

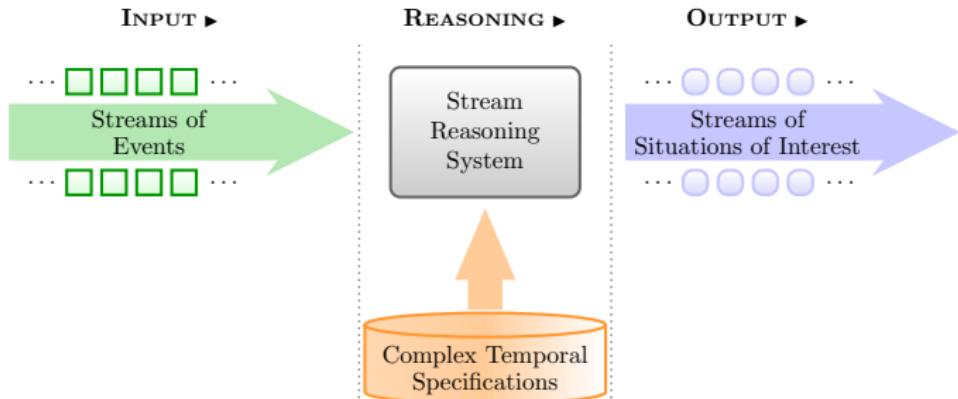
Reasoning over Complex Temporal Specifications and Noisy Data Streams

Periklis Mantenoglou

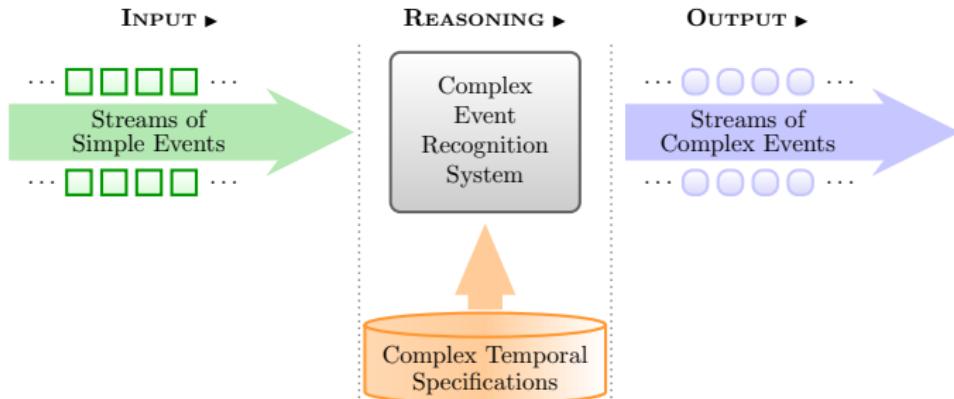
National and Kapodistrian University of Athens, Greece
NCSR Demokritos, Greece



Stream Reasoning



Complex Event Recognition



Requirements and Motivation

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- ▶ 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., Palouras 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., Palouras 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>

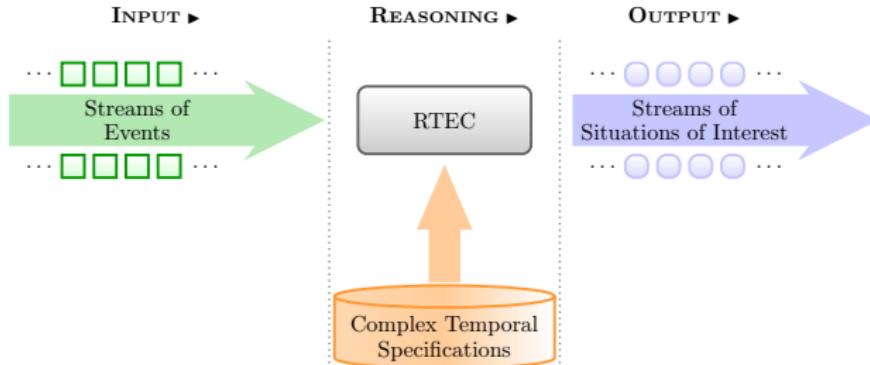
Peripheral Publication:

- ▶ 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>

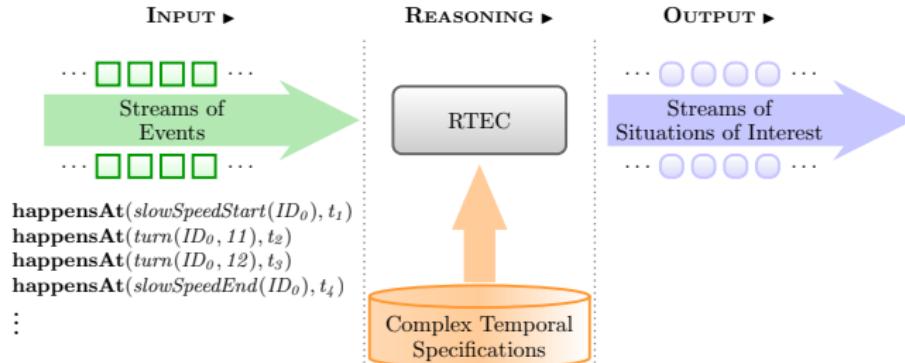
Event Calculus

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

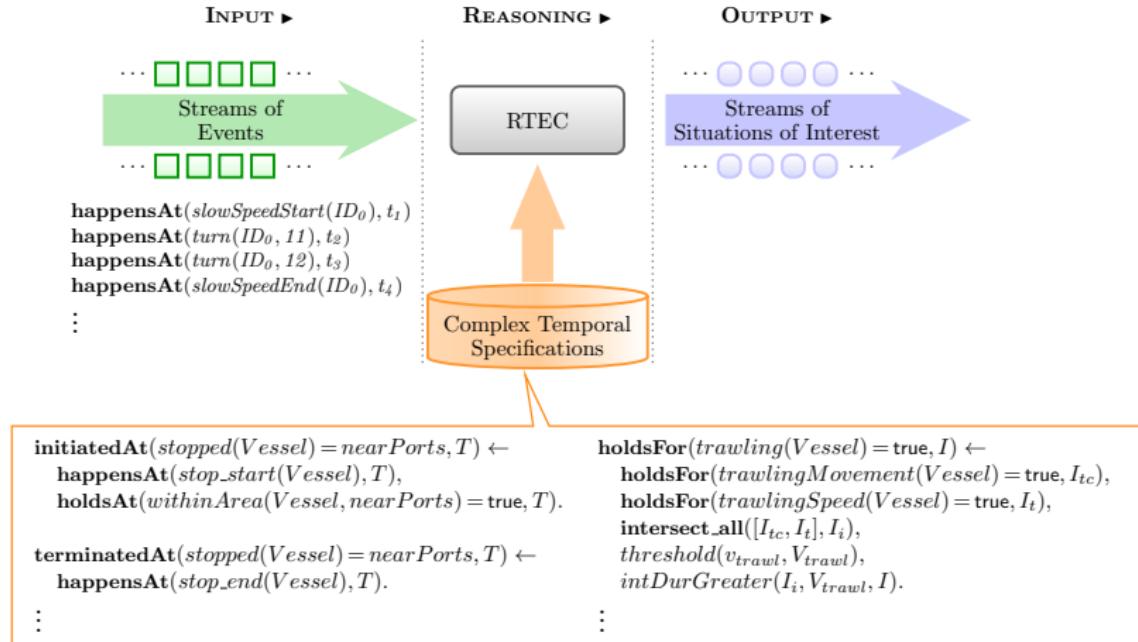
Stream Reasoning with RTEC



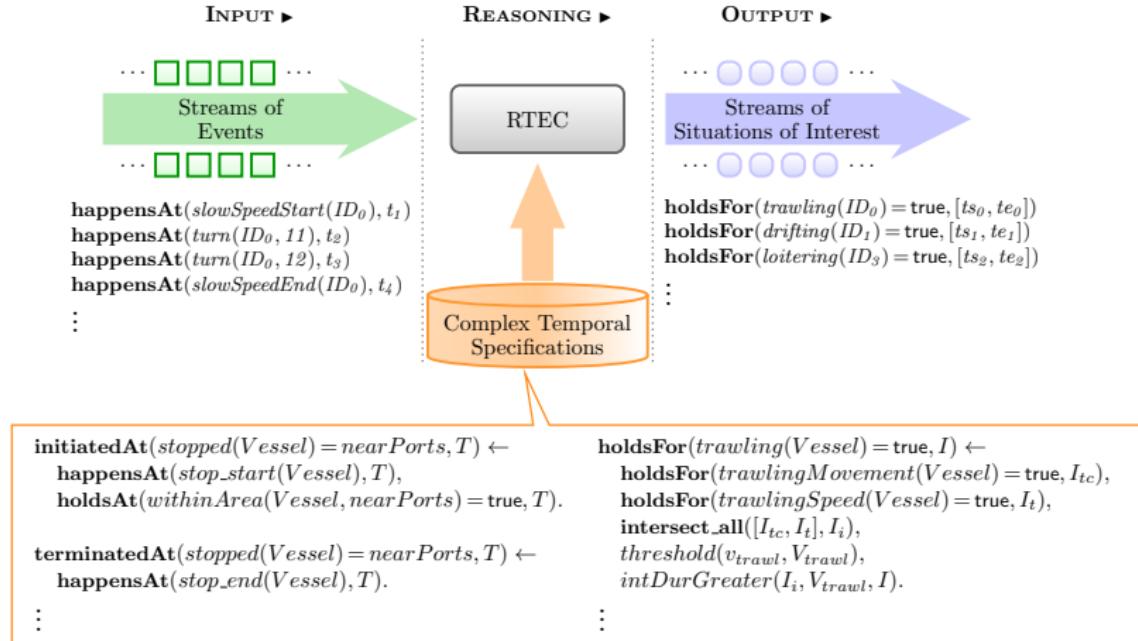
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Stream Reasoning with RTEC



Simple Fluent: High Speed Near Coast

initiatedAt(*highSpeedNC(Vessel)*) = true, *T*) \leftarrow
happensAt(*velocity(Vessel, Speed, _CoG, _TrueHeading)*, *T*),
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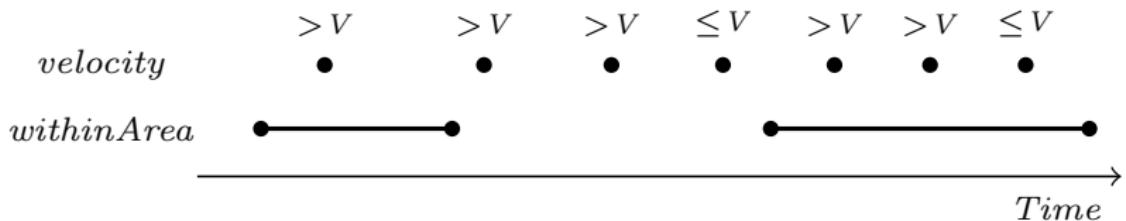
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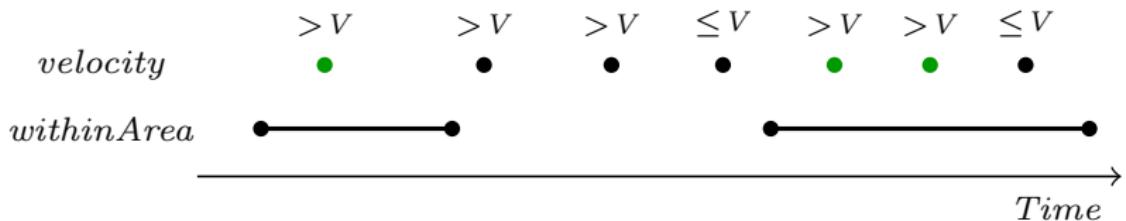
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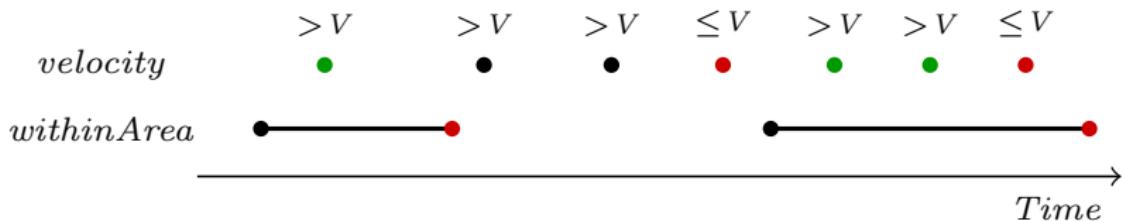
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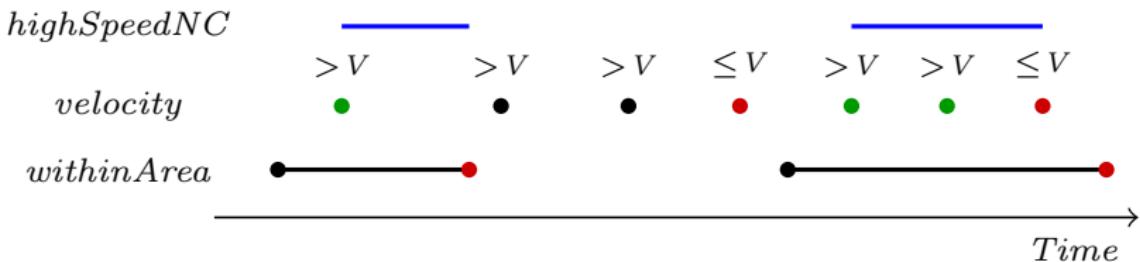
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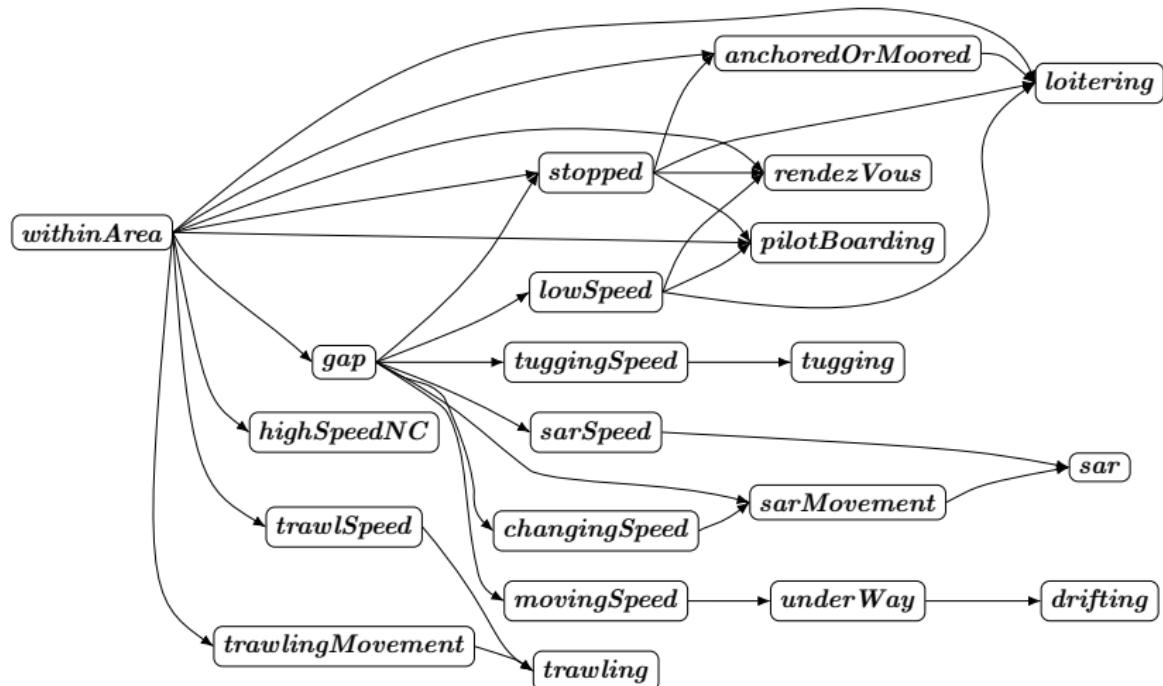
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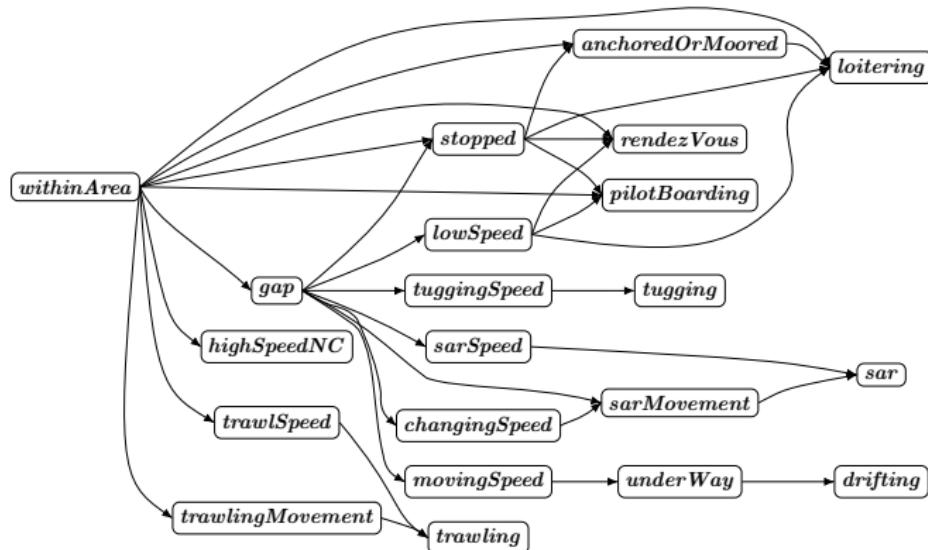
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Hierarchical Knowledge Bases



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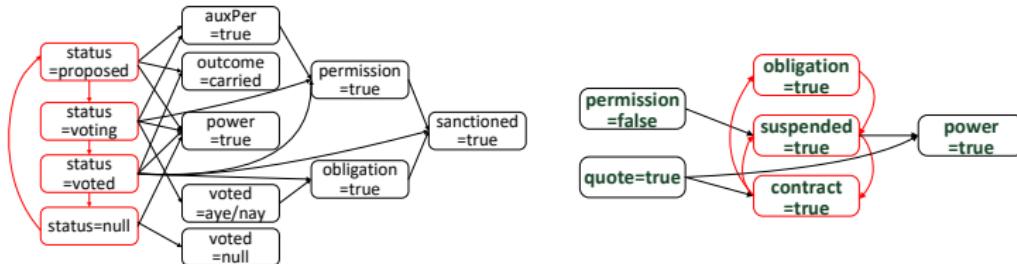


Semantics

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

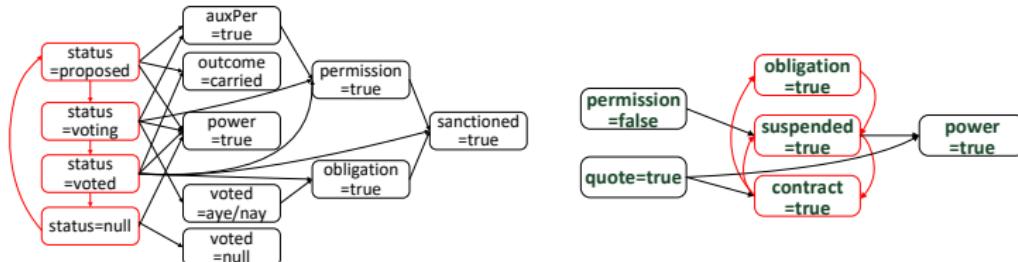
Cyclic Dependencies in Temporal Patterns

- Multi-Agent Systems: Voting & NetBill.

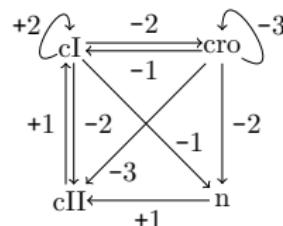
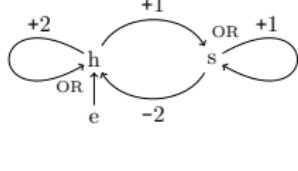


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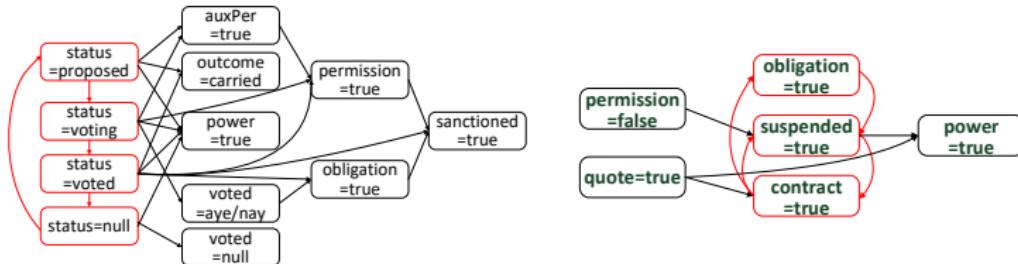


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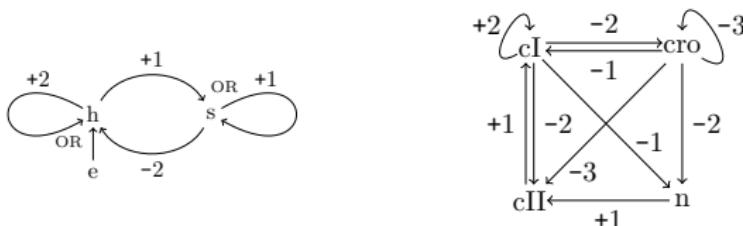


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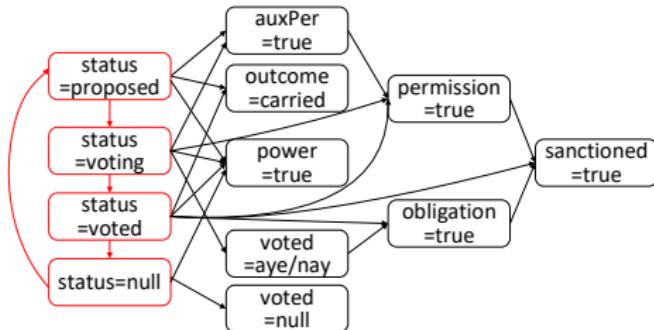


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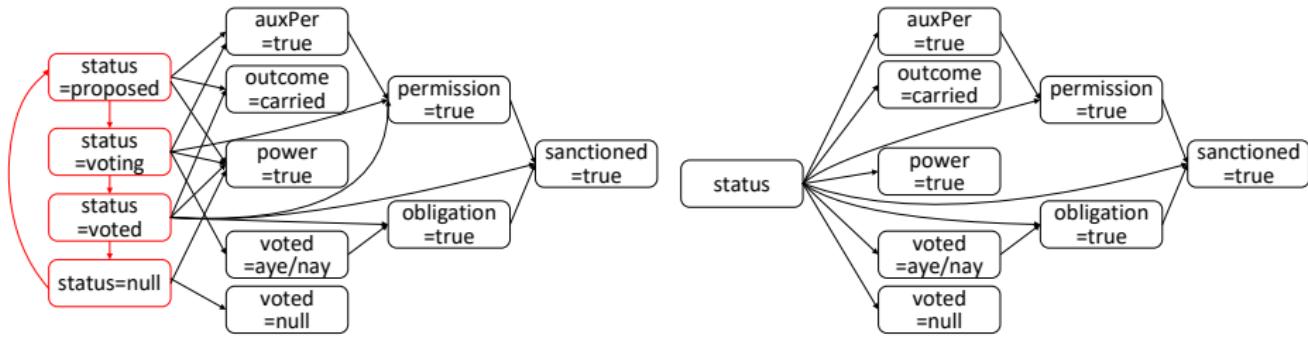


- ▶ Maritime Situational Awareness: the stages of a fishing trip, i.e., *started*, *fishing*, *returning*, *ended*, form a cycle.

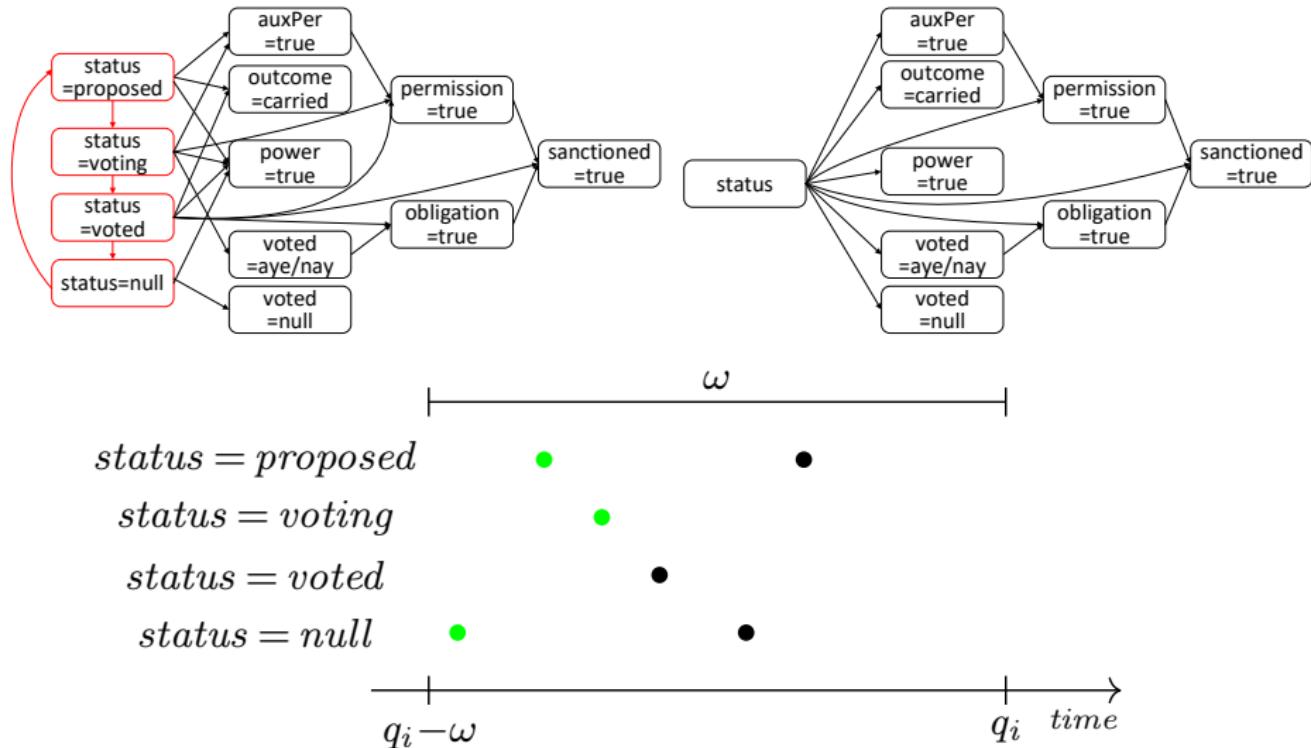
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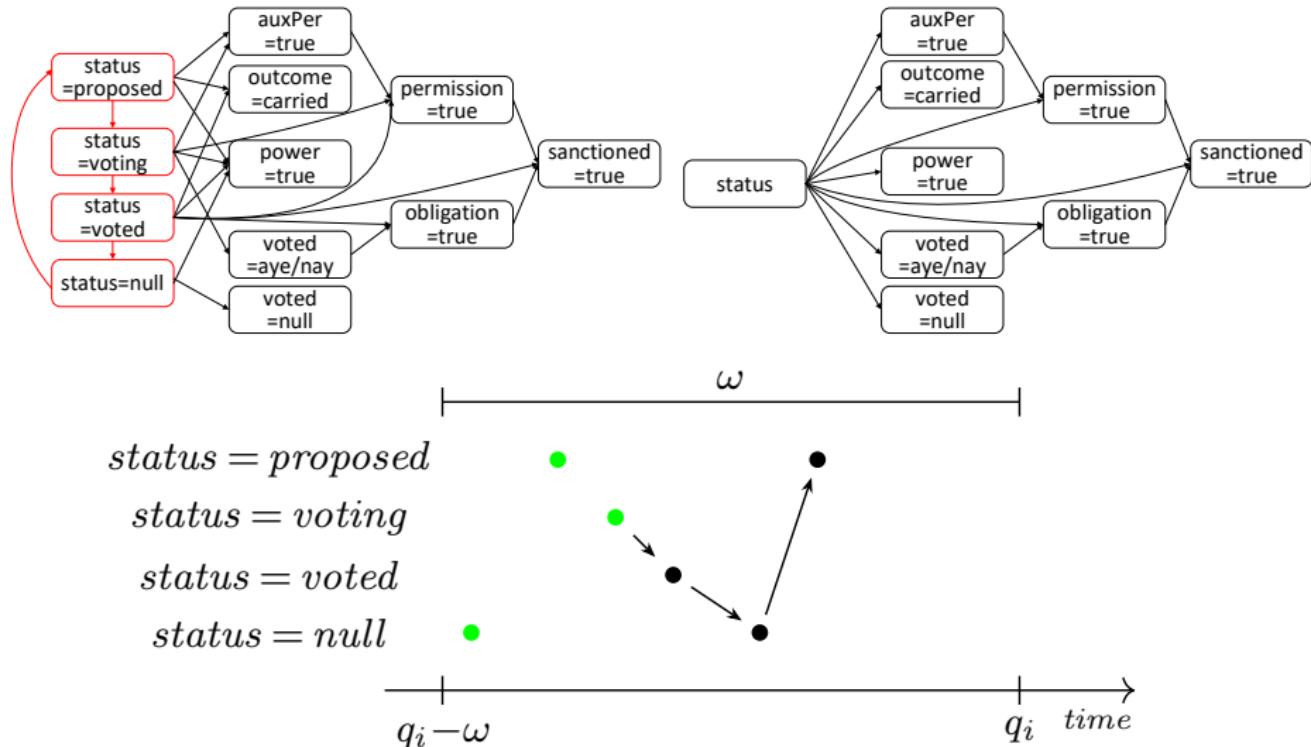
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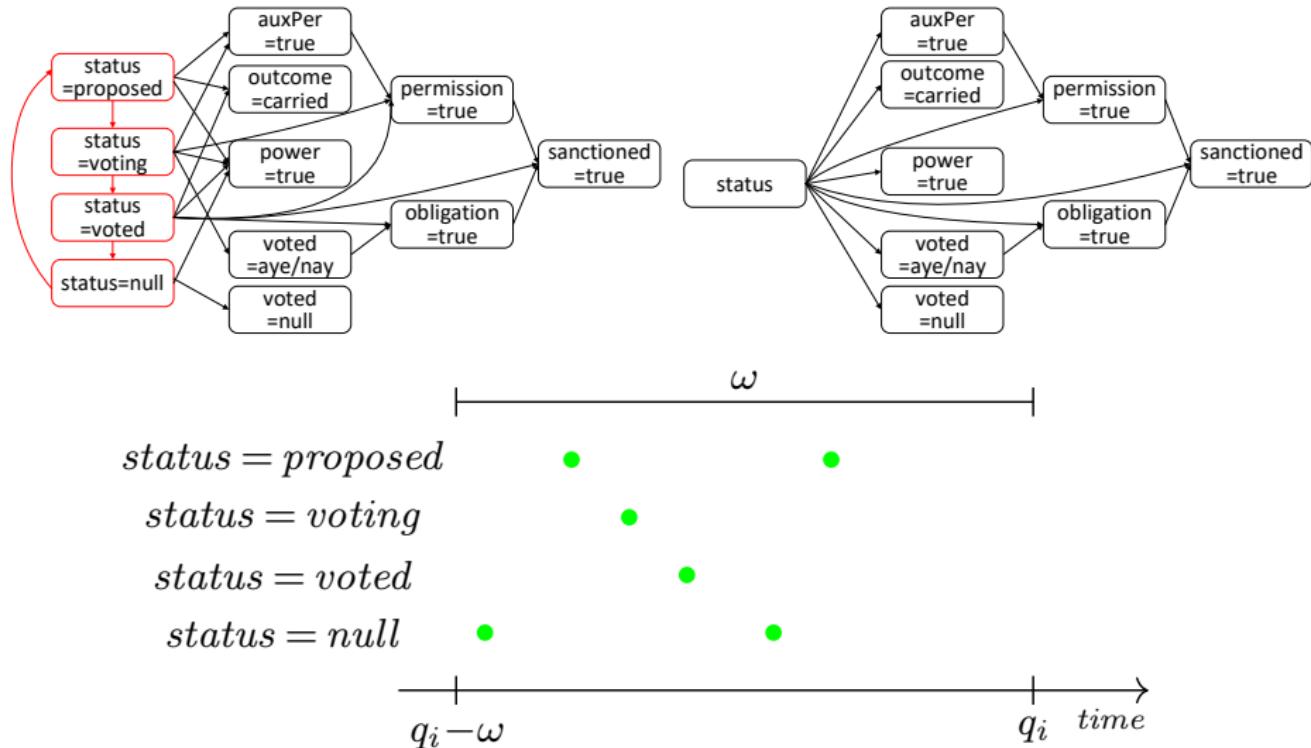
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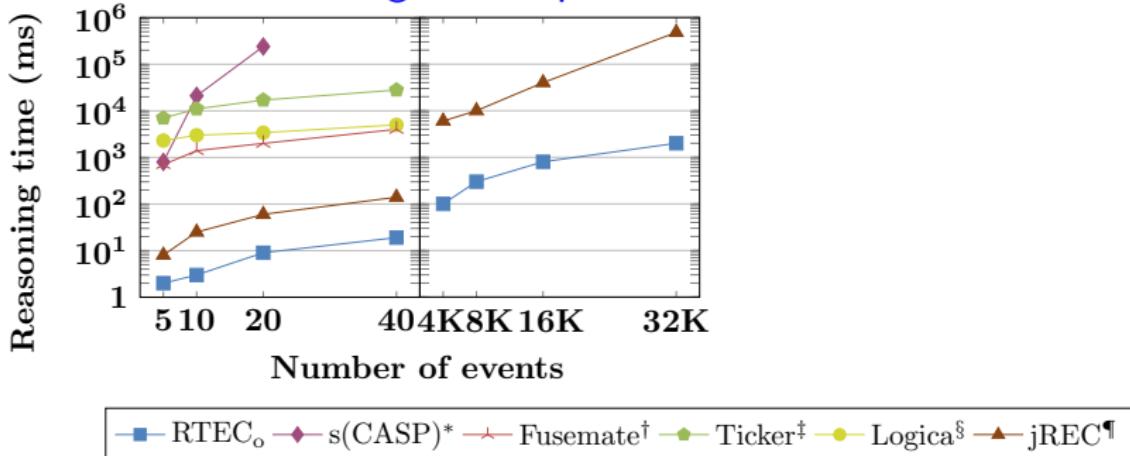
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Complexity

In RTEC_o, the **worst-case time complexity** of maximal interval computation for a fluent definition with cyclic dependencies is $\mathcal{O}(\omega \log(\omega))$, where ω is the size of the window.

1. RTEC_o: Indicative Experimental Results

NetBill: monitoring active quotes



* Arias et al., Modeling and reasoning in event calculus using goal-directed constraint answer set programming. Theory and Practice of Logic Programming, 2022.

† Baumgartner, Combining Event Calculus and Description Logic Reasoning via Logic Programming. Frontiers of Combining Systems, 2021.

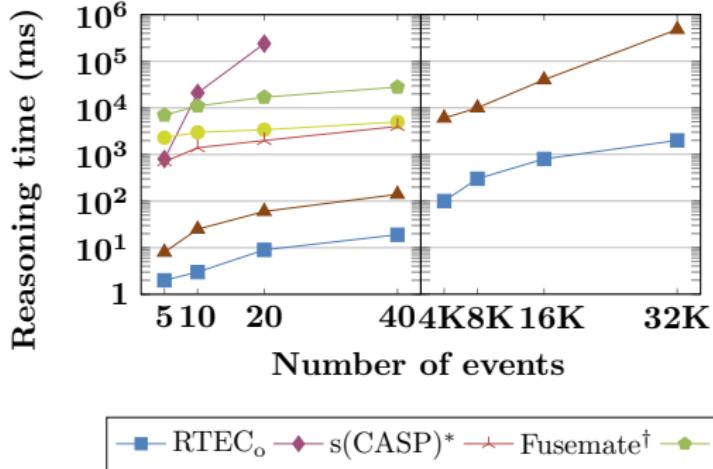
‡ Beck et al., Ticker: A system for incremental asp-based stream reasoning. Theory and Practice of Logic Programming, 2017.

§ Logica: Language of Big Data, <https://github.com/EvgSkv/logica>.

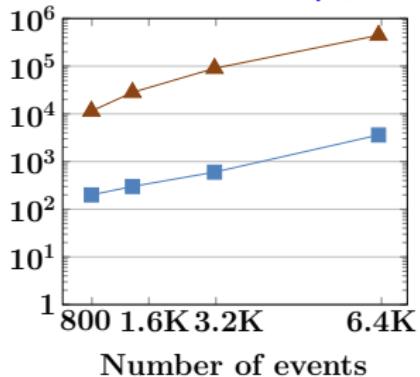
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NetBill: monitoring active quotes



Voting: monitoring the status of motions (cycles)



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- ▶ **Maritime Situational Awareness:** a fishing activity is terminated with a delay after multiple changes in heading.
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- ▶ **RTEC** supports only **immediate initiations**:

initiatedAt($F = V, T \leftarrow$
happensAt(E, T)[,
conditions].

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

2. RTEC \rightarrow : Events with Delayed Effects

- ▶ RTEC \rightarrow : Representation of future initiations:
 - ▶ **fi**(*quote(M, C, G) = in_effect, quote(M, C, G) = expiring, 50*).

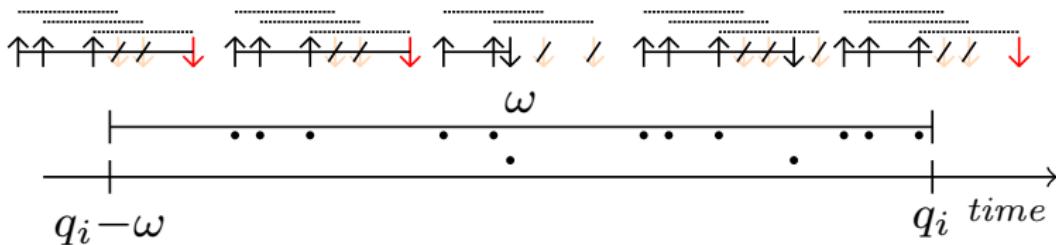
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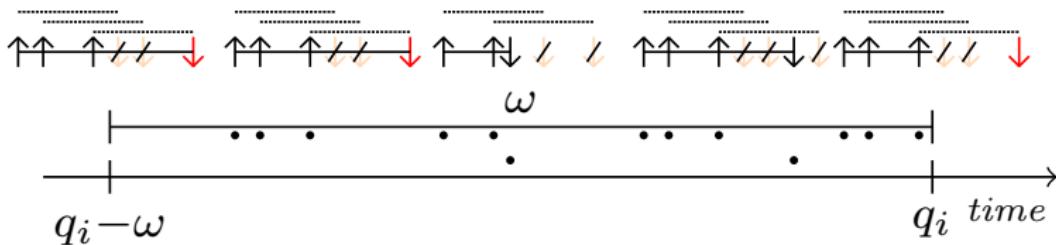
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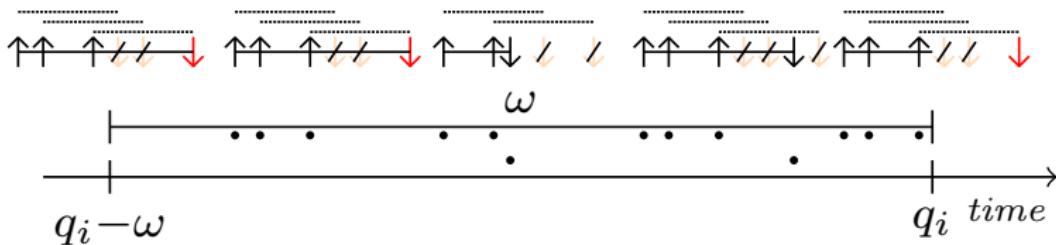


- RTEC \rightarrow : Reasoning over future initiations:

- ▶ Compile-time detection of optimal processing order.

2. RTEC \rightarrow : Events with Delayed Effects

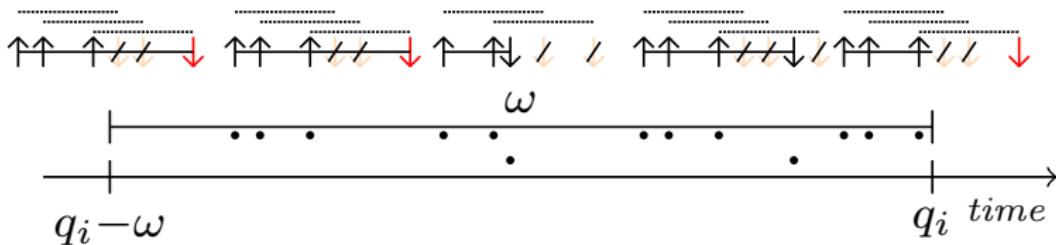
- ▶ RTEC \rightarrow : Representation of future initiations:
 - ▶ $\text{fi}(\text{quote}(M, C, G) = \text{in_effect}, \text{quote}(M, C, G) = \text{expiring}, 50)$.
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- ▶ RTEC \rightarrow : Reasoning over future initiations:
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- ▶ RTEC \rightarrow : Reasoning over future initiations:
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2. RTEC \rightarrow : Formal Properties

Semantics

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

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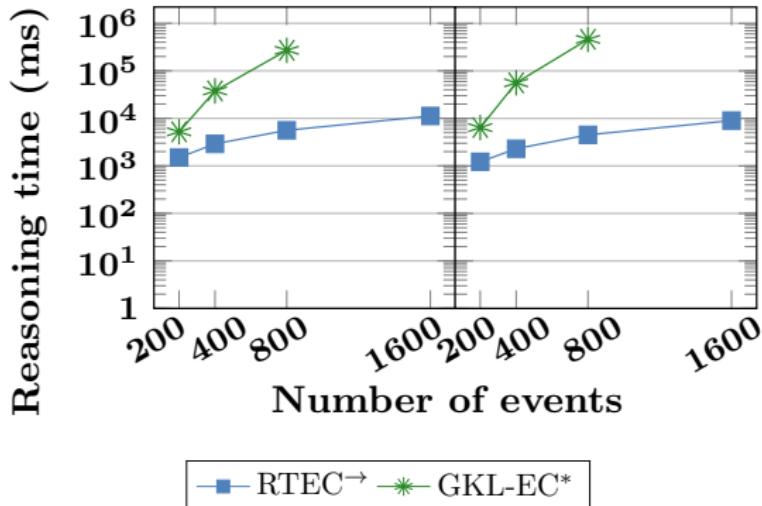
RTEC \rightarrow computes all maximal intervals of the fluents of an event description with events with delayed effects, and no other interval.

Complexity

In RTEC \rightarrow , the worst-case time complexity of maximal interval computation for a fluent definition with events with delayed effects is $\mathcal{O}(\omega \log(\omega))$, where ω is the size of the window.

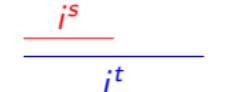
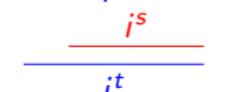
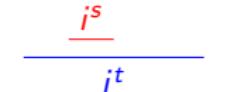
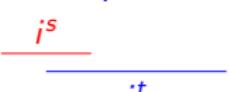
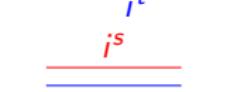
2. RTEC \rightarrow : Indicative Experimental Results

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

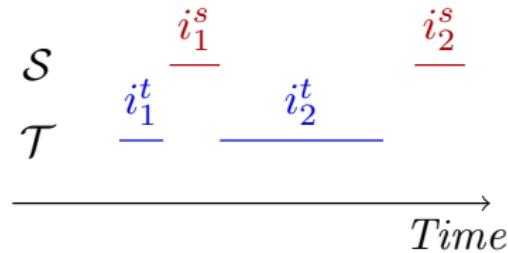
Relation	Illustration
before(i^s, i^t)	
meets(i^s, i^t)	
starts(i^s, i^t)	
finishes(i^s, i^t)	
during(i^s, i^t)	
overlaps(i^s, i^t)	
equal(i^s, i^t)	

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```
holdsFor(disappearedInArea( Vessel, AreaType) = true, I) ←  
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```

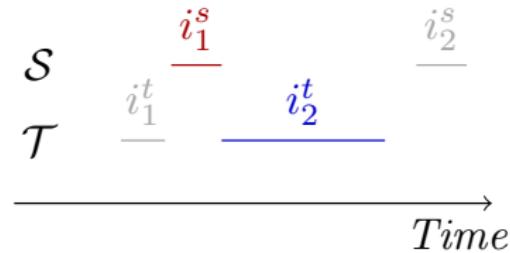
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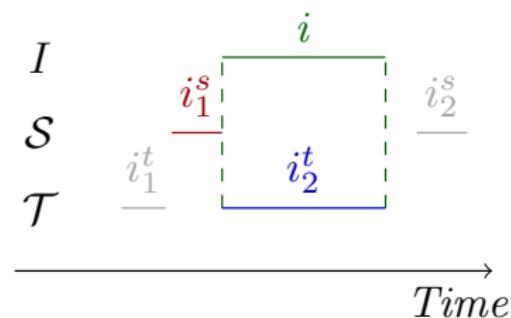
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Complexity

In RTEC_A, the **worst-case time complexity** of maximal interval computation for a fluent definition with Allen relations $\mathcal{O}(\omega)$, where ω is the size of the window.

3. RTEC_A: Indicative Experimental Results

Monitoring maritime activities with Allen relations

Window size		Reasoning Time (ms)		Output Intervals	
Days	Input Intervals	RTEC _A	D ² IA*	RTEC _A	D ² IA*
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
16	297K	285	2.7K	77K	76K

* Awad et al, D²IA: User-defined interval analytics on distributed streams. Information Systems, 2022.

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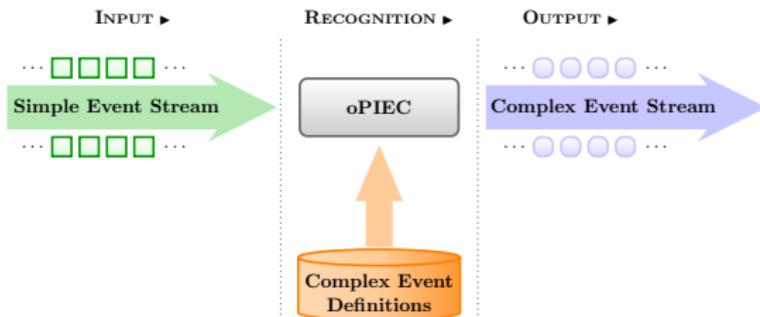
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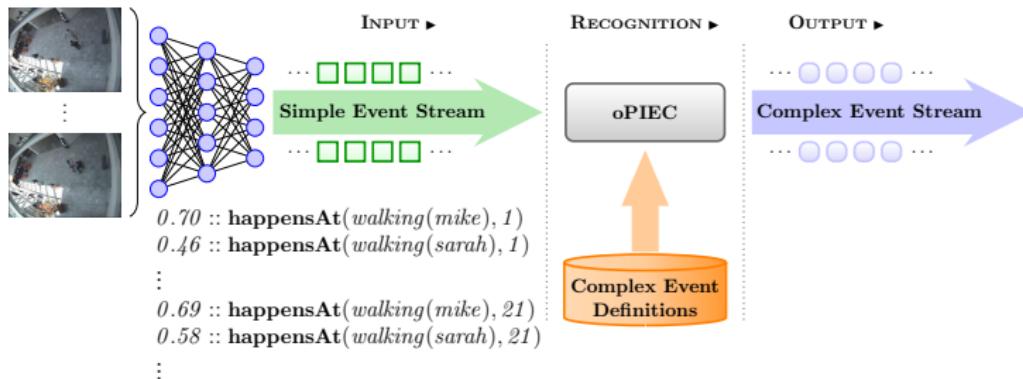
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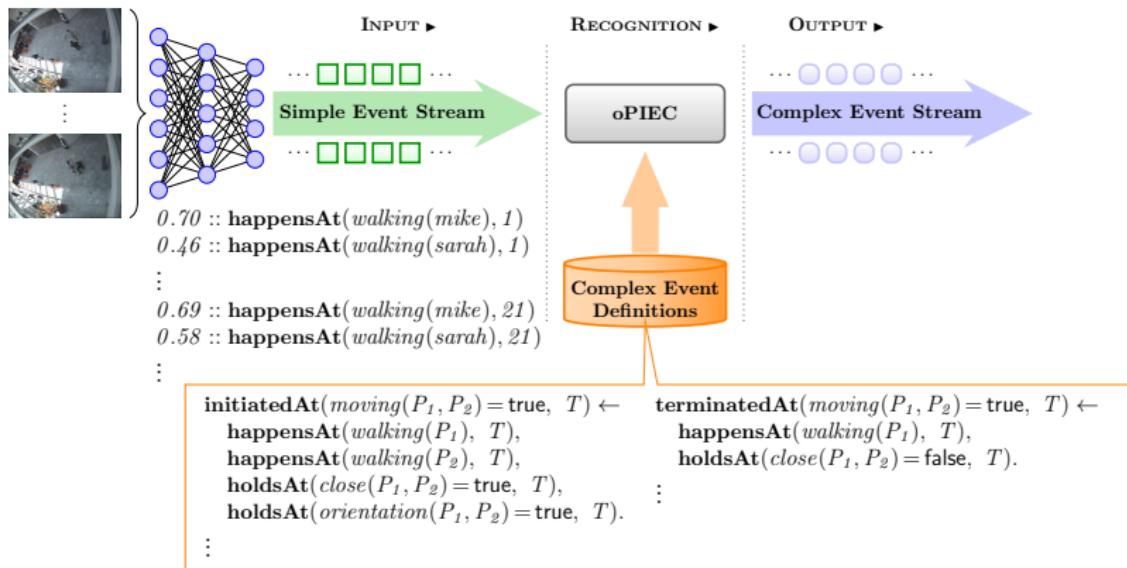
4. Stream Reasoning with oPIEC



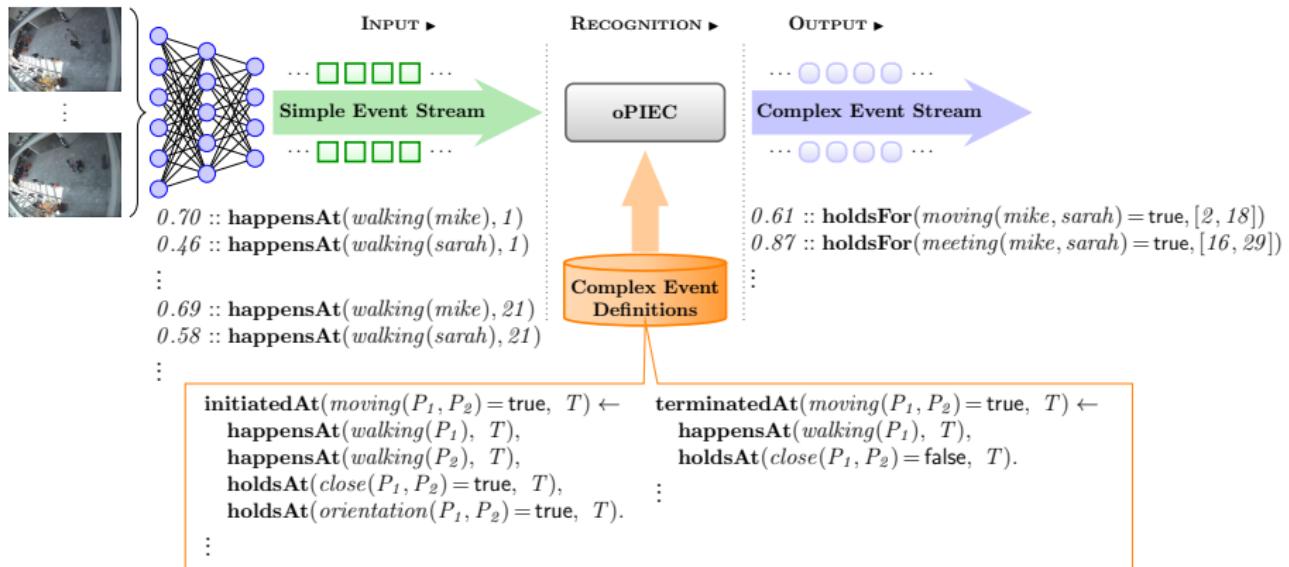
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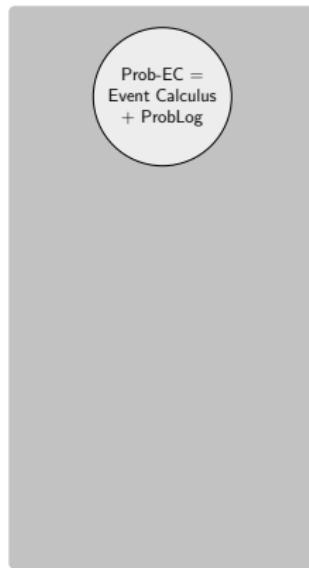
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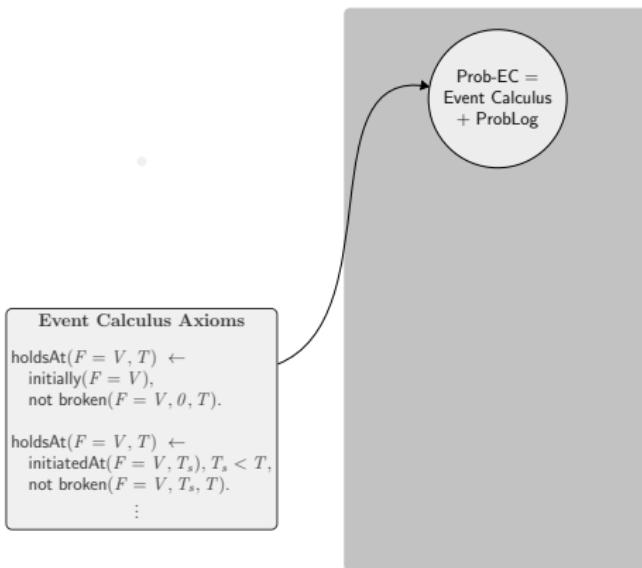
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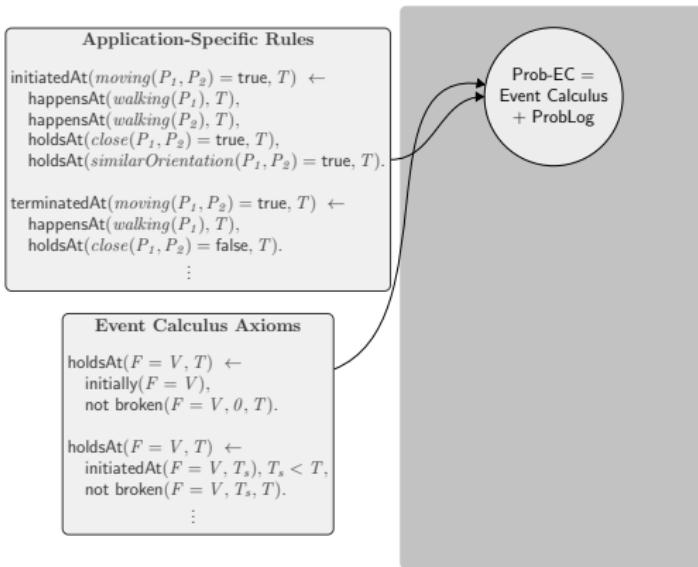
4. Architecture of oPIEC



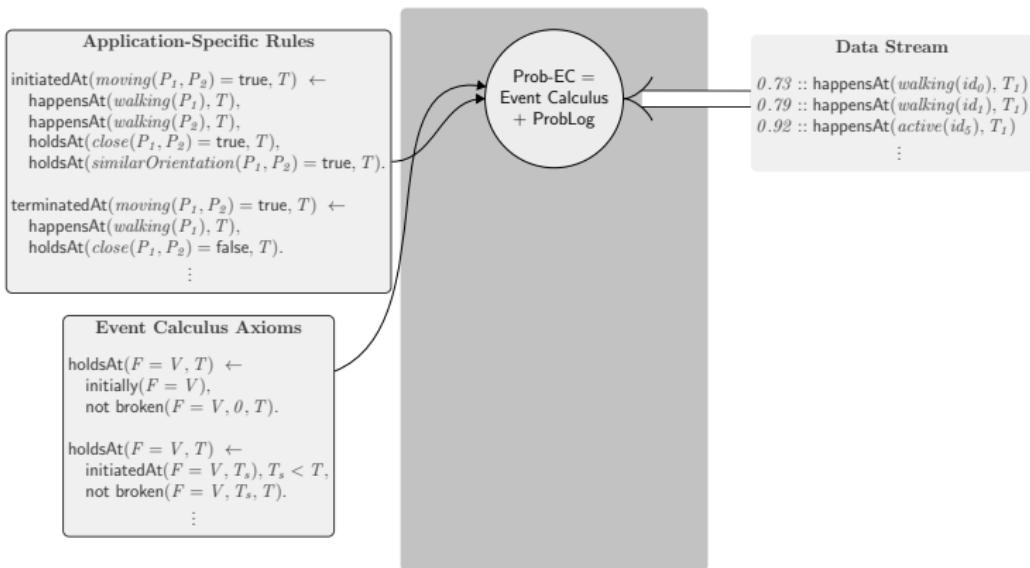
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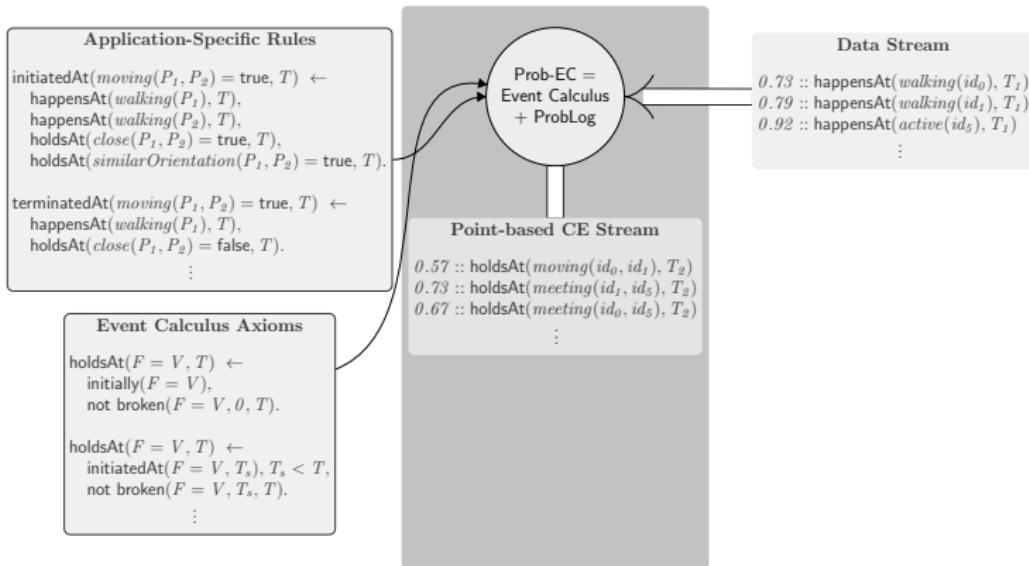
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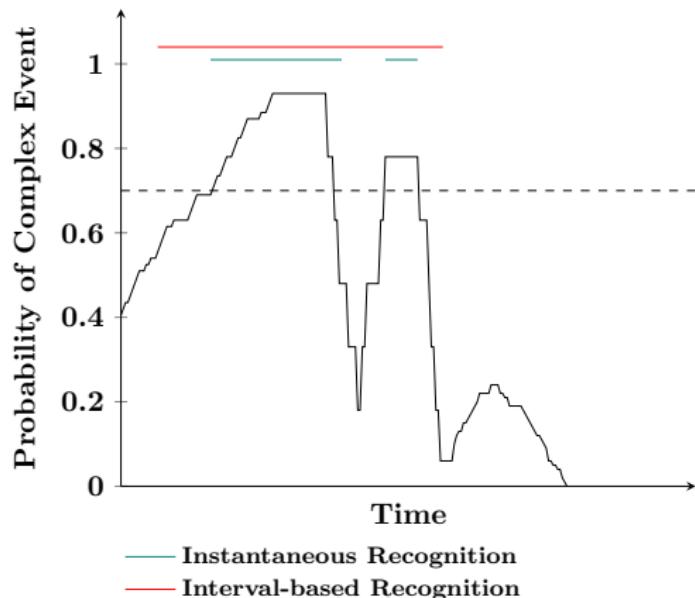
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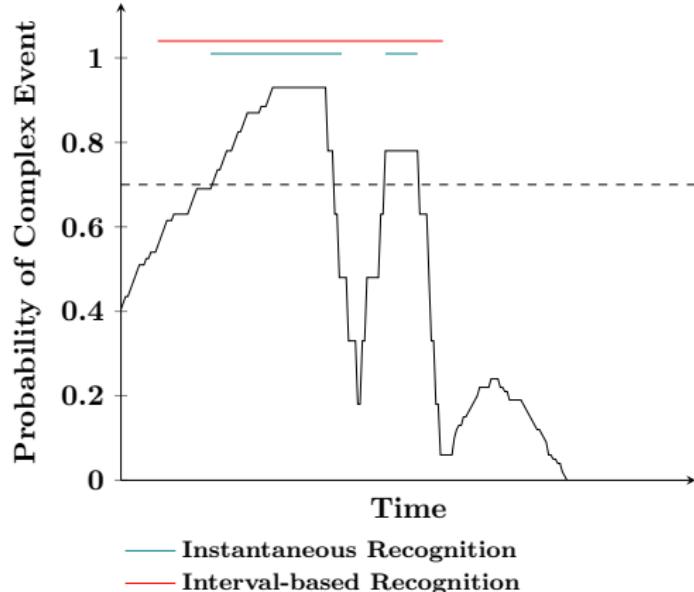
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Time-points vs Temporal Intervals

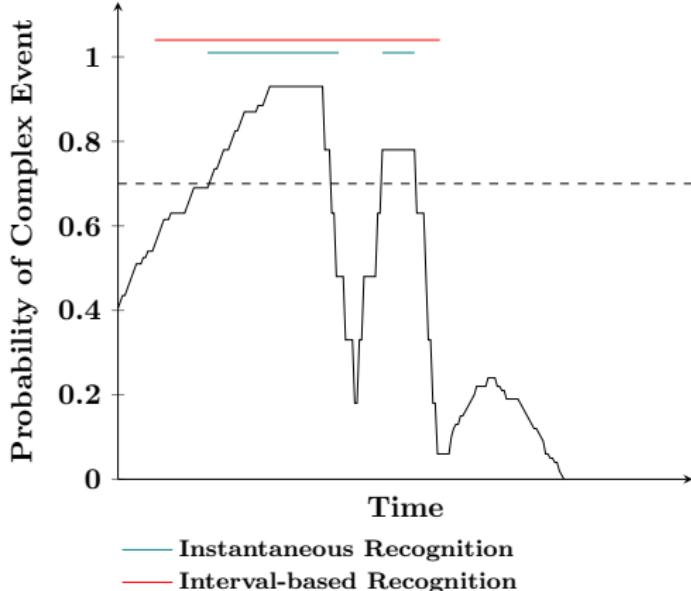


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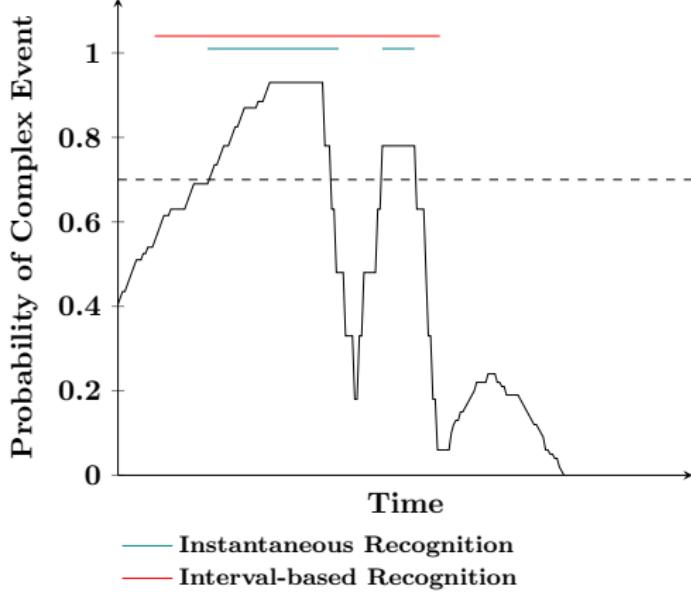
- ▶ **Interval Probability:** average probability of the time-points it contains.

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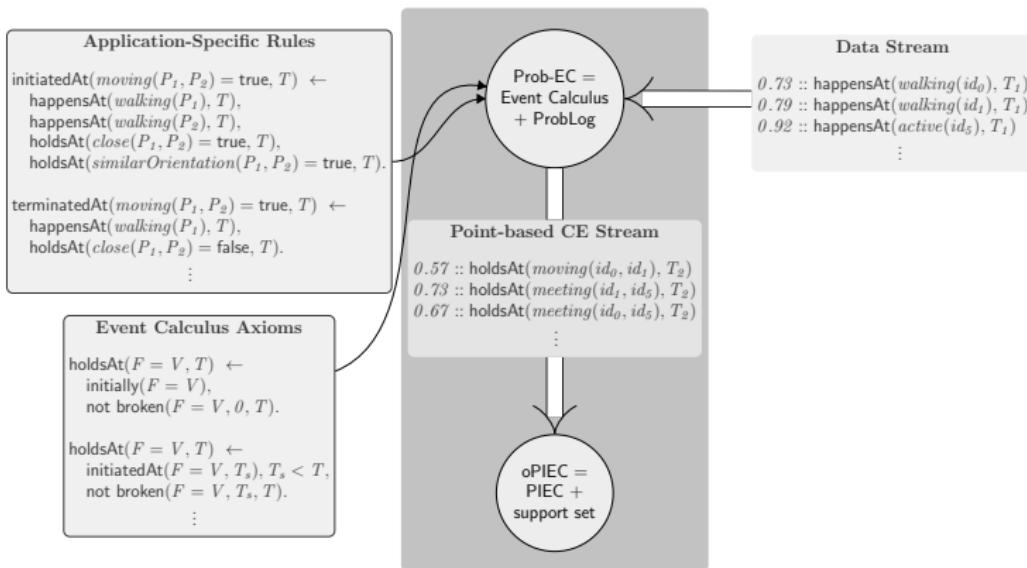
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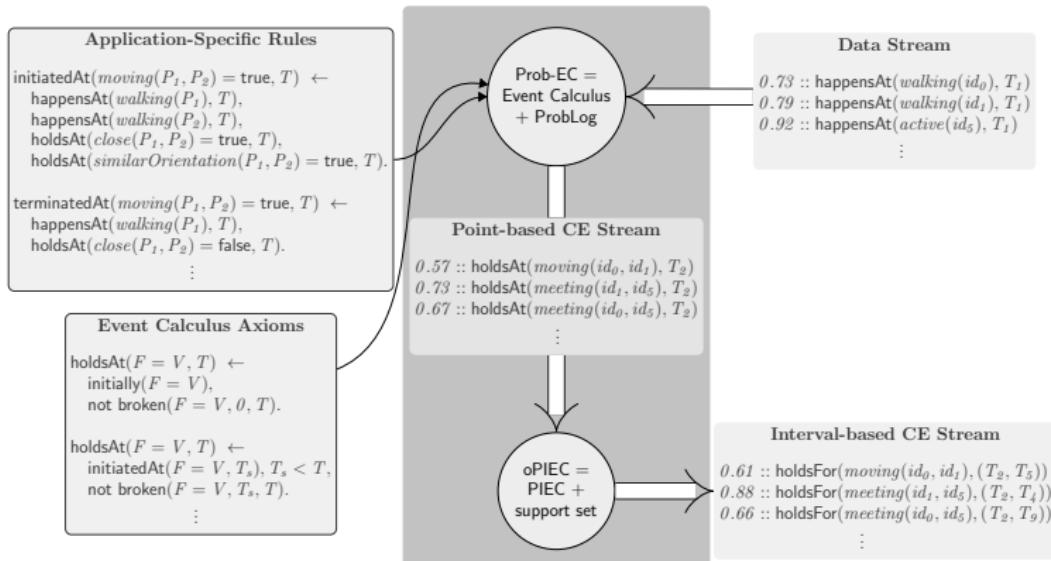


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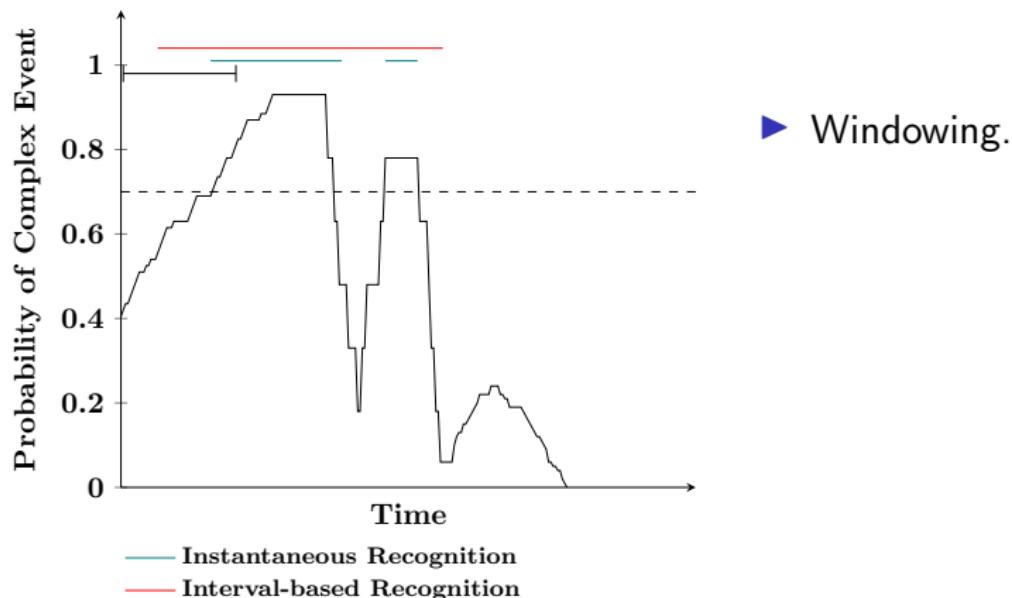
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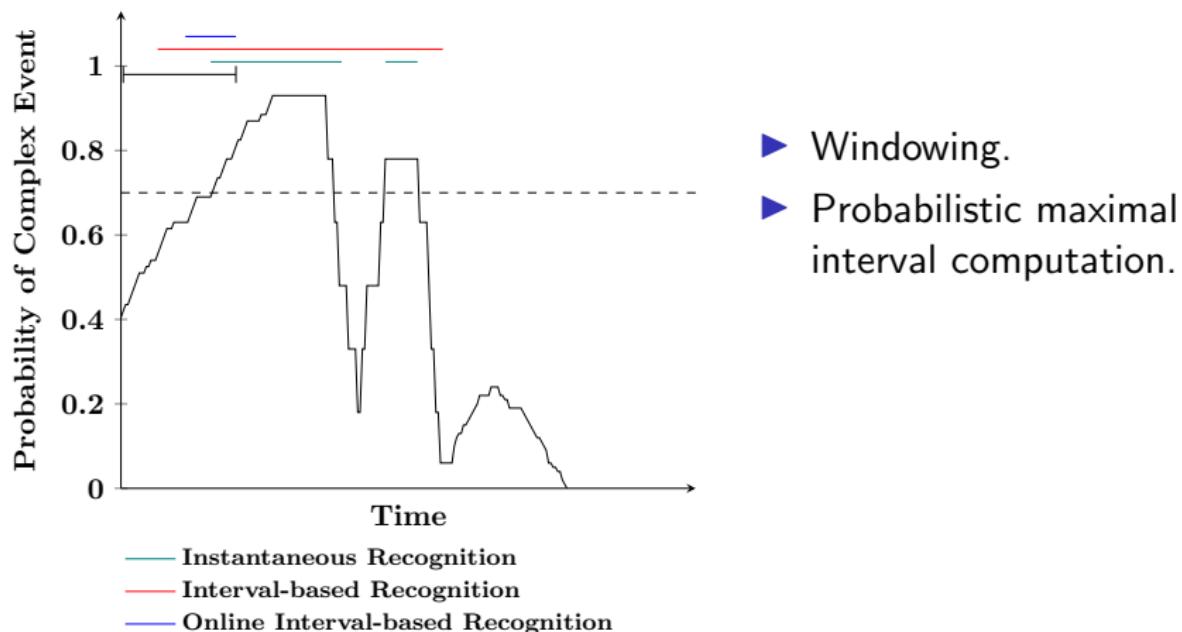
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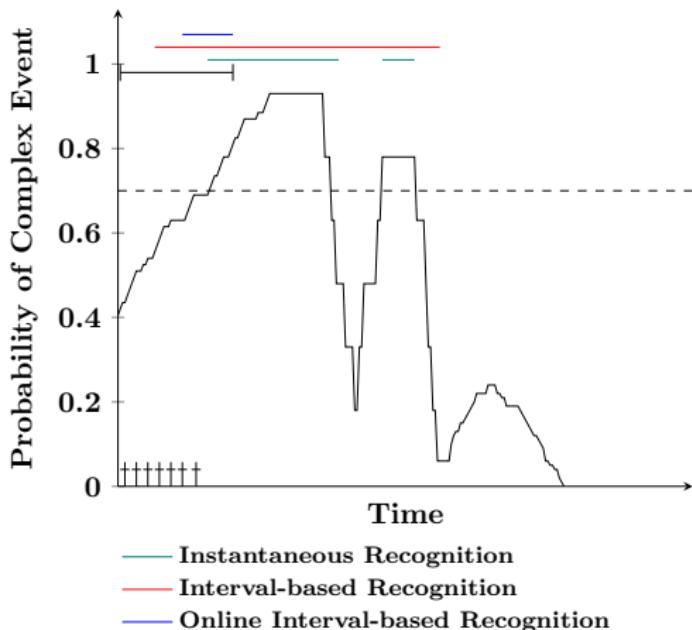
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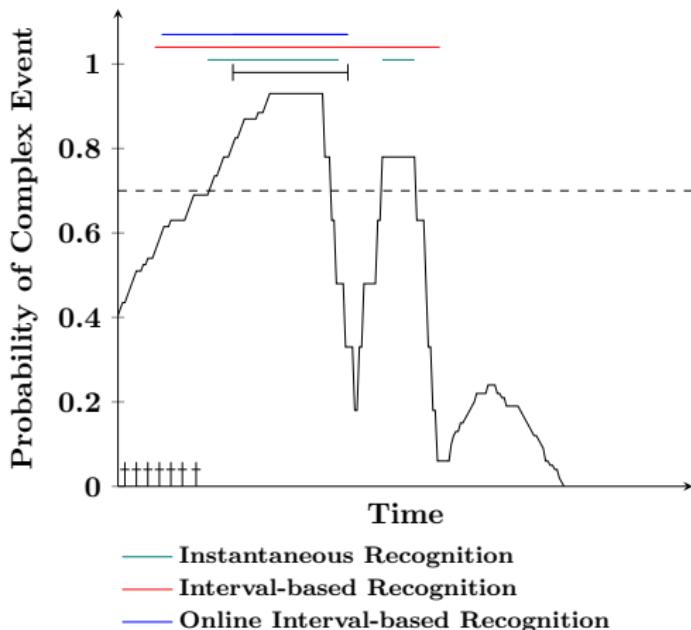


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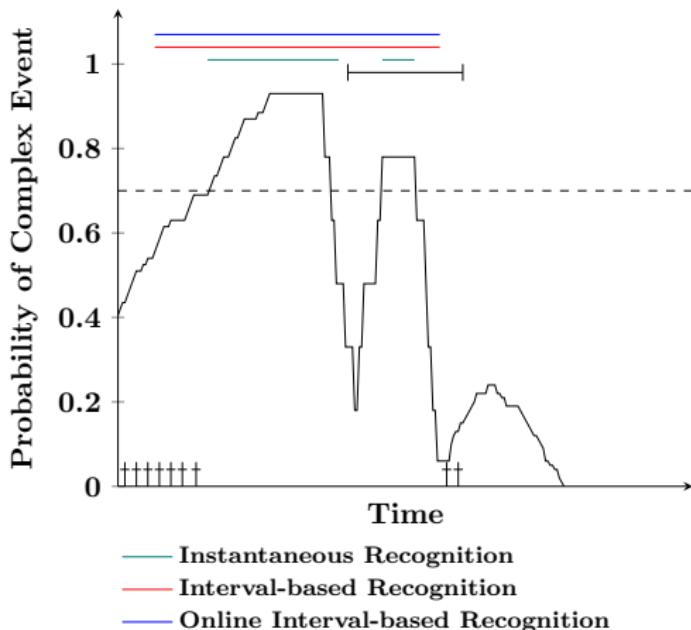
- ▶ Windowing.
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- ▶ Caching **potential starting points**.
 - ▶ Discard time-point t iff there is a $t' < t$ that can be the starting point of a probabilistic maximal interval including t .

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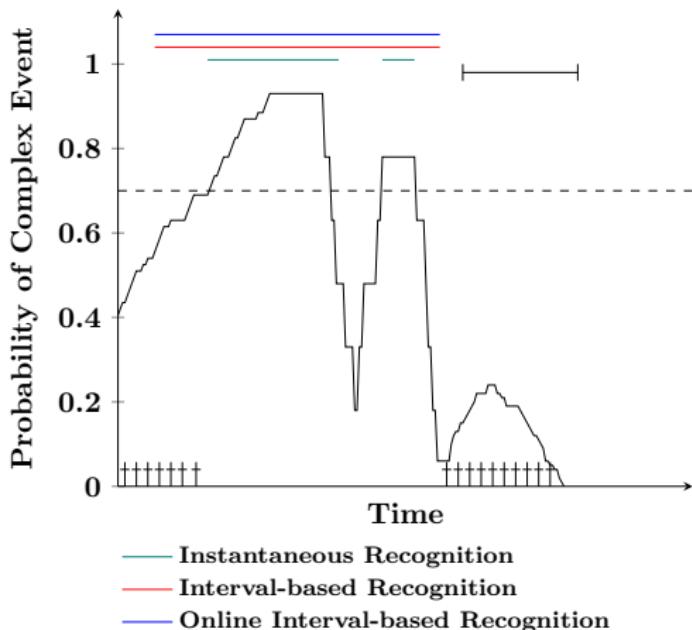
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4. Online Interval-based Recognition with oPIEC: Properties

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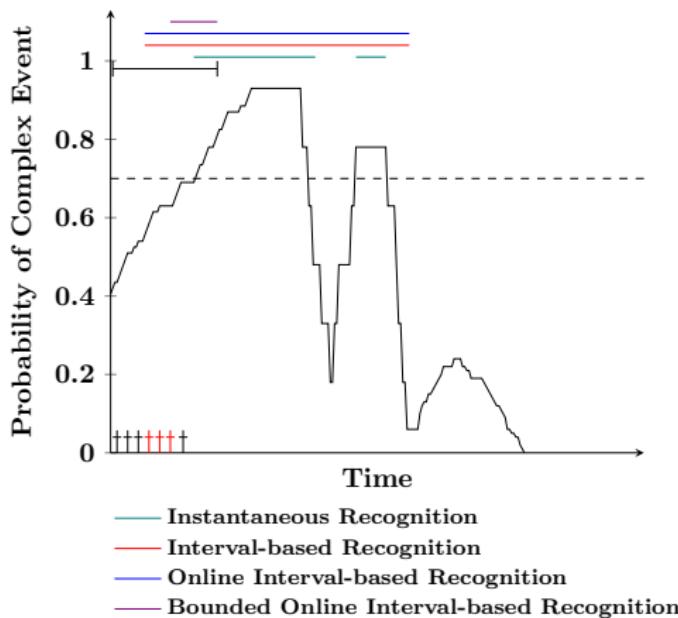
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Complexity

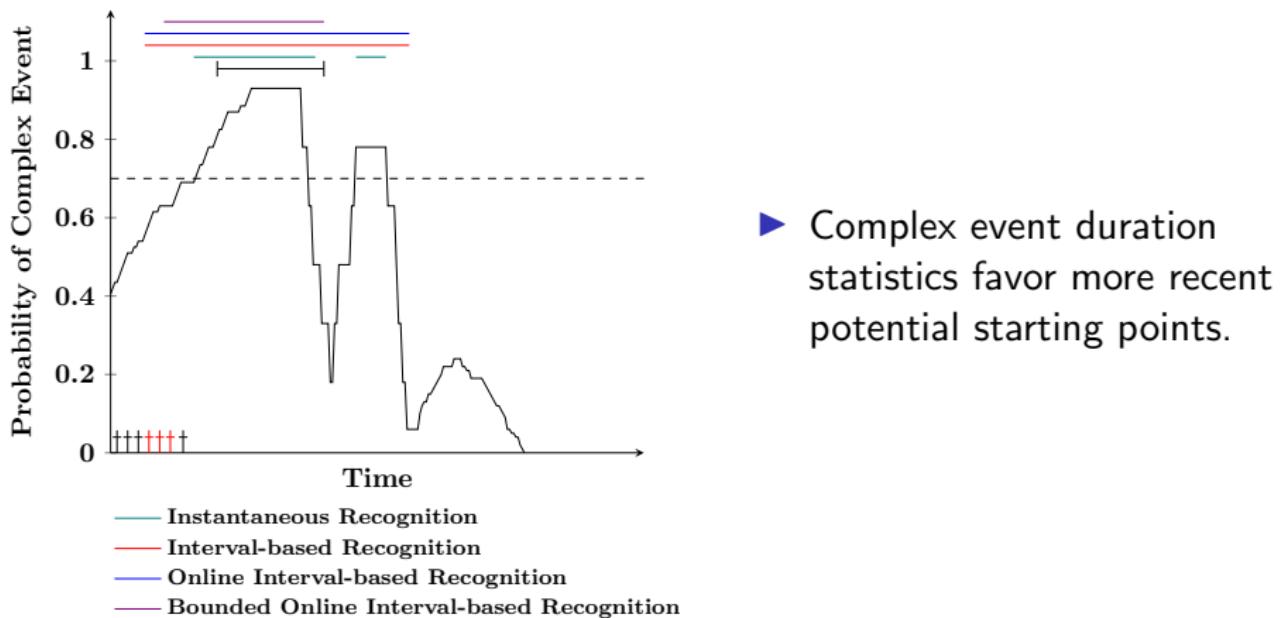
The computation of probabilistic maximal intervals is linear to the window and memory size.

4. Bounded Online Interval-based Recognition with oPIEC

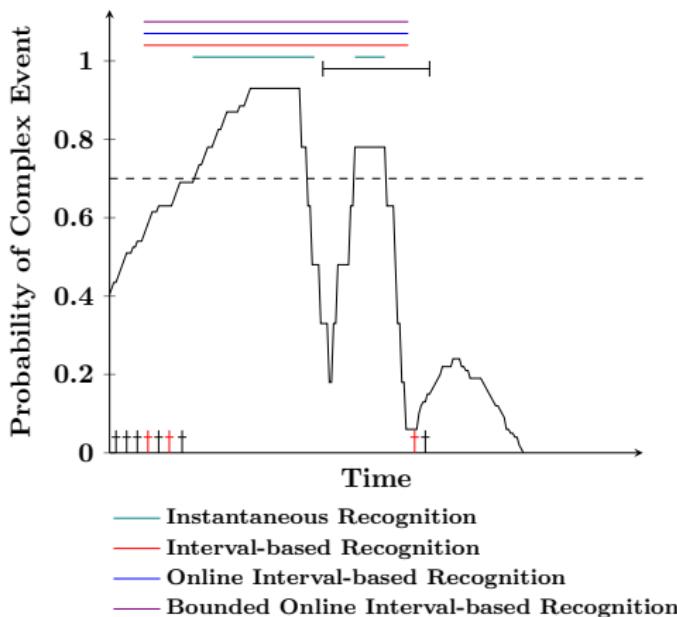


- ▶ Complex event duration statistics favor more recent potential starting points.

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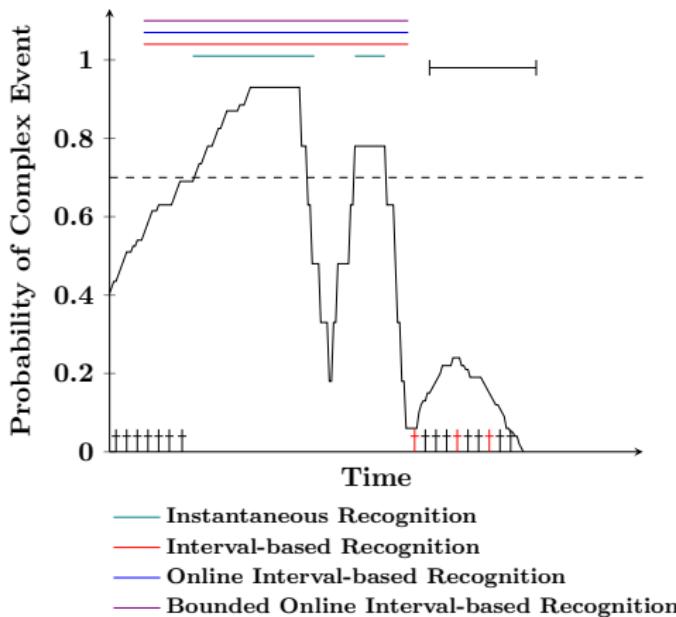


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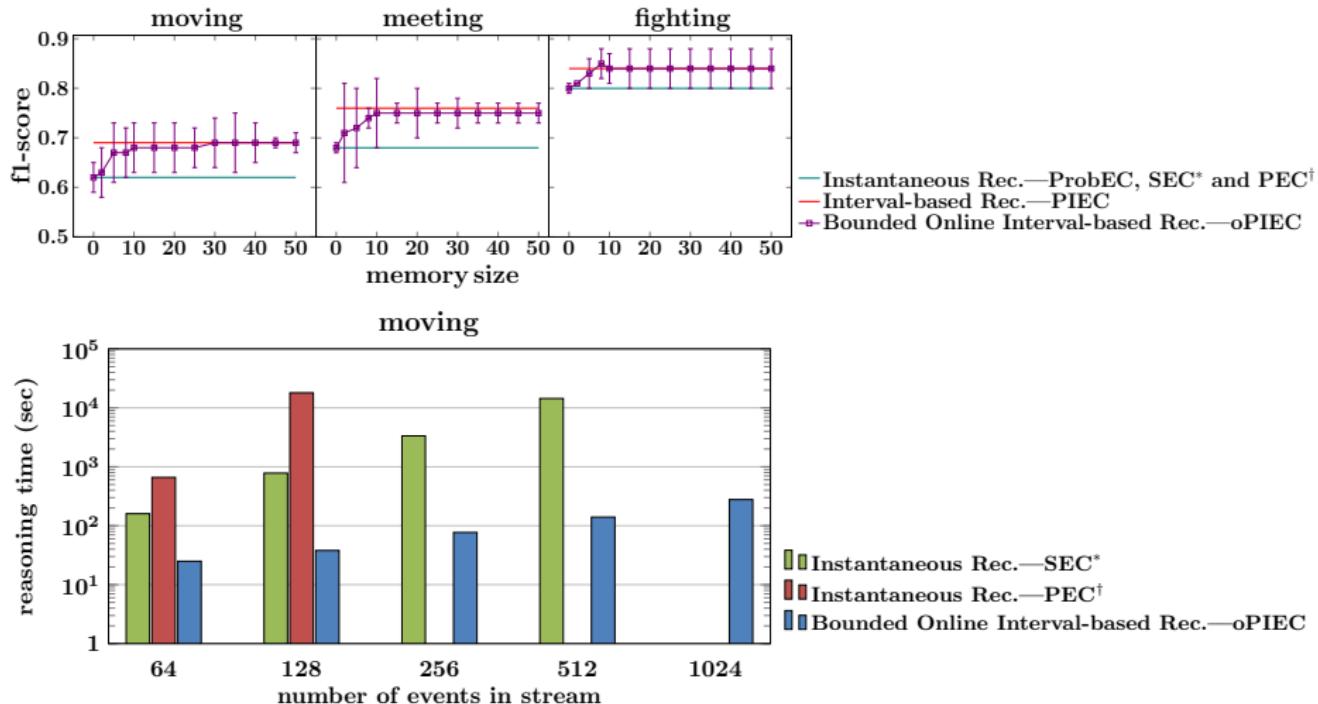
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- ▶ Complex event duration statistics favor more recent potential starting points.
- ▶ Comparable accuracy to batch reasoning.

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*:
 - ▶ RTEC_o supports cyclic dependencies.
 - ▶ RTEC^\rightarrow supports events with delayed effects.
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considerable improvement wrt state-of-the-art.

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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 $a \leftarrow b_1, \dots, b_m, \text{not } c_1, \dots, \text{not } c_k$.

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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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 ($[J_1, \dots, J_n], I$)	$I = (J_1 \cup \dots \cup J_n)$
intersect_all ($[J_1, \dots, J_n], I$)	$I = (J_1 \cap \dots \cap J_n)$
relative_complement_all ($I', [J_1, \dots, J_n], I$)	$I = I' \setminus (J_1 \cup \dots \cup J_n)$

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 ($[J_1, \dots, J_n], I$)	$I = (J_1 \cup \dots \cup J_n)$
intersect_all ($[J_1, \dots, J_n], I$)	$I = (J_1 \cap \dots \cap J_n)$
relative_complement_all ($I', [J_1, \dots, J_n], I$)	$I = I' \setminus (J_1 \cup \dots \cup J_n)$

Run-Time Event Calculus (RTEC): Fluent Specification

Simple Fluents:

initiatedAt($F = V, T$) \leftarrow

happensAt(E_{In_1}, T)[,
 conditions].

⋮

terminatedAt($F = V, T$) \leftarrow

happensAt(E_{T_1}, T)[,
 conditions].

⋮

where conditions:

${}^{0-K}$ [not] **happensAt**(E_k, T),

${}^{0-M}$ [not] **holdsAt**($F_m = V_m, T$),

${}^{0-N}$ atemporal-constraint_n

Run-Time Event Calculus (RTEC): Fluent Specification

Simple Fluents:

initiatedAt($F = V, T \leftarrow$

happensAt(E_{In_1}, T)[,
conditions].

⋮

terminatedAt($F = V, T \leftarrow$

happensAt(E_{T_1}, T)[,
conditions].

⋮

where conditions:

${}^{0-K}[\text{not}]$ **happensAt**(E_k, T),

${}^{0-M}[\text{not}]$ **holdsAt**($F_m = V_m, T$),

${}^{0-N}$ atemporal-constraint_n

Statically Determined Fluents:

holdsFor($F = V, I \leftarrow$

holdsFor($F_1 = V_1, I_1$)[,
holdsFor($F_2 = V_2, I_2$), ...

holdsFor($F_n = V_n, I_n$),

intervalOperation(L_1, I_{n+1}), ...

intervalOperation(L_m, I)].

where intervalOperation:

union_all or

intersect_all or

relative_complement_all

Fluent-Value Pair Computation

Definition:

initiatedAt($F = V, T$) \leftarrow
happensAt(E_{In_1}, T),
[conditions]

...

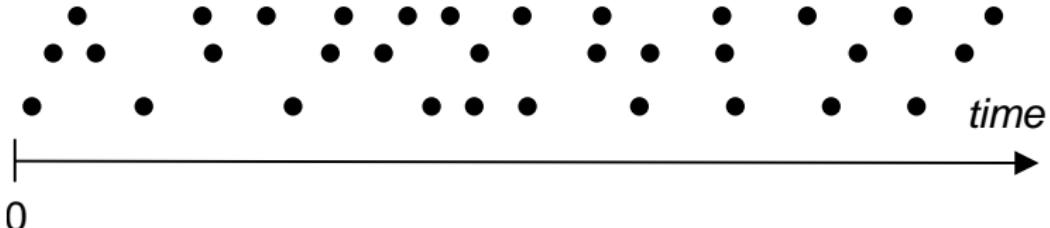
initiatedAt($F = V, T$) \leftarrow
happensAt(E_{In_i}, T),
[conditions]

terminatedAt($F = V, T$) \leftarrow
happensAt(E_{T_1}, T),
[conditions]

...

terminatedAt($F = V, T$) \leftarrow
happensAt(E_{T_j}, T),
[conditions]

Reasoning:



Fluent-Value Pair Computation

Definition:

initiatedAt($F = V, T \leftarrow$
happensAt($E_{In_1}, T),$
[conditions]

...

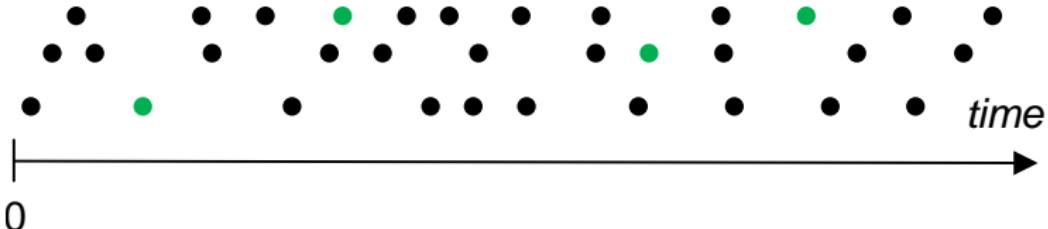
initiatedAt($F = V, T \leftarrow$
happensAt($E_{In_i}, T),$
[conditions]

terminatedAt($F = V, T \leftarrow$
happensAt($E_{T_1}, T),$
[conditions]

...

terminatedAt($F = V, T \leftarrow$
happensAt($E_{T_j}, T),$
[conditions]

Reasoning:



Fluent-Value Pair Computation

Definition:

initiatedAt($F = V, T \leftarrow$
happensAt($E_{In_1}, T),$
[conditions]

...

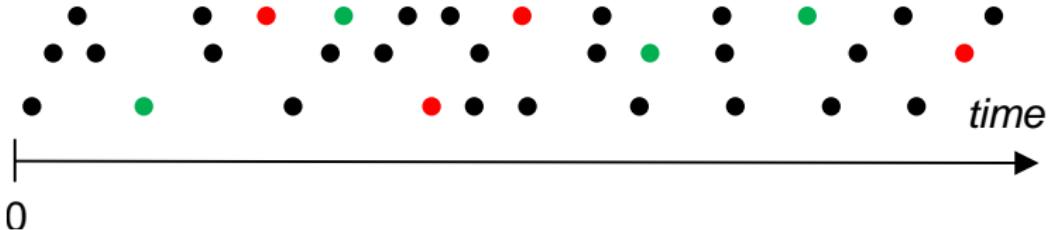
initiatedAt($F = V, T \leftarrow$
happensAt($E_{In_i}, T),$
[conditions]

terminatedAt($F = V, T \leftarrow$
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[conditions]

...

terminatedAt($F = V, T \leftarrow$
happensAt($E_{T_j}, T),$
[conditions]

Reasoning:



Fluent-Value Pair Computation

Definition:

initiatedAt($F = V, T \leftarrow$
happensAt($E_{In_1}, T),$
[conditions]

...

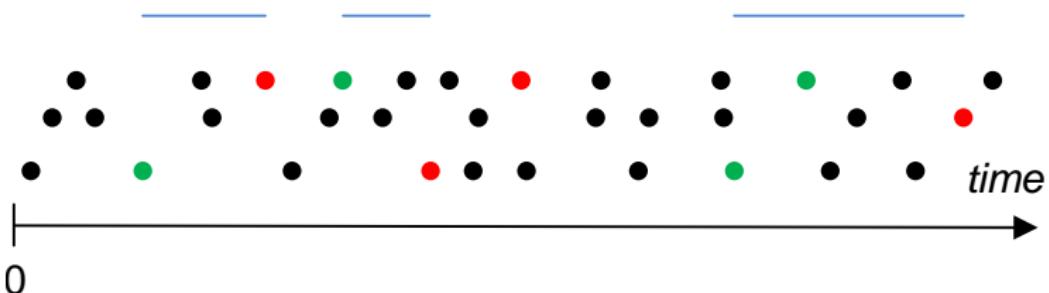
initiatedAt($F = V, T \leftarrow$
happensAt($E_{In_i}, T),$
[conditions]

terminatedAt($F = V, T \leftarrow$
happensAt($E_{T_1}, T),$
[conditions]

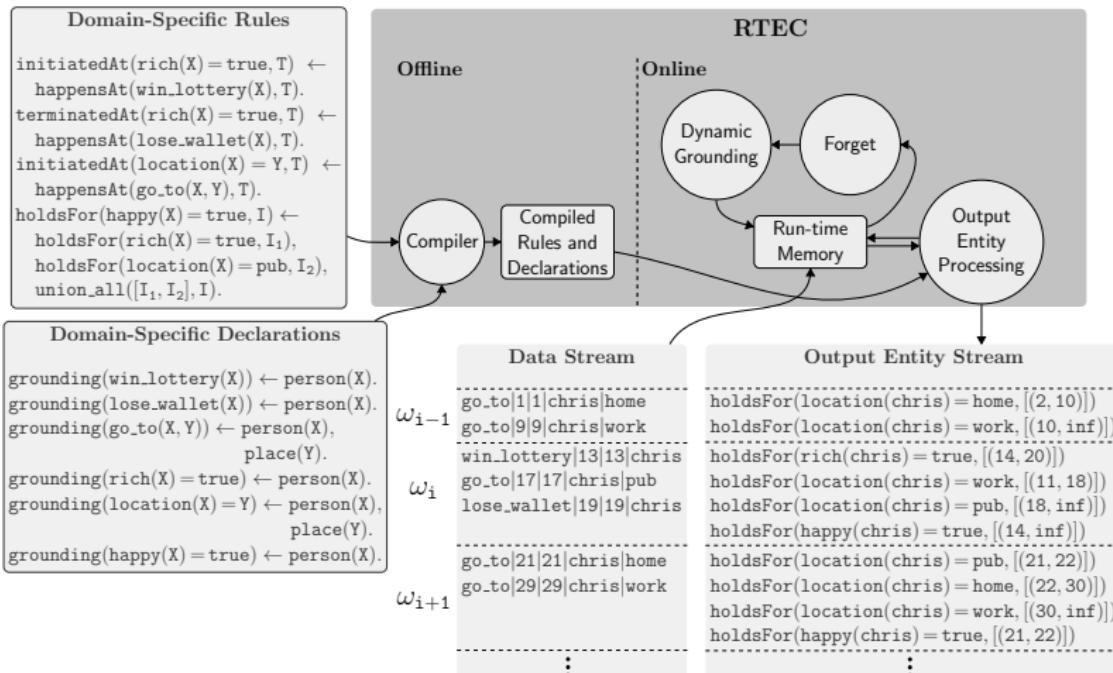
...

terminatedAt($F = V, T \leftarrow$
happensAt($E_{T_j}, T),$
[conditions]

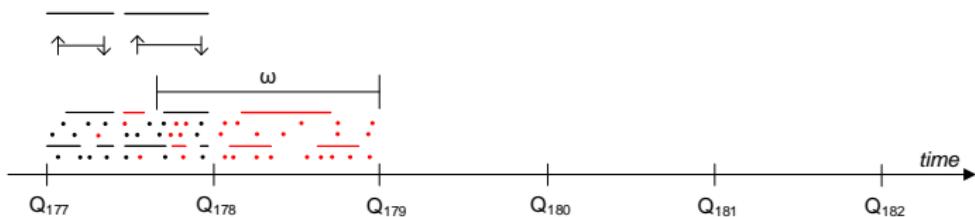
Reasoning: **holdsFor**($F = V, I)$



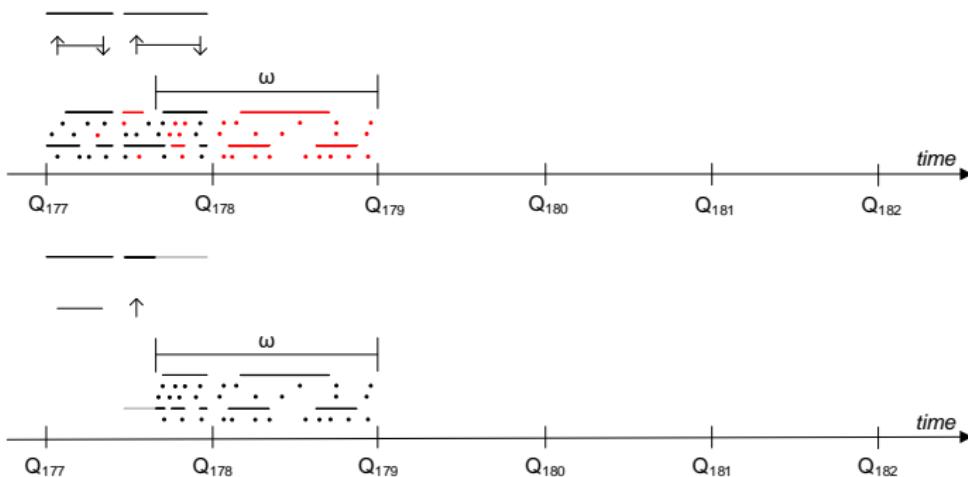
RTEC Architecture



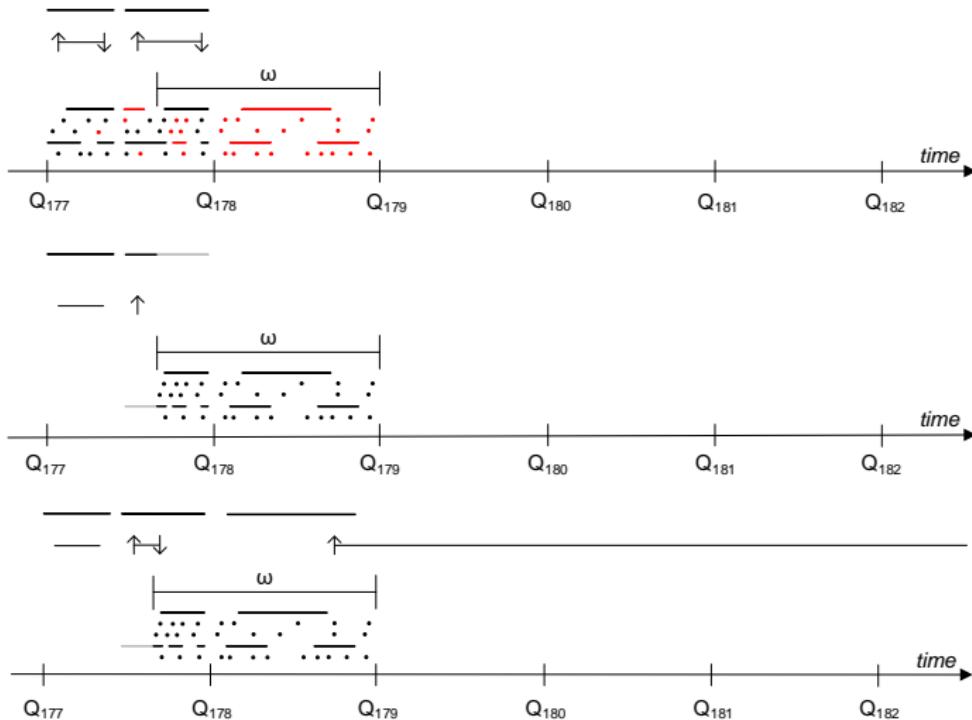
RTEC: Windowing



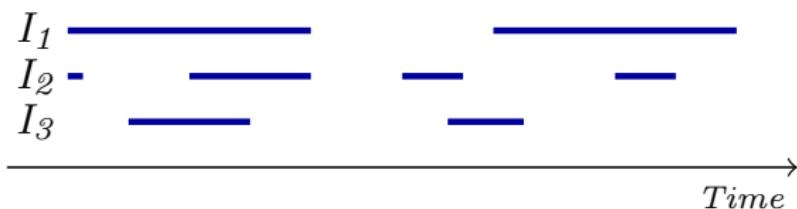
RTEC: Windowing



RTEC: Windowing

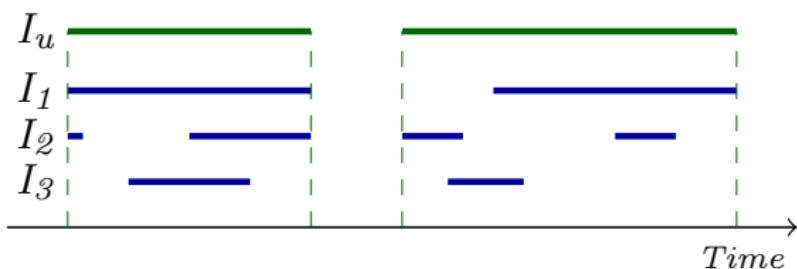


RTEC: Interval-based Reasoning



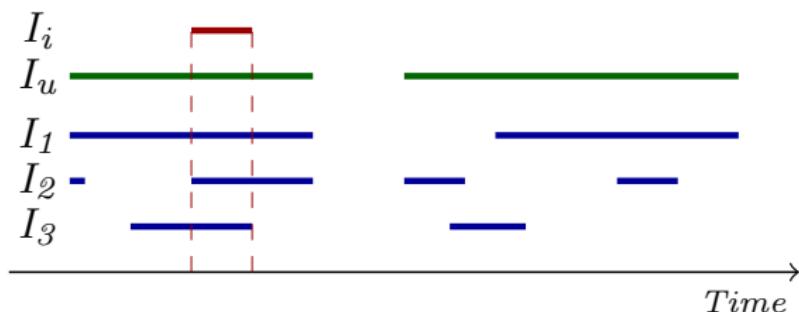
RTEC: Interval-based Reasoning

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



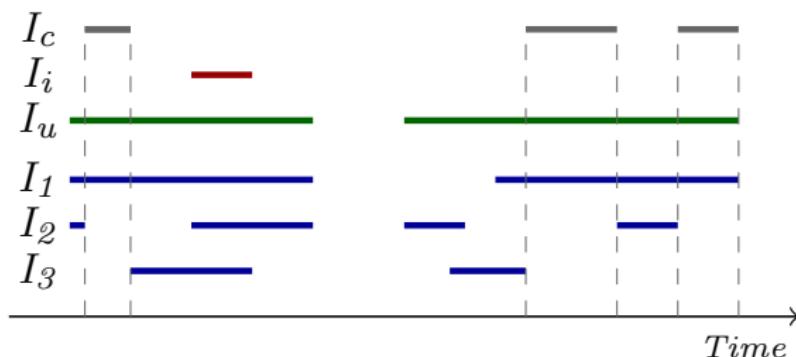
RTEC: Interval-based Reasoning

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



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

```
holdsFor(anchoredOrMoored(Vessel) = true, I) ←  
    holdsFor(stopped(Vessel) = farFromPorts, Isf),  
    holdsFor(withinArea(Vessel, anchorage) = true, Iwa),  
    intersect_all([Isf, Iwa], Isa),  
    holdsFor(stopped(Vessel) = nearPorts, Isn),  
    union_all([Isa, Isn], I).
```

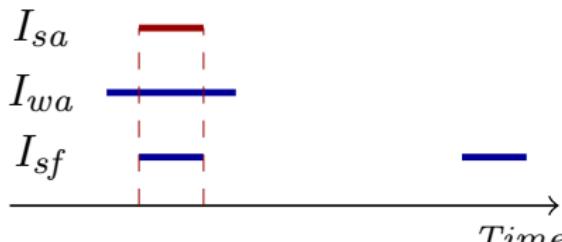
Statically Determined Fluent: Anchored or Moored

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  intersect_all([Isf, Iwa], Isa),  
  holdsFor(stopped(Vessel) = nearPorts, Isn),  
  union_all([Isa, Isn], I).
```



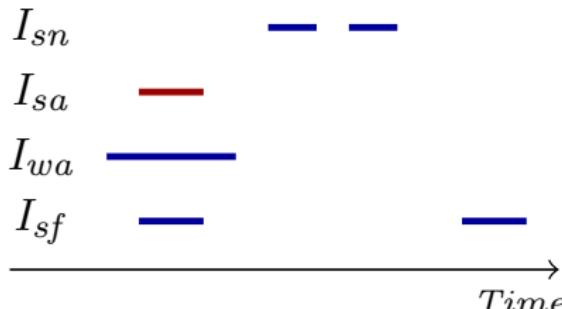
Statically Determined Fluent: Anchored or Moored

```
holdsFor(anchoredOrMoored(Vessel) = true, I) ←  
    holdsFor(stopped(Vessel) = farFromPorts, Isf),  
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intersect_all([Isf, Iwa], Isa),  
    holdsFor(stopped(Vessel) = nearPorts, Isn),  
    union_all([Isa, Isn], I).
```



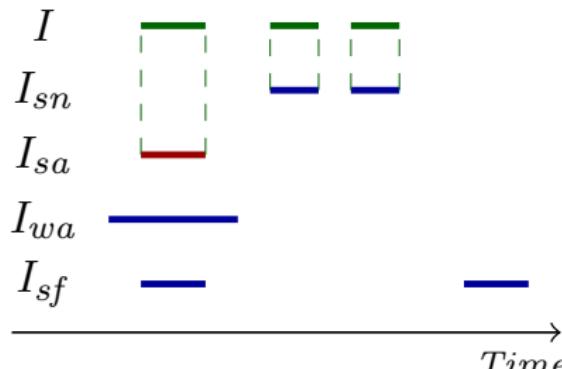
Statically Determined Fluent: Anchored or Moored

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holdsFor(anchoredOrMoored(Vessel) = true, I) ←  
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```



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    intersect_all([Isf, Iwa], Isa),  
    holdsFor(stopped(Vessel) = nearPorts, Isn),  
union_all([Isa, Isn], I).
```



Voting: Cyclic Dependencies

```
initiatedAt(status( $M$ ) = proposed,  $T$ ) ←  
  happensAt(propose( $P, M$ ),  $T$ ),  
  holdsAt(status( $M$ ) = null,  $T$ ).
```

Voting: Cyclic Dependencies

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

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

Voting: Cyclic Dependencies

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

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

initiatedAt($status(M) = voted, T \leftarrow$
happensAt($close_ballot(C, M), T$),
holdsAt($status(M) = voting, T$).

Voting: Cyclic Dependencies

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

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

initiatedAt($\text{status}(M) = \text{voted}$, T) \leftarrow
 happensAt($\text{close_ballot}(C, M)$, T),
 holdsAt($\text{status}(M) = \text{voting}$, T).

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

Voting: Cyclic Dependencies

- initiatedAt**($status(M) = proposed, T$) \leftarrow
 - happensAt**($propose(P, M), T$),
 - holdsAt**($status(M) = null, T$).
- initiatedAt**($status(M) = voting, T$) \leftarrow
 - happensAt**($second(S, M), T$),
 - holdsAt**($status(M) = proposed, T$).
- initiatedAt**($status(M) = voted, T$) \leftarrow
 - happensAt**($close_ballot(C, M), T$),
 - holdsAt**($status(M) = voting, T$).
- initiatedAt**($status(M) = null, T$) \leftarrow
 - happensAt**($declare(C, M, Res), T$),
 - holdsAt**($status(M) = voted, T$).

Voting: Cyclic Dependencies

```
initiatedAt(status(M) = proposed, T) ←  
    happensAt(propose(P, M), T),  
    holdsAt(status(M) = null, T).  
  
initiatedAt(status(M) = voting, T) ←  
    happensAt(second(S, M), T),  
    holdsAt(status(M) = proposed, T).  
  
initiatedAt(status(M) = voted, T) ←  
    happensAt(close_ballot(C, M), T),  
    holdsAt(status(M) = voting, T).  
  
initiatedAt(status(M) = null, T) ←  
    happensAt(declare(C, M, Res), T),  
    holdsAt(status(M) = voted, T).
```

Voting: Cyclic Dependencies

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initiatedAt(status(M) = null, T) ←  
    happensAt(declare(C, M, Res), T),  
    holdsAt(status(M) = voted, T).
```

Voting: Cyclic Dependencies

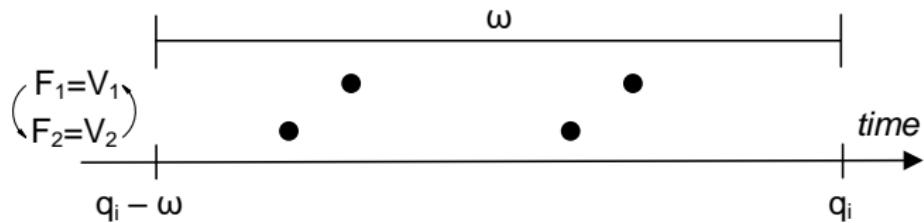
```
initiatedAt(status(M) = proposed, T) ←
    happensAt(propose(P, M), T),
    holdsAt(status(M) = null, T).

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    happensAt(second(S, M), T),
    holdsAt(status(M) = proposed, T).

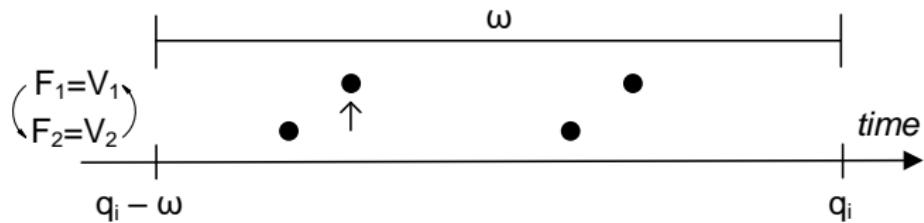
initiatedAt(status(M) = voted, T) ←
    happensAt(close_ballot(C, M), T),
    holdsAt(status(M) = voting, T).

initiatedAt(status(M) = null, T) ←
    happensAt(declare(C, M, Res), T),
    holdsAt(status(M) = voted, T).
```

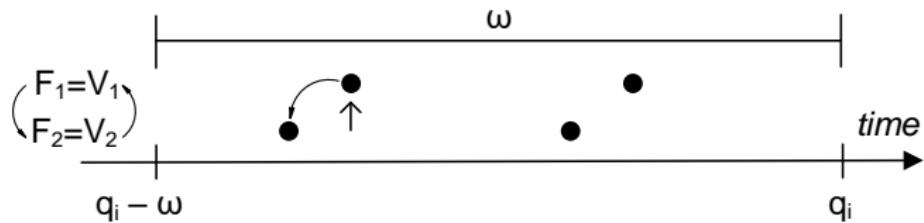
Handling Cyclic Dependencies



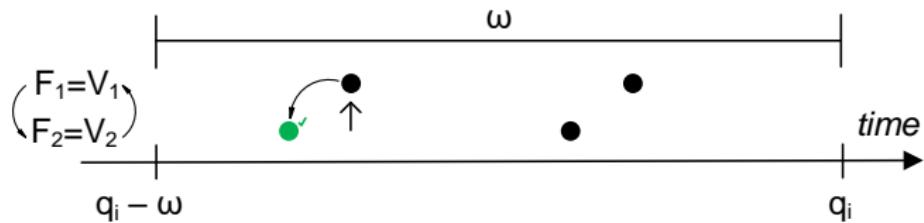
Handling Cyclic Dependencies



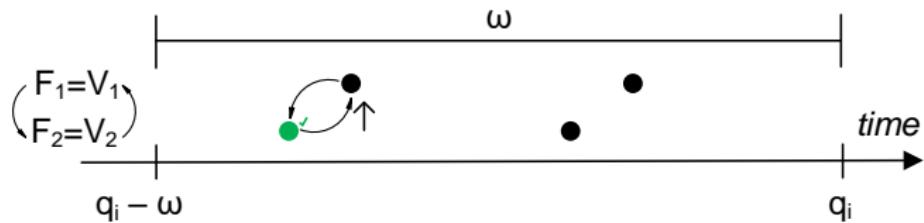
Handling Cyclic Dependencies



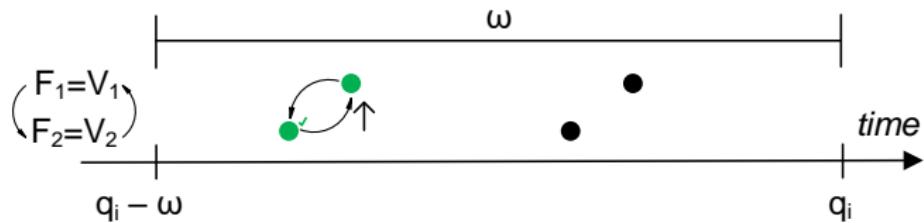
Handling Cyclic Dependencies



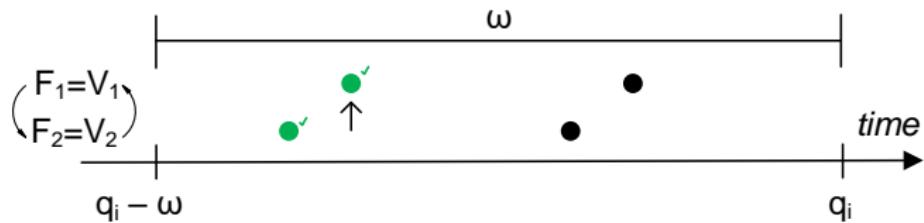
Handling Cyclic Dependencies



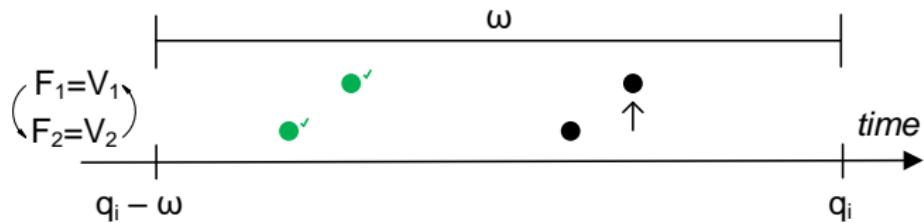
Handling Cyclic Dependencies



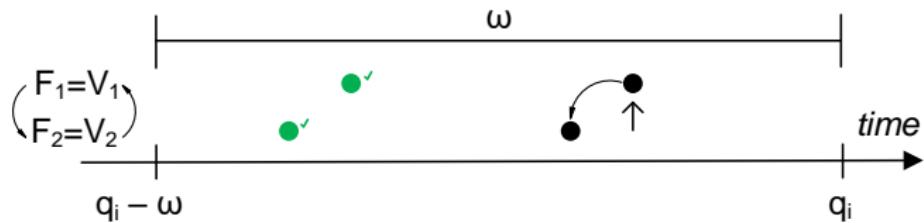
Handling Cyclic Dependencies



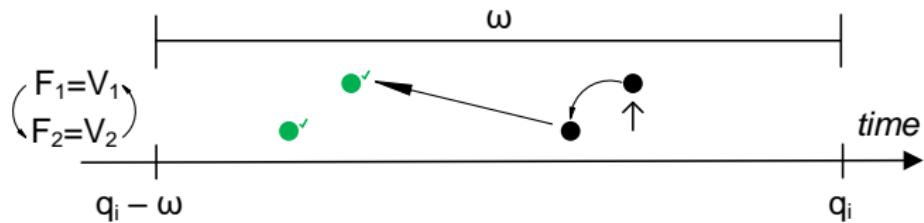
Handling Cyclic Dependencies



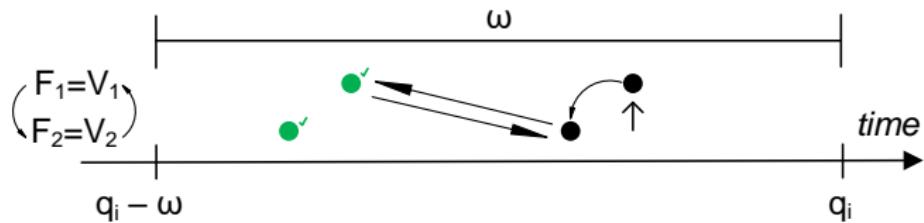
Handling Cyclic Dependencies



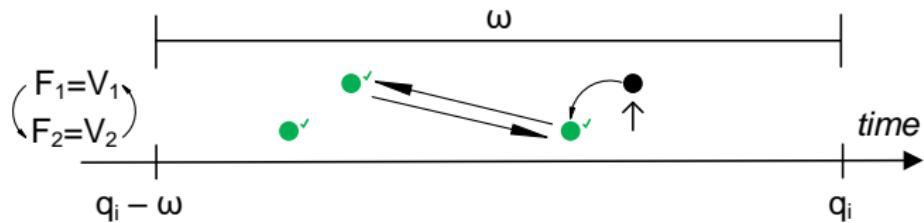
Handling Cyclic Dependencies



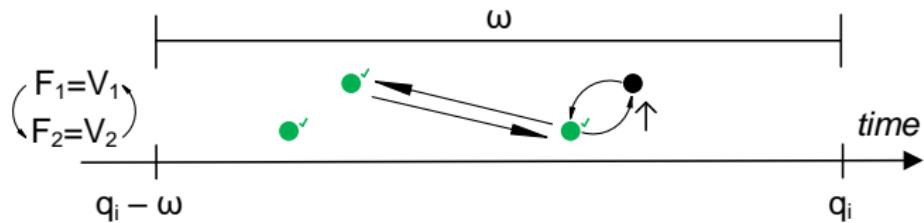
Handling Cyclic Dependencies



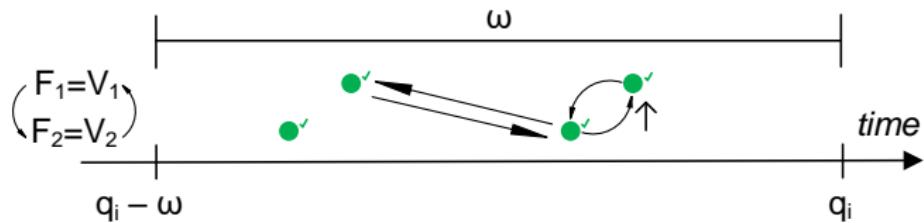
Handling Cyclic Dependencies



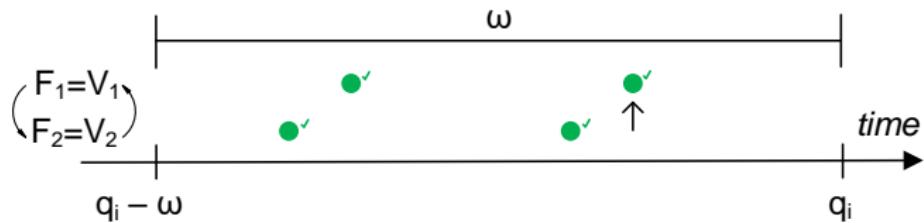
Handling Cyclic Dependencies



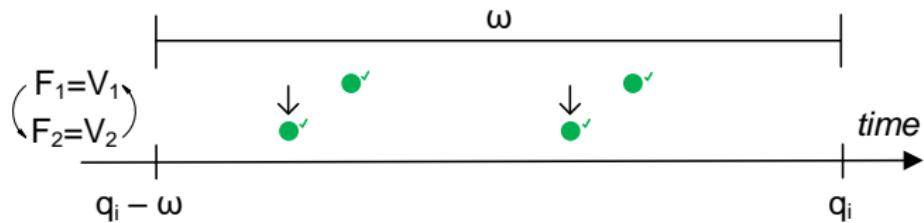
Handling Cyclic Dependencies



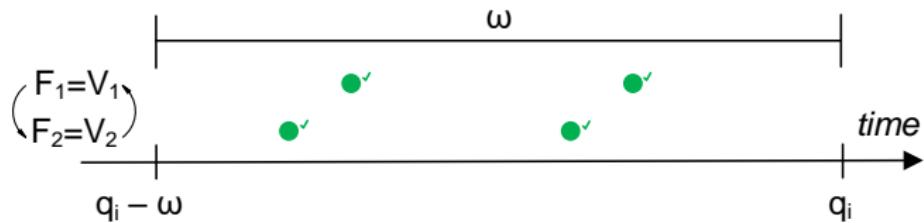
Handling Cyclic Dependencies



Handling Cyclic Dependencies

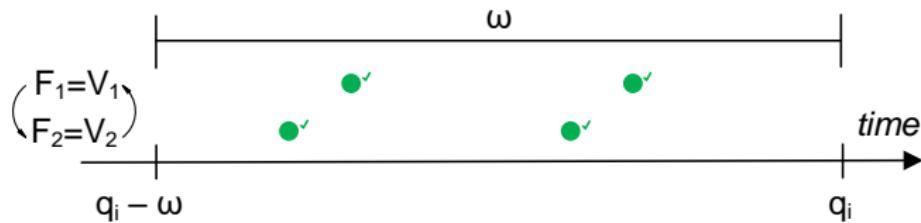


Handling Cyclic Dependencies

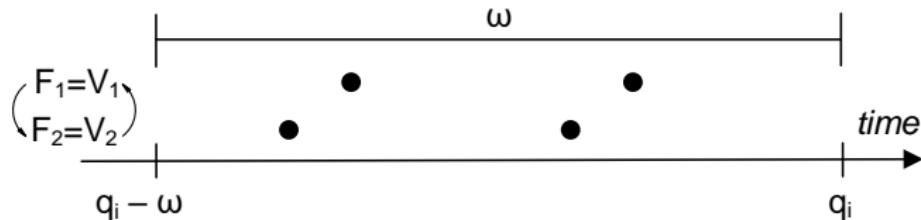


Handling Cyclic Dependencies

RTEC_o

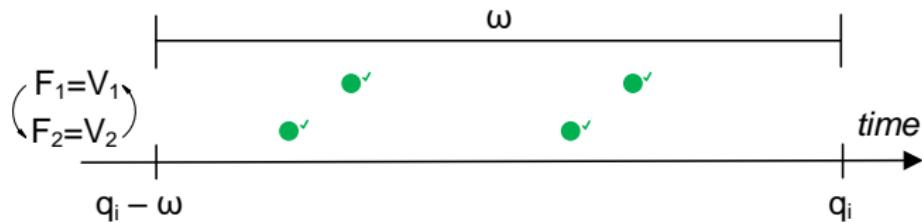


Event Calculus

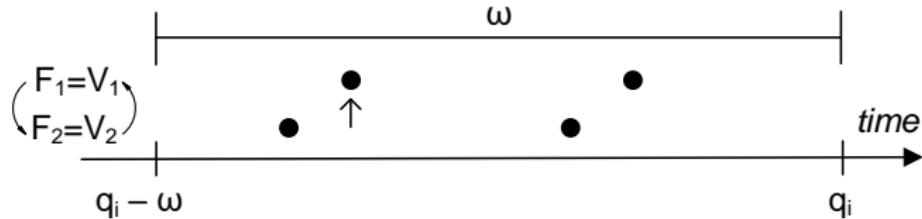


Handling Cyclic Dependencies

RTEC_o

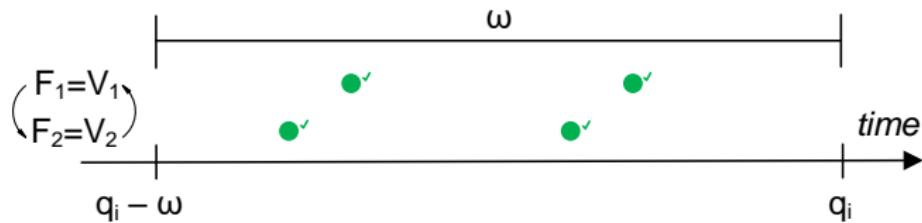


Event Calculus

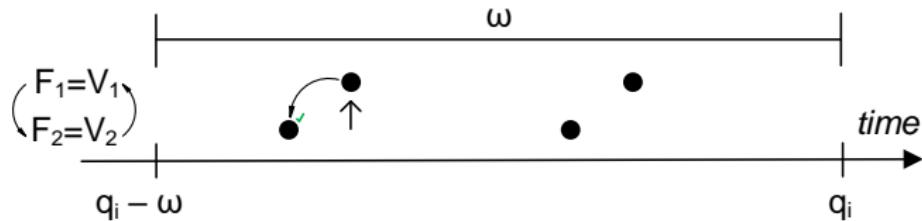


Handling Cyclic Dependencies

RTEC_o

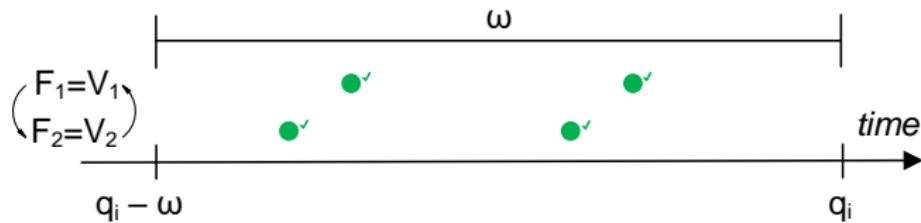


Event Calculus

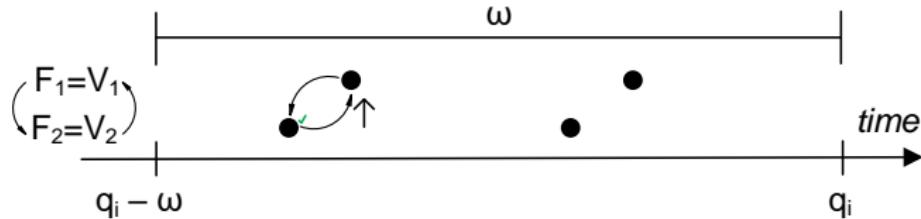


Handling Cyclic Dependencies

RTEC_o

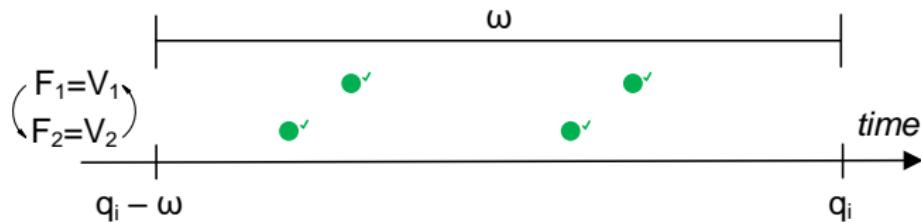


Event Calculus

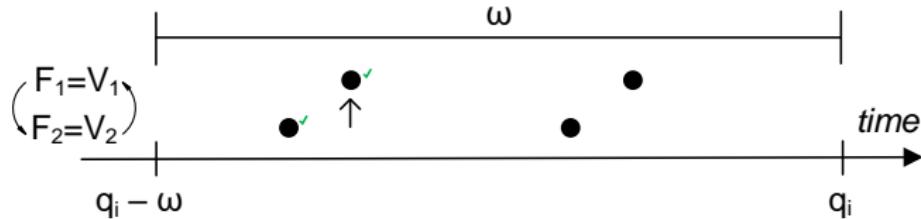


Handling Cyclic Dependencies

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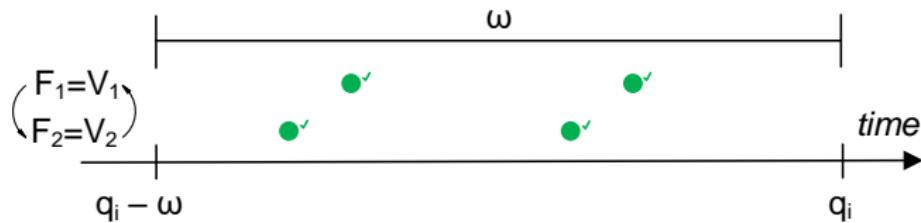


Event Calculus

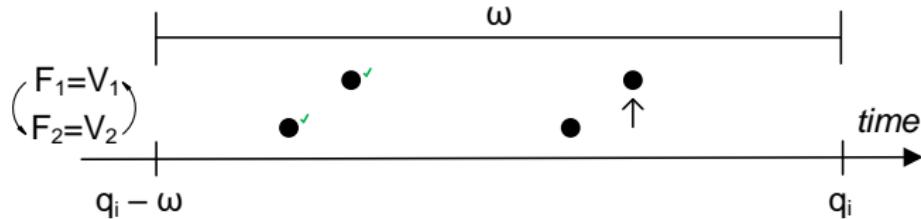


Handling Cyclic Dependencies

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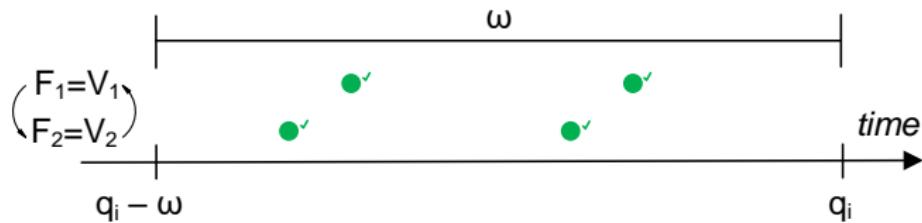


Event Calculus

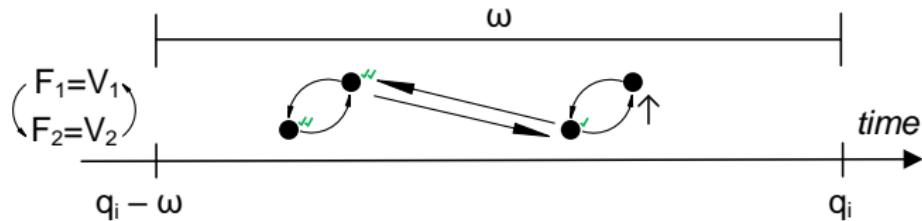


Handling Cyclic Dependencies

RTEC_o

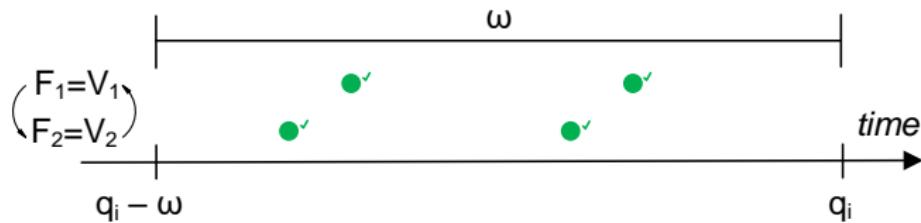


Event Calculus

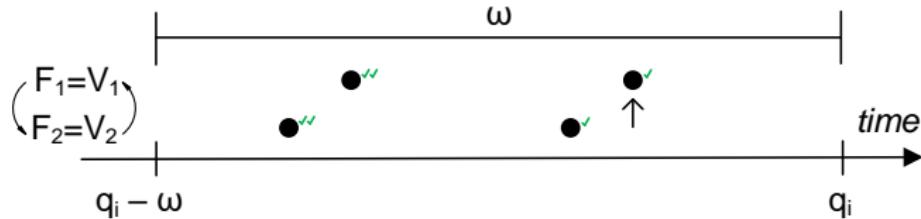


Handling Cyclic Dependencies

RTEC_o

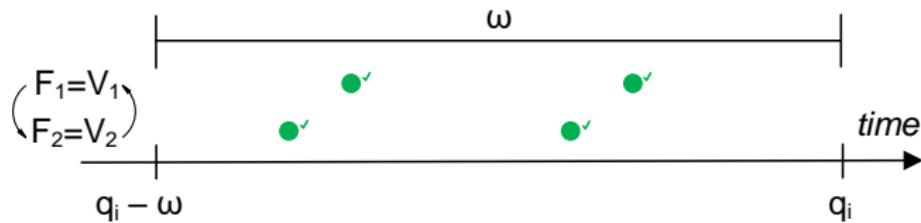


Event Calculus

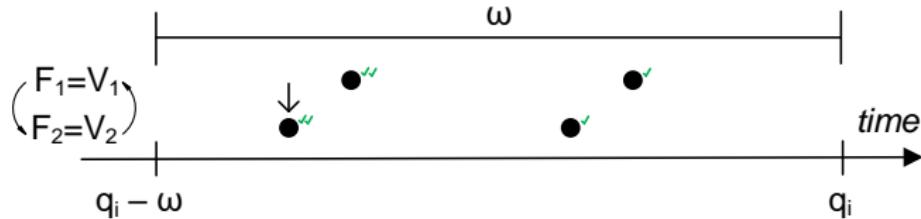


Handling Cyclic Dependencies

RTEC_o

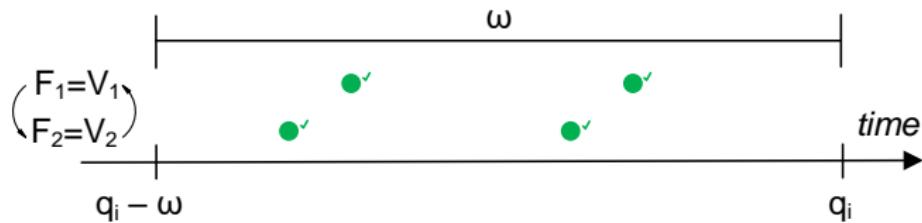


Event Calculus

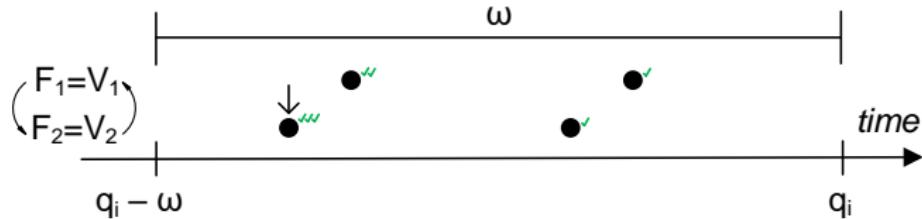


Handling Cyclic Dependencies

RTEC_o

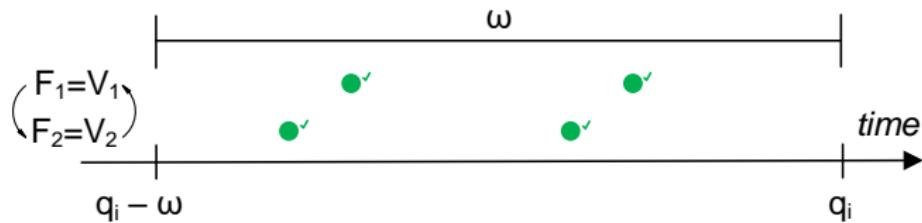


Event Calculus

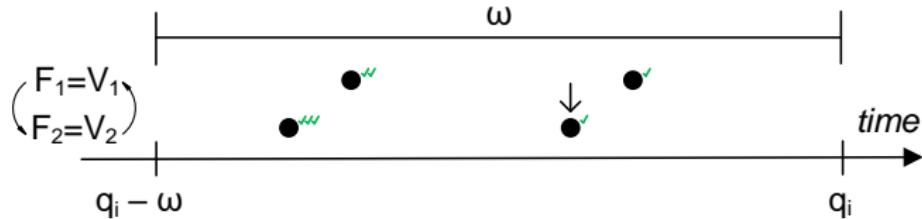


Handling Cyclic Dependencies

RTEC_o

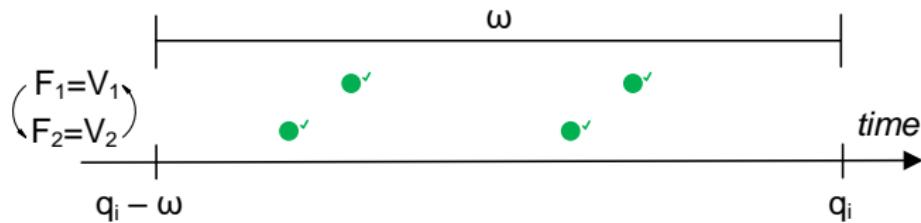


Event Calculus

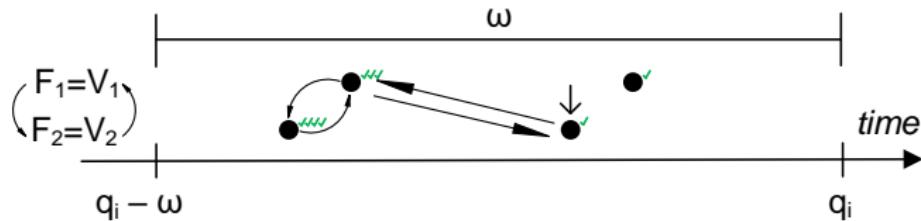


Handling Cyclic Dependencies

RTEC_o

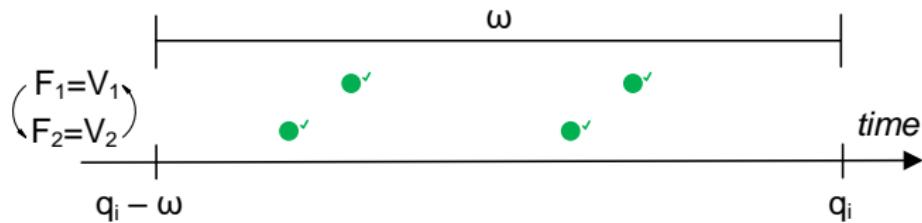


Event Calculus

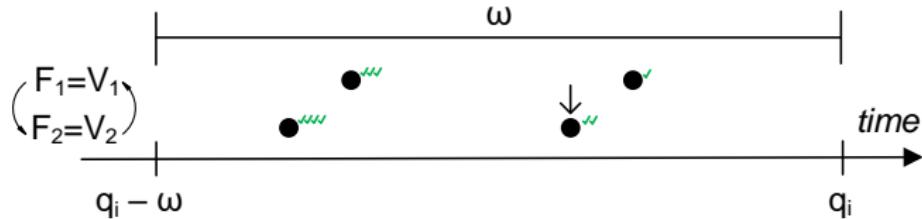


Handling Cyclic Dependencies

RTEC_o

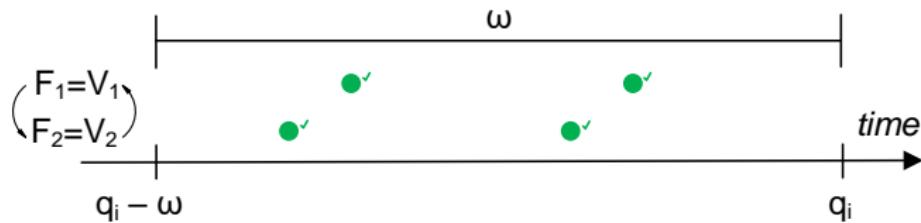


Event Calculus

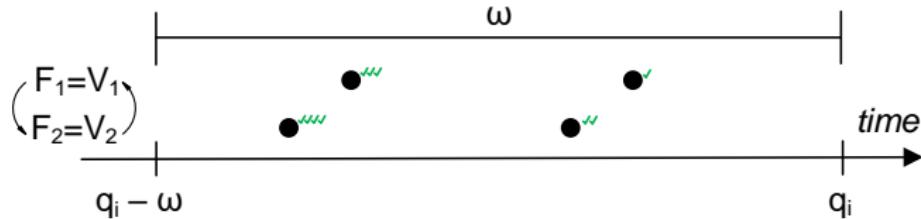


Handling Cyclic Dependencies

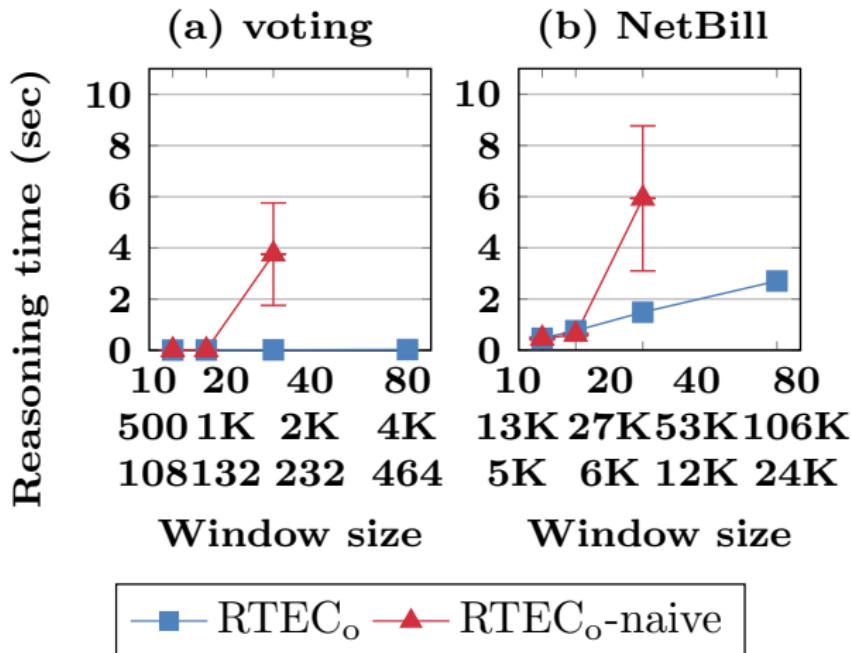
RTEC_o



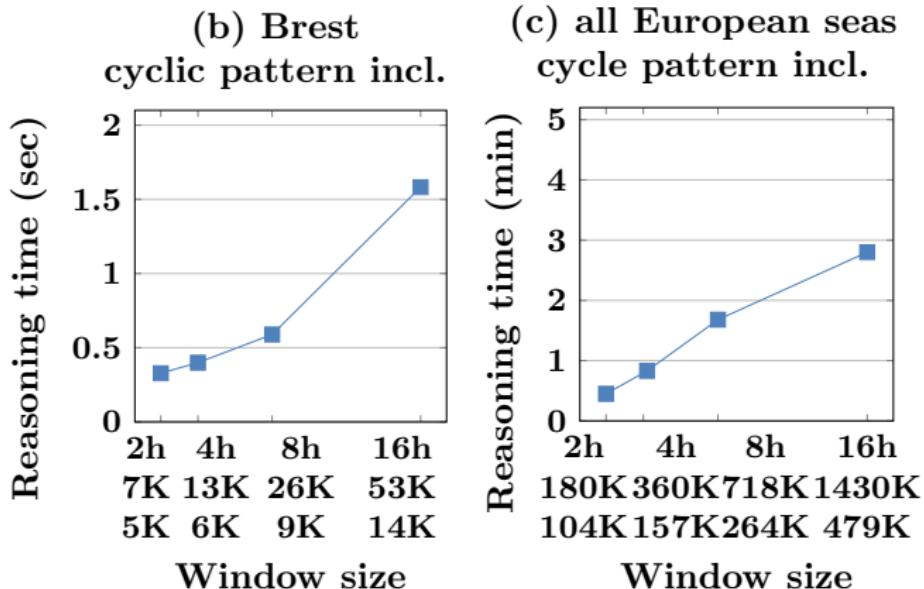
Event Calculus



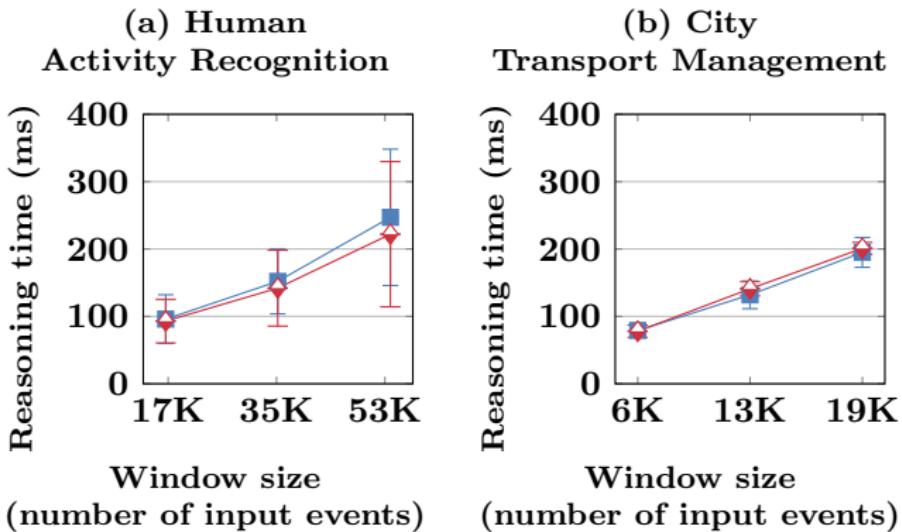
RTEC_o: Experimental Results



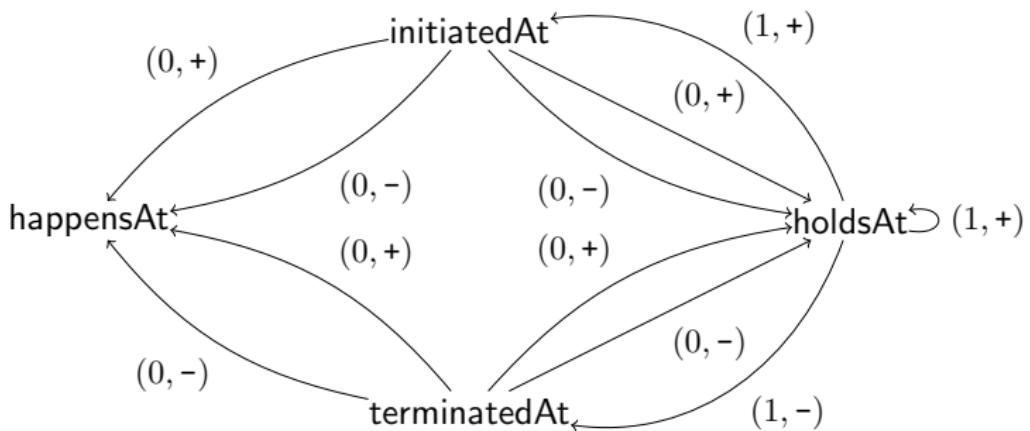
RTEC_o: Experimental Results



RTEC_o: Experimental Results

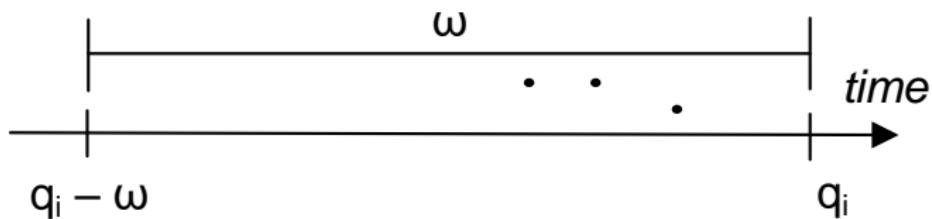


Semantics of RTEC_o

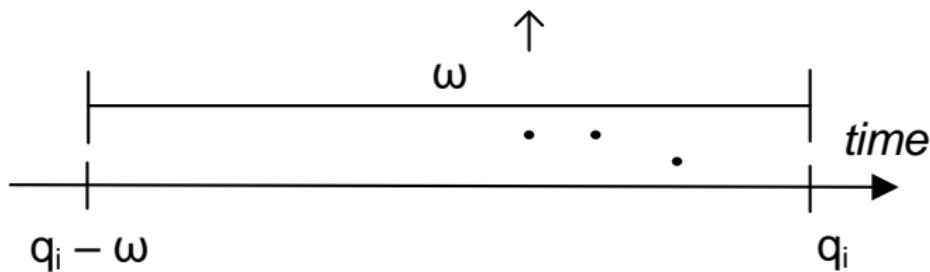


The cycle-sum graph of an RTEC_o program.

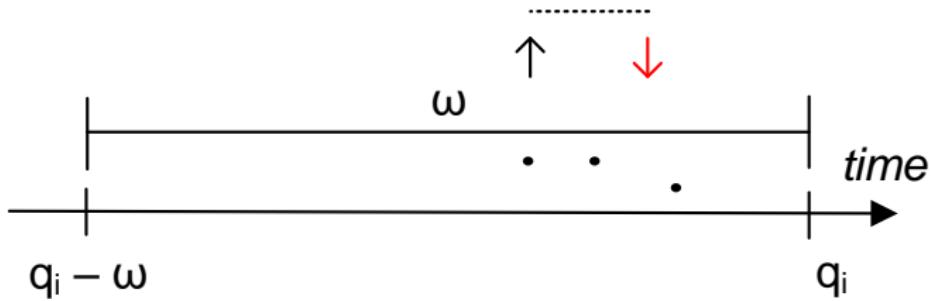
RTEC \rightarrow : Deadlines



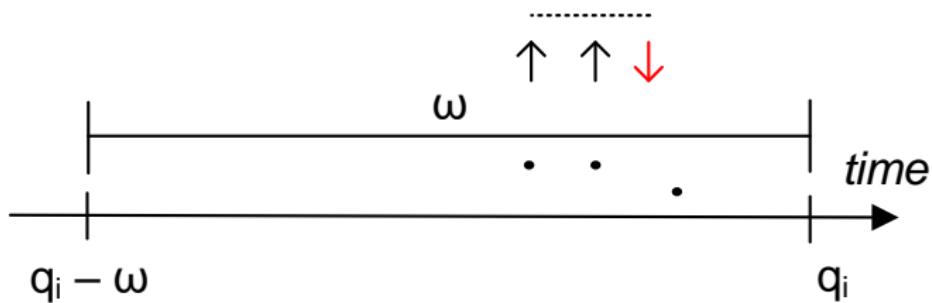
RTEC \rightarrow : Deadlines



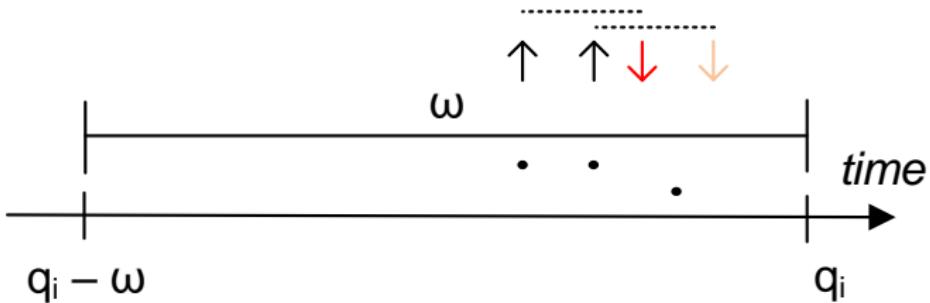
RTEC \rightarrow : Deadlines



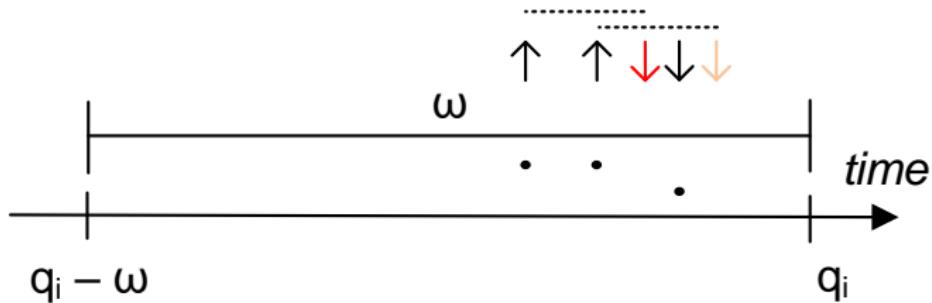
RTEC \rightarrow : Deadlines



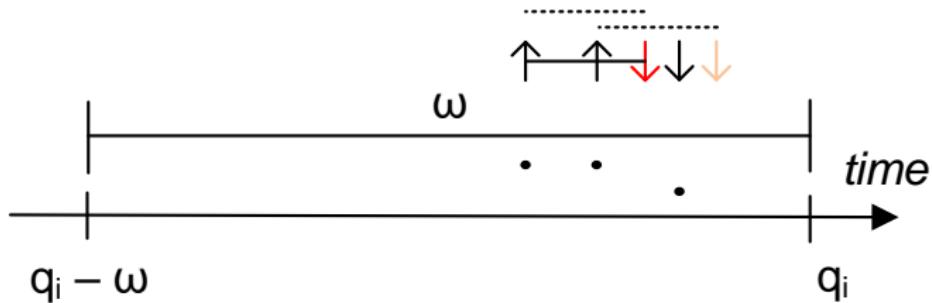
RTEC \rightarrow : Deadlines



RTEC \rightarrow : Deadlines

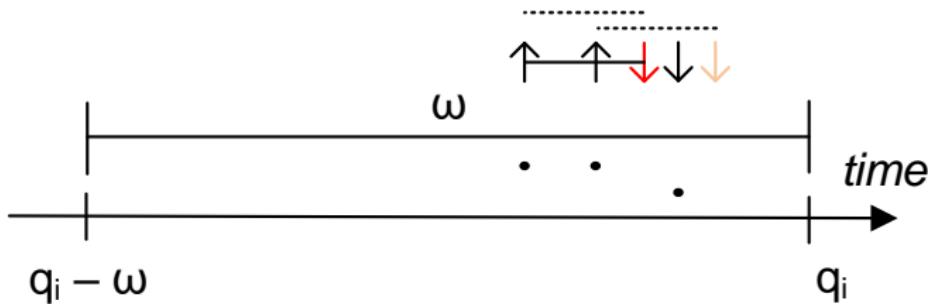


RTEC \rightarrow : Deadlines

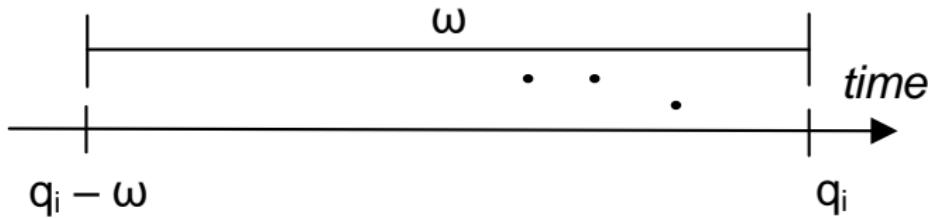


RTEC \rightarrow : Deadlines

non-extensible

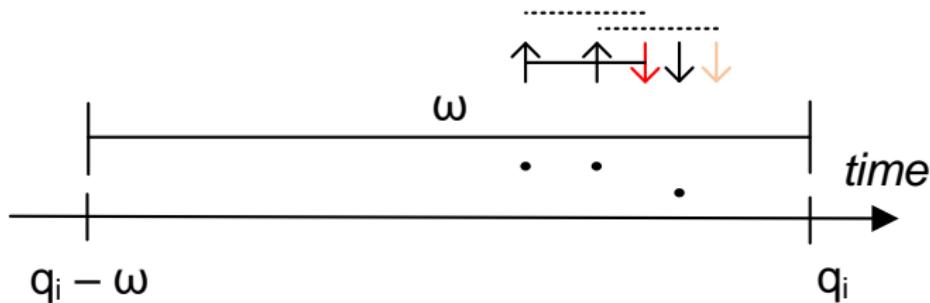


extensible

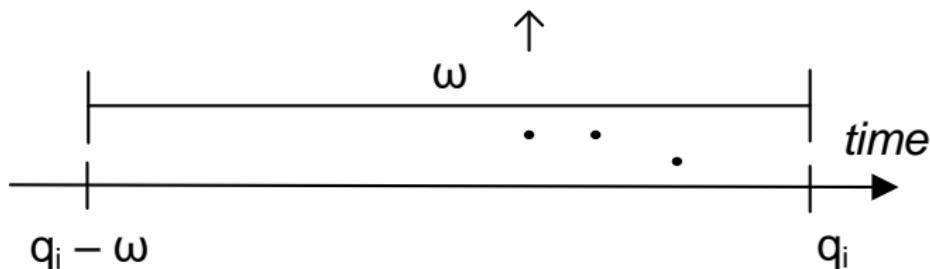


RTEC \rightarrow : Deadlines

non-extensible

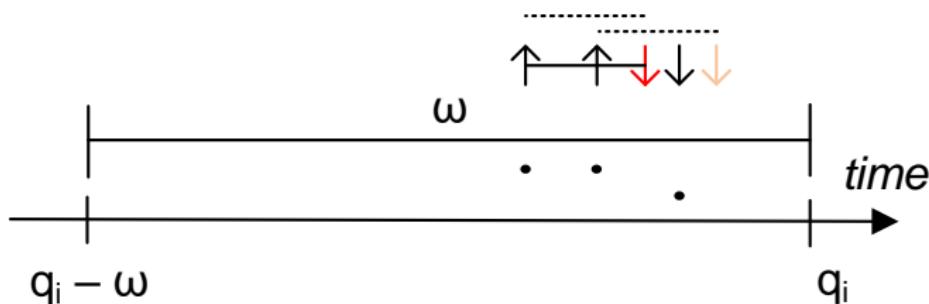


extensible

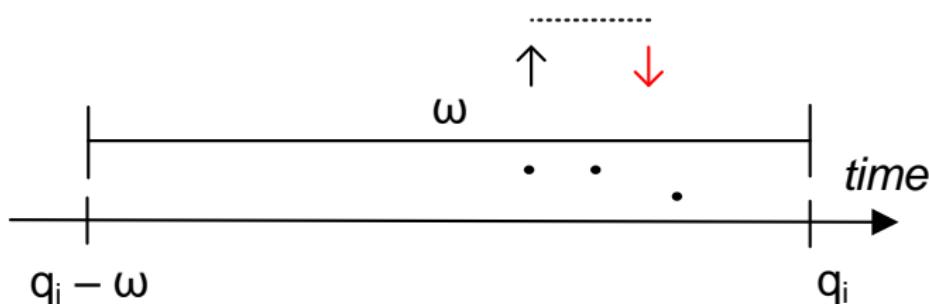


RTEC \rightarrow : Deadlines

non-extensible

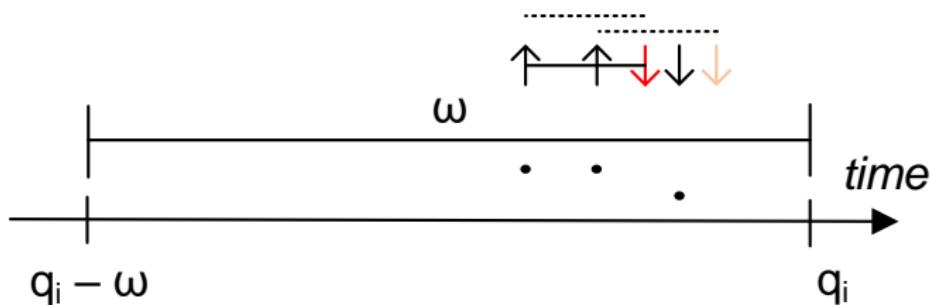


extensible

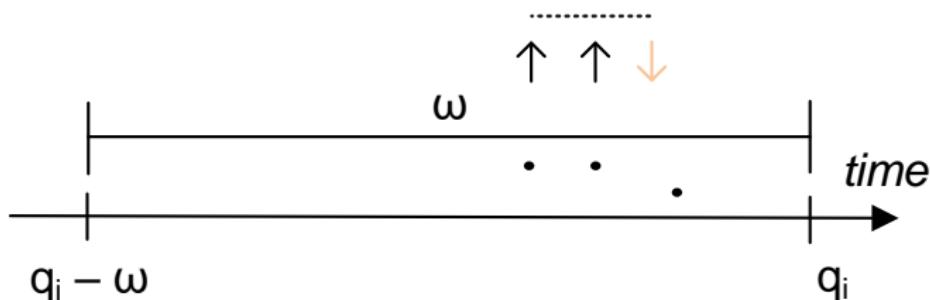


RTEC \rightarrow : Deadlines

non-extensible

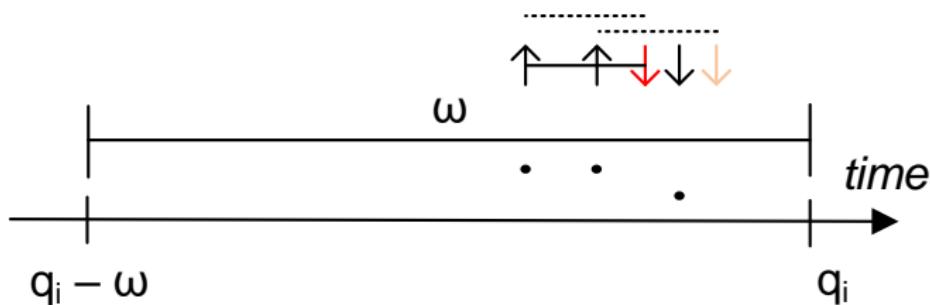


extensible

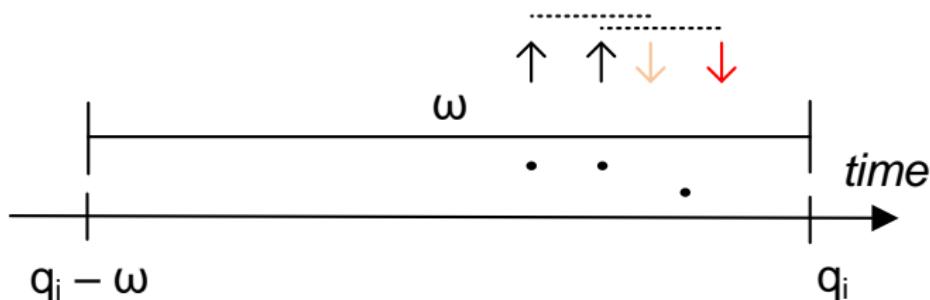


RTEC \rightarrow : Deadlines

non-extensible

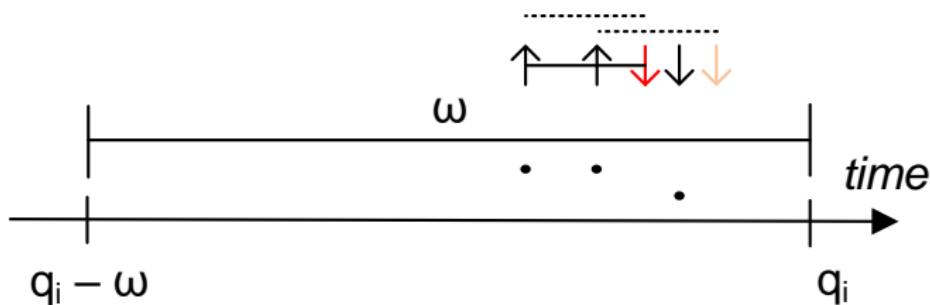


extensible

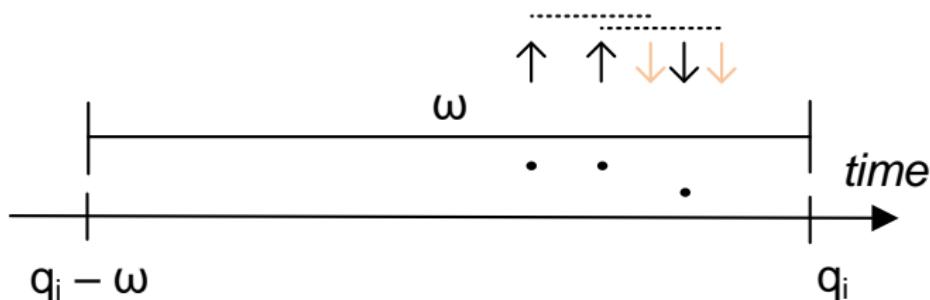


RTEC \rightarrow : Deadlines

non-extensible

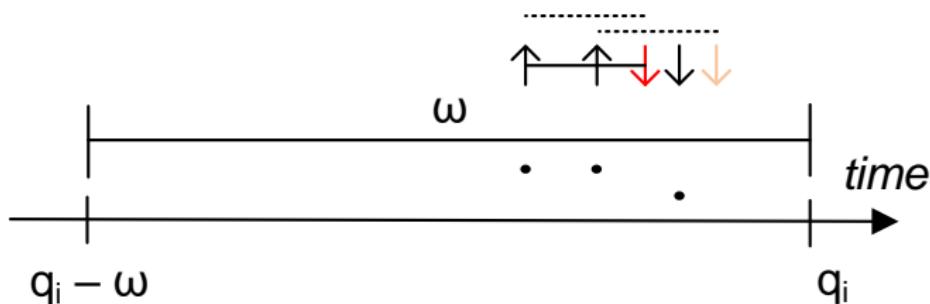


extensible

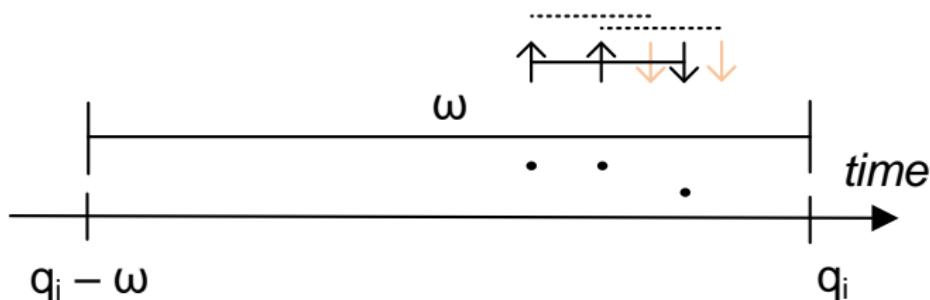


RTEC \rightarrow : Deadlines

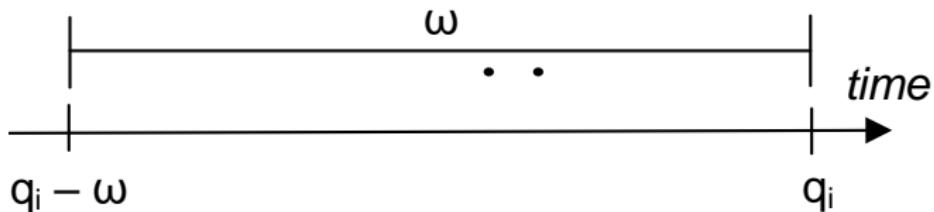
non-extensible



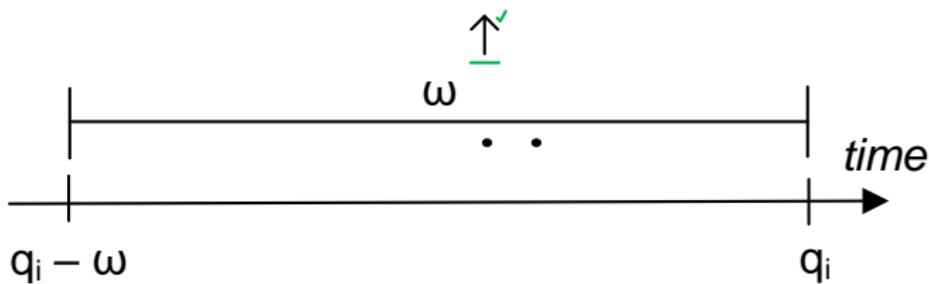
extensible



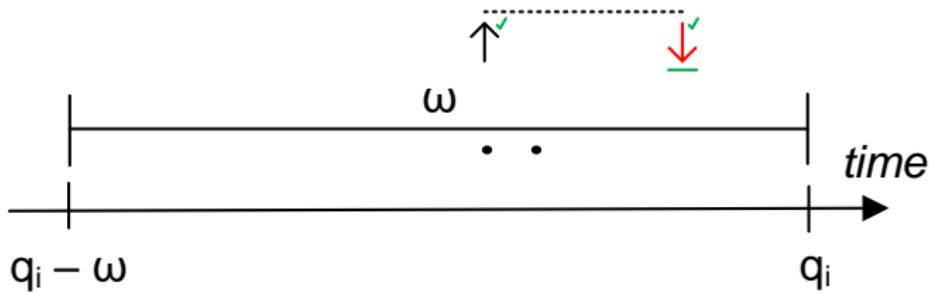
Handling Deadlines: Caching



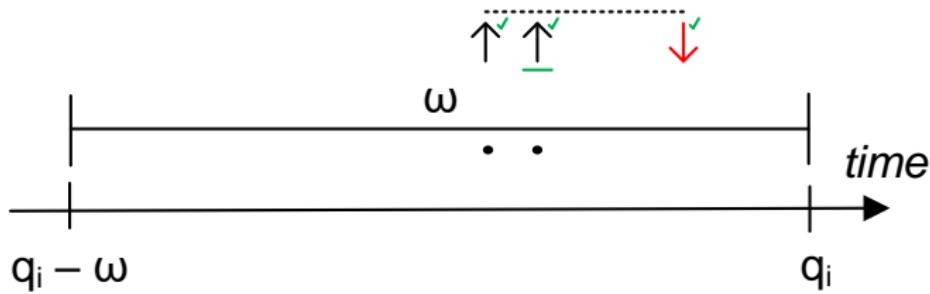
Handling Deadlines: Caching



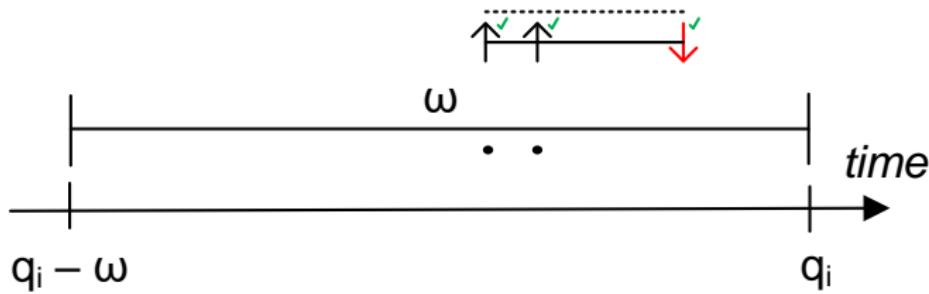
Handling Deadlines: Caching



Handling Deadlines: Caching

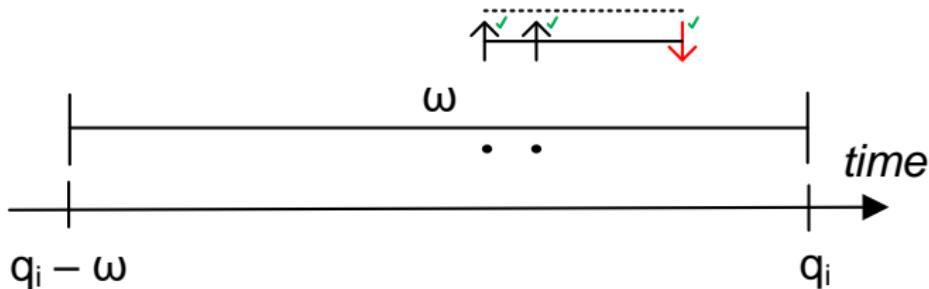


Handling Deadlines: Caching

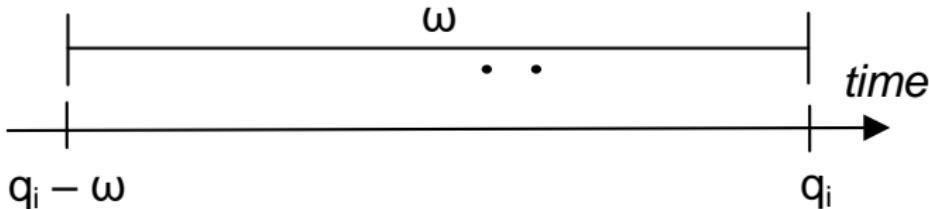


Handling Deadlines: Caching

RTEC \rightarrow

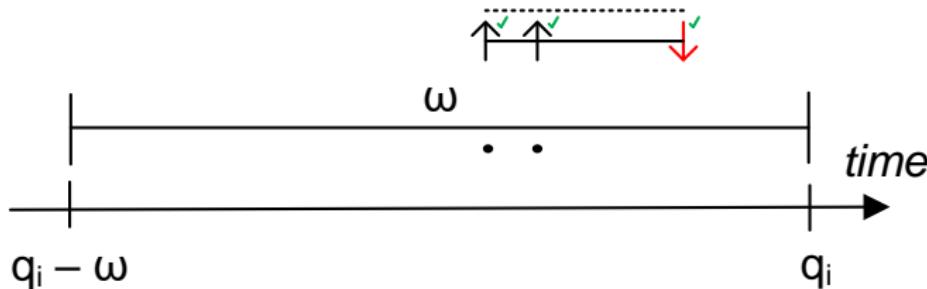


RTEC \rightarrow -naive

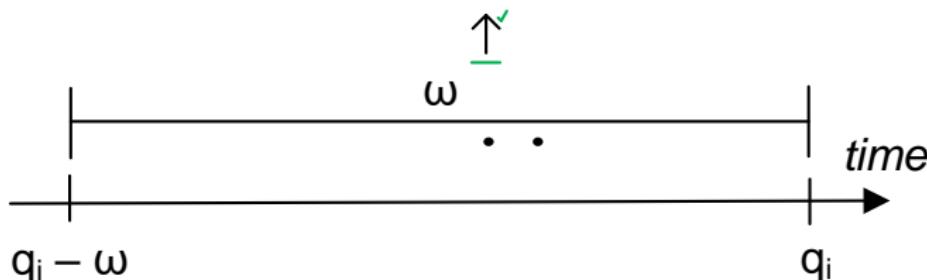


Handling Deadlines: Caching

RTEC \rightarrow

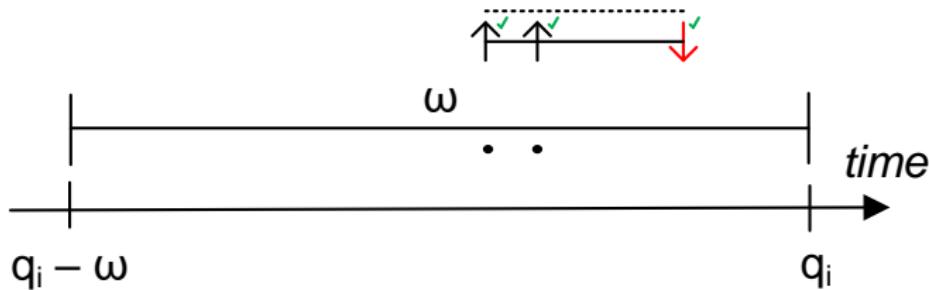


RTEC \rightarrow -naive

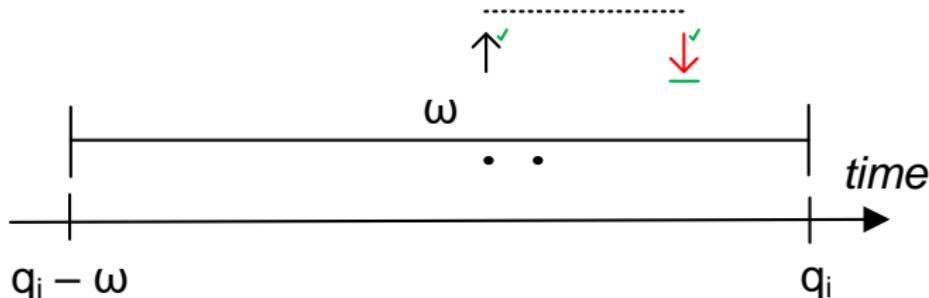


Handling Deadlines: Caching

RTEC \rightarrow

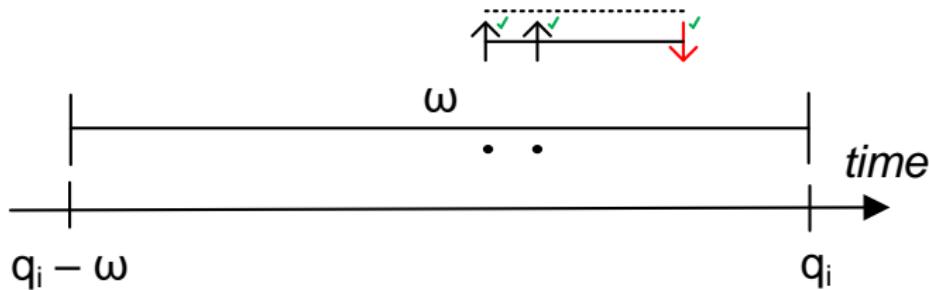


RTEC \rightarrow -naive

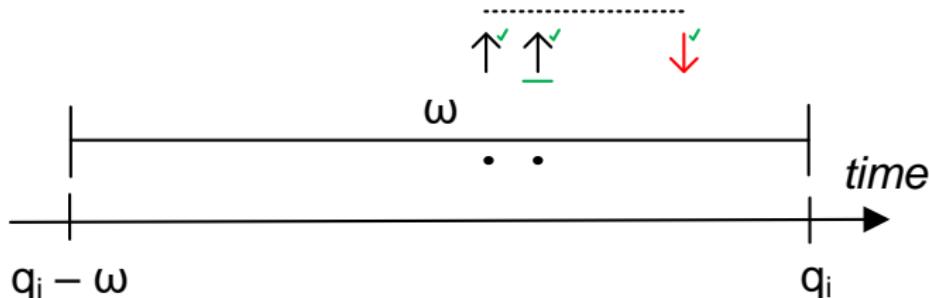


Handling Deadlines: Caching

RTEC \rightarrow

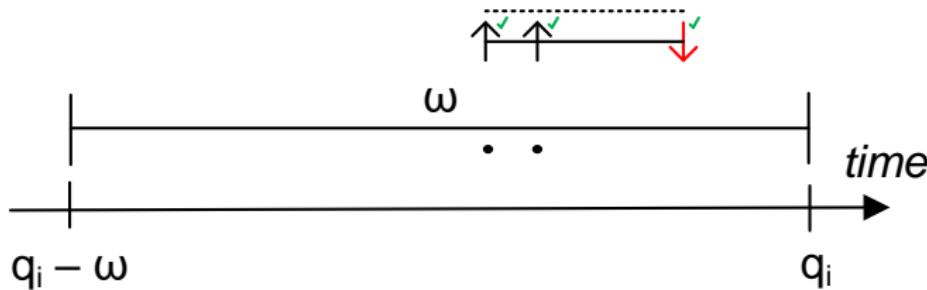


RTEC \rightarrow -naive

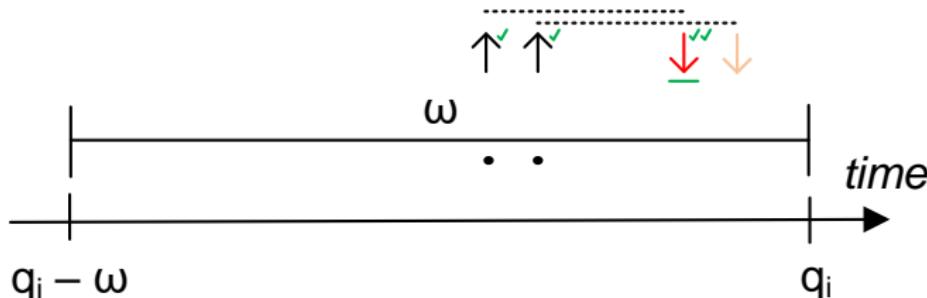


Handling Deadlines: Caching

RTEC \rightarrow

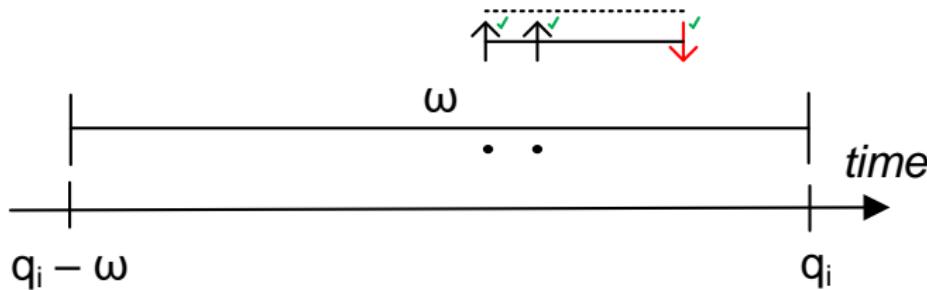


RTEC \rightarrow -naive

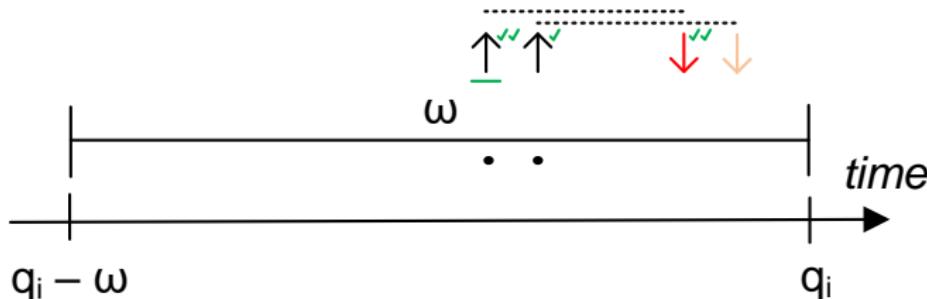


Handling Deadlines: Caching

RTEC \rightarrow

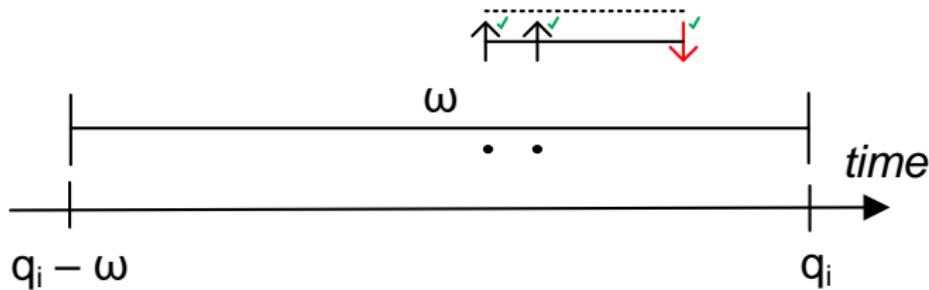


RTEC \rightarrow -naive

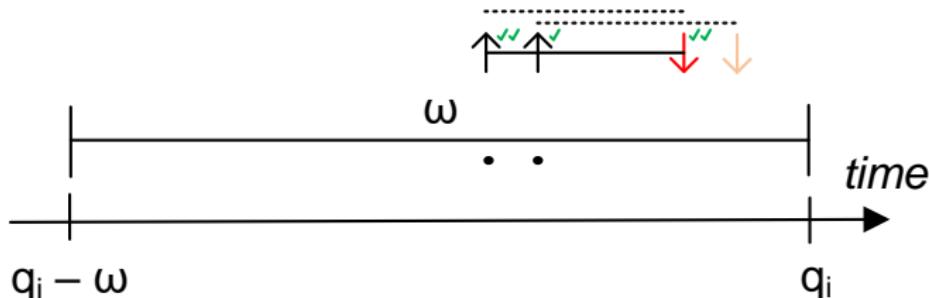


Handling Deadlines: Caching

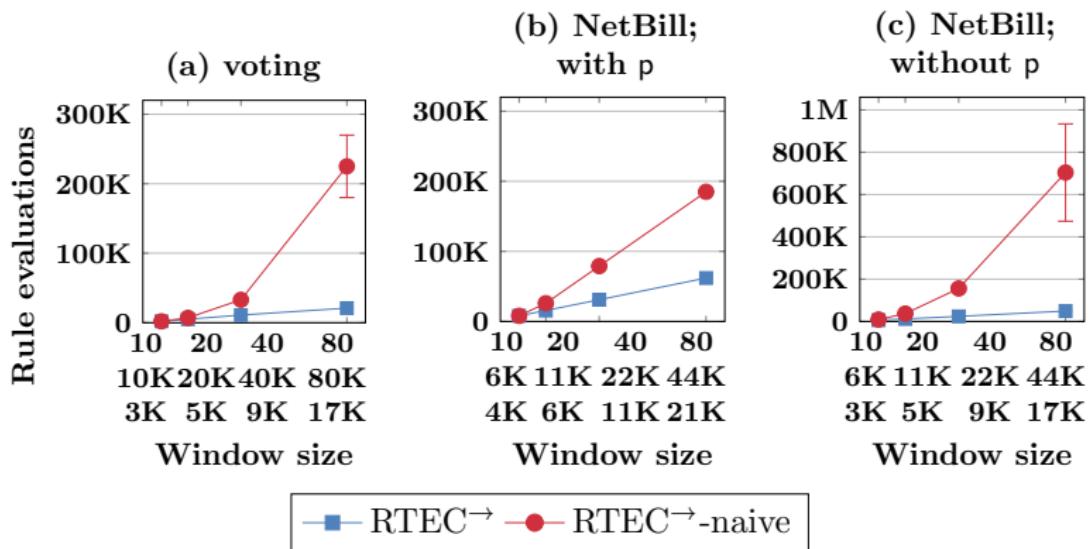
RTEC \rightarrow



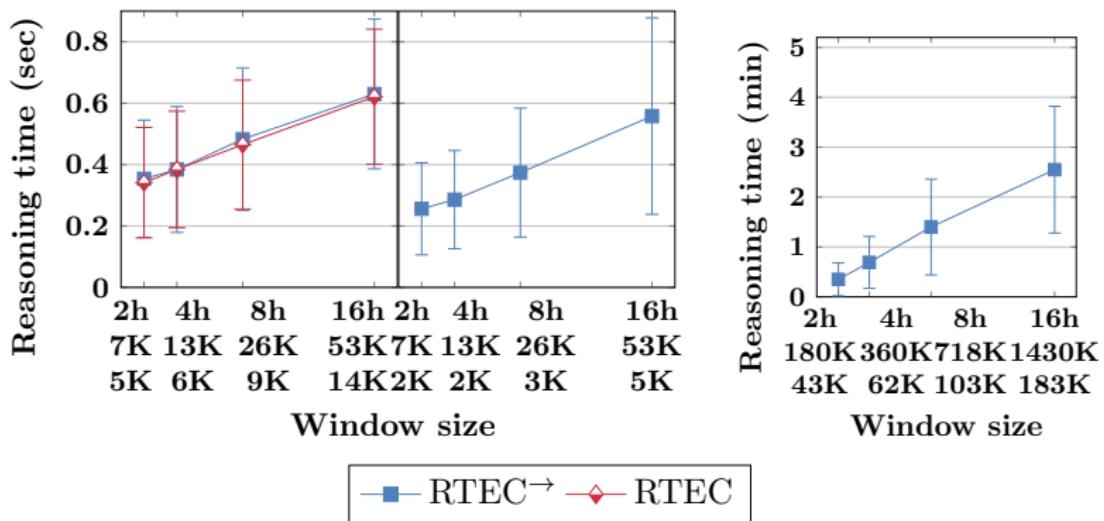
RTEC \rightarrow -naive



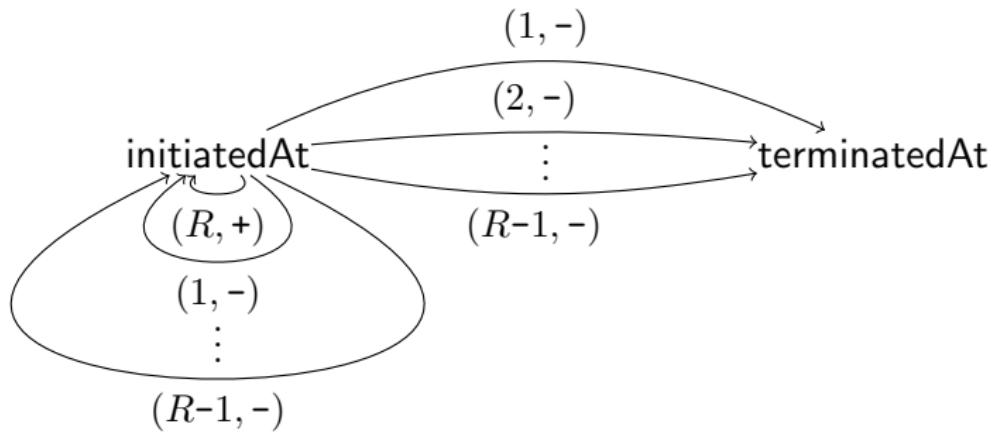
RTEC \rightarrow : Experimental Results



RTEC \rightarrow : Experimental Results



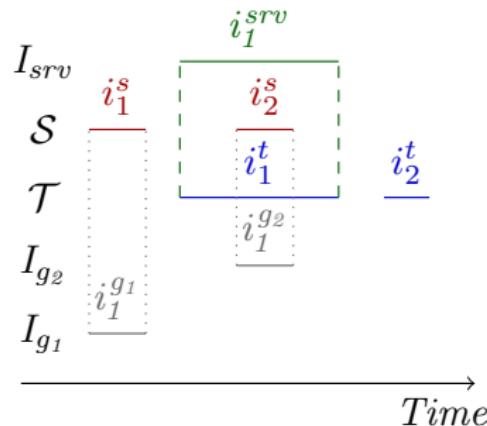
Semantics of RTEC \rightarrow



The cycle-sum graph of an RTEC \rightarrow program.

RTEC_A: Allen Relations

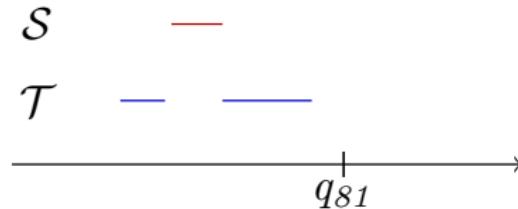
holdsFor(*suspiciousRendezVous(Vessel₁, Vessel₂) = true, I*) ←
holdsFor(*gap(Vessel₁) = farFromPorts, I_{g1}*),
holdsFor(*gap(Vessel₂) = farFromPorts, I_{g2}*),
holdsFor(*proximity(Vessel₁, Vessel₂) = true, T*),
union_all([*I_{g1}, I_{g2}*], \mathcal{S}),
allen(*during, S, T, target, I*).



RTEC_A: Windowing

```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```

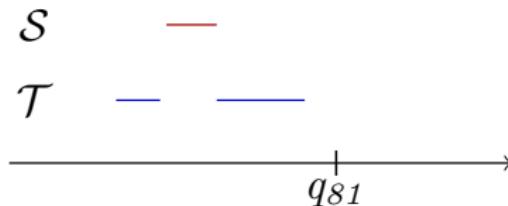
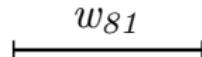
Query time: q_{81}



RTEC_A: Windowing

```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```

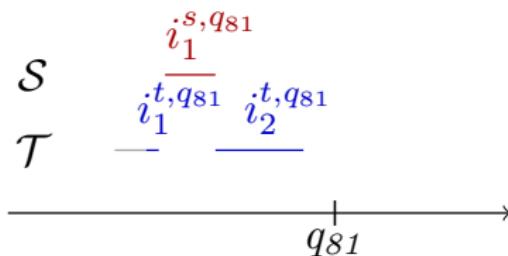
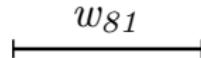
Query time: q_{81}



RTEC_A: Windowing

holdsFor(*disappearedInArea(Vessel, AreaType) = true, I*) \leftarrow
holdsFor(*withinArea(Vessel, AreaType) = true, S*),
holdsFor(*gap(Vessel) = farFromPorts, T*),
allen(*meets, S, T, target, I*).

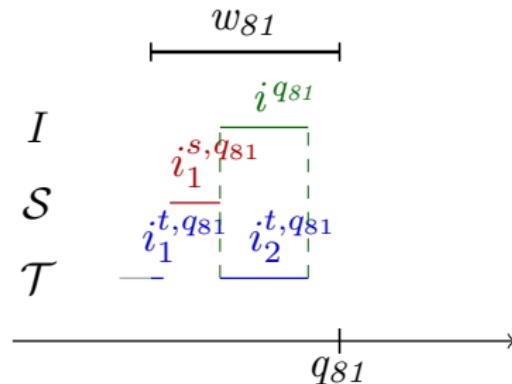
Query time: q_{81}



RTEC_A: Windowing

holdsFor(*disappearedInArea(Vessel, AreaType) = true, I*) \leftarrow
holdsFor(*withinArea(Vessel, AreaType) = true, S*),
holdsFor(*gap(Vessel) = farFromPorts, T*),
allen(*meets, S, T, target, I*).

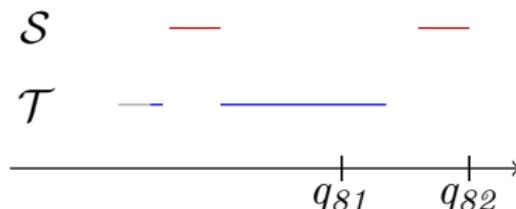
Query time: q_{81}



RTEC_A: Windowing

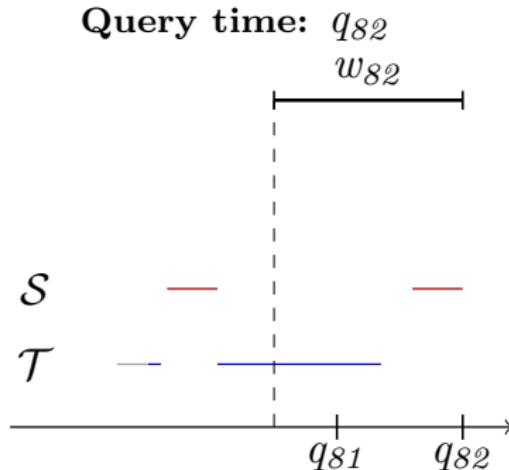
```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```

Query time: q_{82}



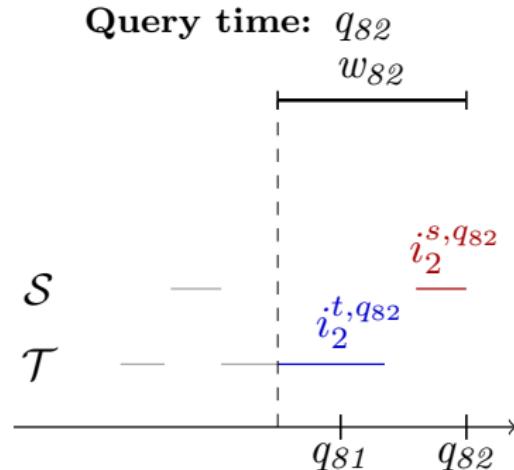
RTEC_A: Windowing

```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```



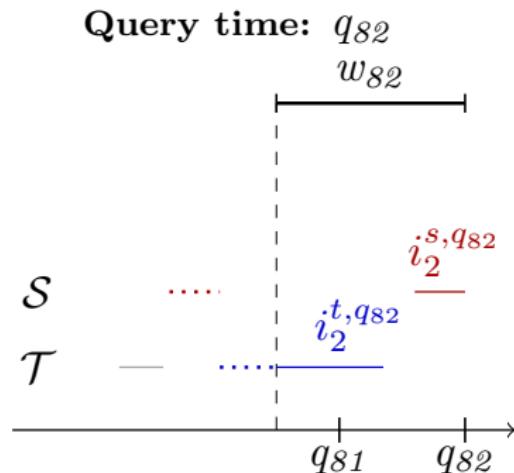
RTEC_A: Windowing

```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```



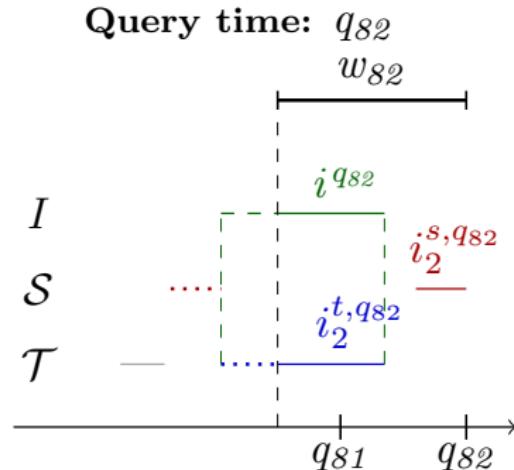
RTEC_A: Windowing

```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```



RTEC_A: Windowing

```
holdsFor(disappearedInArea(Vessel, AreaType) = true, I) ←  
  holdsFor(withinArea(Vessel, AreaType) = true, S),  
  holdsFor(gap(Vessel) = farFromPorts, T),  
  allen(meets, S, T, target, I).
```



RTEC_A: Experimental Evaluation

Batch setting.

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

Streaming setting.

Days	Input Intervals	Window size		Reasoning Time		Output Interval Pairs	
		RTEC _A	D ² IA	RTEC _A	D ² IA	RTEC _A	D ² IA
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

initiatedAt(*moving(P₁, P₂)=true, T*) ←
 happensAt(*walking(P₁), T*),
 happensAt(*walking(P₂), T*),
 holdsAt(*close(P₁, P₂)=true, T*),
 holdsAt(*orientation(P₁, P₂)=true, T*).

terminatedAt(*moving(P₁, P₂)=true, T*) ←
 happensAt(*walking(P₁), T*),
 holdsAt(*close(P₁, P₂)=false, T*).

0.70 :: **happensAt**(*walking(mike), 1*).
0.46 :: **happensAt**(*walking(sarah), 1*).

Instantaneous Recognition

initiatedAt(*moving(P₁, P₂) = true, T*) ←
 happensAt(*walking(P₁), T*),
 happensAt(*walking(P₂), T*),
 holdsAt(*close(P₁, P₂) = true, T*),
 holdsAt(*orientation(P₁, P₂) = true, T*).

terminatedAt(*moving(P₁, P₂) = true, T*) ←
 happensAt(*walking(P₁), T*),
 holdsAt(*close(P₁, P₂) = false, T*).

$$0.70 :: \text{happensAt}(\text{walking(mike)}, 1). \\ 0.46 :: \text{happensAt}(\text{walking(sarah)}, 1). \\ P(\text{initiatedAt}(\text{moving(mike, sarah)} = \text{true}, 1)) = \\ P(\text{happensAt}(\text{walking(mike)}, 1)) \times \\ P(\text{happensAt}(\text{walking(sarah)}, 1)) \times \\ P(\text{holdsAt}(\text{close(mike, sarah)} = \text{true}, 1)) \times \\ P(\text{holdsAt}(\text{orientation(mike, sarah)} = \text{true}, 1)) \\ = 0.7 \times 0.46 \times 1 \times 1 = 0.322$$

Instantaneous Recognition

initiatedAt(*moving(P₁, P₂) = true, T*) \leftarrow
happensAt(*walking(P₁), T*),

happensAt(*walking(P₂), T*),

holdsAt(*close(P₁, P₂) = true, T*),

holdsAt(*orientation(P₁, P₂) = true, T*).

terminatedAt(*moving(P₁, P₂) = true, T*) \leftarrow
happensAt(*walking(P₁), T*),
holdsAt(*close(P₁, P₂) = false, T*).

0.70 :: **happensAt**(*walking(mike), 1*).
0.46 :: **happensAt**(*walking(sarah), 1*).

P(holdsAt(CE = true, t)) =
P(initiatedAt(CE = true, t - 1) \vee
(holdsAt(CE = true, t - 1) \wedge
 \neg terminatedAt(CE = true, t - 1)))

Instantaneous Recognition

initiatedAt(*moving(P₁, P₂)=true, T*) ←
 happensAt(*walking(P₁), T*),

happensAt(*walking(P₂), T*),

holdsAt(*close(P₁, P₂)=true, T*),

holdsAt(*orientation(P₁, P₂)=true, T*).

terminatedAt(*moving(P₁, P₂)=true, T*) ←
 happensAt(*walking(P₁), T*),
 holdsAt(*close(P₁, P₂)=false, T*).

0.70 :: **happensAt**(*walking(mike), 1*).

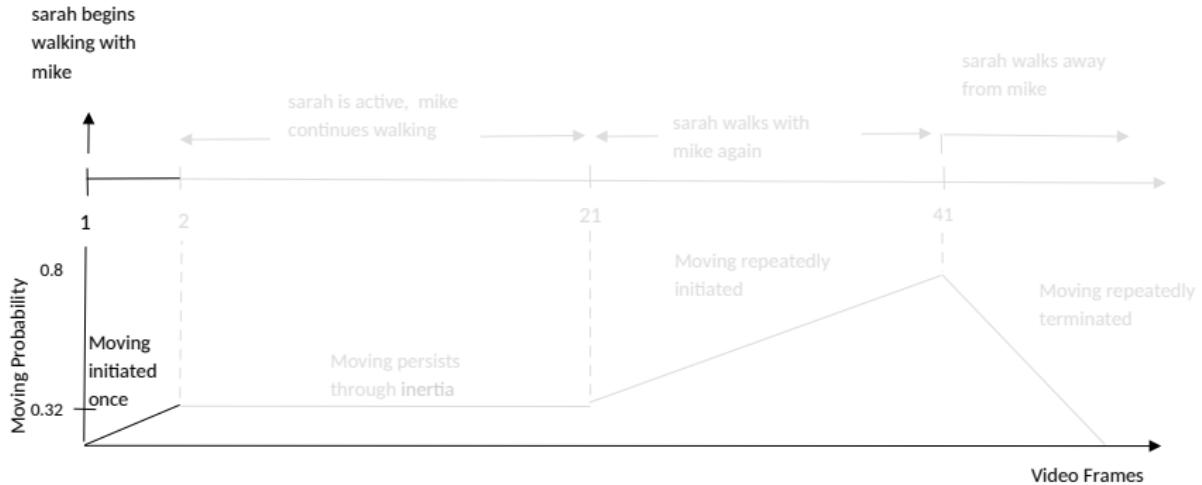
0.46 :: **happensAt**(*walking(sarah), 1*).

$P(\text{holdsAt}(\text{moving(mike, sarah)} = \text{true}, 2)) =$

$P(\text{initiatedAt}(\text{moving(mike, sarah)} = \text{true}, 1) \vee$
 (**holdsAt**(*moving(mike, sarah)=true, 1*) \wedge
 negatedAt(*moving(mike, sarah)=true, 1*)))

$$= 0.322 + 0 \times 1 - 0.322 \times 0 \times 1 = 0.322$$

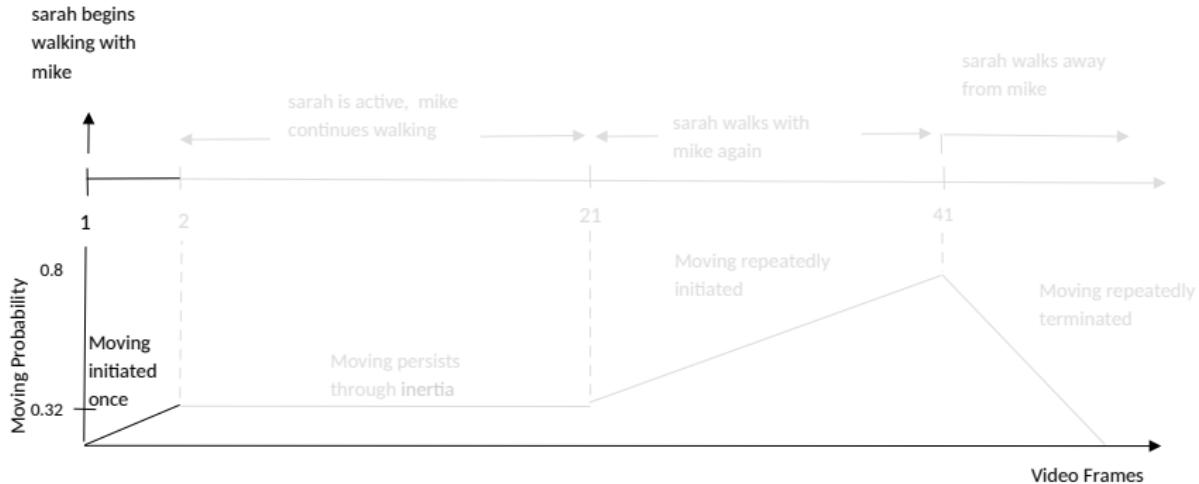
Instantaneous Recognition



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

$$\begin{aligned}
 0.70 &:: \text{happensAt}(\text{walking}(mike), 1). \\
 0.46 &:: \text{happensAt}(\text{walking}(sarah), 1). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 2)) &= \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 1) \vee & \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 1) \wedge & \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 1))) &= \\
 0.322 + 0 \times 1 - 0.322 \times 0 \times 1 &= 0.322
 \end{aligned}$$

Instantaneous Recognition

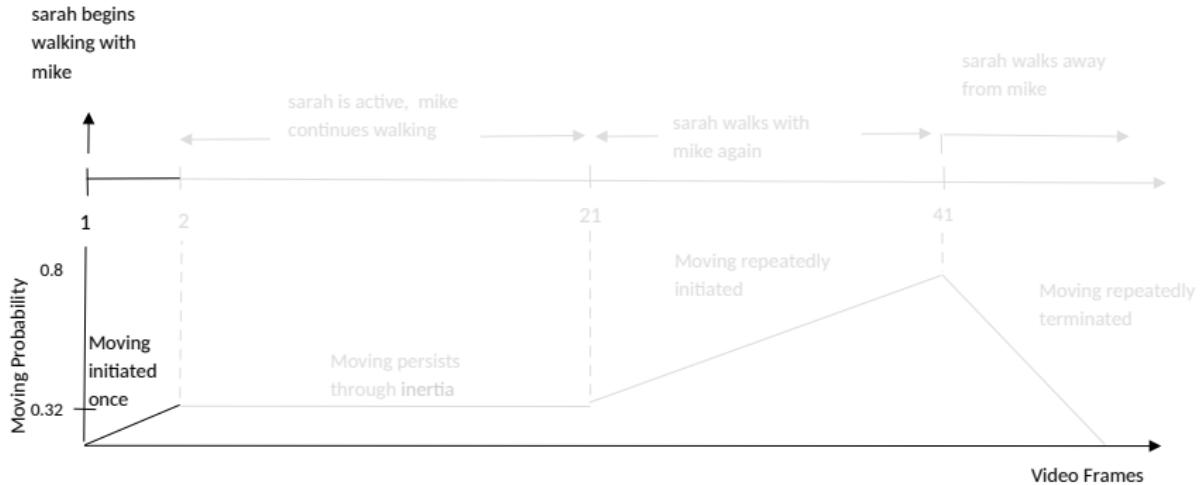


```
initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
happensAt(walking( $P_1$ ),  $T$ ),
happensAt(walking( $P_2$ ),  $T$ ),
holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).
```

```
terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
happensAt(walking( $P_1$ ),  $T$ ),
holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
```

0.73 :: **happensAt**(walking(mike), 2).
 0.55 :: **happensAt**(active(sarah), 2). ...

Instantaneous Recognition

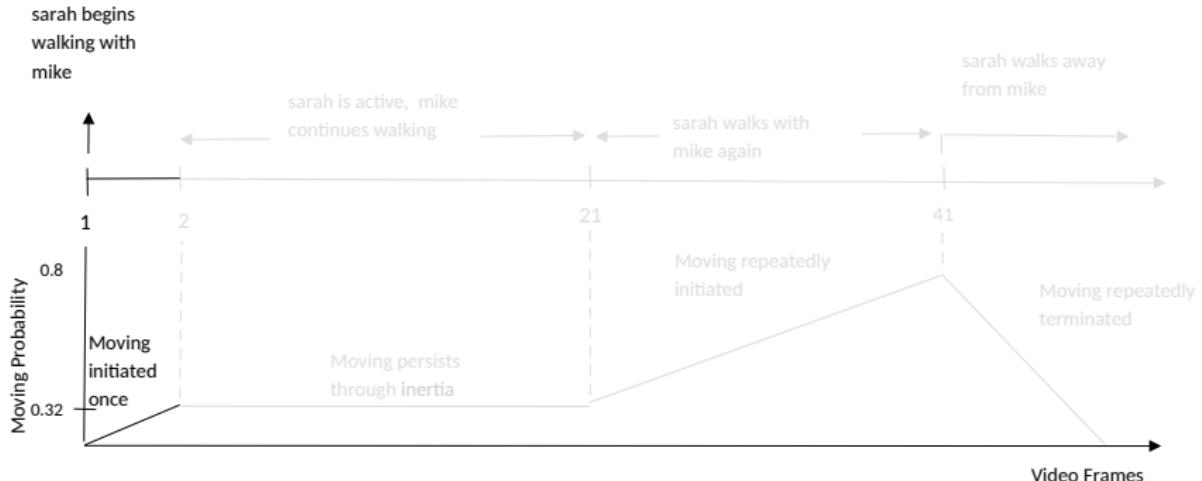


initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T)$ \leftarrow
happensAt($\text{walking}(P_1), T$),
happensAt($\text{walking}(P_2), T$),
holdsAt($\text{close}(P_1, P_2) = \text{true}, T$),
holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T$).

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

$$\begin{aligned}
 & 0.73 :: \mathbf{happensAt}(\text{walking}(mike), 2). \\
 & 0.55 :: \mathbf{happensAt}(\text{active}(sarah), 2). \dots \\
 & P(\mathbf{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 3)) = \\
 & P(\mathbf{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 2) \vee \\
 & (\mathbf{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 2) \wedge \\
 & \neg \mathbf{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 2))) \\
 & = 0 + 0.322 \times 1 - 0 \times 0.322 \times 1 = 0.322
 \end{aligned}$$

Instantaneous Recognition

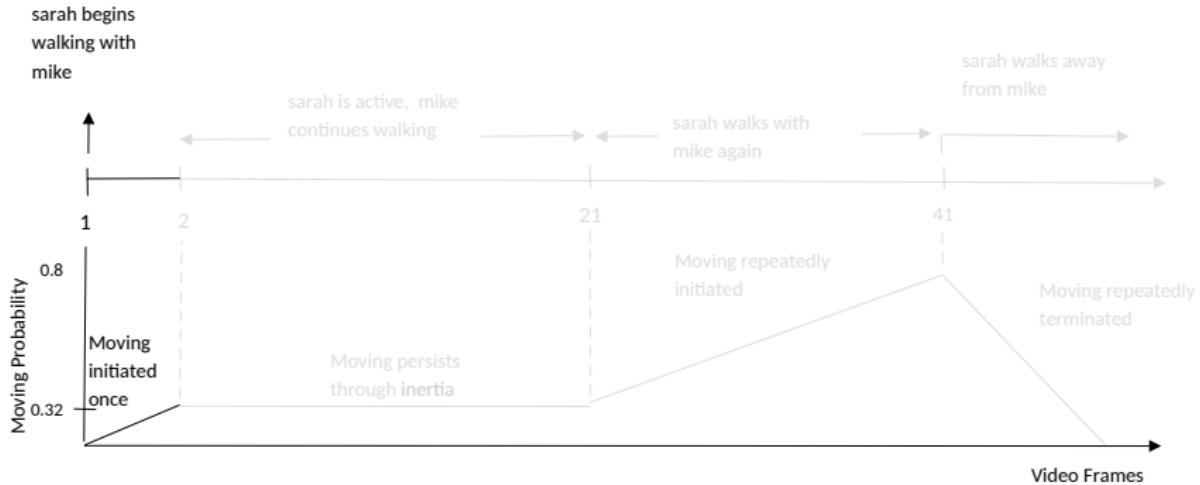


initiatedAt($\text{moving}(P_1, P_2) = \text{true}$, T) \leftarrow
happensAt($\text{walking}(P_1)$, T),
happensAt($\text{walking}(P_2)$, T),
holdsAt($\text{close}(P_1, P_2) = \text{true}$, T),
holdsAt($\text{orientation}(P_1, P_2) = \text{true}$, T).

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

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

Instantaneous Recognition

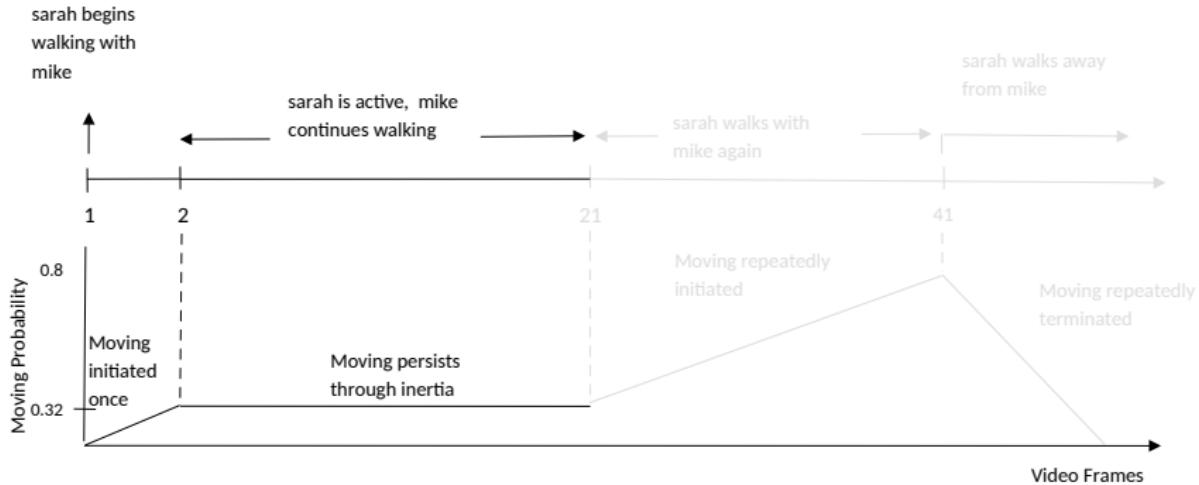


initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T) \leftarrow$
happensAt($\text{walking}(P_1), T),$
happensAt($\text{walking}(P_2), T),$
holdsAt($\text{close}(P_1, P_2) = \text{true}, T),$
holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T).$

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

$$\begin{aligned}
 0.45 &:: \text{happensAt}(\text{walking}(mike), 20). \\
 0.14 &:: \text{happensAt}(\text{active}(sarah), 20). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 21)) &= \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 20) \vee & \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 20) \wedge & \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 20))) &= \\
 0 + 0.322 \times 1 - 0 \times 0.322 \times 1 &= 0.322
 \end{aligned}$$

Instantaneous Recognition



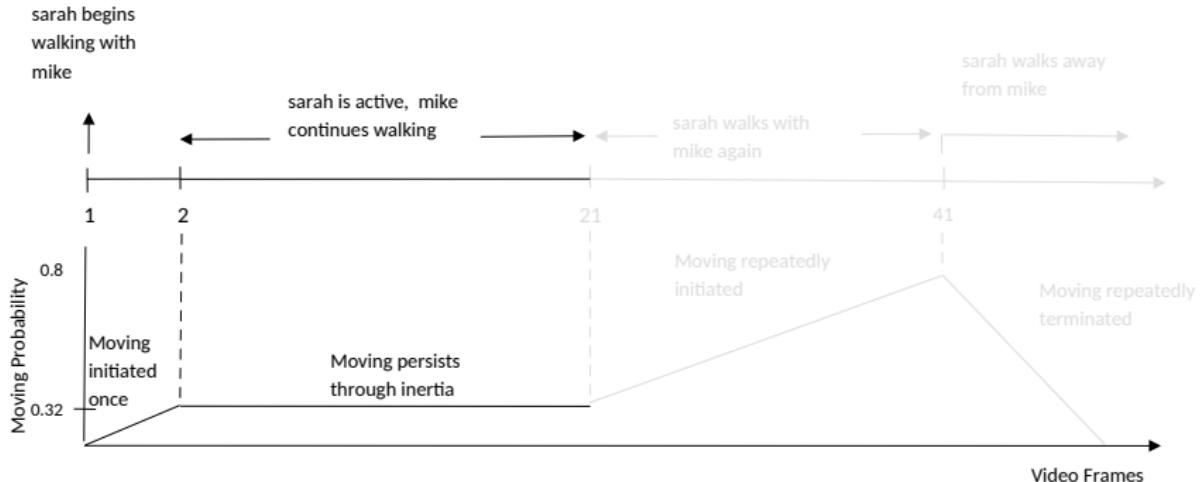
```

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

terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ )  $\leftarrow$ 
  happensAt(walking( $P_1$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
  
```

$$\begin{aligned}
 0.45 &:: \text{happensAt}(\text{walking}(mike), 20). \\
 0.14 &:: \text{happensAt}(\text{active}(sarah), 20). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 21)) &= \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 20) \vee \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 20) \wedge \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 20))) &= \\
 0 + 0.322 \times 1 - 0 \times 0.322 \times 1 &= 0.322
 \end{aligned}$$

Instantaneous Recognition

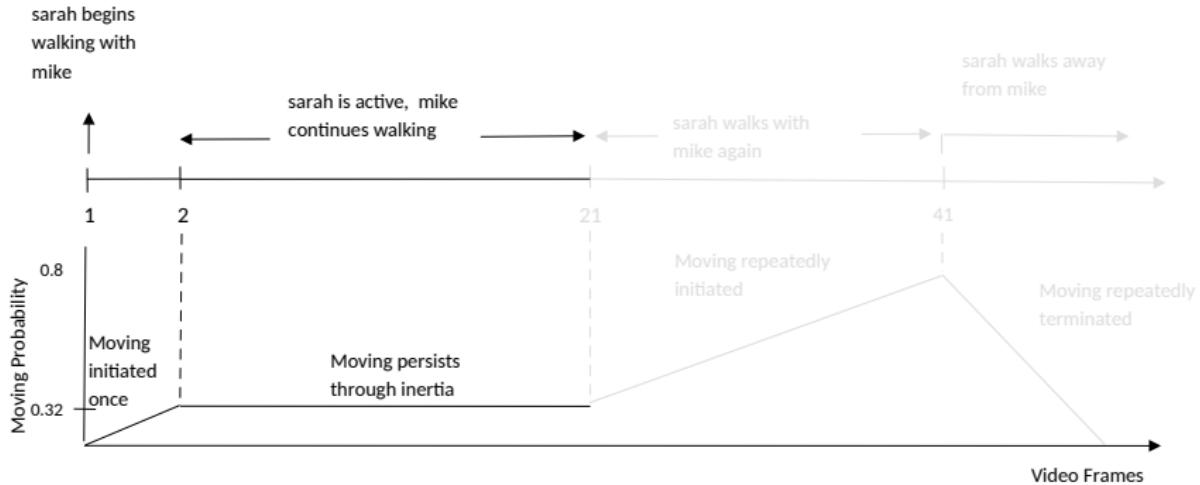


```
initiatedAt(moving(P1, P2) = true, T) ←
  happensAt(walking(P1), T),
  happensAt(walking(P2), T),
  holdsAt(close(P1, P2) = true, T),
  holdsAt(orientation(P1, P2) = true, T).
```

```
terminatedAt(moving(P1, P2) = true, T) ←
  happensAt(walking(P1), T),
  holdsAt(close(P1, P2) = false, T).
```

0.39 :: happensAt(walking(mike), 21).
 0.28 :: happensAt(walking(sarah), 21). ...

Instantaneous Recognition



```

initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  happensAt(walking( $P_2$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
  holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).

terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
  
```

$0.39 :: \text{happensAt}(\text{walking}(mike), 21).$

$0.28 :: \text{happensAt}(\text{walking}(sarah), 21). \dots$

$P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 21)) =$

$$P(\text{happensAt}(\text{walking}(mike), 21)) \times$$

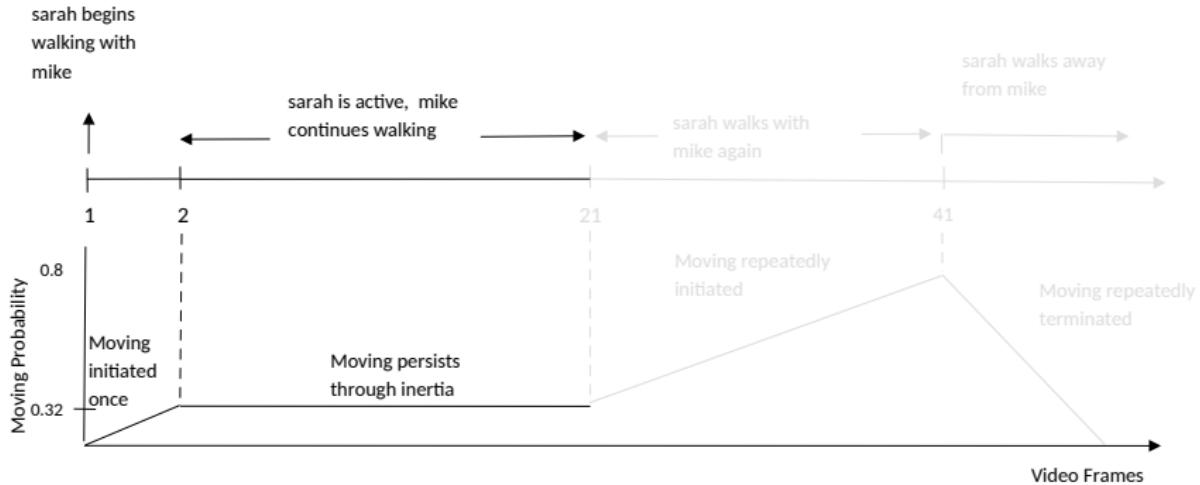
$$P(\text{happensAt}(\text{walking}(sarah), 21)) \times$$

$$P(\text{holdsAt}(\text{close}(mike, sarah) = \text{true}, 21)) \times$$

$$P(\text{holdsAt}(\text{orientation}(mike, sarah) = \text{true}, 21))$$

$$= 0.39 \times 0.28 \times 1 \times 1 = 0.11$$

Instantaneous Recognition

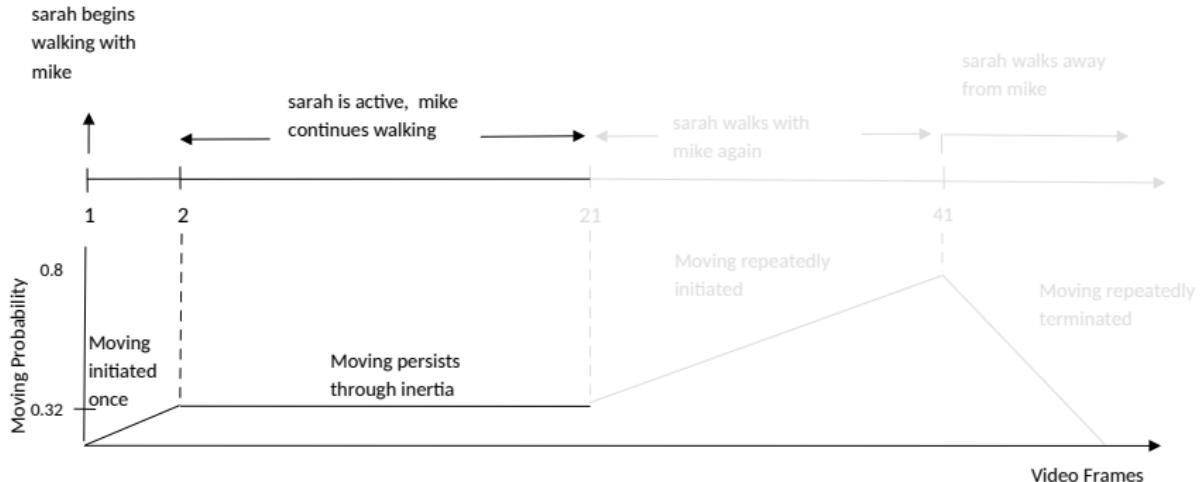


initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T) \leftarrow$
happensAt($\text{walking}(P_1), T),$
happensAt($\text{walking}(P_2), T),$
holdsAt($\text{close}(P_1, P_2) = \text{true}, T),$
holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T).$

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

$$\begin{aligned}
 & 0.39 :: \text{happensAt}(\text{walking}(mike), 21). \\
 & 0.28 :: \text{happensAt}(\text{walking}(sarah), 21). \dots \\
 & P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 22)) = \\
 & P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 21) \vee \\
 & (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 21) \wedge \\
 & \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 21))) \\
 & = 0.11 + 0.322 \times 1 - 0.11 \times 0.322 \times 1 = 0.39
 \end{aligned}$$

Instantaneous Recognition

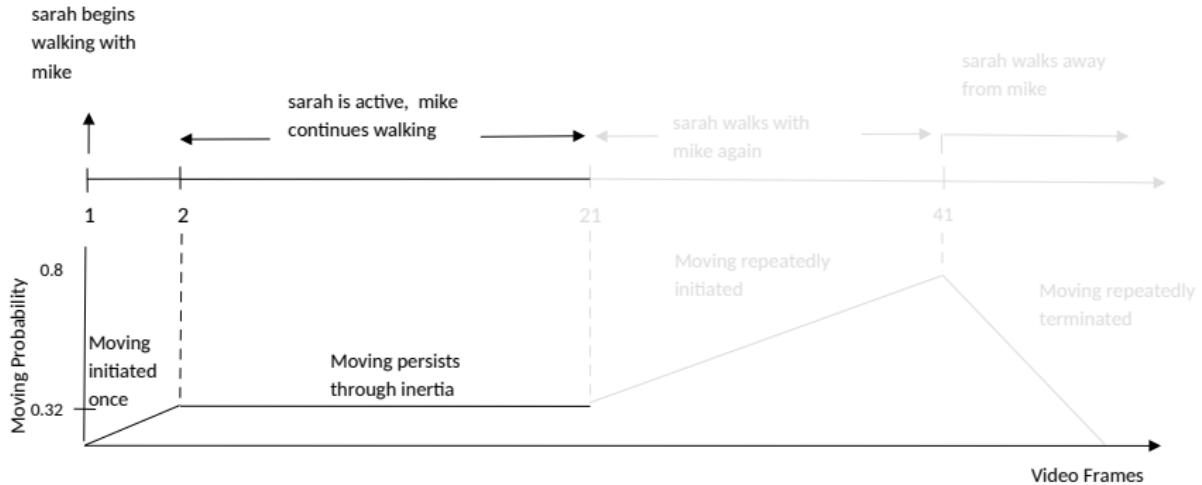


```
initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
happensAt(walking( $P_1$ ),  $T$ ),
happensAt(walking( $P_2$ ),  $T$ ),
holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).
```

```
terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
happensAt(walking( $P_1$ ),  $T$ ),
holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
```

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

Instantaneous Recognition



```

initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  happensAt(walking( $P_2$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
  holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).

terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
  
```

$0.28 :: \text{happensAt}(\text{walking}(mike), 40).$

$0.18 :: \text{happensAt}(\text{walking}(sarah), 40).$

$P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 40)) =$

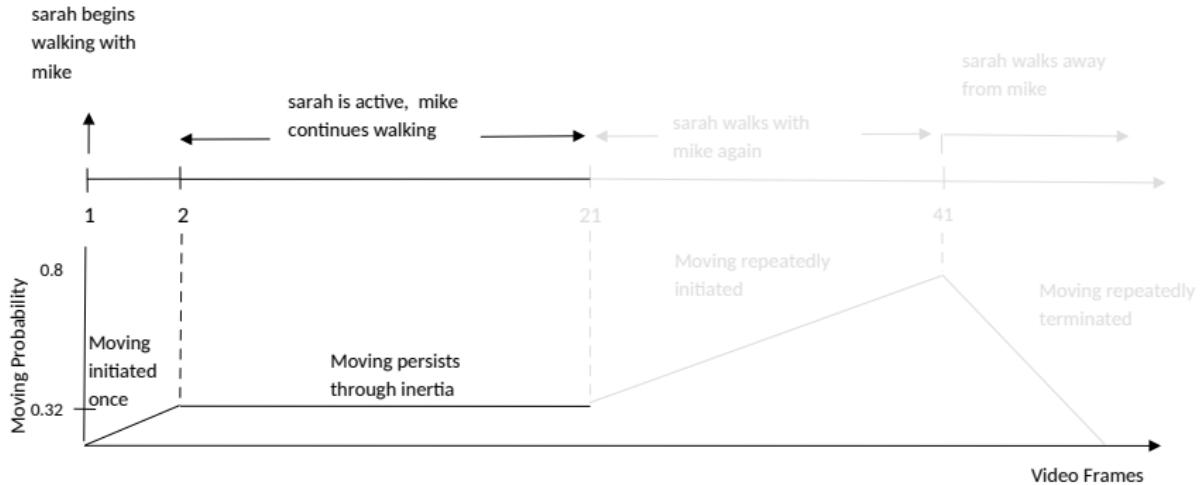
$$P(\text{happensAt}(\text{walking}(mike), 40)) \times$$

$$P(\text{happensAt}(\text{walking}(sarah), 40)) \times$$

$$P(\text{holdsAt}(\text{close}(mike, sarah) = \text{true}, 40)) \times$$

$$P(\text{holdsAt}(\text{orientation}(mike, sarah) = \text{true}, 40))$$
 $= 0.28 \times 0.18 \times 1 \times 1 = 0.05$

Instantaneous Recognition

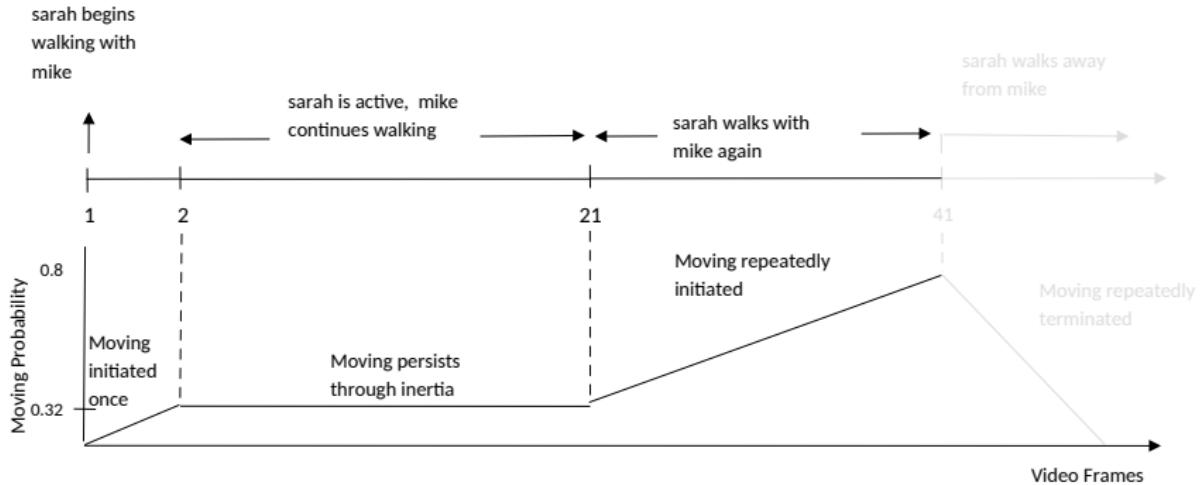


initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T) \leftarrow$
happensAt($\text{walking}(P_1), T),$
happensAt($\text{walking}(P_2), T),$
holdsAt($\text{close}(P_1, P_2) = \text{true}, T),$
holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T).$

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

$$\begin{aligned}
 0.28 &:: \text{happensAt}(\text{walking}(mike), 40). \\
 0.18 &:: \text{happensAt}(\text{walking}(sarah), 40). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 41)) &= \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 40) \vee \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 40) \wedge \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 40))) &= \\
 0.05 + 0.79 \times 1 - 0.05 \times 0.79 \times 1 &= 0.80
 \end{aligned}$$

Instantaneous Recognition

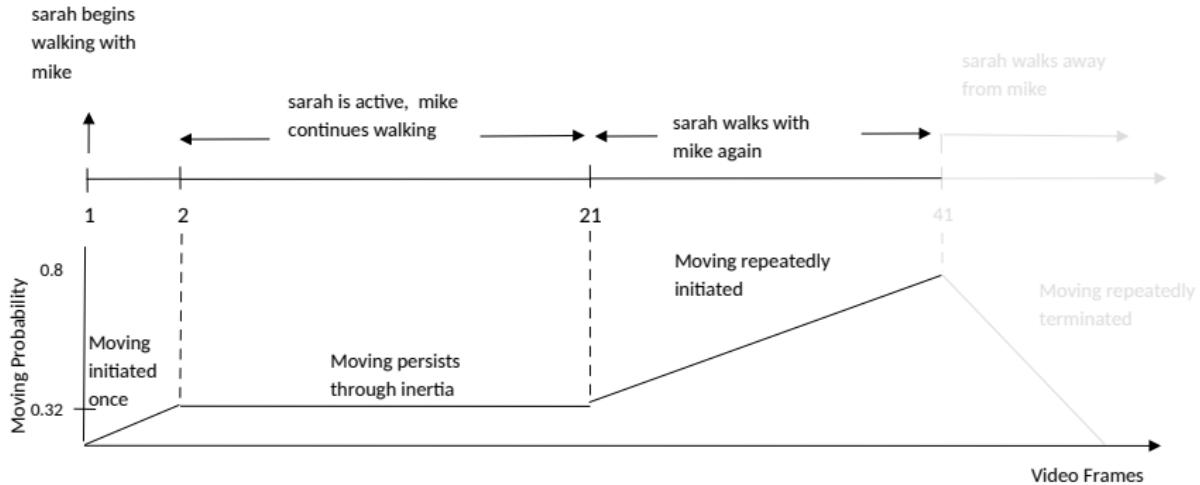


initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T) \leftarrow$
happensAt($\text{walking}(P_1), T),$
happensAt($\text{walking}(P_2), T),$
holdsAt($\text{close}(P_1, P_2) = \text{true}, T),$
holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T).$

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

$$\begin{aligned}
 0.28 &:: \text{happensAt}(\text{walking}(mike), 40). \\
 0.18 &:: \text{happensAt}(\text{walking}(sarah), 40). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 41)) &= \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 40) \vee & \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 40) \wedge & \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 40))) &= \\
 0.05 + 0.79 \times 1 - 0.05 \times 0.79 \times 1 &= 0.80
 \end{aligned}$$

Instantaneous Recognition

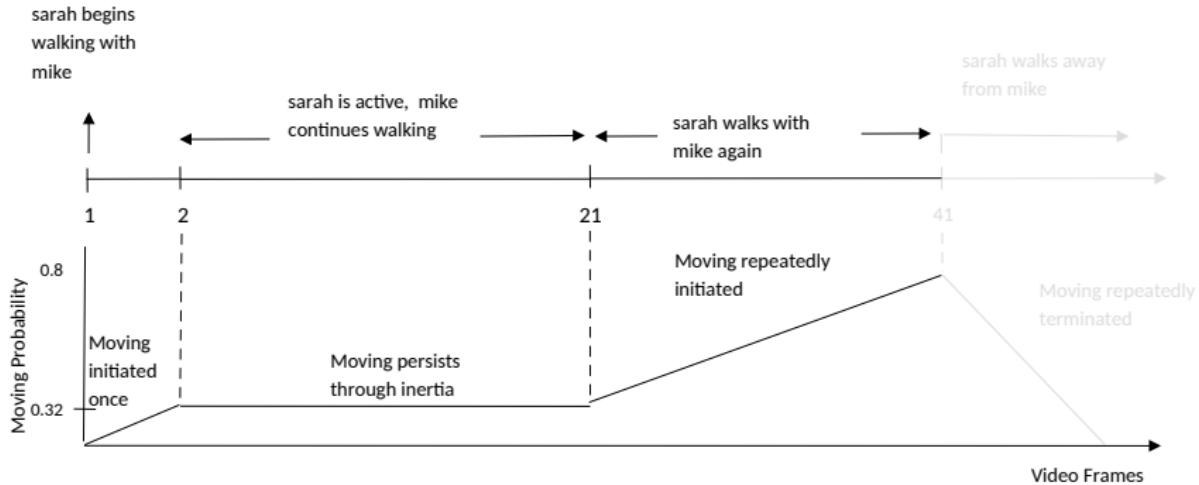


```
initiatedAt(moving(P1, P2) = true, T) ←
    happensAt(walking(P1), T),
    happensAt(walking(P2), T),
    holdsAt(close(P1, P2) = true, T),
    holdsAt(orientation(P1, P2) = true, T).
```

```
terminatedAt(moving(P1, P2) = true, T) ←
    happensAt(walking(P1), T),
    holdsAt(close(P1, P2) = false, T).
```

```
0.18 :: happensAt(walking(mike), 41).
0.79 :: happensAt(inactive(sarah), 41). ...
```

Instantaneous Recognition



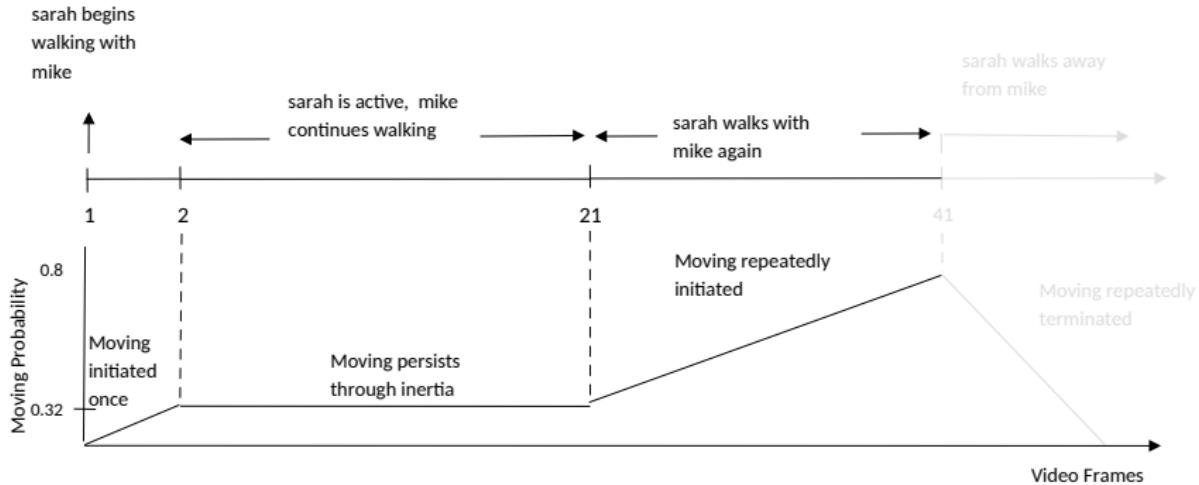
initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T)$ \leftarrow
happensAt($\text{walking}(P_1), T$),
happensAt($\text{walking}(P_2), T$),
holdsAt($\text{close}(P_1, P_2) = \text{true}, T$),
holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T$).

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

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

 $P(\text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 41)) =$
 $P(\text{happensAt}(\text{walking}(mike), 41)) \times$
 $P(\text{holdsAt}(\text{close}(mike, sarah) = \text{false}, 41))$
 $= 0.18 \times 1 = 0.18$

Instantaneous Recognition



initiatedAt($\text{moving}(P_1, P_2) = \text{true}, T) \leftarrow \text{happensAt}(\text{walking}(P_1), T),$

happensAt($\text{walking}(P_2), T)$,

holdsAt($\text{close}(P_1, P_2) = \text{true}, T)$,

holdsAt($\text{orientation}(P_1, P_2) = \text{true}, T)$.

terminatedAt($\text{moving}(P_1, P_2) = \text{true}, T) \leftarrow \text{happensAt}(\text{walking}(P_1), T),$

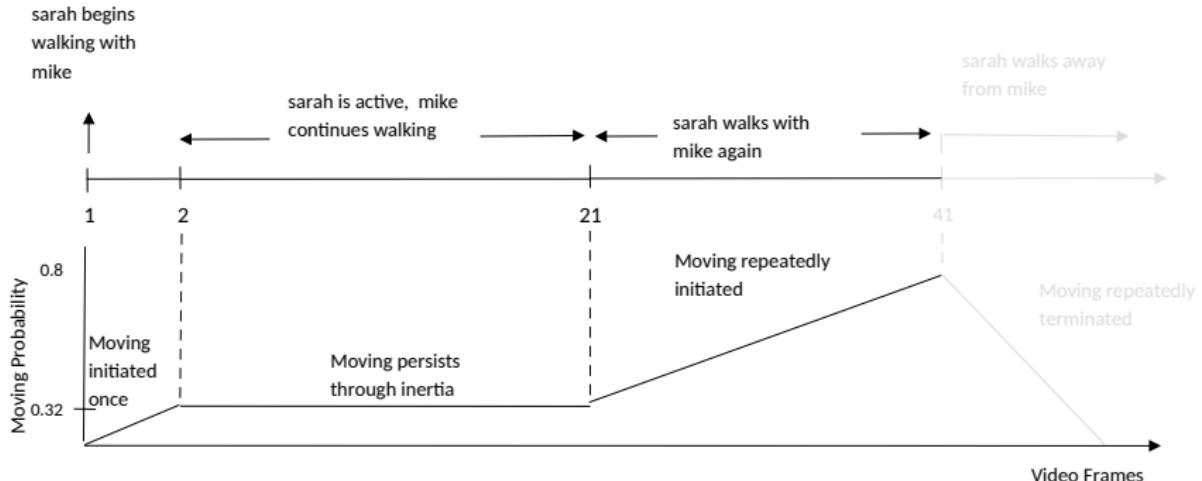
holdsAt($\text{close}(P_1, P_2) = \text{false}, T)$.

$0.18 :: \text{happensAt}(\text{walking}(mike), 41).$

$0.79 :: \text{happensAt}(\text{inactive}(sarah), 41). \dots$

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

Instantaneous Recognition

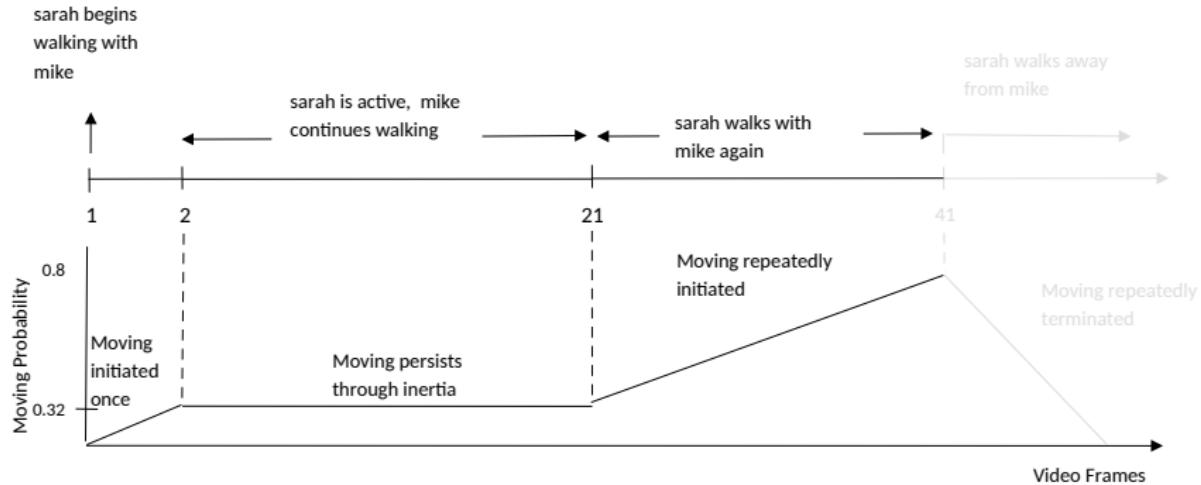


```
initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
happensAt(walking( $P_1$ ),  $T$ ),
happensAt(walking( $P_2$ ),  $T$ ),
holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).
```

```
terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
happensAt(walking( $P_1$ ),  $T$ ),
holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
```

```
1.00 :: happensAt(walking(mike), 49).
0.96 :: happensAt(inactive(sarah), 49).
```

Instantaneous Recognition



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

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

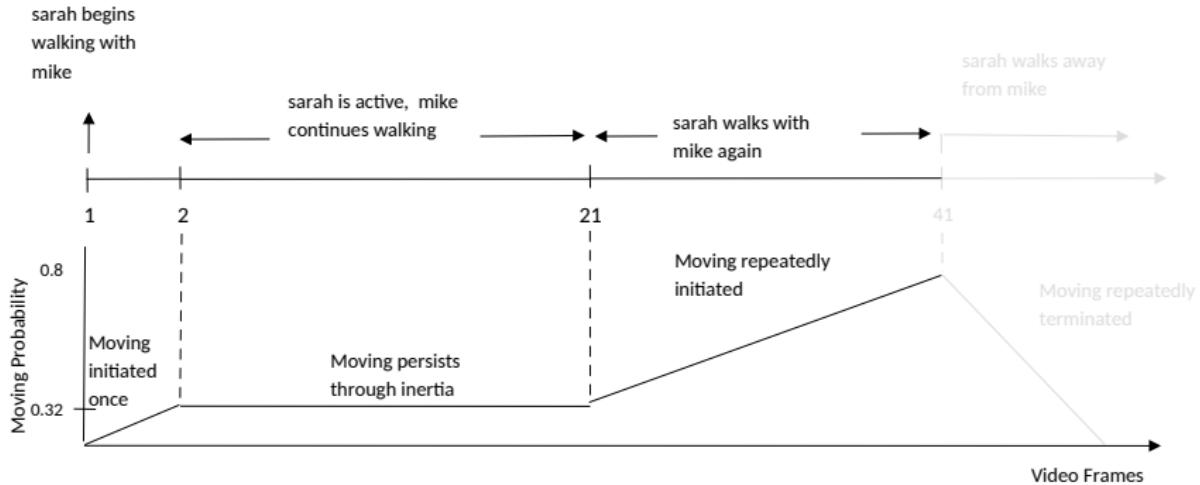
$$P(\text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 49)) =$$

$$P(\text{happensAt}(\text{walking}(mike), 49)) \times$$

$$P(\text{holdsAt}(\text{close}(mike, sarah) = \text{false}, 49))$$

$$= 1 \times 1 = 1$$

Instantaneous Recognition



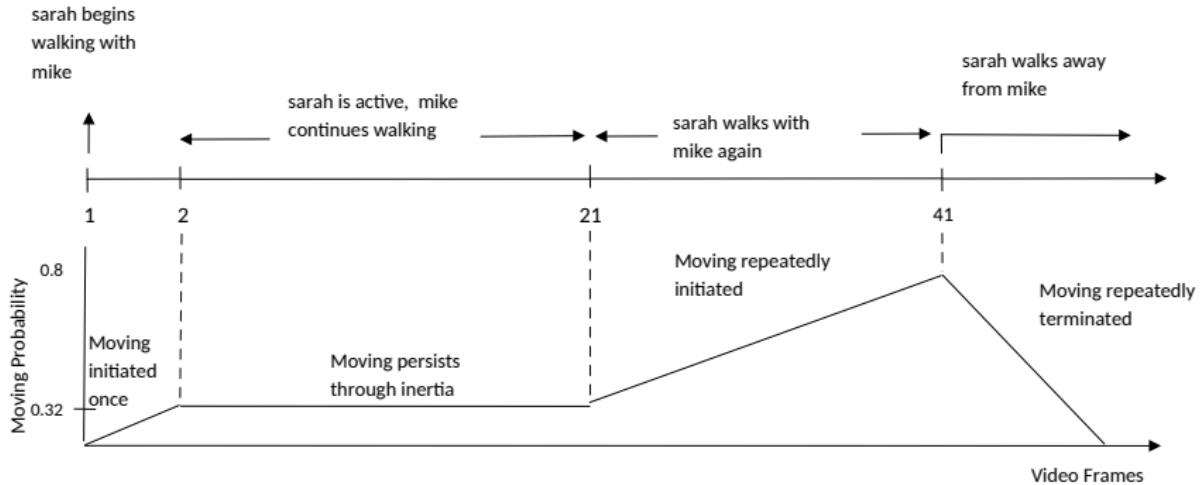
```

initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  happensAt(walking( $P_2$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
  holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).

terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
  
```

$$\begin{aligned}
 & 1.00 :: \text{happensAt}(\text{walking}(mike), 49). \\
 & 0.96 :: \text{happensAt}(\text{inactive}(sarah), 49). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 50)) = & \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 49) \vee & \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 49) \wedge & \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 49))) & \\
 = 0 + 0.07 \times 0 - 0 \times 0.07 \times 0 = 0
 \end{aligned}$$

Instantaneous Recognition



```

initiatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  happensAt(walking( $P_2$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = true,  $T$ ),
  holdsAt(orientation( $P_1, P_2$ ) = true,  $T$ ).

terminatedAt(moving( $P_1, P_2$ ) = true,  $T$ ) ←
  happensAt(walking( $P_1$ ),  $T$ ),
  holdsAt(close( $P_1, P_2$ ) = false,  $T$ ).
  
```

$$\begin{aligned}
 1.00 &:: \text{happensAt}(\text{walking}(mike), 49). \\
 0.96 &:: \text{happensAt}(\text{inactive}(sarah), 49). \\
 P(\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 50)) &= \\
 P(\text{initiatedAt}(\text{moving}(mike, sarah) = \text{true}, 49) \vee \\
 (\text{holdsAt}(\text{moving}(mike, sarah) = \text{true}, 49) \wedge \\
 \neg \text{terminatedAt}(\text{moving}(mike, sarah) = \text{true}, 49))) \\
 &= 0 + 0.07 \times 0 - 0 \times 0.07 \times 0 = 0
 \end{aligned}$$

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
ln	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

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

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
l_n	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
ln	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
ln	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
ln	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
ln	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
ln	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
ln	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
ln	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
l_n	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

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

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

Interval-based Recognition

Time	1	2	3	4	5	6	7	8	9	10
ln	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

$$\begin{aligned}dprange[s, e] &= dp[e] - prefix[s-1] \text{ if } s > 1 \\&= dp[e] \text{ if } s = 1\end{aligned}$$

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

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
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
l_n	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	↑	↓	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	↑	↓	3	4	5	6	7	8	9	10
l_n	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

Time	1	2	3	4	5	6	7	8	9	10
l_n	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

Time	↑ 1	2	3	↓ 4	5	6	7	8	9	10
ln	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
l_n	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
l_n	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
ln	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

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

Interval-based Recognition

Time										
	1	2	3	4	5	6	7	8	9	10
<i>In</i>	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
<i>L</i>	-0.5	0	0.2	0.4	-0.1	-0.4	-0.5	-0.5	0	0.5
<i>prefix</i>	-0.5	-0.5	-0.3	0.1	0	-0.4	-0.9	-1.4	-1.4	-0.9
<i>dp</i>	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
ln	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 Recognition¹

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 Recognition¹

Interval Computation Correctness

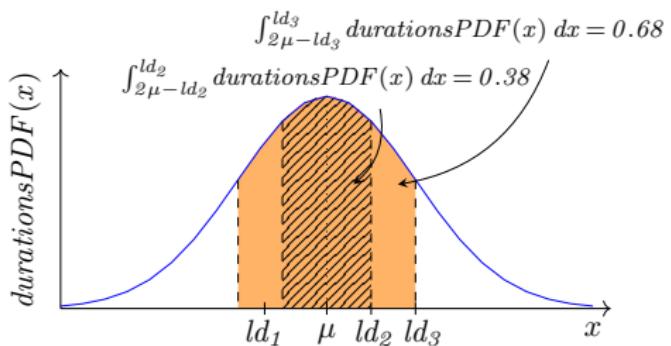
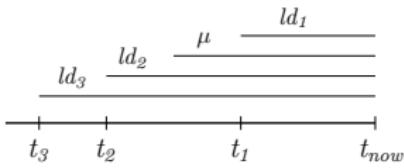
An interval is computed iff it is a probabilistic maximal interval.

Complexity

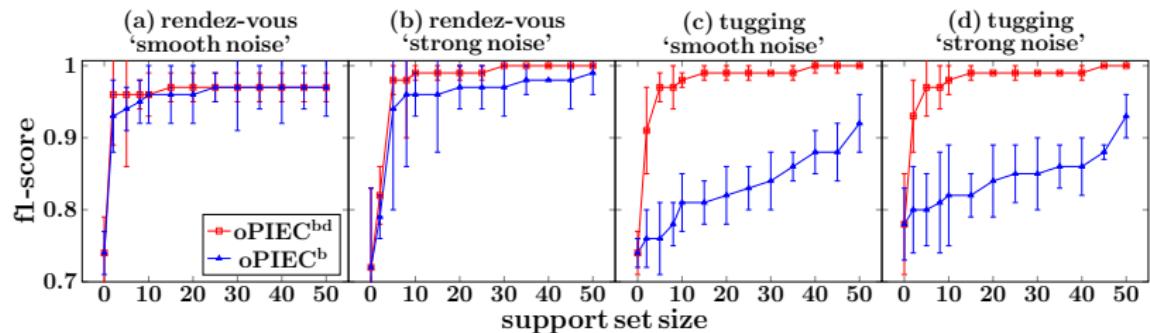
The computation of probabilistic maximal intervals is linear to the dataset size.

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

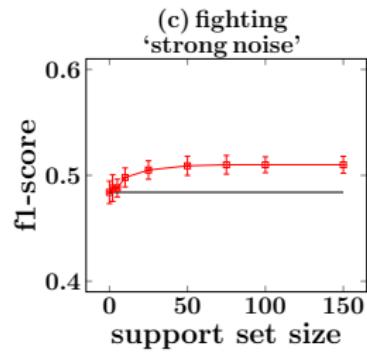
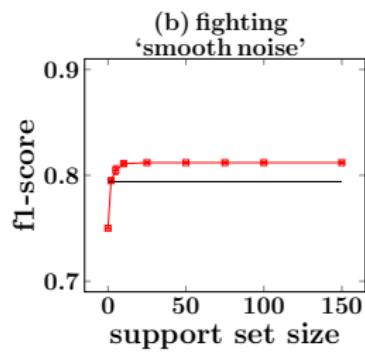
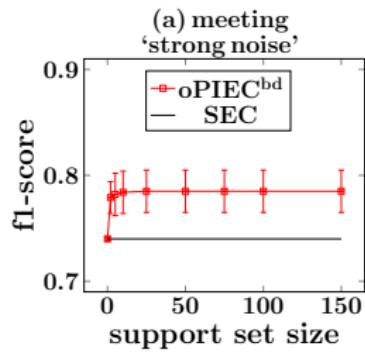
(a) Total run-times of oPIEC^{bd} , oPIEC^{b} and PIEC in seconds when processing data streams of increasing size.

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

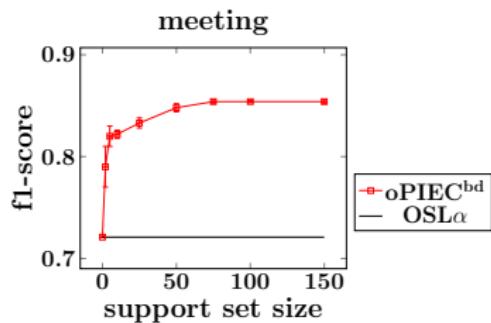
(b) Total run-times of oPIEC^{bd} and oPIEC^{b} in seconds as the support set size increases.

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

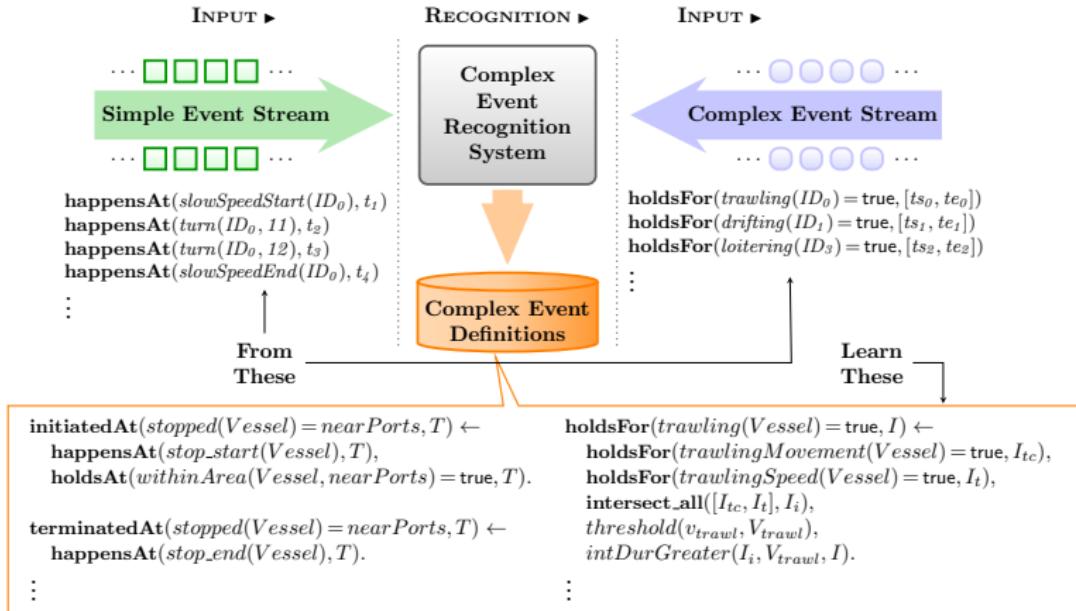
oPIEC: Experimental Results



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Machine Learning for Complex Event Recognition



Katzouris et al, Online Learning Probabilistic Event Calculus Theories in Answer Set Programming. Theory and Practice of Logic Programming, 2023.

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Neuro-Symbolic Complex Event Recognition

