Certain Query Answering on Compressed String Patterns: from Streams to Hyperstreams

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General Context

- Hyperstreams as a generalization of streams [Maneth 2015], [Labath 2013]
- Certain Query Answering (CQA) [David 2010]
- Nondeterministic Finite Automata (NFAs) as regular path queries [Angles 2016]

From Streams to Hyperstreams

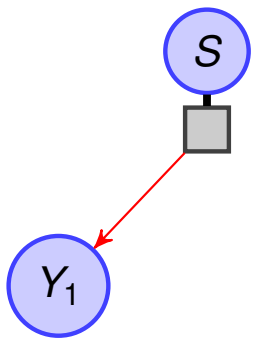
Empty stream

$$S = Y_1$$

From Streams to Hyperstreams

Empty stream

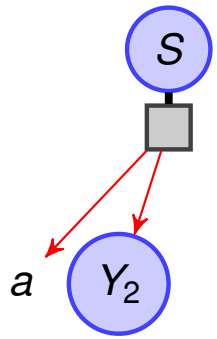
$$S = Y_1$$



From Streams to Hyperstreams

$Y_1 \rightarrow aY_2$

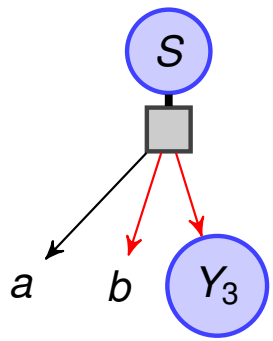
$$S = aY_2$$



From Streams to Hyperstreams

$Y_1 \rightarrow aY_2$, $Y_2 \rightarrow bY_3$,

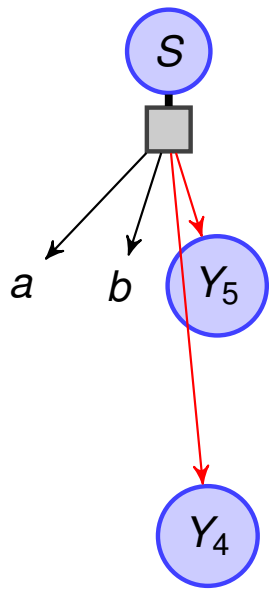
$$S = abY_3$$



From Streams to Hyperstreams

$Y_1 \rightarrow aY_2\ , Y_2 \rightarrow bY_3,$
$Y_3 \rightarrow Y_4 Y_5$

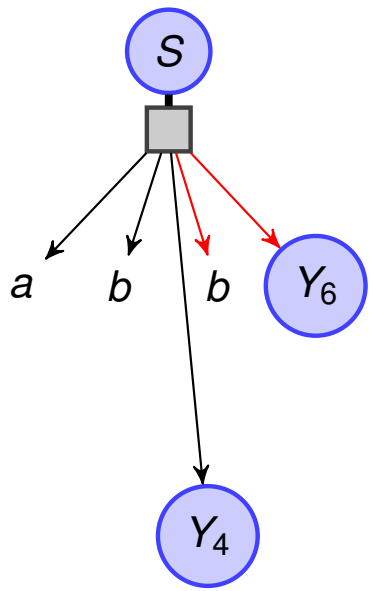
$$S = abY_4 Y_5$$



From Streams to Hyperstreams

$Y_1 \rightarrow aY_2$, $Y_2 \rightarrow bY_3$,
$Y_3 \rightarrow Y_4Y_5$, $Y_5 \rightarrow bY_6$,

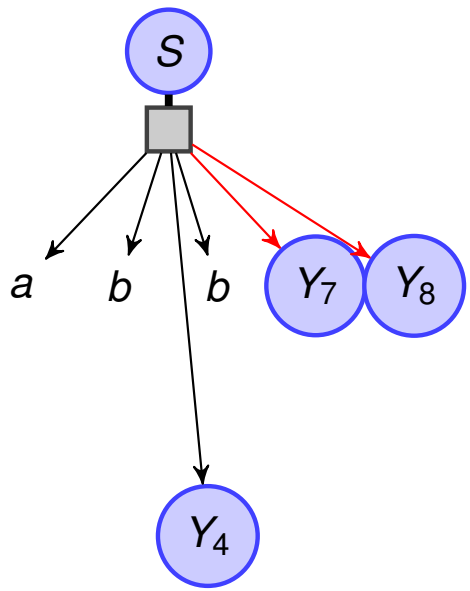
$$S = abY_4bY_6$$



From Streams to Hyperstreams

$Y_1 \rightarrow aY_2\ , Y_2 \rightarrow bY_3,$
$Y_3 \rightarrow Y_4Y_5\ , Y_5 \rightarrow bY_6,$
$Y_6 \rightarrow Y_7Y_8$

$$S = abY_4bY_7Y_8$$



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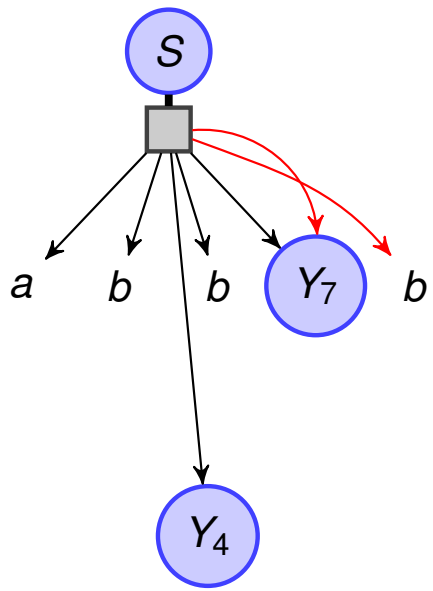

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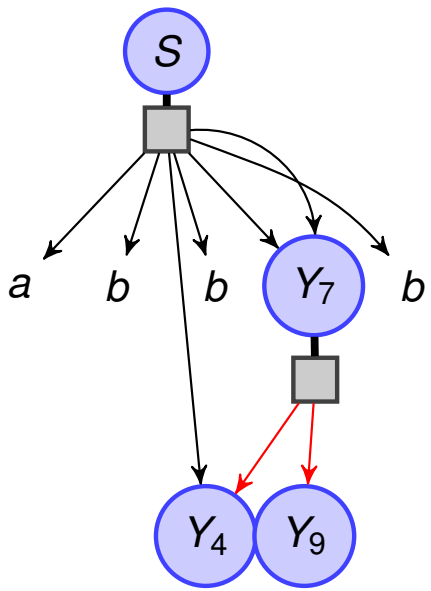
$Y_7 \rightarrow Y_4 Y_9$

$$S = abY_4bY_4Y_9bY_4Y_9$$



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$Y_1 \rightarrow aY_2$, $Y_2 \rightarrow bY_3$,
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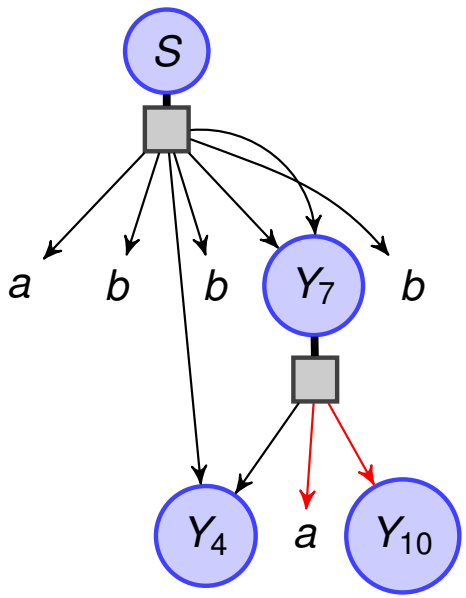
$Y_6 \rightarrow Y_7Y_8$, $Y_8 \rightarrow bY_7$,
$Y_7 \rightarrow Y_4Y_9$
, $Y_9 \rightarrow aY_{10}$,

$$S = abY_4bY_4aY_{10}bY_4aY_{10}$$



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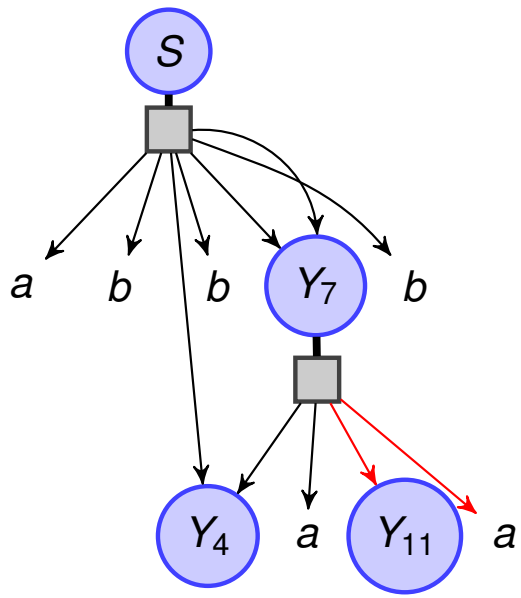
$$S = abY_4bY_4aY_{11}abY_4aY_{11}a$$



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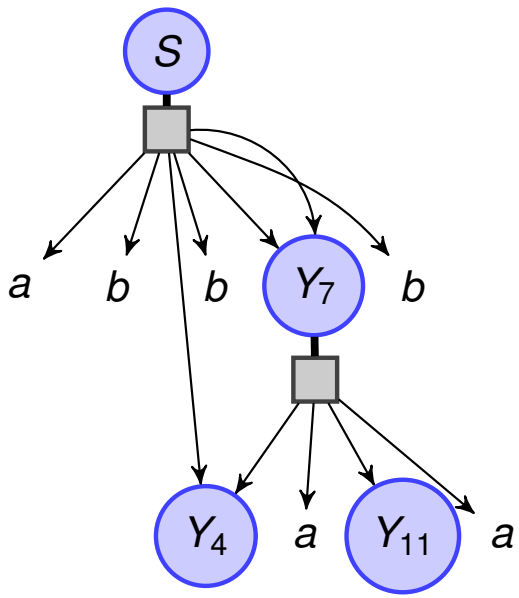
Hyperstreams are compressed string patterns.



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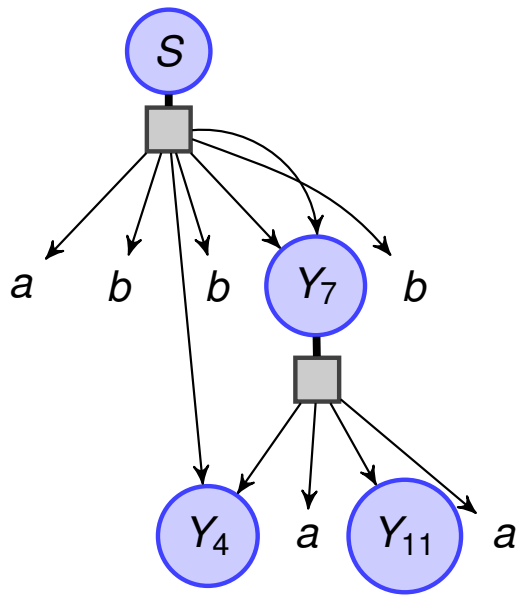
$$S = abY_4bY_4aY_{11}abY_4aY_{11}a$$

$$G = (N, \Sigma, R, S)$$
$$N = \{S, Y_4, Y_7, Y_{11}\}$$
$$R = \left\{ \begin{array}{l} S \rightarrow abY_4bY_7bY_7, \\ Y_7 \rightarrow Y_4aY_{11}a \end{array} \right\}$$



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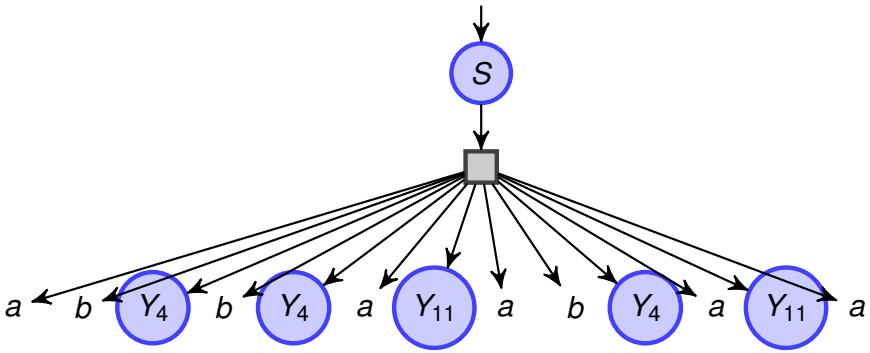

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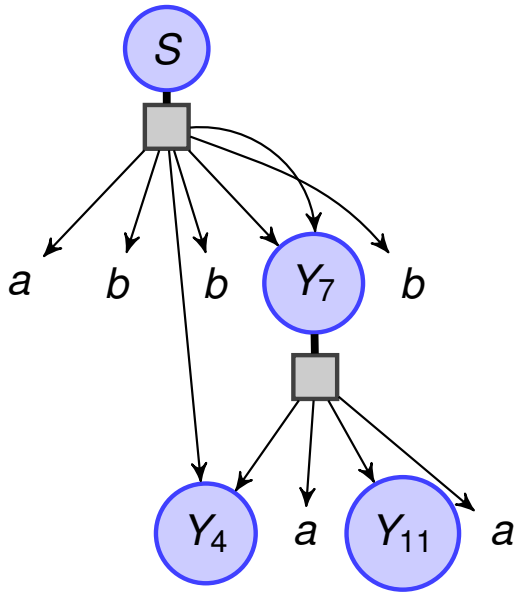

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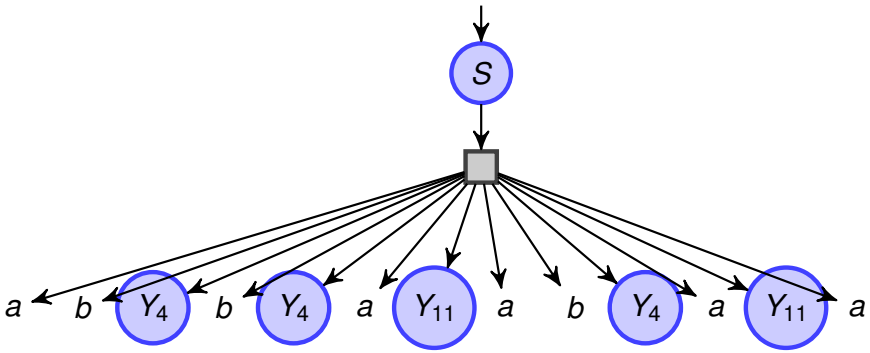

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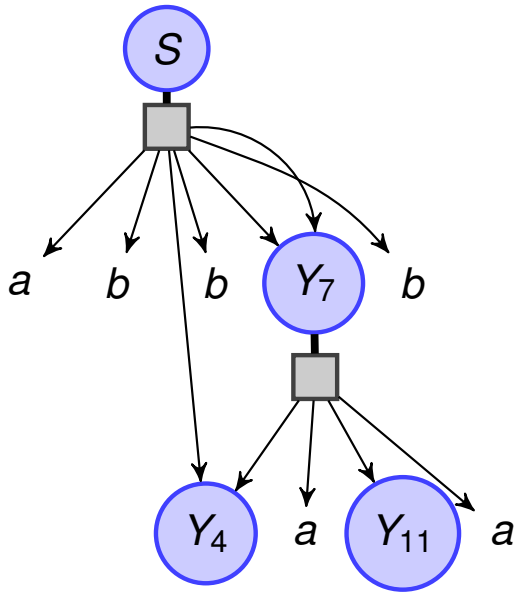
Represents $pat(G)$



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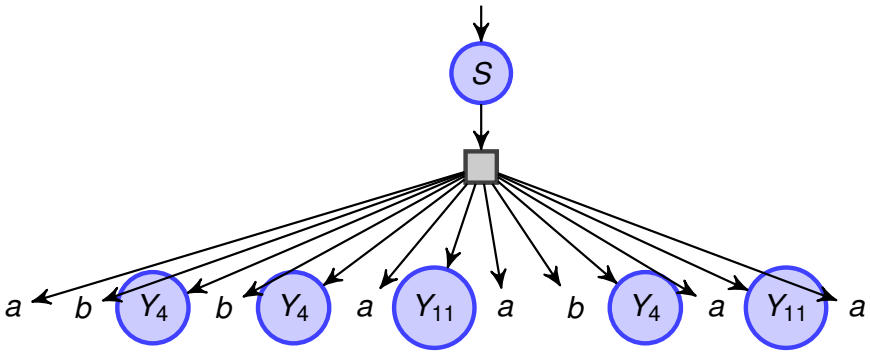

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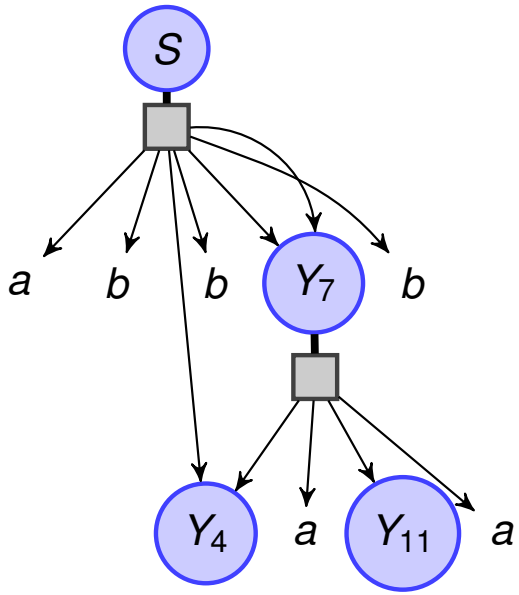
Represents $pat(G)$

$Inst(G) = Inst(pat(G))$



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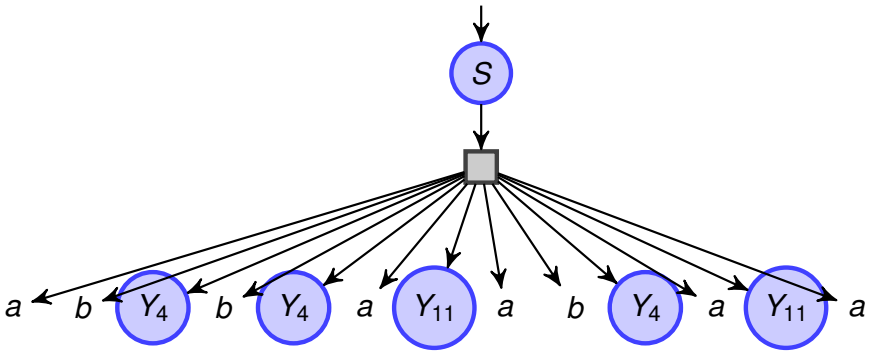

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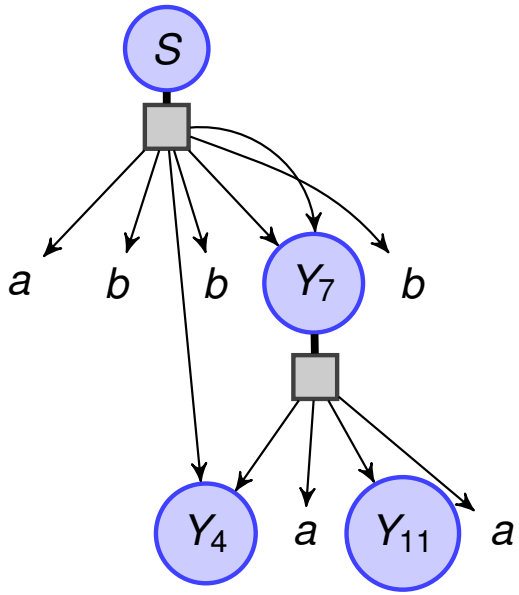
Not linear



Outline

Outline

Queries

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Example (Monadic query)

$\mathbf{Q}_1(w) =$ Set of positions of w labeled by a and followed by b.

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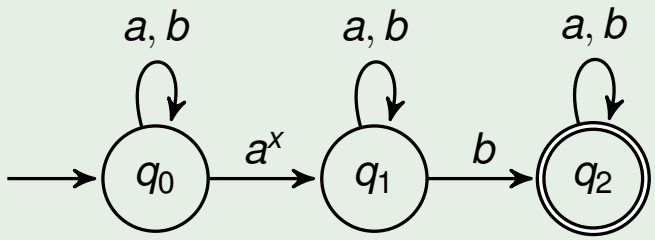

Certain (non) Answers

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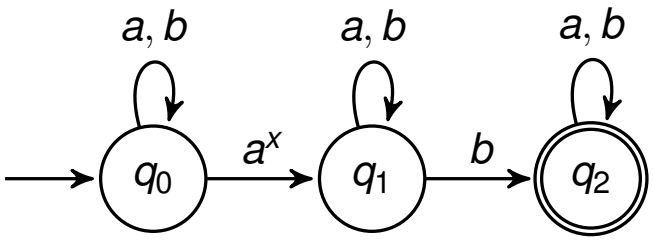

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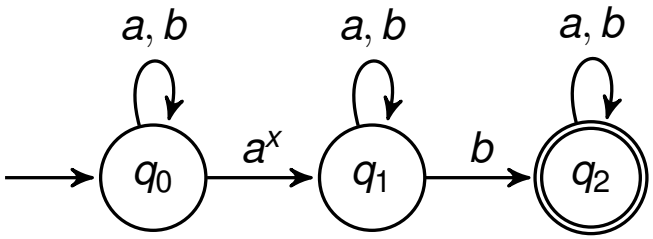

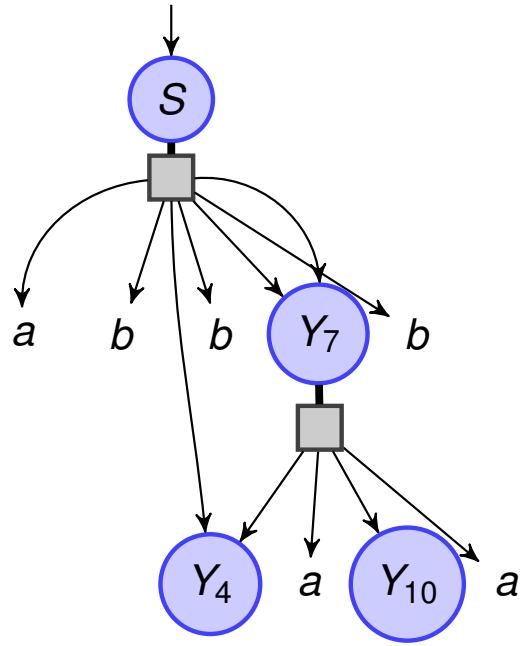

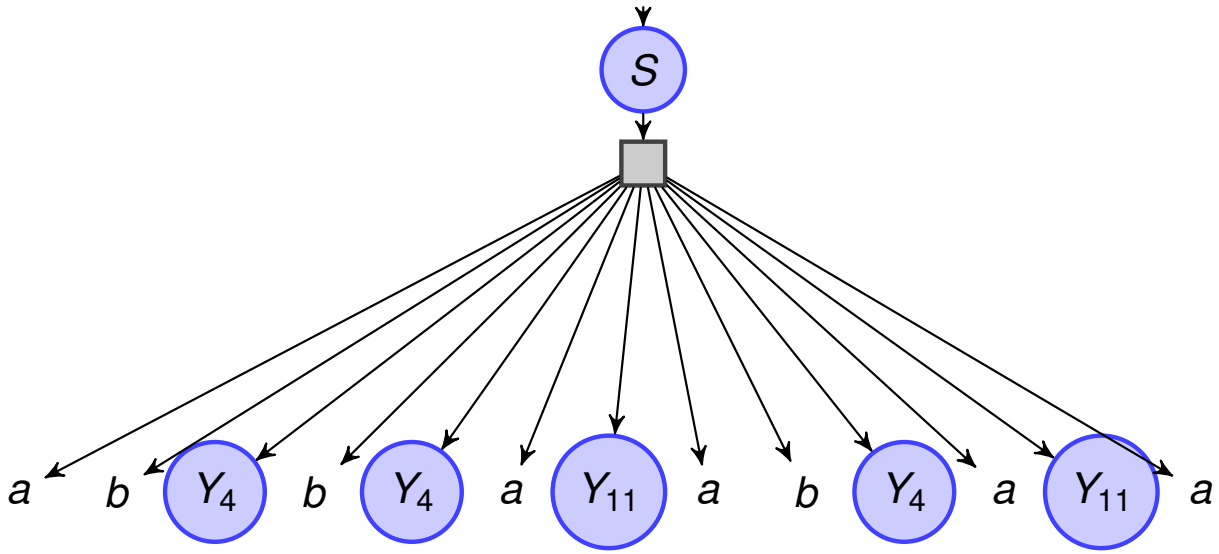

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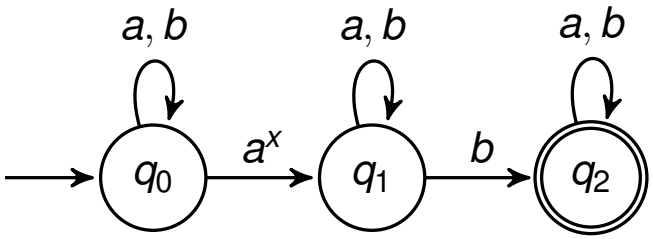

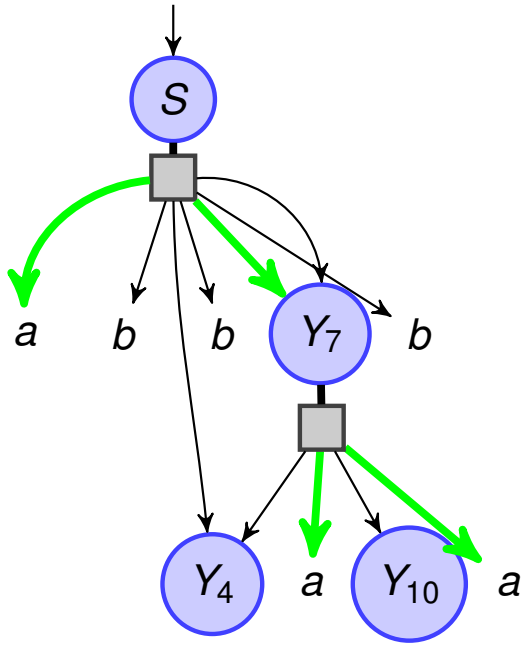

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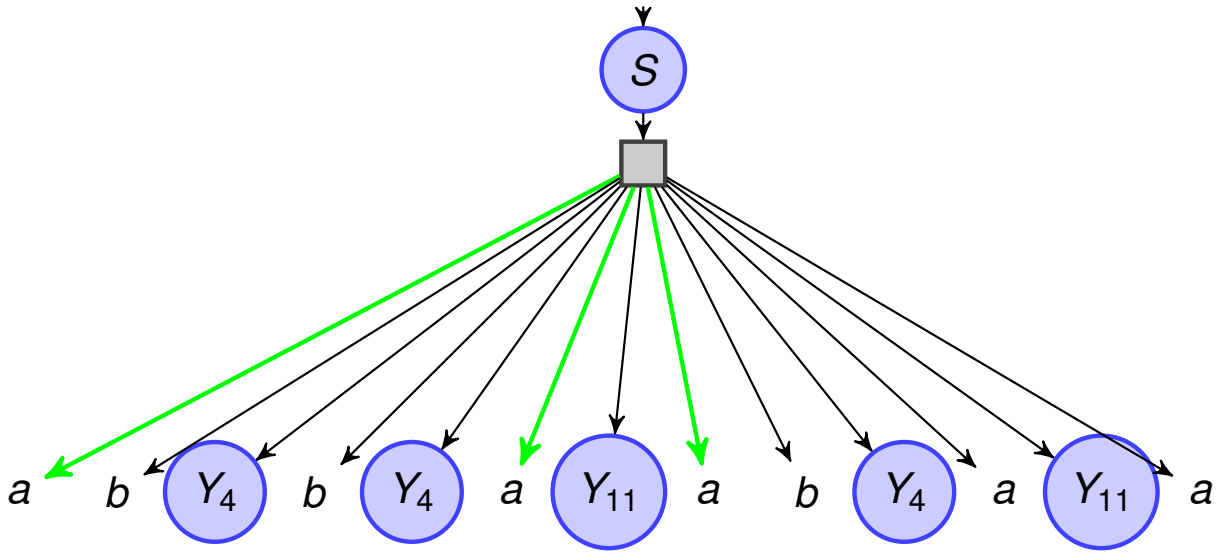

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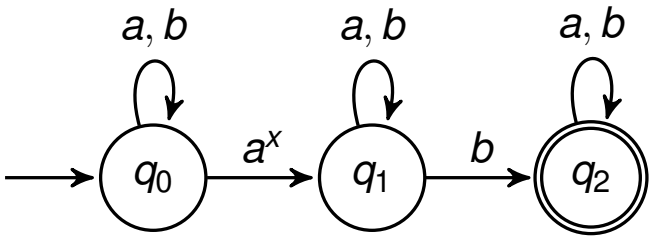
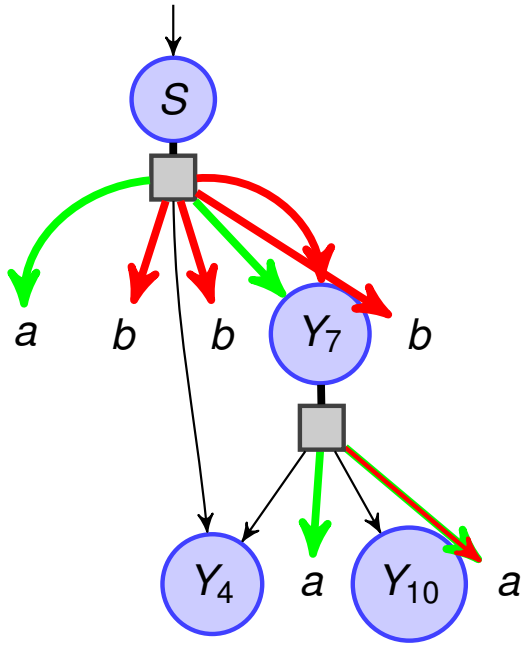
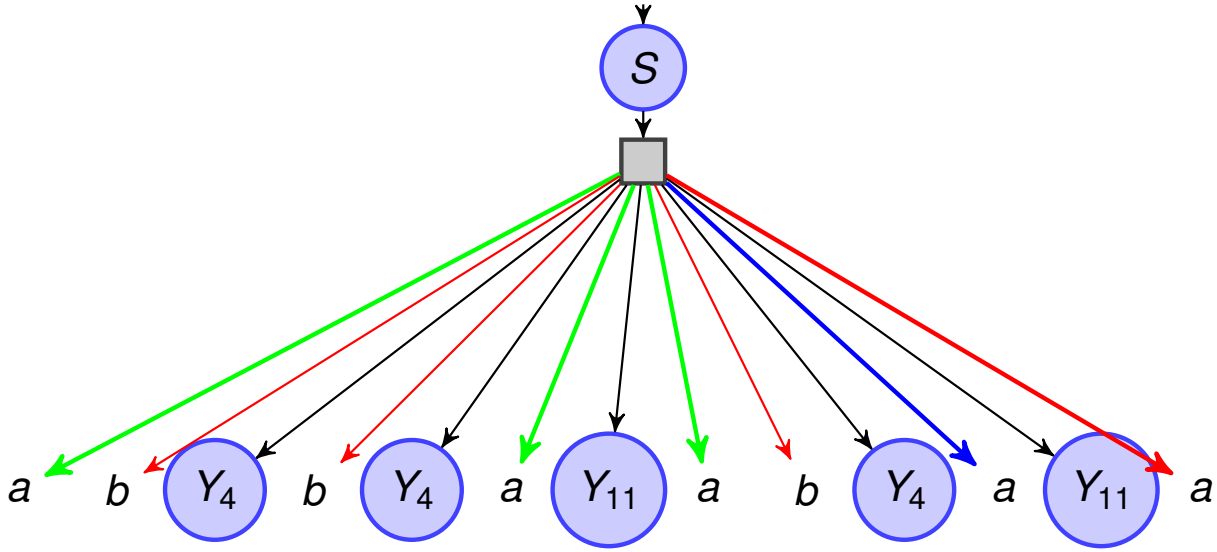




Certain answers

Certain non answers



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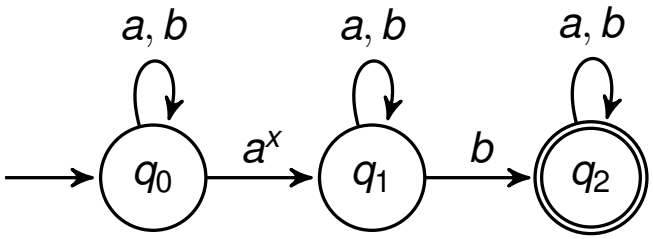
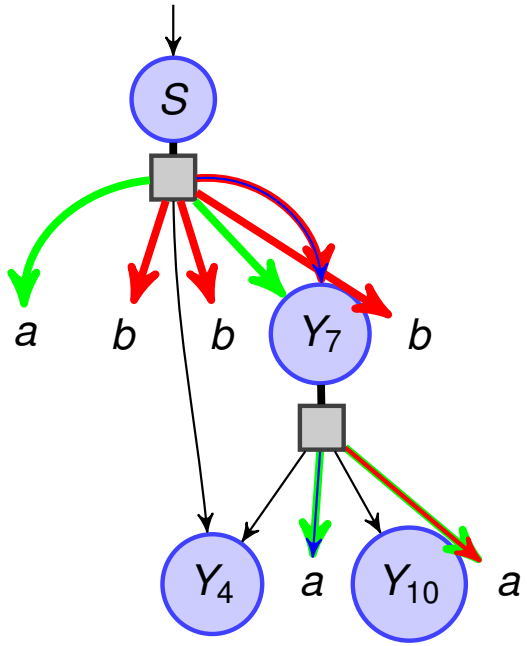
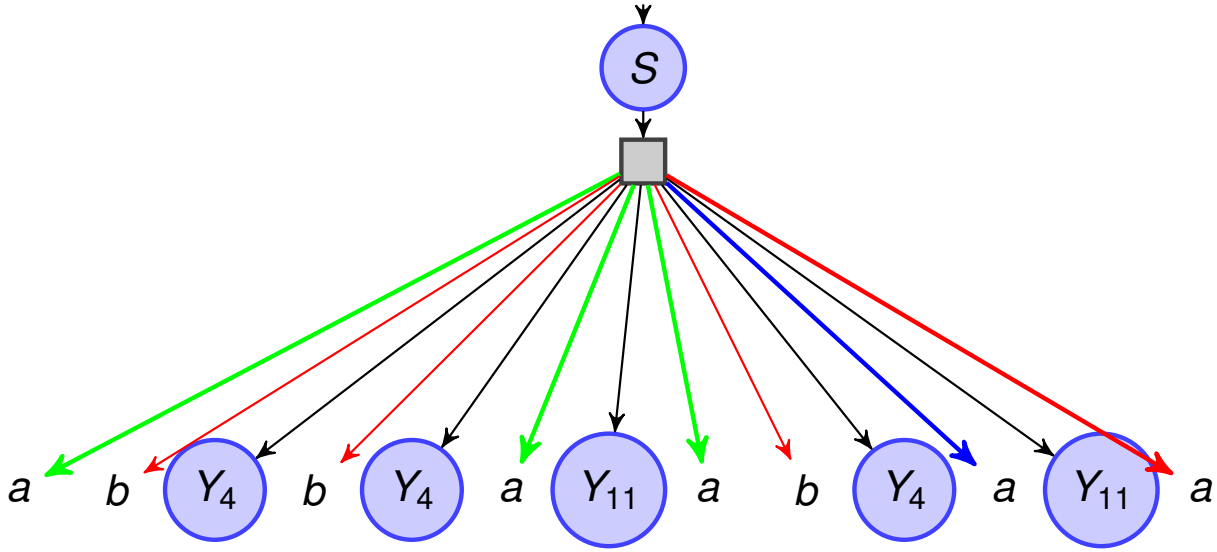




Certain answers

Certain non answers

Neither certain nor certain non answers



Problem

Certain query answering problem

Input: query automaton A, hyperstream G, tuple of positions π of symbols of Σ on $pat(G)$.
Output: π certain answer for $L(A)$ on G ?

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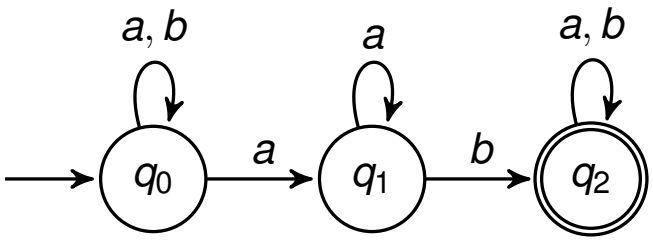
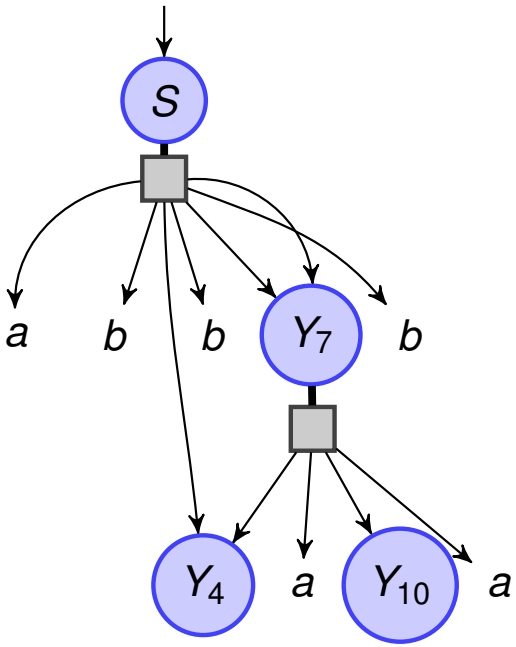
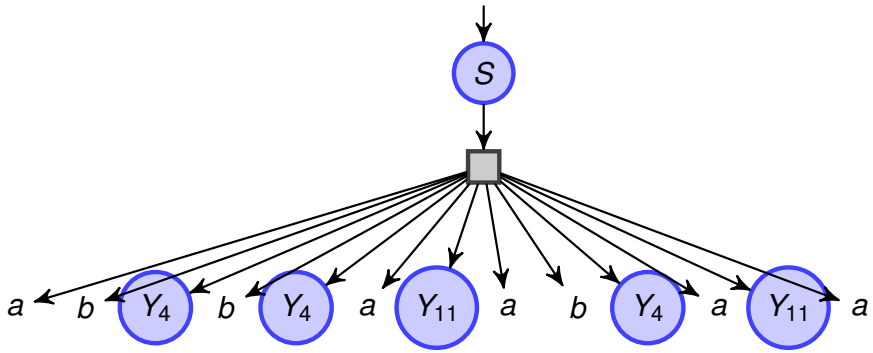
Equivalences in the boolean case

Boolean query automaton A, hyperstream G

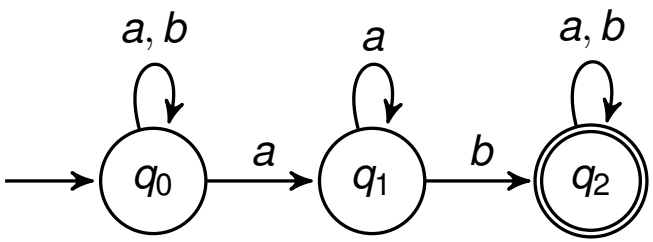




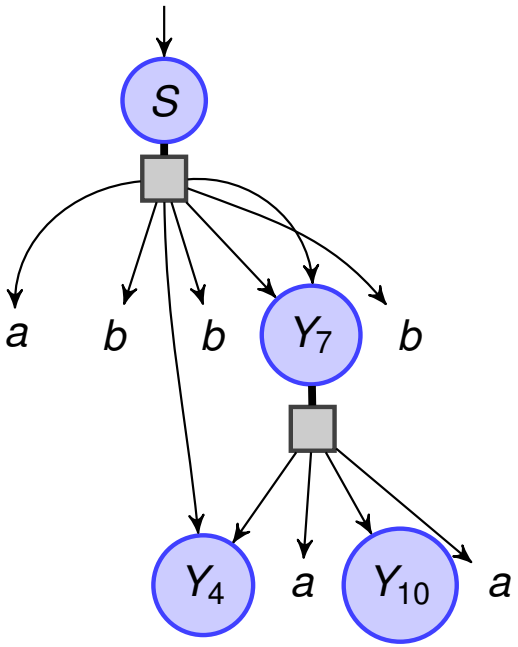


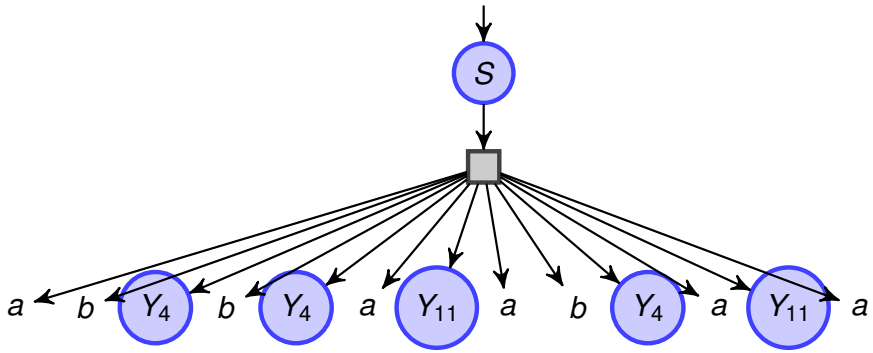
Equivalences in the boolean case

Boolean query automaton A, hyperstream G



() certain answer iff
$Inst(G) = Inst(pat(G)) \subseteq L(A)$





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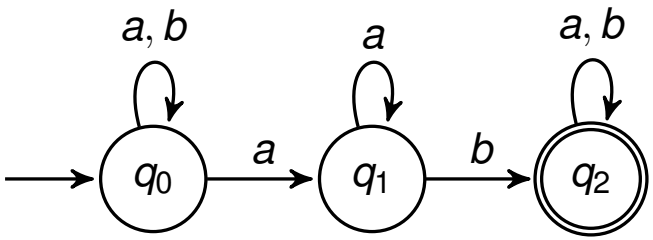

$CQA_{bool} = REGINCL$

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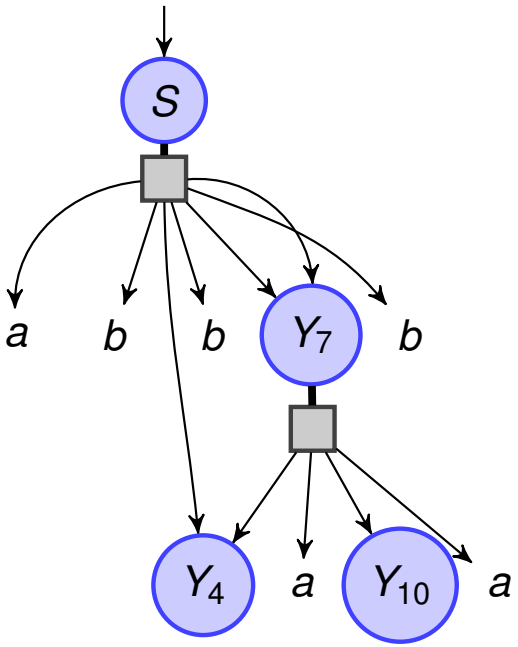

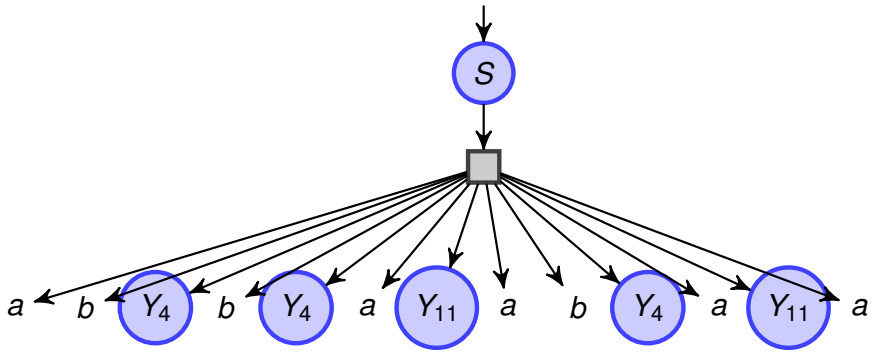

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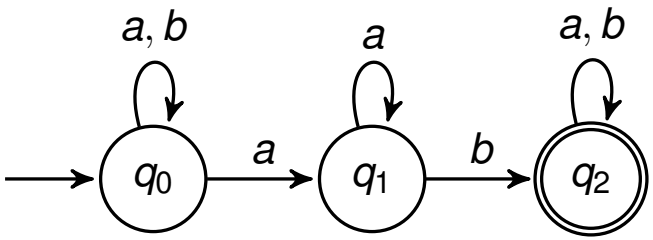

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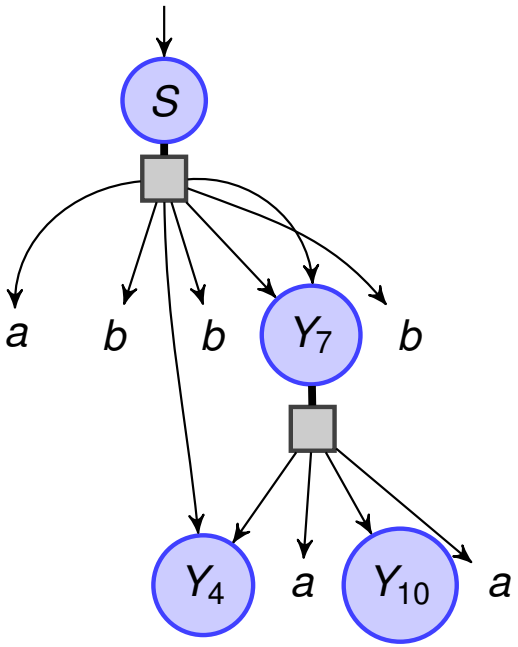
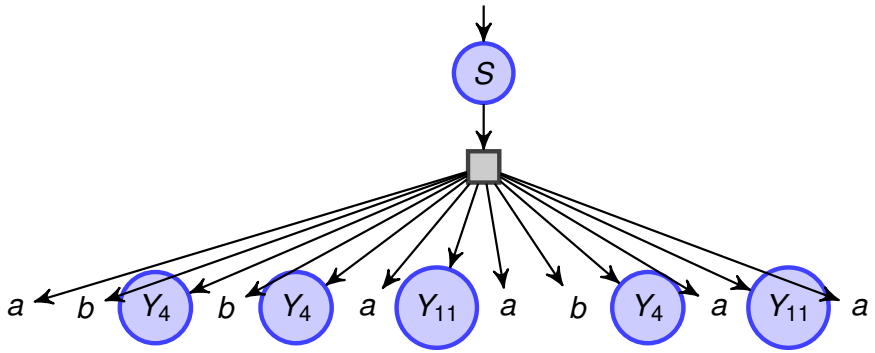
$Inst(G) = Inst(pat(G)) \subseteq L(A)$

() certain non answer iff

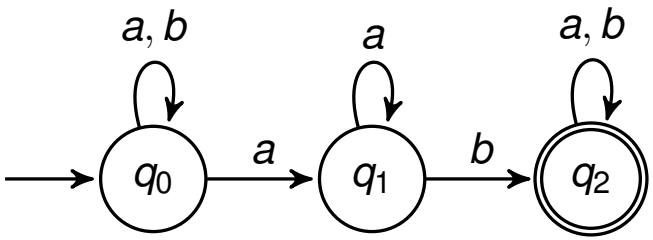
$Inst(G) = Inst(pat(G)) \cap L(A) = \emptyset$





Equivalences in the boolean case

Boolean query automaton A, hyperstream G



$CQA_{bool} = REGINCL$

() certain answer iff

$Inst(G) = Inst(pat(G)) \subseteq L(A)$

$CQ\neg A_{bool} = coREGMATCH$

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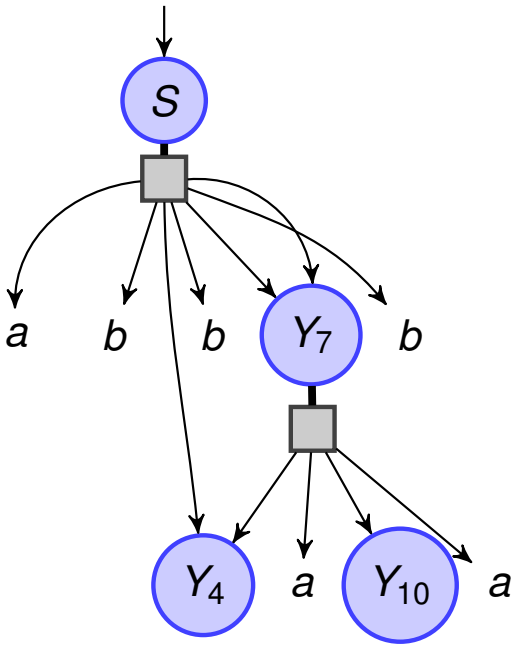

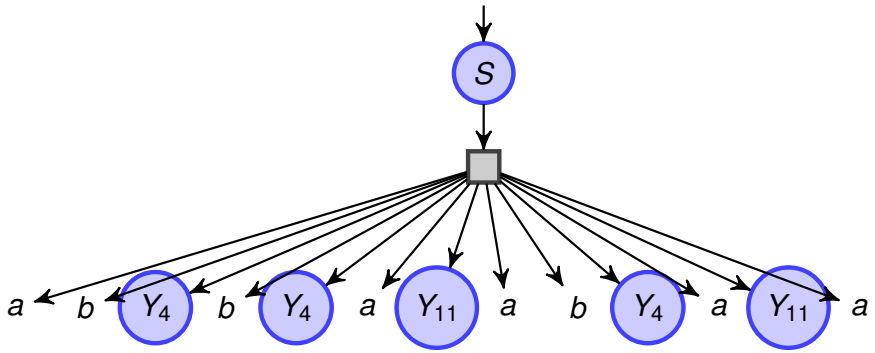

Results

Known results (Complexity of CQA on streams [Gauwin 2009])

	DFAs	NFAs
Answers	PTIME	PSPACE-c
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Contribution (Complexity of CQA on **Hyperstreams**)

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Contribution (Complexity of CQA on **linear hyperstreams**)

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Outline

Hardness of regular compressed pattern inclusion

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PSPACE-complete [Kozen 1977]. □

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Complexity of regular compressed pattern matching

Theorem ([Angluin 1980])

The simpler problem of string pattern matching is NP-complete.

Complexity of regular compressed pattern matching

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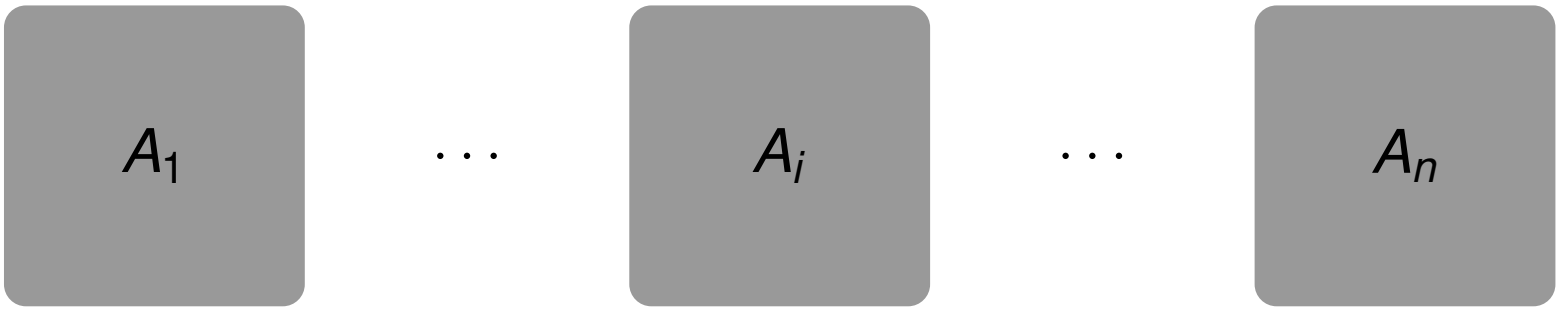
Theorem

REGINCL(*String_patterns*, DFA*s*) *is* PSPACE*-complete.*

Hardness of regular compressed pattern matching



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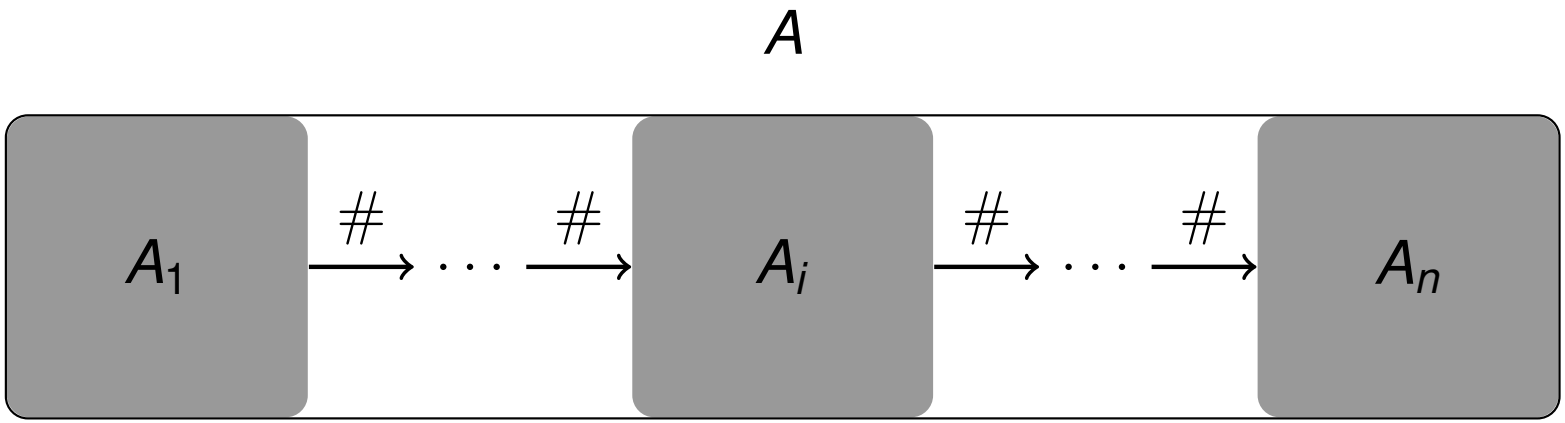

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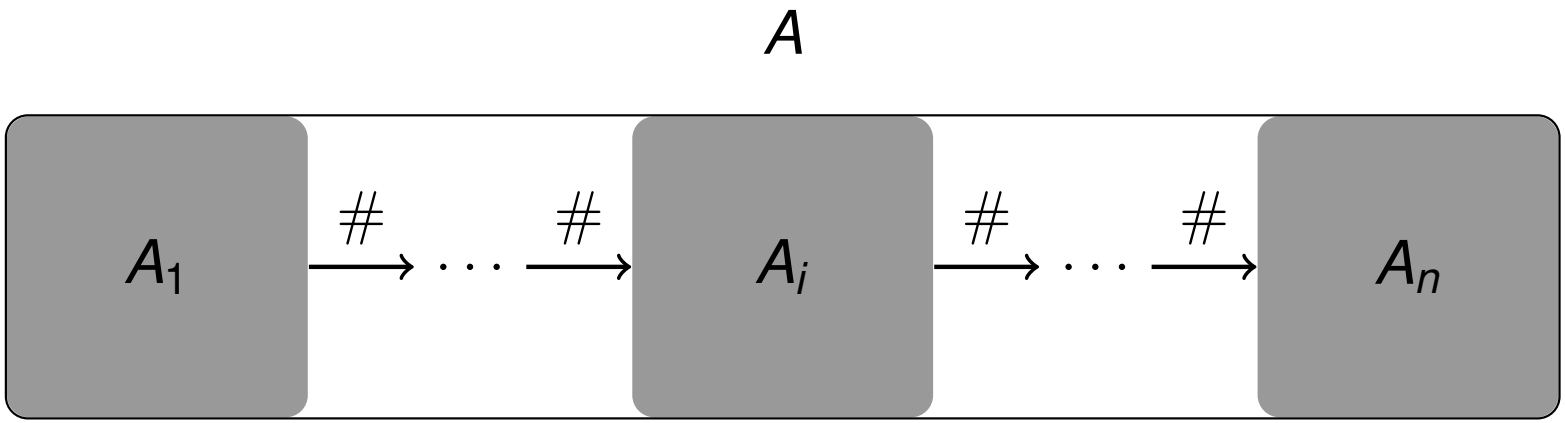
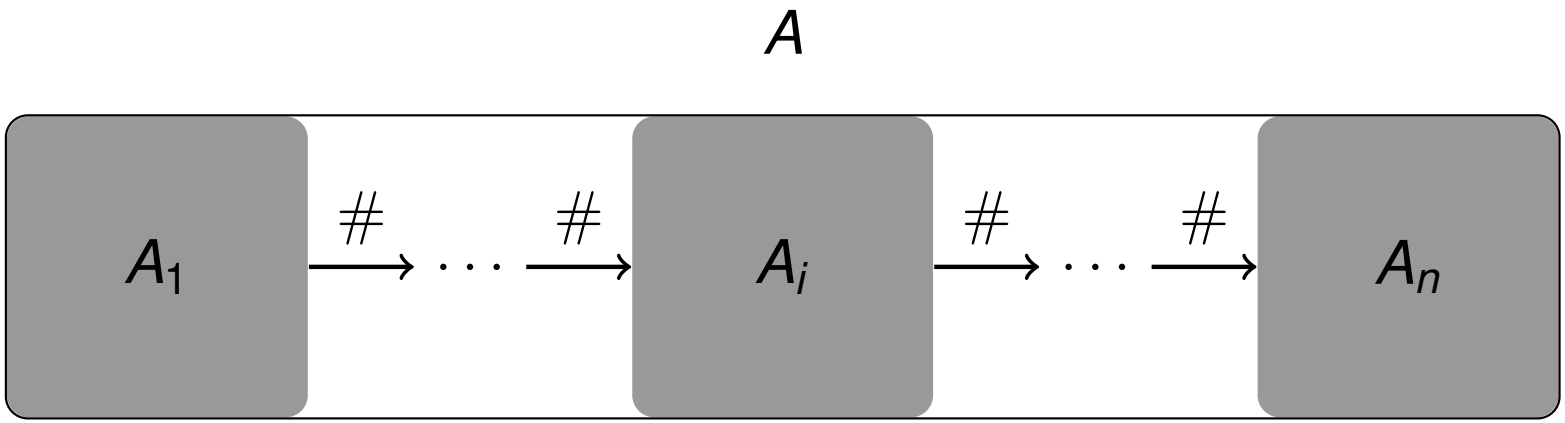


$$L(A) = \{u_1 \# \ldots \# u_n \mid u_1 \in L(A_1), \ldots, u_n \in L(A_n)\}$$

Hardness of regular compressed pattern matching



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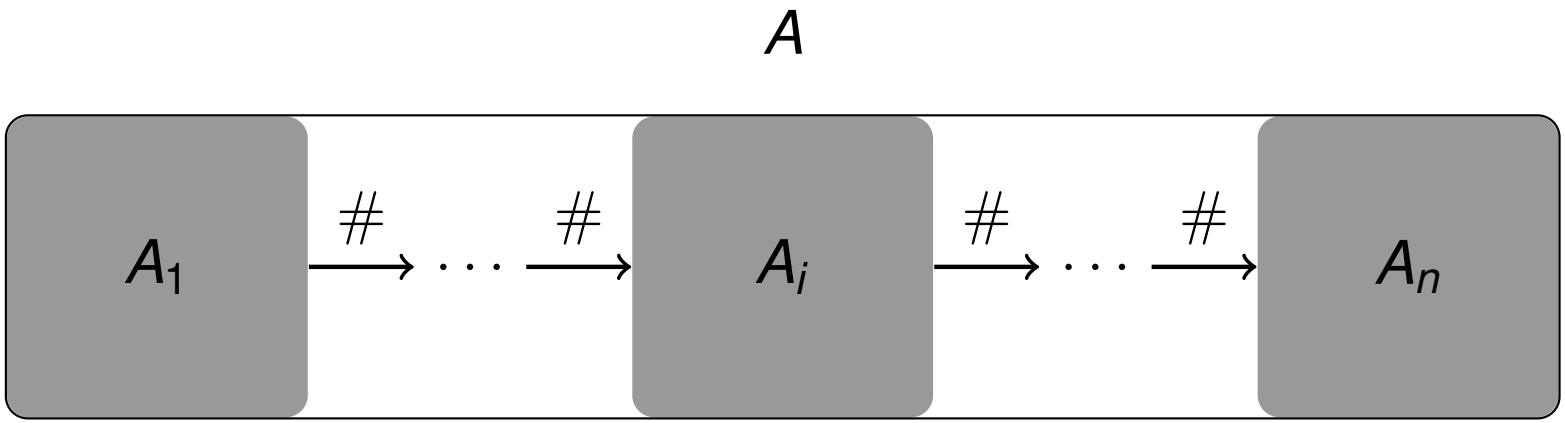

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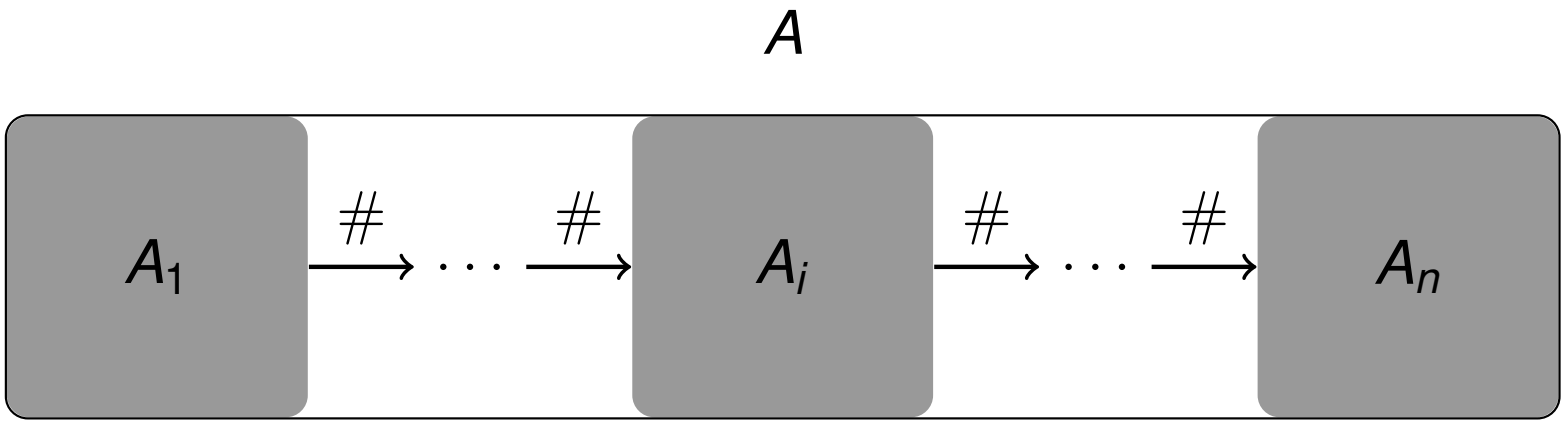

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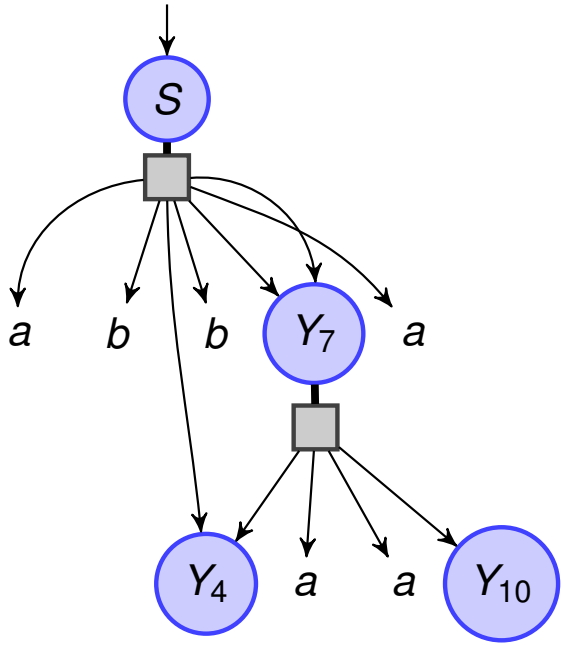
PSPACE-complete [Kozen 1977].

How to decide regular compressed pattern matching ?



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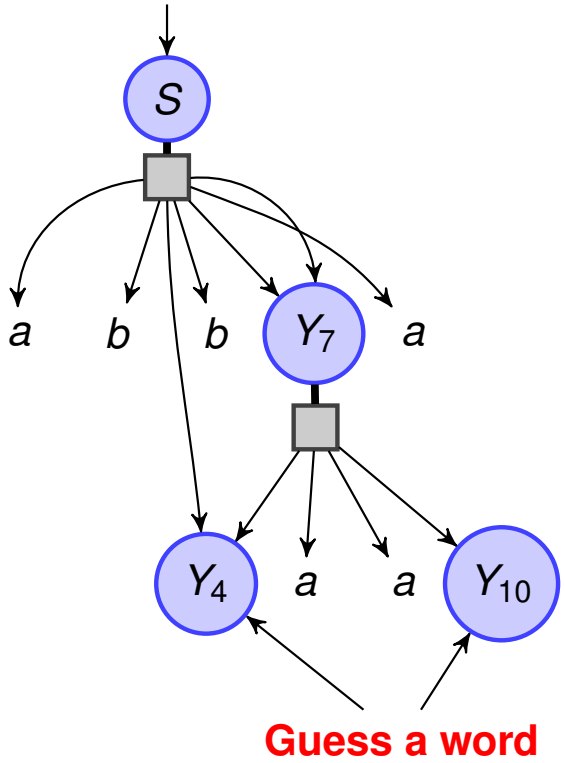

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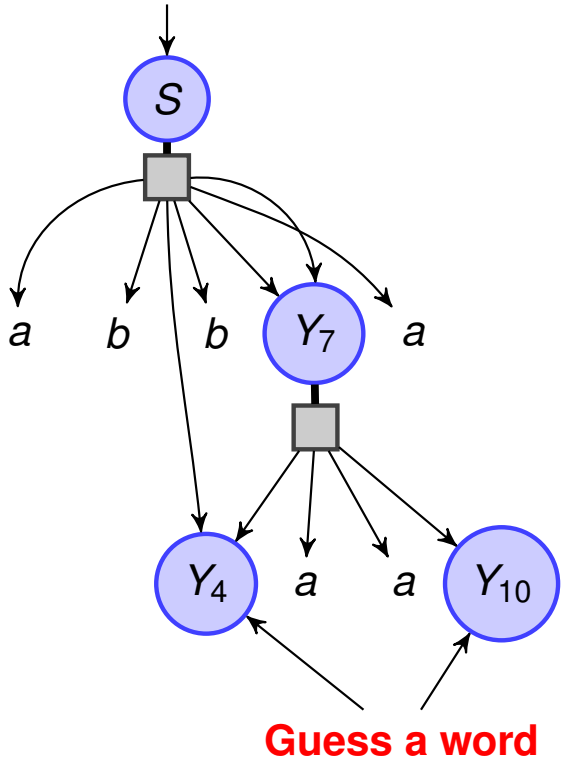

Σ^* is not finite...

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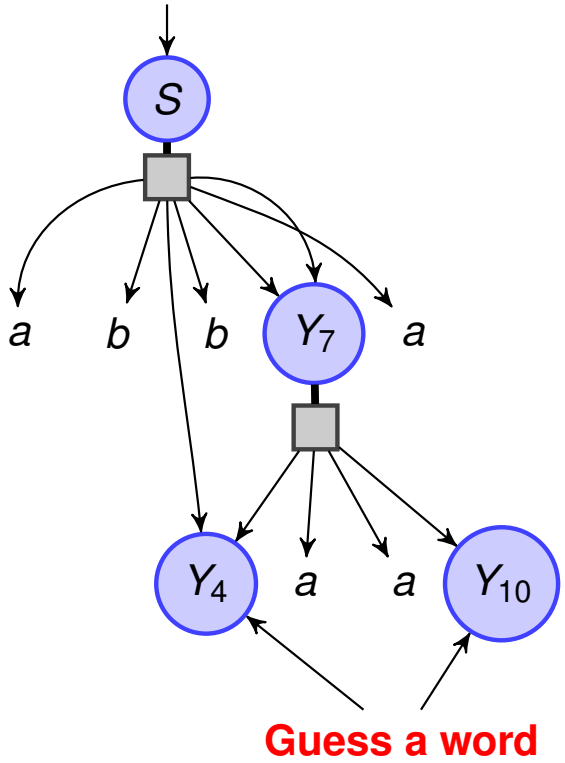
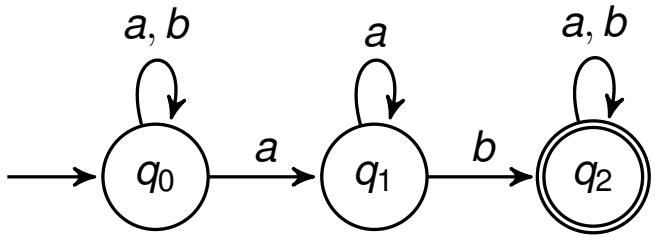
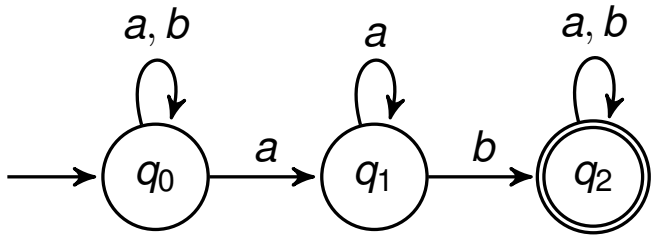


Σ^* is not finite... but the transition monoid is !

Transition monoid

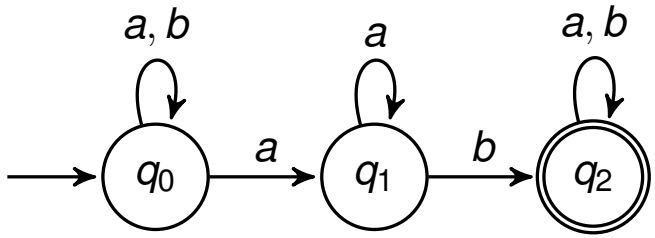


Transition monoid



	τ_a
q_0	q_0
q_1	q_1
q_2	q_2

Transition monoid



τ_a

$q_0 \longrightarrow q_0$

$q_1 \longrightarrow q_1$

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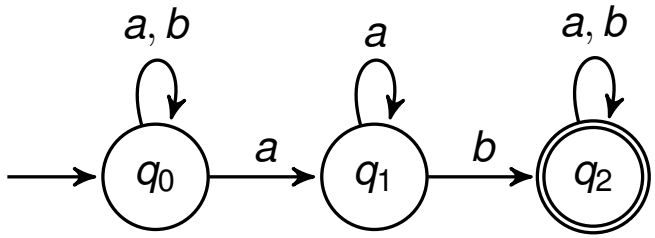
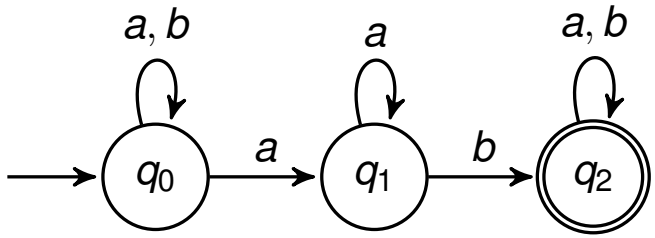
Transition monoid



	τ_a	τ_b
q_0	q_0	q_0
q_1	q_1	q_1
q_2	q_2	q_2

Transition monoid



τ_a

$q_0 \longrightarrow q_0$

$q_1 \longrightarrow q_1$

$q_2 \longrightarrow q_2$

τ_b

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$q_1 \longrightarrow q_1$

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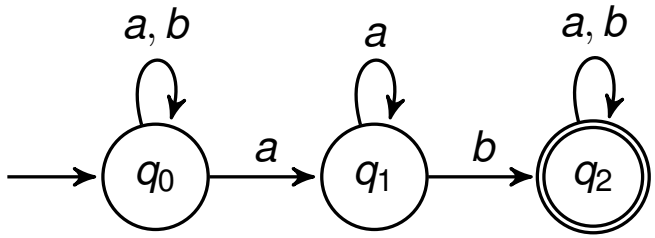
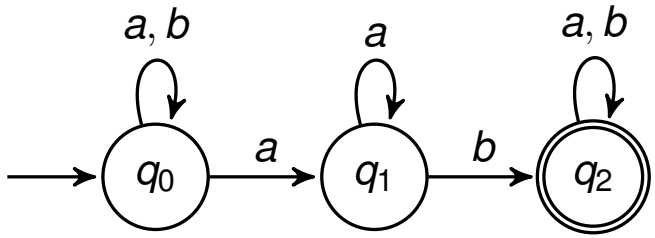
Transition monoid



τ_a τ_b

$$\begin{array}{ccc} q_0 \longrightarrow q_0 & & q_0 \longrightarrow q_0 \\ \searrow & & \\ q_1 \longrightarrow q_1 & \circ & q_1 \longrightarrow q_1 \\ & & \searrow \\ q_2 \longrightarrow q_2 & & q_2 \longrightarrow q_2 \end{array}$$

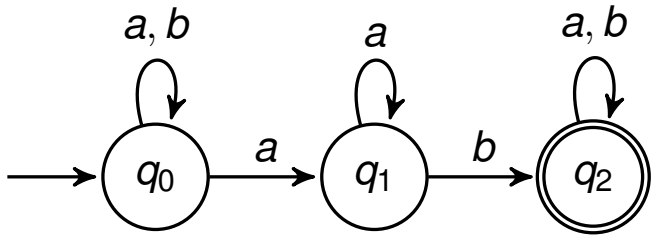
Transition monoid



τ_a τ_b τ_{ab}

$$
\begin{array}{ccc}
q_0 \longrightarrow q_0 & q_0 \longrightarrow q_0 & q_0 \quad q_0 \\
\searrow & & \\
q_1 \longrightarrow q_1 & \circ \quad q_1 \longrightarrow q_1 & q_1 \quad q_1 \\
 & \searrow & \\
q_2 \longrightarrow q_2 & q_2 \longrightarrow q_2 & q_2 \quad q_2
\end{array}
$$

Transition monoid



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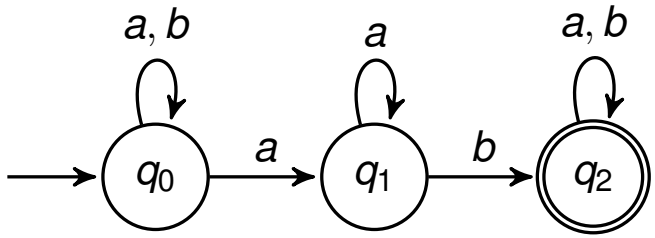

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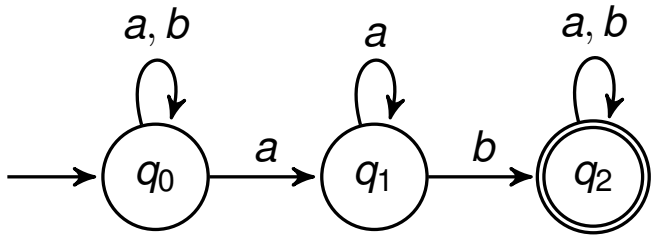
Transition inhabitation problem

Given a binary relation τ' over Q, is there any $w \in \Sigma^*$ such that $\tau' = \tau_w$?

Transition monoid



τ_a τ_b τ_{ab}

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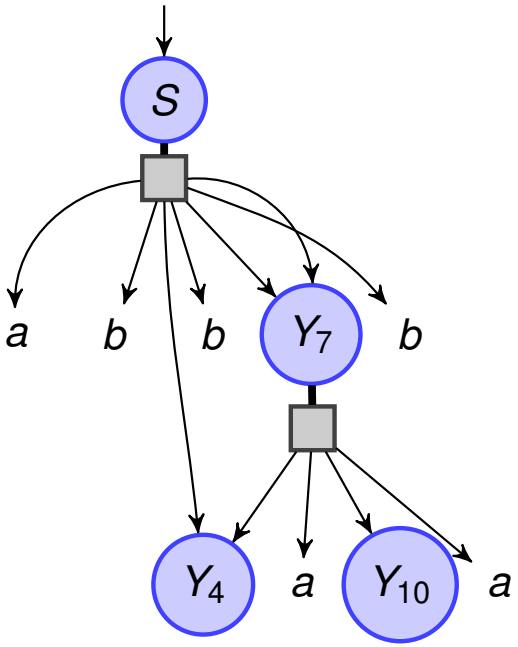
Inhabitation problem is PSPACE-complete [Kozen 1977].

Decision procedure for regular compressed matching problem

Compressed string pattern G and NFA $A = (Q, \Sigma, \delta, I, F)$.



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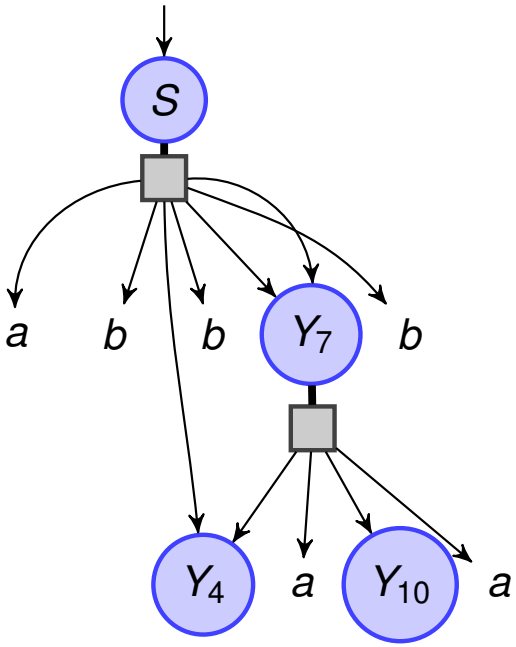

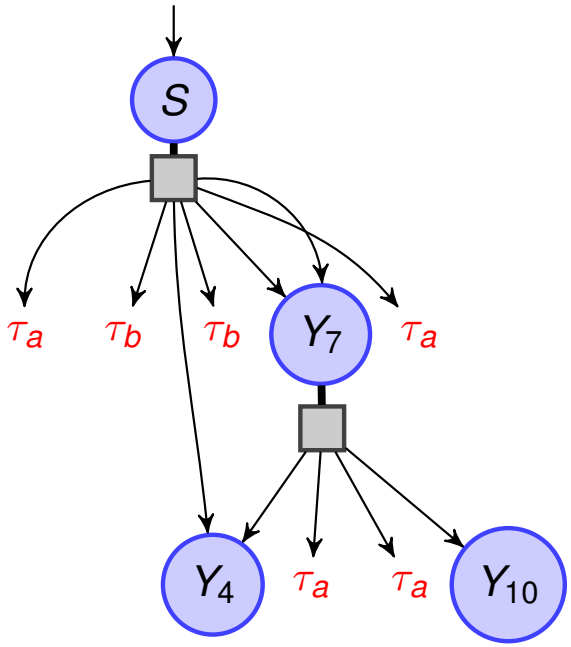

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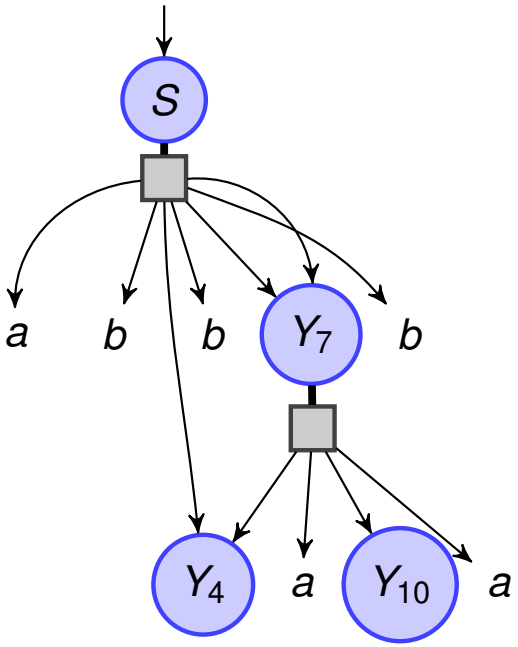

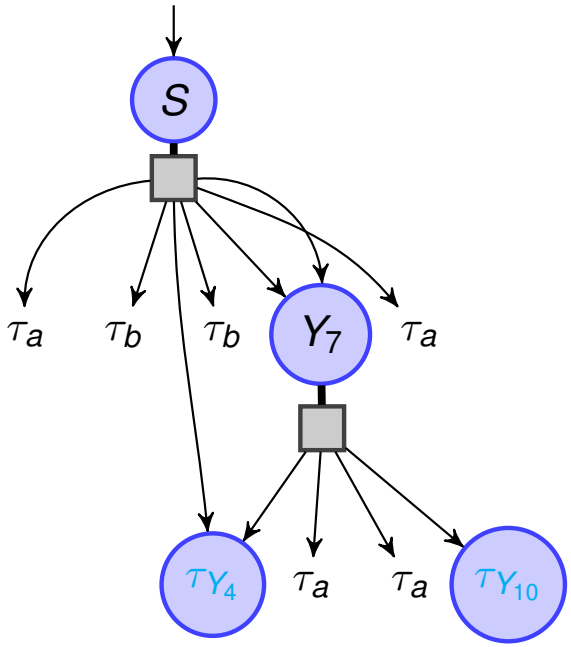

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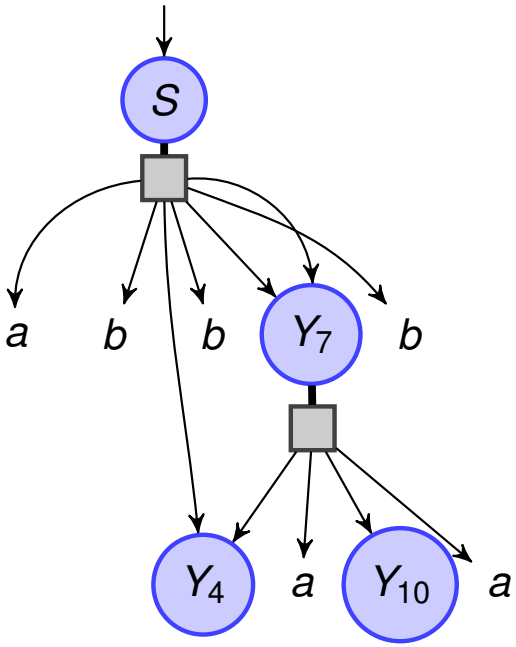

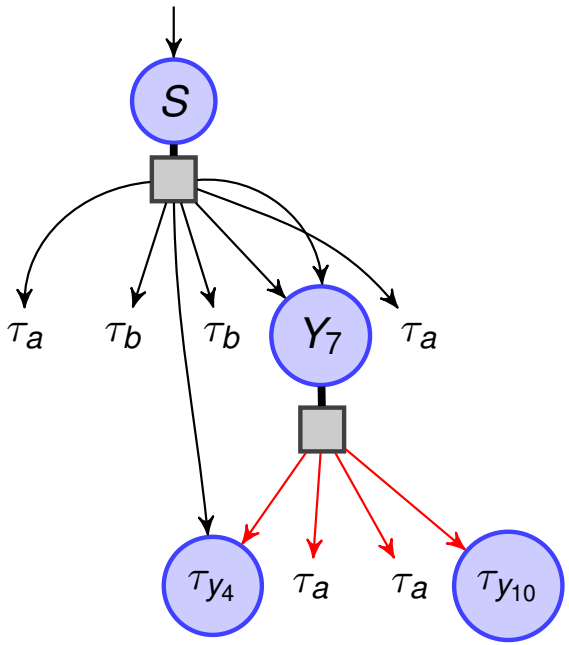

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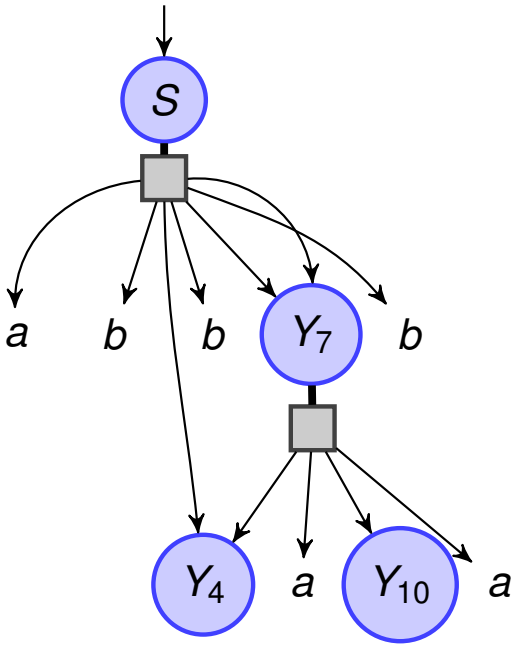

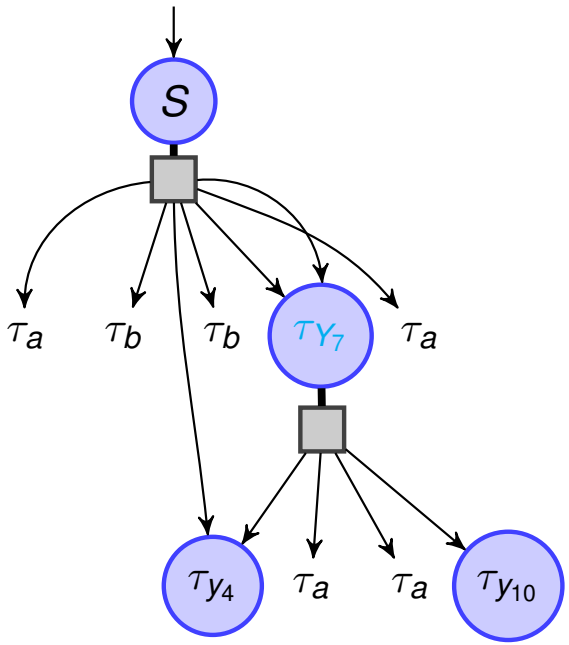

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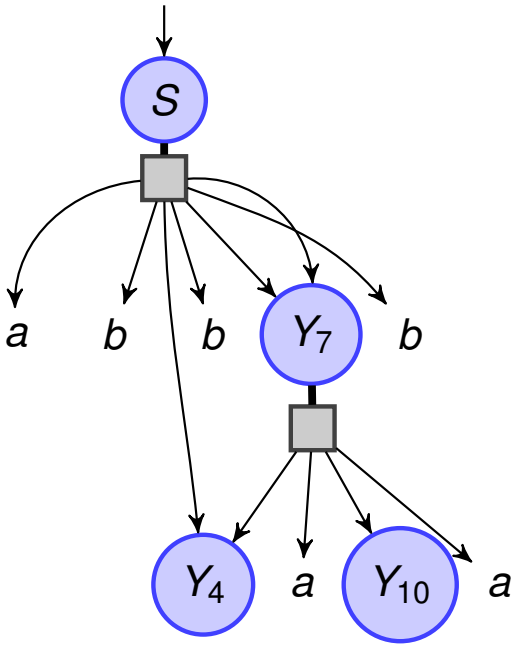

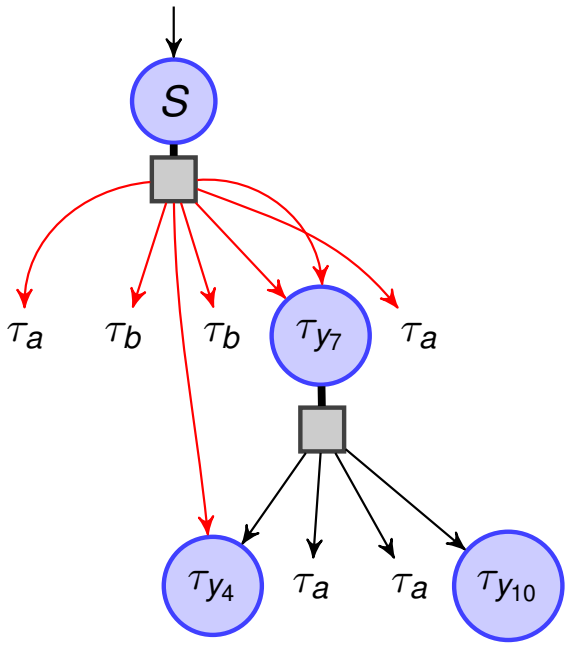

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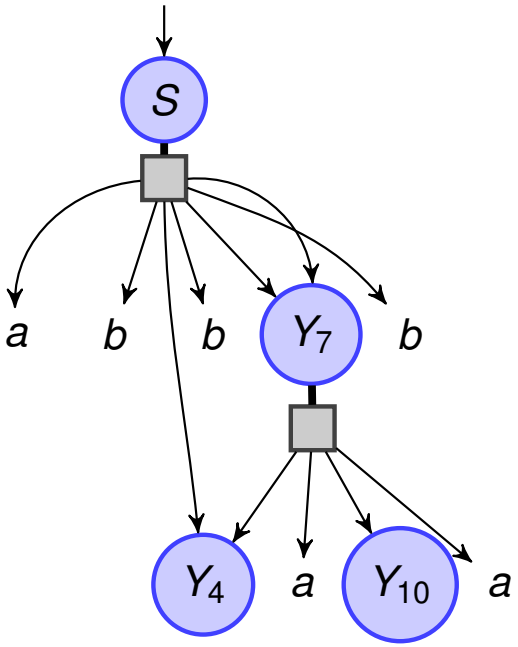

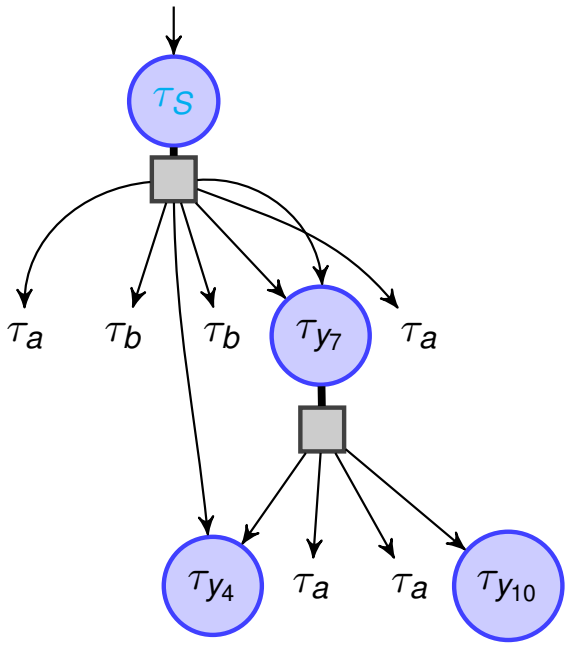

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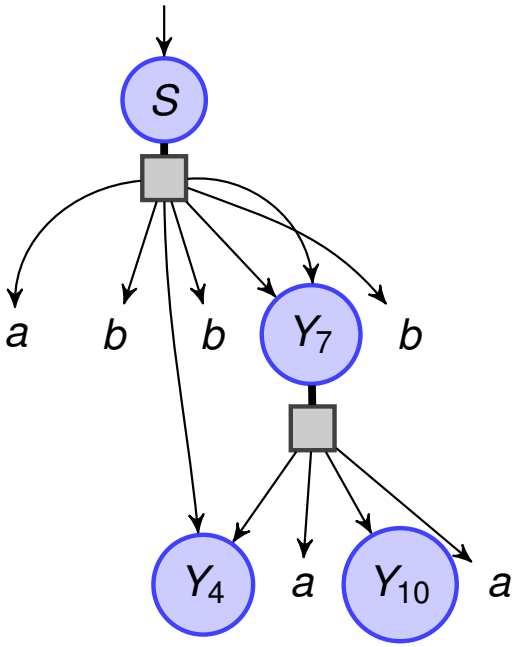
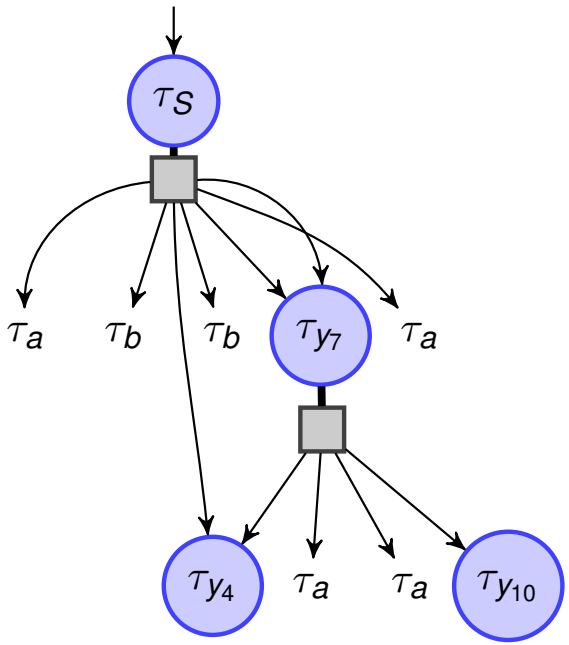
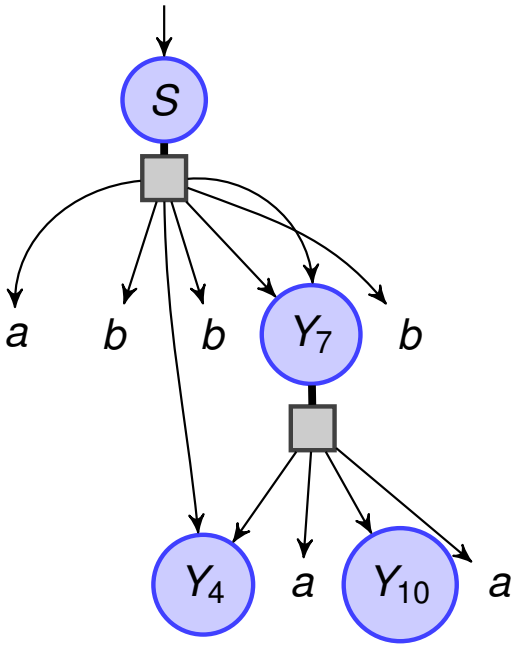


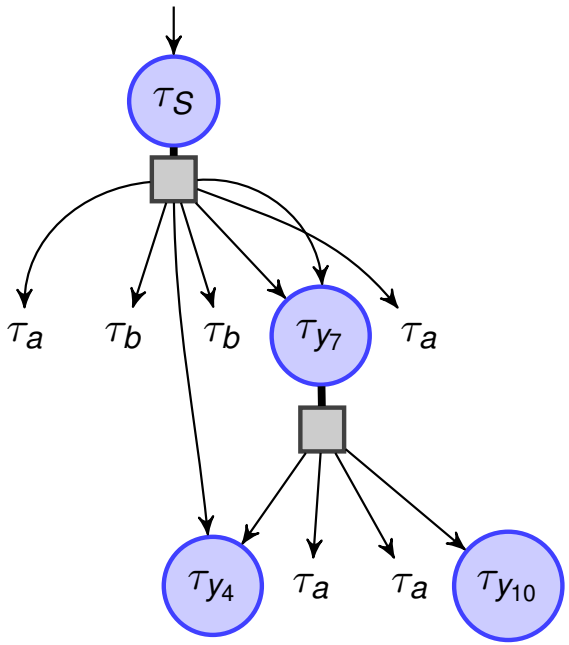


$$\tau_S \cap (I \times F) \neq \emptyset \ ?$$

Decision procedure for regular compressed matching problem

Compressed string pattern G and NFA $A = (Q, \Sigma, \delta, I, F)$.





$\tau_S \cap (I \times F) \neq \emptyset$?

Similar algorithm for Inclusion

Contribution (Complexity of CQA on **Hyperstreams**)

	DFAs	NFAs
Answers (*REGINCL*)	-	PSPACE-hard
Non-answers (*coREGMATCH*)	-	-

Contribution (Complexity of CQA on **linear hyperstreams**)

	DFAs	NFAs
Answers (*REGINCL*)	-	PSPACE-hard
Non-answers (*coREGMATCH*)	-	-

Contribution (Complexity of CQA on **Hyperstreams**)

	DFAs	NFAs
Answers (*REGINCL*)	-	PSPACE-c
Non-answers (*coREGMATCH*)	PSPACE-c	PSPACE-c

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	DFAs	NFAs
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Complexity of *REGINCL* for DFAs

Proposition

$REGINCL(\_, \text{DFA}s) = coREGMATCH(\_, \text{DFA}s)$

Complexity of *REGINCL* for DFAs

Proposition

$REGINCL(\_, \text{DFA}s) = coREGMATCH(\_, \text{DFA}s)$

Proof idea

For hyperstream G and NFA A, $Inst(G) \subseteq L(A)$ iff $Inst(G) \cap L(\bar{A}) = \emptyset$.
PTIME complementation for DFAs.

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An efficient fragment

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Theorem

REGMATCH(*Linear_String_Patterns*, NFA*s*) *is in* PTIME.

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Proof idea

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Corollary

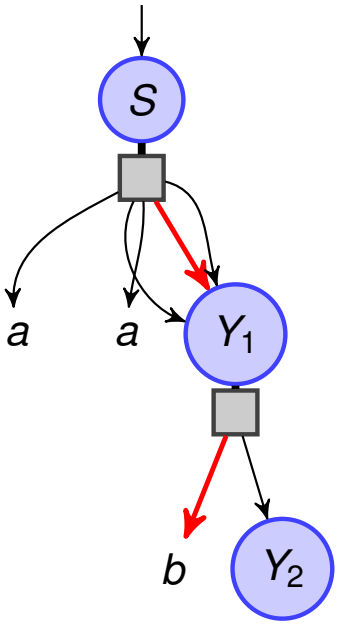
REGINCL(*Linear_String_Patterns*, DFA*s*) *is in* PTIME.

When the query is not boolean

Theorem

CQA(*Linear_Hyperstreams*, DFA*s*) *is in* PTIME.

Example of partial decompression



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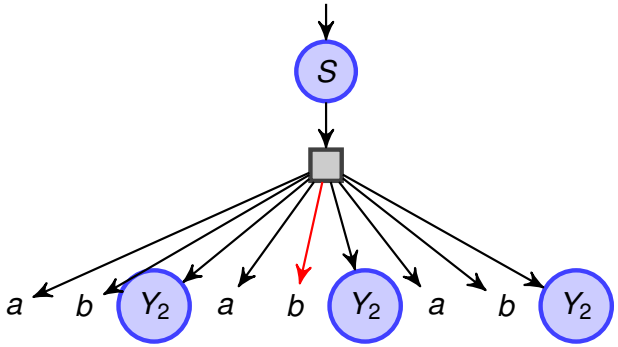
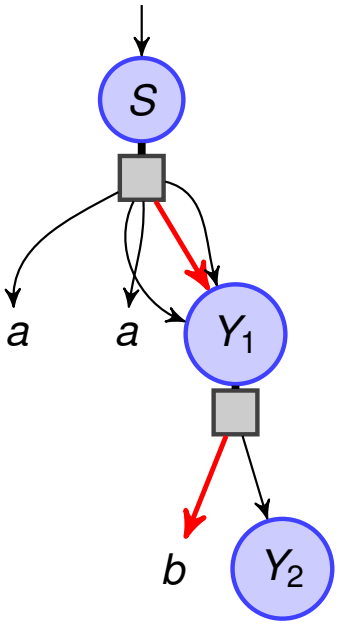
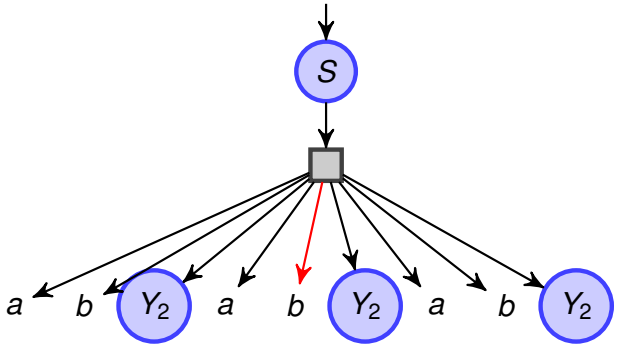
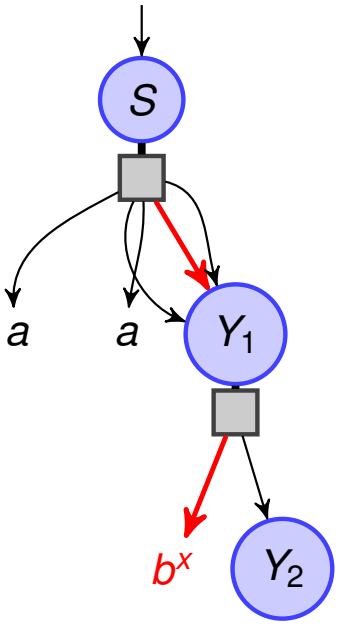


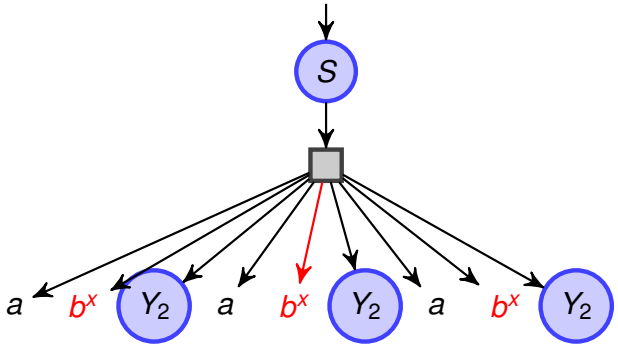


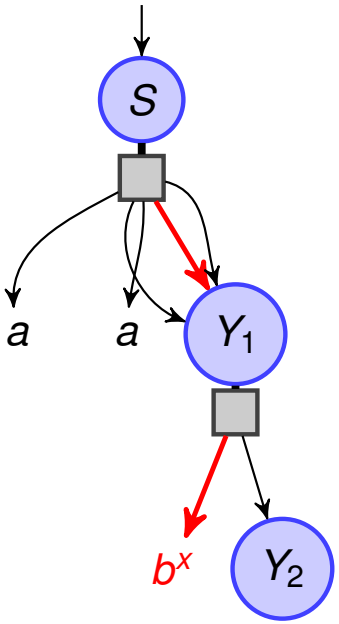
Example of partial decompression





Example of partial decompression





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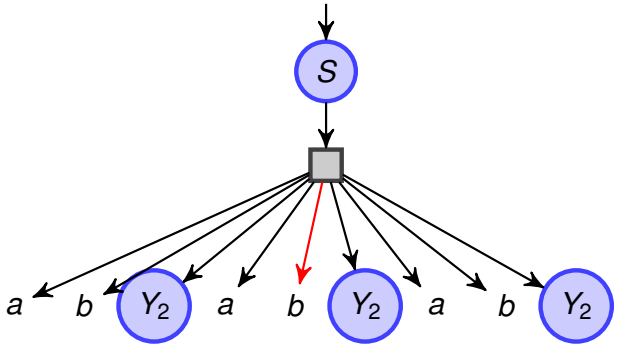

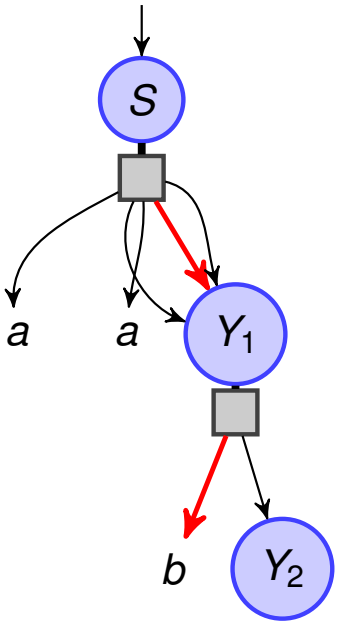

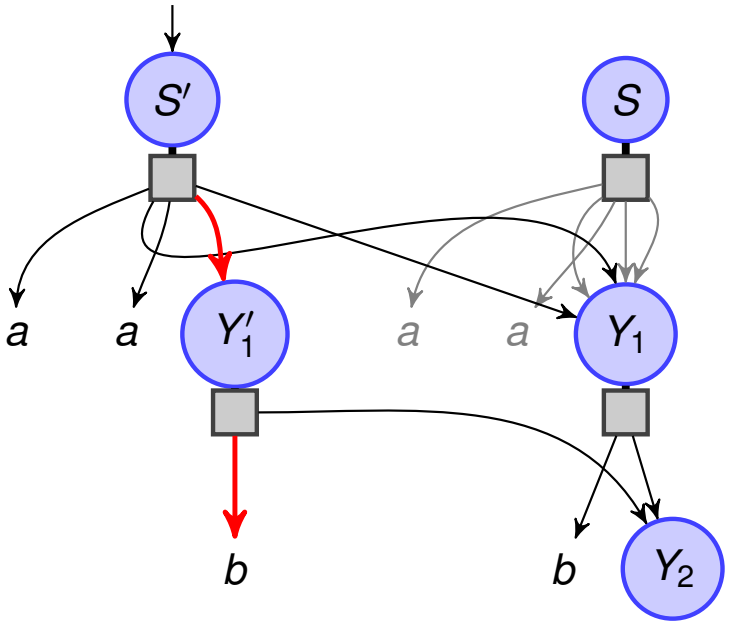

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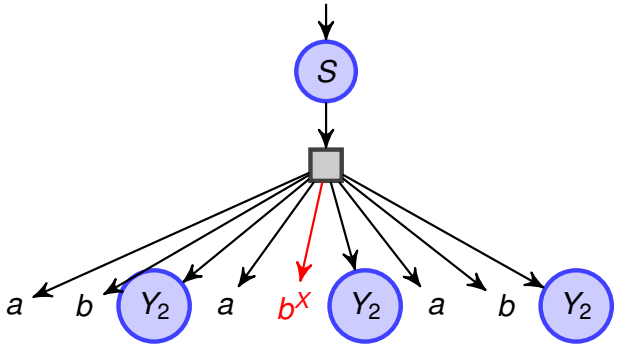

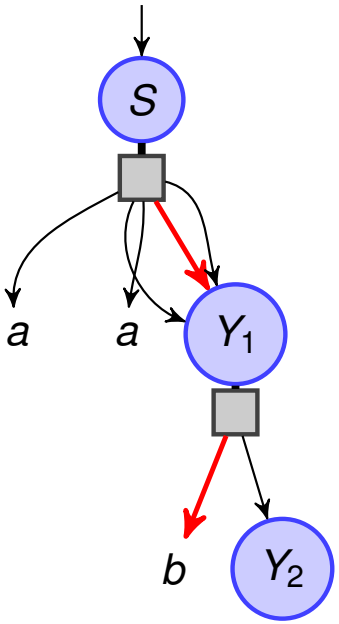

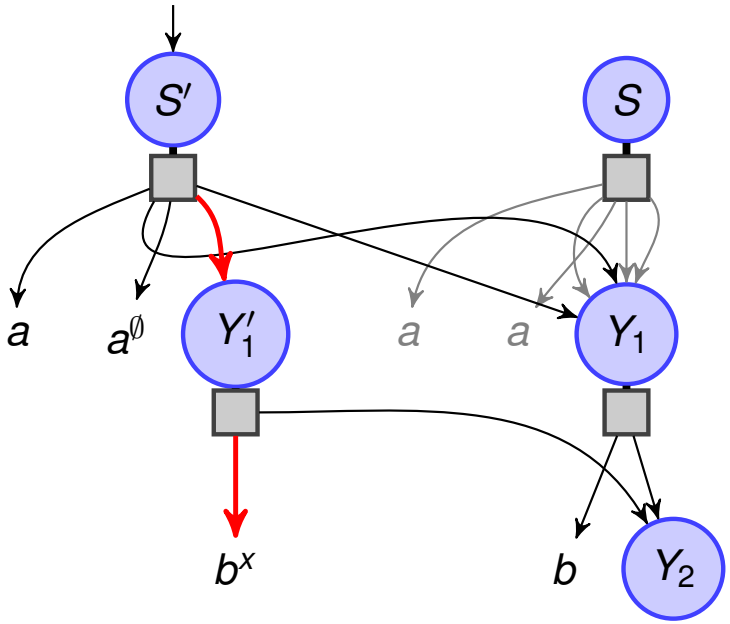

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Contribution (Complexity of CQA on **linear hyperstreams**)

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Non-answers (*coREGMATCH*)	-	-

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Contribution (Complexity of CQA on **linear hyperstreams**)

	DFAs	NFAs
Answers (*REGINCL*)	PTIME	PSPACE-c
Non-answers (*coREGMATCH*)	PTIME	PTIME

Outline

Future Work

- Short and middle term
  - Tractable approximations of Certain query answering on NFAs
  - Practical hyperstreaming algorithms
  - Extension to Trees

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- Long term
  - Extension to transformations
  - Extension to Graphs