

Making Sense of Streaming Data: Tensor-based CER

Alexander Artikis^{1,2}
Periklis Mantenoglou³
Manos Pitsikalis¹
Efthimis Tsilionis¹

¹NCSR Demokritos, Athens, Greece

²University of Piraeus, Greece

³Örebro University, Sweden



Slides, Papers, Code & Data

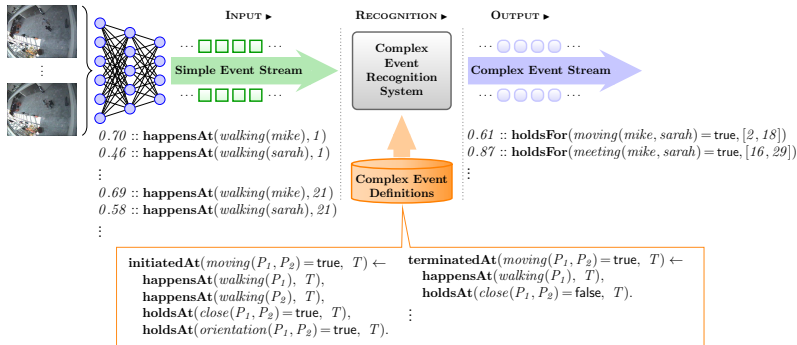


Making Sense of Streaming Data

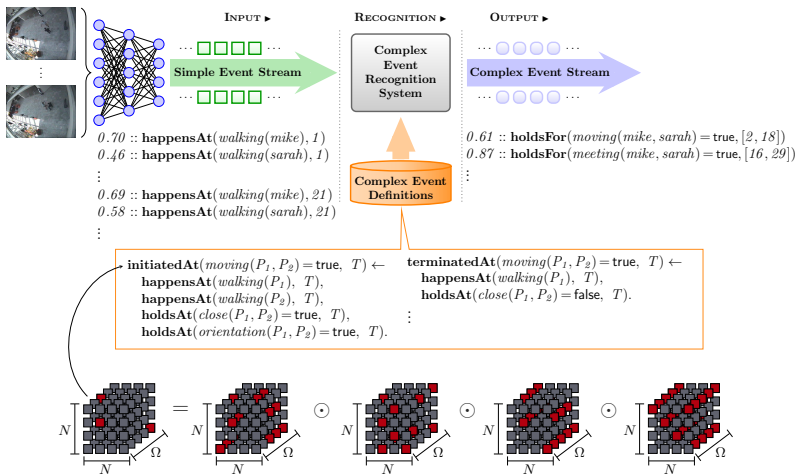


Complex Event Recognition lab

Complex Event Recognition (CER)



Complex Event Recognition (CER)



Tensor-based Event Calculus*: Encoding

- ▶ Application entities: N
- ▶ Window time-points: Ω

$\text{happensAt}(e(X, Y), T)$

*Tsilonis et al., A Tensor-Based Formalization of the Event Calculus. IJCAI, 2024.

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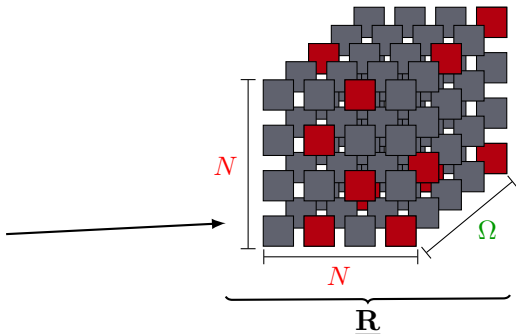
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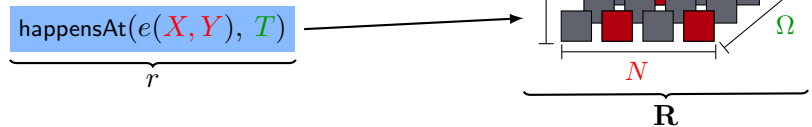
$\underbrace{\text{happensAt}(e(X, Y), T)}_r$



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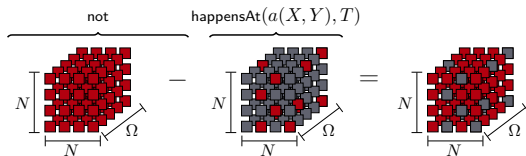
$$\underline{\mathbf{R}}_{i,j,k} = \begin{cases} 1, & \text{if } \mathbf{M}_P \models r, \text{ for } c_i, c_j, t_k \quad \text{Red square} \\ 0, & \text{o.w.} \quad \text{Gray square} \end{cases}$$

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

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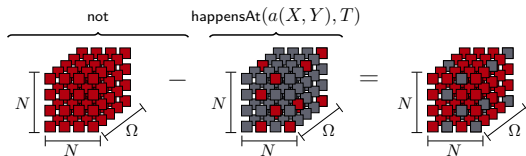
Reasoning: Logical Connectives

Negation:

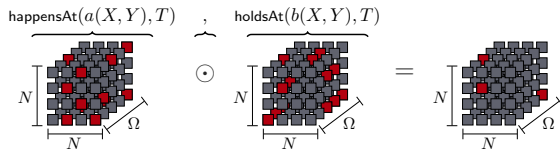


Reasoning: Logical Connectives

Negation:

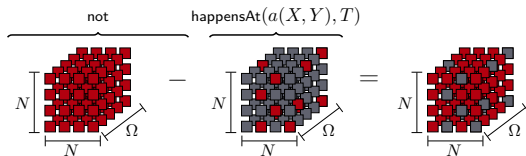


Conjunction:

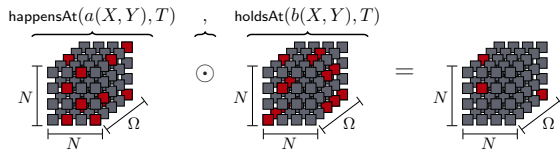


Reasoning: Logical Connectives

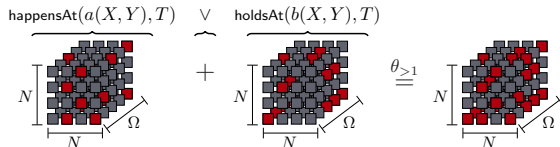
Negation:



Conjunction:



Disjunction:



Reasoning: Rule Evaluation

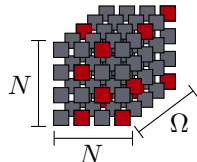
$\text{initiatedAt}(f(X, Y)=v, T) \leftarrow$
 $\text{happensAt}(e(X, Y), T) ,$
 $\text{holdsAt}(d(X, Y)=v_d, T) .$

Reasoning: Rule Evaluation

$\text{initiatedAt}(f(X, Y)=v, T) \leftarrow$

$\text{happensAt}(e(X, Y), T)$,

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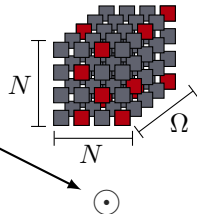


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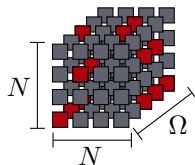
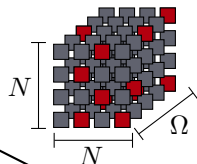


Reasoning: Rule Evaluation

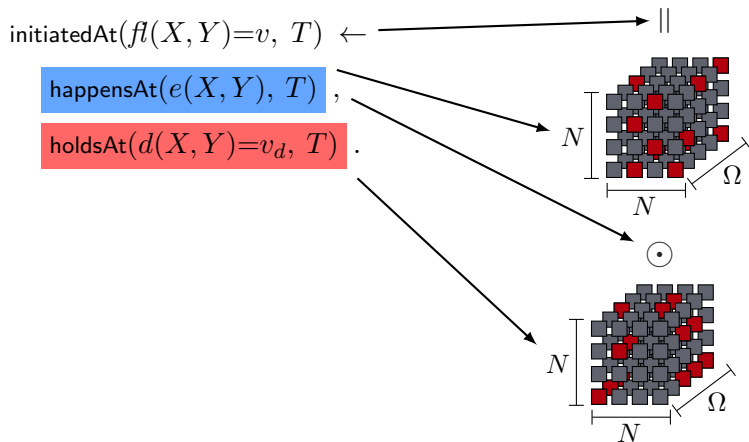
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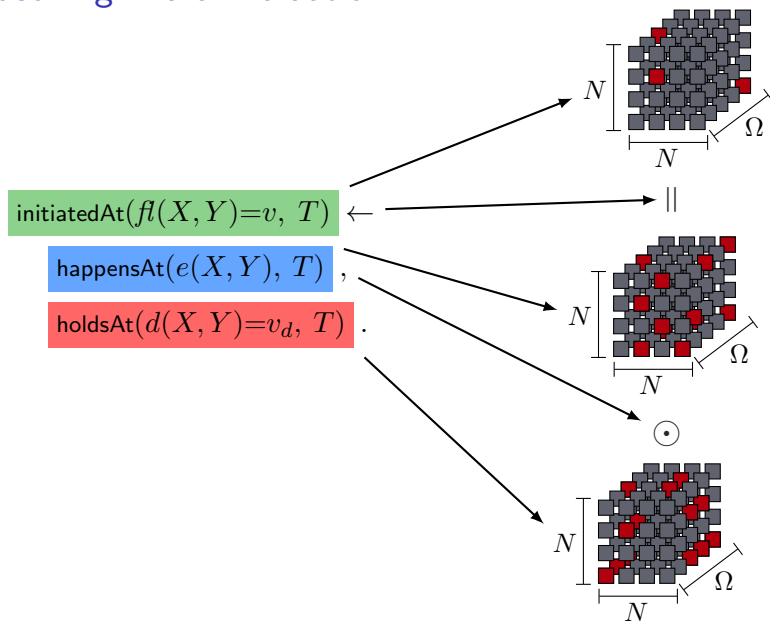
$\text{holdsAt}(d(X, Y)=v_d, T)$.



Reasoning: Rule Evaluation



Reasoning: Rule Evaluation



Model Computation

$\text{holdsAt}(fl(X, Y)=v, T) \leftarrow$
 $\text{initiatedAt}(fl(X, Y)=v, T_{prev}),$
 $\text{not terminatedAt}(fl(X, Y)=v, T_{prev}),$
 $\text{next}(T_{prev}, T).$

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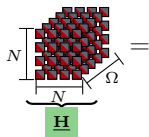
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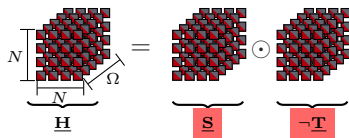
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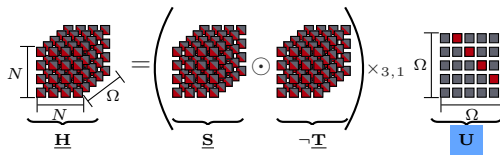
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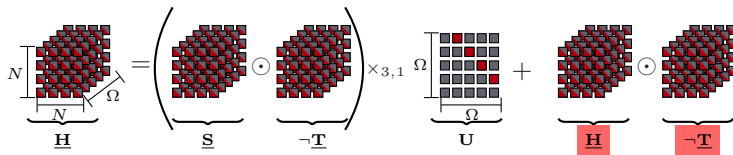
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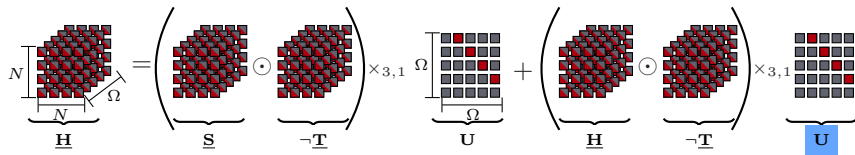
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$$\underbrace{\begin{array}{c} N \\ \text{[Grid of red squares]} \\ N \end{array}}_{\underline{\mathbf{H}}} = \left(\underbrace{\text{[Grid of red squares]}_{\underline{\mathbf{S}}}}_{\underline{\mathbf{S}}} \odot \underbrace{\text{[Grid of red squares]}_{\neg \underline{\mathbf{T}}}}_{\neg \underline{\mathbf{T}}} \right) \times_{3,1} \underbrace{\begin{array}{c} \Omega \\ \text{[Grid of gray and red squares]} \\ \Omega \end{array}}_{\underline{\mathbf{U}}} + \left(\underbrace{\text{[Grid of red squares]}_{\underline{\mathbf{H}}}}_{\underline{\mathbf{H}}} \odot \underbrace{\text{[Grid of red squares]}_{\neg \underline{\mathbf{T}}}}_{\neg \underline{\mathbf{T}}} \right) \times_{3,1} \underbrace{\begin{array}{c} \Omega \\ \text{[Grid of gray and red squares]} \\ \Omega \end{array}}_{\underline{\mathbf{U}}}$$

Equivalence with Symbolic Reasoning

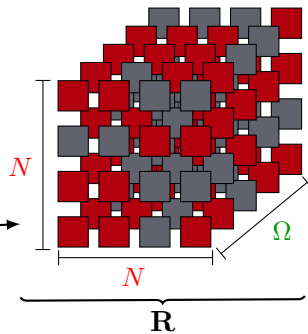
Correctness

The tensor-based Event Calculus computes the same time-points for each FVP as RTEC.

Tensor-based Probabilistic Event Calculus

- ▶ Application entities: N
- ▶ Time-points: Ω

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



Crisp[†]:

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

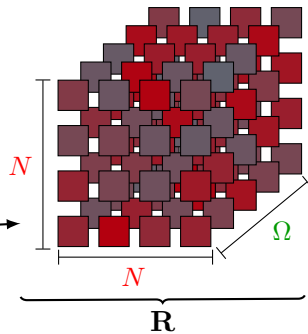
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Tensor-based Probabilistic Event Calculus

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

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

Probabilistic[‡]:

$$\underline{\mathbf{R}}_{i,j,k} = \begin{cases} p, & \text{if } P(\bigvee_{Proofs(r)}) = p \text{ for } c_i, c_j, t_k \\ 0, & \nexists Proof(r) \text{ for } c_i, c_j, t_k \end{cases}$$

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

*Tsilionis et al., A Tensor-Based Formalization of the Event Calculus. IJCAI, 2024.

†Tsilionis et al., A Tensor-Based Probabilistic Event Calculus. KR, 2025.

Summary

Tensor-based CER:

- ▶ Transform symbolic representation into **tensors**.
- ▶ Reason through **algebraic operations**.

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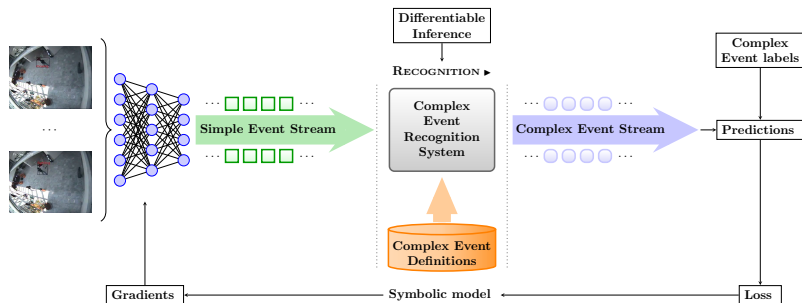
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Summary

Tensor-based CER:

- ▶ Transform symbolic representation into **tensors**.
- ▶ Reason through **algebraic operations**.
- ▶ Maintain formal semantics.
- ▶ Maintain treatment of uncertainty.
- ▶ **Performance improvement** wrt the symbolic counterpart.

Next: Scalable Neuro-Symbolic CER



Course Structure

- ▶ Introduction to Complex Event Recognition (CER).
- ▶ Formal Models for CER
- ▶ Probabilistic CER.
- ▶ Tensor-based CER.

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- ▶ Formal Models for CER
- ▶ Probabilistic CER.
- ▶ Tensor-based CER.
- ▶ Topics not covered.