TADAM: Learning Timed Automata from Noisy Observations

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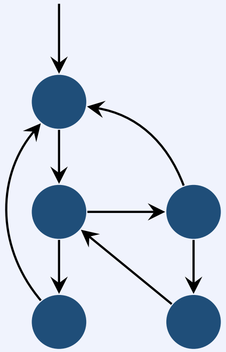
Introduction

communication protocol

system

industrial process

Introduction



communication protocol

system → behavior model

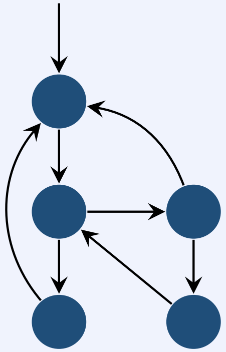
industrial process

Introduction

communication protocol

industrial process

system



behavior model

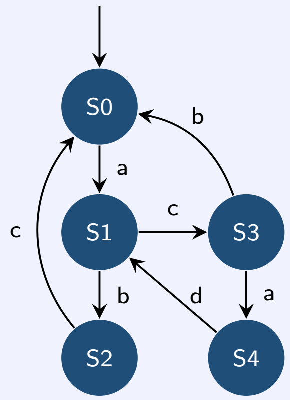
monitoring

model checking

data generation

...

Behavior model formalism



Automata formalism

Finite state automata (FSA)

Natural formalism for **discrete event system (DES)** modeling

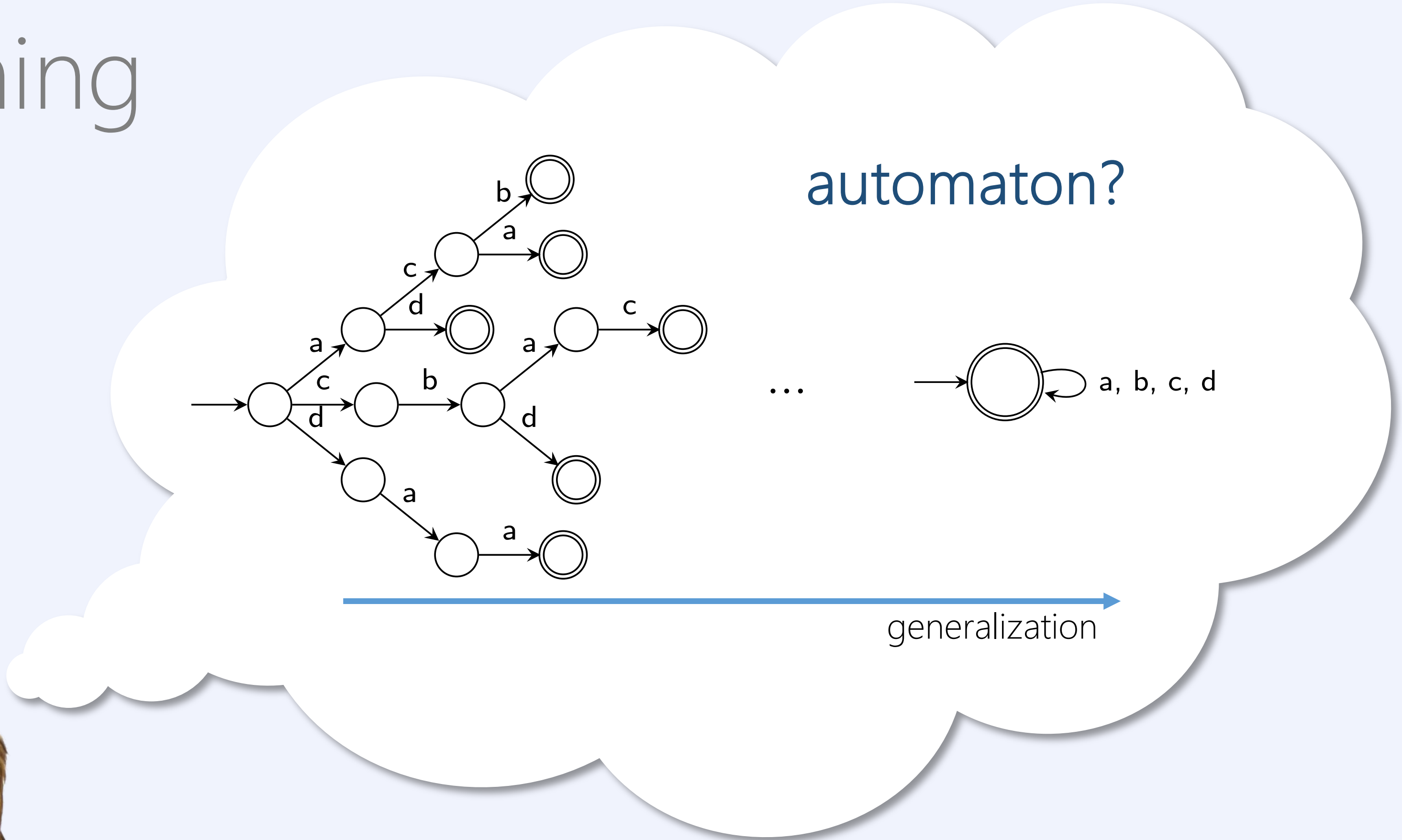
Human-understandable representation of the behavior of a system

Based on a **mathematical formalism** with **extensive literature** and with **software support**

Automata learning

data

a c b
a d
c b a c
a c a
d a a
c b d

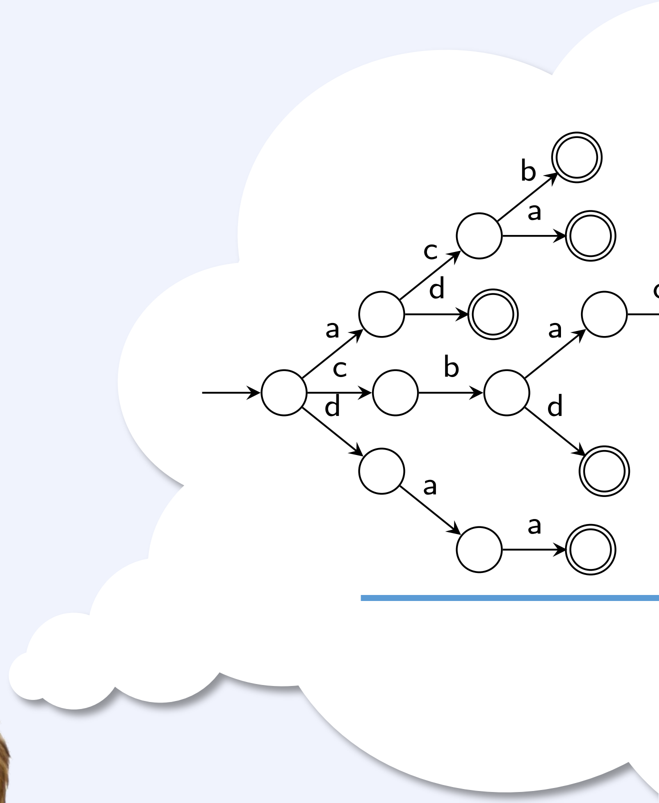


Automata learning

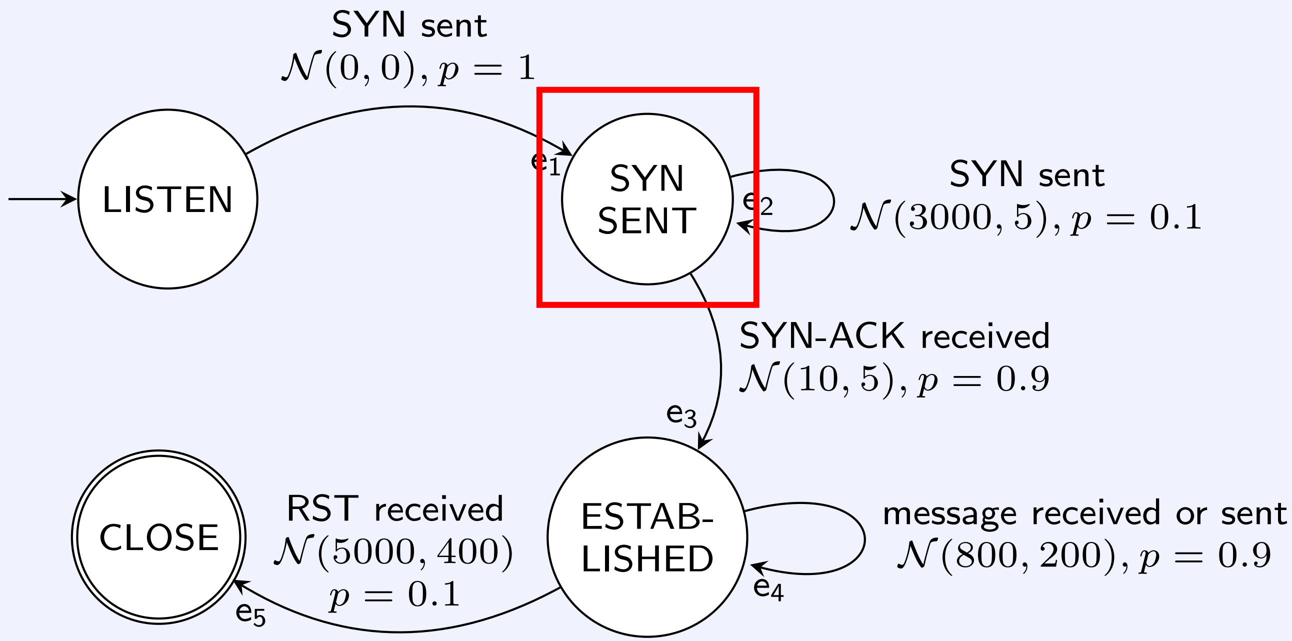
limited mesurement accuracy,
probe configuration error
…

noisy
data

a c b
a d
c b a c
a c a
d a a
c b d

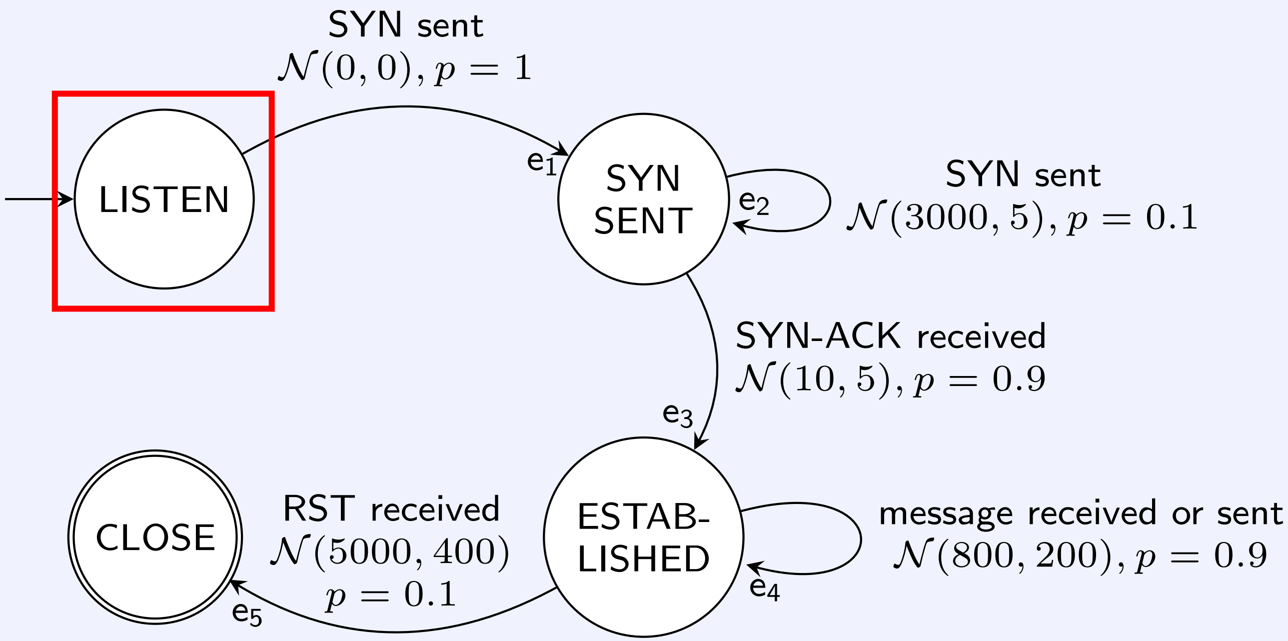


Probabilistic Real-Time Automaton



location
$q \in \mathcal{Q}$

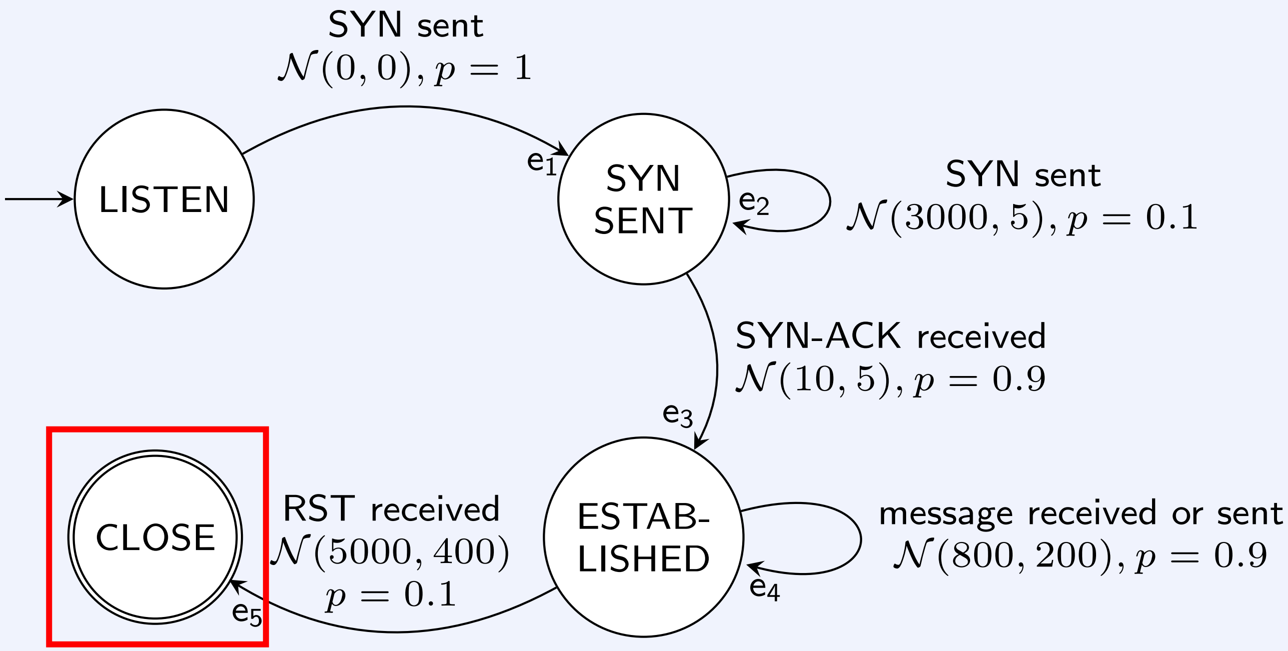
Probabilistic Real-Time Automaton



initial

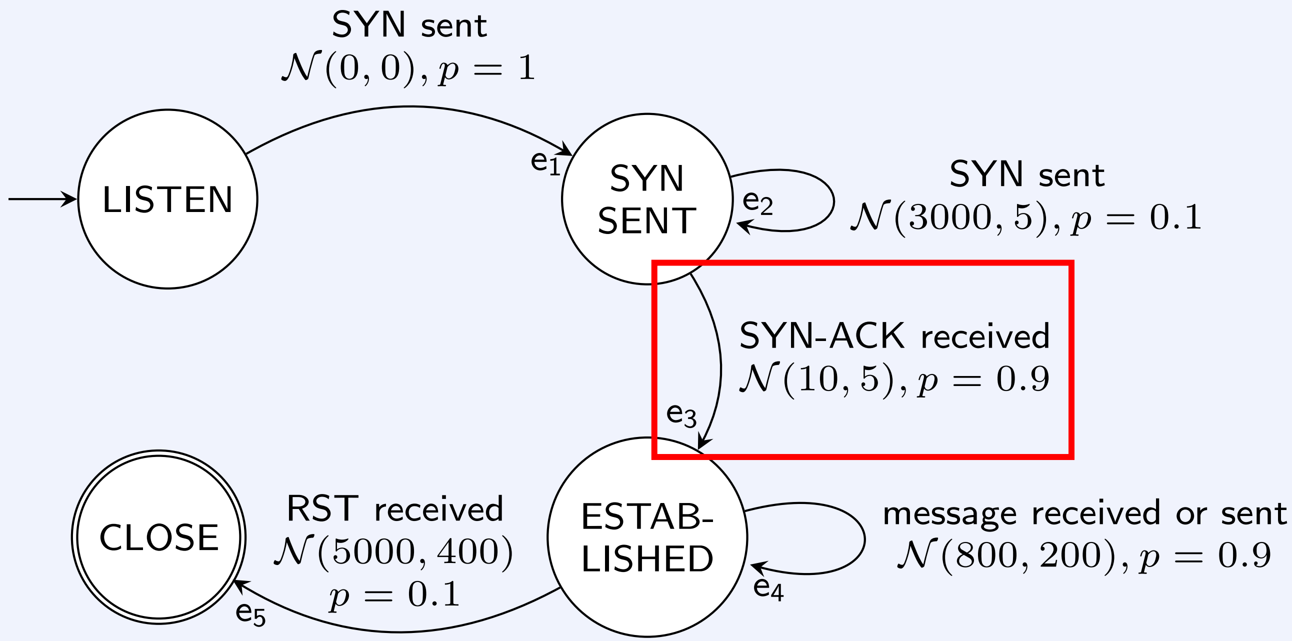
location

Probabilistic Real-Time Automaton



final location

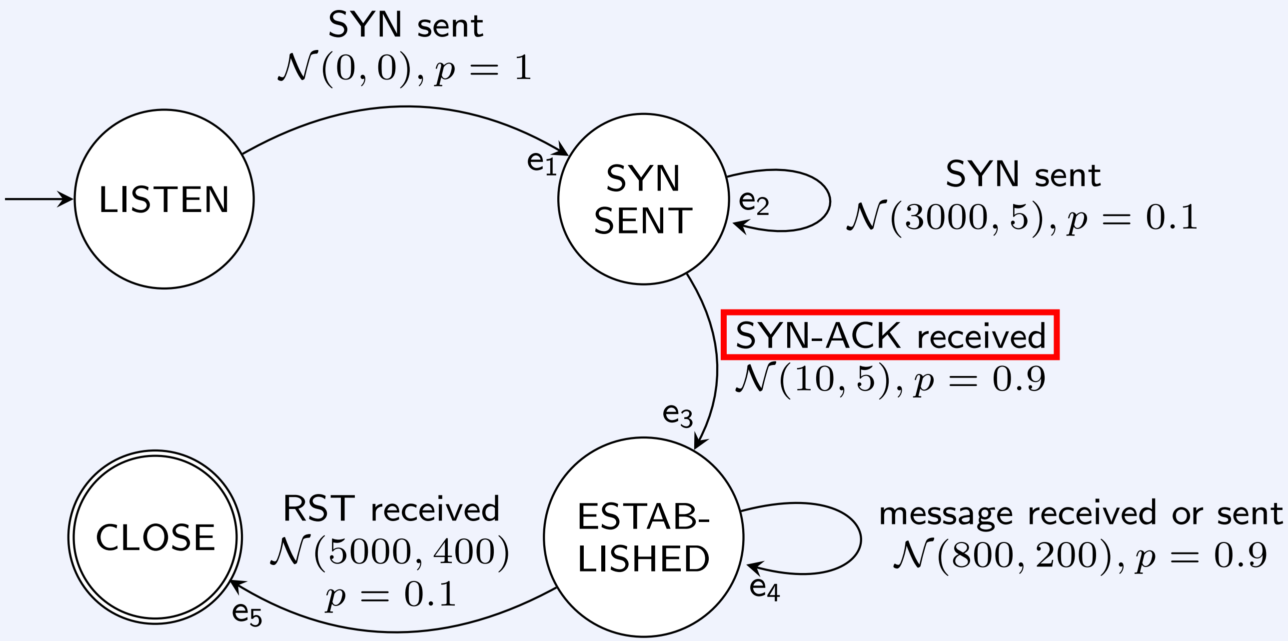
Probabilistic Real-Time Automaton



transition

$e \in \mathcal{E}$

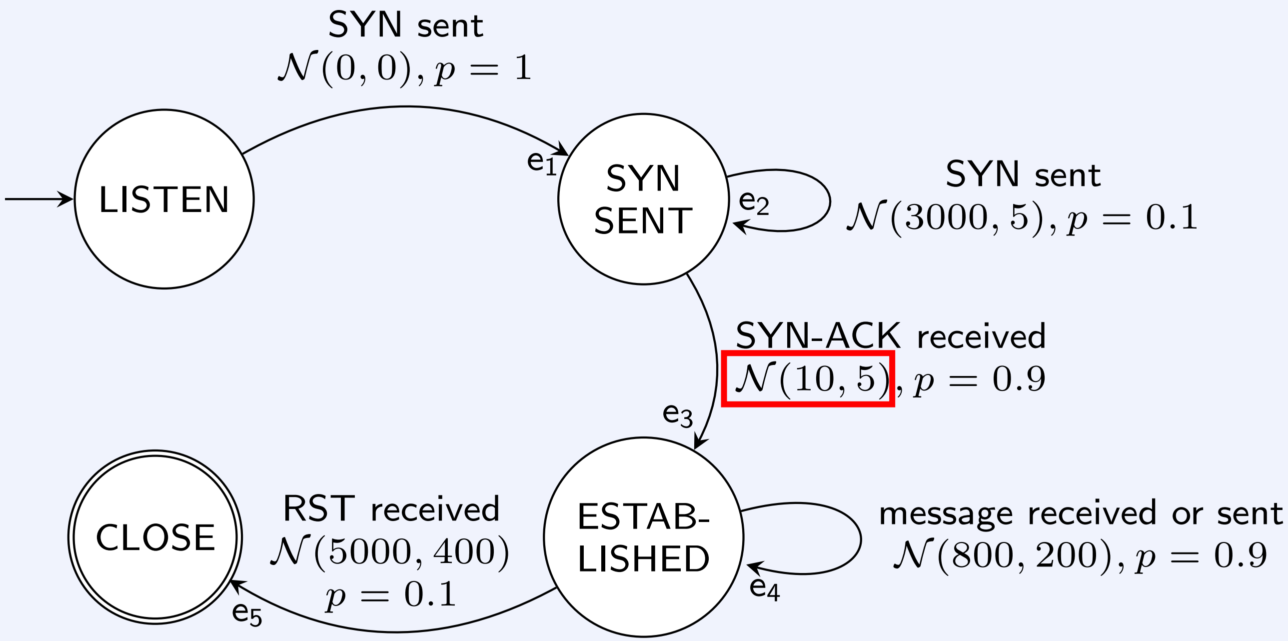
Probabilistic Real-Time Automaton



symbol

$a \in \Sigma$

Probabilistic Real-Time Automaton

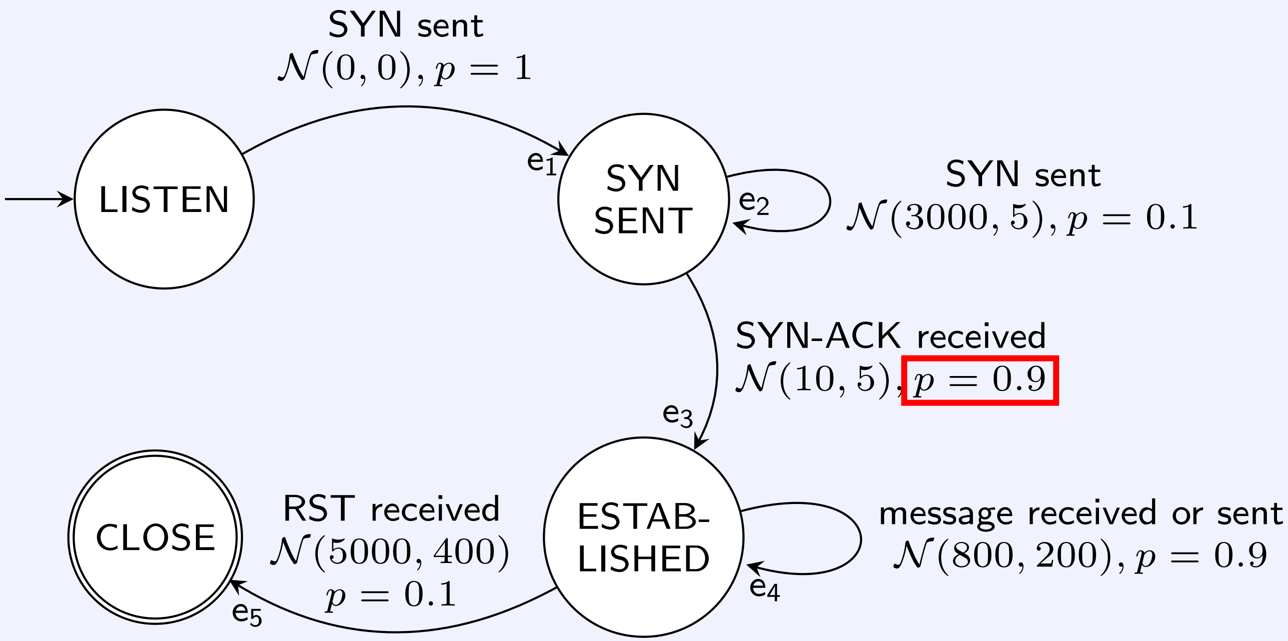


delay

distribution

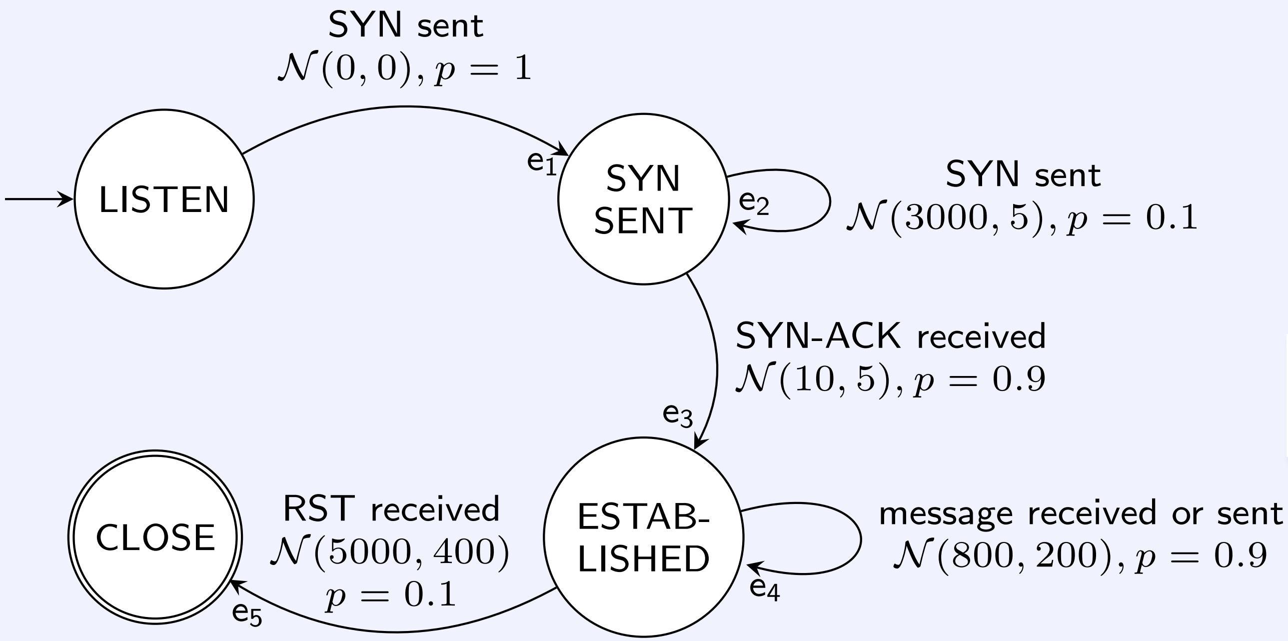
$\mathcal{N}(\mu, \sigma)$

Probabilistic Real-Time Automaton



transition probability p

Probabilistic Real-Time Automaton



timed word

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(RST received, 6500)

$$w = \{(a,d), ...\}$$

Noise model

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(RST received, 6500)

deletion

(SYN sent, 0),(SYN sent, 2000),(RST received, 6500)

Noise model

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(RST received, 6500)

$\downarrow$ insertion

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(SYN sent, 50),(RST received, 6500)

Noise model

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(RST received, 6500)

transposition

(SYN sent, 0),(SYN-ACK received, 10),(SYN sent, 2000),(RST received, 6500)

Noise model

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(RST received, 6500)

symbol repetition

(SYN sent, 0),(SYN sent, 2000),(SYN-ACK received, 10),(SYN-ACK received, 7),(RST received, 6500)

Question

How to learn timed automata from noisy timed words?

Occam's razor

Why won't my car start?

A group of hackers remotely accessed your car's onboard computer overnight, disabling the ignition system as part of a sophisticated cyber-attack targeting random individuals to create chaos.

Your car battery is dead.

Occam’s razor

The simplest model that fits the data is usually the correct one

MDL principle

Two-part description length

$$L(\mathcal{D}, \mathcal{A}) = L(\mathcal{D}|\mathcal{A}) + L(\mathcal{A})$$

MDL principle

Two-part description length

$$L(\mathcal{D}, \mathcal{A}) = L(\mathcal{D}|\mathcal{A}) + L(\mathcal{A})$$

global length

(# of bits needed)

MDL principle

Two-part description length

$$L(\mathcal{D}, \mathcal{A}) = L(\mathcal{D}|\mathcal{A}) + L(\mathcal{A})$$

global length
(# of bits needed)

length of describing
the automaton

MDL principle

Two-part description length

$$L(\mathcal{D}, \mathcal{A}) = L(\mathcal{D}|\mathcal{A}) + L(\mathcal{A})$$

global length
(# of bits needed)

length of describing the
data encoded with
the automaton

length of describing
the automaton

MDL principle

Two-part description length

$$L(\mathcal{D}, \mathcal{A}) = L(\mathcal{D}|\mathcal{A}) + L(\mathcal{A})$$

global length
(# of bits needed)

length of describing the
data encoded with
the automaton

length of describing
the automaton

Minimum Description Length principle

$$\mathcal{A}^* = \underset{\mathcal{A} \in \boldsymbol{\mathcal{A}}}{\operatorname{argmin}}\ L(\mathcal{D}|\mathcal{A}) + L(\mathcal{A})$$

Automaton encoding

$$L(\mathcal{A}) =$$

Automaton encoding

- Locations

$$L(\mathcal{A}) = L_{\mathbb{N}}(|\mathcal{Q}|)$$

Automaton encoding

- Locations
- Alphabet

$$L(\mathcal{A}) = L_{\mathbb{N}}(|\mathcal{Q}|) + L_{\mathbb{N}}(|\Sigma|)$$

Automaton encoding

- Locations
- Alphabet
- Initial and accepting locations

$$L(\mathcal{A}) = L_{\mathbb{N}}(|\mathcal{Q}|) + L_{\mathbb{N}}(|\Sigma|) + 2\log_2(|\mathcal{Q}|) +$$

Automaton encoding

- Locations
- Alphabet
- Initial and accepting locations
- For each transition:

$$L(\mathcal{A}) = L_{\mathbb{N}}(|\mathcal{Q}|) + L_{\mathbb{N}}(|\Sigma|) + 2\log_2(|\mathcal{Q}|) +$$

$$\sum_{e \in \mathcal{E}} \Big(\qquad \Big)$$

Automaton encoding

- Locations
- Alphabet
- Initial and accepting locations
- For each transition:
  - Source and destination locations

$$L(\mathcal{A}) = L_{\mathbb{N}}(|\mathcal{Q}|) + L_{\mathbb{N}}(|\Sigma|) + 2\log_2(|\mathcal{Q}|) +$$

$$\sum_{e \in \mathcal{E}} \Big(2\log_2(|\mathcal{Q}|) \qquad \Big)$$

Automaton encoding

- Locations
- Alphabet
- Initial and accepting locations
- For each transition:
  - Source and destination locations
  - Symbol

$$L(\mathcal{A}) = L_{\mathbb{N}}(|\mathcal{Q}|) + L_{\mathbb{N}}(|\Sigma|) + 2\log_2(|\mathcal{Q}|) +$$

$$\sum_{e \in \mathcal{E}} \Big(2\log_2(|\mathcal{Q}|) + \log_2(|\Sigma|) + \Big)$$

Automaton encoding

- Locations
- Alphabet
- Initial and accepting locations
- For each transition:
  - Source and destination locations
  - Symbol
  - Guards’ normal distributions parameters

$$
\begin{aligned}
L(\mathcal{A}) =& L_{\mathbb{N}}(|\mathcal{Q}|) + L_{\mathbb{N}}(|\Sigma|) + 2\log_2(|\mathcal{Q}|) + \\
& \sum_{e \in \mathcal{E}} \Big(2\log_2(|\mathcal{Q}|) + \log_2(|\Sigma|) + \\
& \qquad L_{\mathbb{N}}(\lfloor \mu_e \rfloor) + L_{\mathbb{N}}(\lfloor \sigma_e^2 \rfloor) \Big)
\end{aligned}
$$

Data encoding

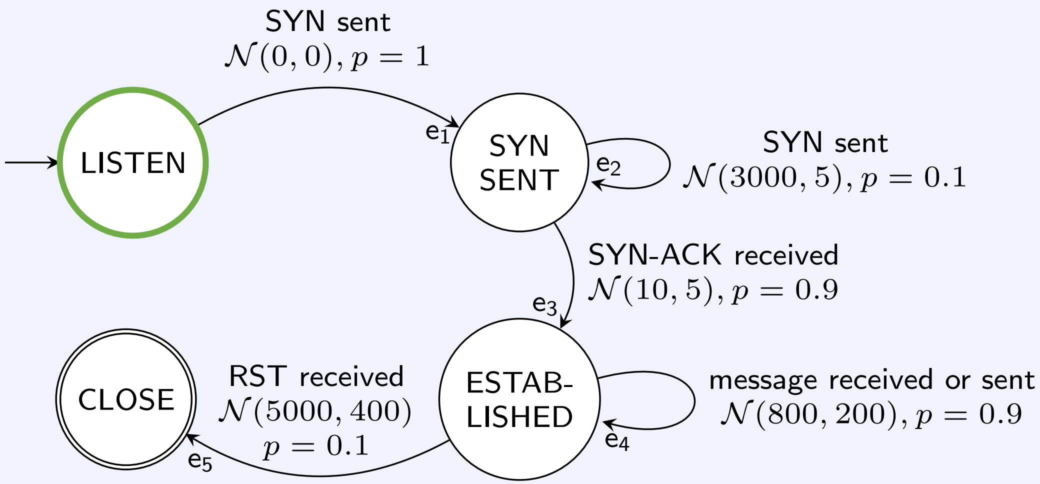
1. Correct the non-accepted words to remove the noise
2. Encode the corrected data

Data correction

Noise type	Correction operation
deletion aa**b**cad → aacad	add
insertion aabcad → aabc**b**ad	skip
transposition aabcad → aa**cb**ad	transpose
symbol repetition aabcad → aabca**a**d	deduplicate
–	follow

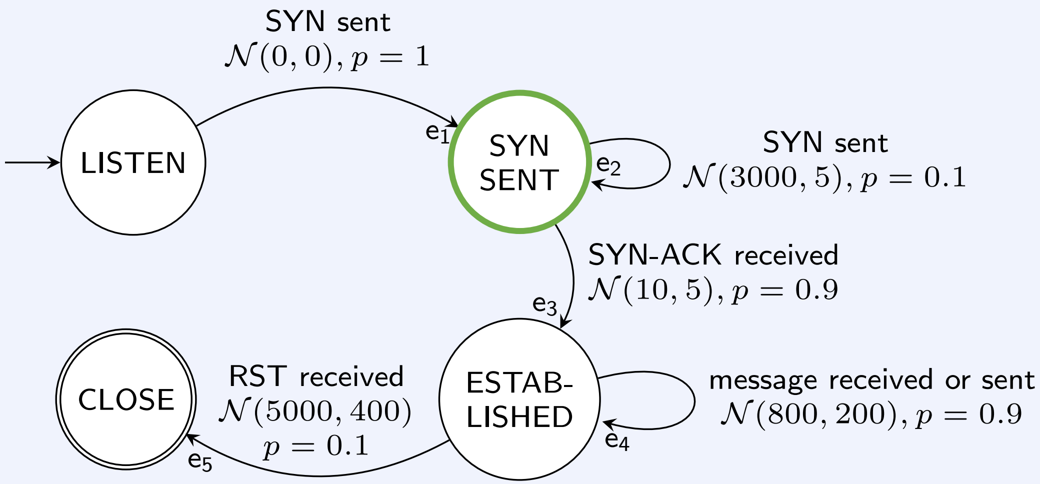
Data correction

word	edit operation sequence {operation, transition to use, delay}	corrected word
(SYN sent, 0), (ACK sent, 500), (SYN sent, 2000), (RST received, 6500)		



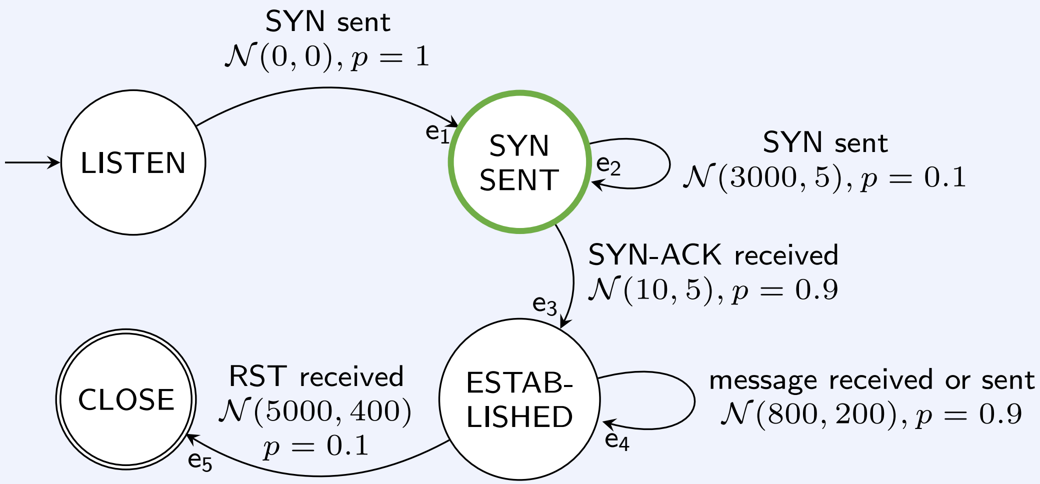
Data correction

word	edit operation sequence {operation, transition to use, delay}	corrected word
(SYN sent, 0), (ACK sent, 500), (SYN sent, 2000), (RST received, 6500)	(follow, e1 , 0),	(SYN sent, 0),



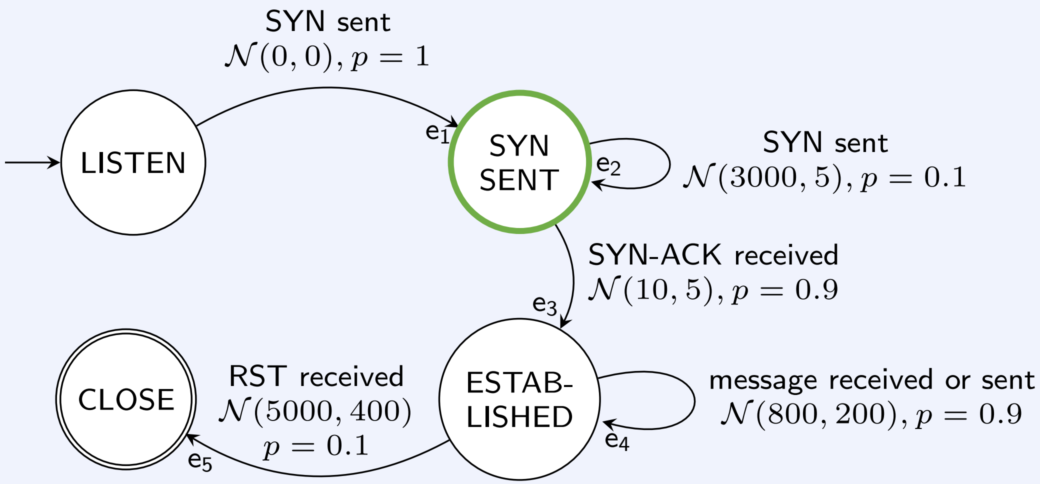
Data correction

word	edit operation sequence {operation, transition to use, delay}	corrected word
(SYN sent, 0), (ACK sent, 500), (SYN sent, 2000), (RST received, 6500)	(follow, e1 , 0), (skip, ε, 500),	(SYN sent, 0),



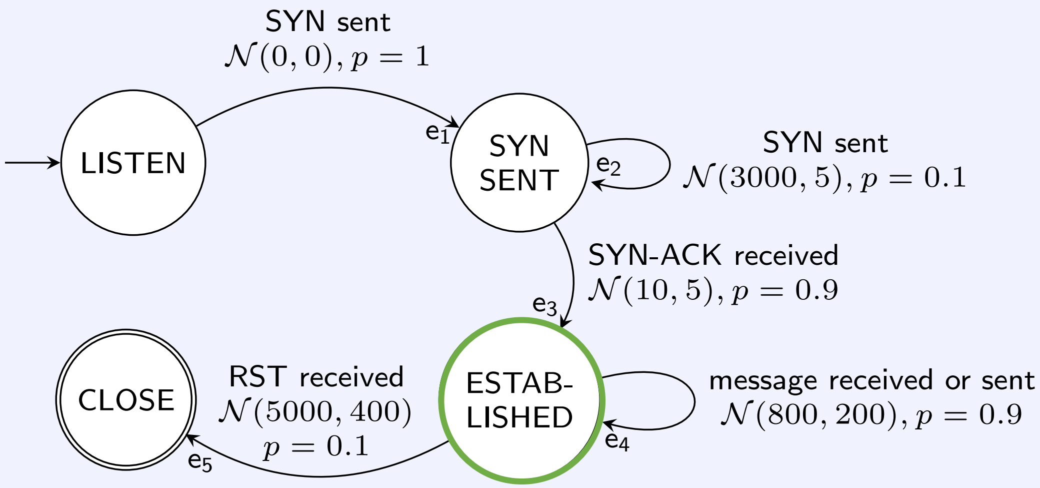
Data correction

word	edit operation sequence {operation, transition to use, delay}	corrected word
(SYN sent, 0),	(follow, e1 , 0),	(SYN sent, 0),
(ACK sent, 500),	(skip, ε, 500),	
(SYN sent, 2000),	(follow, e2 , 2000),	(SYN sent, 2000),
(RST received, 6500)		



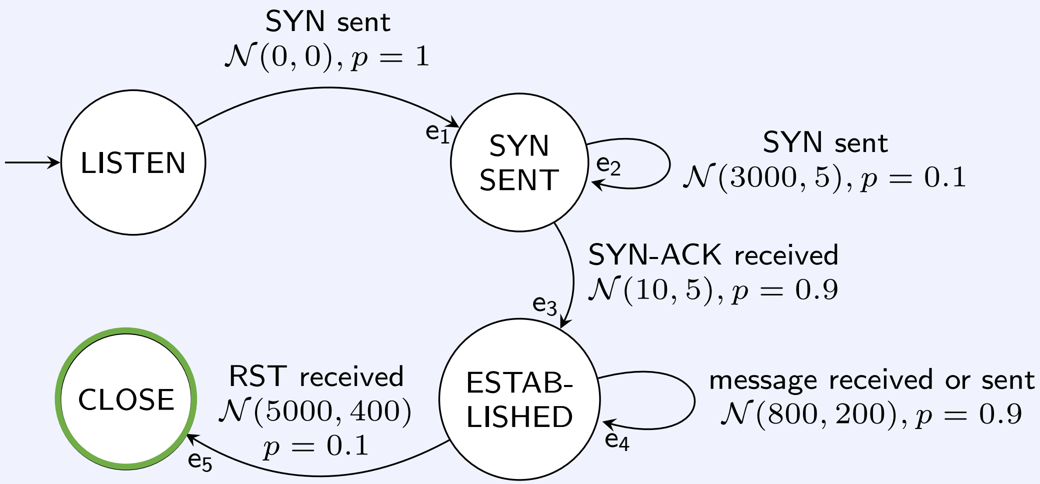
Data correction

word	edit operation sequence {operation, transition to use, delay}	corrected word
(SYN sent, 0),	(follow, e1 , 0),	(SYN sent, 0),
(ACK sent, 500),	(skip, ε, 500),	
(SYN sent, 2000),	(follow, e2 , 2000),	(SYN sent, 2000),
	(add, e3 , 10),	(SYN-ACK received, 10),
(RST received, 6500)		



Data correction

word	edit operation sequence {operation, transition to use, delay}	corrected word
(SYN sent, 0),	(follow, e1 , 0),	(SYN sent, 0),
(ACK sent, 500),	(skip, ε, 500),	
(SYN sent, 2000),	(follow, e2 , 2000),	(SYN sent, 2000),
	(add, e3 , 10),	(SYN-ACK received, 10),
(RST received, 6500)	(follow, e5 , 6500)	(RST received, 6500)



Data correction

(SYN sent, 0),(ACK sent, 500),(SYN sent, 2000),(RST received, 6500)

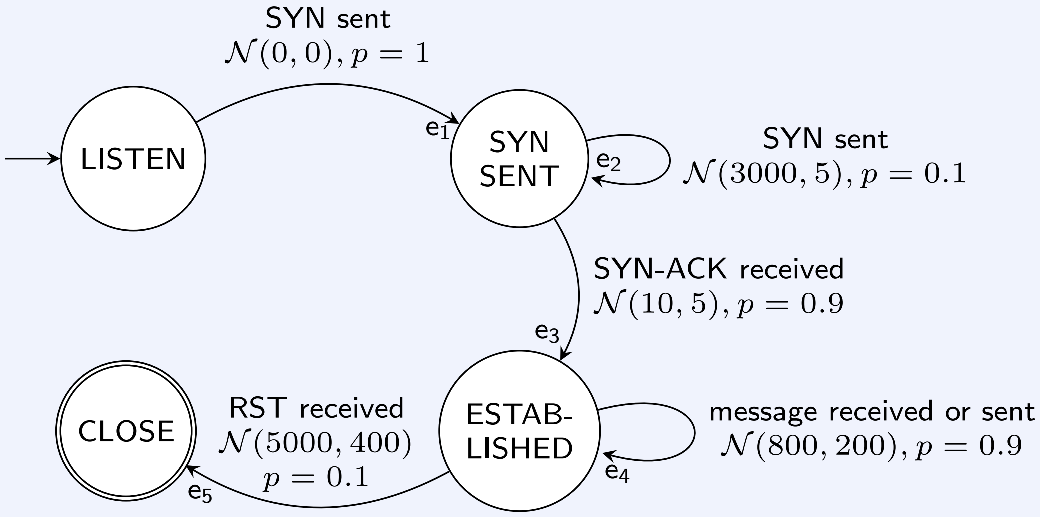
correction

(SYN sent, 0),(SYN-ACK received, 10),(RST received, 6500)

received, 10),(RST received, 6500)

...

Many correction solutions possible...



Data correction

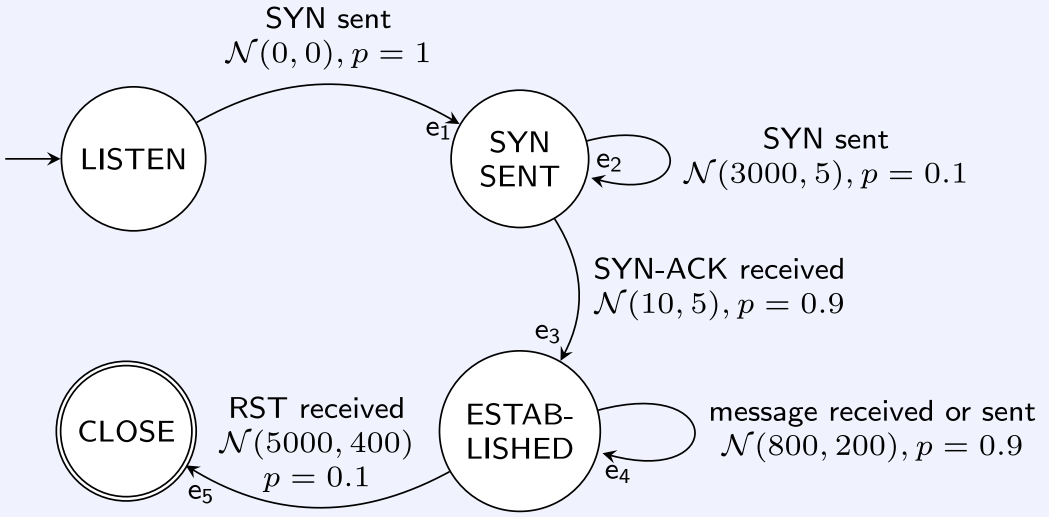
(SYN sent, 0),(ACK sent, 500),(SYN sent, 2000),(RST received, 6500)

correction

(SYN sent, 0),(SYN-ACK received, 10),(RST received, 6500)

received, 10),(RST received, 6500)

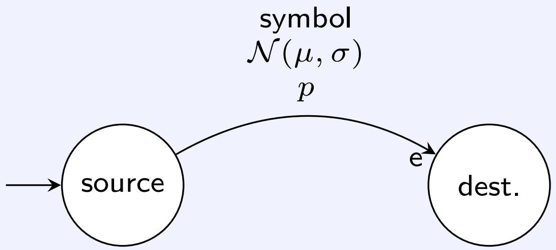
...



Many correction solutions possible…

We choose the one with the minimal description length

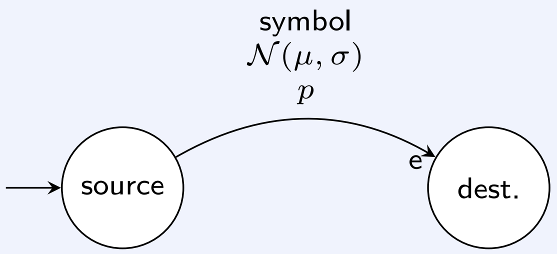
Data encoding



Cost of a followed pair (symbol, delay)

corrected with (operation, transition, delay) depends on

Data encoding



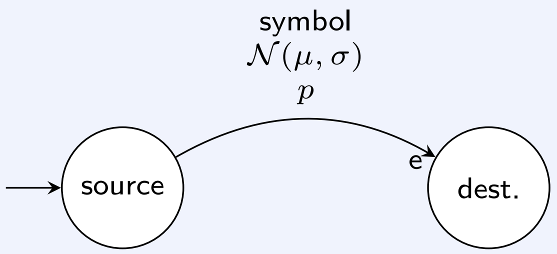
Cost of a followed pair (symbol, delay)

corrected with (operation, transition, delay) depends on

- The probability of the edit operation (follow),

$$-\log_2 p(o)$$

Data encoding



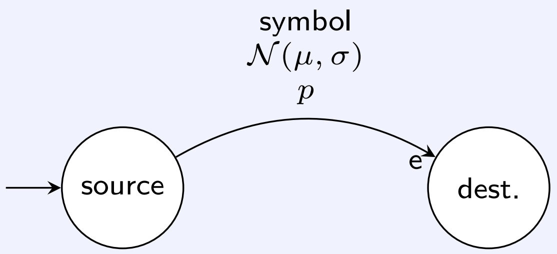
Cost of a followed pair (symbol, delay)

corrected with (operation, transition, delay) depends on

- The probability of the edit operation (follow),
- The probability of the transition given the current state,

$$-\log_2 p(o) - \log_2 p(e|q_s(e))$$

Data encoding



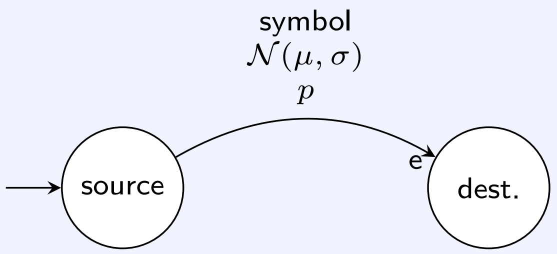
Cost of a followed pair (symbol, delay)

corrected with (operation, transition, delay) depends on

- The probability of the edit operation (follow),
- The probability of the transition given the current state,
- The probability of the delay given the transition guard's parameters.

$$-\log_2 p(o) - \log_2 p(e|q_s(e)) - \log_2 p(d|e)$$

Data encoding



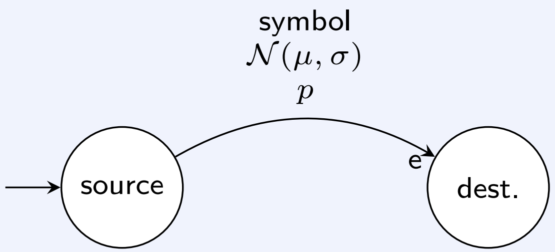
Cost of a transposed pair (symbol, delay)

corrected with (operation, transition, delay) depends on

- The probability of the edit operation (transpose),
- The probability of the transition given the current state,
- The probability of the delay given the transition guard's parameters.

$$-\log_2 p(o) - \log_2 p(e|q_s(e)) - \log_2 p(d|e)$$

Data encoding



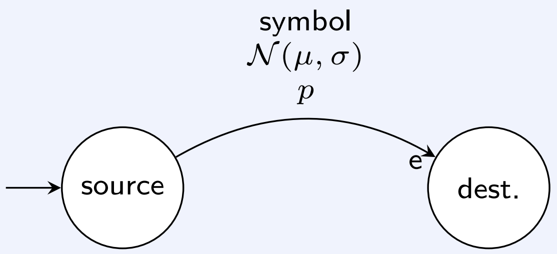
Cost of an added pair (symbol, delay)

corrected with (operation, transition, delay) depends on

- The probability of the edit operation (add),
- The probability of the transition given the current state,
- ~~The probability of the delay given the transition guard's parameters.~~

$$-\log_2 p(o) - \log_2 p(e|q_s(e))$$

Data encoding



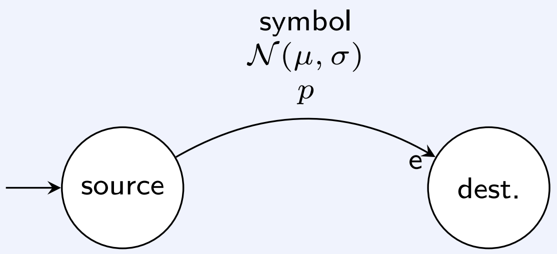
Cost of a deduplicated pair (symbol, delay)

corrected with (operation, transition, delay) depends on

- The probability of the edit operation (deduplicate),
- ~~The probability of the transition given the current state,~~
- The probability of the delay given the transition guard's parameters.

$$-\log_2 p(o) - \log_2 p(d|e)$$

Data encoding



Cost of a skipped pair (symbol, delay) corrected with (operation, ε, delay) depends on

- The probability of the edit operation (skip),
- ~~The probability of the transition given the current state,~~
- ~~The probability of the delay given the transition guard's parameters.~~
- The cost of explicitly encoding the delay and the symbol.

$$-\log_2 p(o) + L_{\mathbb{N}}(d) + \log_2 |\Sigma|$$

Question

How to find the automaton with the minimal MDL cost?

TADAM: MDL-based automata learning

Initialize an automaton $\hat{\mathcal{A}}$ with the data $\mathcal{D}$

Generate candidate automata by transforming $\hat{\mathcal{A}}$

For each candidate automaton $\mathcal{A}$

Correct $\mathcal{D}$ given $\mathcal{A}$

Compute the cost $L(\mathcal{A}, \mathcal{D})$

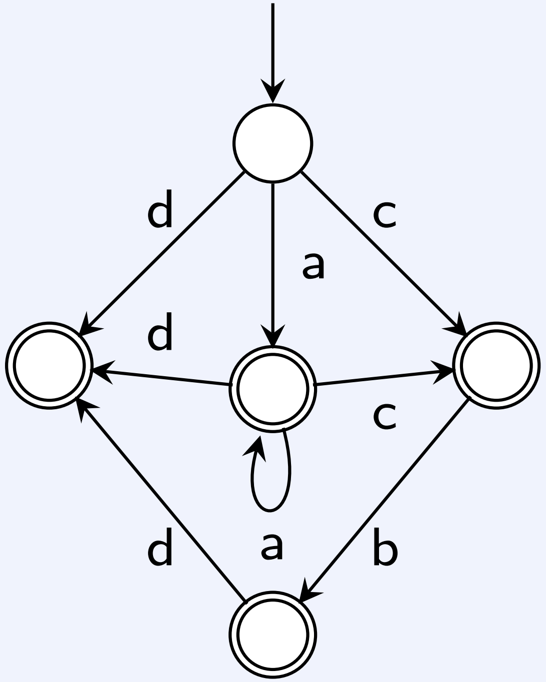
Select the automaton with minimal cost as $\hat{\mathcal{A}}$

Return $\hat{\mathcal{A}}$ when the cost doesn't descrease anymore

Initialization

Markov initialization

a c b
a d
c b a c
a c a
d a a
c b d



guards and probabilities omitted

Candidate automata generation

Automaton transformation operations:

- Location merge
- Location split
- Subpart deletion

One candidate per possible transformation and position in the automaton

Location merge

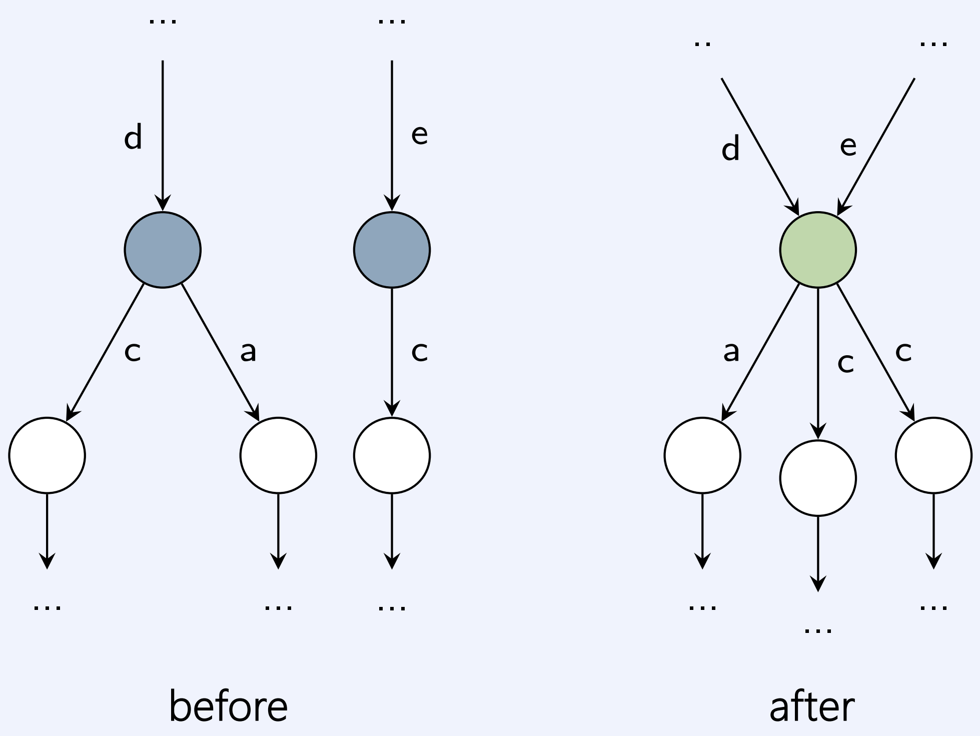
Goal:

Reducing the size of the automaton and generalize the model

(reduces the model cost)

Side effect:

Increases the data cost



guards and probabilities omitted

Location split

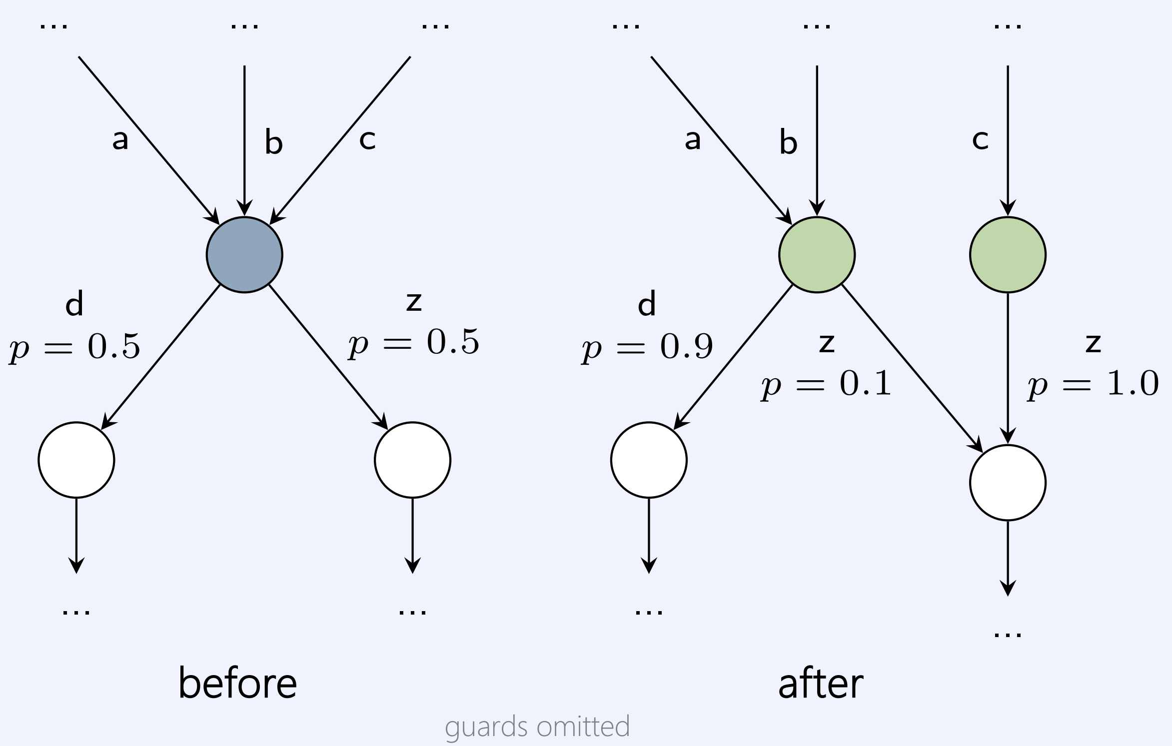
Goal:

Reducing the entropy of the "next triggered transition" at a given location

(reduces the data cost)

Side effect:

Increases the model cost



Subpart deletion

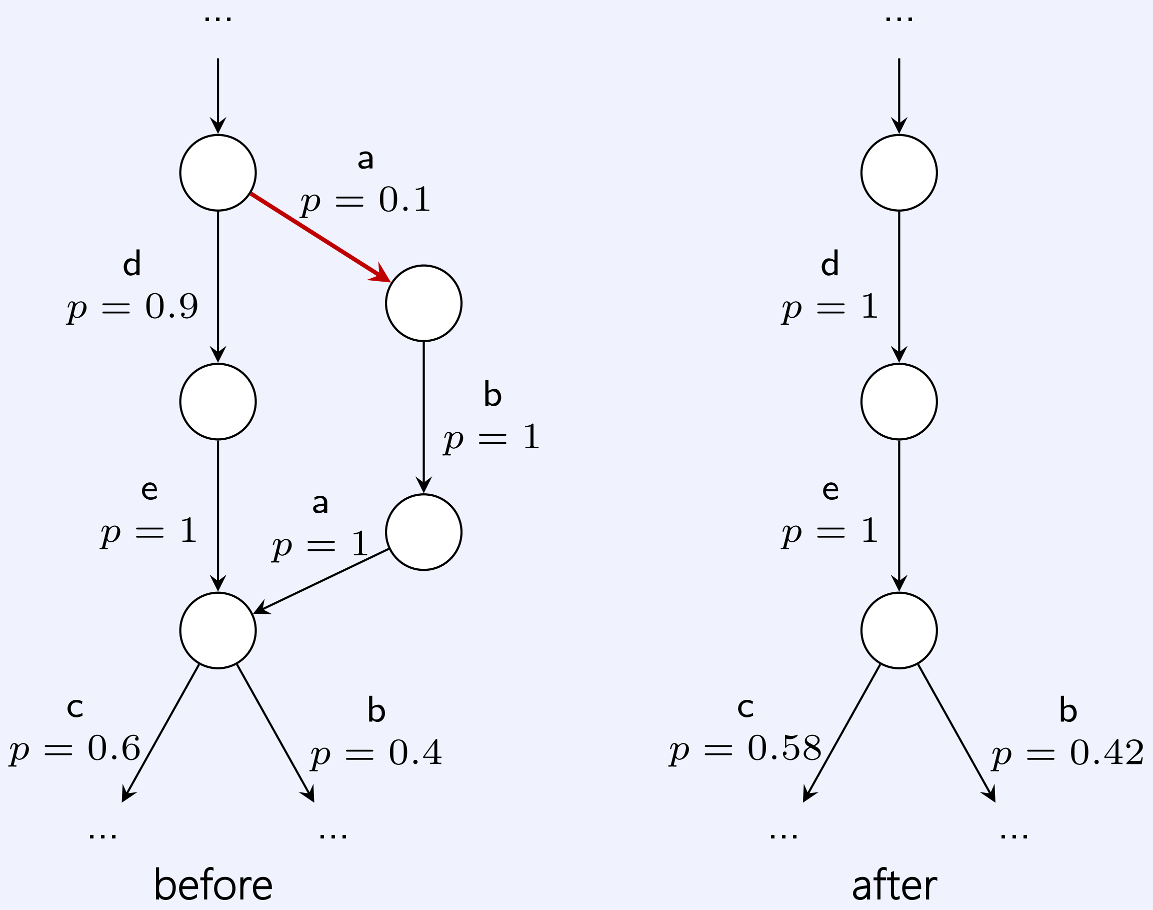
Goal:

Reducing the size of the automaton

(reduces the model cost)

Side effect:

Increases the data cost



guards omitted

Question

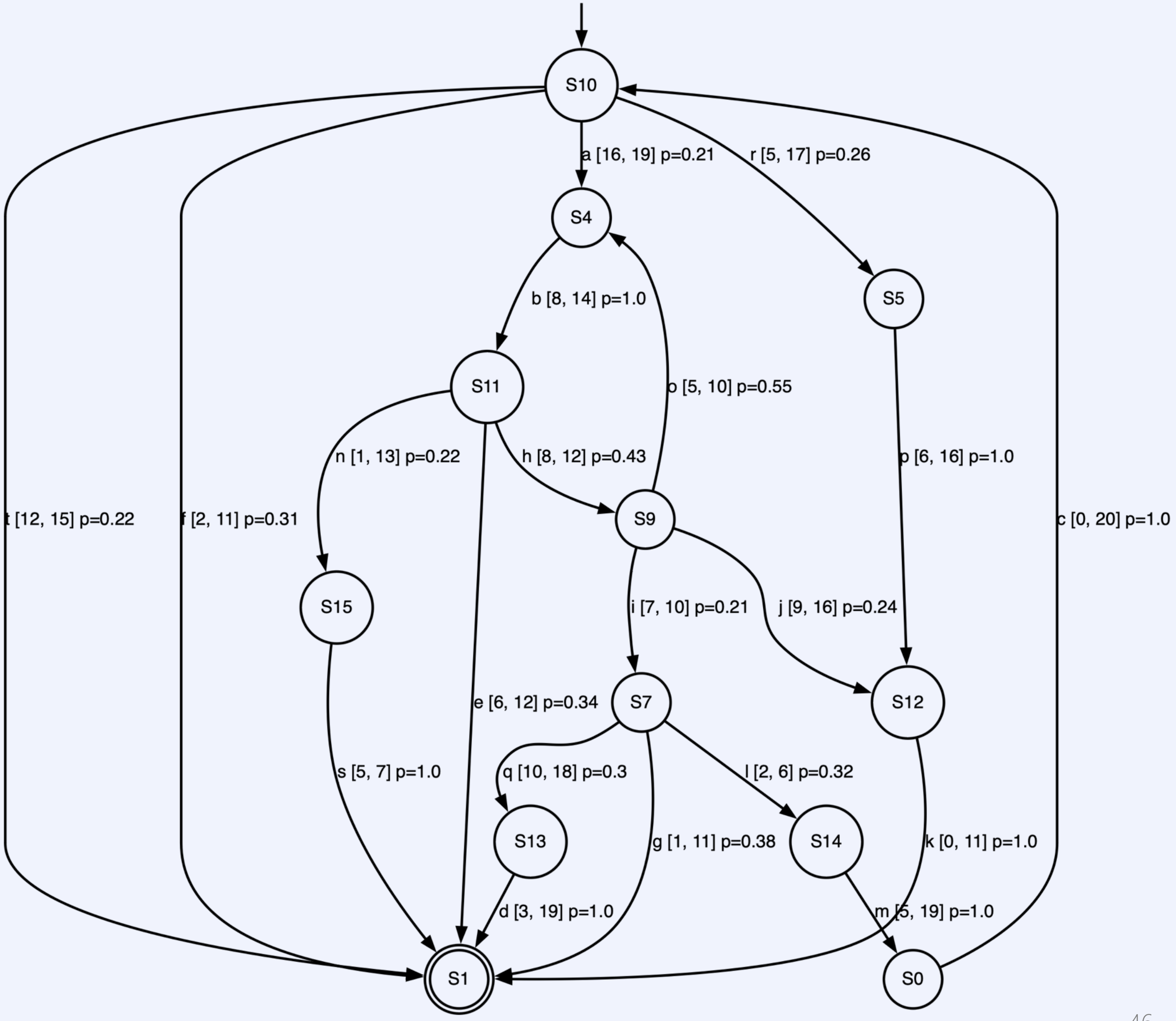
Does it work?

State of the Art

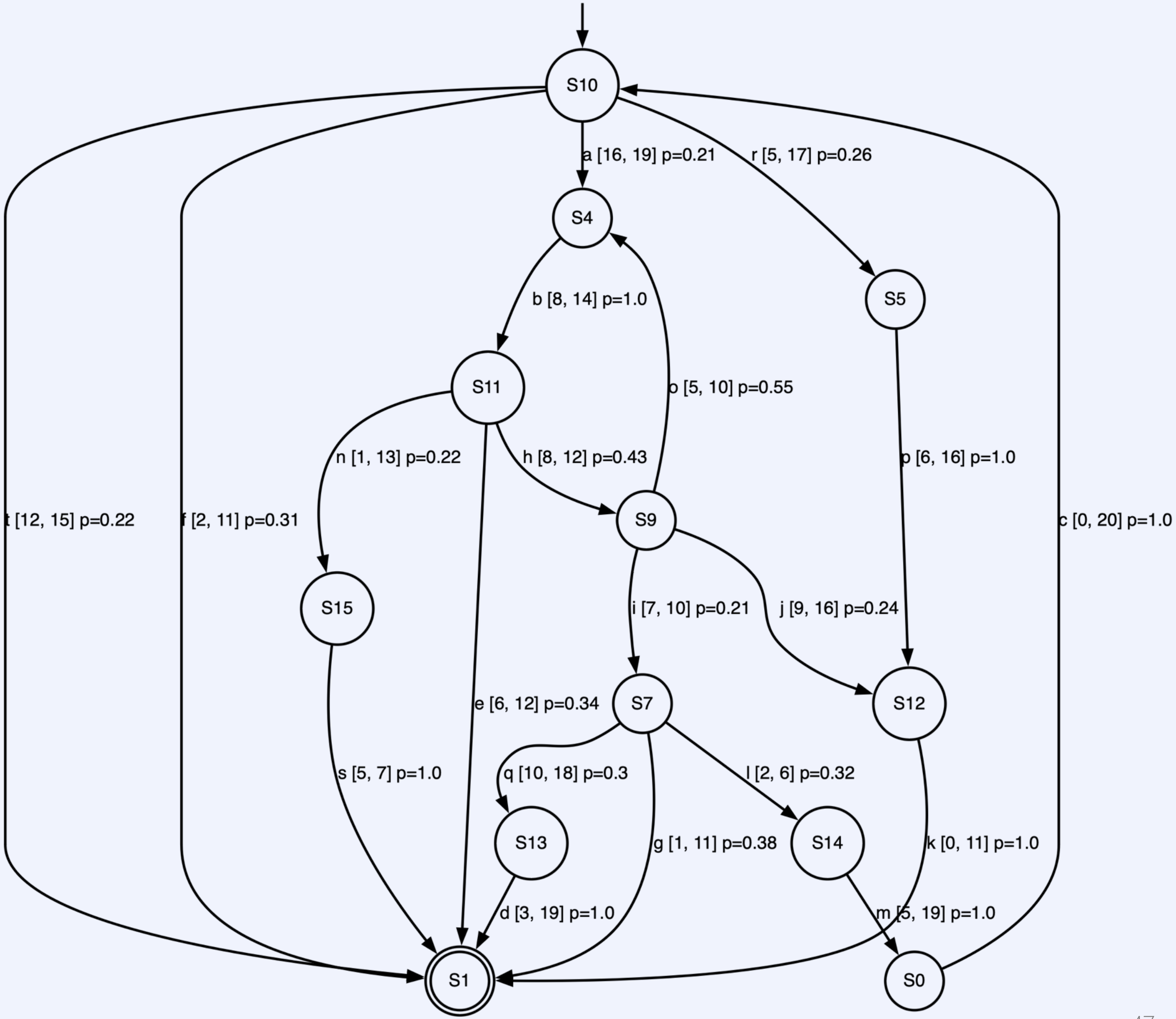
Algorithm	Strategy	Main limitation
TAG (Cornanguer et al., 2022)	Factorization on common sub-parts and location splits	
Timed k-Tail (Pastore et al., 2017)	Factorization on common sub-parts	No noise robustness strategy → requires clean data
RTI+ (Verwer et al., 2010)	Location merge based on likelihood test	

Experiments

Target automaton



Experiments



Target automaton

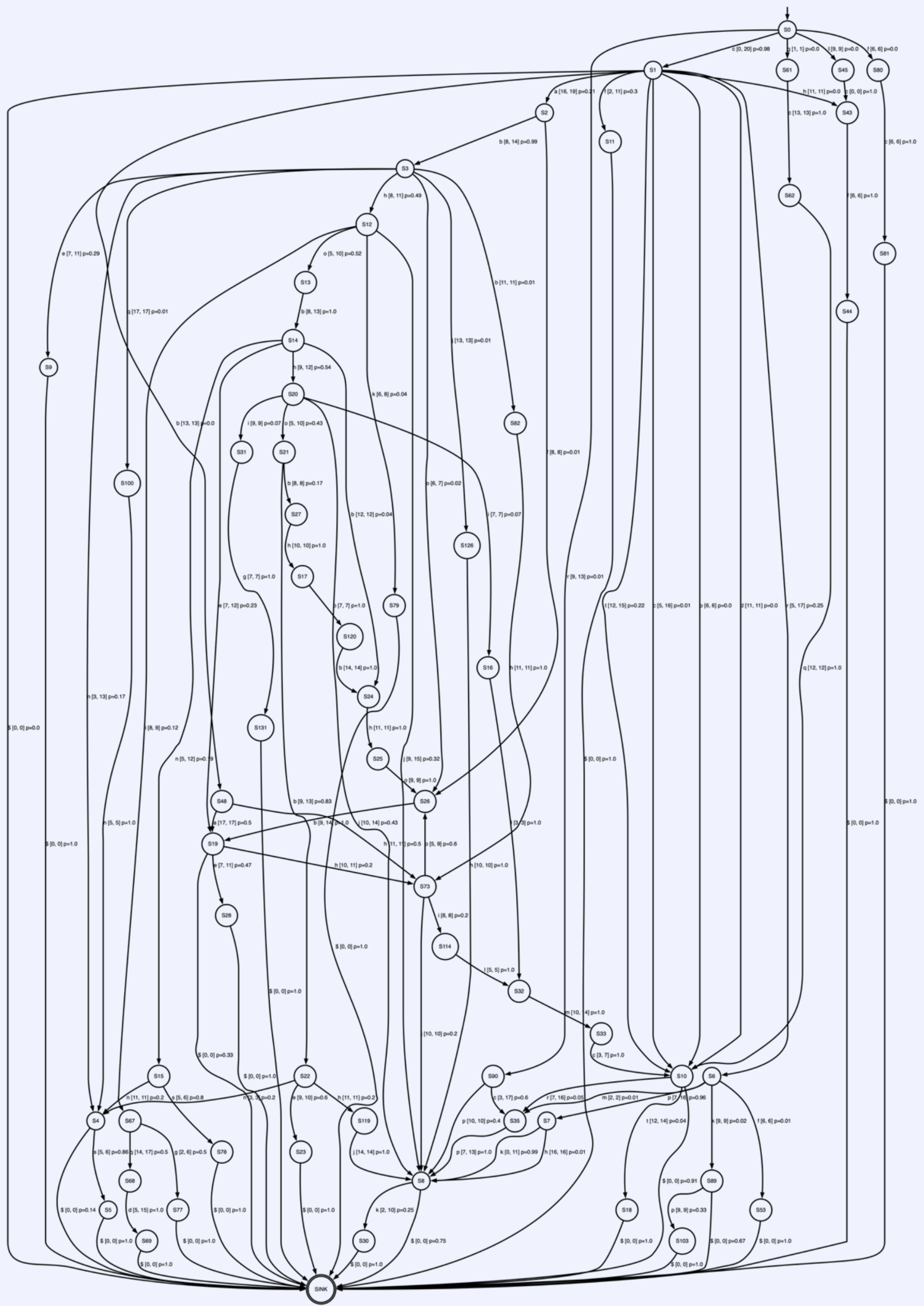
Data:

- 500 timed words
- 2,5% of noisy events

Experiments

TAG

learned automaton



Data:

- 500 timed words
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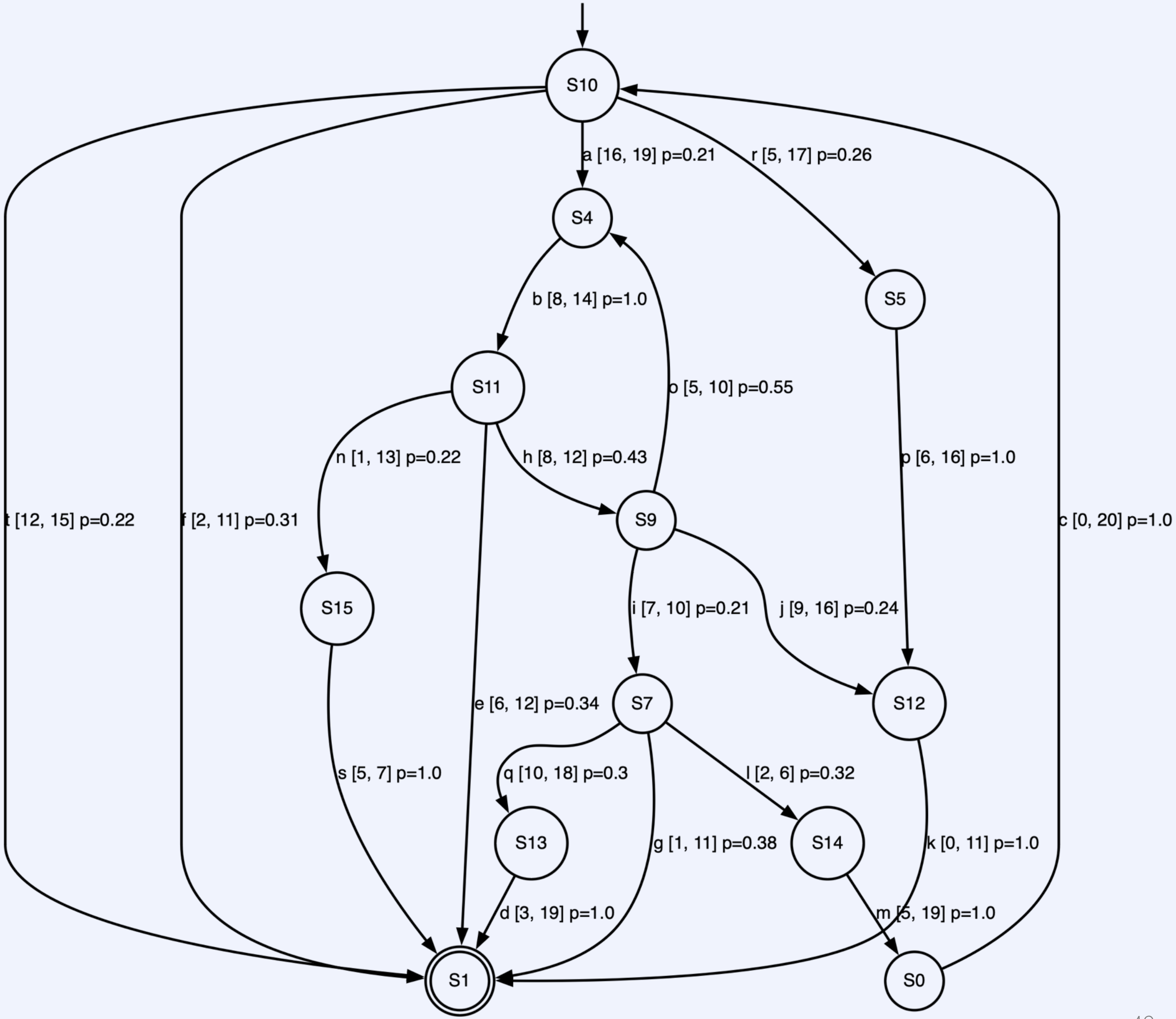
Experiments

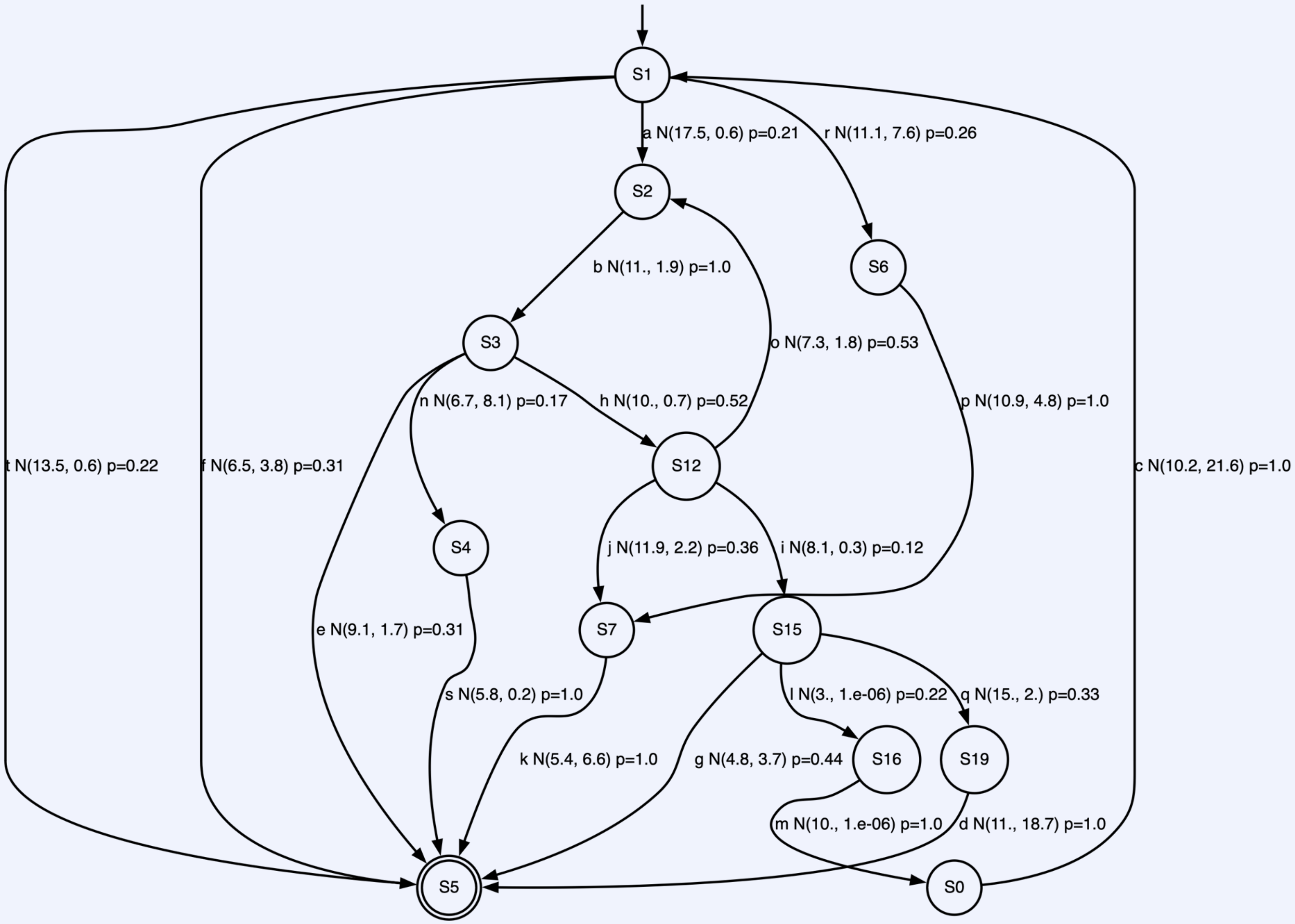
Target automaton



Experiments

TADAM

learned automaton



Data:

- 500 timed words
- 2,5% of noisy events

Experiments

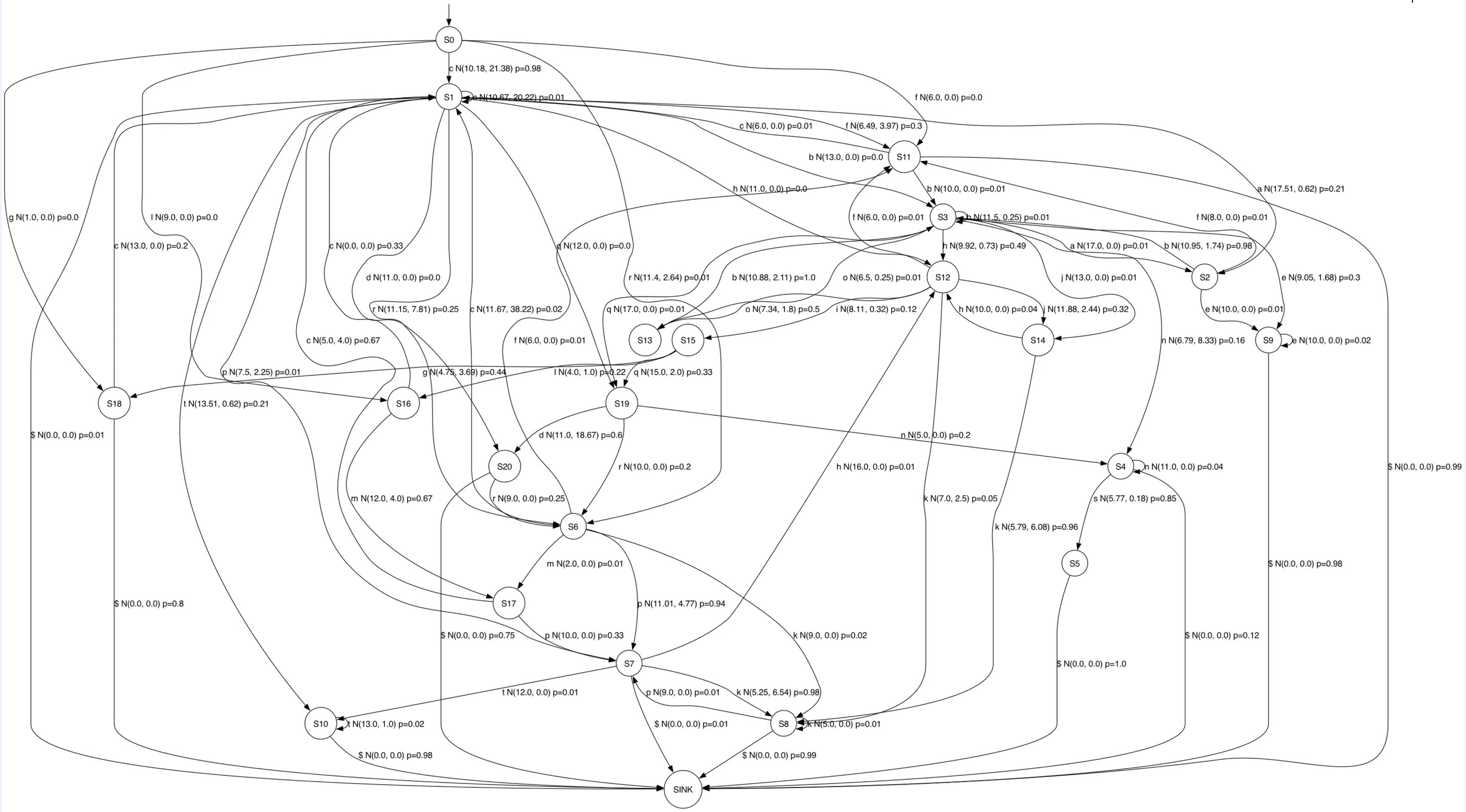
TADAM

learned automaton

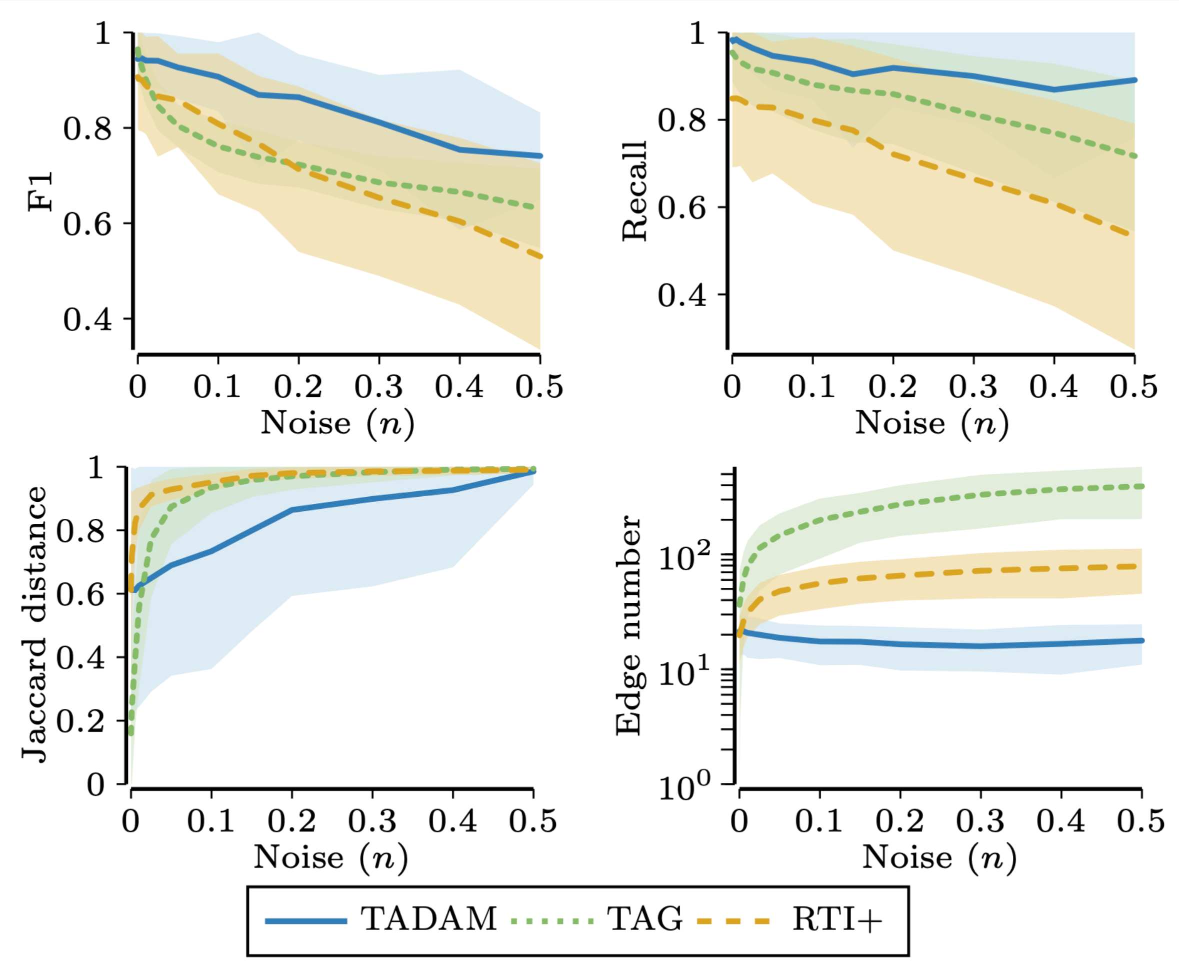
Data:

- 500 timed words
- 2,5% of noisy events

non-actual speed



Experiments



Noise robustness
on synthetic data

Experiments

	Learner	AU-ROC	TPR	FPR	F1
TA learners	TADAM	**0.982**	0.998	**0.025**	**0.705**
	TAG	0.891	**1**	0.142	0.298
	RTI+	0.790	**1**	0.292	0.171
	Hidden Markov Model	0.608	0.640	0.085	0.288

Anomaly detection performances

on HDFS dataset[1]

1. https://github.com/ait-aecid/anomaly-detection-log-datasets

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overfit on the training data and don't generalize well

Anomaly detection performances

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Anomaly detection performances

on HDFS dataset[1]

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Conclusions

Contributions:

- A compression-based (MDL) score to avoid overfitting
- An explicit modelization of the noise

Experiments show that TADAM

- is far more robust to noise
- learns smaller models
- has better performances on real-world classification and anomaly detection tasks

Thank you!

Contributions:

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Fos-R/TADAM

`pip install tadam-learner`

Experiments show that TADAM

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- learns smaller models
- has better performances on real-world classification and anomaly detection tasks