# Scalable Complex Event Recognition

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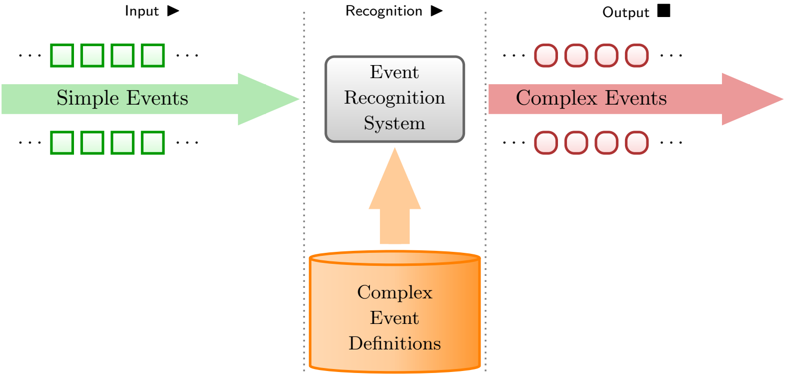
# Complex Event Recognition



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Temporal frameworks:

- Event Calculus: Reasoning about events and their effects.
- Event Calculus for Run-Time Reasoning (RTEC): EC with optimization techniques for CER.

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Contributions:

- $RTEC_{inc}$: Incremental RTEC (the *what*).
- tensor-EC: Tensor-based formalization of EC (the *how*).

# Publications

Journal Publications:

- Tsilionis E., Artikis A., Paliouras G., Incremental Event Calculus for Run-Time Reasoning. In *Journal of Artificial Intelligence Research (JAIR)*, 73, pp. 967—1023, 2022.
- Tsilionis E., Koutroumanis N., Nikitopoulos P., Doulkeridis C. and Artikis A., Online Event Recognition from Moving Vehicles. In *Theory and Practice of Logic Programming (TPLP)*, 19(5-6), pp. 841—856, 2019.

Conference Publications:

- Tsilionis E., Artikis A., Paliouras G., A Tensor-Based Formalization of the Event Calculus. In *Proceedings of the Thirty-Third International Joint Conference on Artificial Intelligence, IJCAI-24*, pp. 3584–3592, 2024.
- Tsilionis E., Artikis A., Paliouras G., Incremental Event Calculus for Run-Time Reasoning (Extended Abstract). In *Proceedings of the Thirty-Second International Joint Conference on Artificial Intelligence, IJCAI–23*, pp. 6974-6978, 2023.
- Tsilionis E., Artikis A. and Paliouras G., Incremental Event Calculus for Run-Time Reasoning. In *13th International Conference on Distributed and Event-Based Systems (DEBS)*, pp. 79–90, 2019.

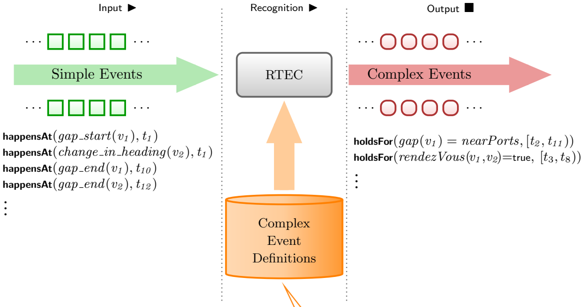
# Background

## Event Calculus

- A logic programming language for representing and reasoning about events and their effects.
- Key components:
  - event (typically instantaneous).
  - fluent: a property that may have different values at different points in time.
- Built-in representation of inertia:
  - $F = V$ holds at a particular time-point if $F = V$ has been *initiated* by an event at some earlier time-point, and not *terminated* by another event in the meantime.

# Background

## Run-Time Event Calculus (RTEC)



$\textsf{happensAt}(\mathit{gap\_start}(v_1), t_1)$
$\textsf{happensAt}(\mathit{change\_in\_heading}(v_2), t_1)$
$\textsf{happensAt}(\mathit{gap\_end}(v_1), t_{10})$
$\textsf{happensAt}(\mathit{gap\_end}(v_2), t_{12})$
$\vdots$

$\textsf{holdsFor}(\mathit{gap}(v_1) = \mathit{nearPorts}, [t_2, t_{11}])$
$\textsf{holdsFor}(\mathit{rendezVous}(v_1, v_2){=}\textsf{true},\ [t_3, t_8])$
$\vdots$

**Simple Fluents**

$$
\begin{aligned}
&\textsf{initiatedAt}(\mathit{gap}(\mathit{Vessel}) = \mathit{nearPorts},\ T) \leftarrow\\
&\quad \textsf{happensAt}(\mathit{gap\_start}(\mathit{Vessel}),\ T),\\
&\quad \textsf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearPorts}) = \textsf{true},\ T).
\end{aligned}
$$

$$
\begin{aligned}
&\textsf{terminatedAt}(\mathit{gap}(\mathit{Vessel}) = \_\mathit{Value},\ T) \leftarrow\\
&\quad \textsf{happensAt}(\mathit{gap\_end}(\mathit{Vessel}),\ T).
\end{aligned}
$$

**Statically Determined Fluents**

$$
\begin{aligned}
&\textsf{holdsFor}(\mathit{rendezVous}(\mathit{Vessel}_1, \mathit{Vessel}_2){=}\textsf{true},\ I) \leftarrow\\
&\quad \textsf{holdsFor}(\mathit{proximity}(\mathit{Vessel}_1, \mathit{Vessel}_2){=}\textsf{true},\ I_p),\\
&\quad \textsf{holdsFor}(\mathit{lowSpeed}(\mathit{Vessel}_1){=}\textsf{true},\ I_{l1}),\\
&\quad \textsf{holdsFor}(\mathit{lowSpeed}(\mathit{Vessel}_2){=}\textsf{true},\ I_{l2}),\\
&\quad \textsf{holdsFor}(\mathit{stopped}(\mathit{Vessel}_1){=}\mathit{farFromPorts},\ I_{s1}),\\
&\quad \textsf{holdsFor}(\mathit{stopped}(\mathit{Vessel}_2){=}\mathit{farFromPorts},\ I_{s2}),\\
&\quad \textsf{union\_all}([I_{l1}, I_{s1}],\ I_1),\\
&\quad \textsf{union\_all}([I_{l2}, I_{s2}],\ I_2),\\
&\quad \textsf{intersect\_all}([I_1, I_2, I_p],\ I).
\end{aligned}
$$

# Simple Fluent: Communication Gap Far From Ports

$$
\begin{aligned}
&\textbf{initiatedAt}(gap(Vessel){=}farFromPorts,\ T) \leftarrow\\
&\quad \textbf{happensAt}(gap\_start(Vessel),\ T),\\
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Reasoning: **holdsFor**$(gap(Vessel){=}farFromPorts,\ I)$

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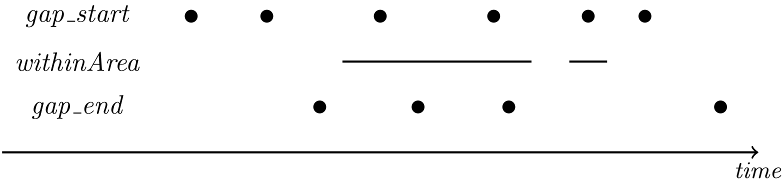

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**initiatedAt**$(gap(Vessel)=farFromPorts,\ T) \leftarrow$

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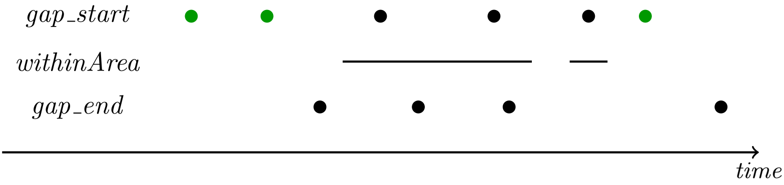

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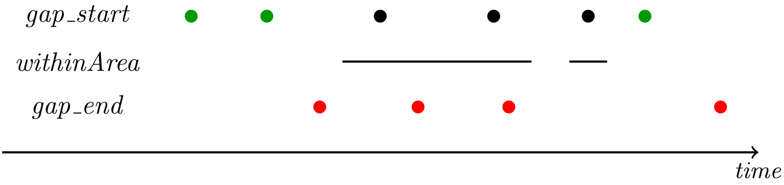

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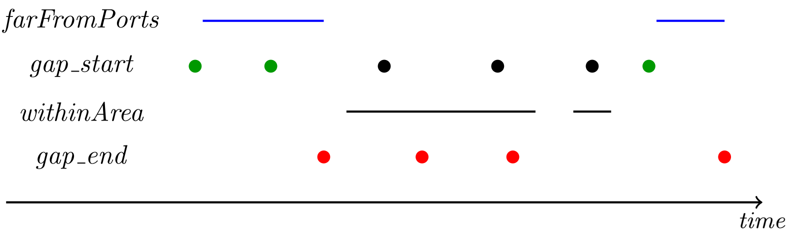
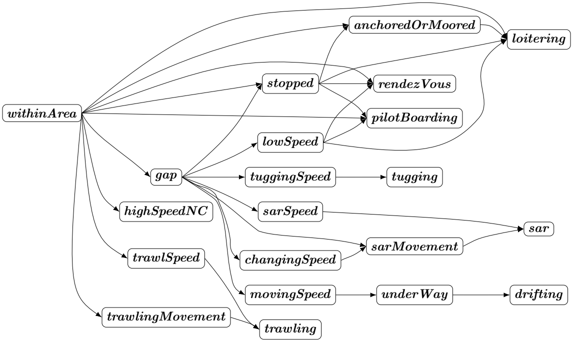


# Hierarchical Event Descriptions



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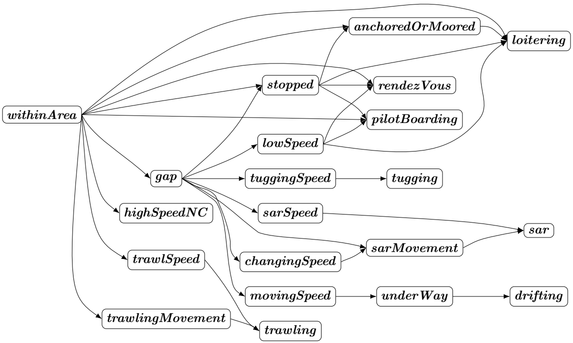
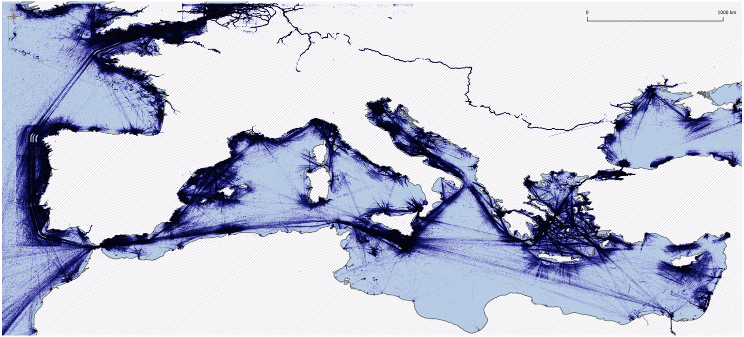


## Semantics

An event description is a locally stratified logic program, i.e., it has a **unique perfect** model.

# Part 1: Modify the *what*

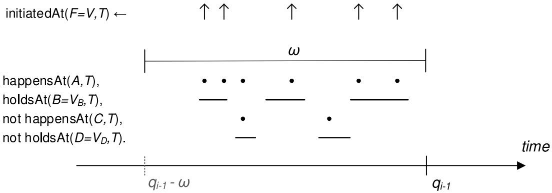
## Incremental CER



- Delayed events (e.g., satellite GPS messages)
- Overlapping temporal windows

# Problem Statement

## RTEC



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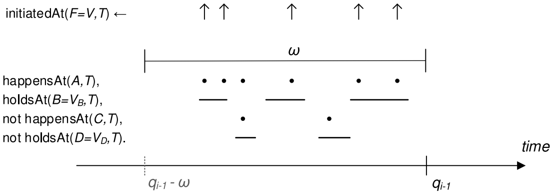

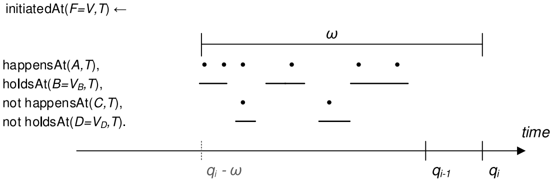

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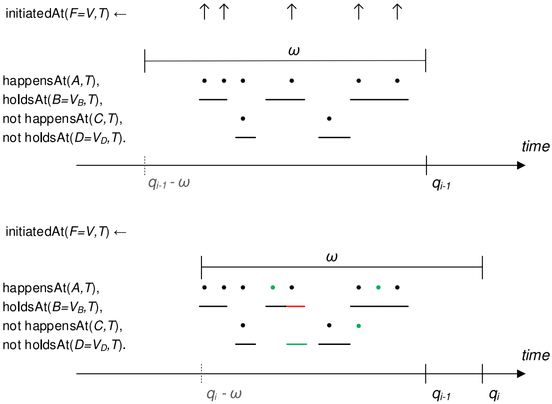

initiatedAt($F$=$V$,$T$) ←

$\omega$

happensAt($A$,$T$),

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*time*

$q_{i\text{-}1}$ - $\omega$

$q_{i\text{-}1}$

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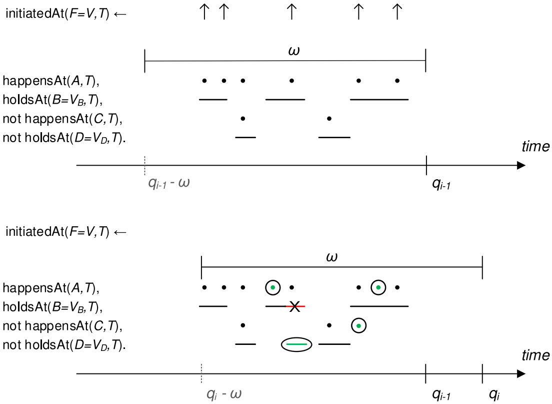
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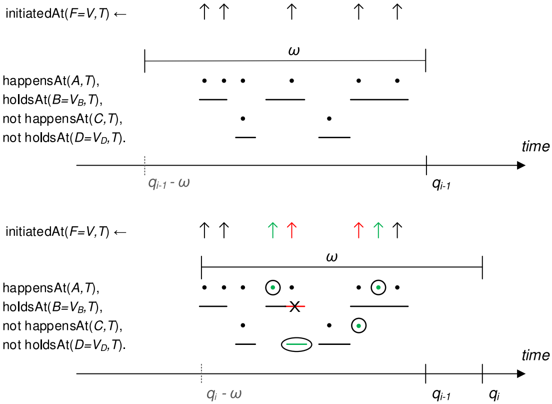

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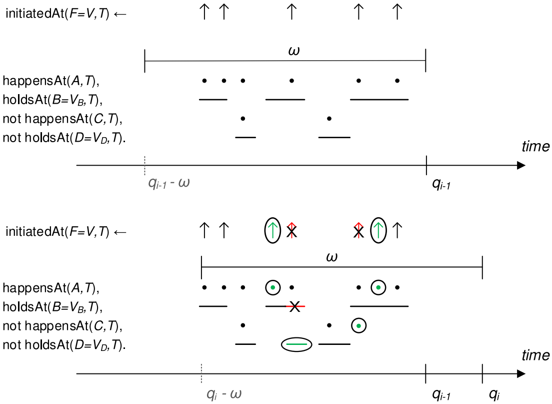
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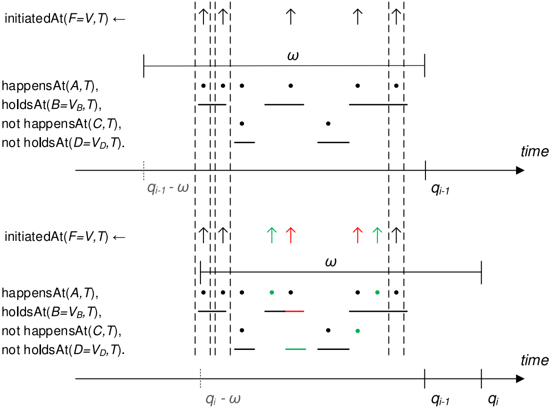

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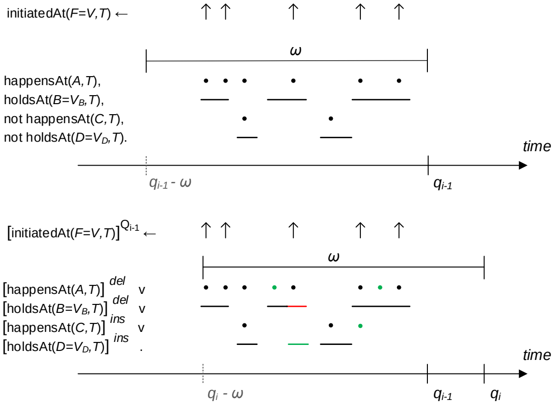

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$[\text{initiatedAt}(F{=}V,T)]^{Q_{i-1}}$ ←
$[\text{happensAt}(A,T)]^{del}$ v
$[\text{holdsAt}(B{=}V_B,T)]^{del}$ v
$[\text{happensAt}(C,T)]^{ins}$ v
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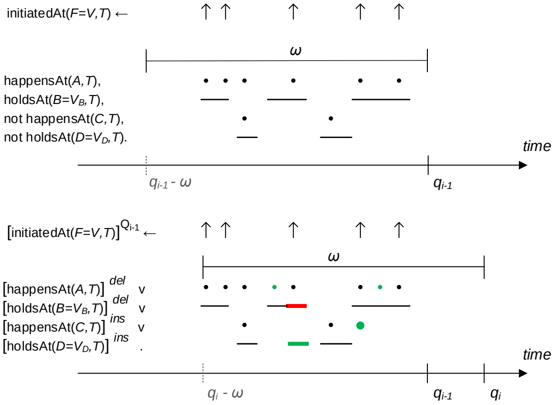

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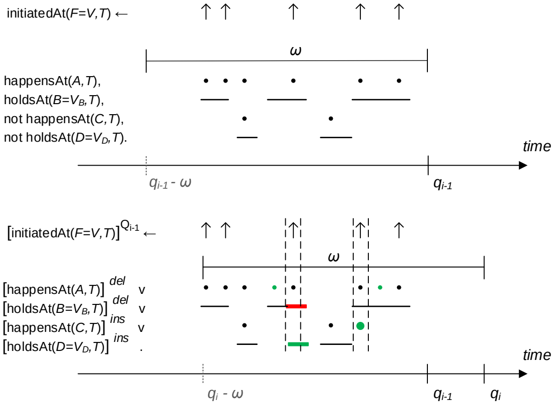

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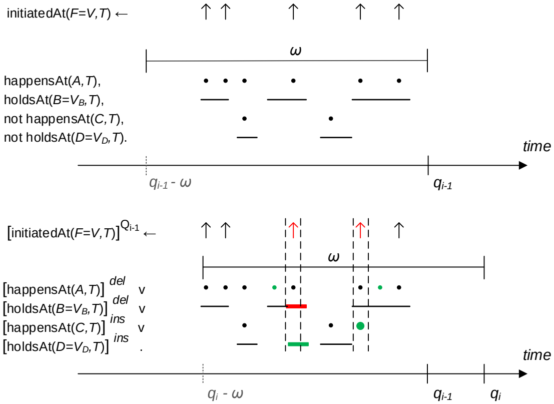

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$[\text{holdsAt}(D{=}V_D,T)]^{ins}$ .

# $RTEC_{inc}$: Addition Phase

$$\begin{aligned}
&\mathsf{initiatedAt}(F{=}V,\ T) \leftarrow \\
&\quad \Big[\mathsf{happensAt}(A,\ T)\Big]^{ins}, \\
&\quad \Big[\mathsf{holdsAt}(B{=}V_B,\ T)\Big]^{\mathsf{Q_i}}, \\
&\quad \mathsf{not}\ \Big[\mathsf{happensAt}(C,\ T)\Big]^{\mathsf{Q_i}}, \\
&\quad \mathsf{not}\ \Big[\mathsf{holdsAt}(D{=}V_D,\ T)\Big]^{\mathsf{Q_i}}.
\end{aligned} \qquad \text{(a)}$$

$$\begin{aligned}
&\mathsf{initiatedAt}(F{=}V,\ T) \leftarrow \\
&\quad \Big[\mathsf{happensAt}(A,\ T)\Big]^{\mathsf{Q_i}\setminus ins}, \\
&\quad \Big[\mathsf{holdsAt}(B{=}V_B,\ T)\Big]^{ins}, \\
&\quad \mathsf{not}\ \Big[\mathsf{happensAt}(C,\ T)\Big]^{\mathsf{Q_i}}, \\
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\end{aligned} \qquad \text{(b)}$$

$$\begin{aligned}
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&\quad \Big[\mathsf{happensAt}(A,\ T)\Big]^{\mathsf{Q_i}\setminus ins}, \\
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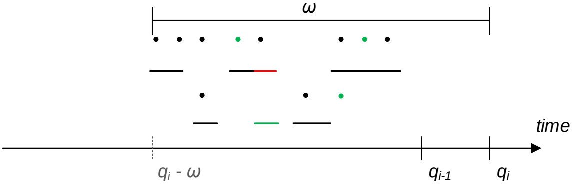
\end{aligned} \qquad \text{(d)}$$

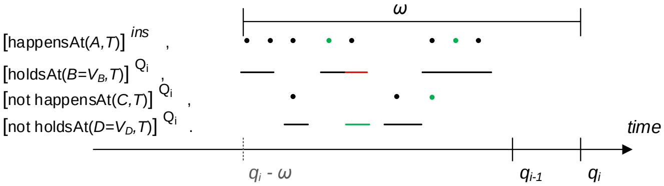
# $RTEC_{inc}$: Addition Phase

## *Delta* rule (a)



# $RTEC_{inc}$: Addition Phase

## *Delta* rule (a)



$[\text{happensAt}(A,T)]^{ins}$ ,

$[\text{holdsAt}(B=V_B,T)]^{Q_i}$ ,

$[\text{not happensAt}(C,T)]^{Q_i}$ ,

$[\text{not holdsAt}(D=V_D,T)]^{Q_i}$ .

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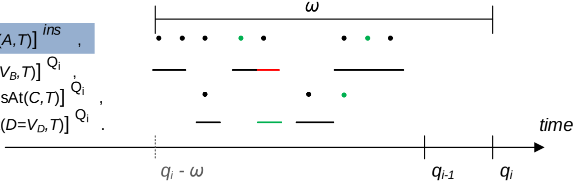

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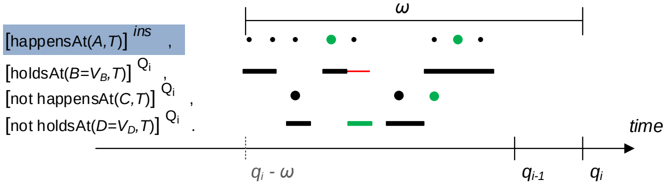

$[\text{happensAt}(A,T)]^{ins}$ ,

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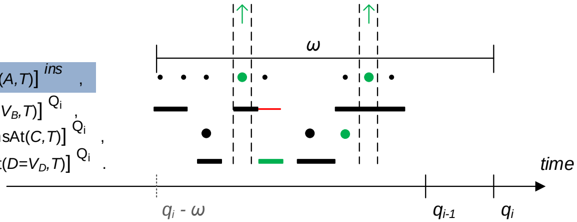

# $RTEC_{inc}$: Formal properties

**Correctness**

$RTEC_{inc}$ computes exactly the same intervals of the fluents of an event description as RTEC, and no other interval.

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### Correctness

$RTEC_{inc}$ computes exactly the same intervals of the fluents of an event description as RTEC, and no other interval.

### Complexity

The most important factor for performance improvement is the ratio of delayed insertions/retractions to the degree of overlap:

$$\frac{n \times e}{m_{\mathsf{ov}}} < 1$$

# $RTEC_{inc}$: Empirical Evaluation

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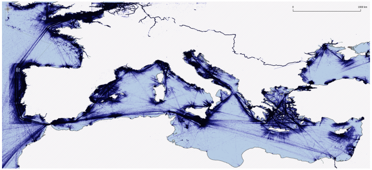

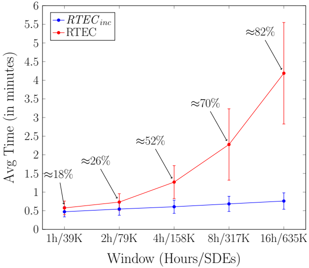

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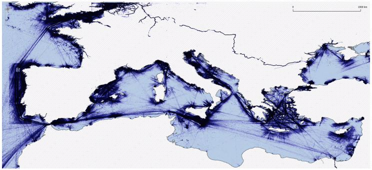

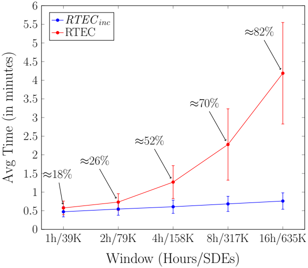

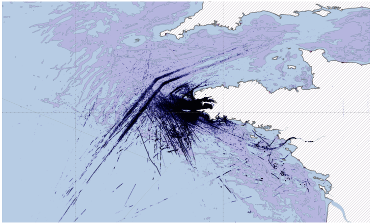

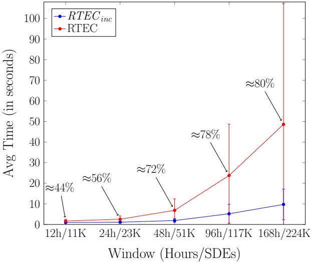

# Part 2: Modify the *how*

## Logical Inference in Tensor Spaces

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## Logical Inference in Tensor Spaces

- Numerical computation has potential to cope with Web scale data.
- Logical reasoning through algebraic operations is a step towards neuro-symbolic integration.
- Use of efficient (parallel) algorithms and great computing resources (GPUs).

# Tensor-EC: Encoding

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- Domain entities: $N$
- Window time-points: $\Omega$

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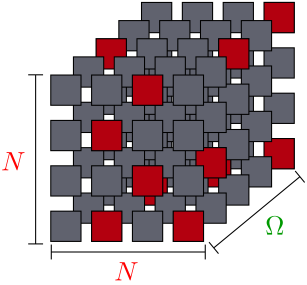

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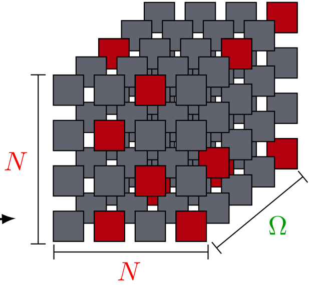
$$\underbrace{\text{happensAt}(e(X, Y),\ T)}_{r} \longrightarrow$$



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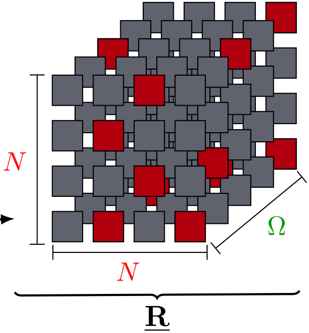

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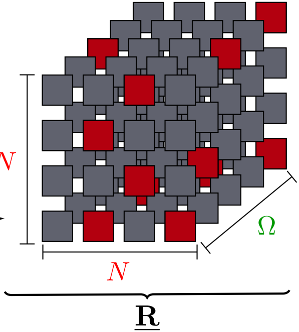

$$\underline{\mathbf{R}}_{\,i,j,k} = \begin{cases} 1, & \text{if } \mathbf{M}_P \models r, \ \text{ for } c_i, c_j, t_k \quad 🟥 \\ 0, & \text{o.w} \quad ⬛ \end{cases}$$

$$\forall\, 1 \leq i,j \leq N, 1 \leq k \leq \Omega \ .$$

# Tensor-EC: Reasoning

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**Negation**:

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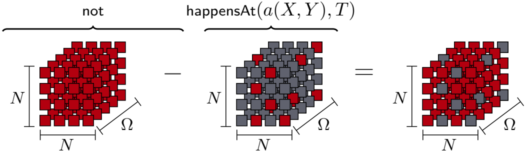

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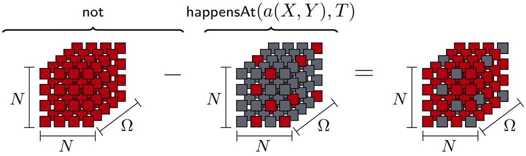

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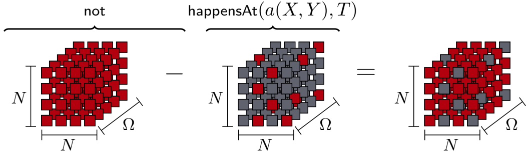

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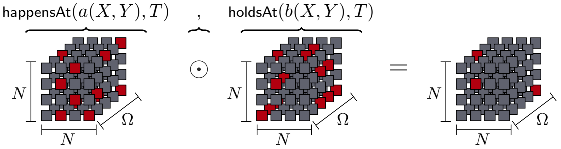

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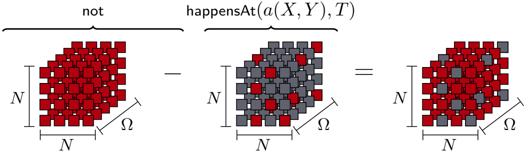

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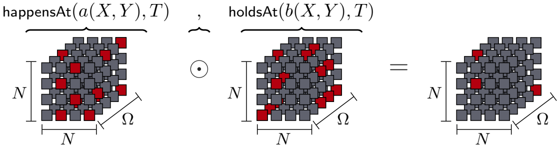

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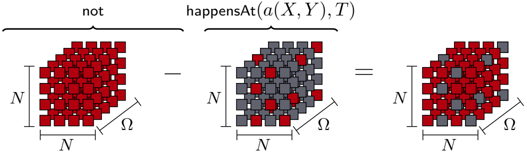

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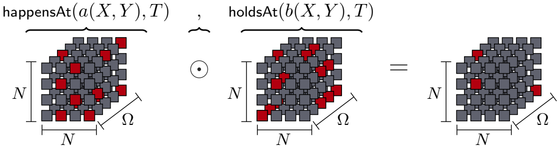

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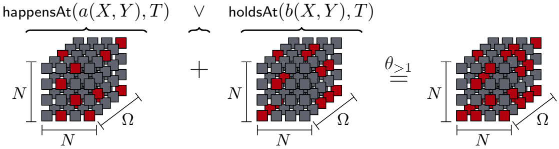

# Tensor-EC: Reasoning

## Rule Evaluation

$$
\begin{aligned}
&\mathsf{initiatedAt}\big(\mathit{fl}(X,Y)=v,\ T\big)\ \leftarrow\\
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&\quad \mathsf{holdsAt}\big(d(X,Y)=v_d,\ T\big)\ \ .
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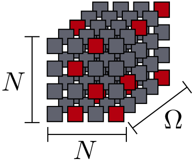

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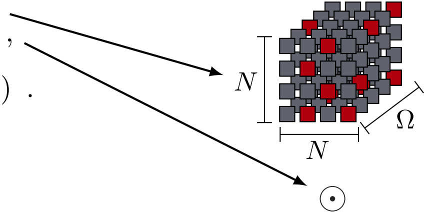

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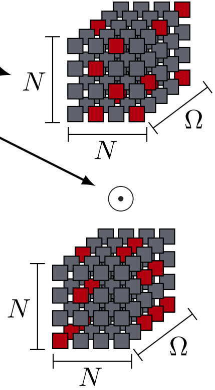

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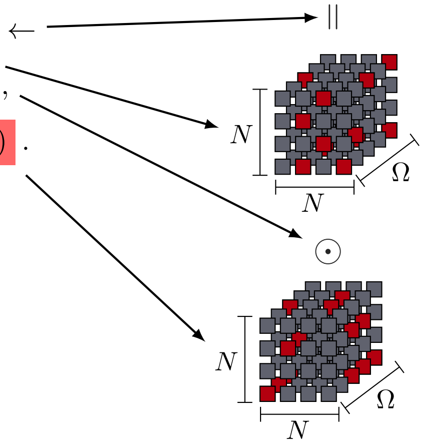

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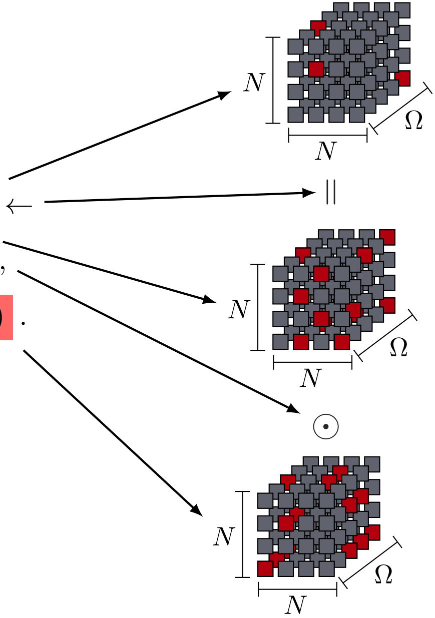

# Tensor-EC: Computing a Model

$$
\begin{array}{l}
\mathsf{holdsAt}(\mathit{fl}(X,Y){=}v,\ T) \leftarrow \\
\quad \mathsf{initiatedAt}(\mathit{fl}(X,Y){=}v,\ T_{prev}), \\
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\end{array}
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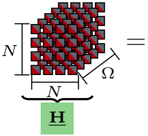

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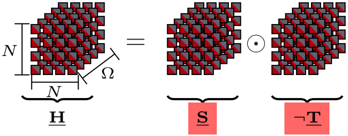

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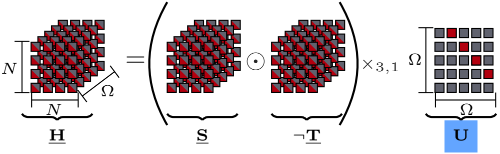

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holdsAt($fl(X, Y){=}v,\ T$) ←<br>
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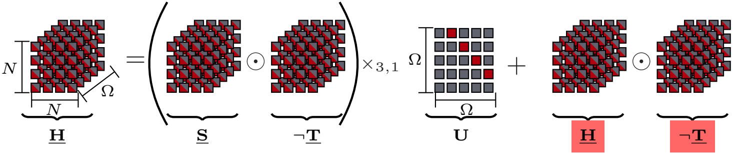

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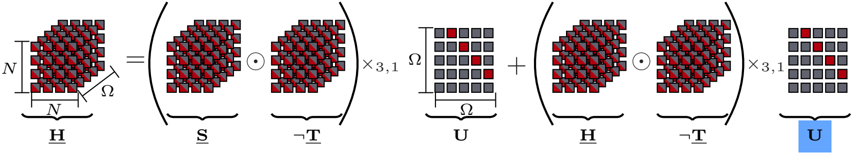

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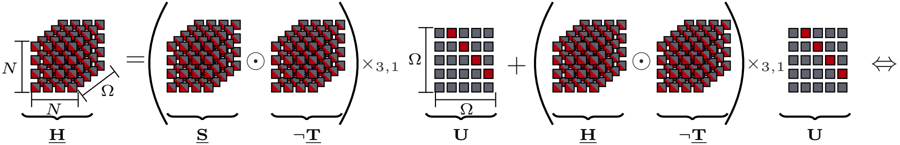

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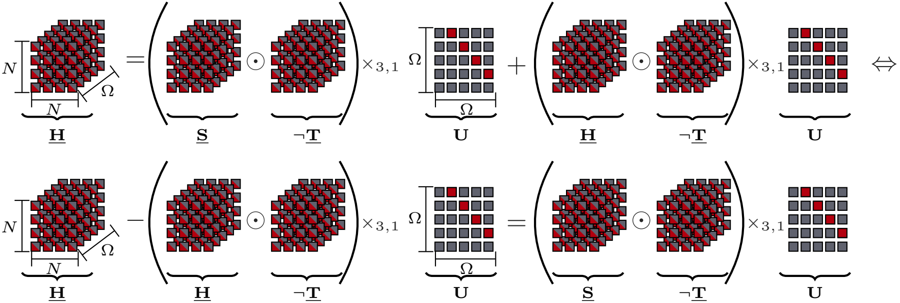

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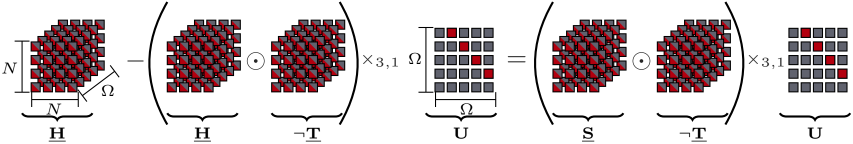

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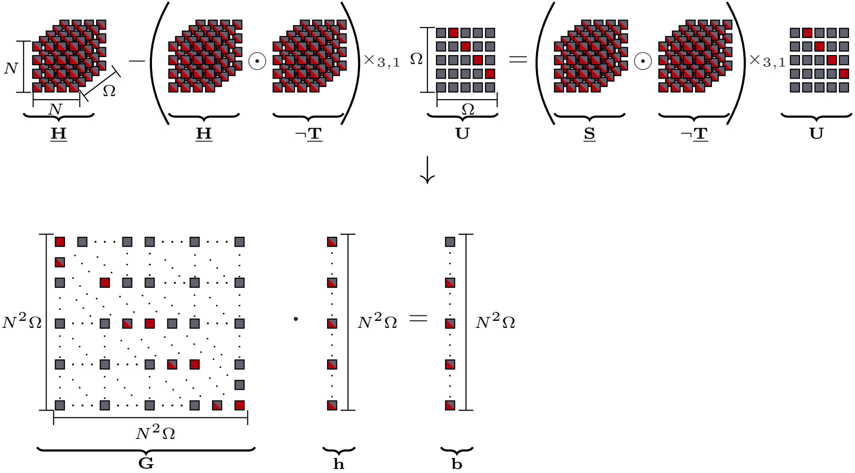

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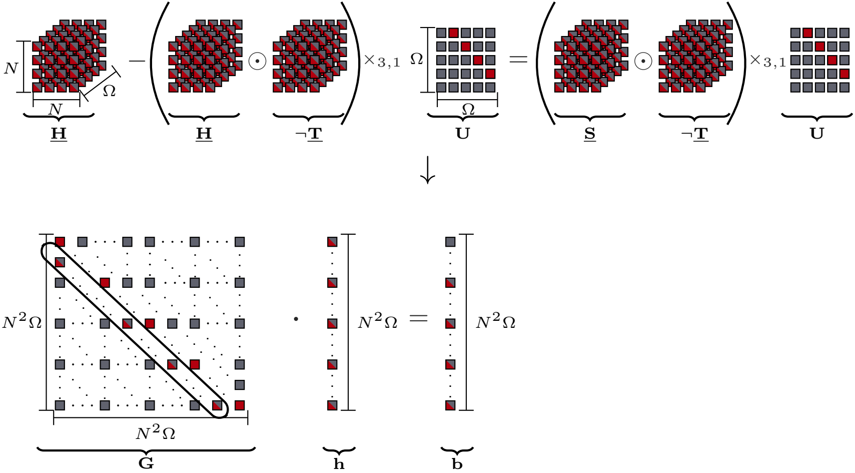

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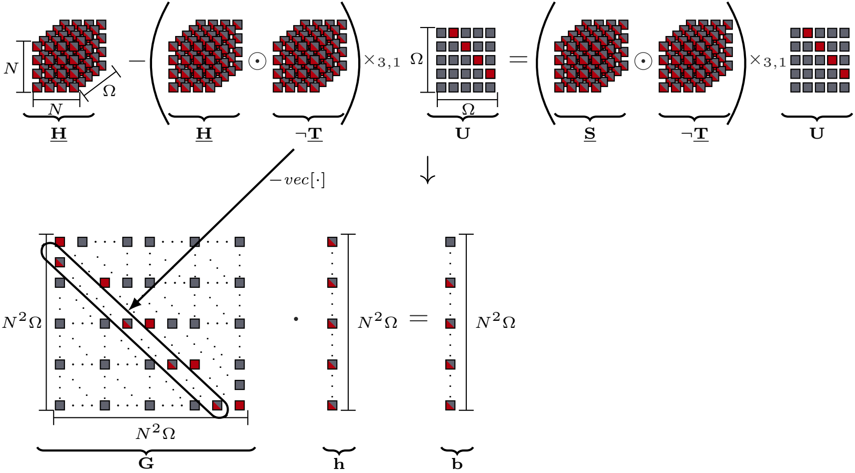

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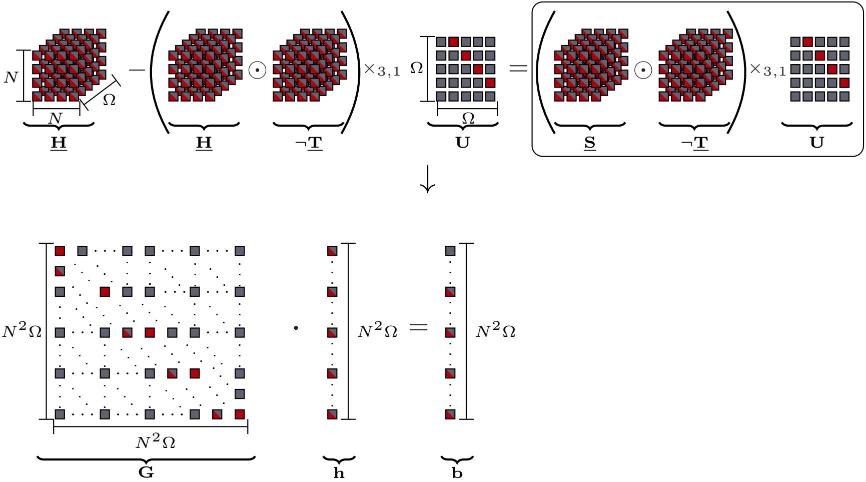

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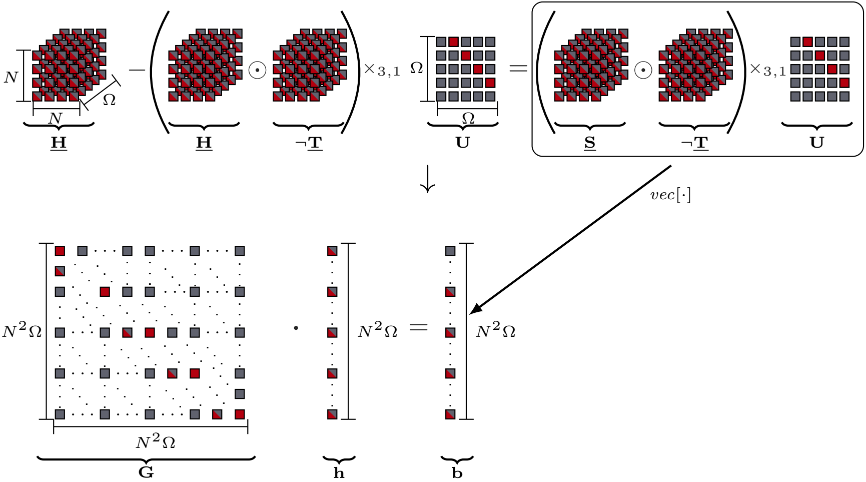

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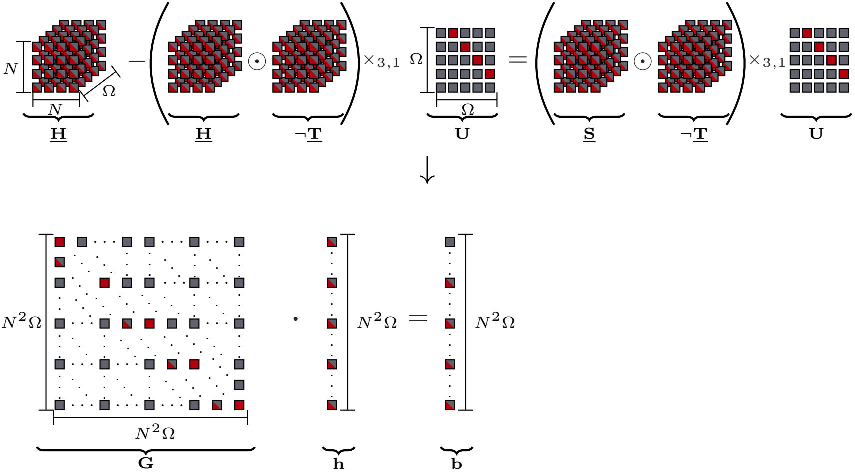

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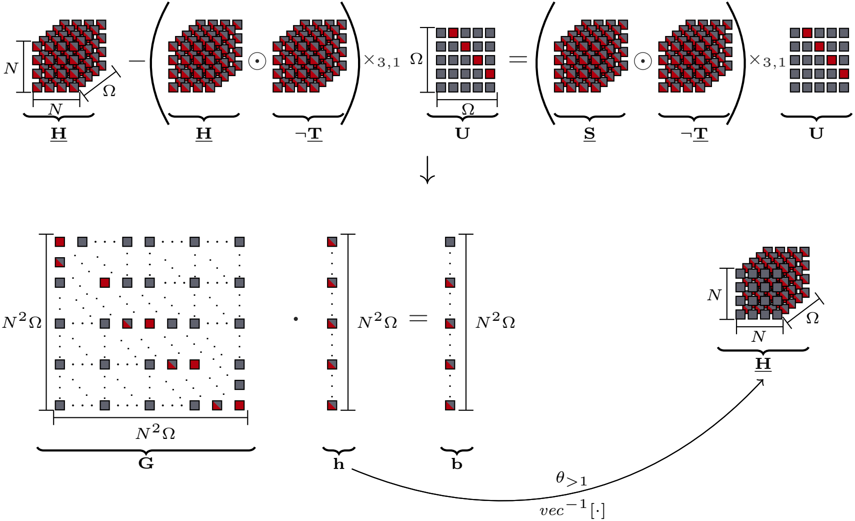


# Tensor-EC: Formal Properties

### Correctness

The **unique solution** of the equation coincides with the time-points at which a fluent-value pair holds, as expressed by the **perfect model** of the corresponding logic program.

# Tensor-EC: Formal Properties

## Correctness

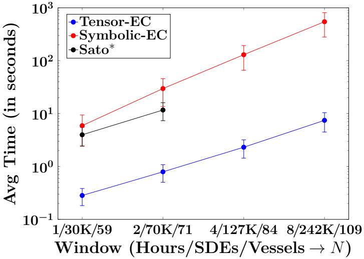
The **unique solution** of the equation coincides with the time-points at which a fluent-value pair holds, as expressed by the **perfect model** of the corresponding logic program.

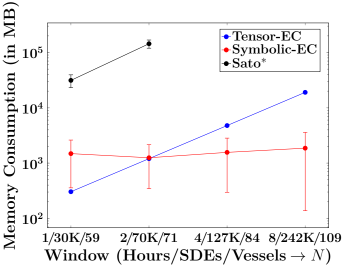
## Complexity

The time complexity of solving the equation is $\mathcal{O}(N^{p-1}\Omega)$ for order-$p$ tensors.

# Tensor-EC: Experimental Evaluation

## Brest





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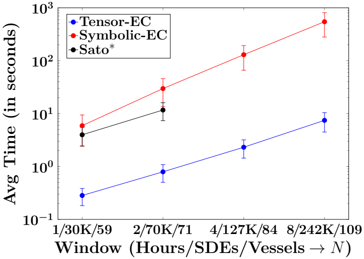

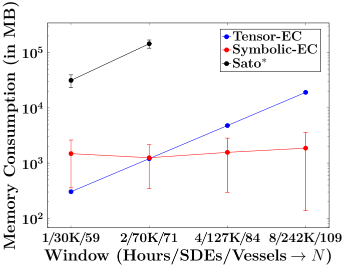

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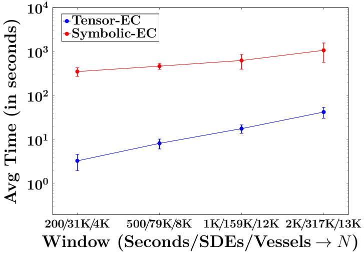

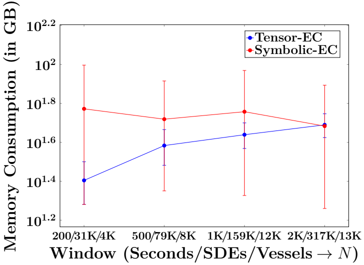

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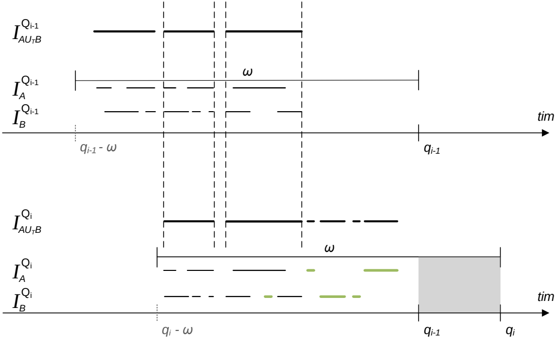
# Appendix

# $RTEC_{inc}$: Statically Determined Fluents

## Union

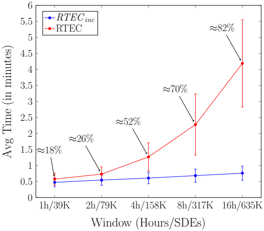
$$I_F^{\mathsf{Q_i}} = \left[ (I_{A \cup_T B}^{\mathsf{Q_{i-1}}}) \setminus_T \left[ \left[ (I_A^{del} \cup_T I_B^{del}) \setminus_T (I_{A \cap_T B}^{\mathsf{Q_{i-1}}}) \right] \cup_T (I_A^{del} \cap_T I_B^{del}) \right] \right] \cup_T (I_A^{ins} \cup_T I_B^{ins})$$



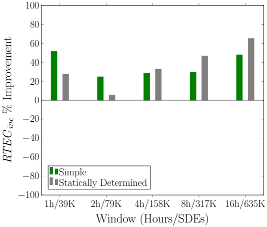
# $RTEC_{inc}$: Evaluation (Natural Delays)

## European seas

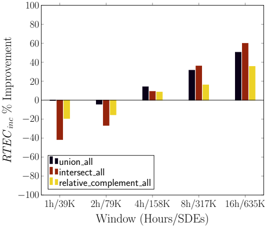
- Delays up to 16 hours
- $17M$ position signals, $34K$ vessels
- January 2016



(a)



(b)

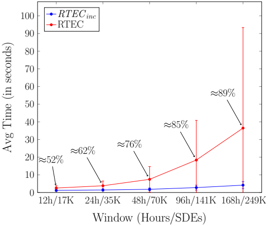


(c)

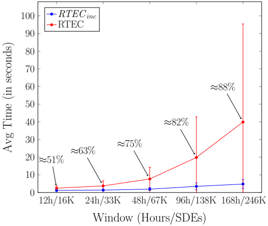
# $RTEC_{inc}$: Evaluation (Synthetic Delays)

## Brest

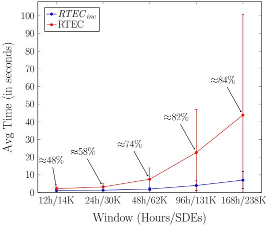
- $5M$ position signals, $5K$ vessels
- October 2015 — March 2016



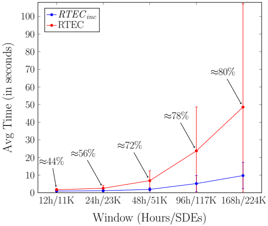
(a) 5%



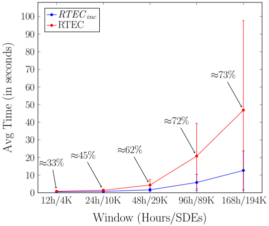
(b) 10%



(c) 20%



(d) 40%



(e) 80%

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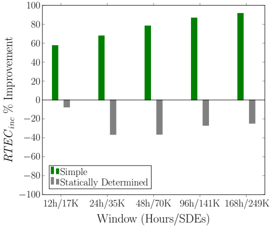

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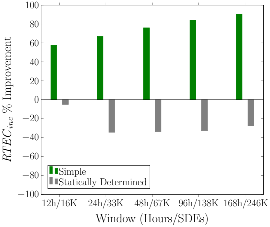

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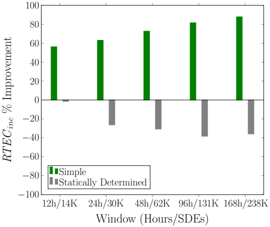

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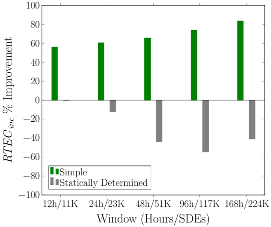

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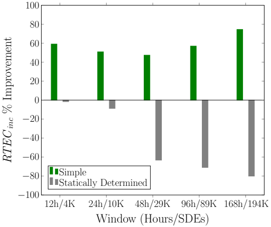

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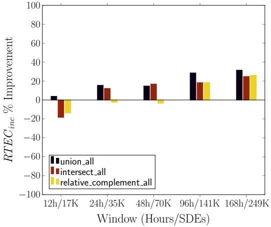

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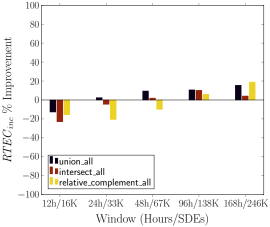

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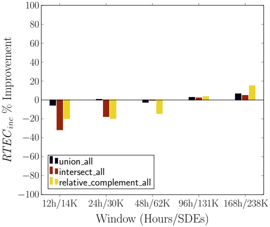

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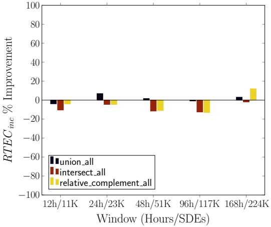

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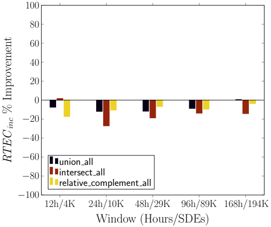
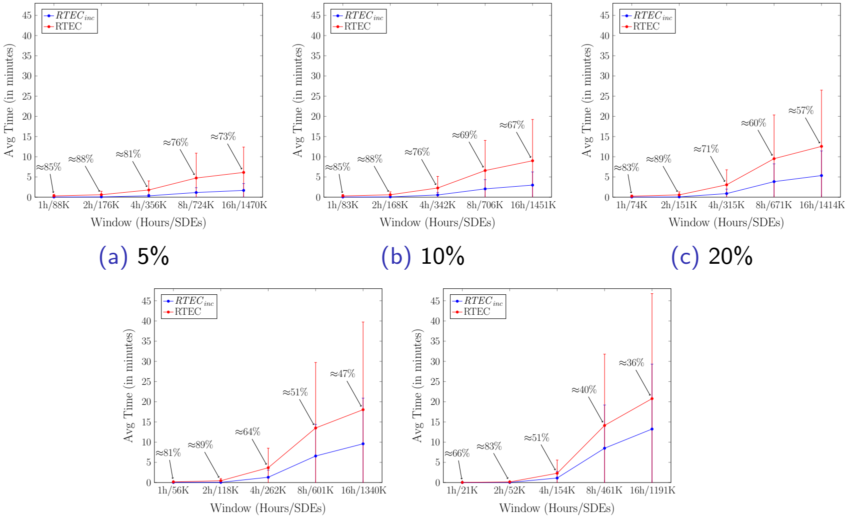


(e) 80%

# $RTEC_{inc}$: Evaluation (Synthetic Delays)

## Fleet Management

- $70M$ position signals, $6K$ vessels
- June 2018 — August 2018



(a) 5%

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(e) 80%

# Tensor-EC: Evaluation

## Simple Event Description

- One fluent and three input events.
- The fluent is defined by one initiatedAt and one terminatedAt rule, plus the *inertia* axiom.
- Temporal window of 20 time-points.

| **Method** | Reasoning time (msec) | Memory (MB) |
|---|---|---|
| tensor-EC | 1 | 0.01 |
| symbolic-EC | 0 | 5 |
| Sato[§] | 1 | 0.01 |
| Sakama et al.[¶] | 9205 | 475.3 |

[§] Sato, T. A linear algebraic approach to datalog evaluation. *Theory and Practice of Logic Programming*, 17(3):244–265, 2017.

[¶] Sakama et al. Logic programming in tensor spaces. *Annals of Mathematics and Artificial Intelligence*, 89, 12 2021.