Reasoning over Complex Temporal Specifications and Noisy Data Streams

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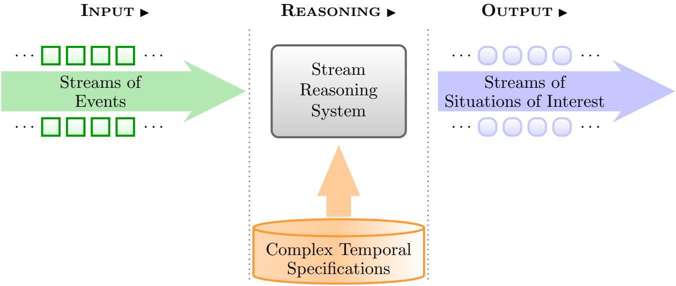
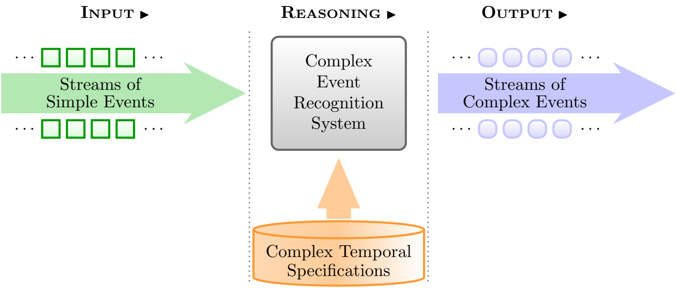
NCSR Demokritos, Greece

Stream Reasoning



Complex Event Recognition



Requirements and Motivation

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- Temporal specification language:
  - Formal, declarative formalism.

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  - Wide range of temporal specifications.

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- Highly efficient reasoning algorithms:
  - Windowing.

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- Run-Time Event Calculus (RTEC):
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- Probabilistic Interval-based Event Calculus (PIEC):
  - Event Calculus + noisy events.

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Motivation: No framework fulfills all requirements.

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- RTEC_{o}: RTEC + cyclic dependencies.
- $\text{RTEC}^{\rightarrow}$: RTEC + events with delayed effects.
- RTEC_{A}: RTEC + Allen relations.

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- $\mathsf{RTEC}_{\mathsf{A}}$: RTEC + Allen relations.
- oPIEC: PIEC + data streams.

Publications

Journal Publications:

- Mantenoglou P., Pitsikalis M., Artikis A., *Reasoning over Streams of Events with Delayed Effects.*
  In *IEEE Transactions on Knowledge and Data Engineering (TKDE)*, **under review since January 2024**.
- Mantenoglou P., Artikis A., Paliouras G., *Online Event Recognition over Noisy Data Streams.*
  In *International Journal of Approximate Reasoning (IJAR)*, 161, 2023.
  DOI: *https://doi.org/10.1016/j.ijar.2023.108993*

Conference Publications:

- Mantenoglou P., Kelesis D., Artikis A., *Complex Event Recognition with Allen Relations.*
  In *Proceedings of the 20th International Conference on Principles of Knowledge Representation and Reasoning (KR)*, pp. 502–511, 2023.
  DOI: *https://doi.org/10.24963/kr.2023/49*
- Mantenoglou P., Pitsikalis M., Artikis A., *Stream Reasoning with Cycles.*
  In *Proceedings of the 19th International Conference on Principles of Knowledge Representation and Reasoning (KR)*, pp. 533–553, 2022.
  DOI: *https://doi.org/10.24963/kr.2022/56*
- Mantenoglou P., Artikis A., Paliouras G., *Online Probabilistic Interval-based Event Calculus.*
  In *Proceedings of the 24th European Conference on Artificial Intelligence (ECAI)*, pp. 2624–2631, 2020.
  DOI: *https://doi.org/10.3233/FAIA200399*

Peripheral Publication:

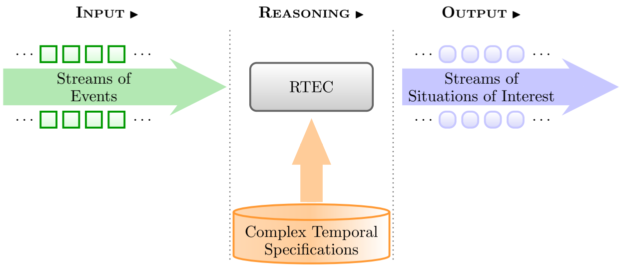
- Andrienko N., Andrienko G., Artikis A., Mantenoglou P., Rinzivillo S., *Human-in-the-Loop: Visual Analytics for Building Models Recognising Behavioural Patterns in Time Series.*
  In *IEEE Computer Graphics and Applications (CG&A)*, pp. 1–15, 2024.
  DOI: *https://doi.org/10.1109/MCG.2024.3379851*

Event Calculus

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
holdsAt$(F = V, T)$	The value of fluent F is V at time T
holdsFor$(F = V, I)$	I is the list of the maximal intervals for which $F = V$ holds continuously

Kowalski et al., A Logic-based Calculus of Events. New Gener. Comput. 4(1): 67–95, 1986.

Stream Reasoning with RTEC



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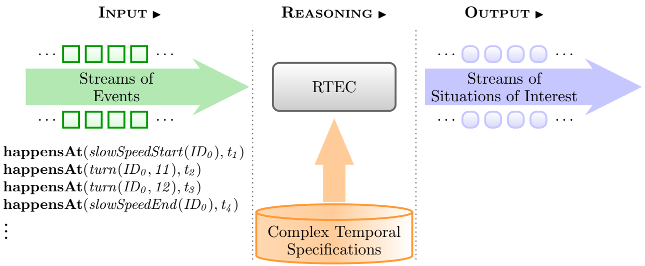

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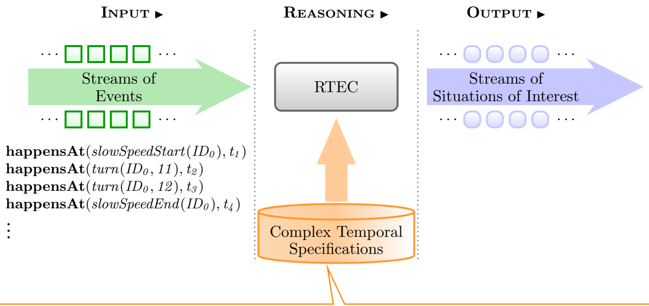

$\mathbf{initiatedAt}(stopped(Vessel) = nearPorts, T) \leftarrow$
$\quad \mathbf{happensAt}(stop\_start(Vessel), T),$
$\quad \mathbf{holdsAt}(withinArea(Vessel, nearPorts) = \mathsf{true}, T).$

$\mathbf{terminatedAt}(stopped(Vessel) = nearPorts, T) \leftarrow$
$\quad \mathbf{happensAt}(stop\_end(Vessel), T).$

⋮

$\mathbf{holdsFor}(trawling(Vessel) = \mathsf{true}, I) \leftarrow$
$\quad \mathbf{holdsFor}(trawlingMovement(Vessel) = \mathsf{true}, I_{tc}),$
$\quad \mathbf{holdsFor}(trawlingSpeed(Vessel) = \mathsf{true}, I_t),$
$\quad \mathbf{intersect\_all}([I_{tc}, I_t], I_i),$
$\quad threshold(v_{trawl}, V_{trawl}),$
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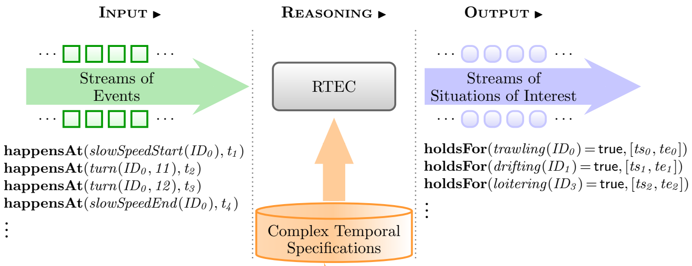

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Simple Fluent: High Speed Near Coast

$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}, \_\mathit{CoG}, \_\mathit{TrueHeading}), T), \\
&\quad \textbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \text{true}, T), \\
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\end{aligned}
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initiatedAt(*highSpeedNC*(*Vessel*) = true, T) $\leftarrow$
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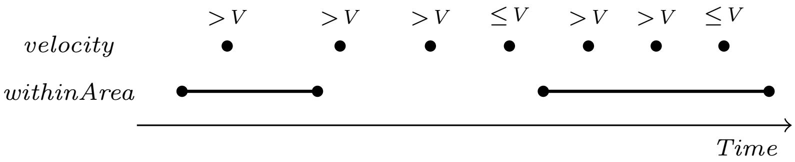
Reasoning: **holdsFor**(*highSpeedNC*(*Vessel*) = true, I)



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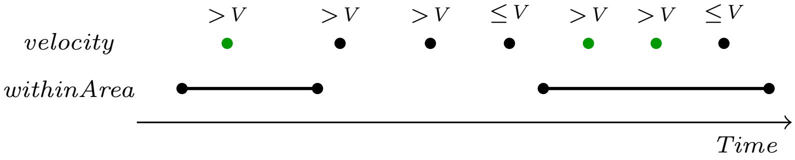

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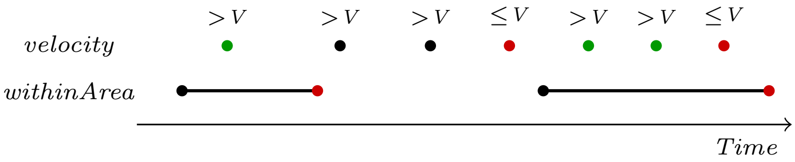

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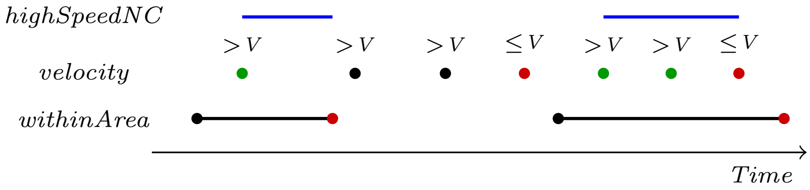
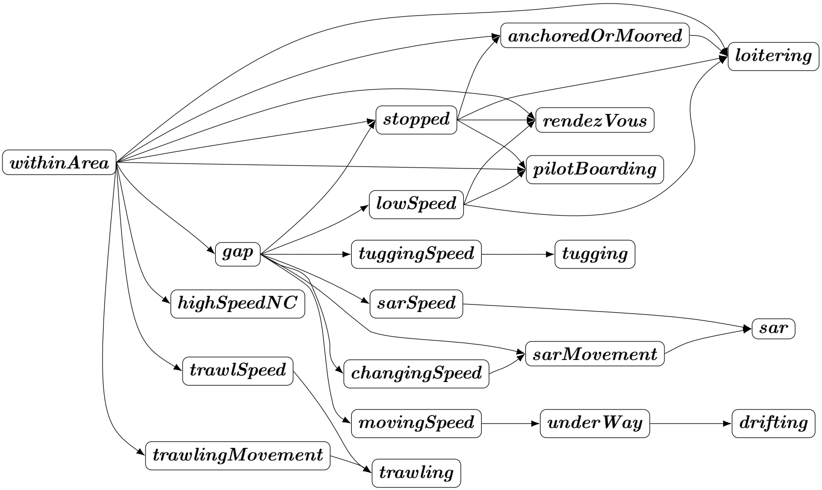


Hierarchical Knowledge Bases



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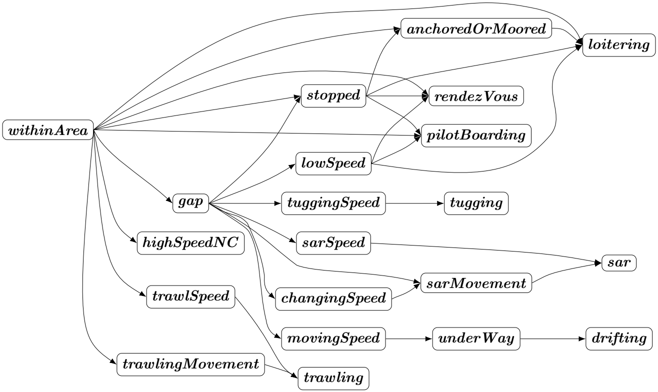
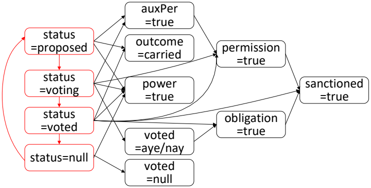


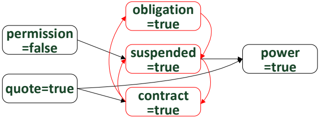
Semantics

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

Cyclic Dependencies in Temporal Patterns

- Multi-Agent Systems: Voting & NetBill.





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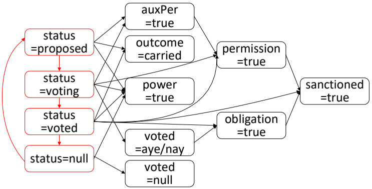
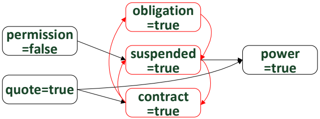
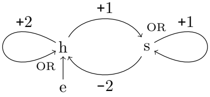
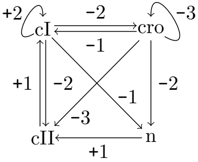




- Biological Feedback Processes.





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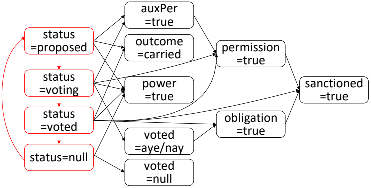

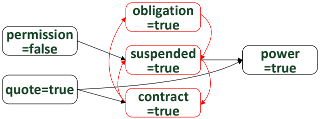

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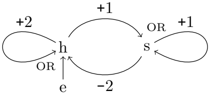
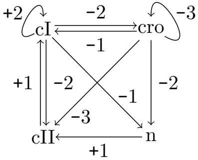
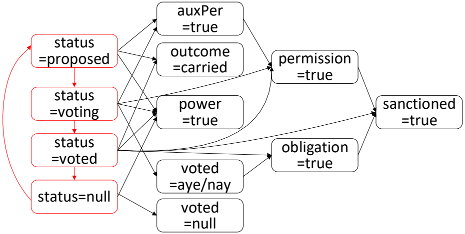




- Maritime Situational Awareness: the stages of a fishing trip, i.e., *started*, *fishing*, *returning*, *ended*, form a cycle.

1. RTEC$_o$: Cyclic Dependencies



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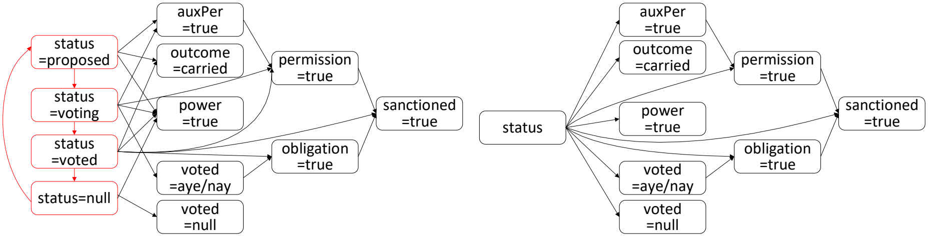

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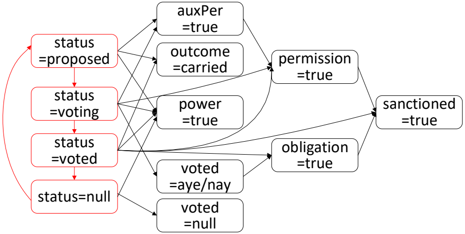

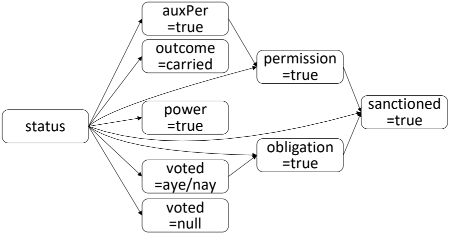

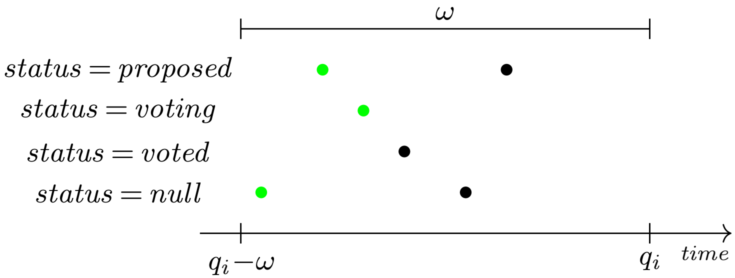

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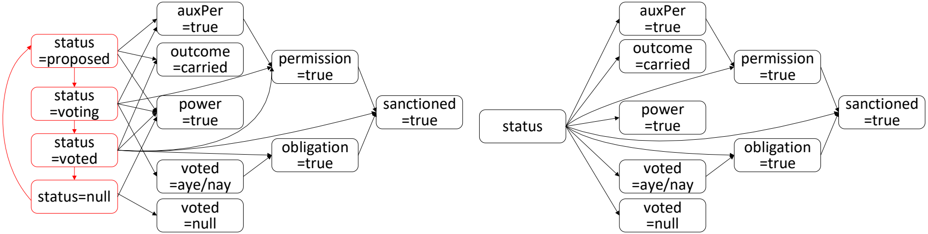

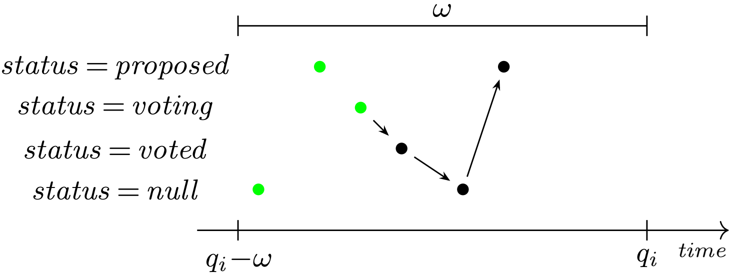

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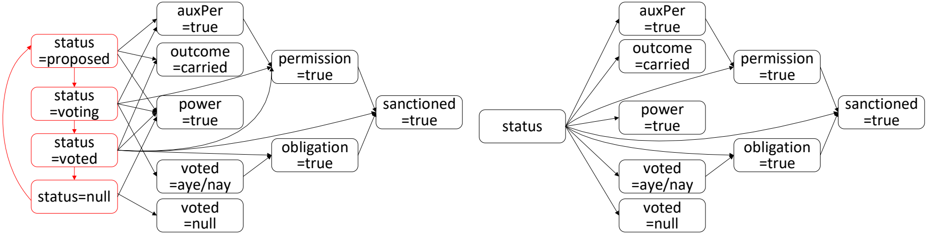

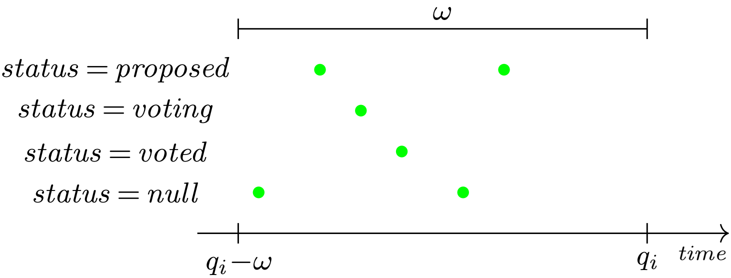

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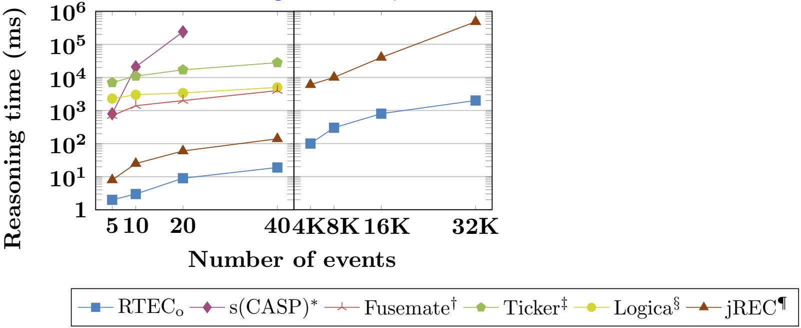

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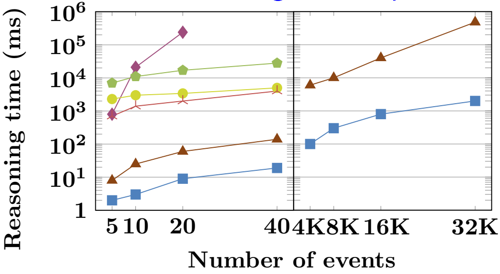
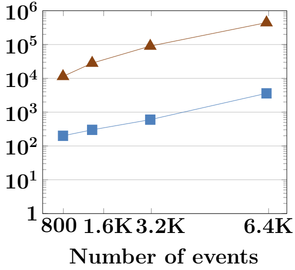
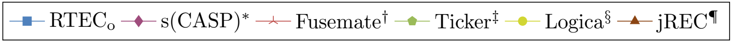


Voting: monitoring the status of motions (cycles)





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Events with Delayed Effects

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- RTEC supports only immediate initiations:

$\textbf{initiatedAt}(F = V, T) \leftarrow$
$\quad \textbf{happensAt}(E, T)[,$
$\quad \text{conditions}].$

where conditions:
$^{0-K}$[not] $\textbf{happensAt}(E_k, T)$,
$^{0-M}$[not] $\textbf{holdsAt}(F_m = V_m, T)$,
$^{0-N}$atemporal-constraint$_n$.

2. RTEC$^{\rightarrow}$: Events with Delayed Effects

- RTEC$^{\rightarrow}$: Representation of future initiations:
  - $\mathbf{fi}(quote(M, C, G) = in\_effect, quote(M, C, G) = expiring, 50)$.

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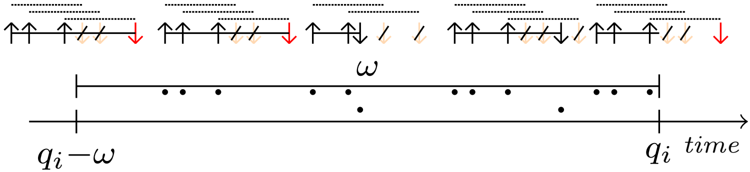

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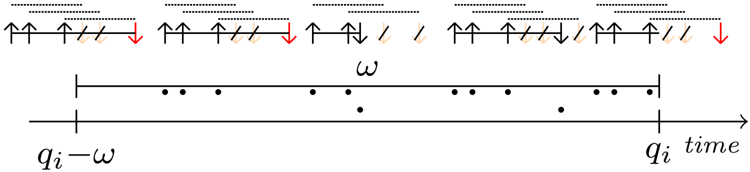

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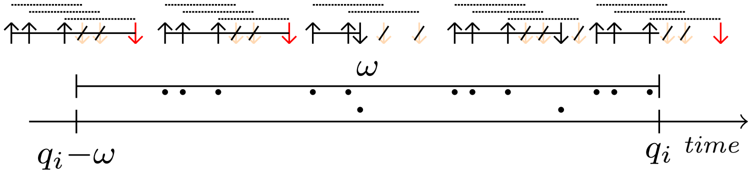

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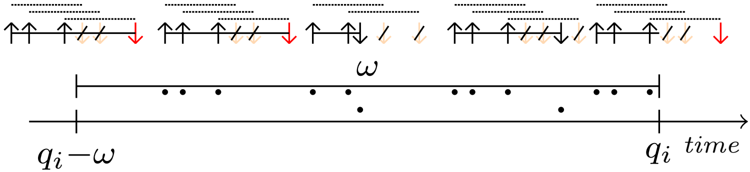

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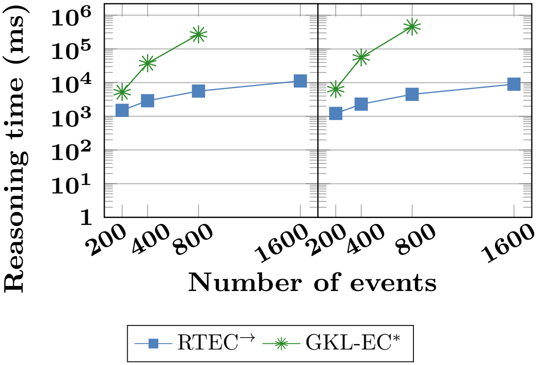
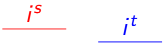
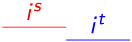
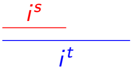
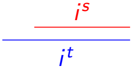
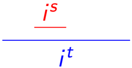
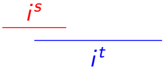
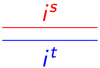
Biological Processes: Immune Response and Phage Infection (delayed effects & cycles)



*Srinivasan et al., Learning explanations for biological feedback with delays using an event calculus. Machine Learning, 2022.

The Relations of Allen's Interval Algebra

Relation	**Illustration**
before(i^s, i^t)	
meets(i^s, i^t)	
starts(i^s, i^t)	
finishes(i^s, i^t)	
during(i^s, i^t)	
overlaps(i^s, i^t)	
equal(i^s, i^t)	

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$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{disappearedInArea}(\mathit{Vessel}, \mathit{AreaType}) = \mathrm{true}, I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{AreaType}) = \mathrm{true}, \mathcal{S}), \\
&\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}), \\
&\quad \textbf{allen}(\mathrm{meets}, \mathcal{S}, \mathcal{T}, \mathrm{target}, I).
\end{aligned}
$$

Mantenoglou et al., Complex Event Recognition with Allen Relations. In International Conference on Principles of Knowledge Representation and Reasoning (KR), 502–511, 2023.

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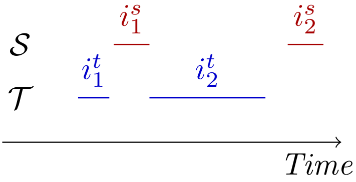

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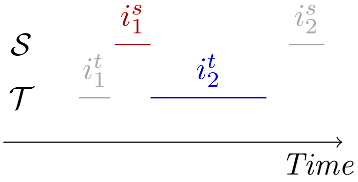

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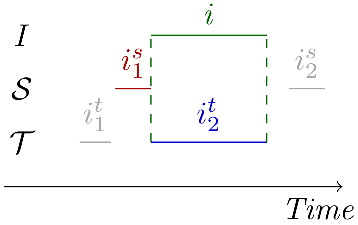

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Monitoring maritime activities with Allen relations

Window size		Reasoning Time (ms)		Output Intervals	
Days	Input Intervals	$RTEC_A$	D^2IA^*	$RTEC_A$	D^2IA^*
1	19K	40	410	6K	6K
2	37K	65	592	9K	9K
4	74K	99	1.1K	16K	16K
8	148K	156	1.6K	32K	31K
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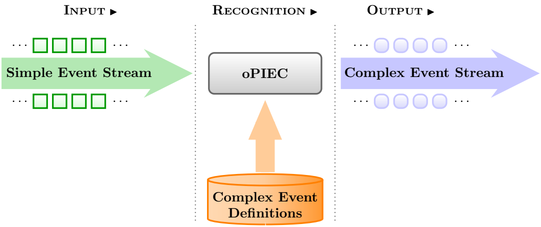

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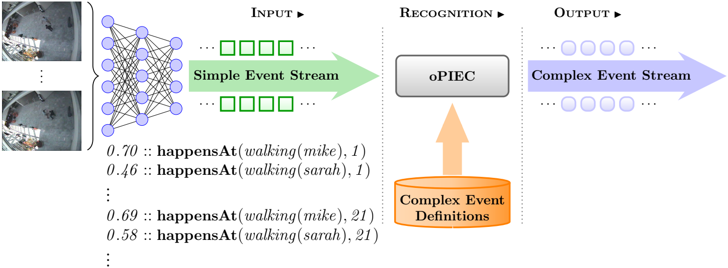

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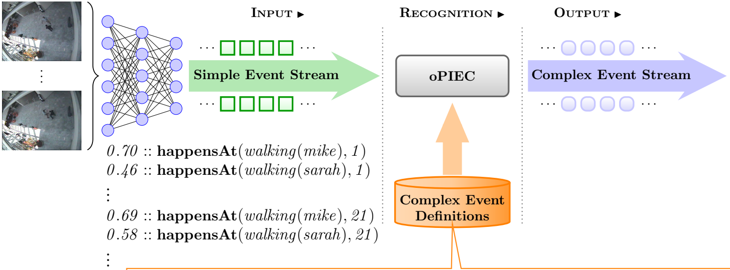

$\textbf{initiatedAt}(moving(P_1, P_2) = \mathsf{true},\ T) \leftarrow$
$\quad \textbf{happensAt}(walking(P_1),\ T),$
$\quad \textbf{happensAt}(walking(P_2),\ T),$
$\quad \textbf{holdsAt}(close(P_1, P_2) = \mathsf{true},\ T),$
$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \mathsf{true},\ T).$

⋮

$\textbf{terminatedAt}(moving(P_1, P_2) = \mathsf{true},\ T) \leftarrow$
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⋮

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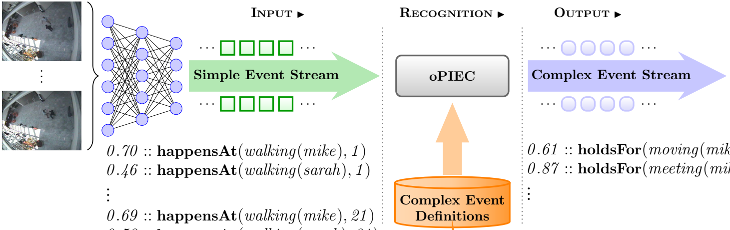

0.70 :: **happensAt**$(walking(mike), 1)$
0.46 :: **happensAt**$(walking(sarah), 1)$
⋮
0.69 :: **happensAt**$(walking(mike), 21)$
0.58 :: **happensAt**$(walking(sarah), 21)$
⋮

0.61 :: **holdsFor**$(moving(mike, sarah) = \text{true}, [2, 18])$
0.87 :: **holdsFor**$(meeting(mike, sarah) = \text{true}, [16, 29])$
⋮

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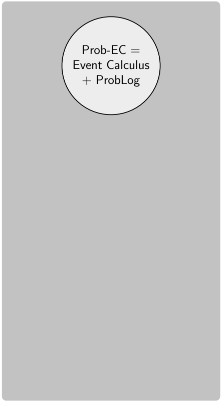

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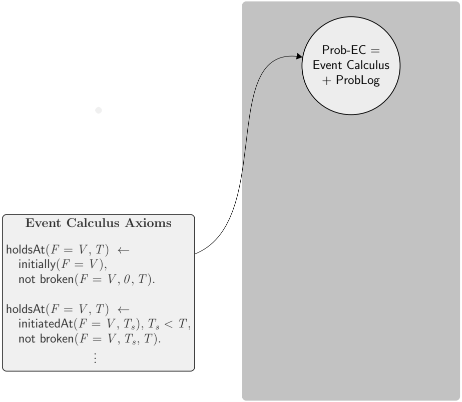

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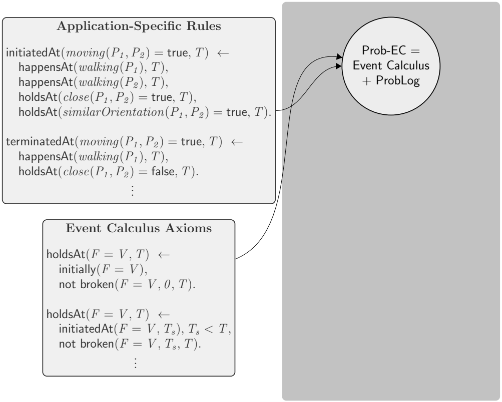

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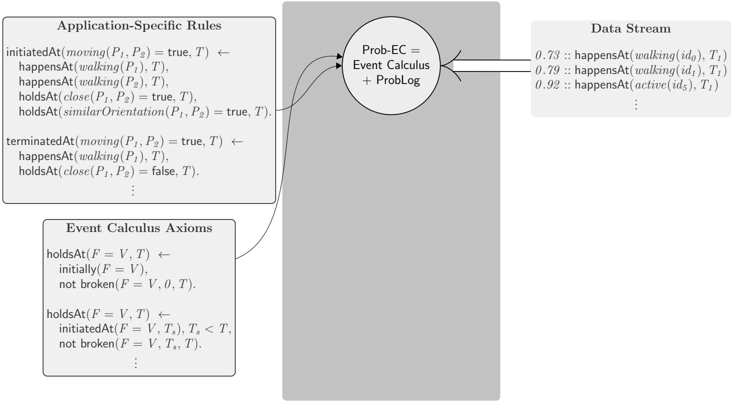

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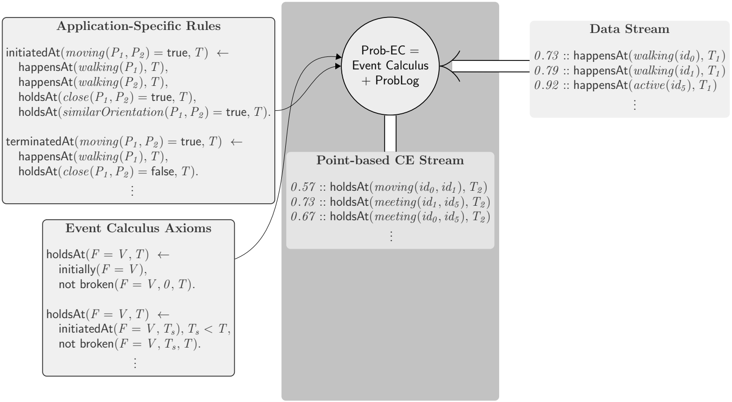
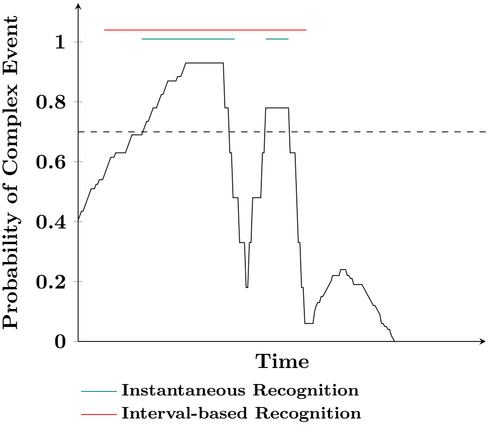


Time-points vs Temporal Intervals



Artikis et al., A Probabilistic Interval-based Event Calculus for Activity Recognition. Annals of Mathematics and Artificial Intelligence, 2021.

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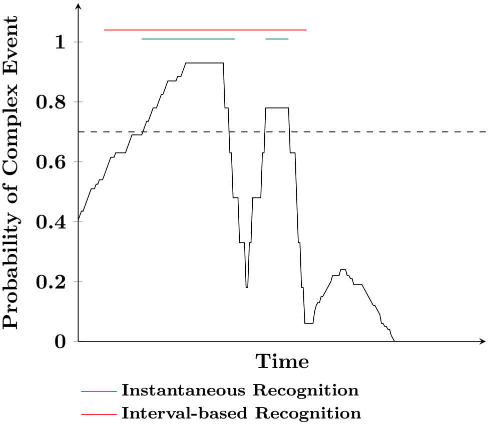

- Interval Probability: average probability of the time-points it contains.

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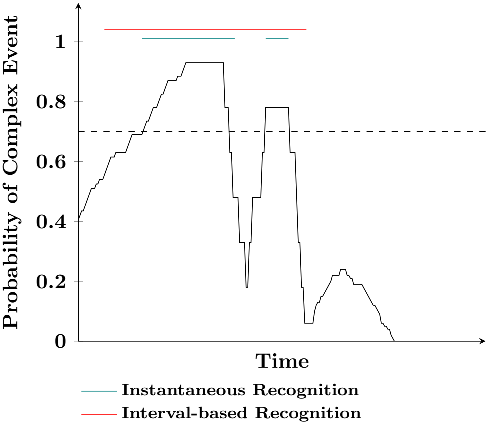
Time-points vs Temporal Intervals



- Interval Probability: average probability of the time-points it contains.
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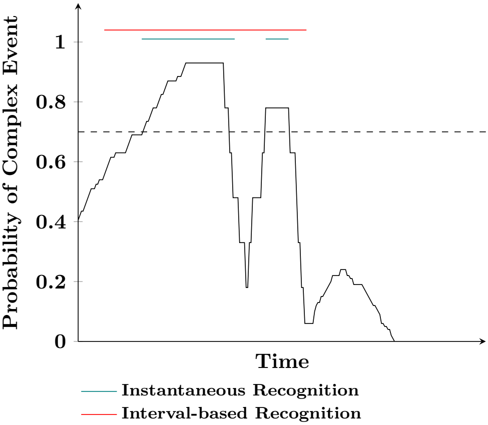

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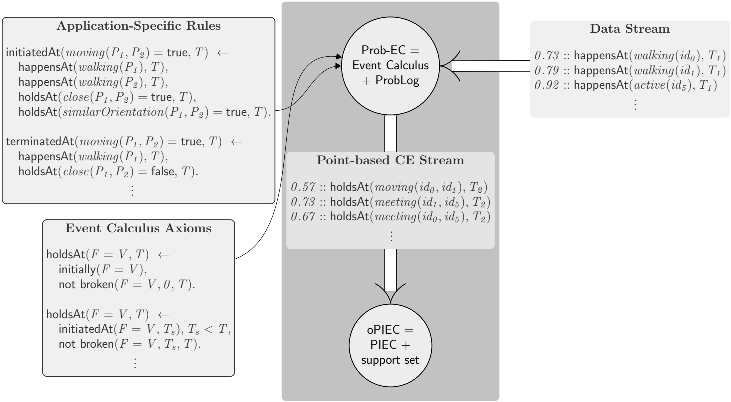

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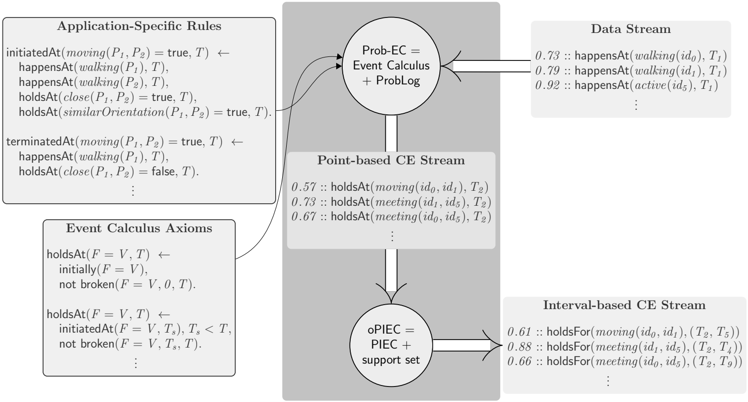
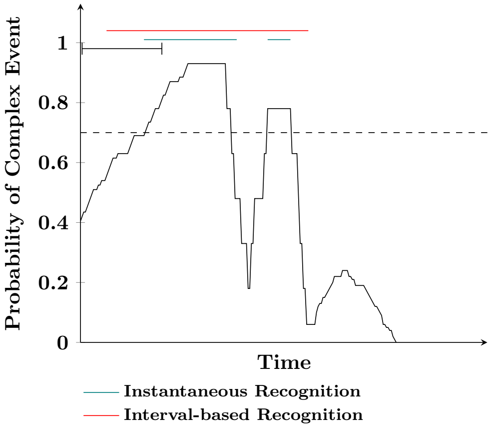


4. Online Interval-based Recognition with oPIEC



- Windowing.

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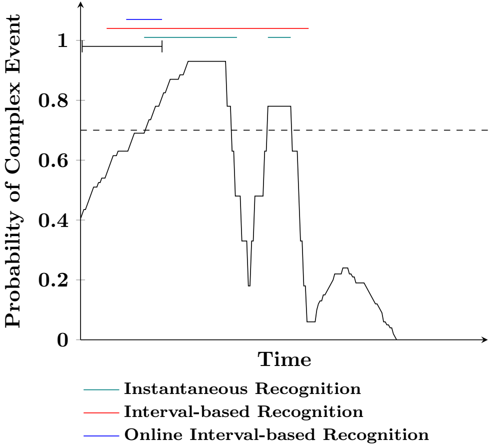

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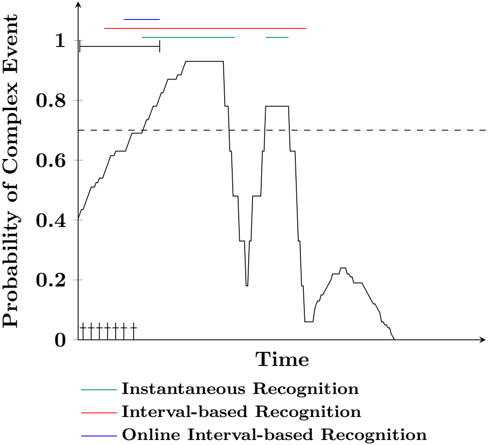

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- Probabilistic maximal interval computation.
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  - Discard time-point t iff there is a $t' < t$ that can be the starting point of a probabilistic maximal interval including t.

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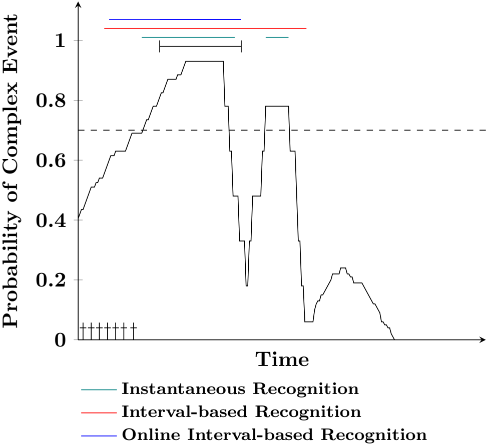

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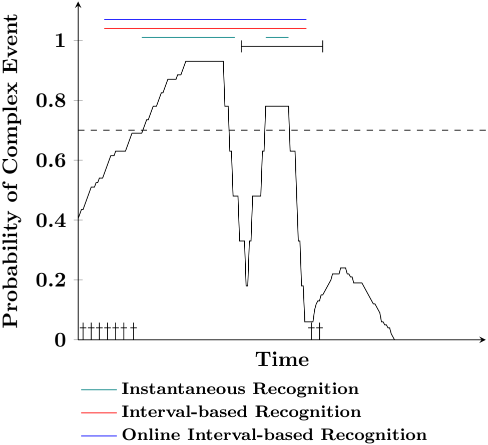

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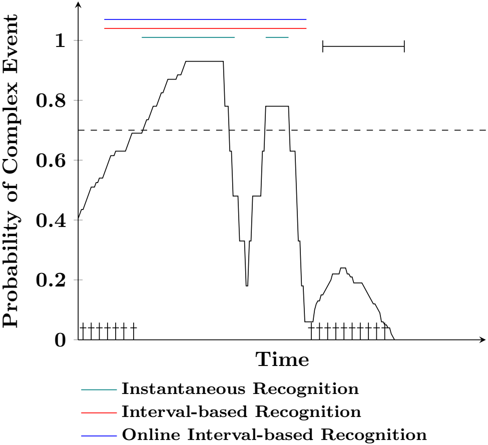

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Memory Minimality

A time-point is cached iff it may be the starting point of a future probabilistic maximal interval.

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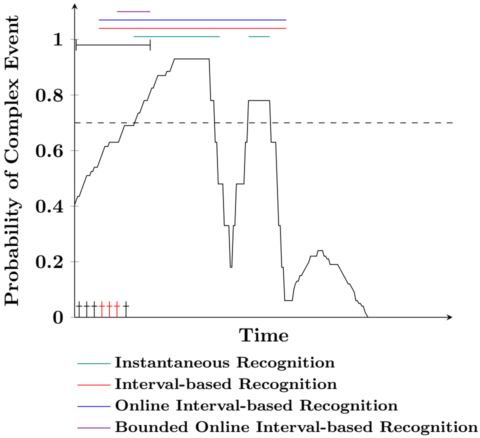
Complexity

The computation of probabistic maximal intervals is linear to the window and memory size.

4. Bounded Online Interval-based Recognition with oPIEC



- Complex event duration statistics favor more recent potential starting points.

Mantenoglou et al., Online Event Recognition over Noisy Data Streams. International Journal of Approximate Reasoning, 2023.

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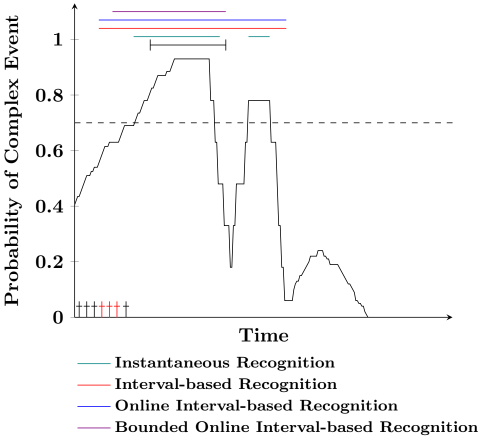

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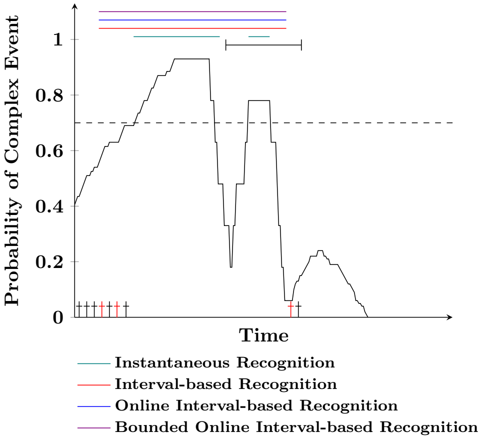

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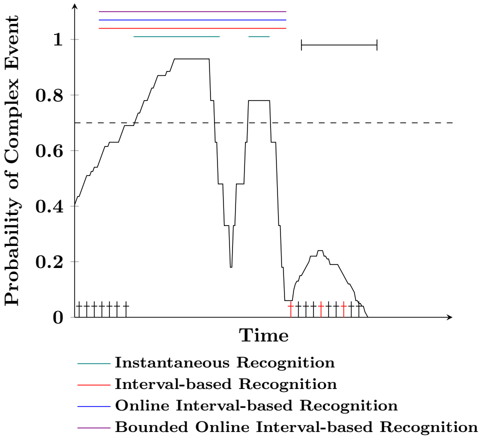

- Complex event duration statistics favor more recent potential starting points.
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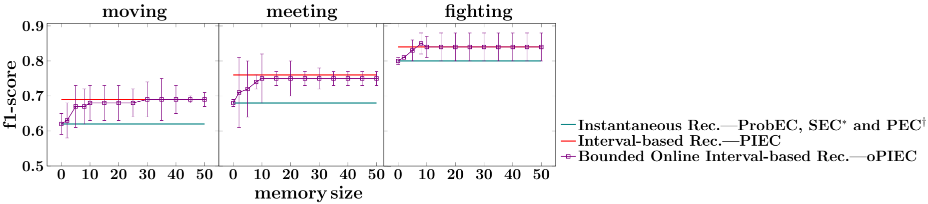
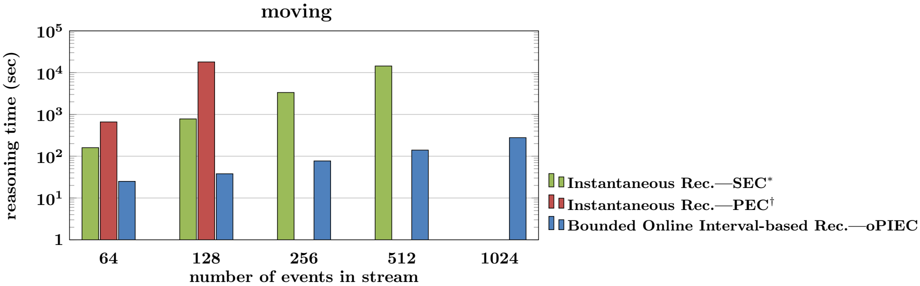
4. oPIEC: Indicative Experimental Results





* McAreavey et al., The event calculus in probabilistic logic programming with annotated disjunctions. AAMAS, 2017.

† D'Asaro et al., Probabilistic reasoning about epistemic action narratives. Artificial Intelligence, 2021.

Summary

- Stream Reasoning over Complex Temporal Specifications*:
  - $\text{RTEC}_{\circ}$ supports cyclic dependencies.
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Future Work

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- Explanations for derived situations.

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Appendix

Logic Programming

Logic program:

- A set of rules $a \leftarrow b_1, \ldots, b_m, \text{not } c_1, \ldots, \text{not } c_k$.

Przymusinski T. C., On declarative semantics of deductive databases and logic programs. In Foundations of Deductive Databases and Logic Programming. 193–216, 1988.

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Locally stratified logic program P:

- There is a partitioning $P_0, \ldots, P_n$ of the ground atoms of P, such that, for each ground rule, if $a \in P_i$, then
  - $b_1, \ldots, b_m \in P_j$, where $j \leq i$, and
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Our frameworks operate on locally stratified logic programs.

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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 $(I',\ [J_1, \ldots, J_n],\ I)$	$I = I' \setminus (J_1 \cup \ldots \cup J_n)$

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Run-Time Event Calculus (RTEC): Fluent Specification

Simple Fluents:

$\textbf{initiatedAt}(F = V, T) \leftarrow$
$\quad \textbf{happensAt}(E_{In_1}, T)[,$
$\quad \text{conditions}].$
$\quad \vdots$

$\textbf{terminatedAt}(F = V, T) \leftarrow$
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$\quad \vdots$

where conditions:
$^{0-K}[\text{not}]\ \textbf{happensAt}(E_k, T),$
$^{0-M}[\text{not}]\ \textbf{holdsAt}(F_m = V_m, T),$
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Statically Determined Fluents:

$\textbf{holdsFor}(F = V, I) \leftarrow$
$\quad \textbf{holdsFor}(F_1 = V_1, I_1)[,$
$\quad \textbf{holdsFor}(F_2 = V_2, I_2), \ldots$
$\quad \textbf{holdsFor}(F_n = V_n, I_n),$
$\quad \text{intervalOperation}(L_1, I_{n+1}), \ldots$
$\quad \text{intervalOperation}(L_m, I)].$

where intervalOperation:
union_all or
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relative_complement_all

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Fluent-Value Pair Computation

Definition:

$$\textbf{initiatedAt}(F=V,\ T) \leftarrow$$
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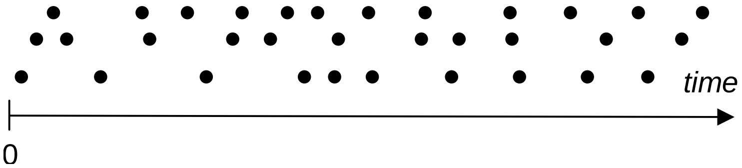
Reasoning:



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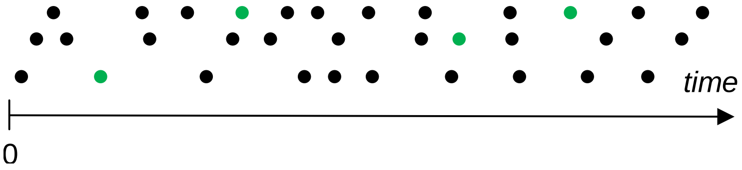

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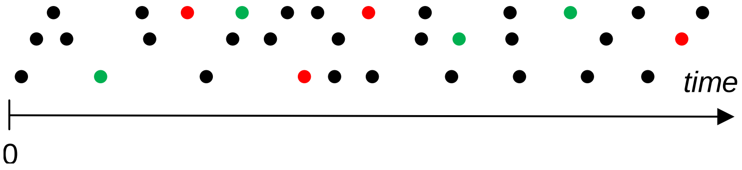

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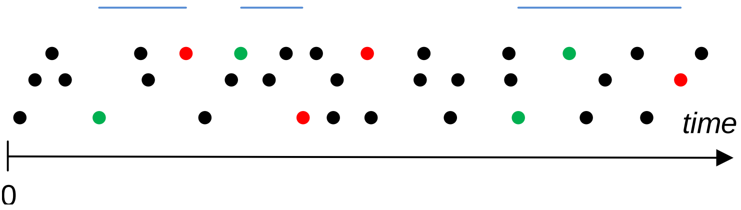
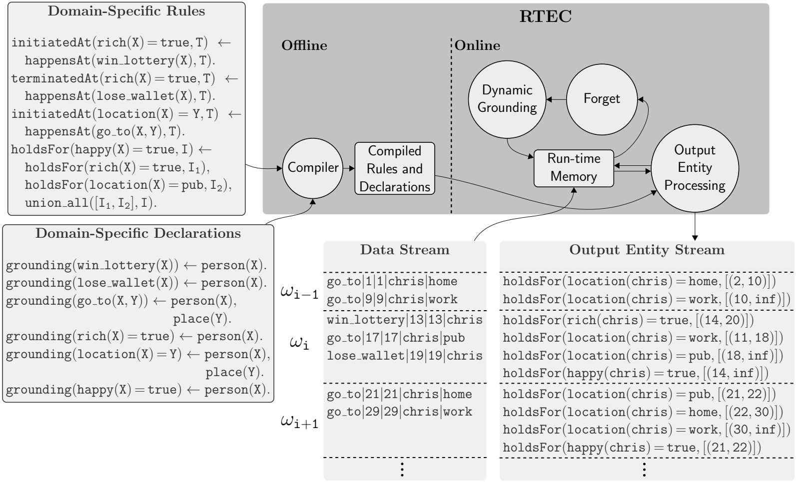
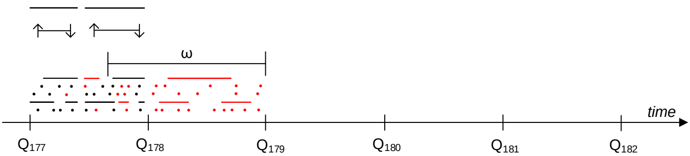


RTEC Architecture



RTEC: Windowing



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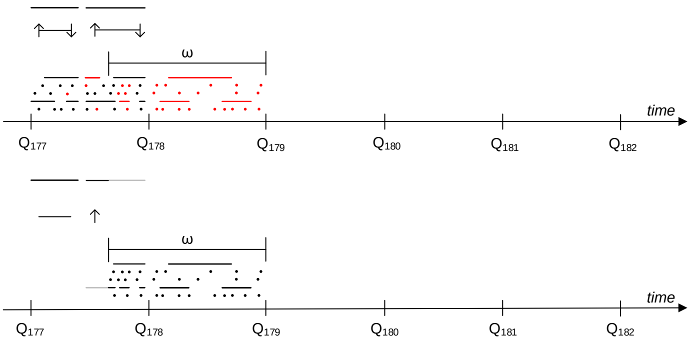

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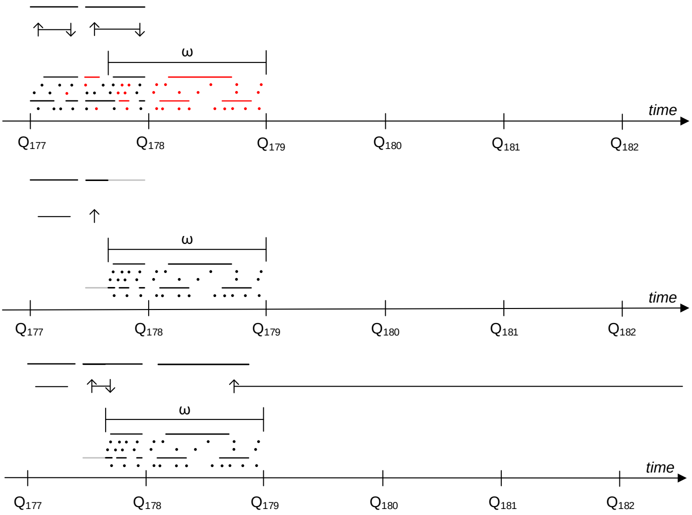
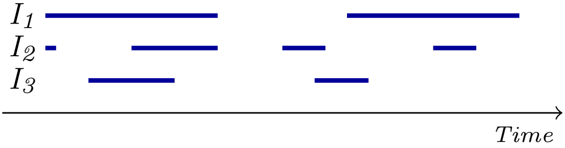
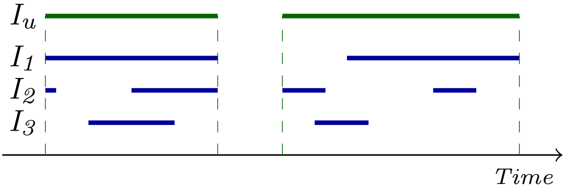


RTEC: Interval-based Reasoning



RTEC: Interval-based Reasoning

union_all$([I_1, I_2, I_3], I_u)$



RTEC: Interval-based Reasoning

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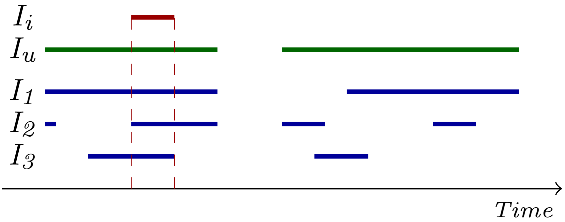
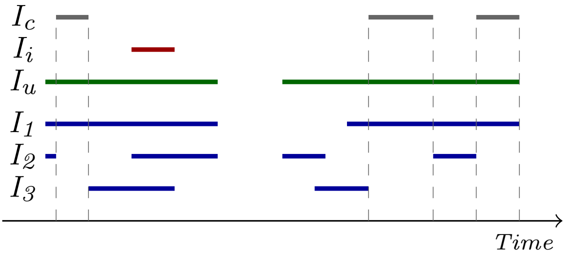


RTEC: Interval-based Reasoning

relative_complement_all$(I_1, [I_2, I_3], I_c)$

intersect_all$([I_1, I_2, I_3], I_i)$

union_all$([I_1, I_2, I_3], I_u)$

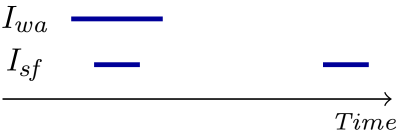


Statically Determined Fluent: Anchored or Moored

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{anchoredOrMoored}(\mathit{Vessel})=\mathrm{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel})=\mathit{farFromPorts},\ I_{sf}), \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel},\mathit{anchorage})=\mathit{true},\ I_{wa}), \\
&\quad \textbf{intersect\_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel})=\mathit{nearPorts},\ I_{sn}), \\
&\quad \textbf{union\_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}
$$

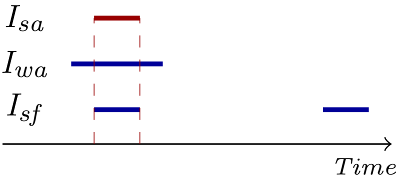
Statically Determined Fluent: Anchored or Moored

$$\begin{aligned}
&\textbf{holdsFor}(\mathit{anchoredOrMoored}(\mathit{Vessel}) = \text{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{farFromPorts},\ I_{sf}), \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{anchorage}) = \mathit{true},\ I_{wa}), \\
&\quad \textbf{intersect_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{nearPorts},\ I_{sn}), \\
&\quad \textbf{union_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}$$



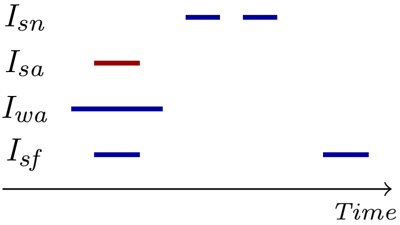
Statically Determined Fluent: Anchored or Moored

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{anchoredOrMoored}(\mathit{Vessel}) = \mathrm{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{farFromPorts},\ I_{sf}), \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{anchorage}) = \mathit{true},\ I_{wa}), \\
&\quad \textbf{intersect\_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{nearPorts},\ I_{sn}), \\
&\quad \textbf{union\_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}
$$



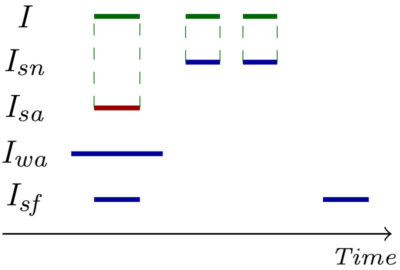
Statically Determined Fluent: Anchored or Moored

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{anchoredOrMoored}(\mathit{Vessel}) = \mathrm{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{farFromPorts},\ I_{sf}), \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{anchorage}) = \mathit{true},\ I_{wa}), \\
&\quad \textbf{intersect\_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{nearPorts},\ I_{sn}), \\
&\quad \textbf{union\_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}
$$



Statically Determined Fluent: Anchored or Moored

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{anchoredOrMoored}(\mathit{Vessel}) = \mathrm{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{farFromPorts},\ I_{sf}), \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{anchorage}) = \mathit{true},\ I_{wa}), \\
&\quad \textbf{intersect\_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{nearPorts},\ I_{sn}), \\
&\quad \textbf{union\_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}
$$



Voting: Cyclic Dependencies

$$\begin{aligned}&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{propose}(P, M), T),\\ &\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T).\end{aligned}$$

Voting: Cyclic Dependencies

$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{propose}(P, M), T),\\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T).\\
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voting}, T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{second}(S, M), T),\\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{proposed}, T).
\end{aligned}$$

Voting: Cyclic Dependencies

$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{propose}(P, M), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T). \\
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voting}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{second}(S, M), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{proposed}, T). \\
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voted}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{close\_ballot}(C, M), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{voting}, T).
\end{aligned}
$$

Voting: Cyclic Dependencies

$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{propose}(P, M), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T). \\
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voting}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{second}(S, M), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{proposed}, T). \\
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voted}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{close\_ballot}(C, M), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{voting}, T). \\
&\textbf{initiatedAt}(\mathit{status}(M) = \mathit{null}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{declare}(C, M, \mathit{Res}), T), \\
&\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{voted}, T).
\end{aligned}
$$

Voting: Cyclic Dependencies

$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow$$
$$\textbf{happensAt}(\mathit{propose}(P, M), T),$$
$$\textbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T).$$

$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voting}, T) \leftarrow$$
$$\textbf{happensAt}(\mathit{second}(S, M), T),$$
$$\textbf{holdsAt}(\mathit{status}(M) = \mathit{proposed}, T).$$

$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voted}, T) \leftarrow$$
$$\textbf{happensAt}(\mathit{close\_ballot}(C, M), T),$$
$$\textbf{holdsAt}(\mathit{status}(M) = \mathit{voting}, T).$$

$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{null}, T) \leftarrow$$
$$\textbf{happensAt}(\mathit{declare}(C, M, \mathit{Res}), T),$$
$$\textbf{holdsAt}(\mathit{status}(M) = \mathit{voted}, T).$$

Voting: Cyclic Dependencies

$$
\begin{aligned}
&\textbf{initiatedAt}(status(M)=proposed,\ T) \leftarrow \\
&\quad \textbf{happensAt}(propose(P, M),\ T), \\
&\quad \textbf{holdsAt}(status(M)=null,\ T). \\
&\textbf{initiatedAt}(status(M)=voting,\ T) \leftarrow \\
&\quad \textbf{happensAt}(second(S, M),\ T), \\
&\quad \textbf{holdsAt}(status(M)=proposed,\ T). \\
&\textbf{initiatedAt}(status(M)=voted,\ T) \leftarrow \\
&\quad \textbf{happensAt}(close\_ballot(C, M),\ T), \\
&\quad \textbf{holdsAt}(status(M)=voting,\ T). \\
&\textbf{initiatedAt}(status(M)=null,\ T) \leftarrow \\
&\quad \textbf{happensAt}(declare(C, M, Res),\ T), \\
&\quad \textbf{holdsAt}(status(M)=voted,\ T).
\end{aligned}
$$

Voting: Cyclic Dependencies

$$
\begin{aligned}
&\mathbf{initiatedAt}(status(M) = proposed, T) \leftarrow \\
&\quad \mathbf{happensAt}(propose(P, M), T), \\
&\quad \mathbf{holdsAt}(status(M) = null, T). \\
&\mathbf{initiatedAt}(status(M) = voting, T) \leftarrow \\
&\quad \mathbf{happensAt}(second(S, M), T), \\
&\quad \mathbf{holdsAt}(status(M) = proposed, T). \\
&\mathbf{initiatedAt}(status(M) = voted, T) \leftarrow \\
&\quad \mathbf{happensAt}(close\_ballot(C, M), T), \\
&\quad \mathbf{holdsAt}(status(M) = voting, T). \\
&\mathbf{initiatedAt}(status(M) = null, T) \leftarrow \\
&\quad \mathbf{happensAt}(declare(C, M, Res), T), \\
&\quad \mathbf{holdsAt}(status(M) = voted, T).
\end{aligned}
$$

Voting: Cyclic Dependencies

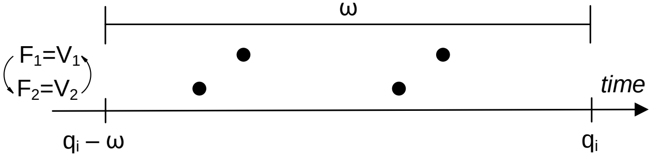
$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{propose}(P, M), T),$$
$$\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T).$$

$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voting}, T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{second}(S, M), T),$$
$$\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{proposed}, T).$$

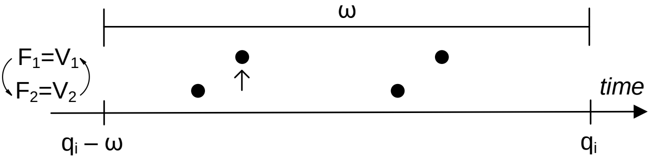
$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{voted}, T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{close\_ballot}(C, M), T),$$
$$\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{voting}, T).$$

$$\textbf{initiatedAt}(\mathit{status}(M) = \mathit{null}, T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{declare}(C, M, \mathit{Res}), T),$$
$$\quad \textbf{holdsAt}(\mathit{status}(M) = \mathit{voted}, T).$$

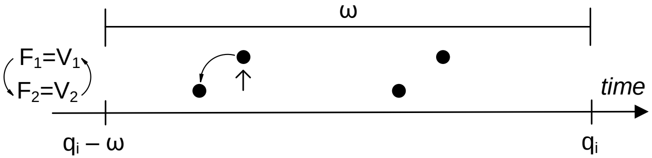
Handling Cyclic Dependencies



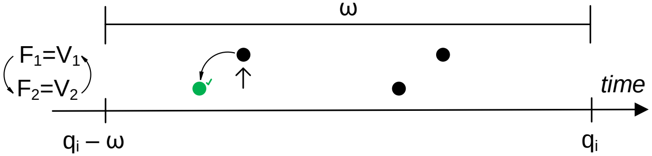
Handling Cyclic Dependencies



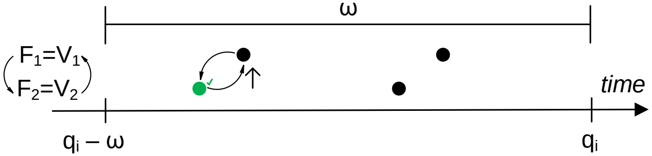
Handling Cyclic Dependencies



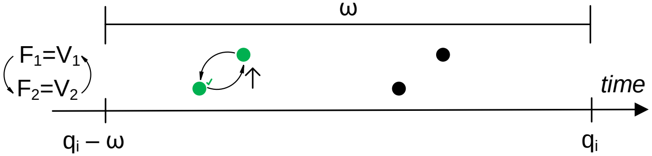
Handling Cyclic Dependencies



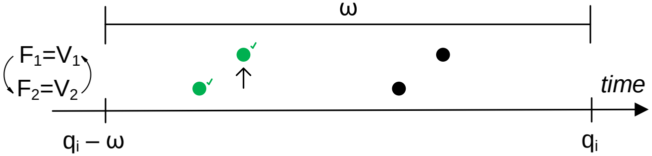
Handling Cyclic Dependencies



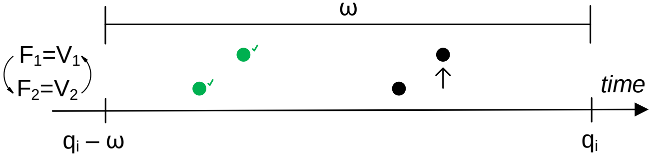
Handling Cyclic Dependencies



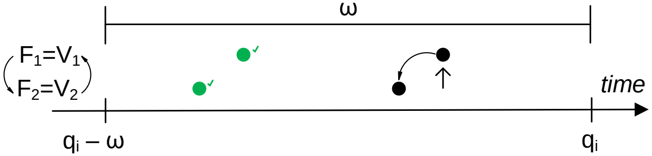
Handling Cyclic Dependencies



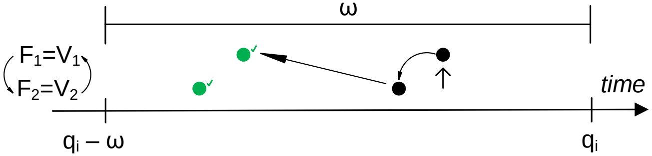
Handling Cyclic Dependencies



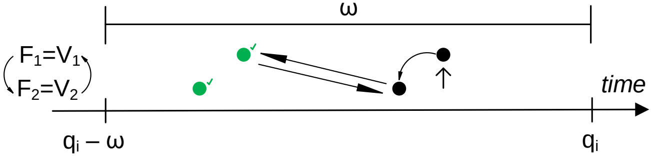
Handling Cyclic Dependencies



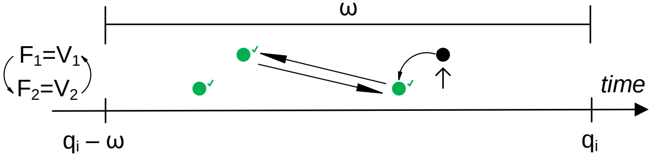
Handling Cyclic Dependencies



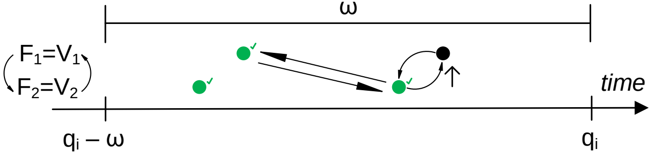
Handling Cyclic Dependencies



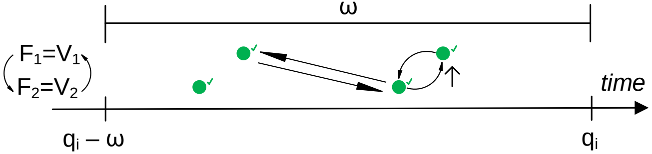
Handling Cyclic Dependencies



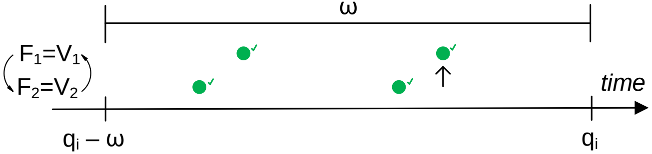
Handling Cyclic Dependencies



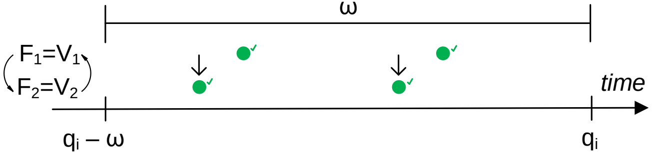
Handling Cyclic Dependencies



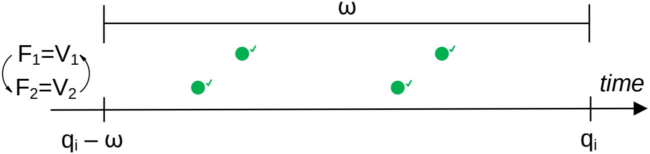
Handling Cyclic Dependencies



Handling Cyclic Dependencies

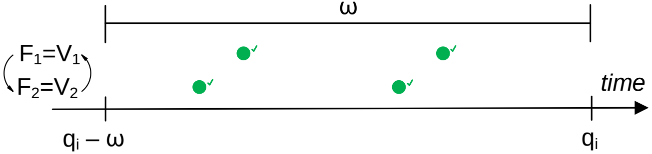


Handling Cyclic Dependencies

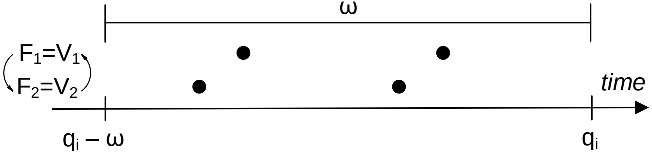


Handling Cyclic Dependencies

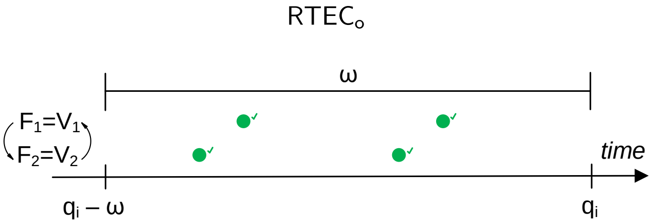
RTEC$_o$

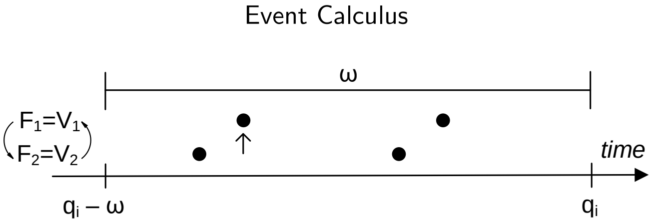


Event Calculus



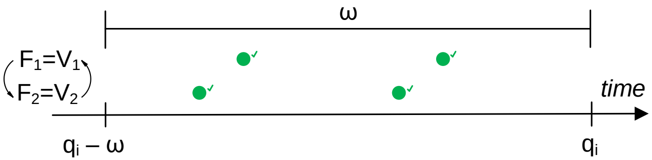
Handling Cyclic Dependencies



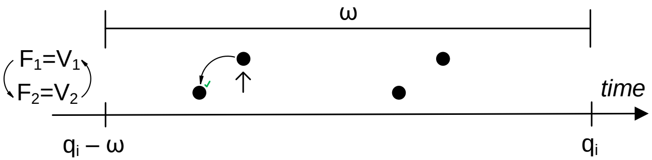


Handling Cyclic Dependencies

RTEC$_\circ$

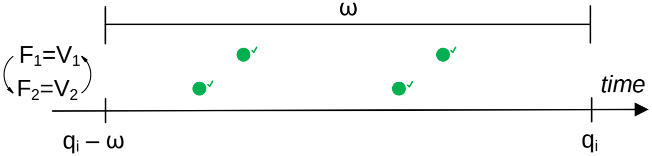


Event Calculus

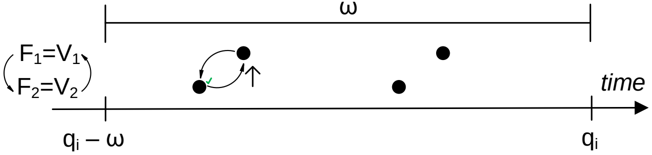


Handling Cyclic Dependencies

RTEC$_\circ$

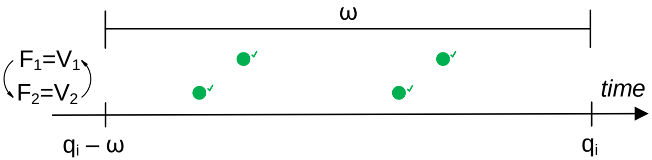


Event Calculus

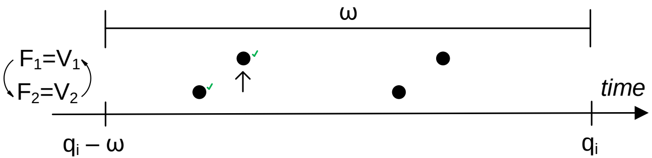


Handling Cyclic Dependencies

RTEC$_o$

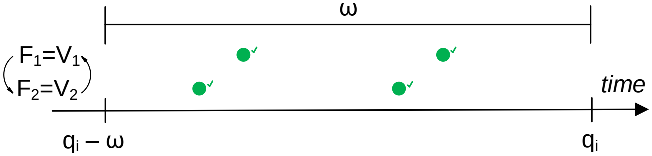


Event Calculus

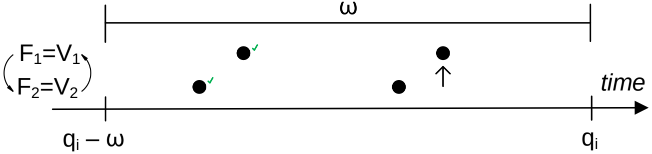


Handling Cyclic Dependencies

RTEC$_{\circ}$

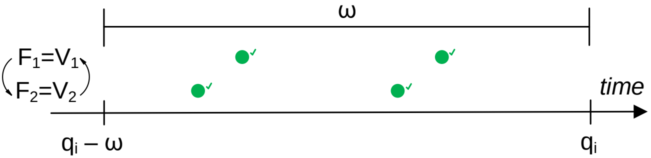


Event Calculus

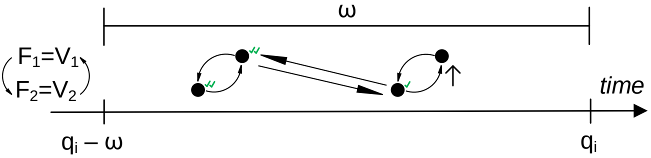


Handling Cyclic Dependencies

RTEC$_o$

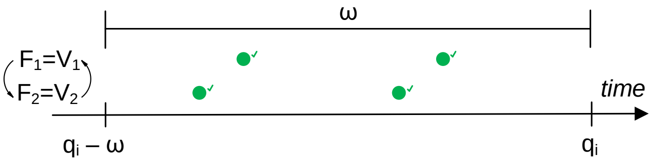


Event Calculus

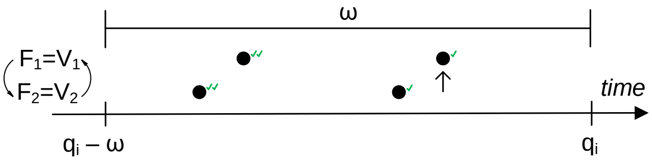


Handling Cyclic Dependencies

RTEC$_o$

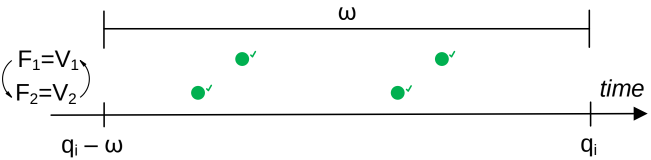


Event Calculus

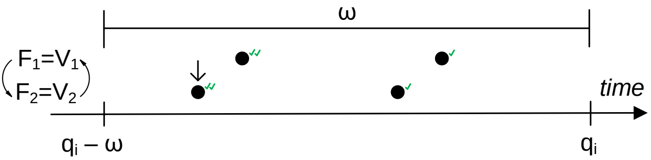


Handling Cyclic Dependencies

RTEC$_o$

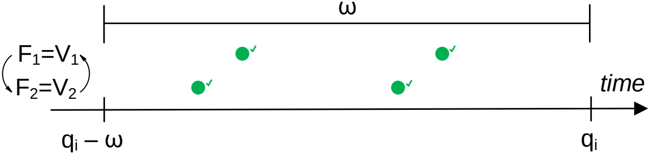


Event Calculus

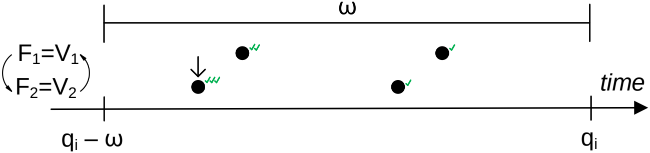


Handling Cyclic Dependencies

RTEC$_{\circ}$

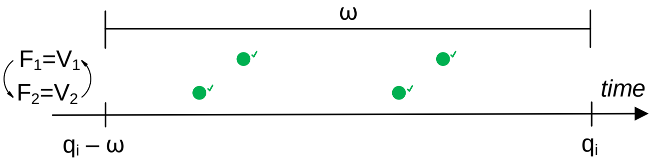


Event Calculus

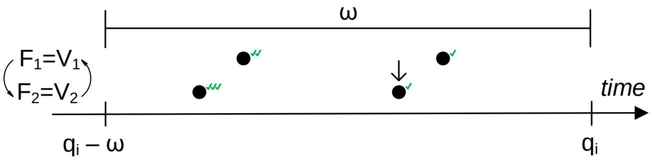


Handling Cyclic Dependencies

RTEC$_\circ$

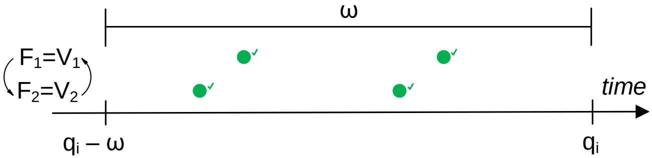


Event Calculus

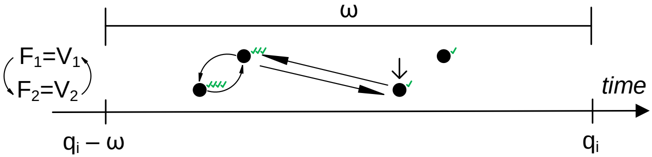


Handling Cyclic Dependencies

RTEC$_\circ$

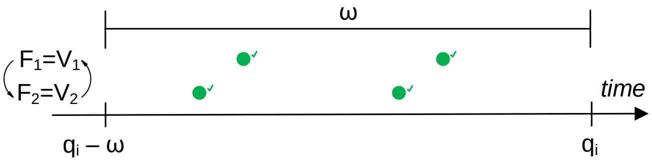


Event Calculus

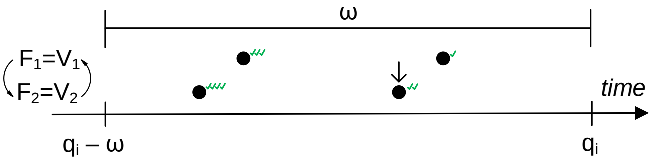


Handling Cyclic Dependencies

RTEC$_o$

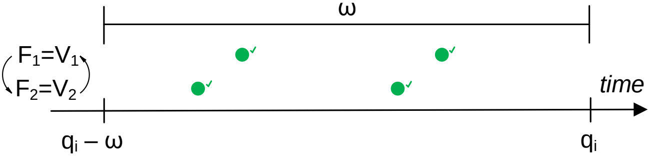


Event Calculus

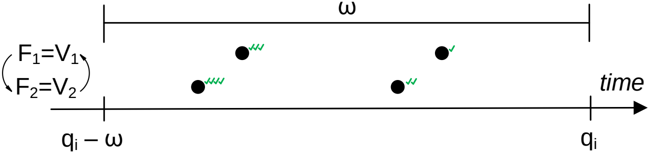


Handling Cyclic Dependencies

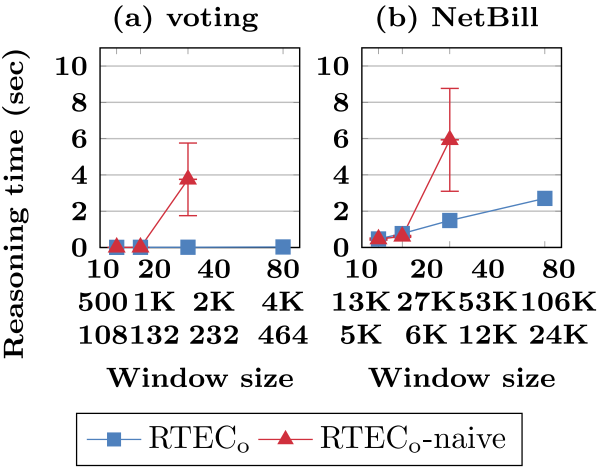
RTEC$_\circ$



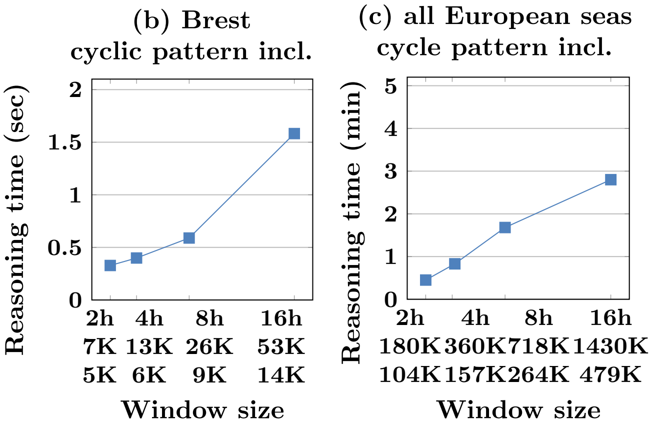
Event Calculus



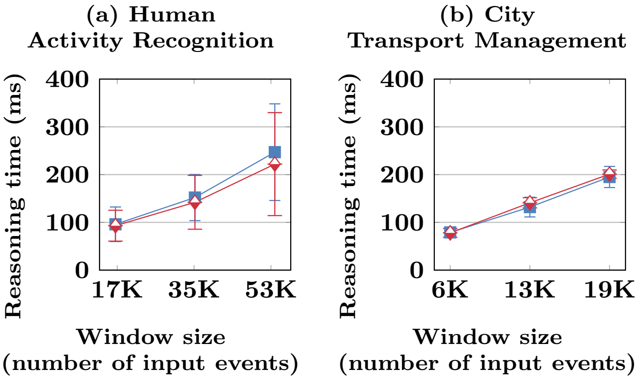
RTEC$_\circ$: Experimental Results



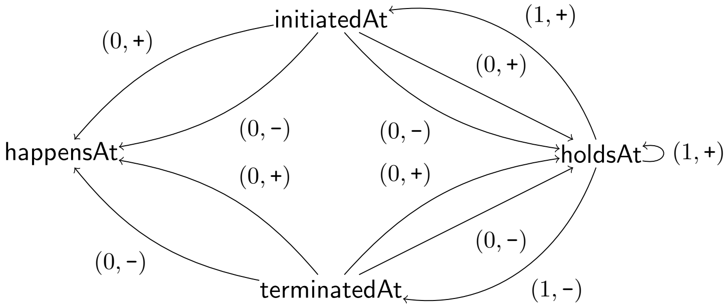
RTEC$_{\circ}$: Experimental Results



RTEC$_o$: Experimental Results

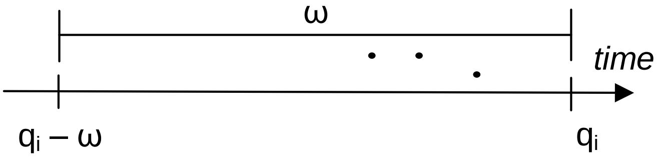


Semantics of RTEC$_\circ$

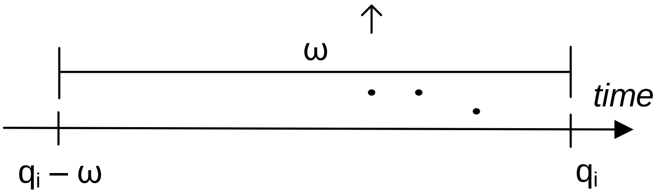


The cycle-sum graph of an RTEC$_\circ$ program.

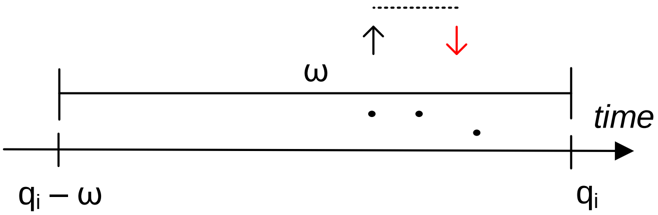
RTEC$^{\rightarrow}$: Deadlines



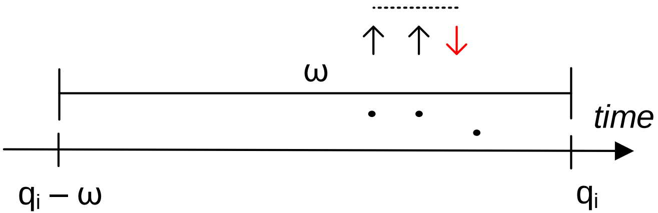
RTEC$^{\rightarrow}$: Deadlines



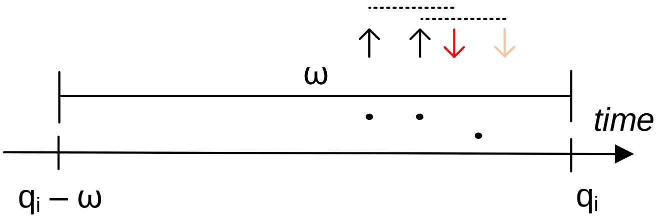
RTEC$^{\rightarrow}$: Deadlines



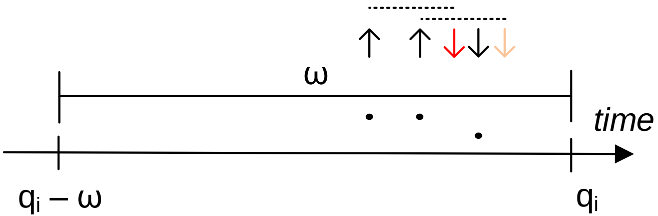
RTEC$^{\rightarrow}$: Deadlines



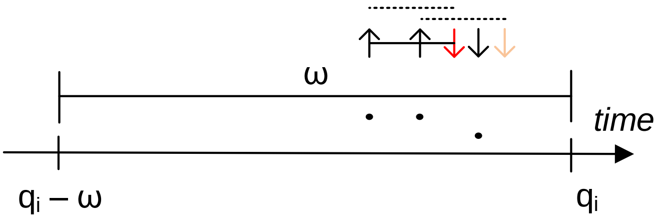
RTEC$^{\rightarrow}$: Deadlines



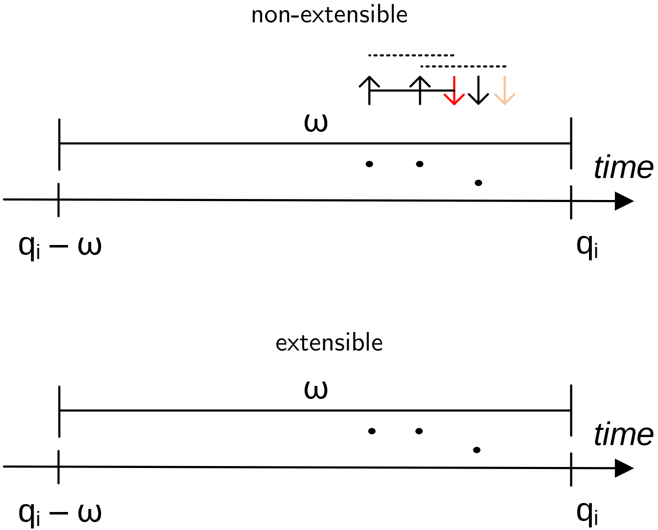
RTEC$^{\rightarrow}$: Deadlines



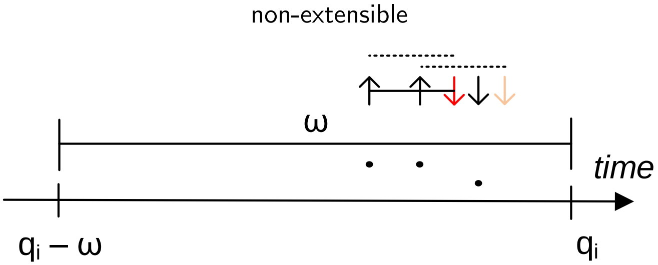
RTEC$^{\rightarrow}$: Deadlines

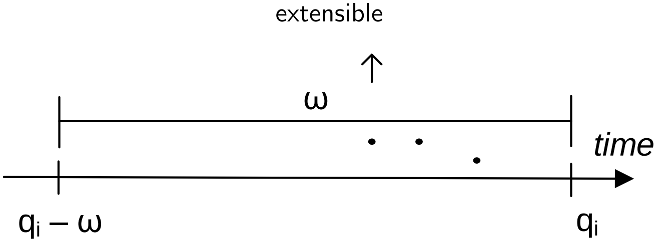


RTEC$^{\rightarrow}$: Deadlines

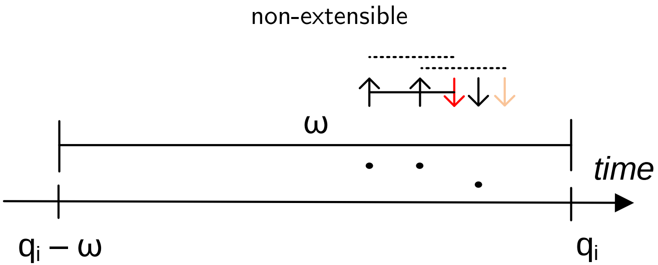


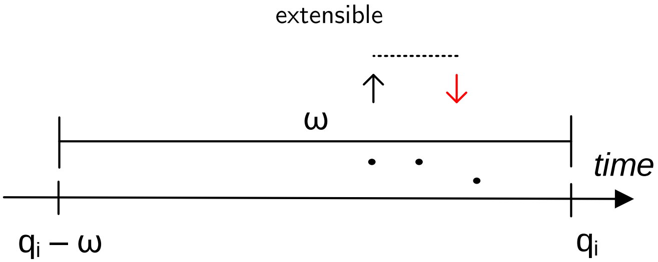
RTEC$^{\rightarrow}$: Deadlines





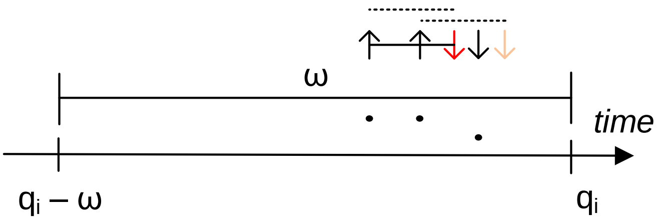
RTEC$^{\rightarrow}$: Deadlines



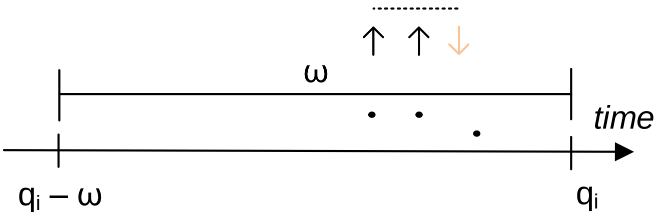


RTEC$^{\rightarrow}$: Deadlines

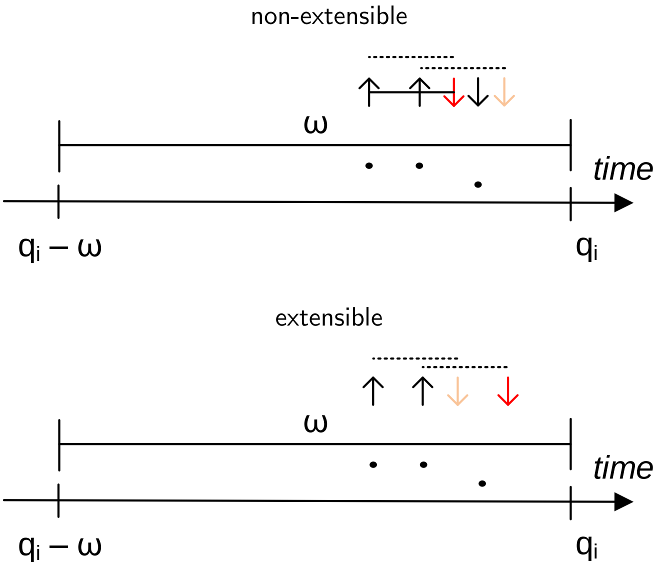
non-extensible



extensible

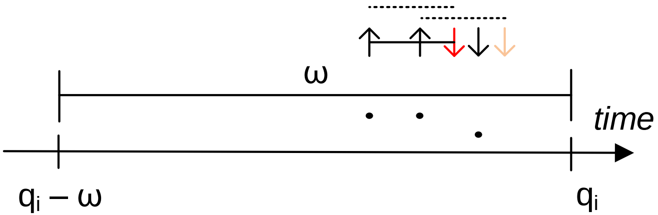


RTEC$^{\rightarrow}$: Deadlines

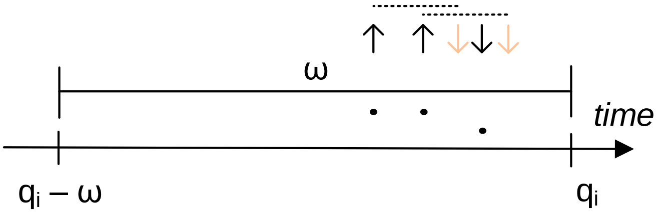


RTEC$^{\rightarrow}$: Deadlines

non-extensible

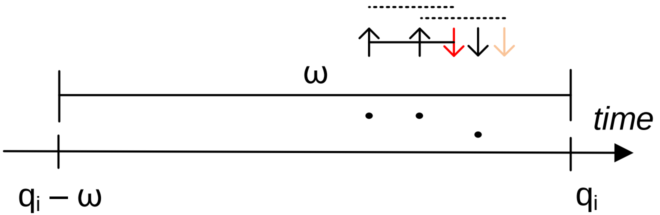


extensible

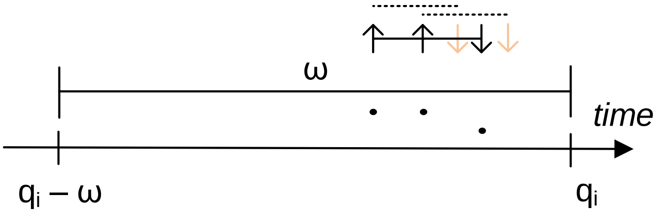


RTEC$^{\rightarrow}$: Deadlines

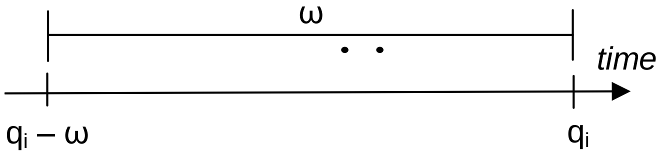
non-extensible



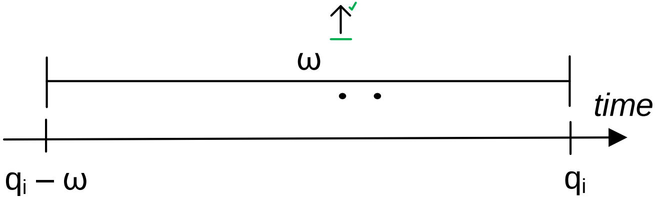
extensible



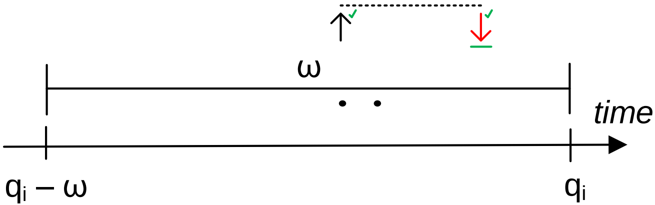
Handling Deadlines: Caching



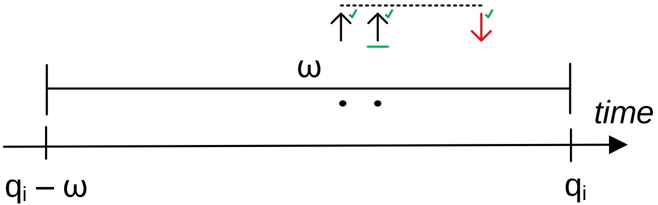
Handling Deadlines: Caching



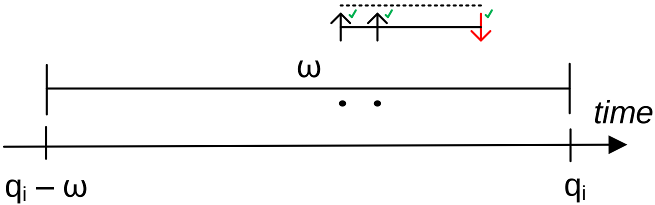
Handling Deadlines: Caching



Handling Deadlines: Caching

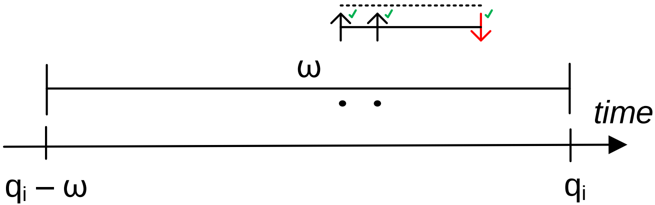


Handling Deadlines: Caching

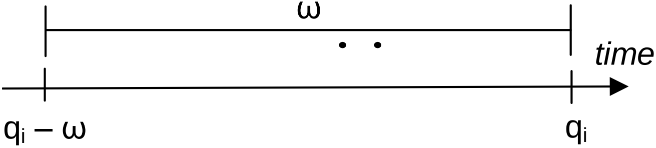


Handling Deadlines: Caching

RTEC$^{\rightarrow}$

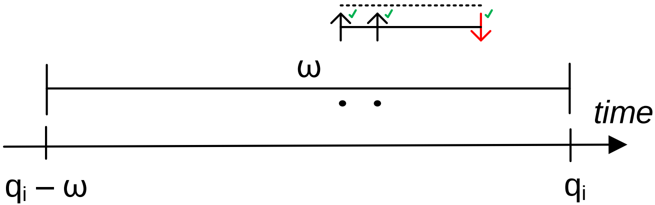


RTEC$^{\rightarrow}$-naive

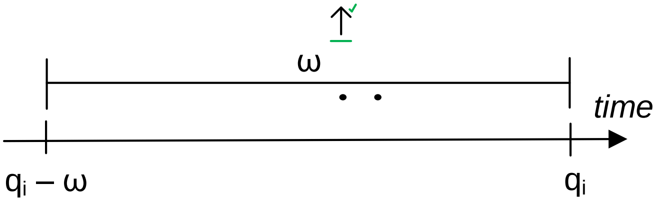


Handling Deadlines: Caching

RTEC$^{\rightarrow}$

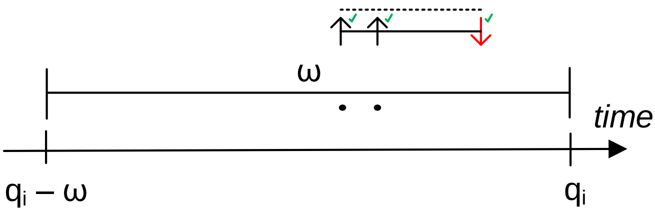


RTEC$^{\rightarrow}$-naive

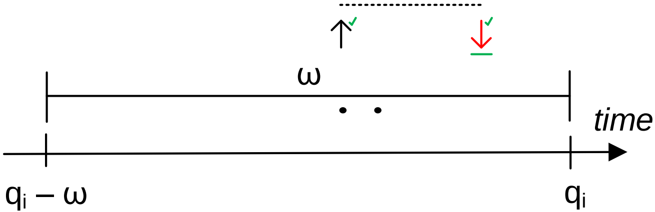


Handling Deadlines: Caching

RTEC$^{\rightarrow}$

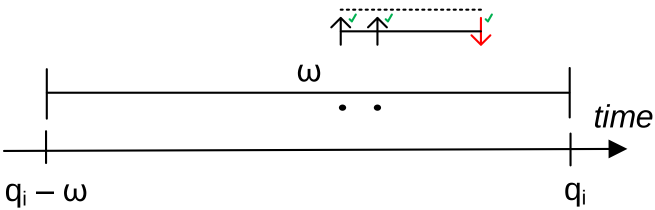


RTEC$^{\rightarrow}$-naive

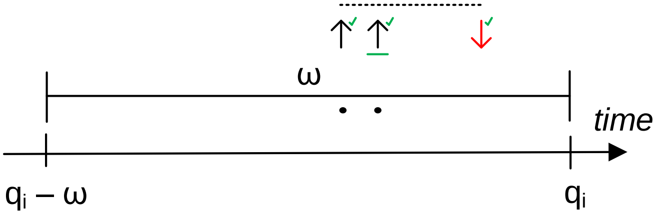


Handling Deadlines: Caching

RTEC→

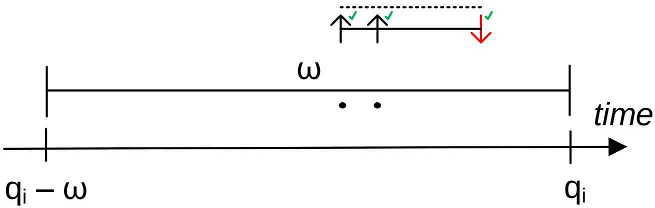


RTEC→-naive

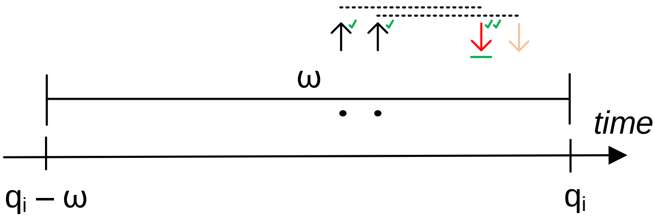


Handling Deadlines: Caching

RTEC$^{\rightarrow}$

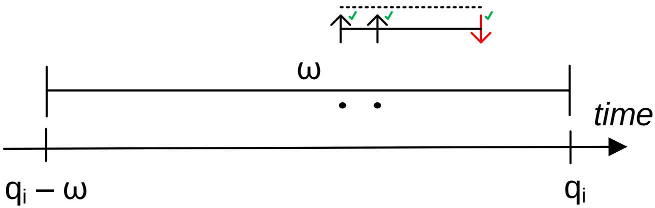


RTEC$^{\rightarrow}$-naive

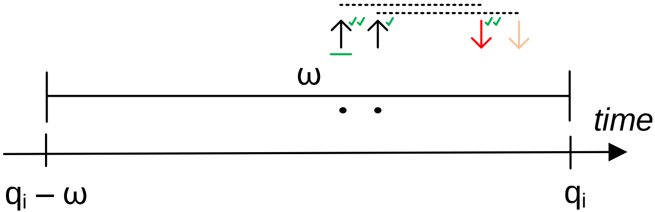


Handling Deadlines: Caching

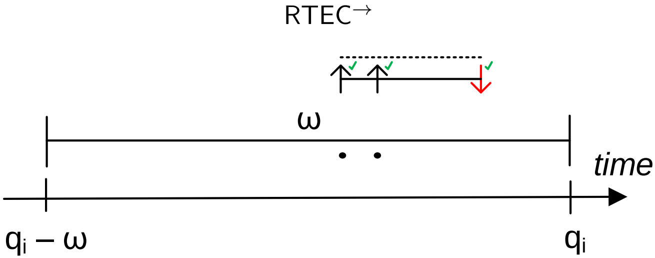
RTEC$^{\rightarrow}$

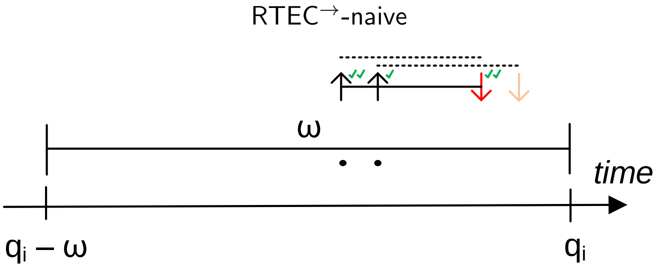


RTEC$^{\rightarrow}$-naive

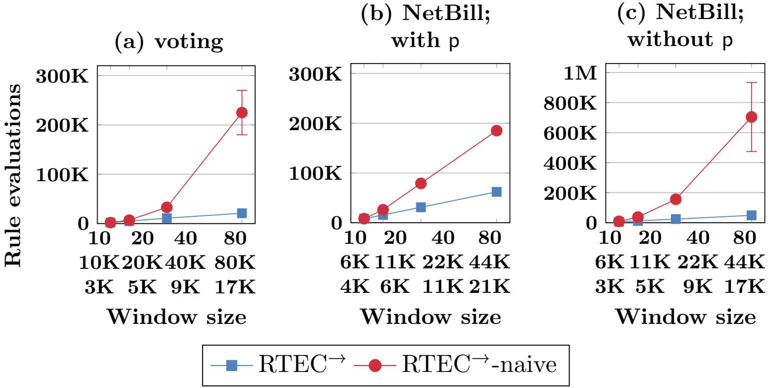


Handling Deadlines: Caching

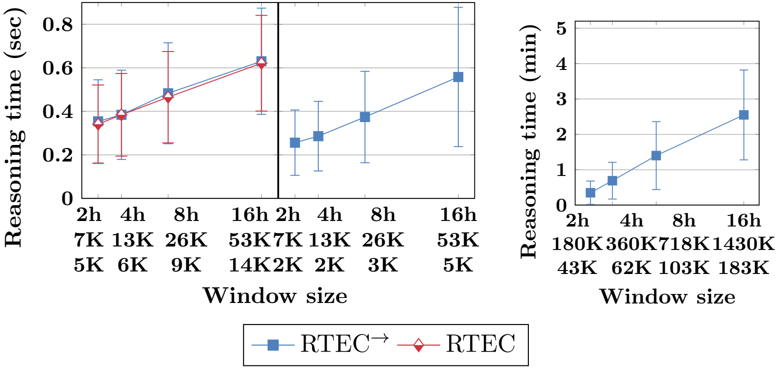




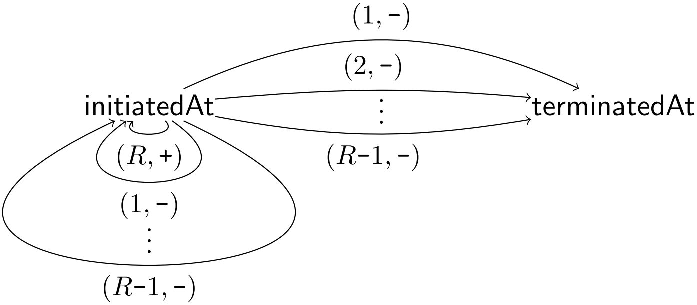
RTEC$^{\rightarrow}$: Experimental Results



RTEC$^{\rightarrow}$: Experimental Results



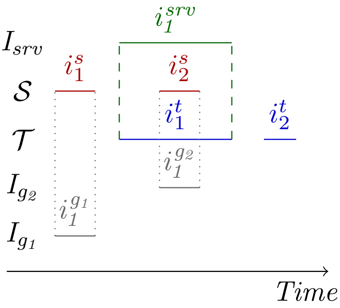
Semantics of RTEC$^{\rightarrow}$



The cycle-sum graph of an RTEC$^{\rightarrow}$ program.

RTEC$_A$: Allen Relations

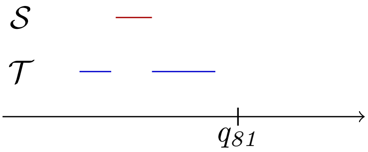
$\textbf{holdsFor}(\textit{suspiciousRendezVous}(\textit{Vessel}_1, \textit{Vessel}_2) = \text{true}, I) \leftarrow$
$\quad \textbf{holdsFor}(\textit{gap}(\textit{Vessel}_1) = \textit{farFromPorts}, I_{g_1}),$
$\quad \textbf{holdsFor}(\textit{gap}(\textit{Vessel}_2) = \textit{farFromPorts}, I_{g_2}),$
$\quad \textbf{holdsFor}(\textit{proximity}(\textit{Vessel}_1, \textit{Vessel}_2) = \text{true}, \mathcal{T}),$
$\quad \textbf{union\_all}([I_{g_1}, I_{g_2}], \mathcal{S}),$
$\quad \textbf{allen}(\text{during}, \mathcal{S}, \mathcal{T}, \text{target}, I).$



RTEC$_\mathsf{A}$: Windowing

$\textbf{holdsFor}(\textit{disappearedInArea}(\textit{Vessel}, \textit{AreaType}) = \text{true}, I) \leftarrow$
$\quad \textbf{holdsFor}(\textit{withinArea}(\textit{Vessel}, \textit{AreaType}) = \text{true}, \mathcal{S}),$
$\quad \textbf{holdsFor}(\textit{gap}(\textit{Vessel}) = \textit{farFromPorts}, \mathcal{T}),$
$\quad \textbf{allen}(\text{meets}, \mathcal{S}, \mathcal{T}, \text{target}, I).$

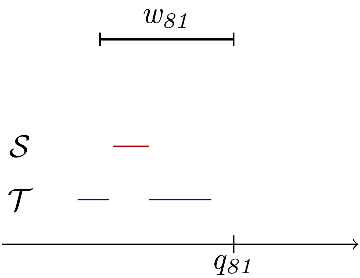
Query time: q_{81}



RTEC$_A$: Windowing

$\textbf{holdsFor}(\textit{disappearedInArea}(\textit{Vessel}, \textit{AreaType}) = \text{true}, I) \leftarrow$
  $\textbf{holdsFor}(\textit{withinArea}(\textit{Vessel}, \textit{AreaType}) = \text{true}, \mathcal{S}),$
  $\textbf{holdsFor}(\textit{gap}(\textit{Vessel}) = \textit{farFromPorts}, \mathcal{T}),$
  $\textbf{allen}(\text{meets}, \mathcal{S}, \mathcal{T}, \text{target}, I).$

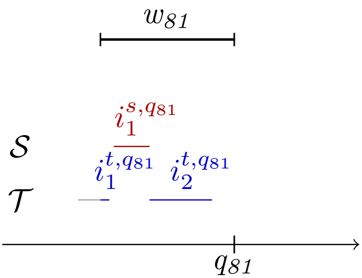
Query time: q_{81}



RTEC$_A$: Windowing

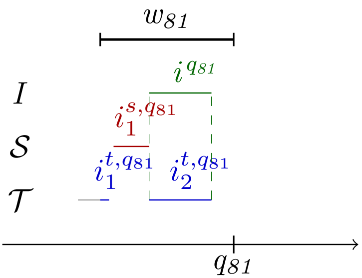
$$\textbf{holdsFor}(\mathit{disappearedInArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, I) \leftarrow$$
$$\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, \mathcal{S}),$$
$$\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}),$$
$$\quad \textbf{allen}(\text{meets}, \mathcal{S}, \mathcal{T}, \text{target}, I).$$

Query time: q_{81}



holdsFor(*disappearedInArea*(*Vessel*, *AreaType*) = true, *I*) ←
holdsFor(*withinArea*(*Vessel*, *AreaType*) = true, $\mathcal{S}$),
holdsFor(*gap*(*Vessel*) = *farFromPorts*, $\mathcal{T}$),
allen(meets, $\mathcal{S}$, $\mathcal{T}$, target, *I*).

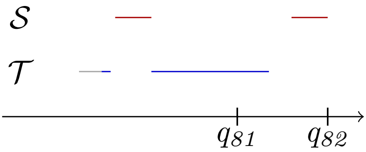
Query time: q_{81}



RTEC$_A$: Windowing

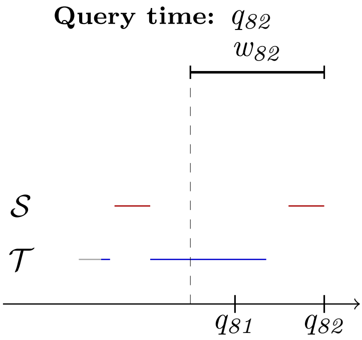
$$\textbf{holdsFor}(\mathit{disappearedInArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, I) \leftarrow$$
$$\textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, \mathcal{S}),$$
$$\textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}),$$
$$\textbf{allen}(\text{meets}, \mathcal{S}, \mathcal{T}, \text{target}, I).$$

Query time: q_{82}



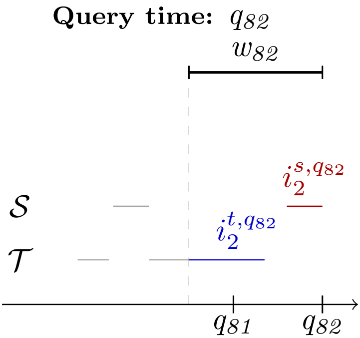
RTEC$_A$: Windowing

holdsFor(*disappearedInArea*(*Vessel*, *AreaType*) = true, *I*) ←
  holdsFor(*withinArea*(*Vessel*, *AreaType*) = true, $\mathcal{S}$),
  holdsFor(*gap*(*Vessel*) = *farFromPorts*, $\mathcal{T}$),
  allen(meets, $\mathcal{S}$, $\mathcal{T}$, target, *I*).



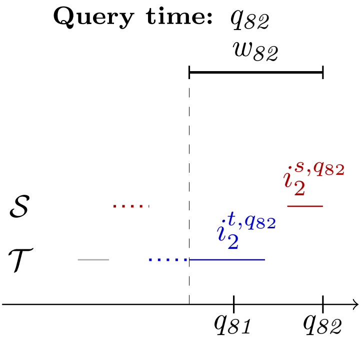
RTEC$_A$: Windowing

$\textbf{holdsFor}(\textit{disappearedInArea}(\textit{Vessel}, \textit{AreaType}) = \text{true}, I) \leftarrow$
  $\textbf{holdsFor}(\textit{withinArea}(\textit{Vessel}, \textit{AreaType}) = \text{true}, \mathcal{S}),$
  $\textbf{holdsFor}(\textit{gap}(\textit{Vessel}) = \textit{farFromPorts}, \mathcal{T}),$
  $\textbf{allen}(\text{meets}, \mathcal{S}, \mathcal{T}, \text{target}, I).$



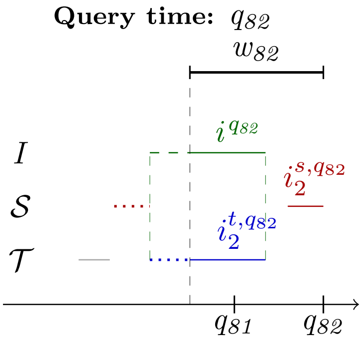
RTEC$_A$: Windowing

$\textbf{holdsFor}(\mathit{disappearedInArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, I) \leftarrow$
$\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, \mathcal{S}),$
$\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}),$
$\quad \textbf{allen}(\text{meets}, \mathcal{S}, \mathcal{T}, \text{target}, I).$



RTEC$_A$: Windowing

holdsFor(*disappearedInArea*(*Vessel*, *AreaType*) = true, *I*) ←
  holdsFor(*withinArea*(*Vessel*, *AreaType*) = true, $\mathcal{S}$),
  holdsFor(*gap*(*Vessel*) = *farFromPorts*, $\mathcal{T}$),
  allen(meets, $\mathcal{S}$, $\mathcal{T}$, target, *I*).



$RTEC_A$: Experimental Evaluation

Batch setting.

Batch size	Reasoning Time		
Input Intervals	$RTEC_A$	AEGLE	D^2IA
200	**1**	980	2K
2K	**14**	4K	6K
20K	**154**	71.5K	395K
200K	**1.8K**	MEM	>3.6M

Streaming setting.

Window size		Reasoning Time		Output Interval Pairs	
Days	Input Intervals	$RTEC_A$	D^2IA	$RTEC_A$	D^2IA
1	125	**1**	48	5K	5K
2	250	**2**	164	19K	18K
4	500	**4**	568	72K	71K
8	1K	**8**	1.7K	237K	236K
16	2K	**15**	7.8K	878K	874K

Instantaneous Recognition

$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).
\end{aligned}$$

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

$$\mathit{0.70} :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ \mathit{1}).$$
$$\mathit{0.46} :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ \mathit{1}).$$

Instantaneous Recognition

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

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

$$0.70 :: \textbf{happensAt}(walking(mike),\ 1).$$
$$0.46 :: \textbf{happensAt}(walking(sarah),\ 1).$$

$$P(\textbf{initiatedAt}(moving(mike, sarah) = \text{true}, 1)) =$$
$$P(\textbf{happensAt}(walking(mike), 1)) \times$$
$$P(\textbf{happensAt}(walking(sarah), 1)) \times$$
$$P(\textbf{holdsAt}(close(mike, sarah) = \text{true}, 1)) \times$$
$$P(\textbf{holdsAt}(orientation(mike, sarah) = \text{true}, 1))$$
$$= 0.7 \times 0.46 \times 1 \times 1 = 0.322$$

Instantaneous Recognition

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

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

$\mathit{0.70} :: \mathbf{happensAt}(\mathit{walking}(\mathit{mike}),\ \mathit{1}).$
$\mathit{0.46} :: \mathbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ \mathit{1}).$

$P(\mathbf{holdsAt}(CE = \text{true}, t)) =$
$\quad P(\mathbf{initiatedAt}(CE = \text{true}, t{-}\mathit{1}) \vee$
$\quad\quad (\mathbf{holdsAt}(CE = \text{true}, t{-}\mathit{1}) \wedge$
$\quad\quad \neg\ \mathbf{terminatedAt}(CE = \text{true}, t{-}\mathit{1})))$

Instantaneous Recognition

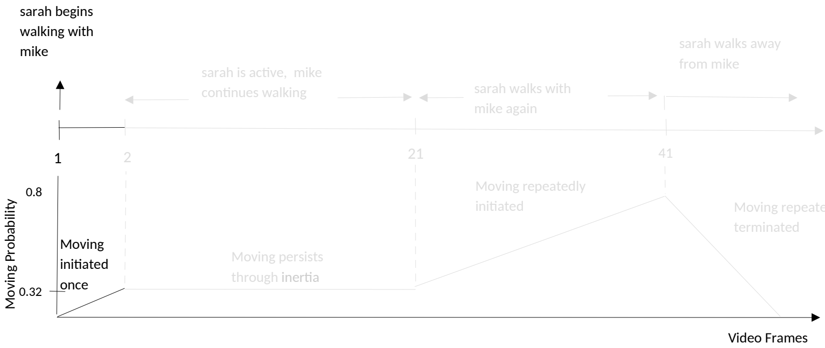
$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
$\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),$
$\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),$
$\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),$
$\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

$0.70 :: \textbf{happensAt}(\textit{walking}(\textit{mike}),\ 1).$
$0.46 :: \textbf{happensAt}(\textit{walking}(\textit{sarah}),\ 1).$

$P(\textbf{holdsAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 2)) =$
$P(\textbf{initiatedAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 1) \vee$
$\quad (\textbf{holdsAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 1) \wedge$
$\quad \neg\textbf{terminatedAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 1)))$
$= 0.322 + 0 \times 1 - 0.322 \times 0 \times 1 = 0.322$

Instantaneous Recognition



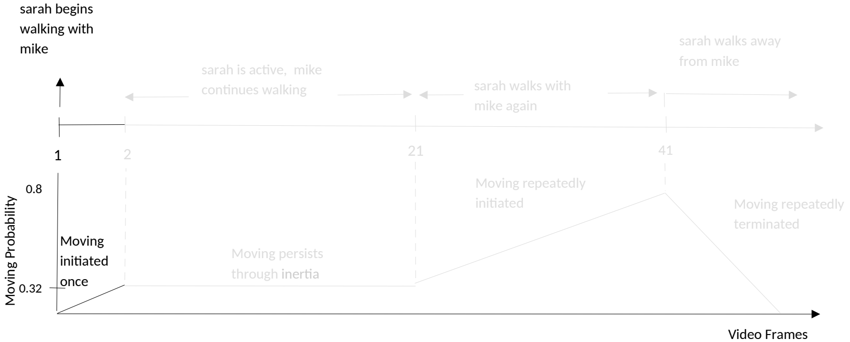
$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

$$0.70 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 1).$$
$$0.46 :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 1).$$

$$P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 2)) =$$
$$P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1) \vee$$
$$(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1) \wedge$$
$$\neg\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1)))$$
$$= 0.322 + 0 \times 1 - 0.322 \times 0 \times 1 = 0.322$$

Instantaneous Recognition

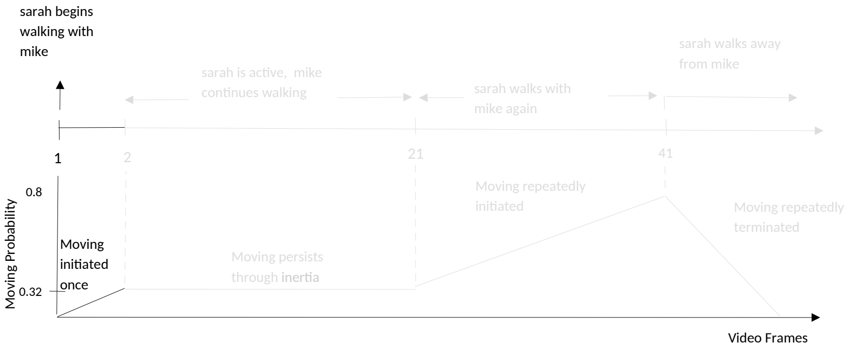


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

$$0.73 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 2).$$
$$0.55 :: \textbf{happensAt}(\mathit{active}(\mathit{sarah}),\ 2).\ \cdots$$

Instantaneous Recognition



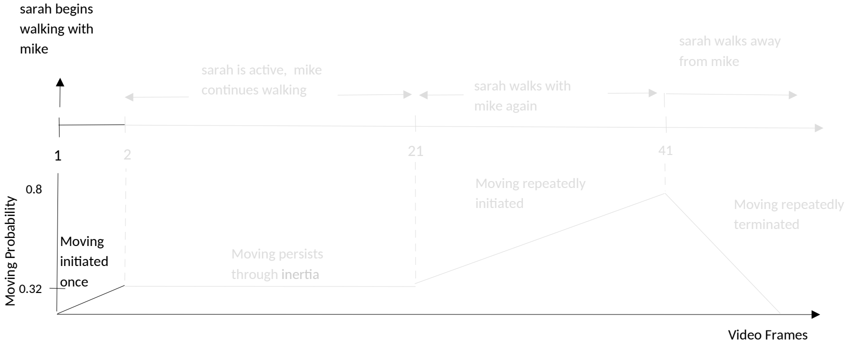
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

$$0.73 :: \textbf{happensAt}(walking(mike),\ 2).$$
$$0.55 :: \textbf{happensAt}(active(sarah),\ 2).\ \cdots$$

$$P(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 3)) =$$
$$P(\textbf{initiatedAt}(moving(mike, sarah) = \text{true}, 2) \lor$$
$$(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 2) \land$$
$$\neg\textbf{terminatedAt}(moving(mike, sarah) = \text{true}, 2)))$$
$$= 0 + 0.322 \times 1 - 0 \times 0.322 \times 1 = 0.322$$

Instantaneous Recognition

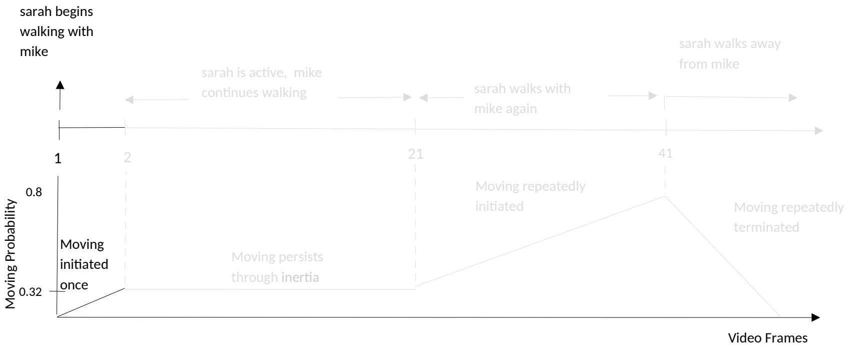


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

$$\mathit{0.45} :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ \mathit{20}).$$
$$\mathit{0.14} :: \textbf{happensAt}(\mathit{active}(\mathit{sarah}),\ \mathit{20}).$$

Instantaneous Recognition



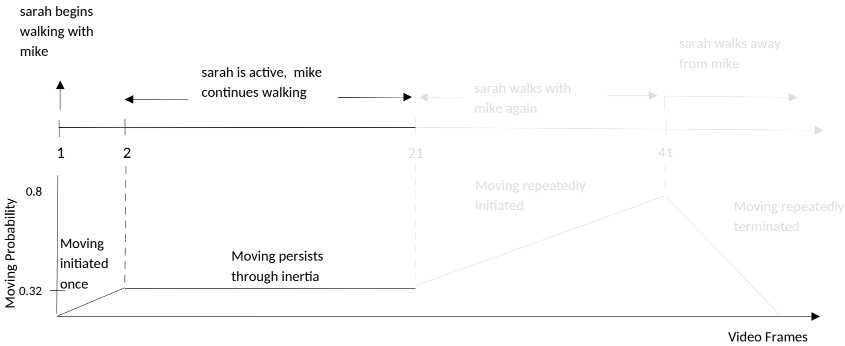
$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$
$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$
$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$
$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

$0.45 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 20).$
$0.14 :: \textbf{happensAt}(\mathit{active}(\mathit{sarah}),\ 20).$

$$P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21)) =$$
$$P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 20) \lor$$
$$(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 20) \land$$
$$\neg\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 20)))$$
$$= 0 + 0.322 \times 1 - 0 \times 0.322 \times 1 = 0.322$$

Instantaneous Recognition



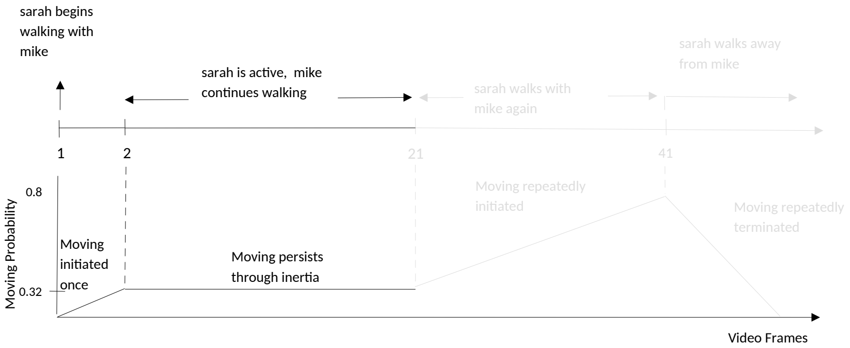
$$\begin{aligned}&\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),\\ &\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),\\ &\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),\\ &\quad \textbf{holdsAt}(\textit{orientation}(P_1, P_2) = \text{true},\ T).\end{aligned}$$

$$\begin{aligned}&\textbf{terminatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),\\ &\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{false},\ T).\end{aligned}$$

$$0.45 :: \textbf{happensAt}(\textit{walking}(\textit{mike}),\ 20).$$
$$0.14 :: \textbf{happensAt}(\textit{active}(\textit{sarah}),\ 20).$$

$$\begin{aligned}&P(\textbf{holdsAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 21)) =\\ &P(\textbf{initiatedAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 20) \vee\\ &\quad (\textbf{holdsAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 20) \wedge\\ &\quad \neg\textbf{terminatedAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 20)))\\ &= 0 + 0.322 \times 1 - 0 \times 0.322 \times 1 = 0.322\end{aligned}$$

Instantaneous Recognition

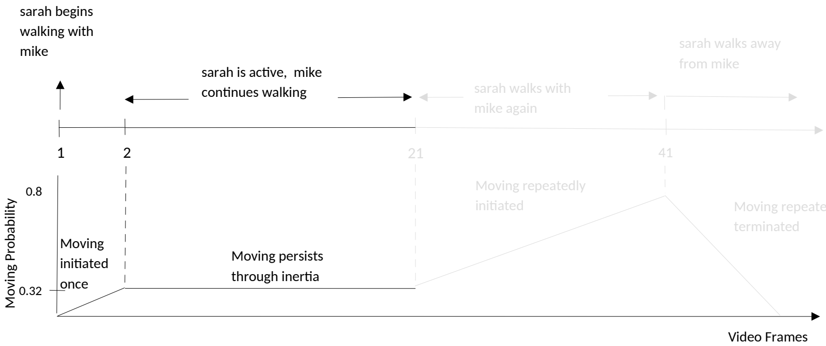


$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \mathrm{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \mathrm{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \mathrm{true},\ T).
\end{aligned}
$$

$$
\begin{aligned}
&\textbf{terminatedAt}(\mathit{moving}(P_1, P_2) = \mathrm{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \mathrm{false},\ T).
\end{aligned}
$$

$$
\begin{aligned}
&0.39 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 21). \\
&0.28 :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 21).\ \cdots
\end{aligned}
$$

Instantaneous Recognition



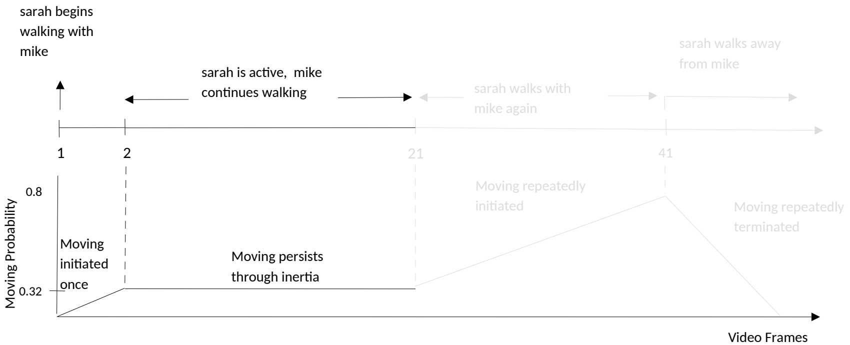
$$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\mathbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\mathbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\mathbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

$$0.39 :: \mathbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 21).$$
$$0.28 :: \mathbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 21).\ \cdots$$

$$P(\mathbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21)) =$$
$$P(\mathbf{happensAt}(\mathit{walking}(\mathit{mike}), 21)) \times$$
$$P(\mathbf{happensAt}(\mathit{walking}(\mathit{sarah}), 21)) \times$$
$$P(\mathbf{holdsAt}(\mathit{close}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21)) \times$$
$$P(\mathbf{holdsAt}(\mathit{orientation}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21))$$
$$= 0.39 \times 0.28 \times 1 \times 1 = 0.11$$

Instantaneous Recognition



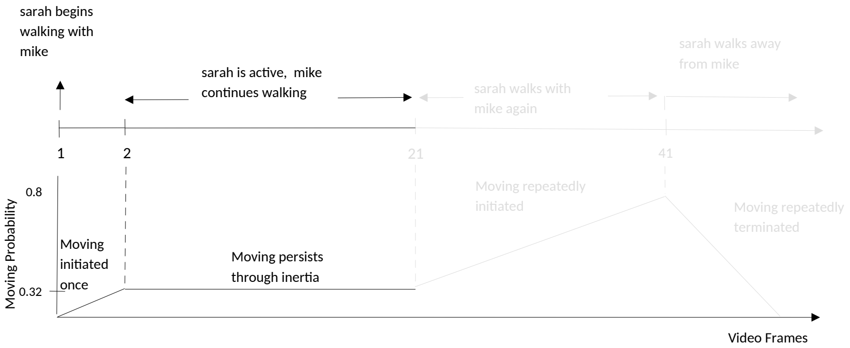
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

$$0.39 :: \textbf{happensAt}(walking(mike),\ 21).$$
$$0.28 :: \textbf{happensAt}(walking(sarah),\ 21).\ \cdots$$

$$P(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 22)) =$$
$$P(\textbf{initiatedAt}(moving(mike, sarah) = \text{true}, 21) \vee$$
$$(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 21) \wedge$$
$$\neg\textbf{terminatedAt}(moving(mike, sarah) = \text{true}, 21)))$$
$$= 0.11 + 0.322 \times 1 - 0.11 \times 0.322 \times 1 = 0.39$$

Instantaneous Recognition

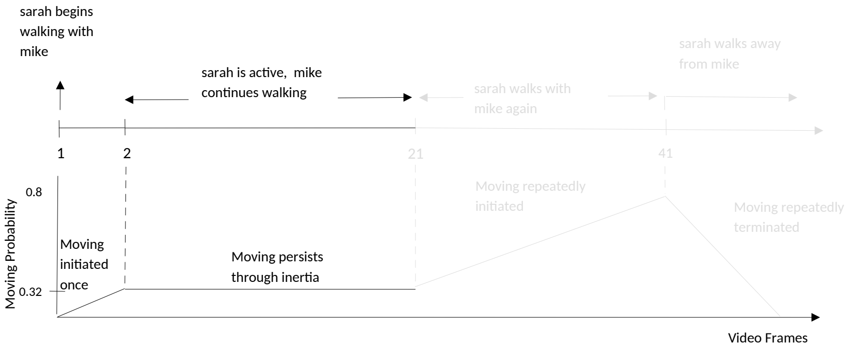


$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).
\end{aligned}$$

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

$$\begin{aligned}
&\mathit{0.28} :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ \mathit{40}). \\
&\mathit{0.18} :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ \mathit{40}).
\end{aligned}$$

Instantaneous Recognition



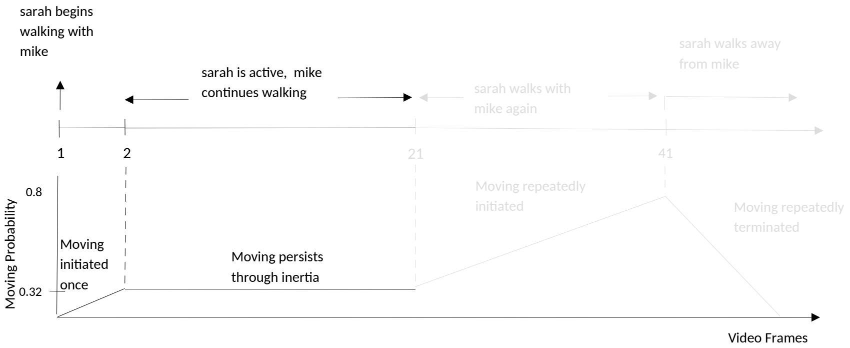
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).
\end{aligned}$$

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

$$0.28 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 40).$$
$$0.18 :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 40).$$

$$\begin{aligned}
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 40)) = \\
&\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{mike}), 40)) \times \\
&\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{sarah}), 40)) \times \\
&\quad P(\textbf{holdsAt}(\mathit{close}(\mathit{mike}, \mathit{sarah}) = \text{true}, 40)) \times \\
&\quad P(\textbf{holdsAt}(\mathit{orientation}(\mathit{mike}, \mathit{sarah}) = \text{true}, 40)) \\
&\quad = 0.28 \times 0.18 \times 1 \times 1 = 0.05
\end{aligned}$$

Instantaneous Recognition



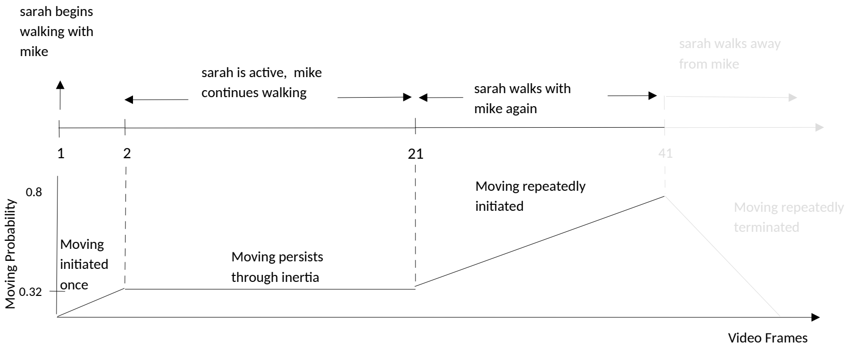
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

$$0.28 :: \textbf{happensAt}(walking(mike),\ 40).$$
$$0.18 :: \textbf{happensAt}(walking(sarah),\ 40).$$

$$P(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 41)) =$$
$$P(\textbf{initiatedAt}(moving(mike, sarah) = \text{true}, 40) \vee$$
$$\quad (\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 40) \wedge$$
$$\quad \neg\textbf{terminatedAt}(moving(mike, sarah) = \text{true}, 40)))$$
$$= 0.05 + 0.79 \times 1 - 0.05 \times 0.79 \times 1 = 0.80$$

Instantaneous Recognition



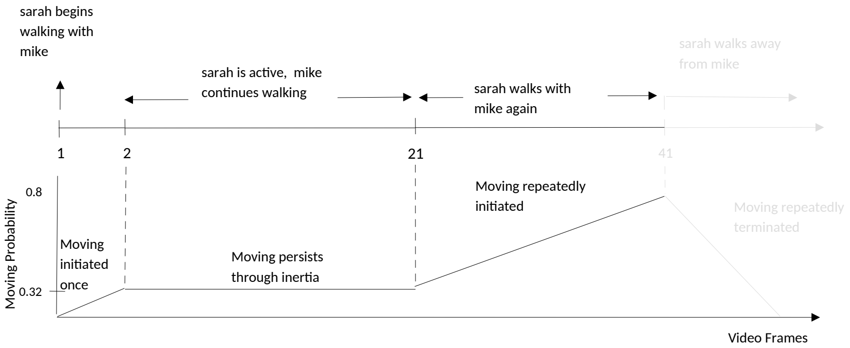
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

$$0.28 :: \textbf{happensAt}(walking(mike),\ 40).$$
$$0.18 :: \textbf{happensAt}(walking(sarah),\ 40).$$

$$P(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 41)) =$$
$$P(\textbf{initiatedAt}(moving(mike, sarah) = \text{true}, 40) \vee$$
$$(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 40) \wedge$$
$$\neg\textbf{terminatedAt}(moving(mike, sarah) = \text{true}, 40)))$$
$$= 0.05 + 0.79 \times 1 - 0.05 \times 0.79 \times 1 = 0.80$$

Instantaneous Recognition

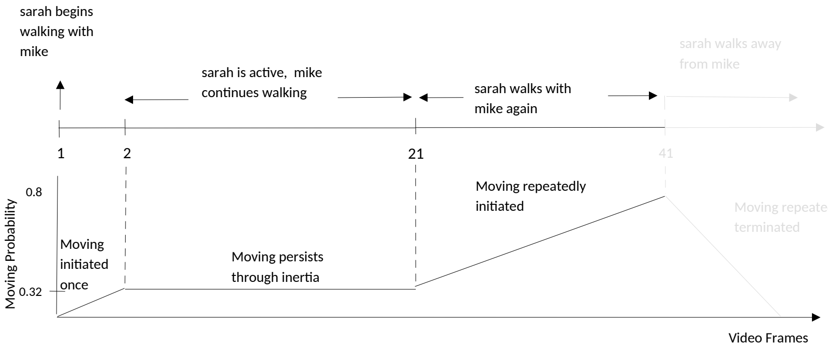


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

$$\mathit{0.18} :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ \mathit{41}).$$
$$\mathit{0.79} :: \textbf{happensAt}(\mathit{inactive}(\mathit{sarah}),\ \mathit{41}).\ \cdots$$

Instantaneous Recognition



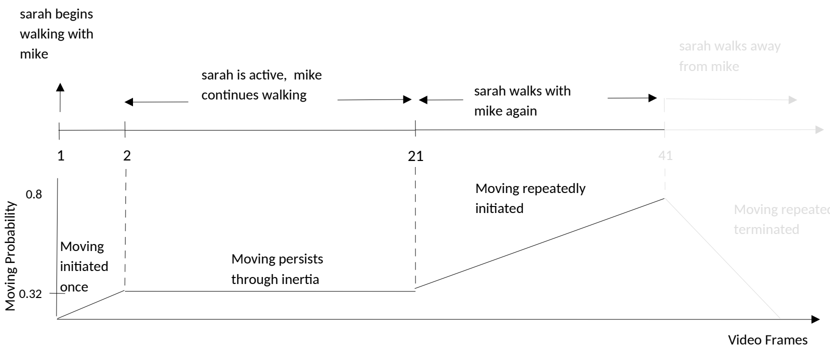
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).
\end{aligned}$$

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

$$\begin{aligned}
&0.18 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 41). \\
&0.79 :: \textbf{happensAt}(\mathit{inactive}(\mathit{sarah}),\ 41).\ \cdots
\end{aligned}$$

$$\begin{aligned}
&P(\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 41)) = \\
&\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{mike}), 41)) \times \\
&\quad P(\textbf{holdsAt}(\mathit{close}(\mathit{mike}, \mathit{sarah}) = \text{false}, 41)) \\
&\quad = 0.18 \times 1 = 0.18
\end{aligned}$$

Instantaneous Recognition



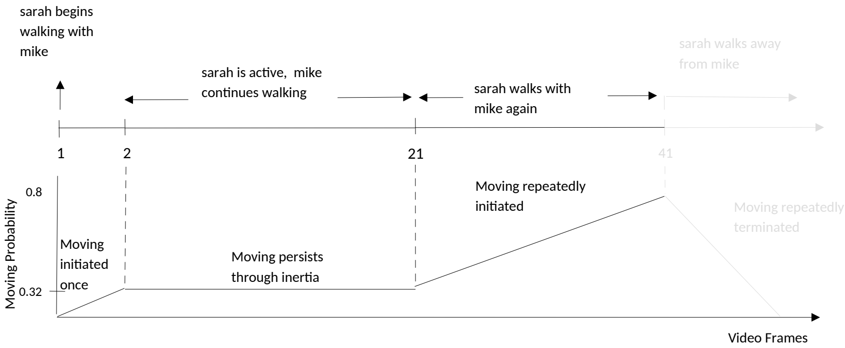
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

$$0.18 :: \textbf{happensAt}(walking(mike),\ 41).$$
$$0.79 :: \textbf{happensAt}(inactive(sarah),\ 41).\ \cdots$$

$$P(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 42)) =$$
$$P(\textbf{initiatedAt}(moving(mike, sarah) = \text{true}, 41) \vee$$
$$(\textbf{holdsAt}(moving(mike, sarah) = \text{true}, 41) \wedge$$
$$\neg\textbf{terminatedAt}(moving(mike, sarah) = \text{true}, 41)))$$
$$= 0 + 0.8 \times (1 - 0.18) - 0 \times 0.8 \times (1 - 0.18) = 0.66$$

Instantaneous Recognition

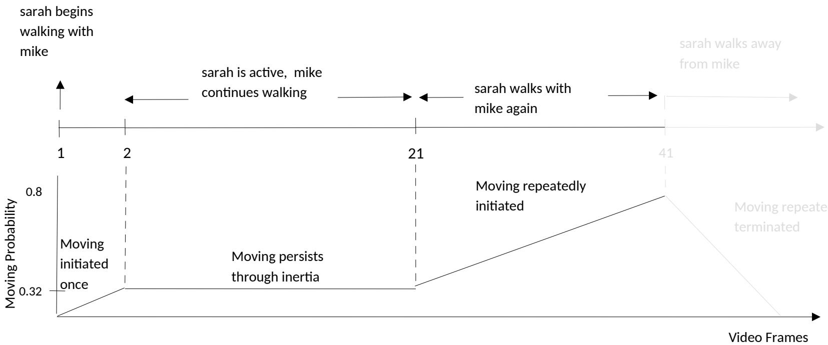


$$\mathbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\mathbf{happensAt}(walking(P_1),\ T),$$
$$\mathbf{happensAt}(walking(P_2),\ T),$$
$$\mathbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\mathbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

$$1.00 :: \mathbf{happensAt}(walking(mike),\ 49).$$
$$0.96 :: \mathbf{happensAt}(inactive(sarah),\ 49).$$

Instantaneous Recognition



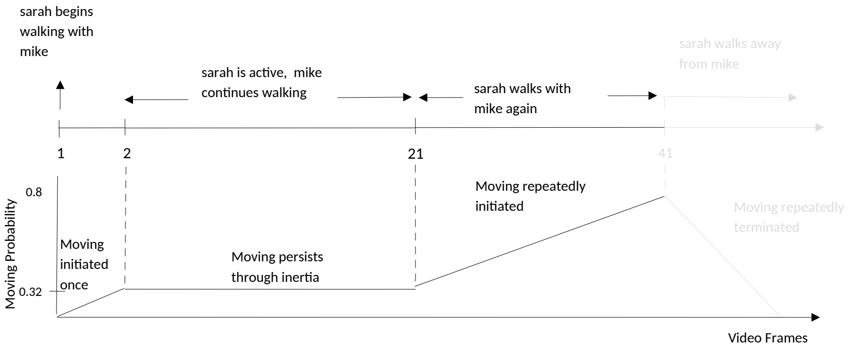
$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\&\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).\end{aligned}$$

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

$$\mathit{1.00} :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ \mathit{49}).$$
$$\mathit{0.96} :: \textbf{happensAt}(\mathit{inactive}(\mathit{sarah}),\ \mathit{49}).$$

$$\begin{aligned}&P(\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{49})) =\\&\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{mike}), \mathit{49})) \times\\&\quad P(\textbf{holdsAt}(\mathit{close}(\mathit{mike}, \mathit{sarah}) = \text{false}, \mathit{49}))\\&\quad = \mathit{1} \times \mathit{1} = \mathit{1}\end{aligned}$$

Instantaneous Recognition



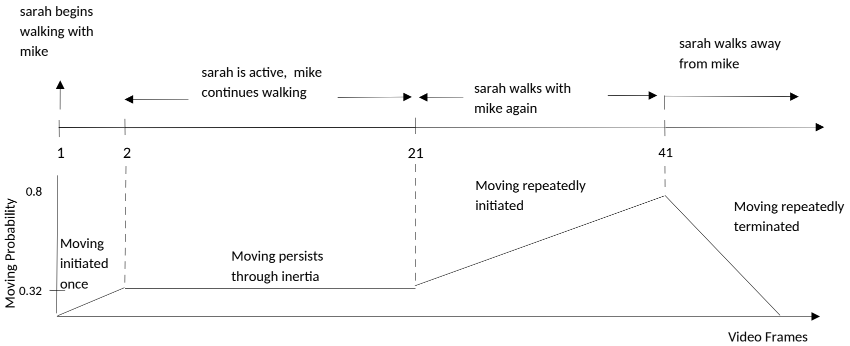
$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

$$1.00 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 49).$$
$$0.96 :: \textbf{happensAt}(\mathit{inactive}(\mathit{sarah}),\ 49).$$

$$P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 50)) =$$
$$P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \vee$$
$$\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \wedge$$
$$\quad \neg \textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49)))$$
$$= 0 + 0.07 \times 0 - 0 \times 0.07 \times 0 = 0$$

Instantaneous Recognition



$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\ &\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\ &\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\ &\quad \textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).\end{aligned}$$

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

$$\begin{aligned}&1.00 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 49).\\ &0.96 :: \textbf{happensAt}(\mathit{inactive}(\mathit{sarah}),\ 49).\end{aligned}$$

$$\begin{aligned}&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 50)) =\\ &P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \vee\\ &\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \wedge\\ &\quad \neg\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49)))\\ &= 0 + 0.07 \times 0 - 0 \times 0.07 \times 0 = 0\end{aligned}$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	*0*	*0.5*	*0.7*	*0.9*	*0.4*	*0.1*	*0*	*0*	*0.5*	*1*

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	*0*	*0.5*	*0.7*	*0.9*	*0.4*	*0.1*	*0*	*0*	*0.5*	*1*
L	*−0.5*	*0*	*0.2*	*0.4*	*−0.1*	*−0.4*	*−0.5*	*−0.5*	*0*	*0.5*

$$L[i] = In[i] - \mathcal{T}$$

Interval-based Recognition

Time	1	2	3	4	5	6	7	8	9	10
In	*0*	*0.5*	*0.7*	*0.9*	*0.4*	*0.1*	*0*	*0*	*0.5*	*1*
L	-0.5	*0*	*0.2*	*0.4*	-0.1	-0.4	-0.5	-0.5	*0*	*0.5*

$$\sum_{i=s}^{e} L[i] \geq 0 \Leftrightarrow P([s,e]) \geq \mathcal{T}$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9

$$prefix[i] = \sum_{j=1}^{i} L[j]$$

Interval-based Recognition

Time	1	2	3	4	5	6	7	8	9	10
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	−0.5	0	0.2	0.4	−0.1	−0.4	−0.5	−0.5	0	0.5
prefix	−0.5	−0.5	−0.3	0.1	0	−0.4	−0.9	−1.4	−1.4	−0.9
dp										

$$dp[i] = \max_{i \leq j \leq n} (prefix[j])$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp										-0.9

$$dp[10] = \max_{10 \leq j \leq 10} (prefix[j])$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp									-0.9	-0.9

$$dp[9] = \max_{9 \leq j \leq 10} (prefix[j])$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp								-0.9	-0.9	-0.9

$$dp[8] = \max_{8 \leq j \leq 10} (prefix[j])$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp							-0.9	-0.9	-0.9	-0.9

$$dp[7] = \max_{7 \leq j \leq 10} (prefix[j])$$

Interval-based Recognition

Time	1	2	3	4	5	6	7	8	9	10
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp						-0.4	-0.9	-0.9	-0.9	-0.9

$$dp[6] = \max_{6 \leq j \leq 10} (prefix[j])$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	−0.5	0	0.2	0.4	−0.1	−0.4	−0.5	−0.5	0	0.5
prefix	−0.5	−0.5	−0.3	0.1	0	−0.4	−0.9	−1.4	−1.4	−0.9
dp	0.1	0.1	0.1	0.1	0	−0.4	−0.9	−0.9	−0.9	−0.9

$$dp[i] = \max_{i \leq j \leq 10}(prefix[j])$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	−0.5	0	0.2	0.4	−0.1	−0.4	−0.5	−0.5	0	0.5
prefix	−0.5	−0.5	−0.3	0.1	0	−0.4	−0.9	−1.4	−1.4	−0.9
dp	0.1	0.1	0.1	0.1	0	−0.4	−0.9	−0.9	−0.9	−0.9

$$dprange[s, e] = dp[e] - prefix[s-1] \textbf{ if } s > 1$$

$$= dp[e] \textbf{ if } s = 1$$

Interval-based Recognition

Time	1	2	3	4	5	6	7	8	9	10
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	−0.5	0	0.2	0.4	−0.1	−0.4	−0.5	−0.5	0	0.5
prefix	−0.5	−0.5	−0.3	0.1	0	−0.4	−0.9	−1.4	−1.4	−0.9
dp	0.1	0.1	0.1	0.1	0	−0.4	−0.9	−0.9	−0.9	−0.9

$$dprange[s, e] = dp[e] - prefix[s-1] \textbf{ if } s > 1$$

$$= dp[e] \textbf{ if } s = 1$$

$$dprange[s, e] \geq 0 \Rightarrow \exists e^* : e^* \geq e,\ P([s, e^*]) \geq \mathcal{T}$$

Interval-based Recognition

$\Uparrow\Downarrow$

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

Interval-based Recognition

Time	⇑⇓ 1	2	3	4	5	6	7	8	9	10
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	−0.5	0	0.2	0.4	−0.1	−0.4	−0.5	−0.5	0	0.5
prefix	−0.5	−0.5	−0.3	0.1	0	−0.4	−0.9	−1.4	−1.4	−0.9
dp	0.1	0.1	0.1	0.1	0	−0.4	−0.9	−0.9	−0.9	−0.9

$$dprange[1,1] = dp[1] = 0.1 \geq 0$$

Interval-based Recognition

	⇑	⇓								
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

Interval-based Recognition

	⇑	⇓								
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[1, 2] = dp[2] = 0.1 \geq 0$$

Interval-based Recognition

	$\Uparrow$		$\Downarrow$							
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[1,3] = dp[3] = 0.1 \geq 0$$

Interval-based Recognition

	$\Uparrow$			$\Downarrow$						
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[1, 4] = dp[4] = 0.1 \geq 0$$

Interval-based Recognition

	⇑				⇓					
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[1, 5] = dp[5] = 0 \geq 0$$

Interval-based Recognition

	⇑					⇓				
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[1,6] = dp[6] = -0.4 < 0$$

Interval-based Recognition

	⇑					⇓				
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[1,6] = dp[6] = -0.4 < 0$$

Interval-based Recognition

		$\Uparrow$				$\Downarrow$				
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[2,6] = dp[6] - prefix[1] = 0.1 \geq 0$$

Interval-based Recognition

		$\Uparrow$					$\Downarrow$			
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[2,7] = dp[7] - prefix[1] = -0.4 < 0$$

Interval-based Recognition

		$\Uparrow$					$\Downarrow$			
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

$$dprange[2,7] = dp[7] - prefix[1] = -0.4 < 0$$

Interval-based Recognition

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
L	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
prefix	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
dp	0.1	0.1	0.1	0.1	0	-0.4	-0.9	-0.9	-0.9	-0.9

Interval-based Recognition[1]

Interval Computation Correctness

An interval is computed iff it is a probabilistic maximal interval.

[1] Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Annals of Mathematics and Artificial Intelligence, 2021.

Interval-based Recognition[1]

Interval Computation Correctness

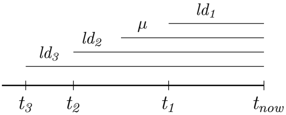
An interval is computed iff it is a probabilistic maximal interval.

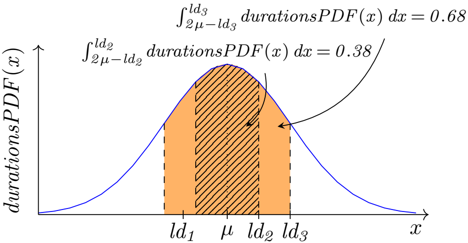
Complexity

The computation of probabilistic maximal intervals is linear to the dataset size.

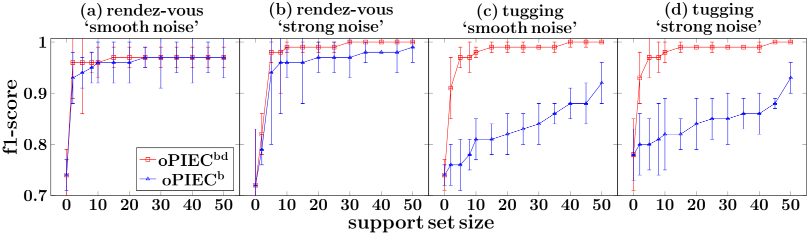
[1] Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Annals of Mathematics and Artificial Intelligence, 2021.

Deletion Probabilities of Support Set Elements





oPIEC: Experimental Results



oPIEC: Experimental Results

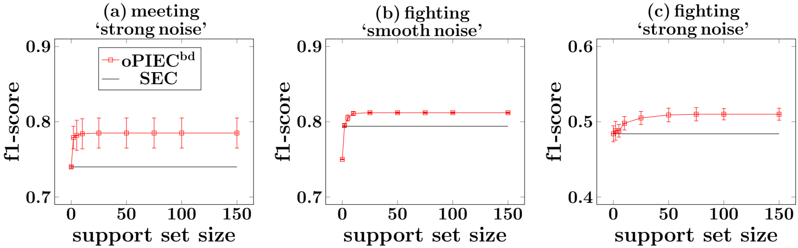
(a) Total run-times of oPIEC^{bd}, oPIEC^{b} and PIEC in seconds when processing data streams of increasing size.

total stream size (number of time-points)	**1K**	**2K**	**4K**	**8K**
PIEC	*1.92 ± 0.32*	*7.53 ± 1.24*	*29.76 ± 4.9*	*134.63 ± 22*
oPIEC^{b}	**0.09 ± 0.02**	**0.19 ± 0.05**	**0.38 ± 0.1**	**0.7 ± 0.2**
oPIEC^{bd}	**0.09 ± 0.02**	**0.19 ± 0.05**	*0.39 ± 0.1*	*0.72±0.23*

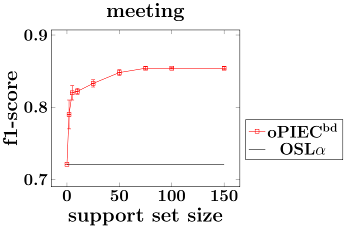
(b) Total run-times of oPIEC^{bd} and oPIEC^{b} in seconds as the support set size increases.

support set size (number of elements)	**50**	**100**	**200**	**400**
oPIEC^{b}	**0.7 ± 0.21**	**1.27 ± 0.5**	**2.4 ± 1.1**	**4.79 ± 2.41**
oPIEC^{bd}	**0.7 ± 0.23**	**1.27 ± 0.53**	**2.4 ± 1.1**	**4.79 ± 2.41**

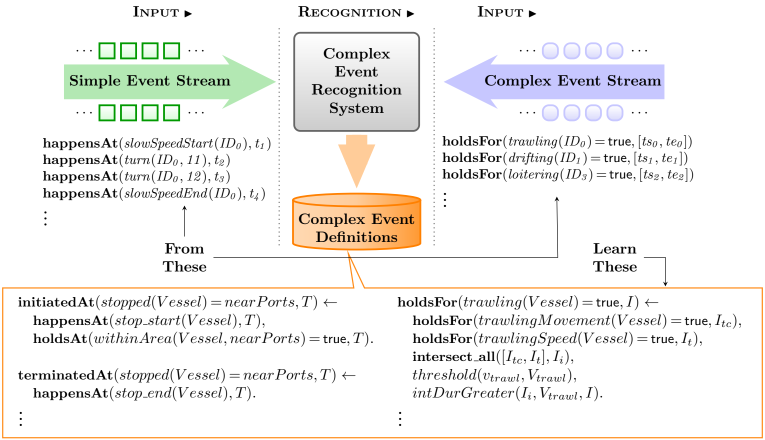
oPIEC: Experimental Results



oPIEC: Experimental Results



Machine Learning for Complex Event Recognition



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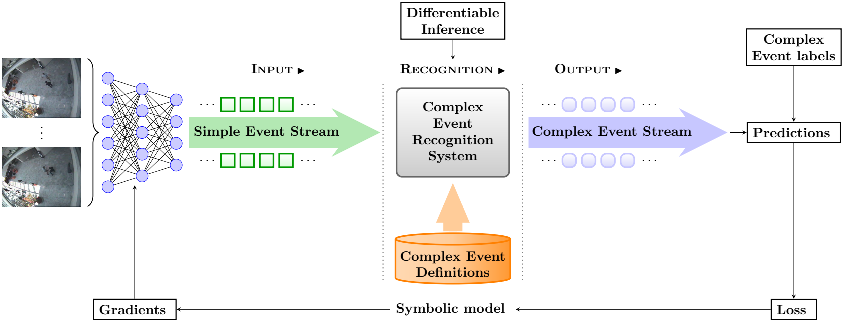
Michelioudakis et al, Online semi-supervised learning of composite event rules by combining structure and mass-based predicate similarity. Machine Learning, 2024.

Neuro-Symbolic Complex Event Recognition



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