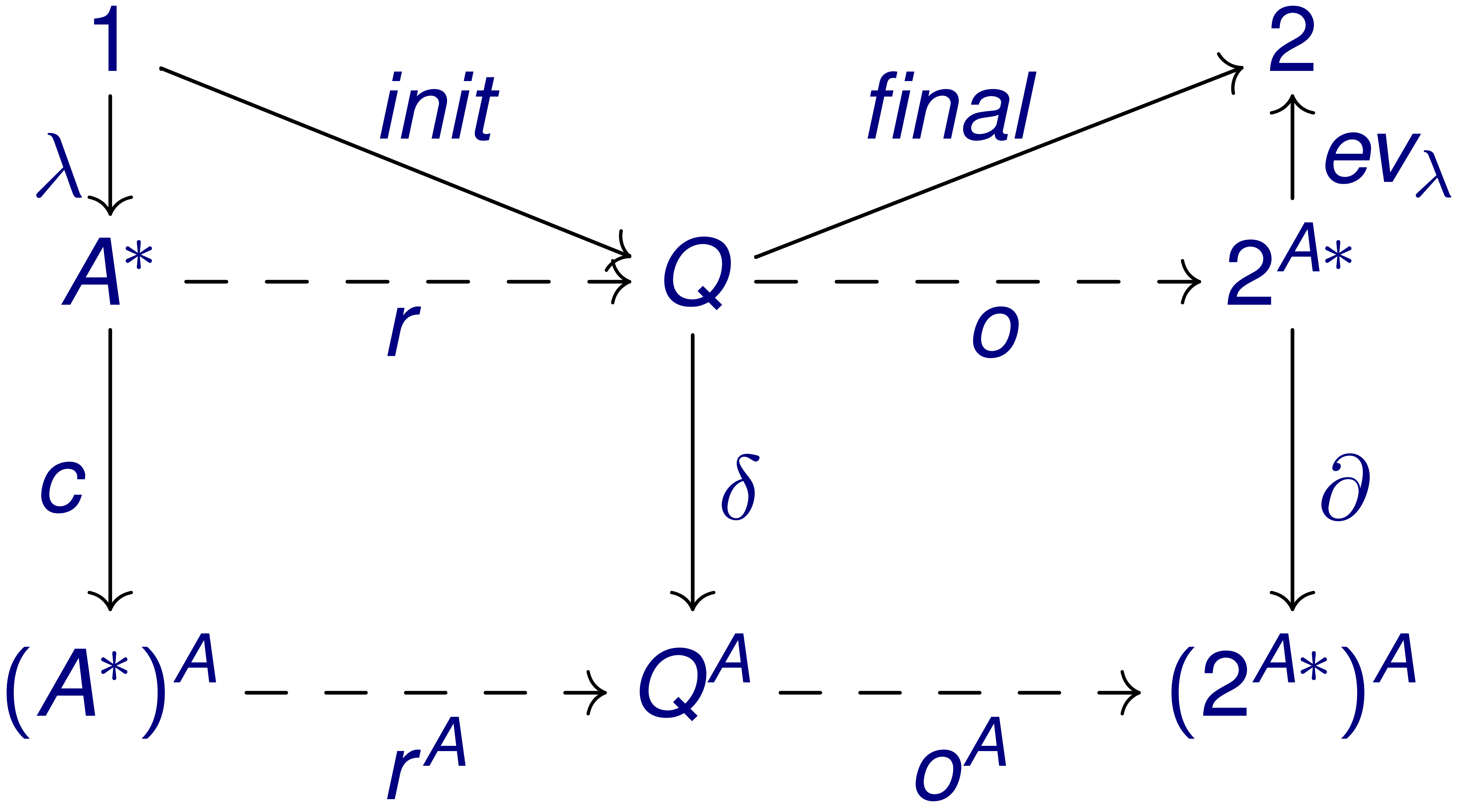

Abstract automata

Category $\mathbf{C}$ **= universe of state-spaces**

Endofunctor $F \colon \mathbf{C} \to \mathbf{C}$ **= automaton type**

$$
\begin{array}{ccccc}
 & & FQ & & \\
 & & \big\downarrow{\scriptstyle \delta_Q} & & \\
 & {\scriptstyle \mathsf{init}_Q} \nearrow & Q & \searrow {\scriptstyle \mathsf{out}_Q} & \\
I & & & & Y
\end{array}
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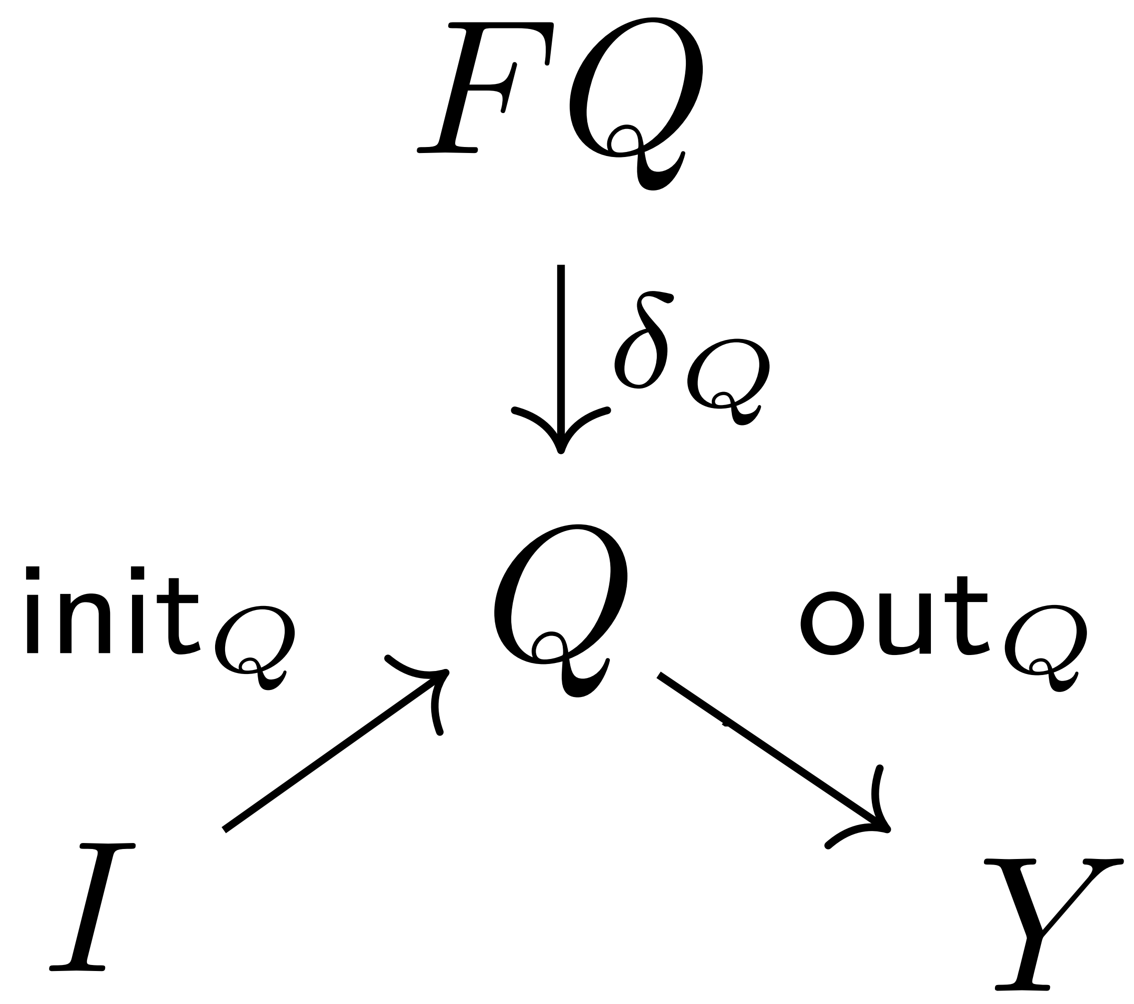
DFAs

$\mathbf{C} = \mathbf{Set}$

$F = (-) \times A$



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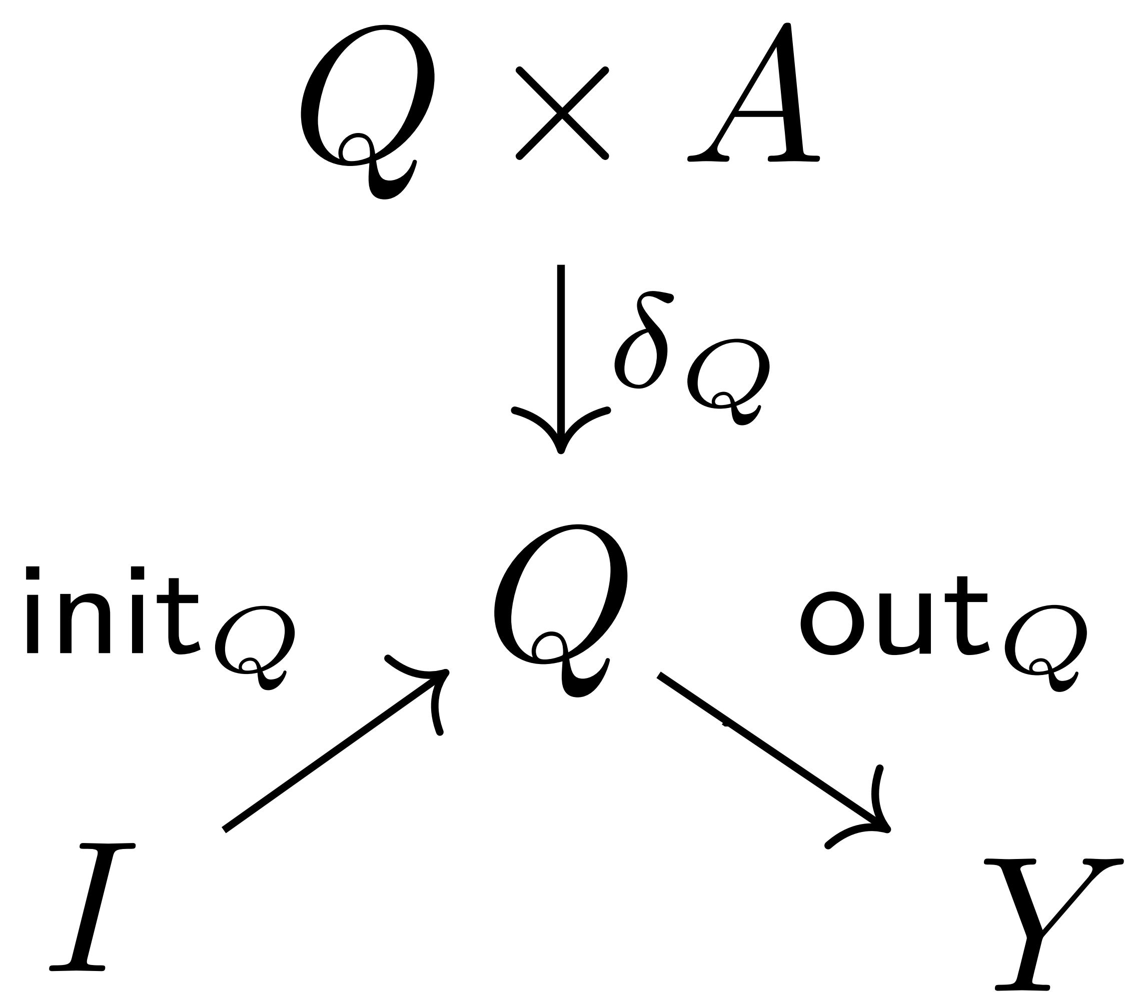

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$$\mathbf{1} \nearrow \qquad \searrow Y$$

$q_0 \in Q$

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$$Q \times A \xrightarrow{\delta_Q} Q$$

$$\mathbf{1} \xrightarrow{\mathsf{init}_Q} Q \xrightarrow{\mathsf{out}_Q} \mathbf{2}$$

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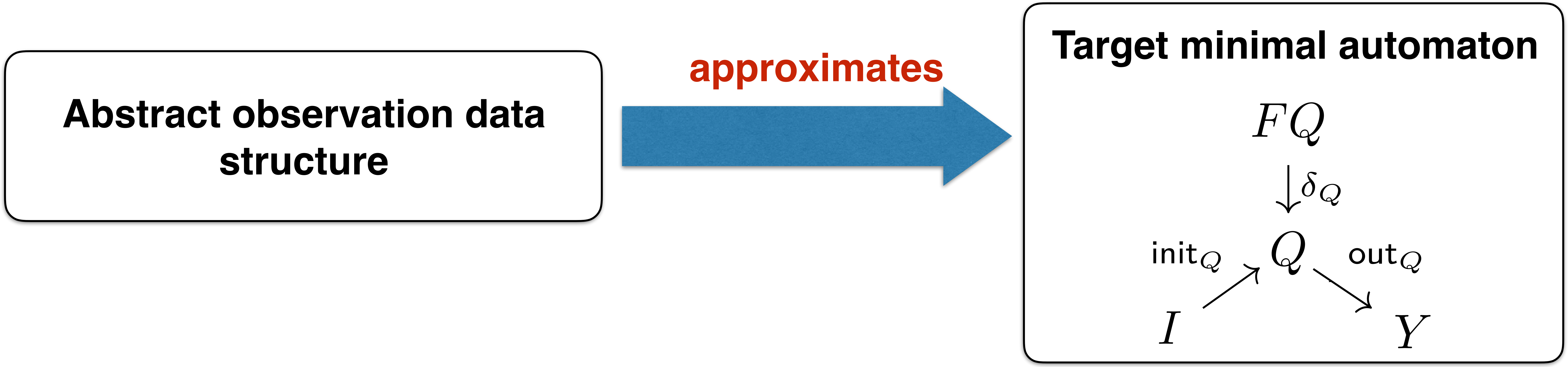
$q_0 \in Q$ $\qquad$ $F \subseteq Q$

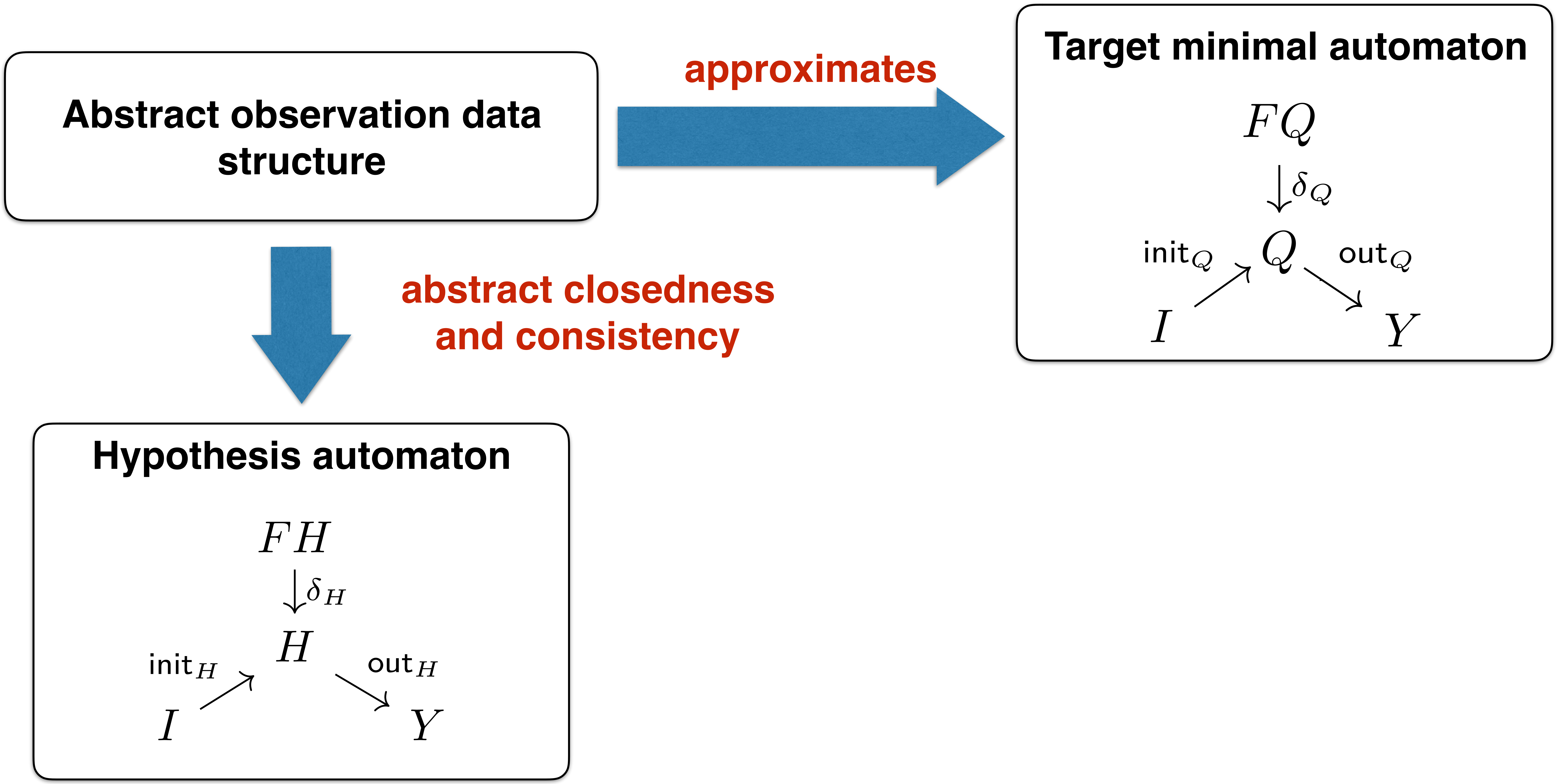
Abstract learning

Abstract observation data structure

Abstract learning



Abstract learning



Abstract learning

Abstract observation data structure

approximates

Target minimal automaton

$$FQ \xrightarrow{\delta_Q} Q, \qquad I \xrightarrow{\mathsf{init}_Q} Q \xrightarrow{\mathsf{out}_Q} Y$$

abstract closedness and consistency

Hypothesis automaton

$$FH \xrightarrow{\delta_H} H, \qquad I \xrightarrow{\mathsf{init}_H} H \xrightarrow{\mathsf{out}_H} Y$$

General correctness theorem

Guidelines for implementation

Abstract learning

Abstract observation data structure

approximates →

Target minimal automaton

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↓ **abstract closedness and consistency**

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General correctness theorem

Guidelines for implementation

CALF: Categorical Automata Learning Framework **(arXiv:1704.05676)**

Gerco van Heerdt, Matteo Sammartino, Alexandra Silva

Other automata & optimizations

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Change base category

Set	**DFAs**
Nom	**Nominal automata**
Vect	**Weighted automata**

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Side-effects (via monads)

Powerset	**NFAs**
Powerset with intersection	**Universal automata**
Double powerset	**Alternating automata**
Maybe monad	**Partial automata**

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Change main data structure

Observation tables

Discrimination trees

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Joshua Moerman, Matteo Sammartino, Alexandra Silva, Bartek Klin, Michal Szynwelski

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Learning Automata with Side-effects (arXiv:1704.08055)

Gerco van Heerdt, Matteo Sammartino, Alexandra Silva

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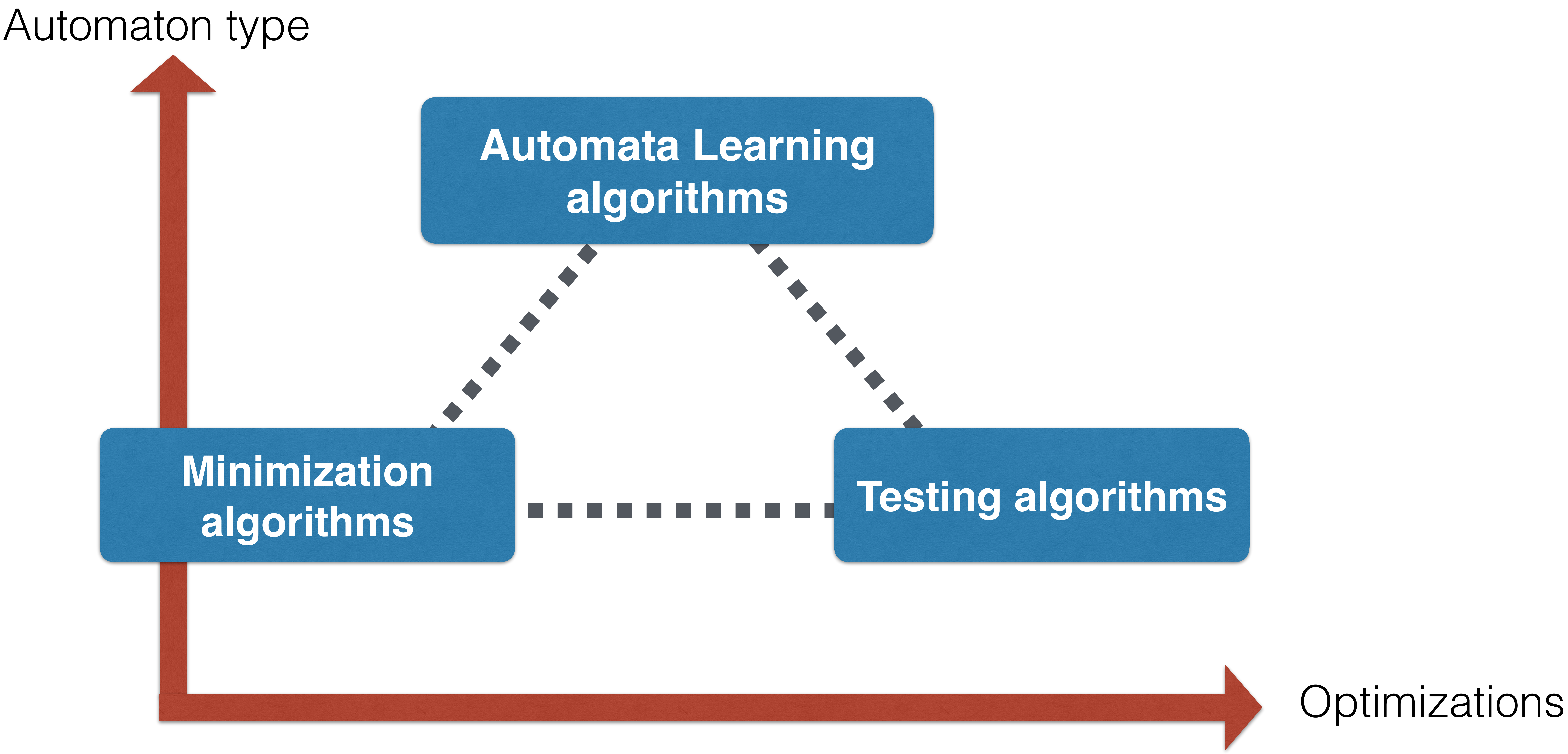
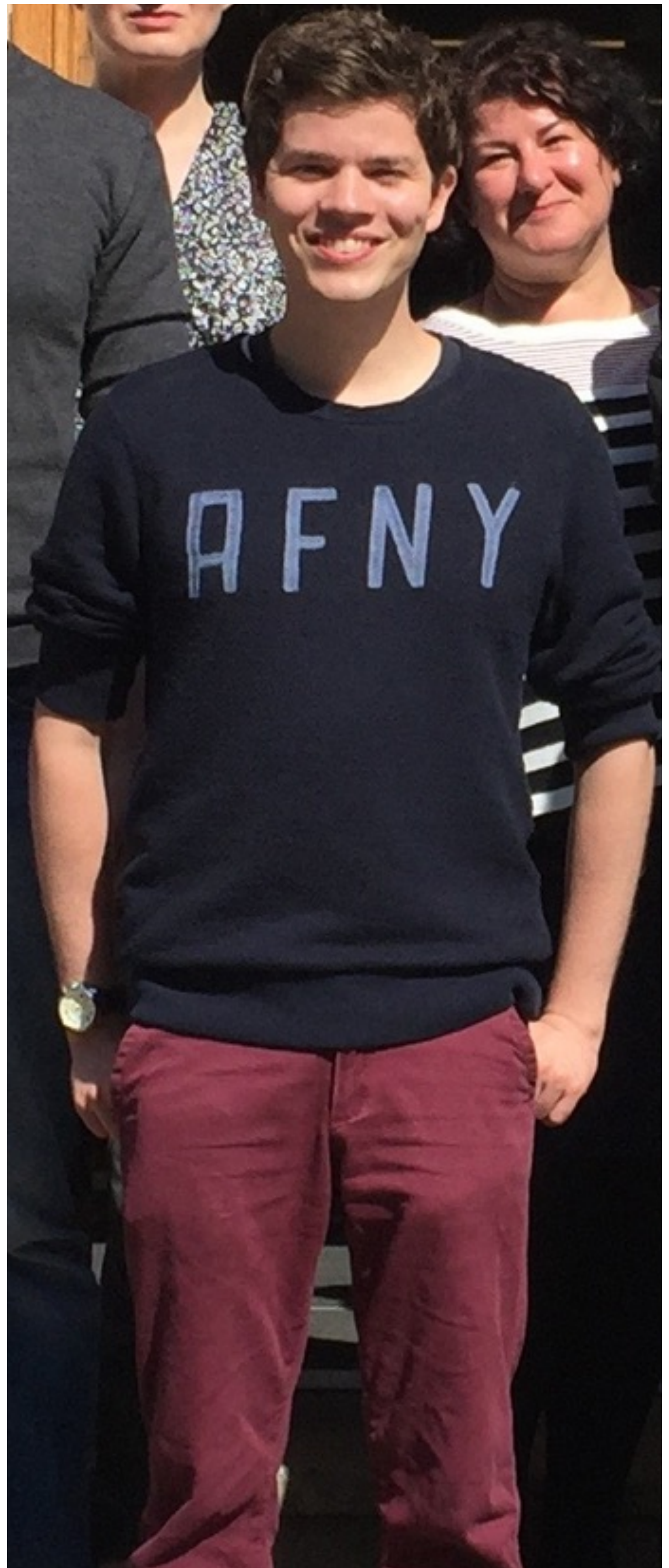
Connections with other algorithms



Ongoing and future work

- **Library & tool** to learn control + data-flow models (as **nominal automata**)
- Applications:
  - Specification mining
  - Network verification, with amazon
  - Verification of cryptographic protocols
  - Ransomware detection

Ongoing and future work



Learning convex automata

Rich algebraic structure

Challenging analytical properties

Conclusions

Category theory is a good playground to understand and generalise algorithms

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Category theory is a good playground to understand and generalise algorithms

Unveils connections and sets the scene
—
No free lunch

Questions?