Formal Models of Complex Event Recognition

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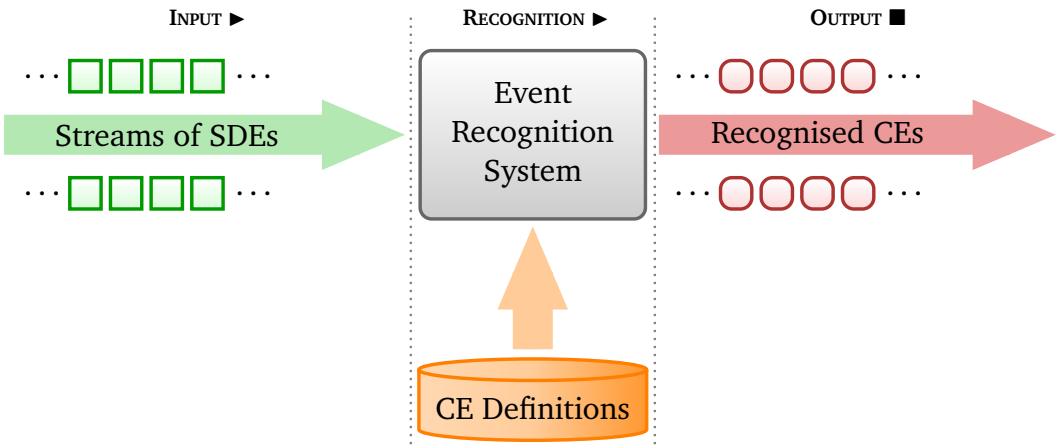
https://cer.iit.demokritos.gr

DEBS 2022

Complex Event Recognition (Event Pattern Matching)



Giatrakos et al, Complex event recognition in the Big Data era: a survey, VLDB Journal, 2020.

Gugola and Margara, Processing flows of information: From data stream to complex event processing. ACM Computing Surveys, 2012.

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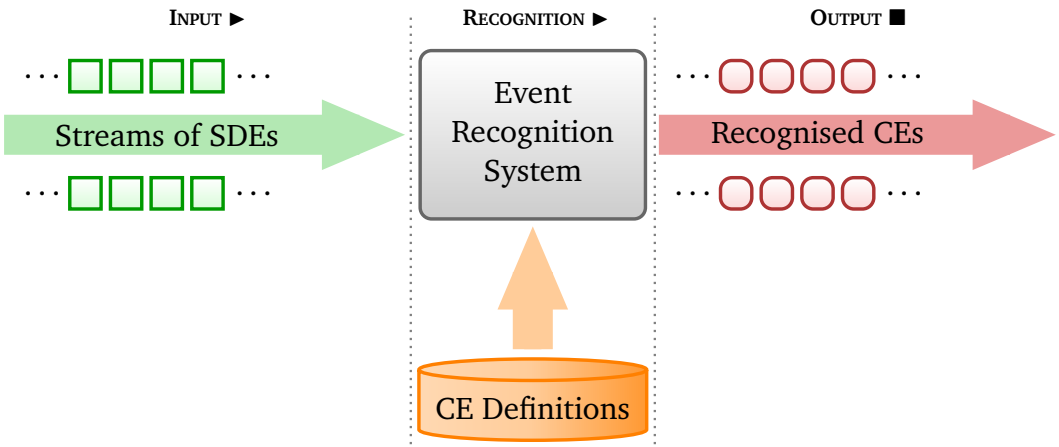

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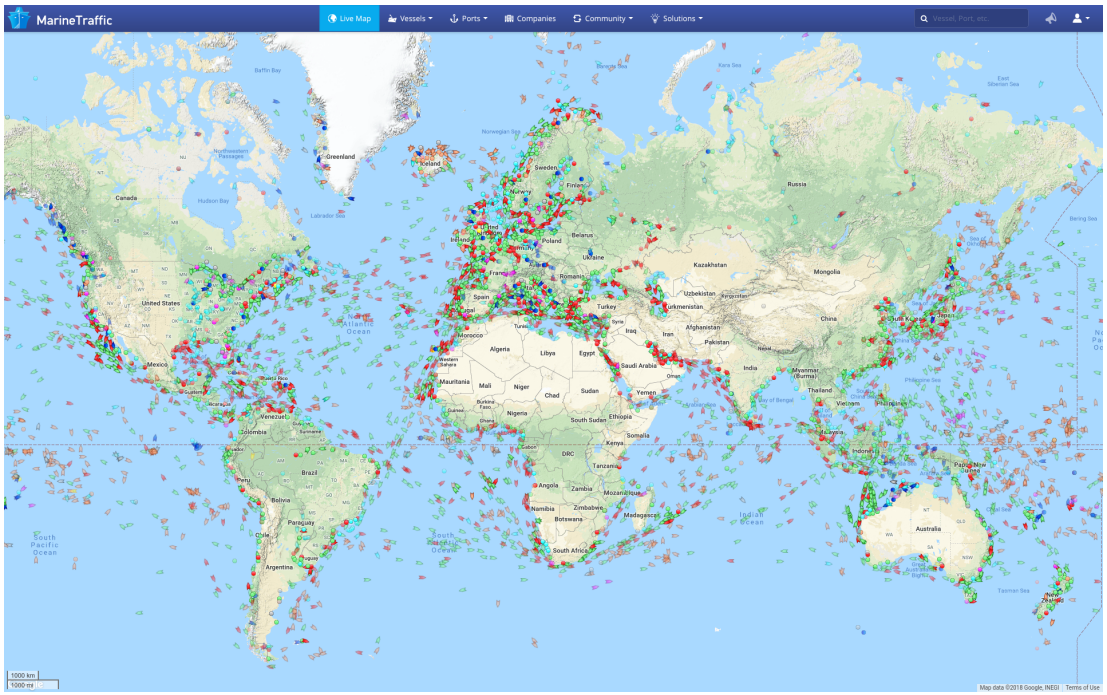
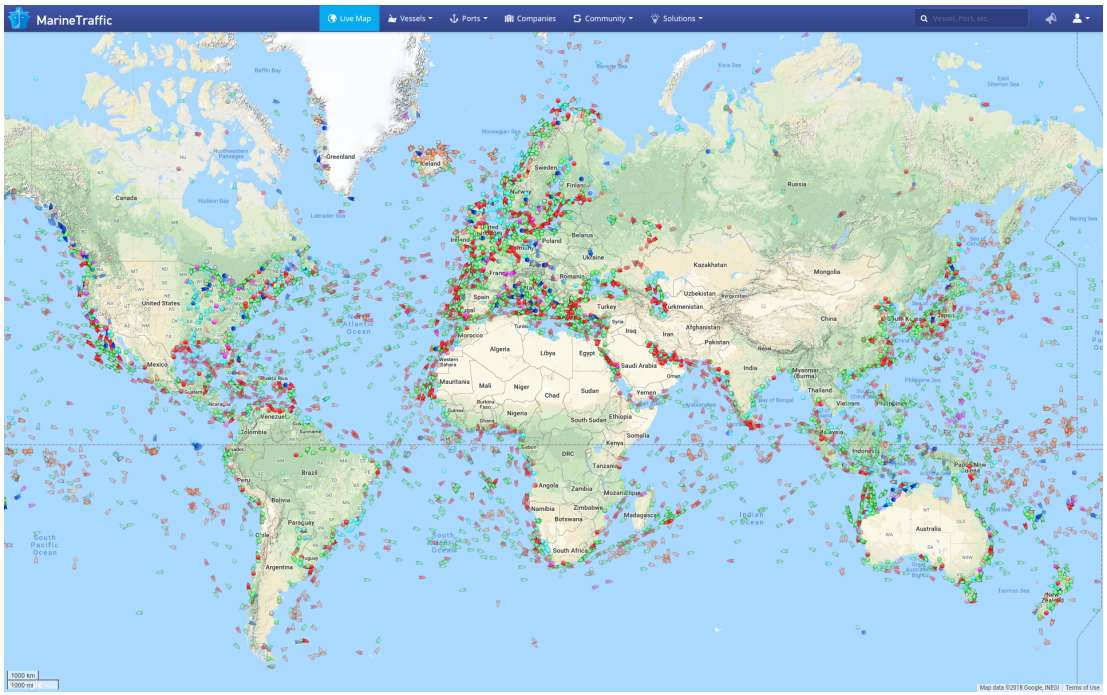
https://rdcu.be/cNkQE

Maritime Situational Awareness



http://www.marinetraffic.com

Maritime Situational Awareness



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https://cer.iit.demokritos.gr (maritime)

Data Challenges

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- Lack of Veracity: GPS manipulation, vessels reporting false identity, communication gaps.
- Distribution: Vessels operating across the globe.

Many Other Applications

- Cardiac arrhythmia recognition.
- Financial fraud detection.
- Human activity recognition.
- Intrusion detection in computer networks.
- Traffic congestion recognition and forecasting in smart cities.

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- Reasoning under uncertainty
  - to deal with various types of noise.
- Complex event forecasting
  - to support proactive decision-making.

Issues

- The main research focus in CER has been on practical issues.
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- The semantics of the CER operators is often defined indirectly, by means of examples, or by translation into evaluation models.
- Even when a formal semantics is given, this semantics is unsatisfactory because it has unintuitive behaviour (eg, sequencing is non-associative) or is restricted (eg, operators cannot be nested).
- As a result, it is not straightforward to understand and compare CER languages (and systems).

Grez et al, A Formal Framework for Complex Event Recognition. ACM Transactions on Database Systems, 2021.

Event Calculus

- A logic programming language for representing and reasoning about events and their effects.
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- 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.

Kowalski and Sergot, A Logic-based Calculus of Events. New Generation Computing, 1986.

Run-Time Event Calculus (RTEC)

Predicate	Meaning
happensAt(E, T)	Event E occurs at time T
initiatedAt$(F = V, T)$	At time T a period of time for which $F = V$ is initiated
terminatedAt$(F = V, T)$	At time T a period of time for which $F = V$ is terminated
holdsFor$(F = V, I)$	I is the list of the maximal intervals for which $F = V$ holds continuously
holdsAt$(F = V, T)$	The value of fluent F is V at time T
union_all$([J_1, \ldots, J_n],\ I)$	$I = (J_1 \cup \ldots \cup J_n)$
intersect_all$([J_1, \ldots, J_n],\ I)$	$I = (J_1 \cap \ldots \cap J_n)$
relative_complement_all $(I',\ [J_1, \ldots, J_n],\ I)$	$I = I' \setminus (J_1 \cup \ldots \cup J_n)$

Artikis et al, An Event Calculus for Event Recognition. IEEE TKDE, 2015. https://github.com/aartikis/RTEC

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CE Definitions in the Run-Time Event Calculus

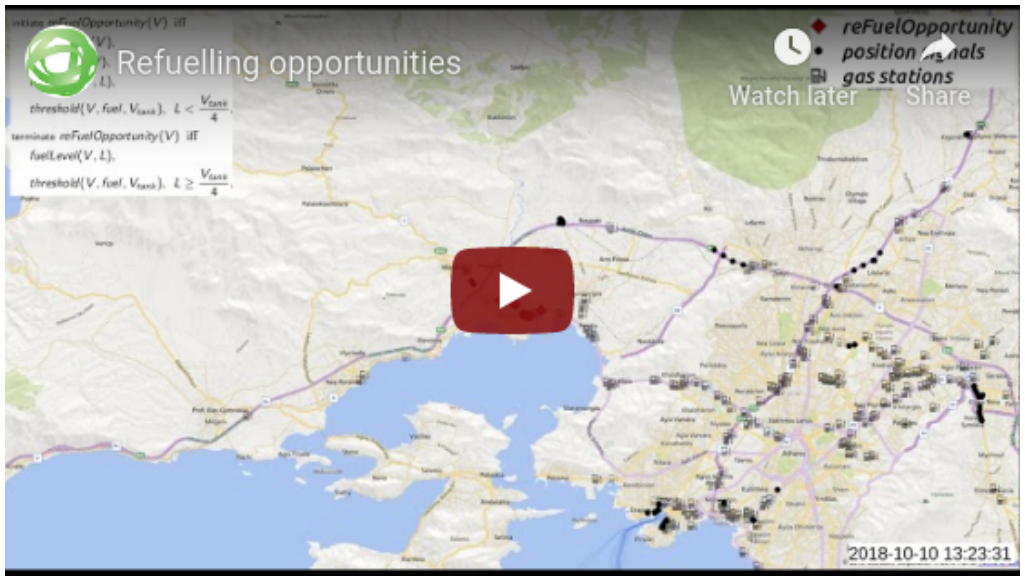
$$\textbf{initiatedAt}(CE,\ T) \leftarrow \textbf{happensAt}(E_{In_1},\ T), [\text{conditions}]$$
$$\ldots$$
$$\textbf{initiatedAt}(CE,\ T) \leftarrow \textbf{happensAt}(E_{In_i},\ T), [\text{conditions}]$$

$$\textbf{terminatedAt}(CE,\ T) \leftarrow \textbf{happensAt}(E_{T_1},\ T), [\text{conditions}]$$
$$\ldots$$
$$\textbf{terminatedAt}(CE,\ T) \leftarrow \textbf{happensAt}(E_{T_j},\ T), [\text{conditions}]$$

where

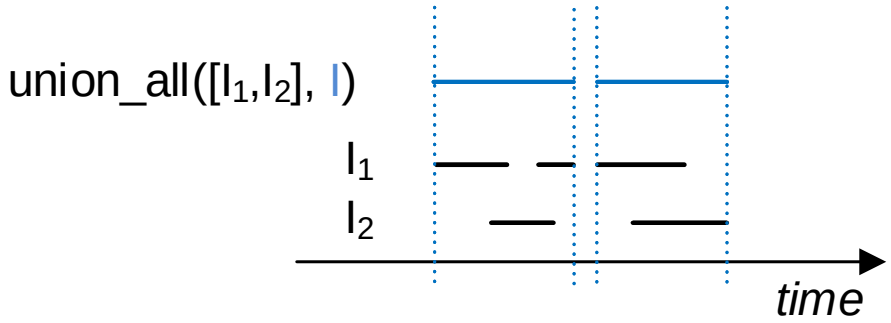
$$\text{conditions:} \quad {}^{0-K}\textbf{happensAt}(E_k,\ T),\ {}^{0-M}\textbf{holdsAt}(F_m,\ T),\ {}^{0-N}\text{atemporal-constraint}_n$$

Fleet Management



https://cer.iit.demokritos.gr (fleet management)

Interval Manipulation



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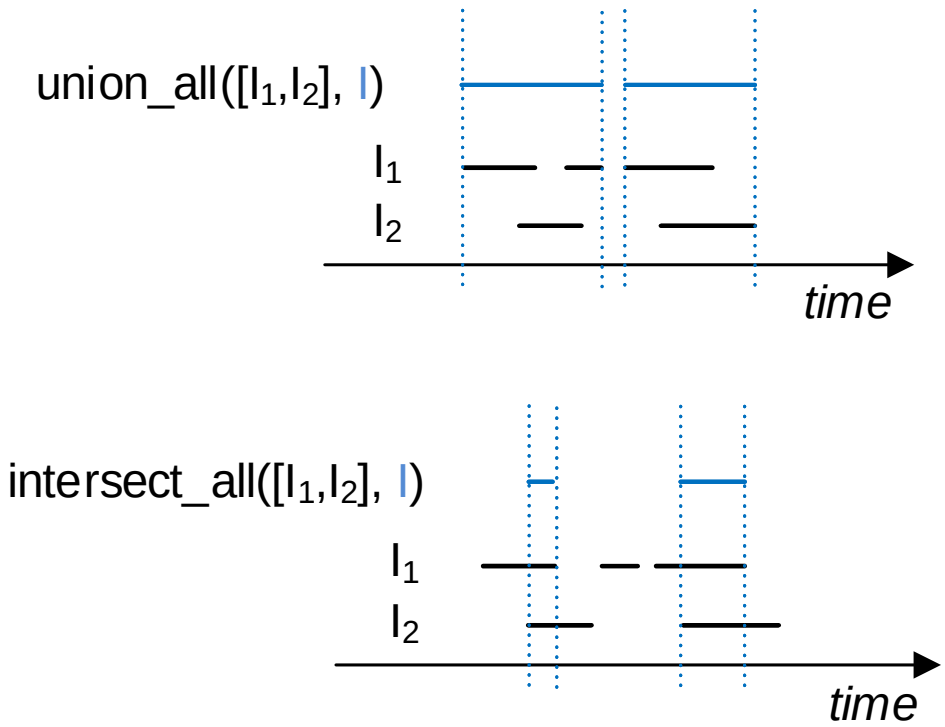

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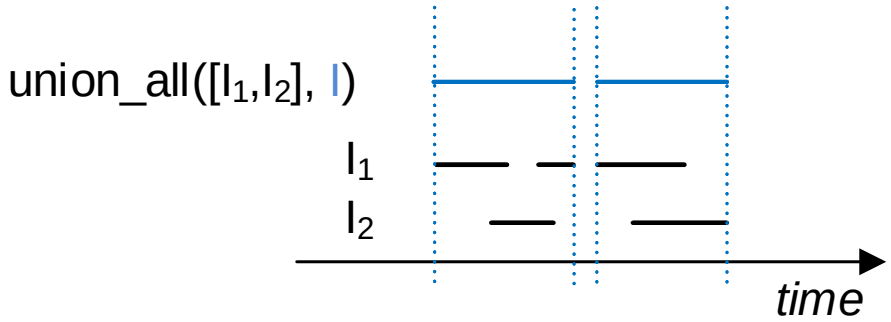

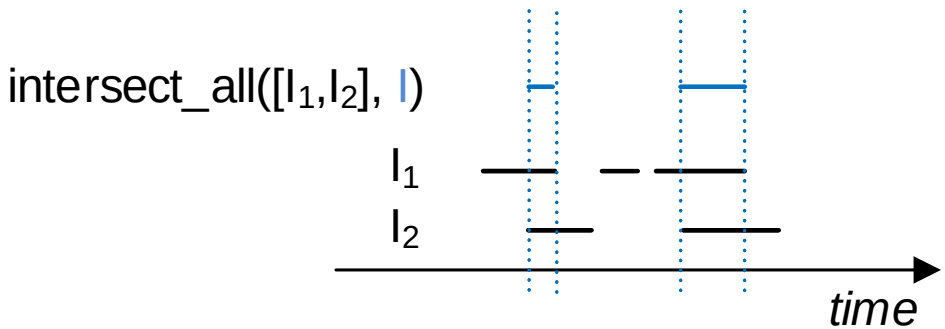

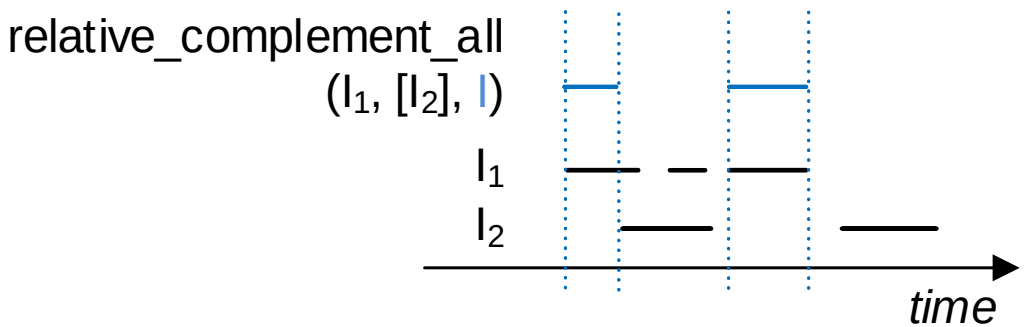

CE Definitions in the Run-Time Event Calculus

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{fighting}(P_1, P_2) = \text{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{abrupt}(P_1) = \text{true},\ I_1), \\
&\quad \textbf{holdsFor}(\mathit{abrupt}(P_2) = \text{true},\ I_2), \\
&\quad \textbf{union\_all}([I_1, I_2],\ I_3), \\
&\quad \textbf{holdsFor}(\mathit{close}(P_1, P_2) = \text{true},\ I_4), \\
&\quad \textbf{intersect\_all}([I_3, I_4],\ I_5), \\
&\quad \textbf{holdsFor}(\mathit{inactive}(P_1) = \text{true},\ I_6), \\
&\quad \textbf{holdsFor}(\mathit{inactive}(P_2) = \text{true},\ I_7), \\
&\quad \textbf{relative\_complement\_all}(I_5,\ [I_6, I_7],\ I)
\end{aligned}
$$

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&\quad \textbf{holdsFor}(\mathit{inactive}(P_2) = \text{true},\ I_7), \\
&\quad \textbf{relative_complement_all}(I_5,\ [I_6, I_7],\ I)
\end{aligned}$$

Shorthand:

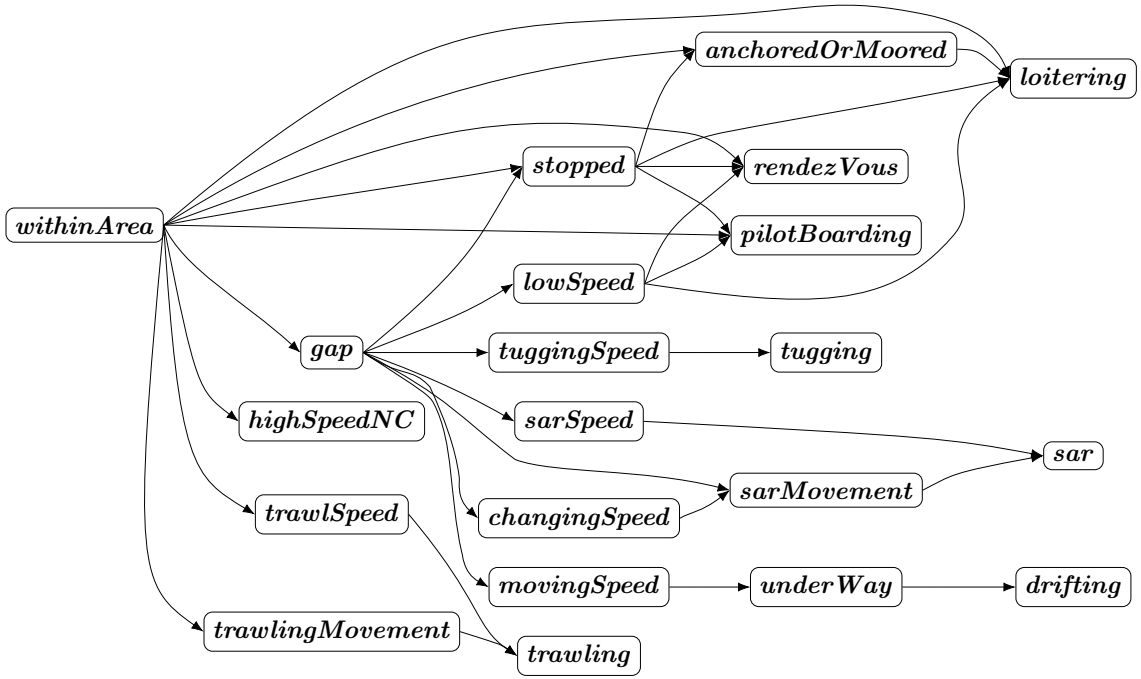
$$\begin{aligned}
&\mathit{fighting}(P_1, P_2) \text{ iff} \\
&\quad (\mathit{abrupt}(P_1) \text{ or } \mathit{abrupt}(P_2)), \\
&\quad \mathit{close}(P_1, P_2), \\
&\quad \text{not } (\mathit{inactive}(P_1) \text{ or } \mathit{inactive}(P_2))
\end{aligned}$$

Fighting

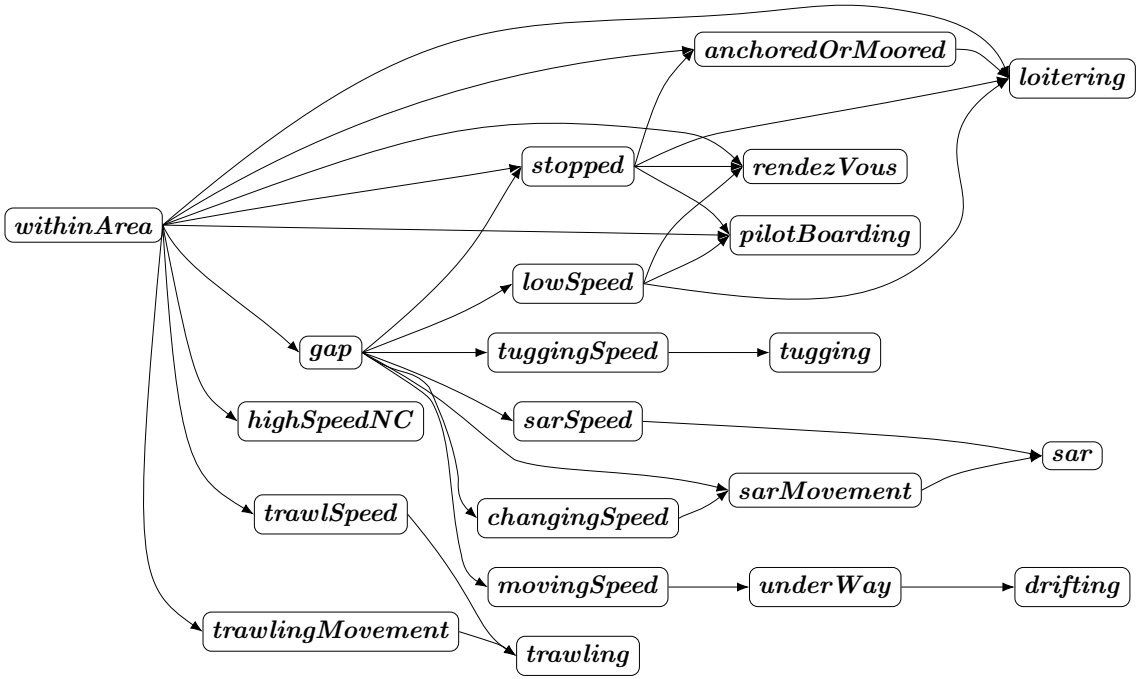
https://cer.iit.demokritos.gr (activity-recognition-i)

https://cer.iit.demokritos.gr (activity-recognition-ii)

Semantics


withinArea
anchoredOrMoored
loitering
stopped
rendezVous
pilotBoarding
lowSpeed
gap
tuggingSpeed
tugging
highSpeedNC
sarSpeed
sar
sarMovement
trawlSpeed
changingSpeed
movingSpeed
underWay
drifting
trawlingMovement
trawling

Semantics


withinArea
anchoredOrMoored
loitering
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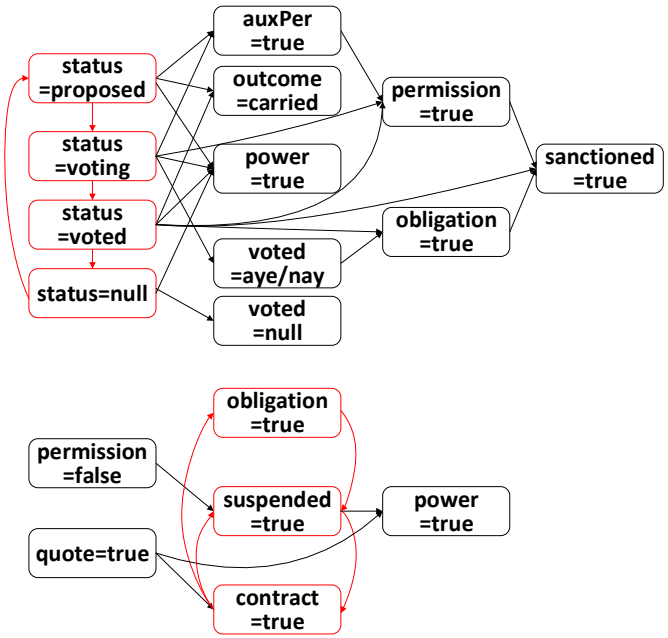
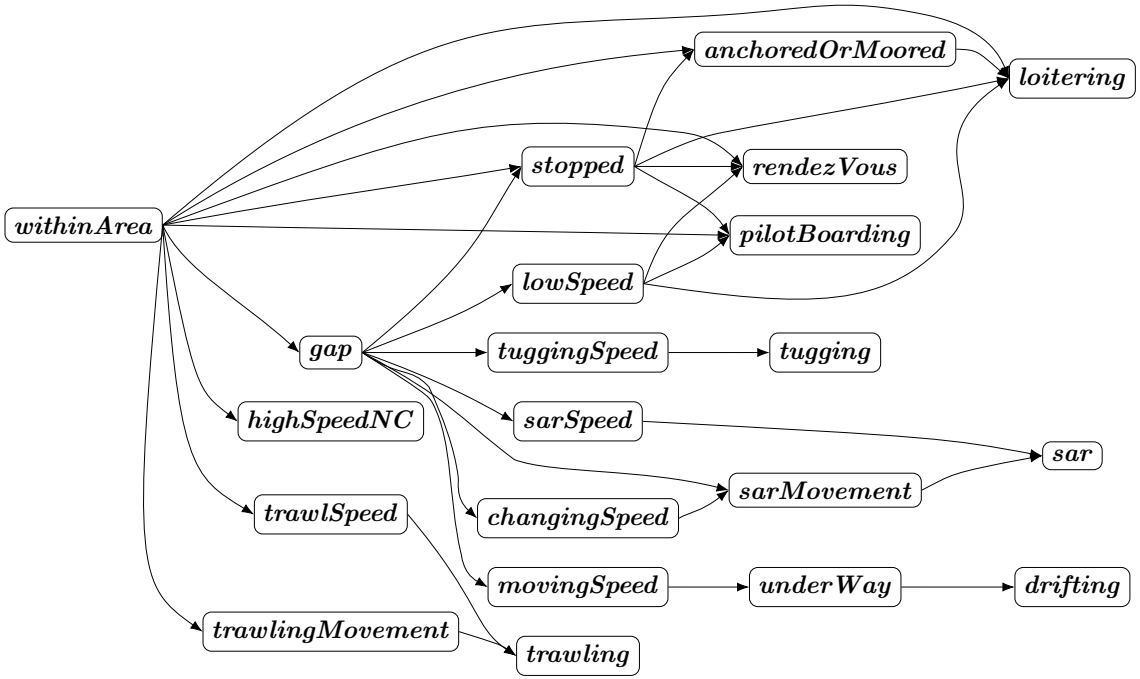
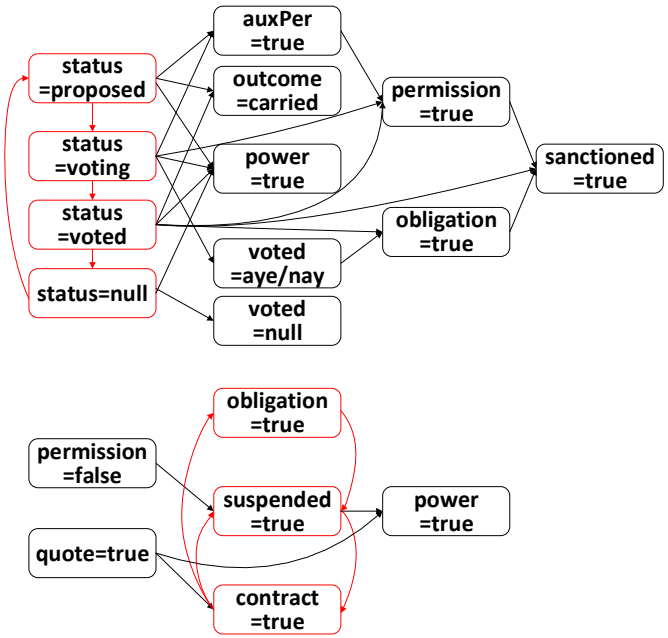
lowSpeed
gap
tuggingSpeed
tugging
highSpeedNC
sarSpeed
sar
sarMovement
trawlSpeed
changingSpeed
movingSpeed
underWay
drifting
trawlingMovement
trawling


status =proposed
status =voting
status =voted
status=null
auxPer =true
outcome =carried
power =true
voted =aye/nay
voted =null
permission =true
obligation =true
sanctioned =true

permission =false
quote=true
obligation =true
suspended =true
contract =true
power =true

Semantics



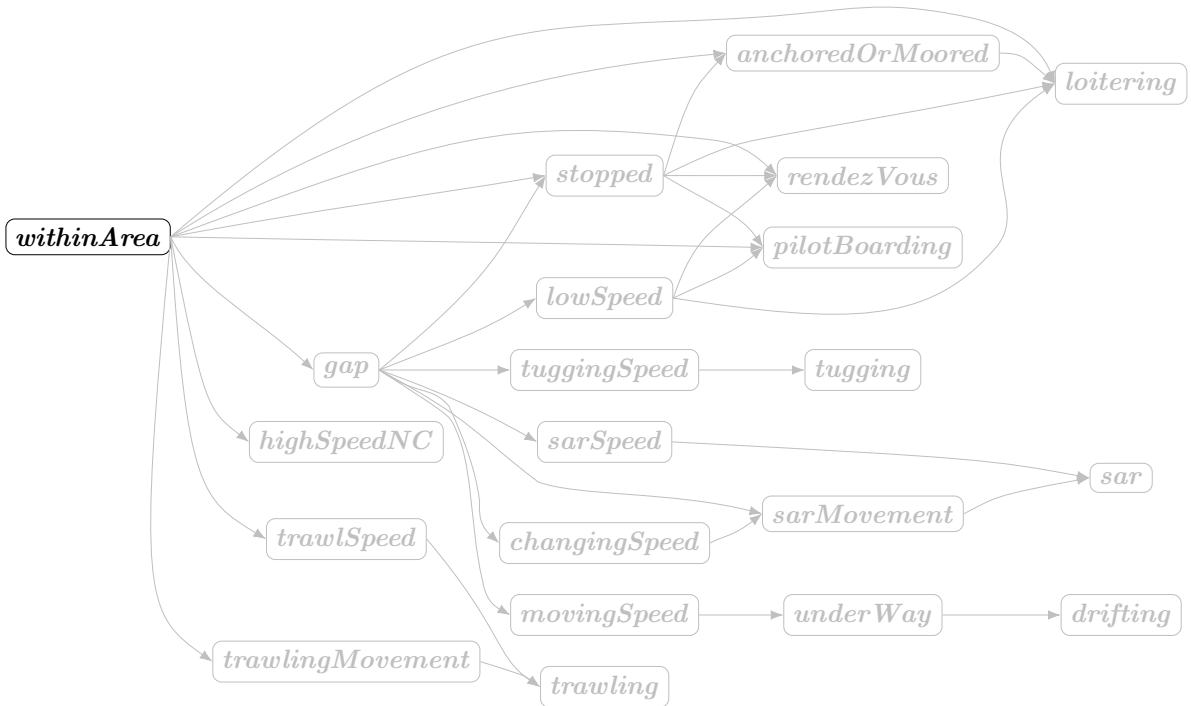


Proposition

An event description in RTEC is a locally stratified logic program.

Mantenoglou et al, Stream Reasoning with Cycles. Knowledge Representation and Reasoning (KR), 2022.

Stratification & Reasoning



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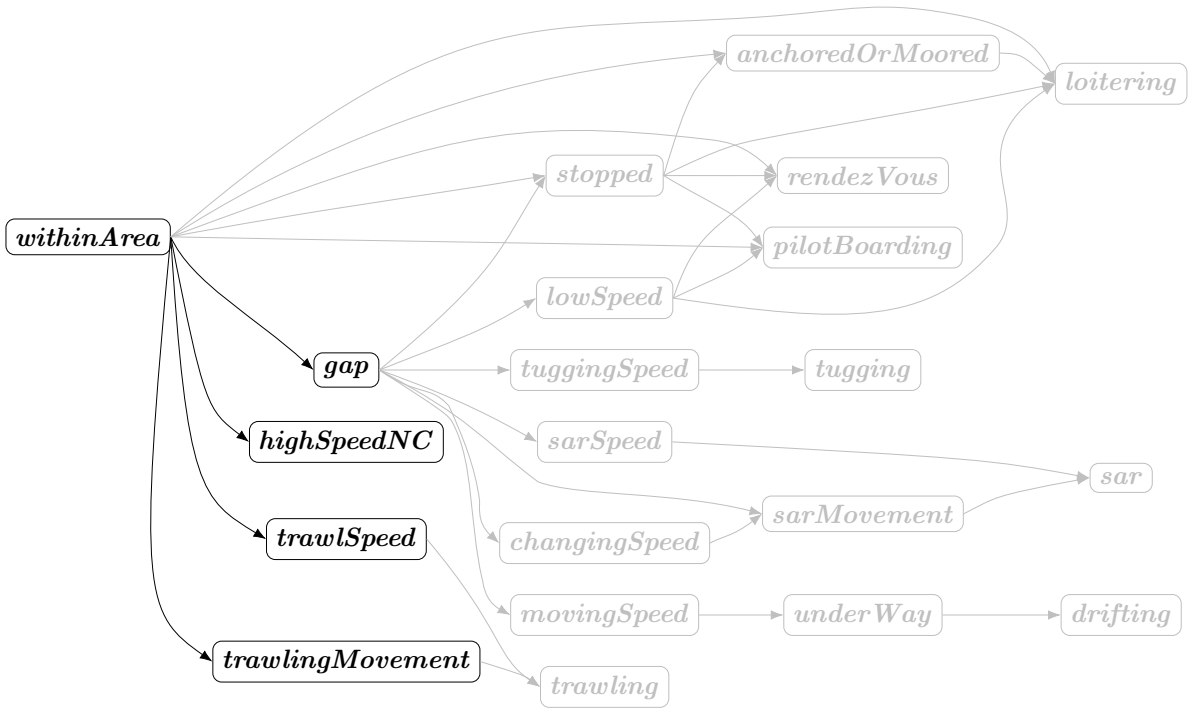

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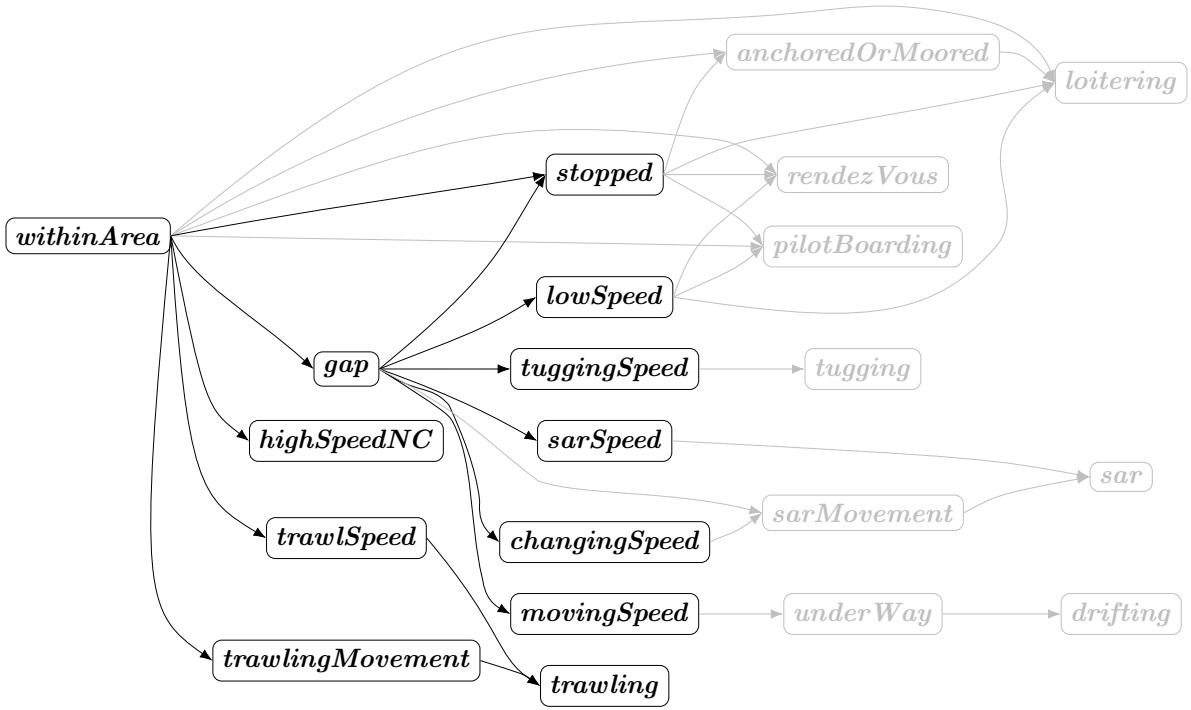

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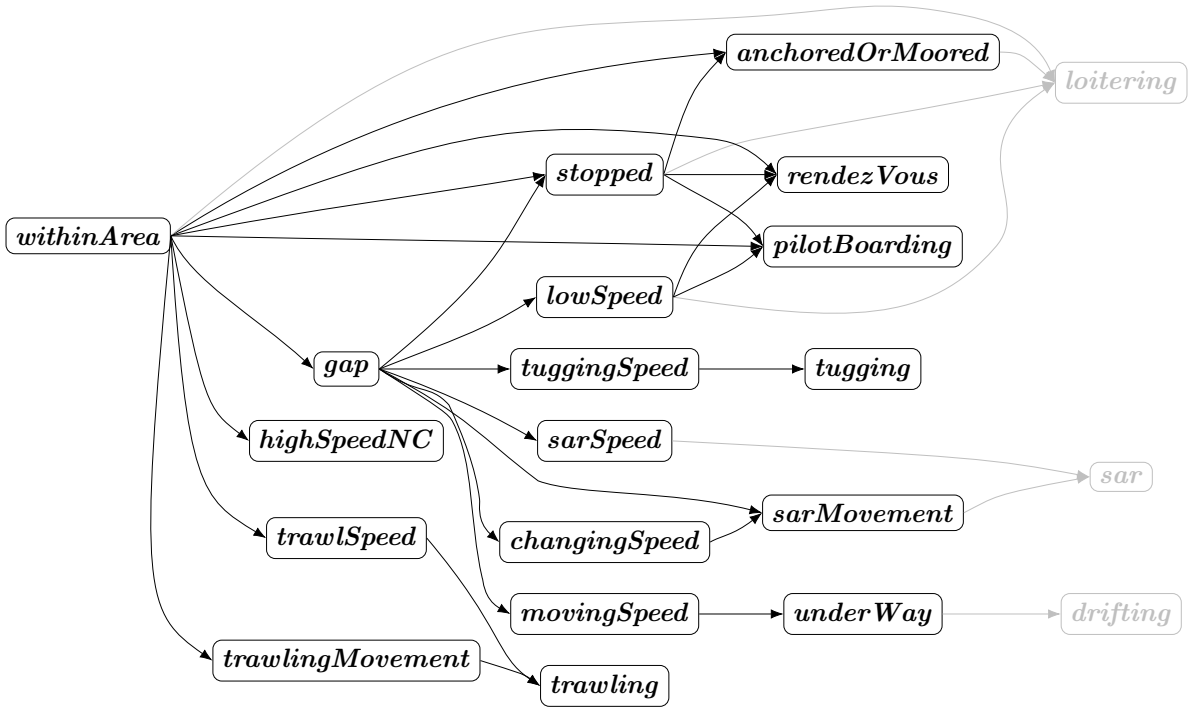

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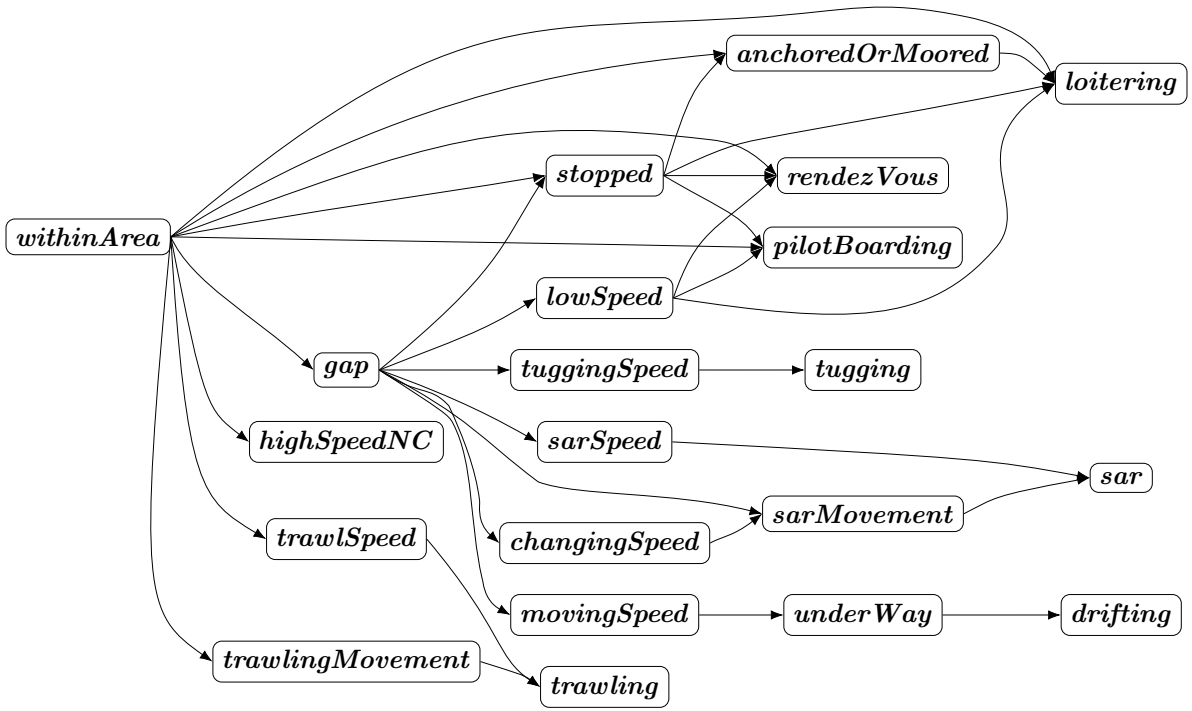
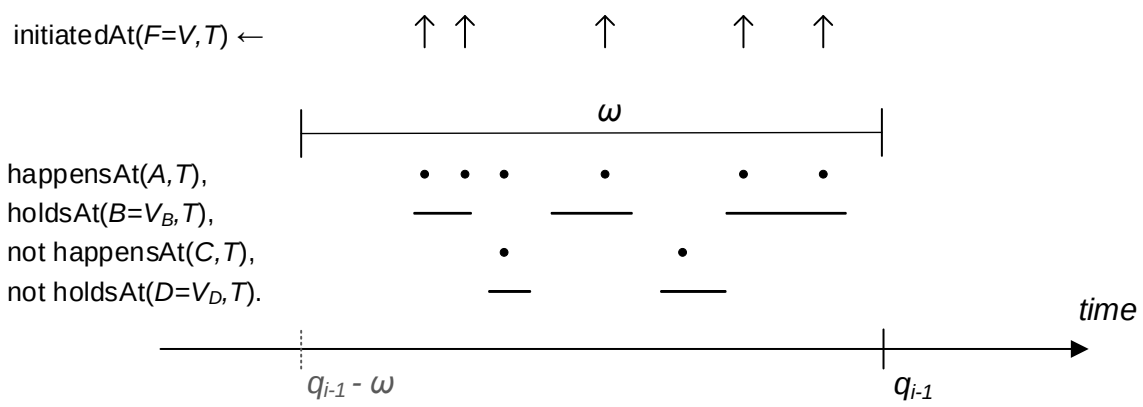
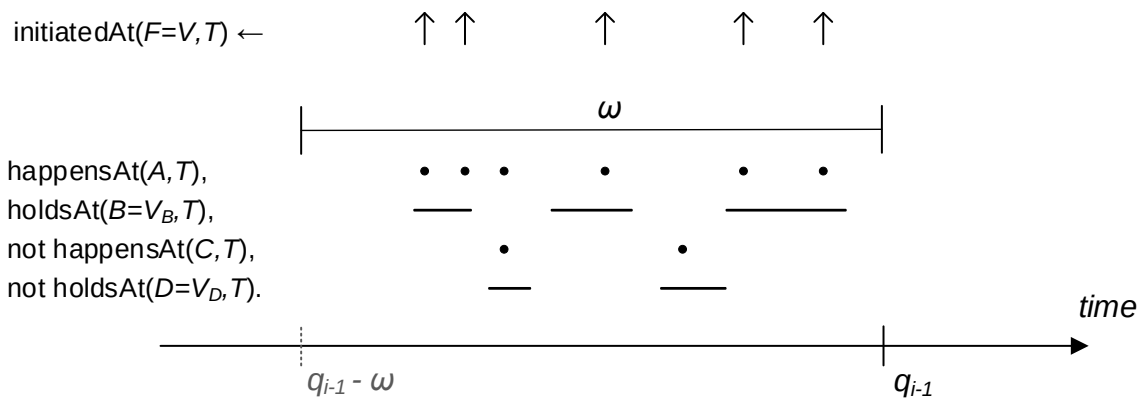


Windowing


initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_{i-1} - ω
q_{i-1}

Windowing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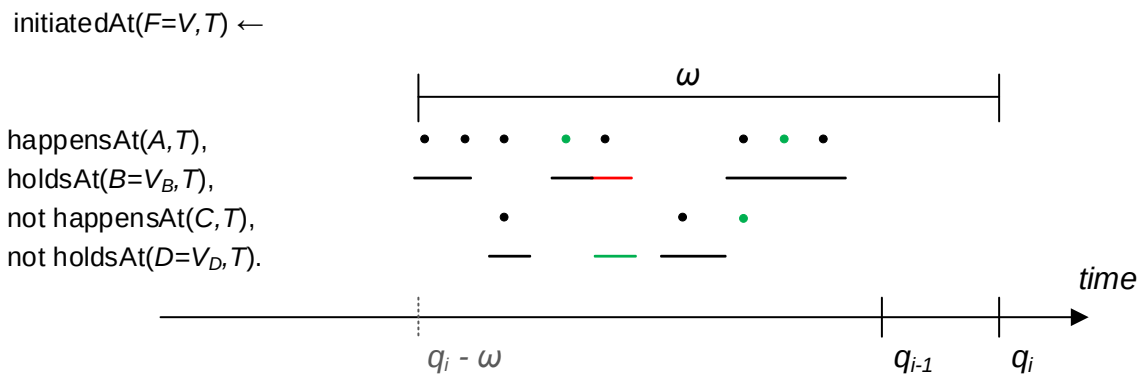
q_{i-1}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happensAt(A,T),
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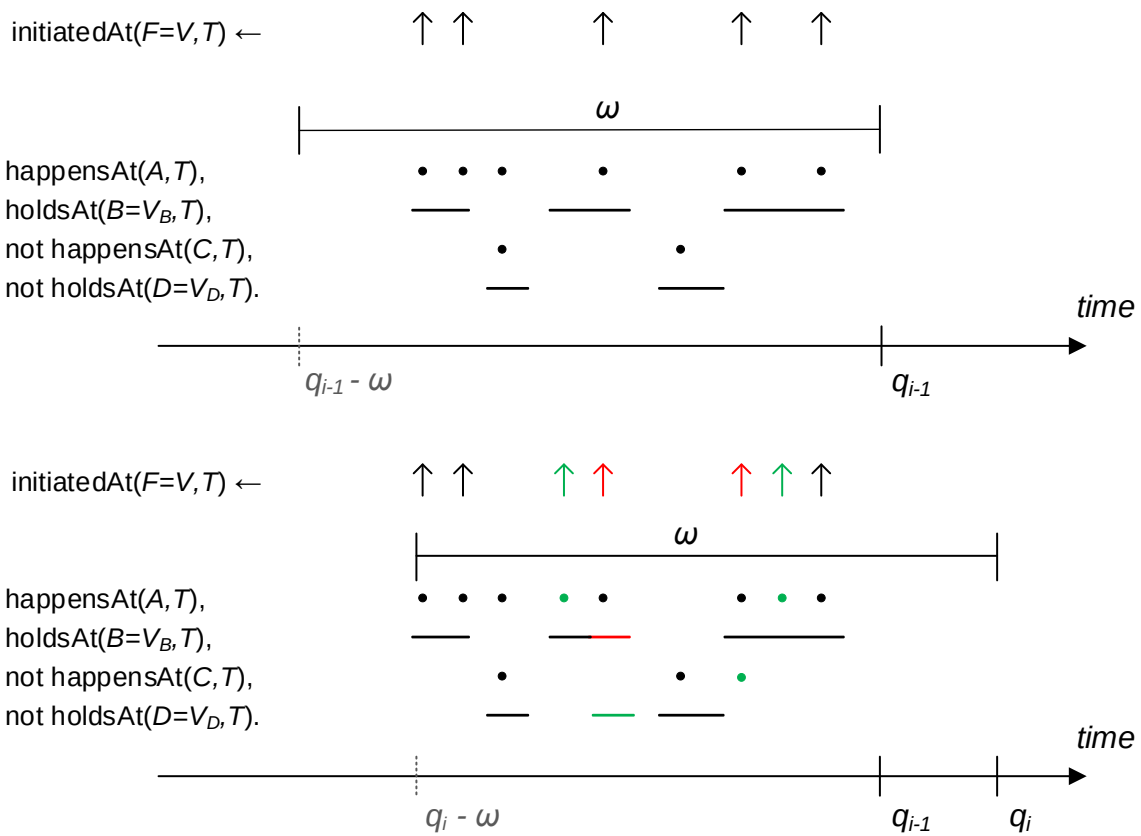
time
q_i - ω
q_{i-1}
q_i

Windowing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q_{i-1} - ω
q_{i-1}
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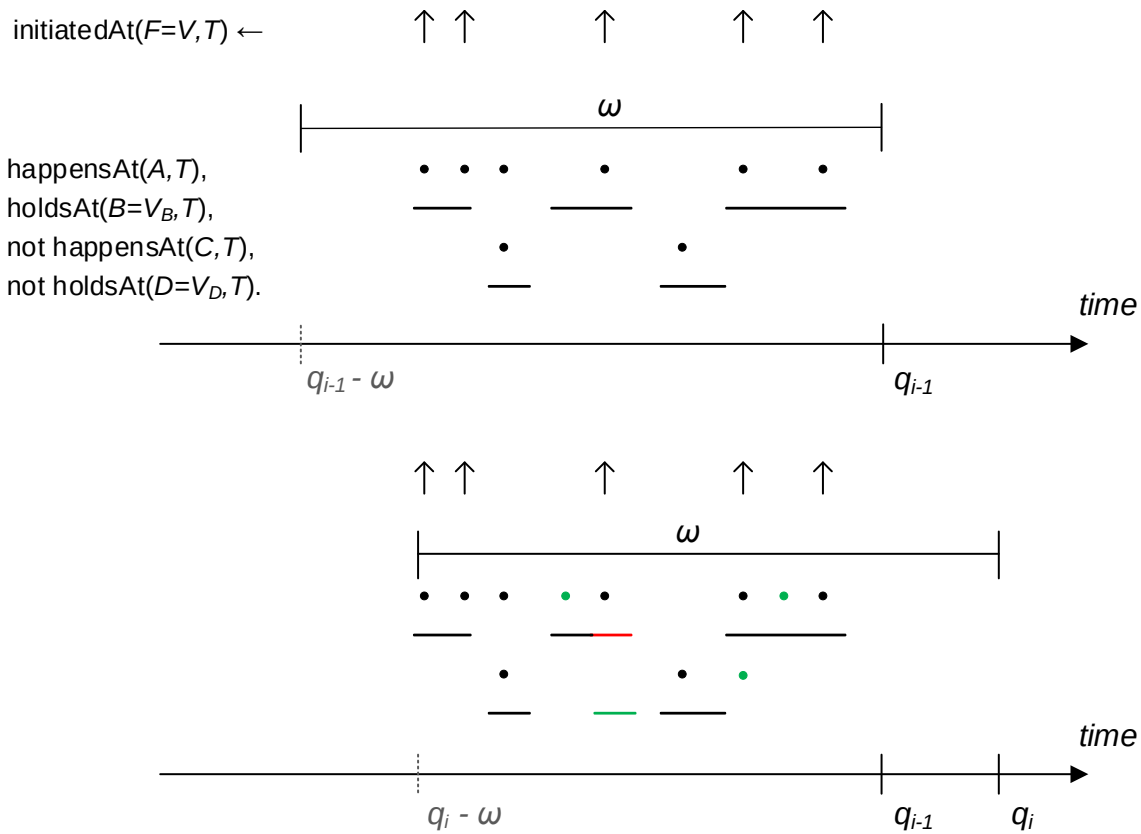
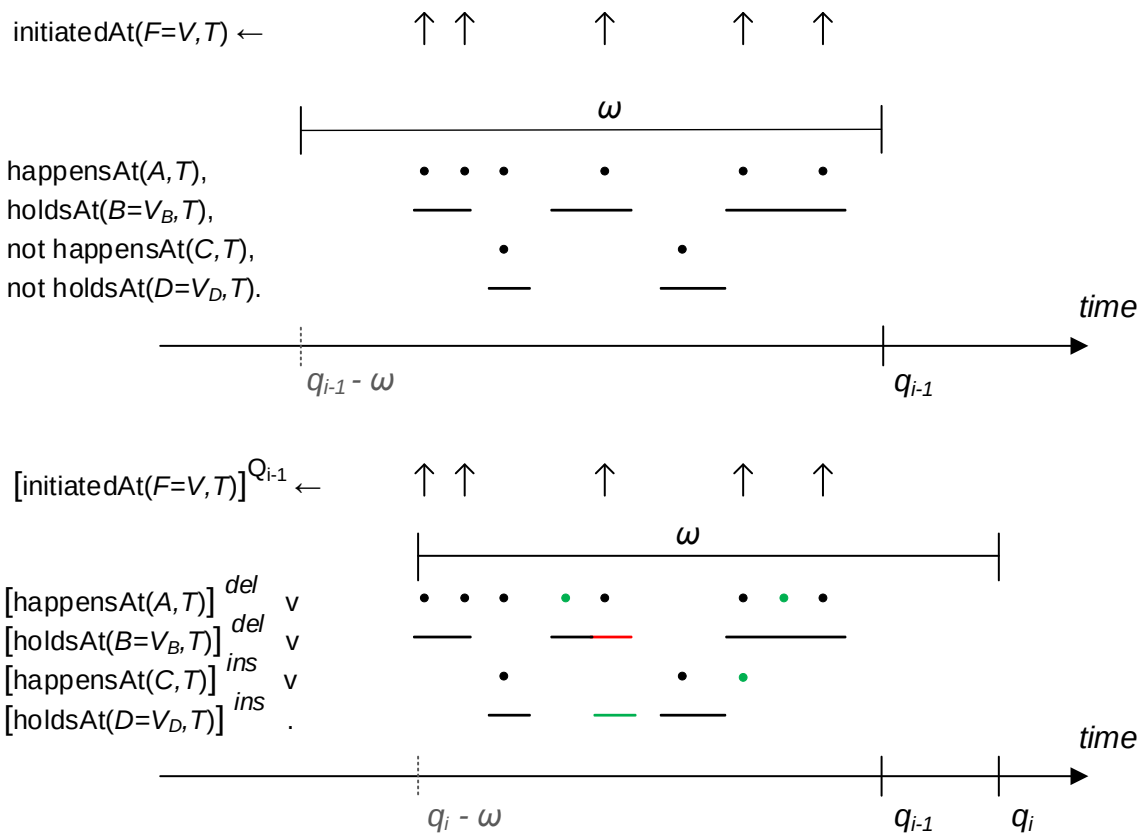
q_i - ω
q_{i-1}
q_i

Incremental Reasoning: Deletion Phase



Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

Incremental Reasoning: Deletion Phase



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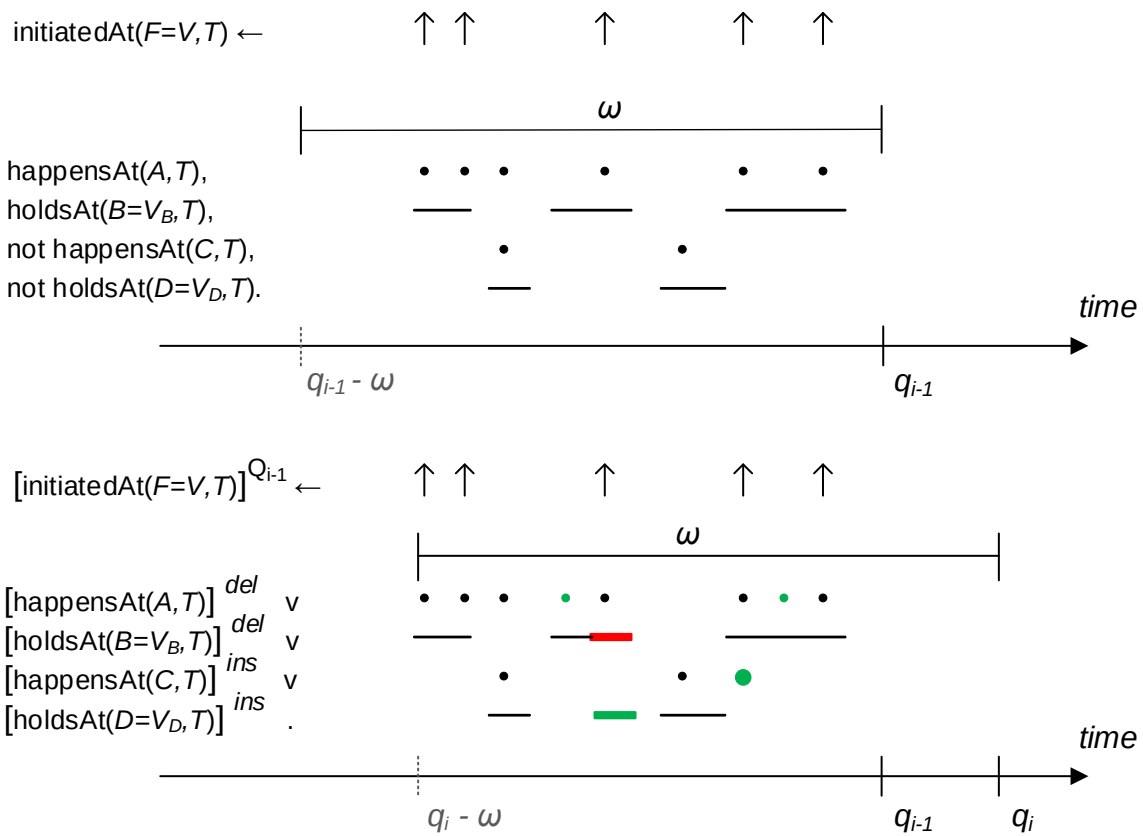

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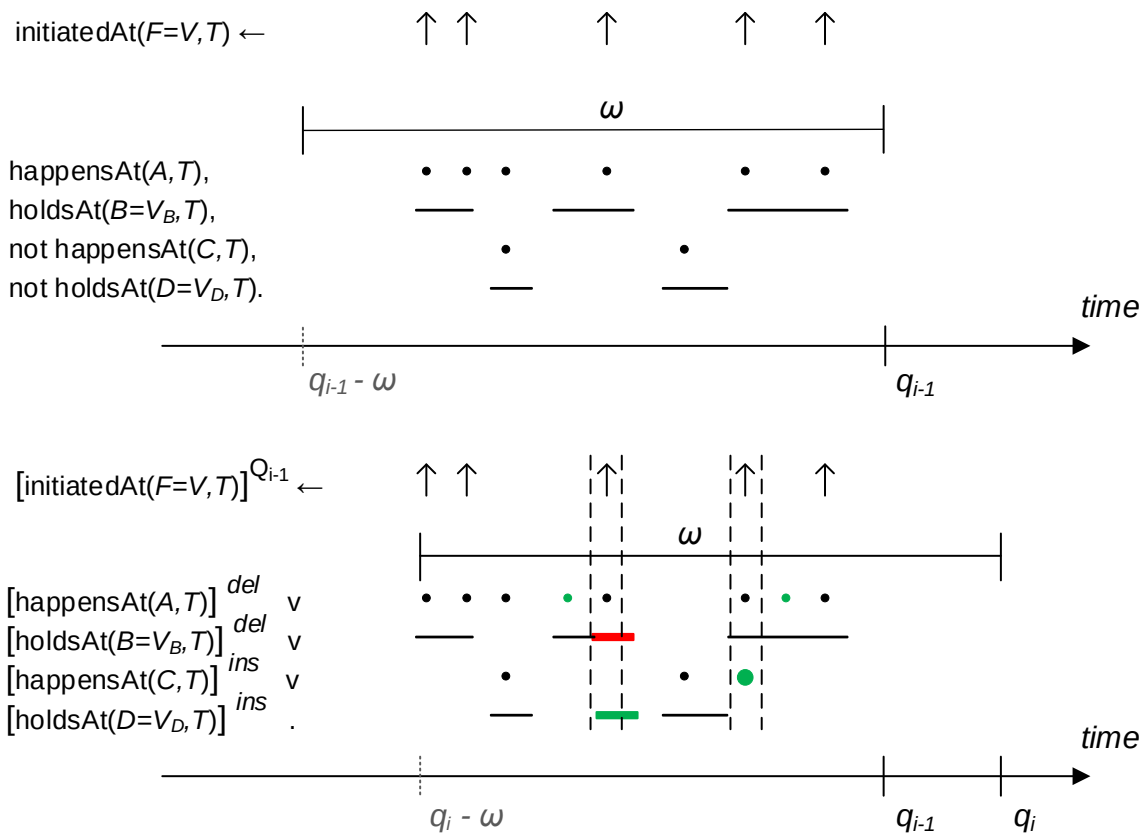

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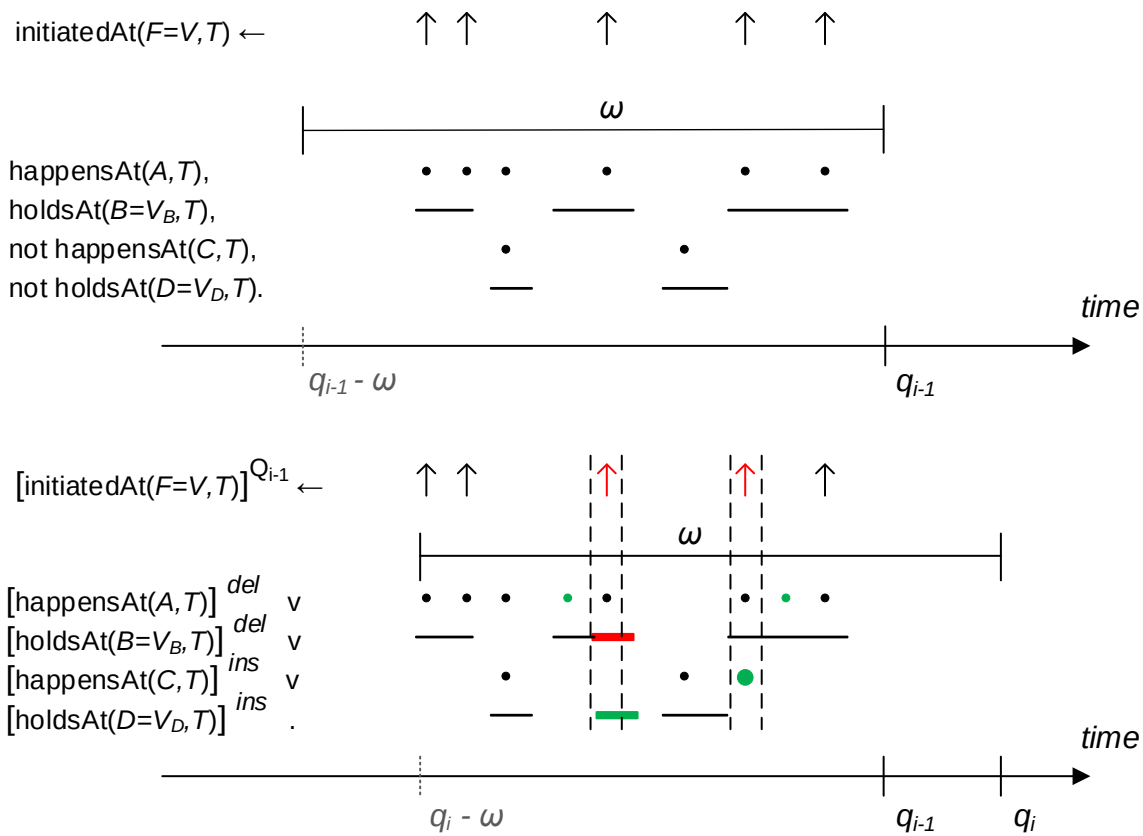
Incremental Reasoning: Deletion Phase



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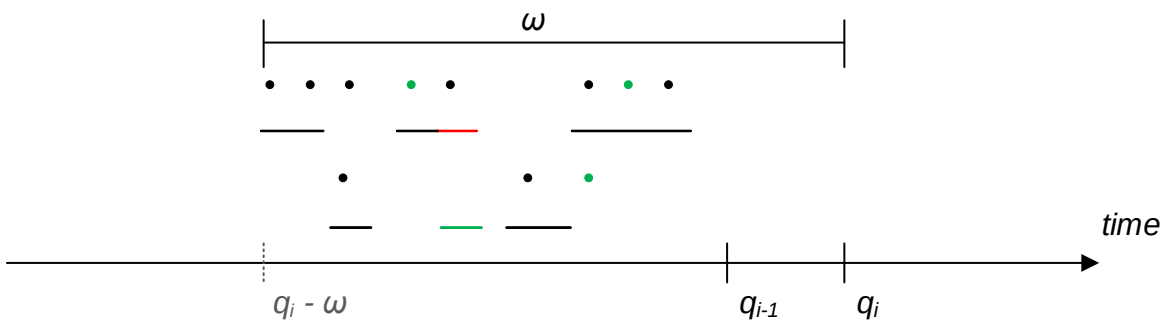
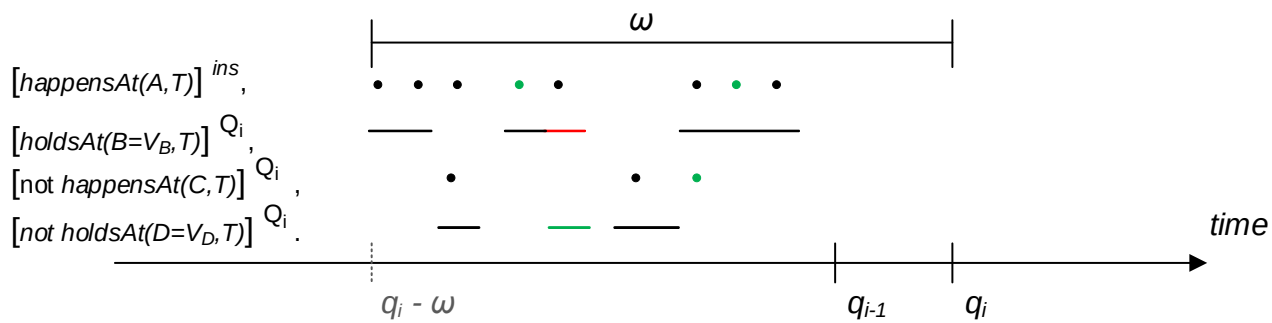
Incremental Reasoning: Addition Phase



Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

Incremental Reasoning: Addition Phase



Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

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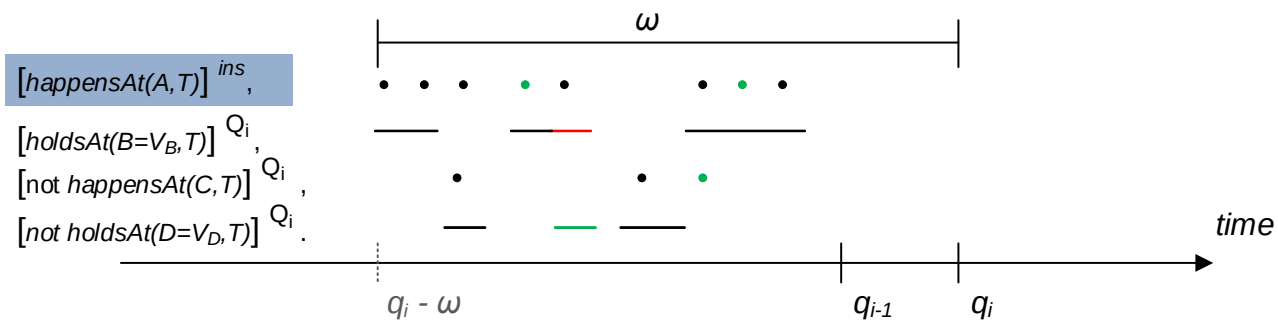
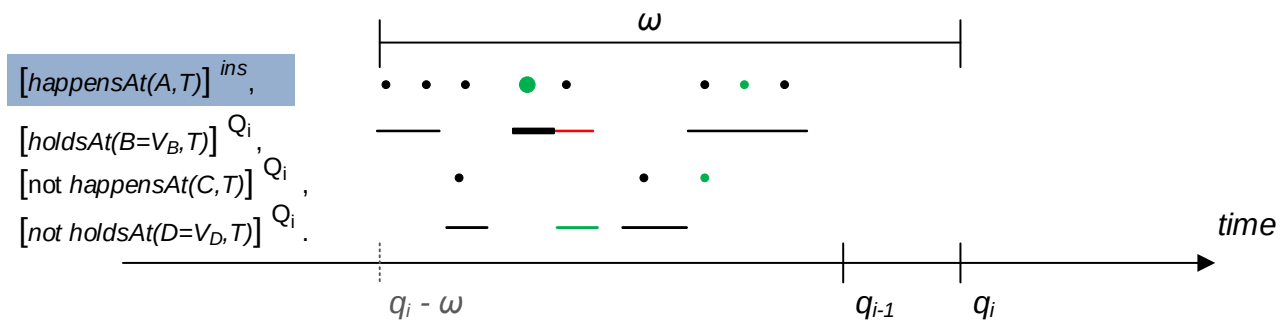


Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

Incremental Reasoning: Addition Phase



Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

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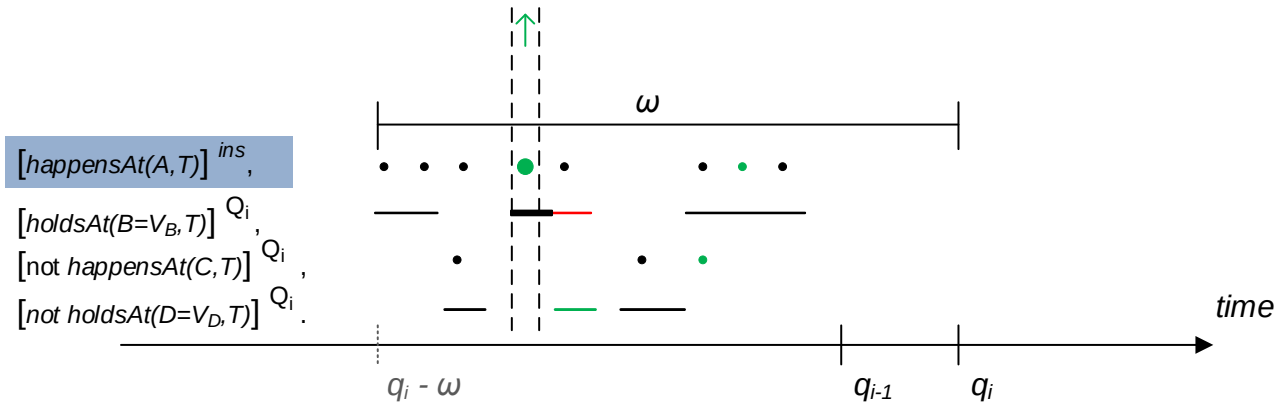

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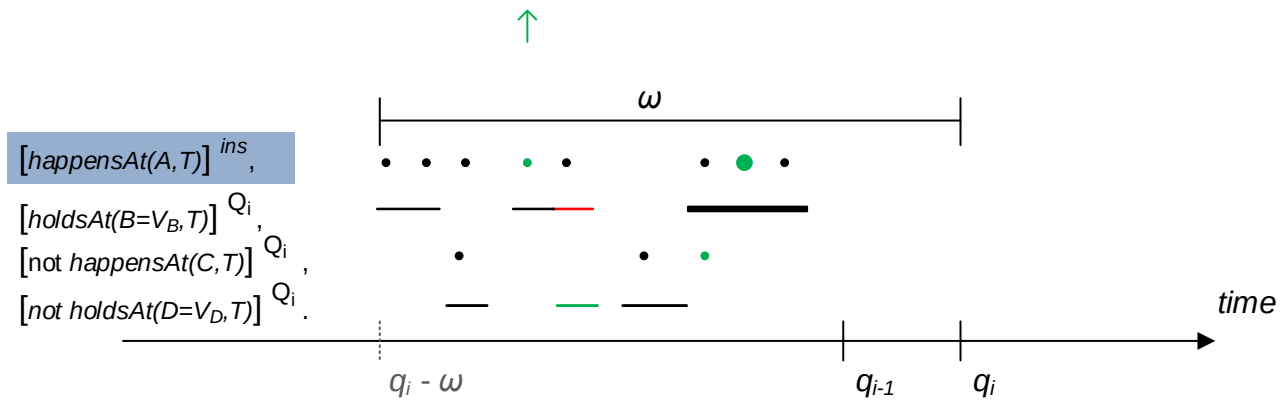

Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

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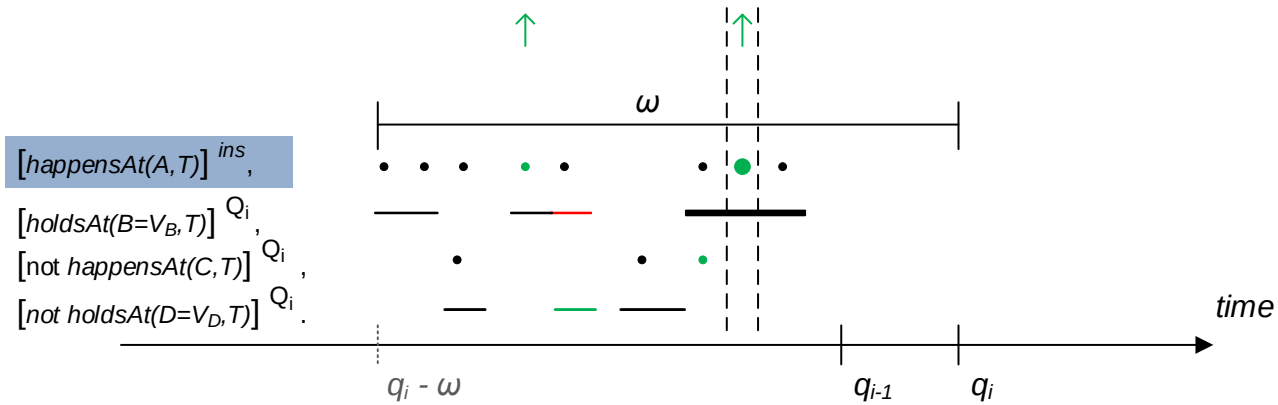
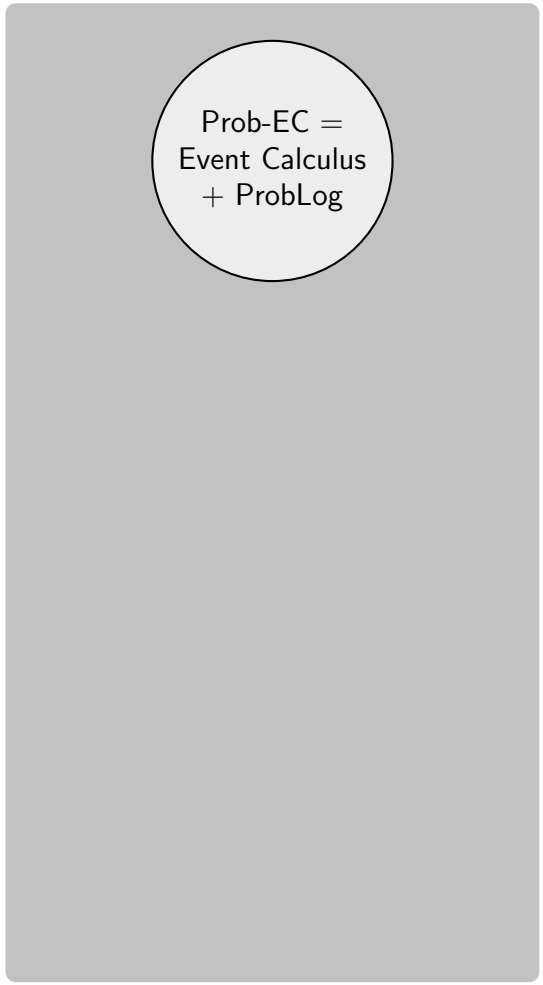


Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

Noisy Data Streams: A Probabilistic Event Calculus



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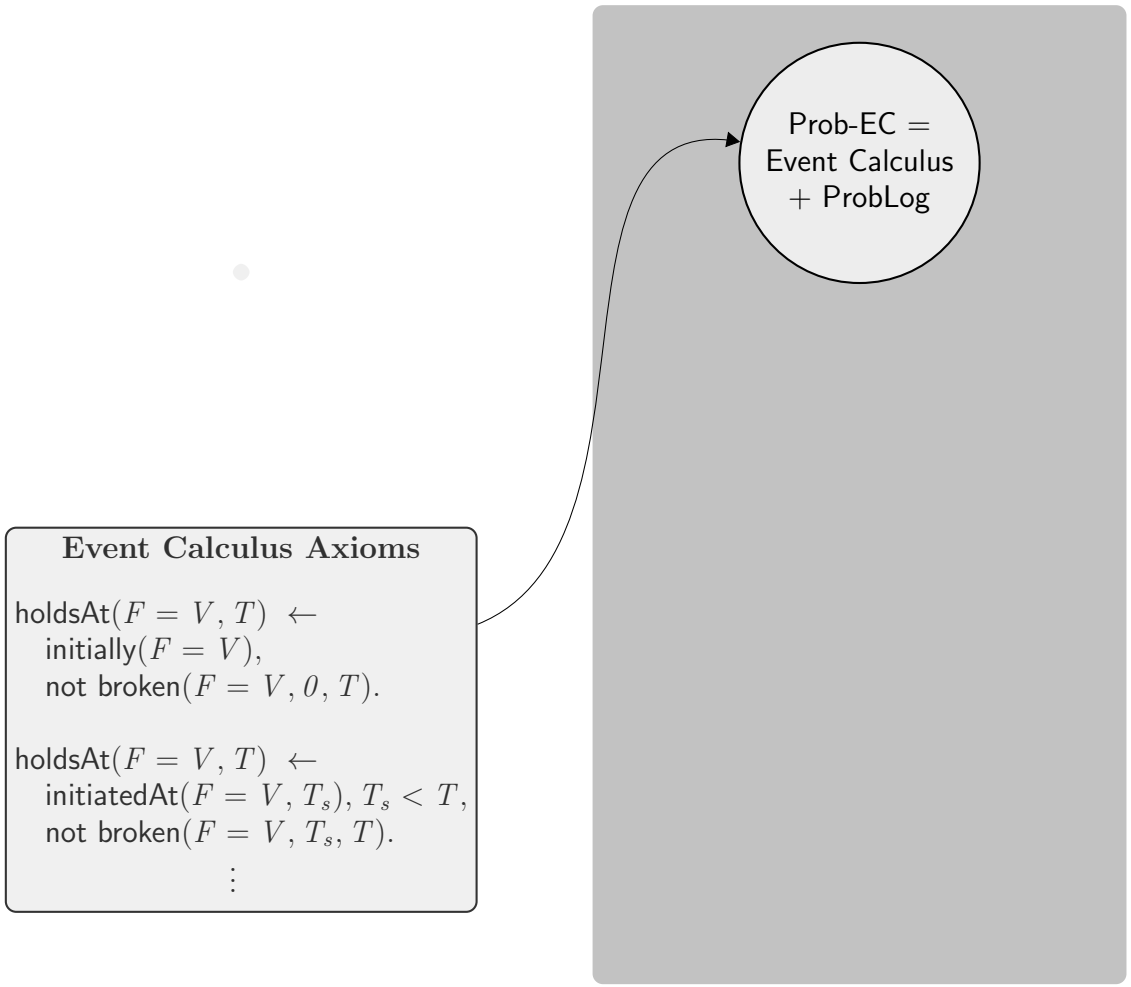

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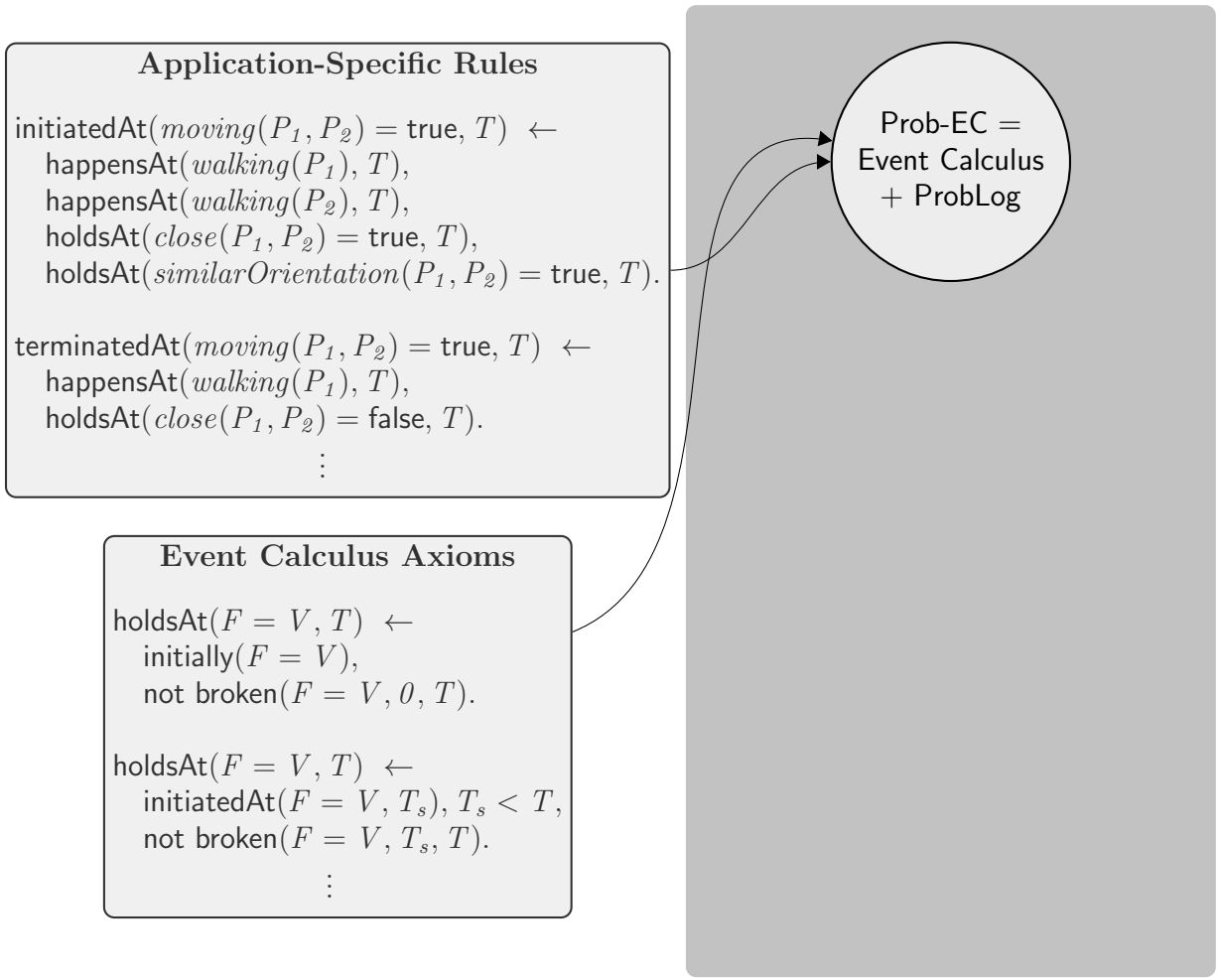

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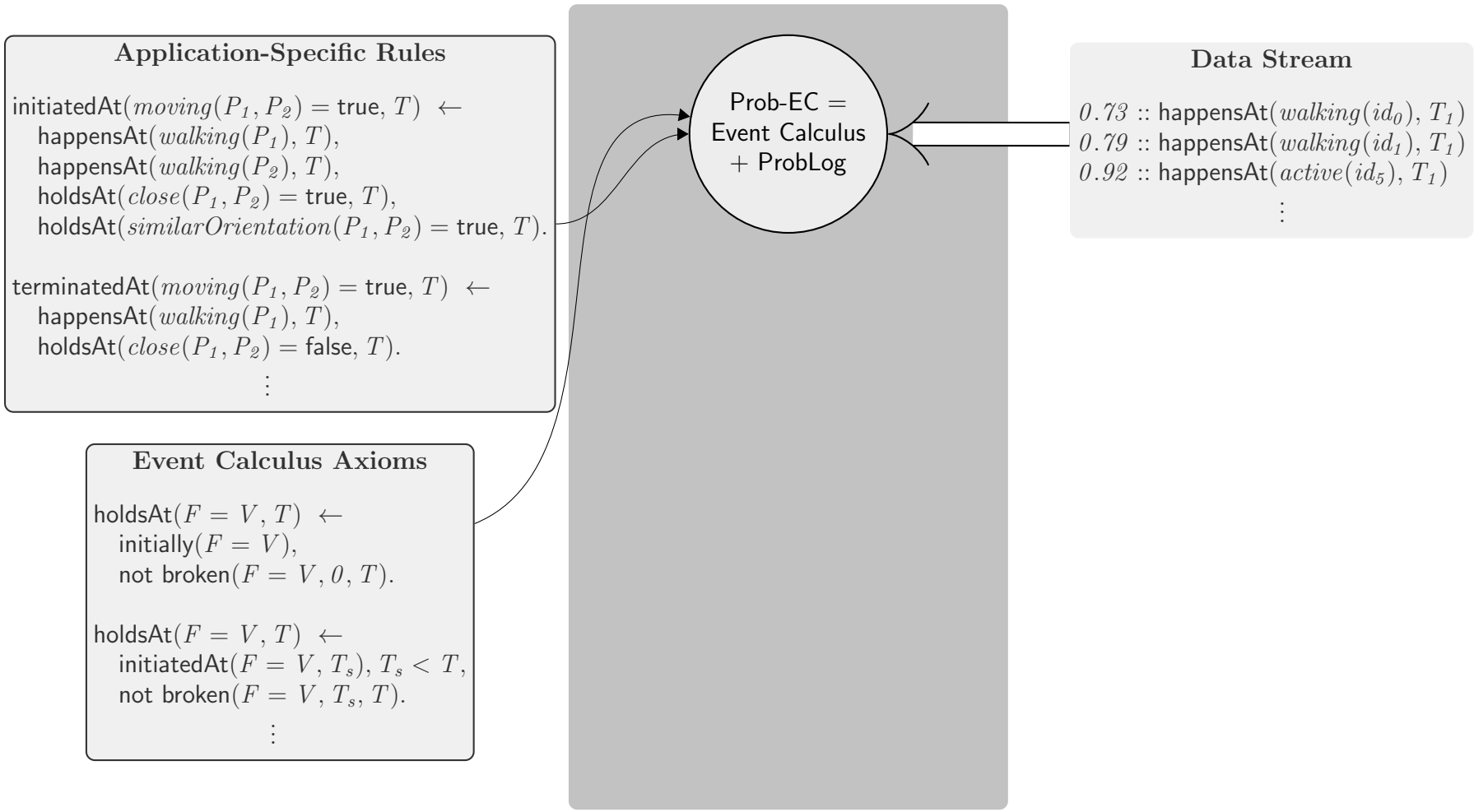

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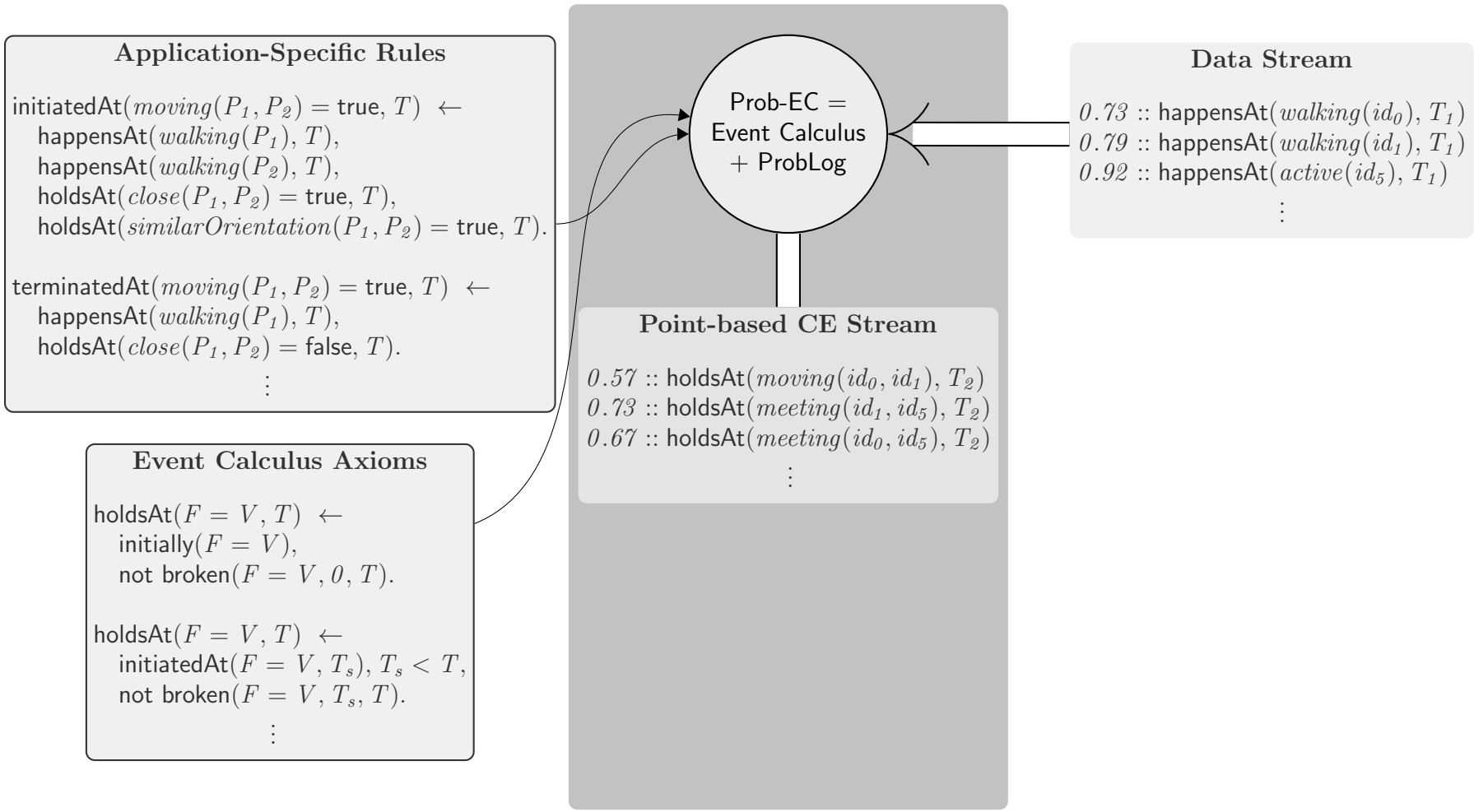

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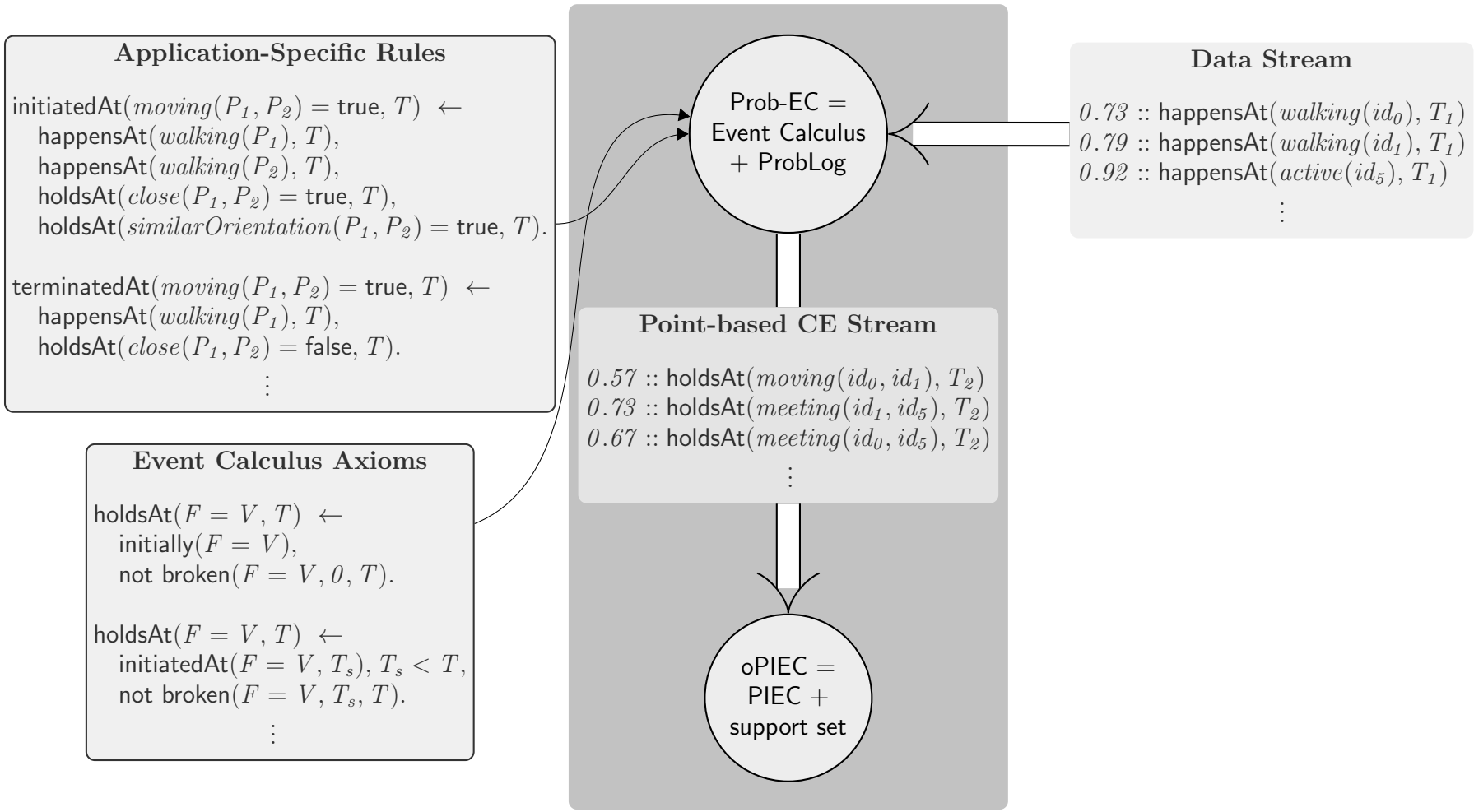

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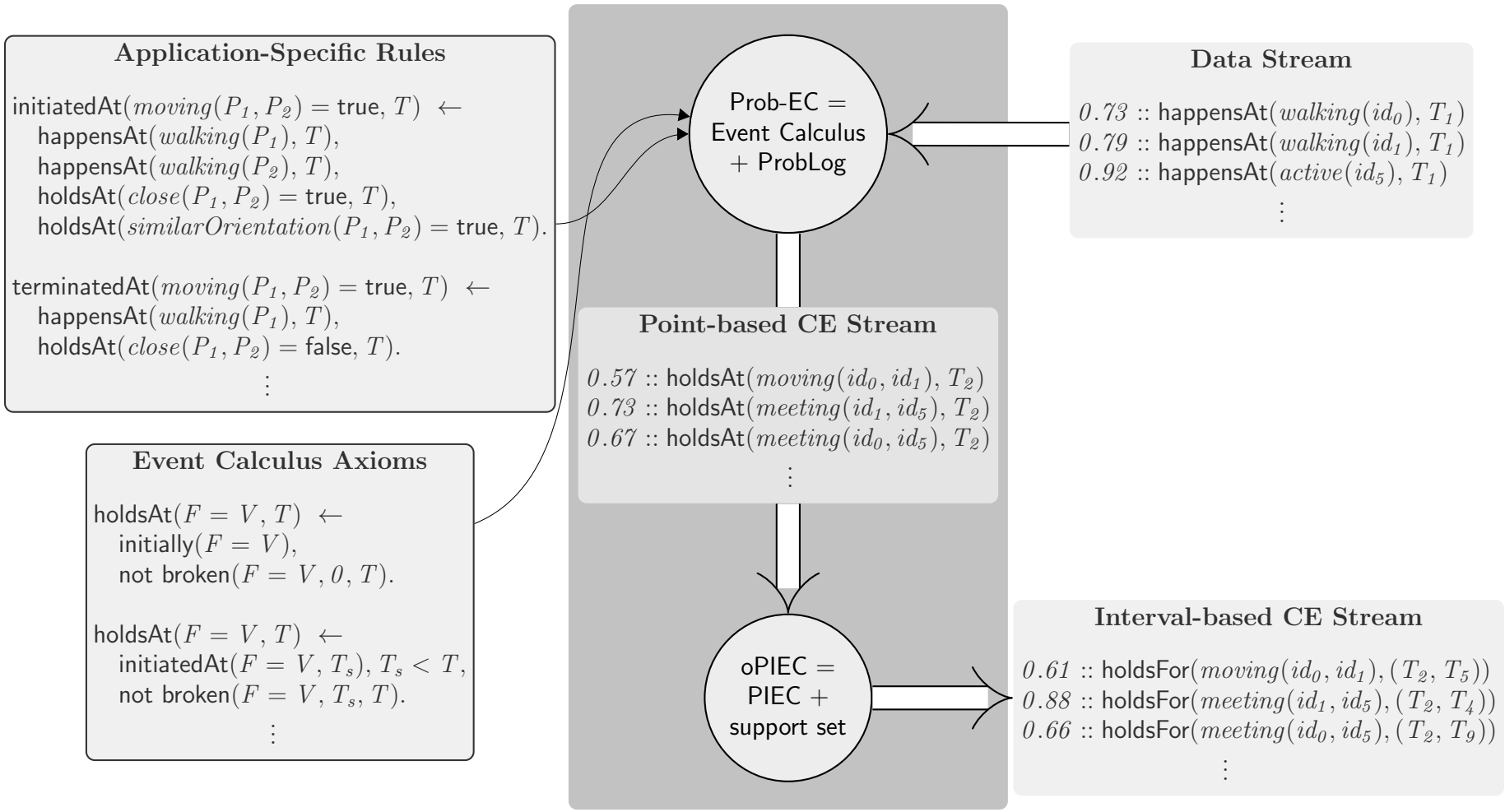
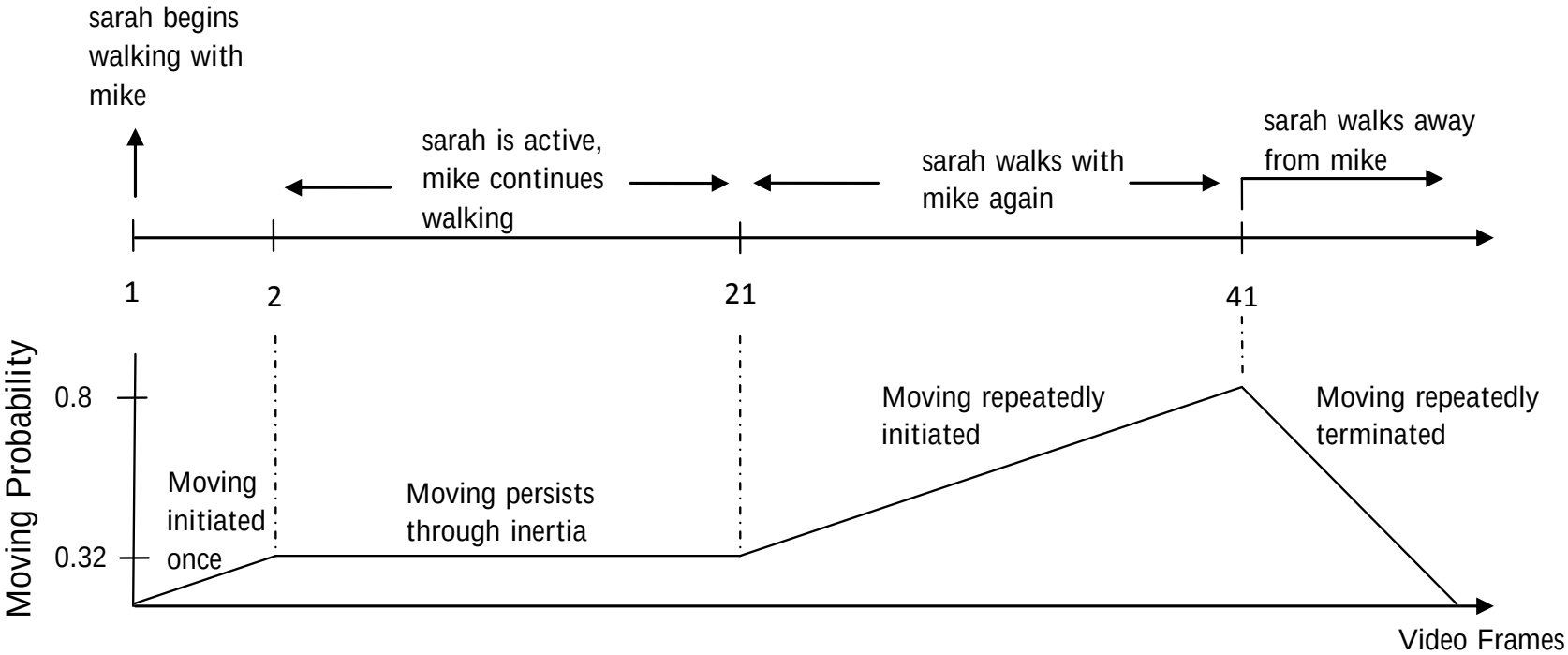


Human Activity Recognition

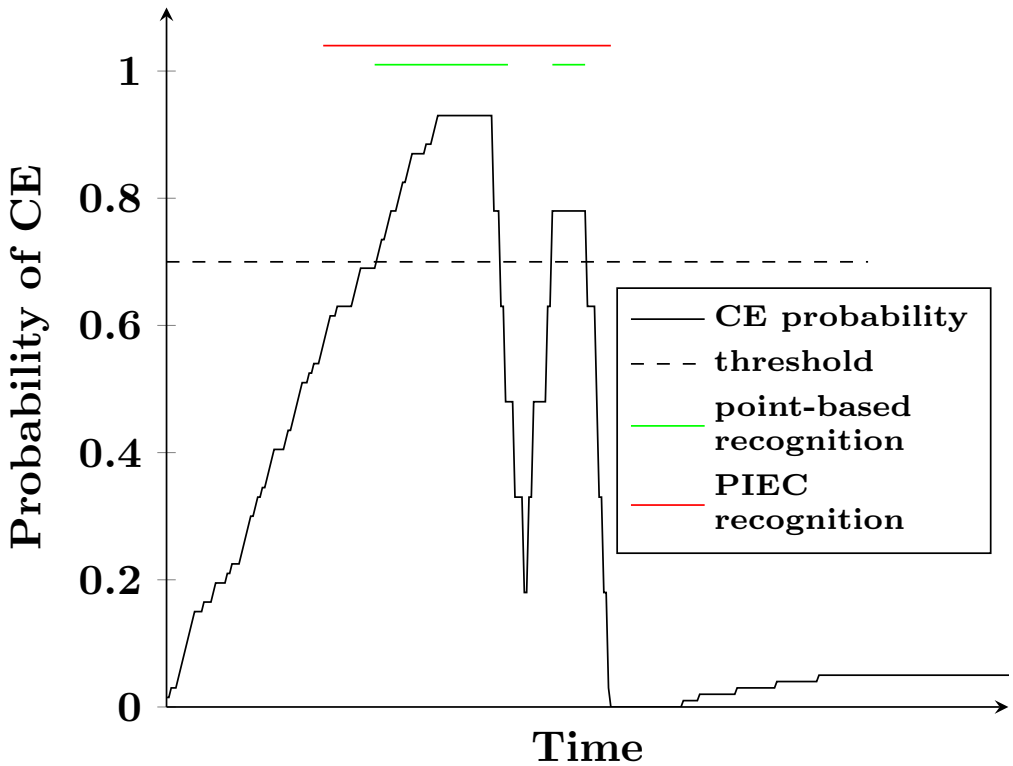


$\text{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
$\quad \text{happensAt}(\mathit{walking}(P_1),\ T),$
$\quad \text{happensAt}(\mathit{walking}(P_2),\ T),$
$\quad \text{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$
$\quad \text{holdsAt}(\mathit{similarOrientation}(P_1, P_2) = \text{true},\ T).$

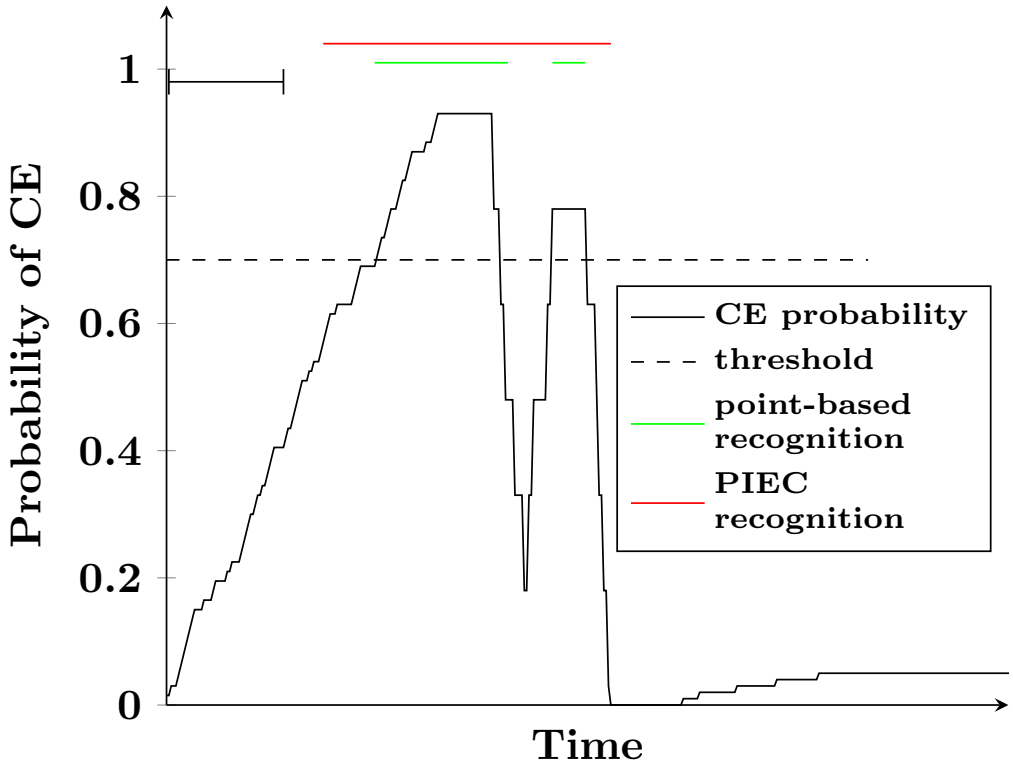
$\text{terminatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
$\quad \text{happensAt}(\mathit{walking}(P_1),\ T),$
$\quad \text{holdsAt}(\mathit{close}(P_1, P_2) = \text{false},\ T).$

$0.70 :: \text{happensAt}(\mathit{walking}(\mathit{mike}),\ 1).$
$0.46 :: \text{happensAt}(\mathit{walking}(\mathit{sarah}),\ 1).$
$0.73 :: \text{happensAt}(\mathit{walking}(\mathit{mike}),\ 2).$
$0.55 :: \text{happensAt}(\mathit{active}(\mathit{sarah}),\ 2).$
$0.69 :: \text{happensAt}(\mathit{walking}(\mathit{mike}),\ 21).$
$0.58 :: \text{happensAt}(\mathit{walking}(\mathit{sarah}),\ 21).$
$0.18 :: \text{happensAt}(\mathit{inactive}(\mathit{mike}),\ 41).$
$0.32 :: \text{happensAt}(\mathit{walking}(\mathit{sarah}),\ 41).$

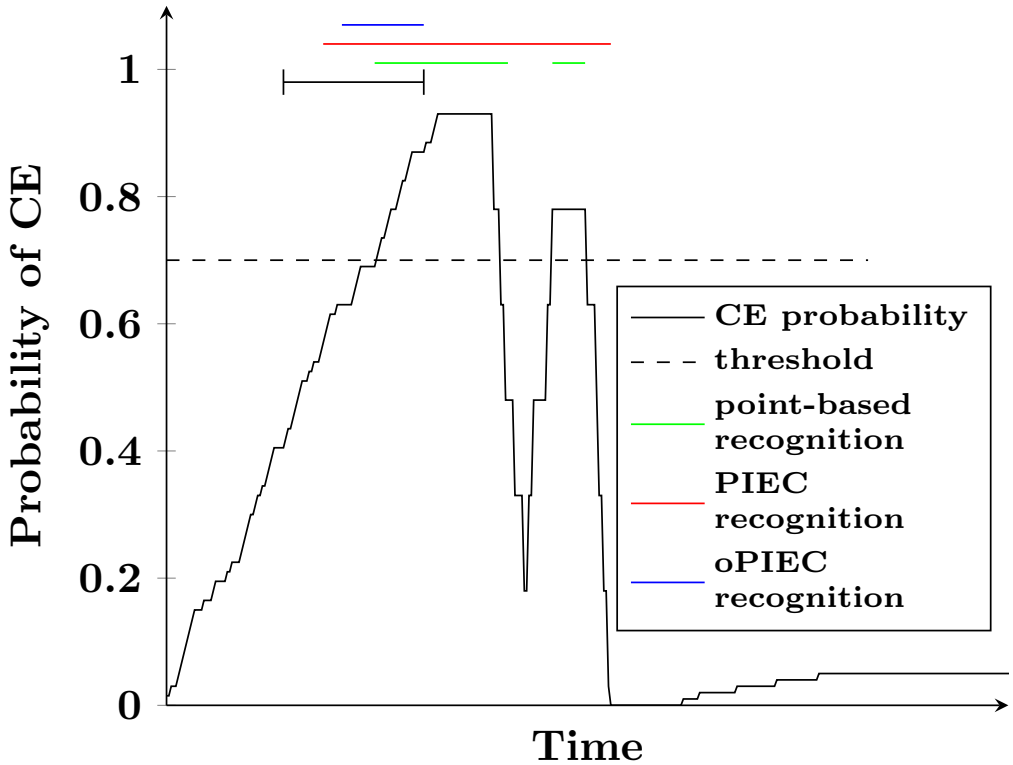
Instantaneous vs Interval-based Recognition



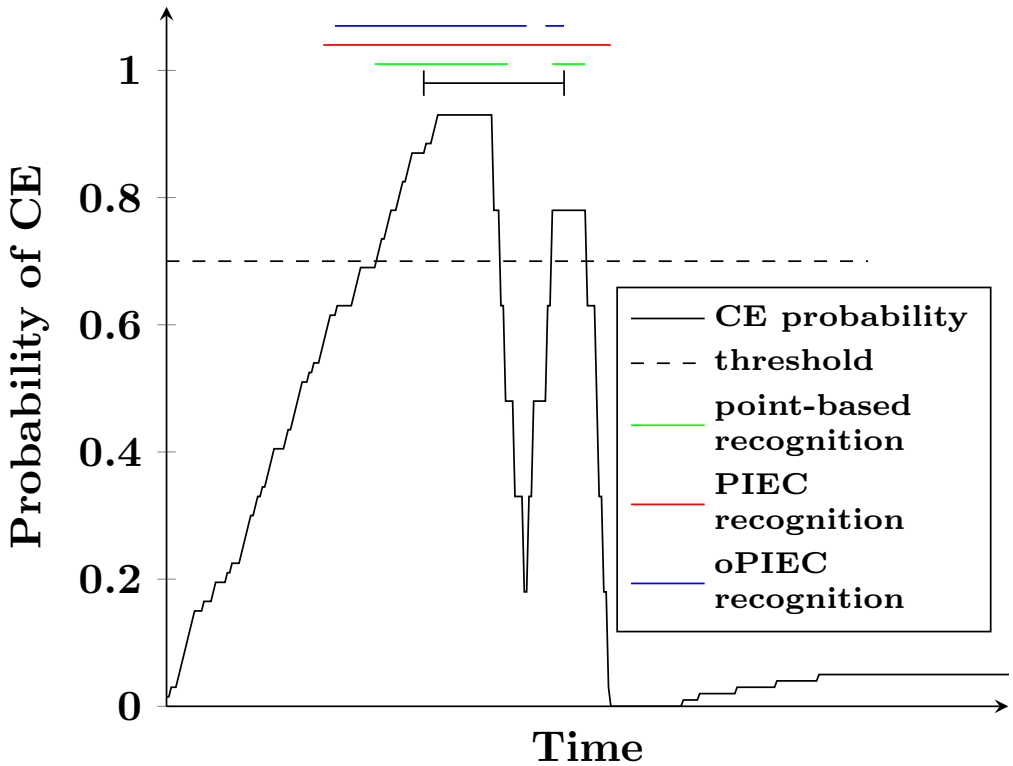
Online Interval-based Recognition



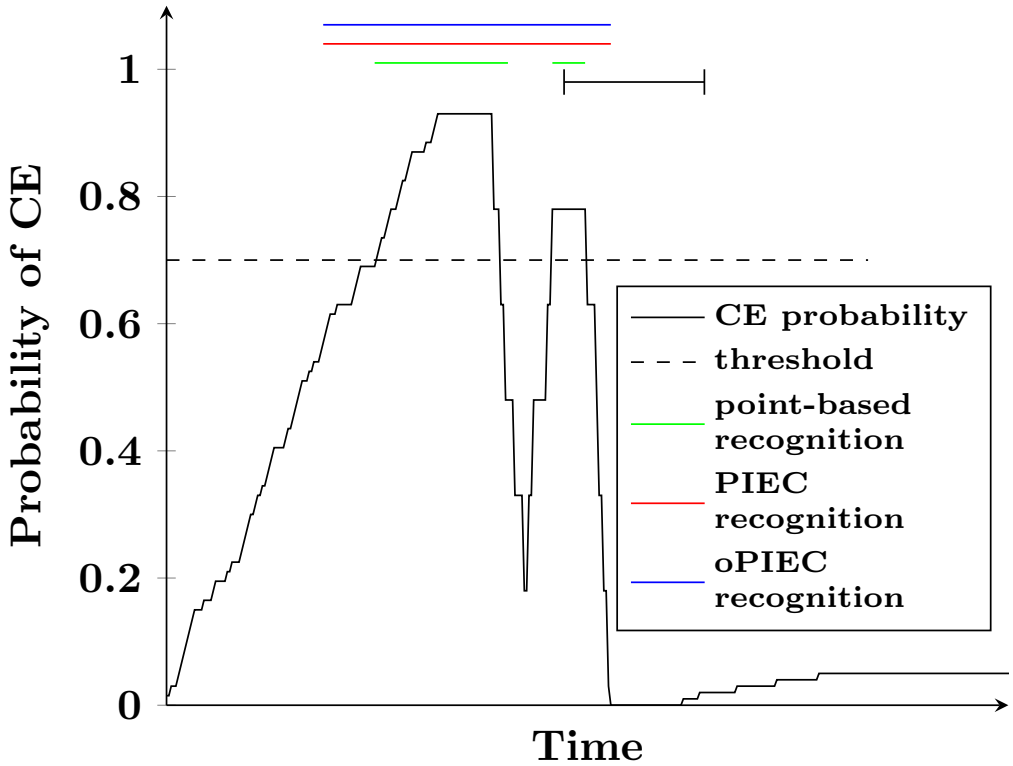
Online Interval-based Recognition



Online Interval-based Recognition



Online Interval-based Recognition



- Optimal stream history compression.
- Comparable accuracy to batch processing with very small memory.

Mantenoglou et al, Online Probabilistic Interval-based Event Calculus. European Conference on AI (ECAI), 2020.

https://github.com/Periklismant/oPIEC

Topics not covered

- Uncertainty in the event patterns*.
- Automated construction of event patterns†.
  - Semi-supervised ML‡.
- Neuro-symbolic reasoning for end-to-end CER◇.
- **Other approaches on formal CER▽**.
- Complex event forecasting♠.

* *Alevizos et al, Probabilistic Complex Event Recognition: A Survey. ACM Computing Surveys, 2017.*

† *Katzouris et al, Online Learning Probabilistic Event Calculus Theories in Answer Set Programming. Theory and Practice of Logic Programming, 2022.* https://github.com/nkatzz/ORL

‡ *Michelioudakis et al, Semi-Supervised Online Structure Learning for Composite Event Recognition. Machine Learning, 2019.* https://github.com/anskarl/LoMRF

◇ *Manhaeve et al, Neural probabilistic logic programming in DeepProbLog. Artificial Intelligence, 2021.* https://github.com/ML-KULeuven/deepproblog

▽ *Artikis et al, Dagstuhl Seminar on the Foundations of Composite Event Recognition. SIGMOD Record, 2020.*

♠ *Alevizos et al, Complex Event Forecasting with Prediction Suffix Trees. VLDB Journal, 2022.* https://github.com/ElAlev/Wayeb