Probabilistic Interval-based Event Recognition

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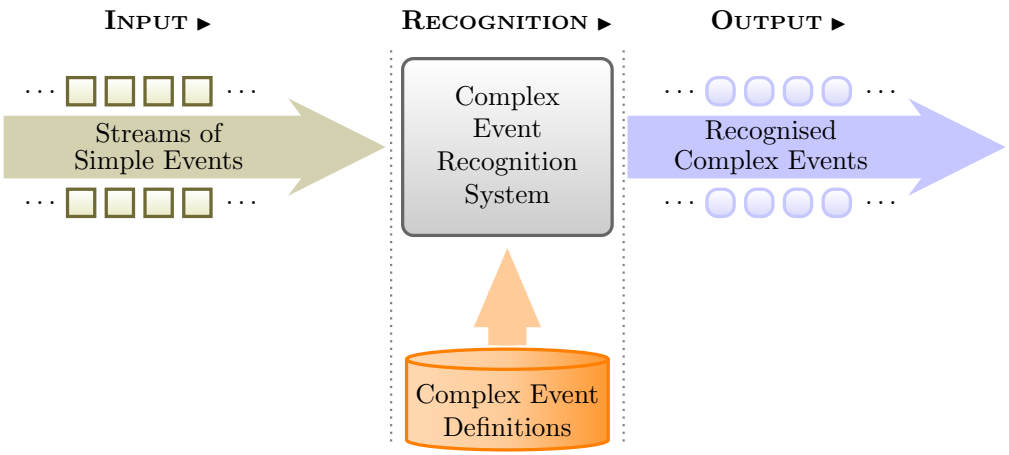
Complex Event Recognition (Event Pattern Matching)[*,†,‡]



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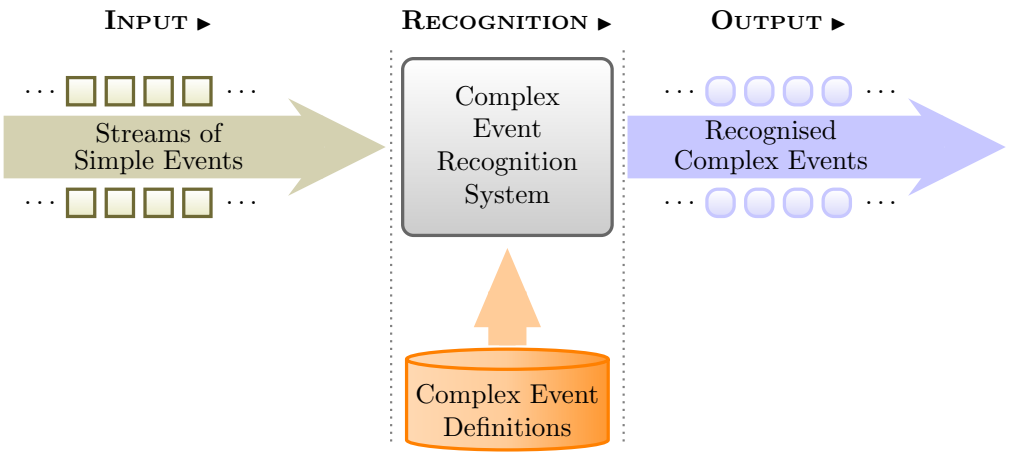

https://cer.iit.demokritos.gr (activity recognition)

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Event Calculus*

- A logic programming language for representing and reasoning about events and their effects.
- Key components:
  - event (typically instantaneous).
  - fluent: a property that may have different values at different points in time.

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

Event Calculus*

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

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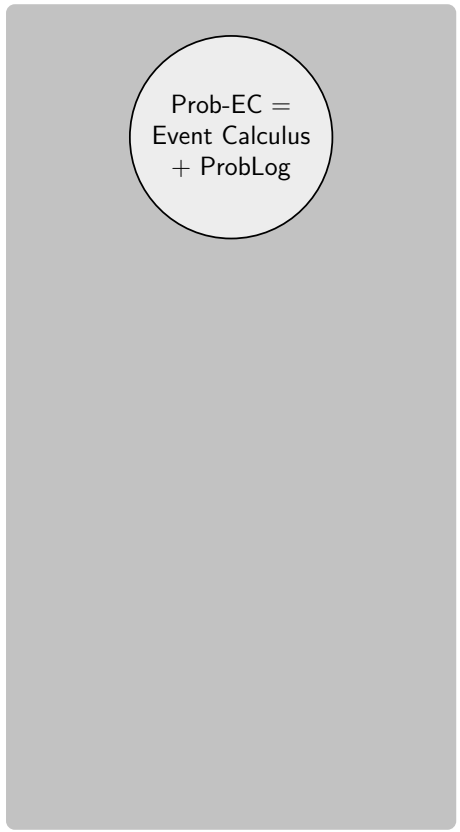
Event Calculus + ProbLog



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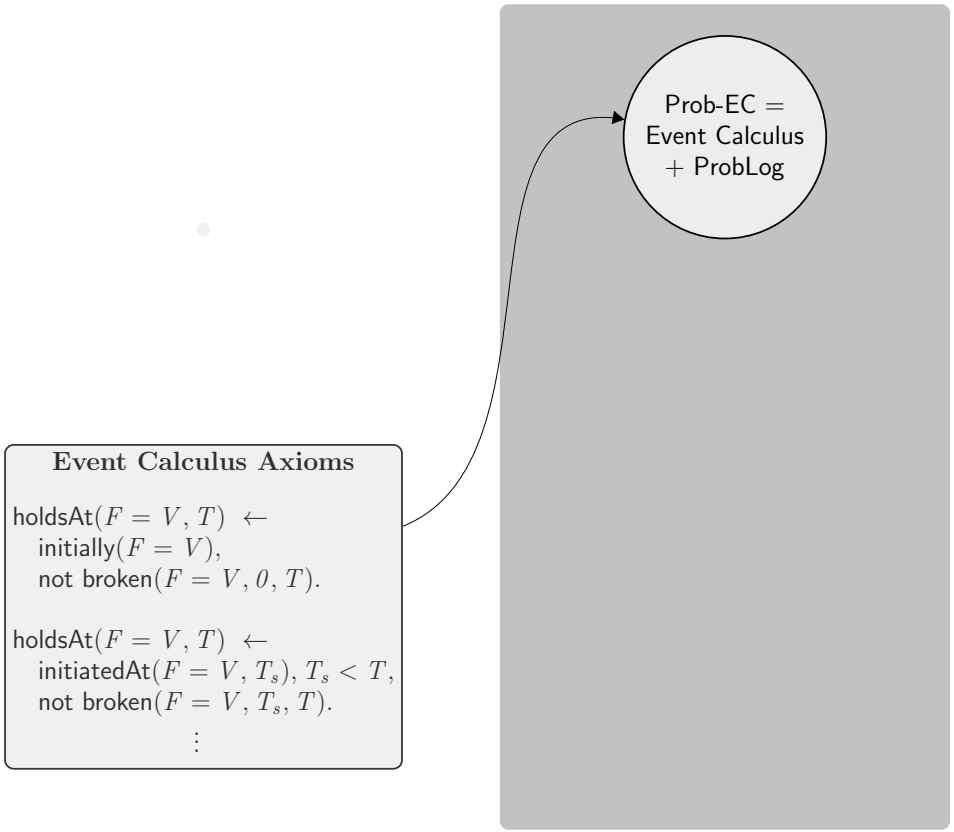

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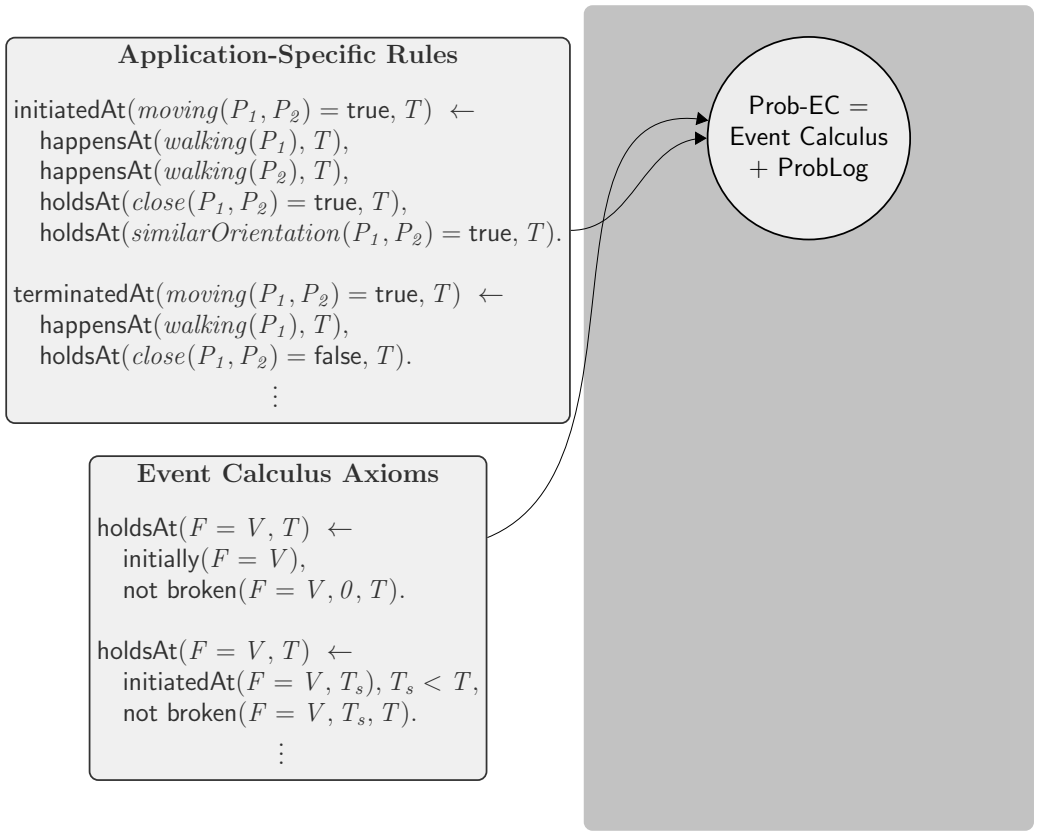

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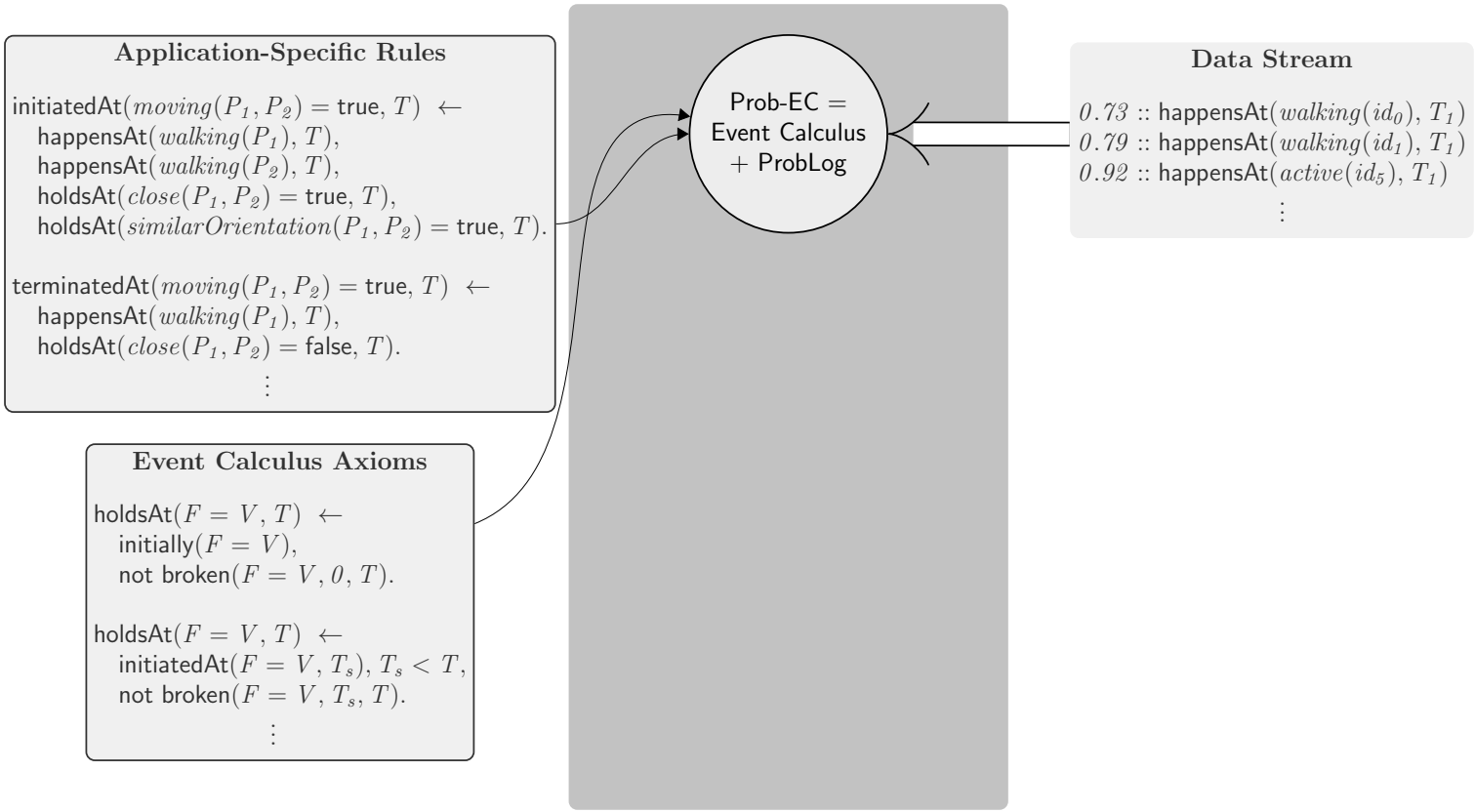

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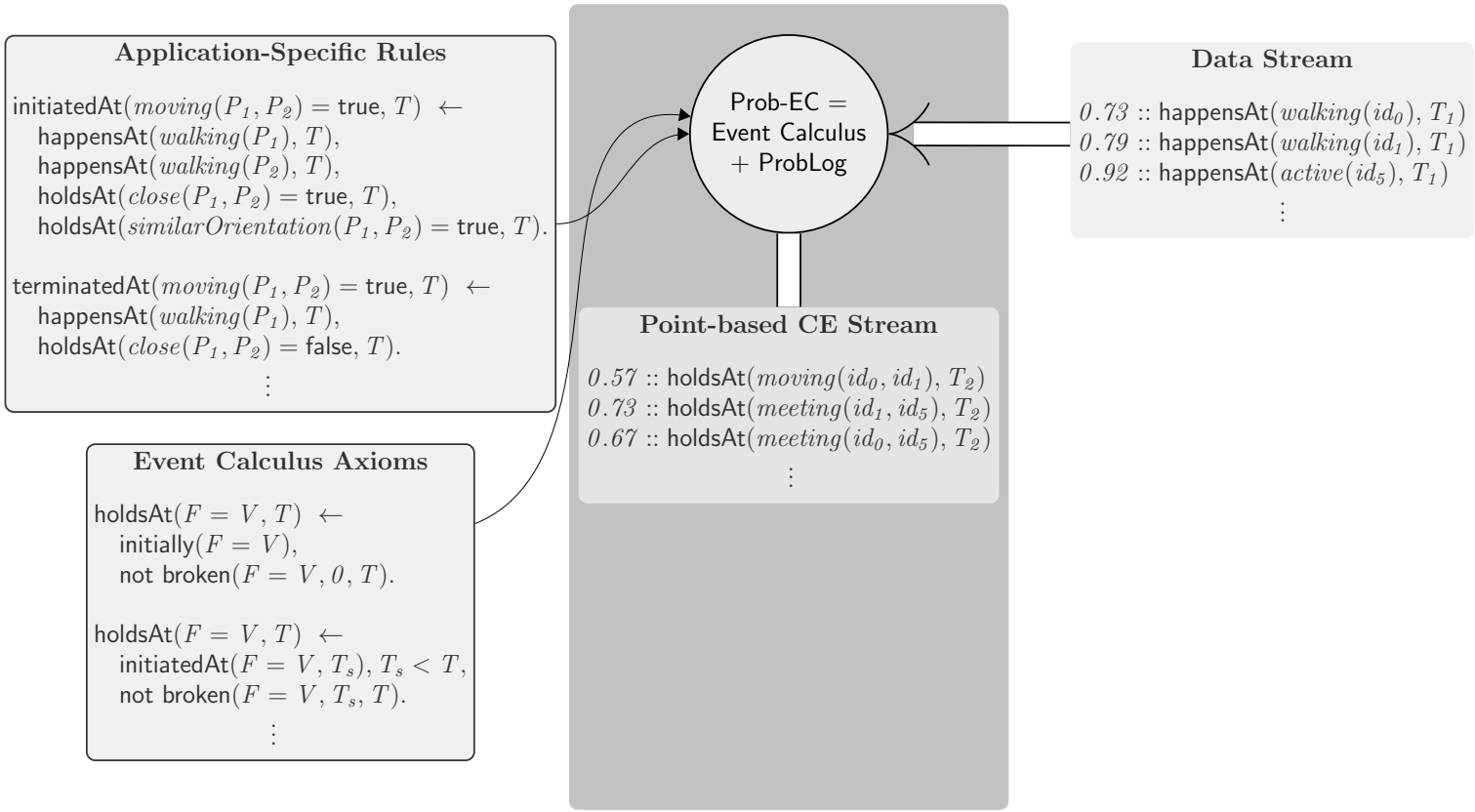
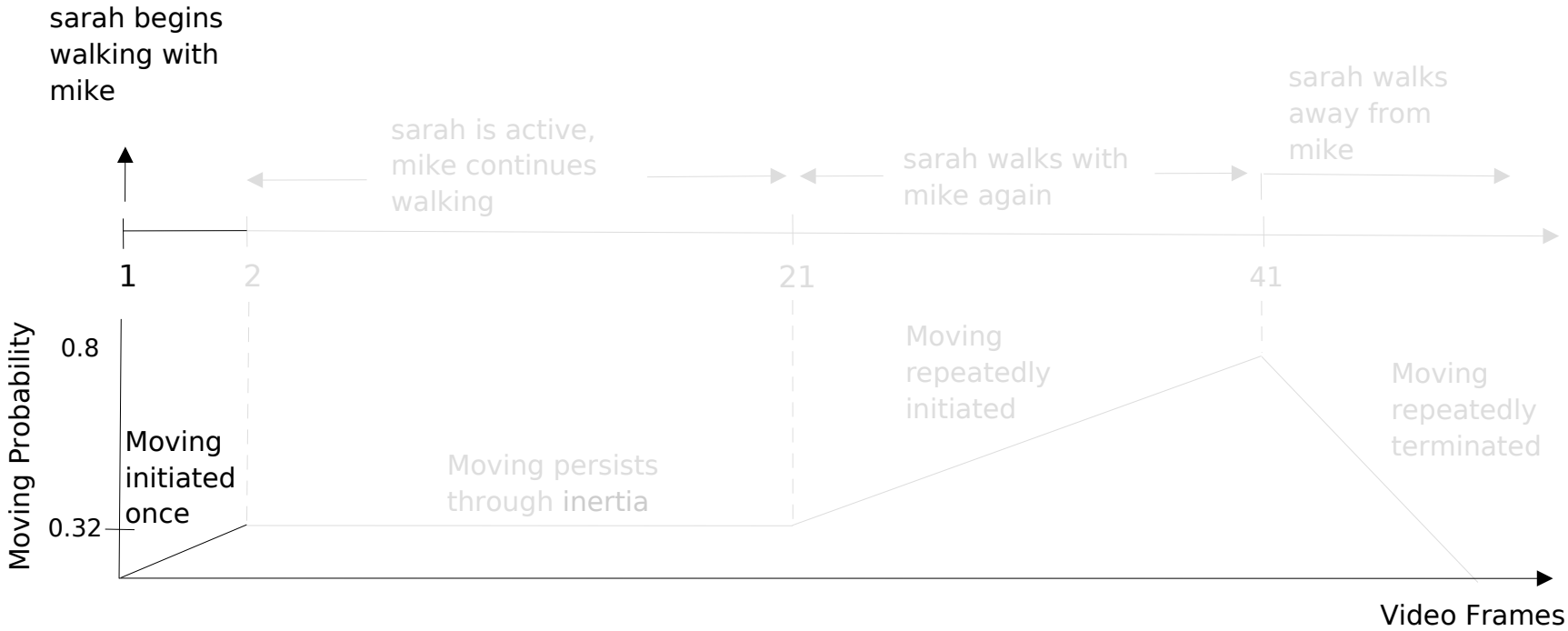


Instantaneous Probabilistic Recognition



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

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$$0.70 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 1).$$
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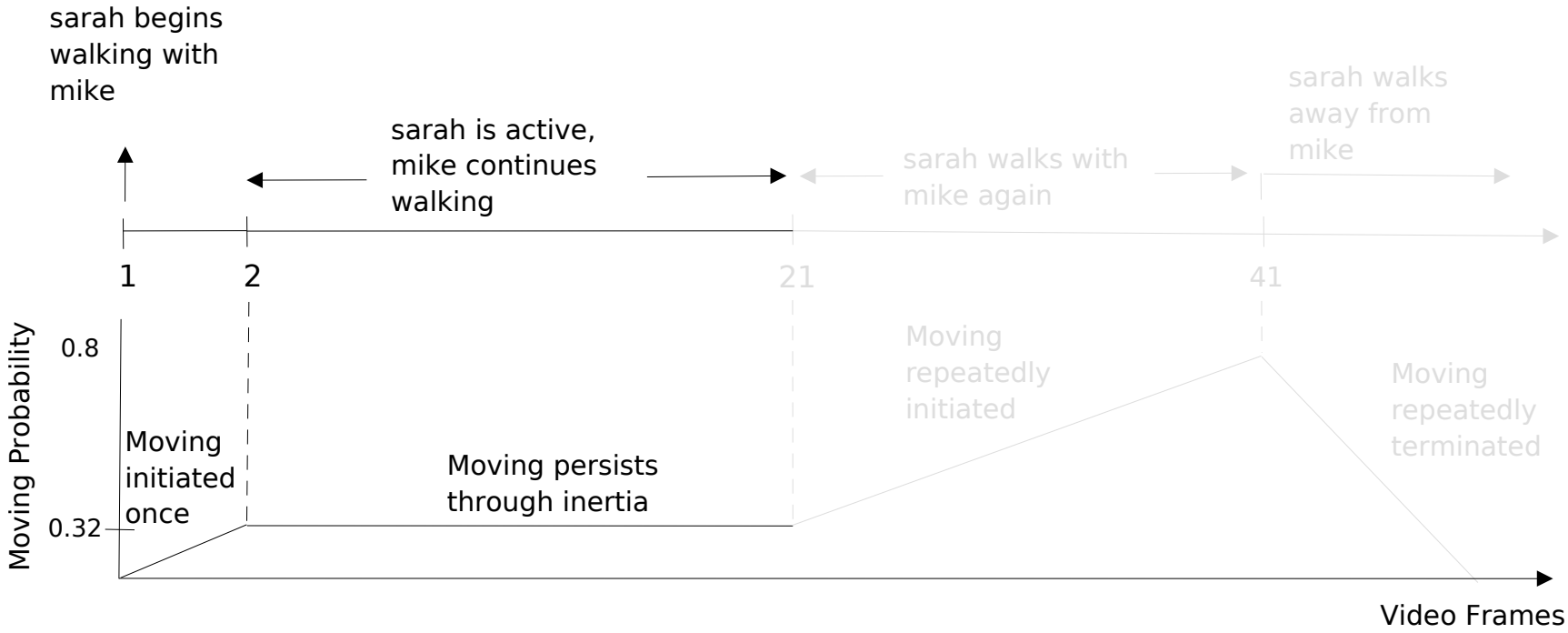
Instantaneous Probabilistic Recognition



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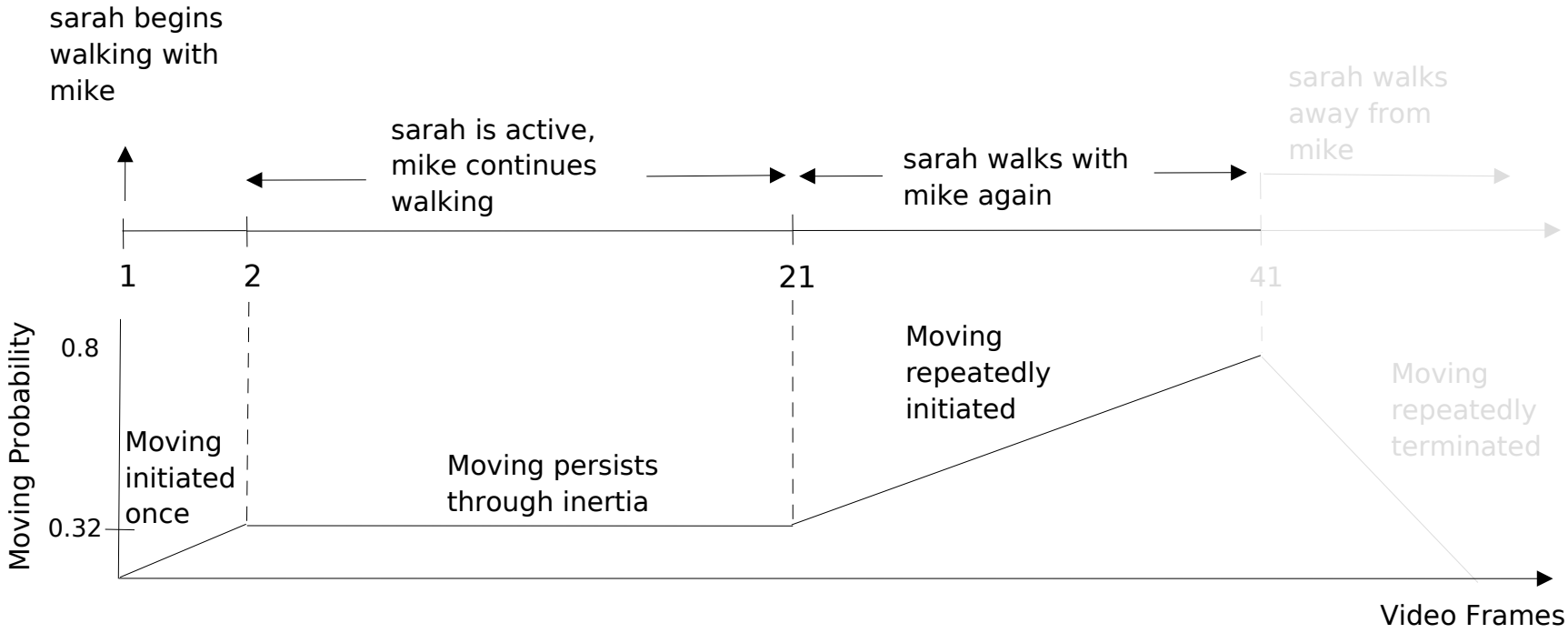

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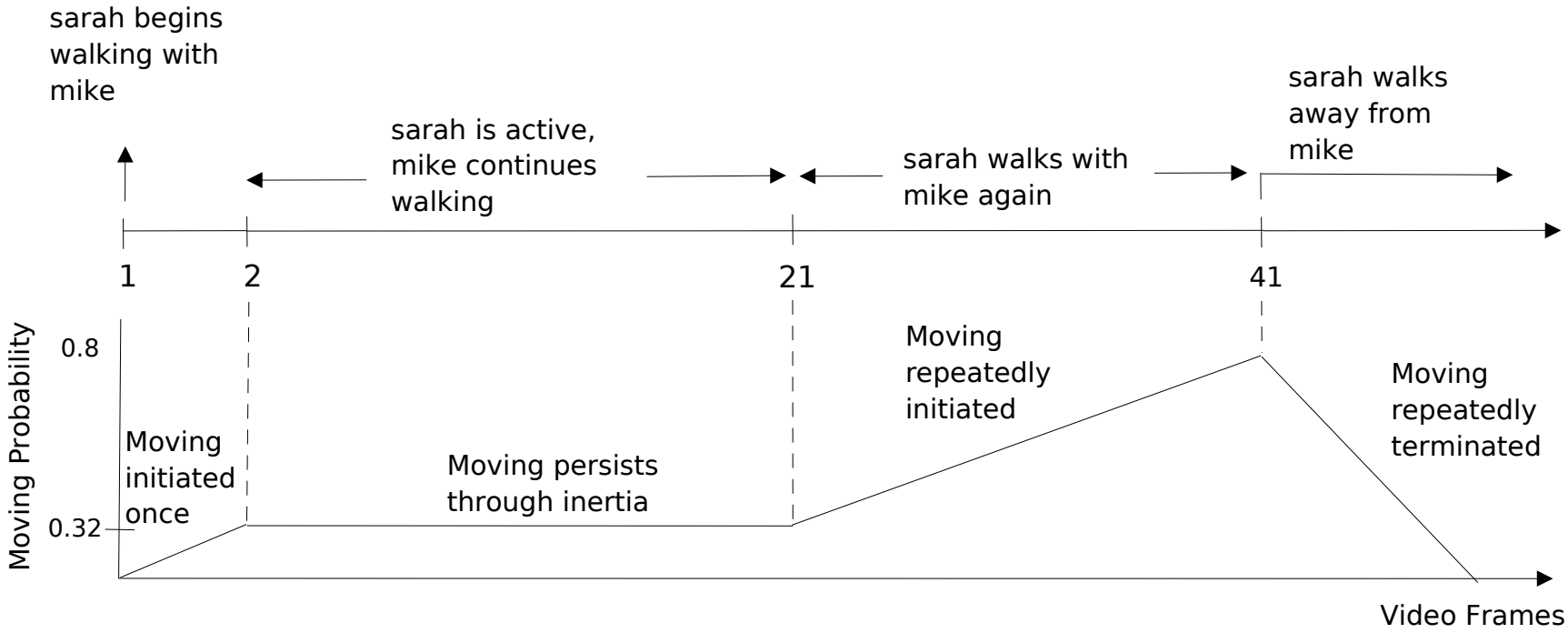

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$$0.82 :: \textbf{happensAt}(inactive(mike),\ 41).$$
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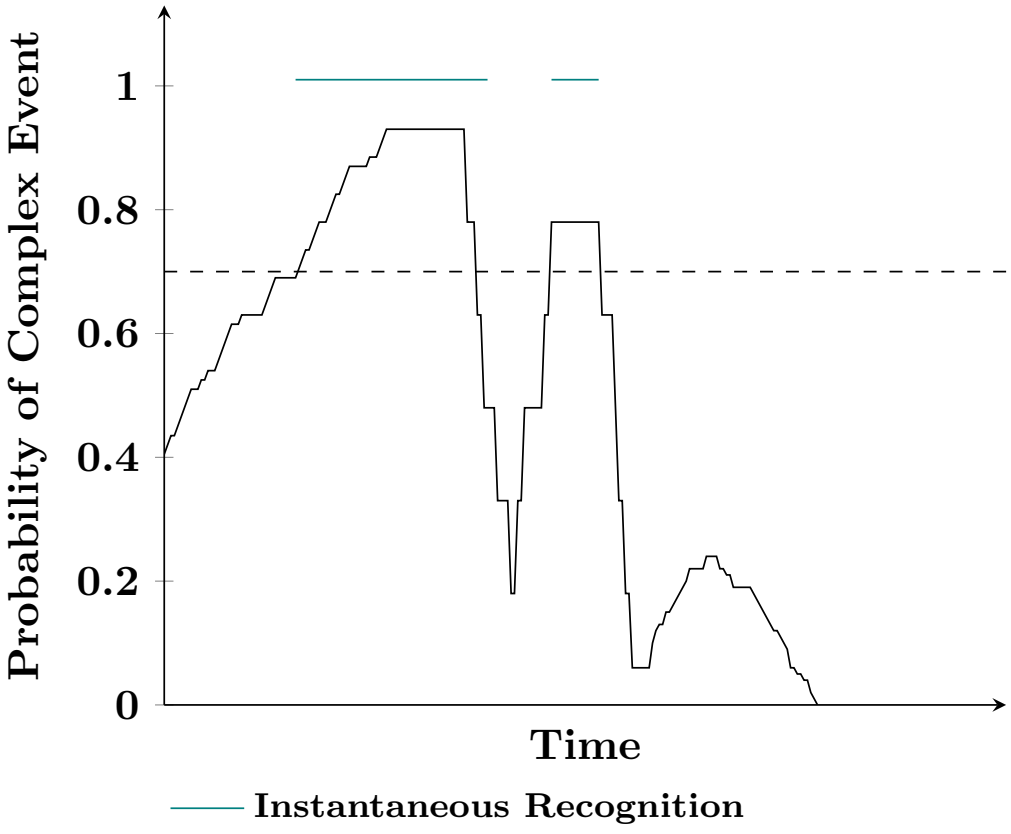
Instantaneous Recognition*



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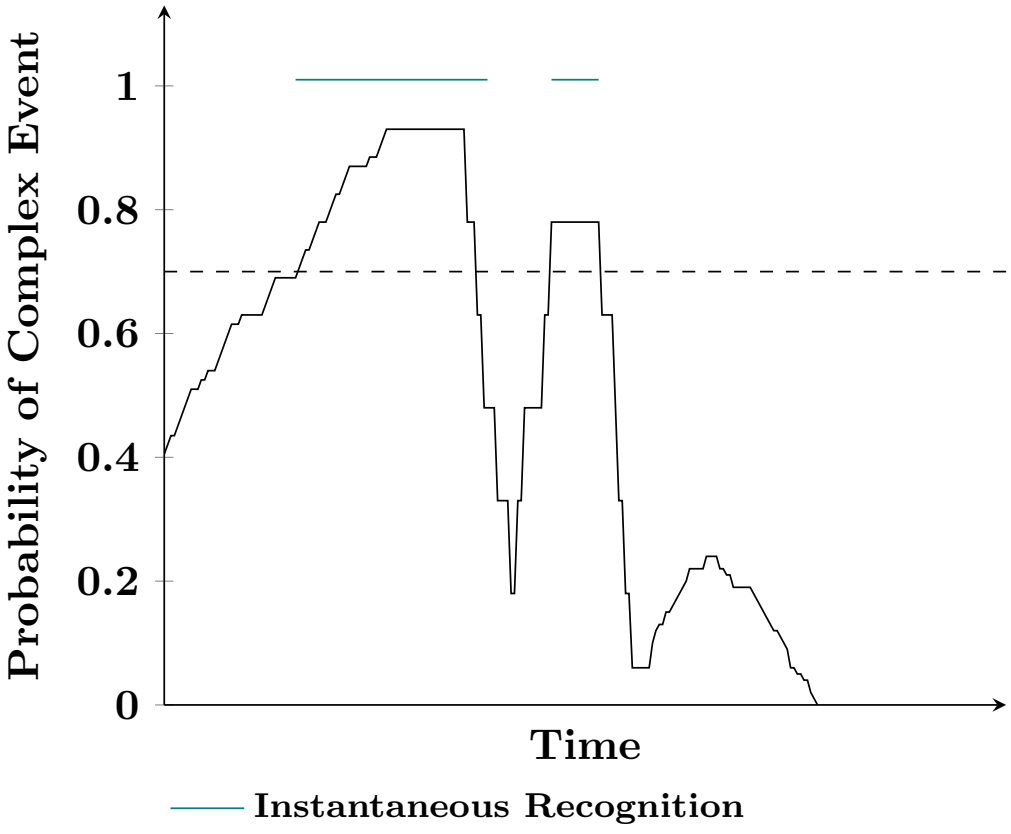

Higher accuracy than crisp reasoning in the presence of:

- several initiations and terminations;
- few probabilistic conjuncts.

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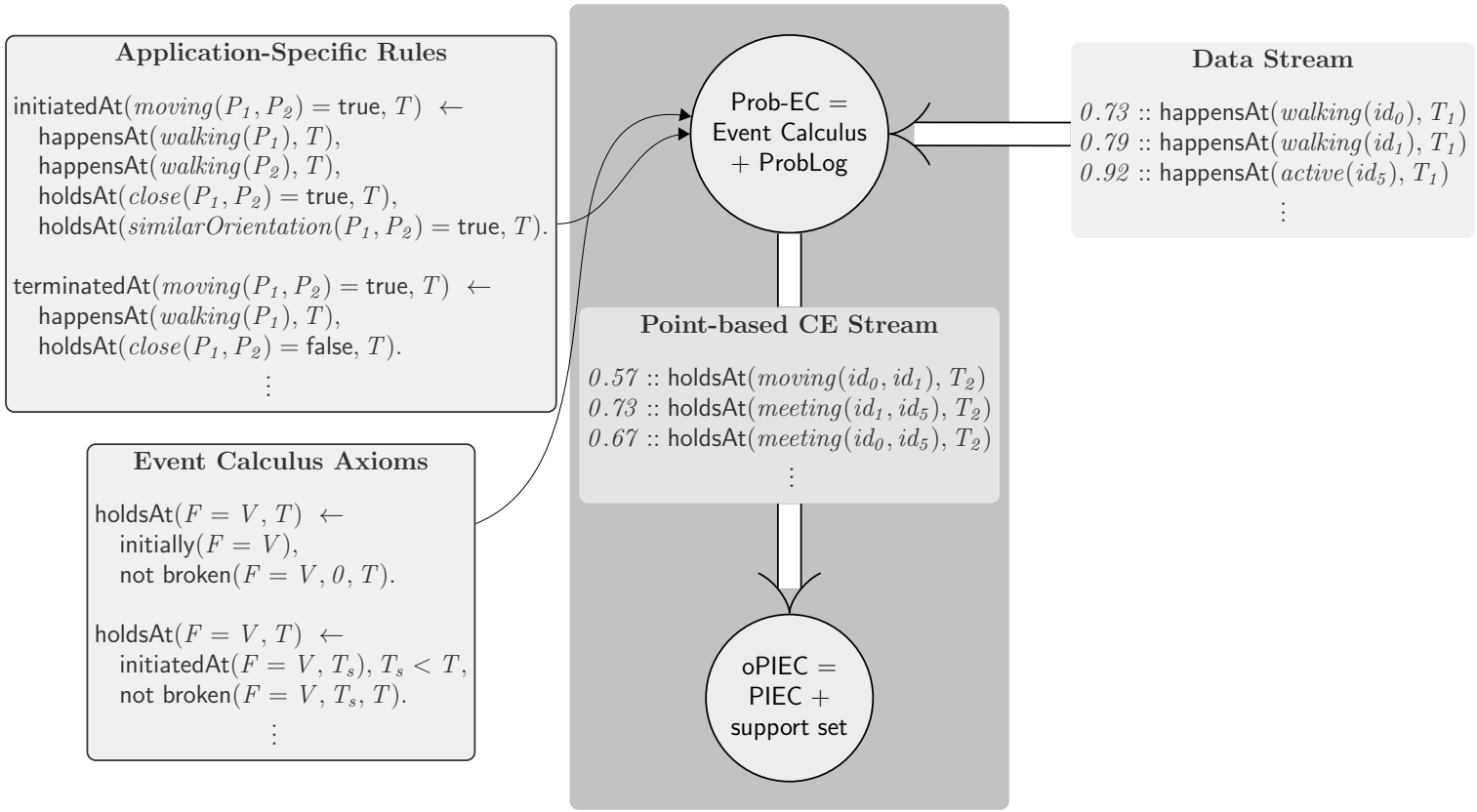
Online Probabilistic Interval-Based Event Calculus



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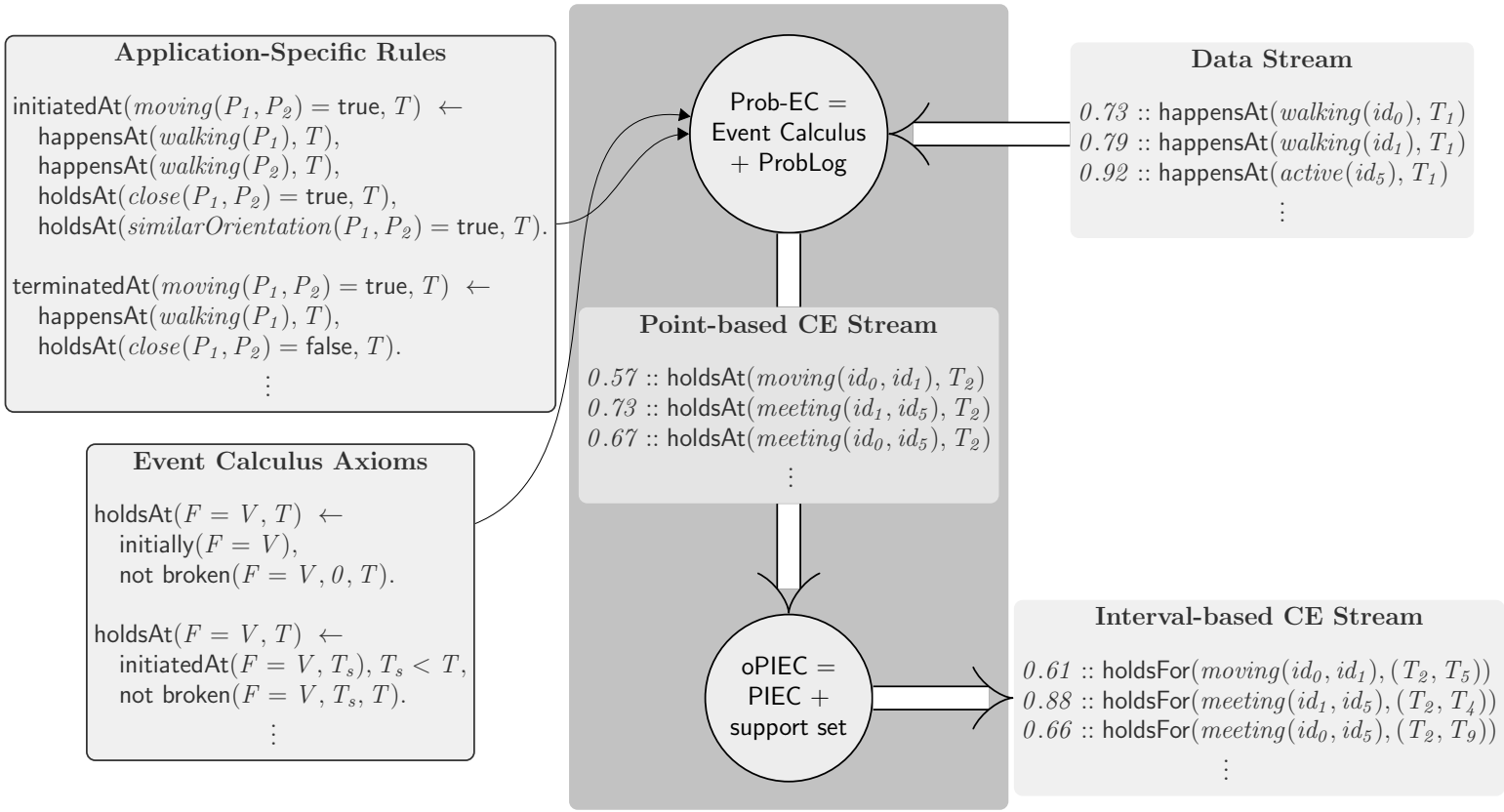
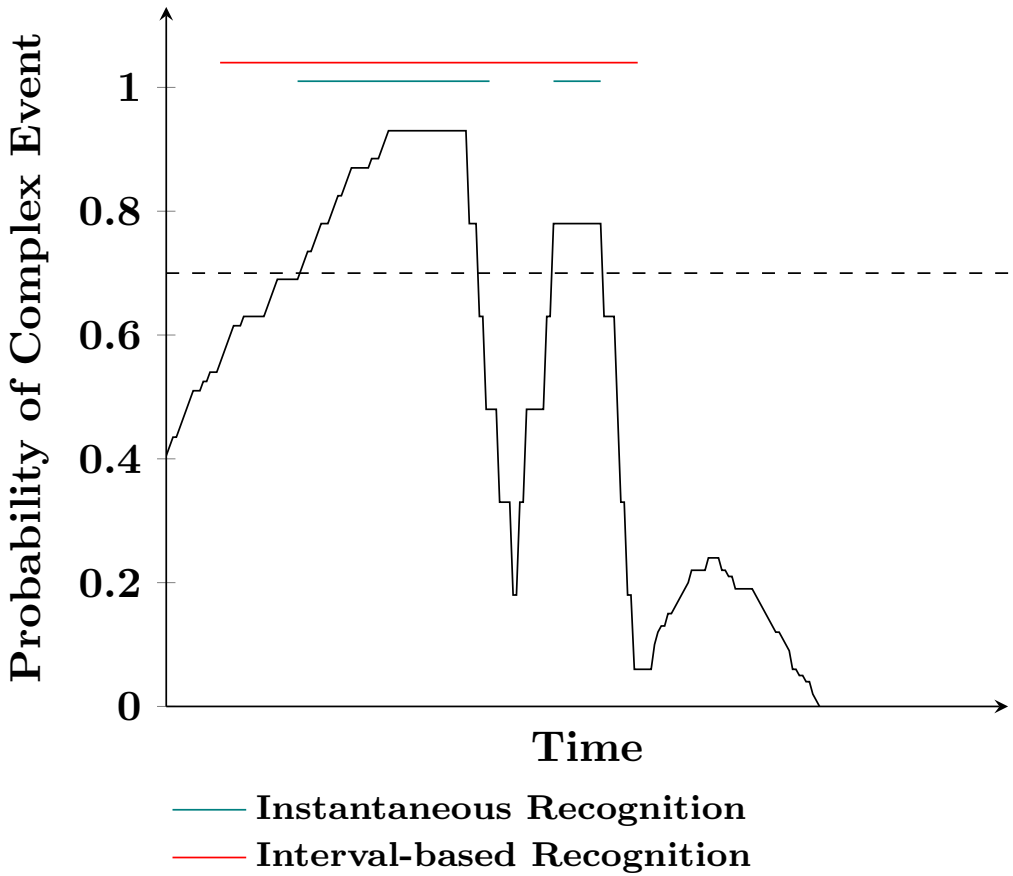


Instantaneous vs Interval-based Recognition



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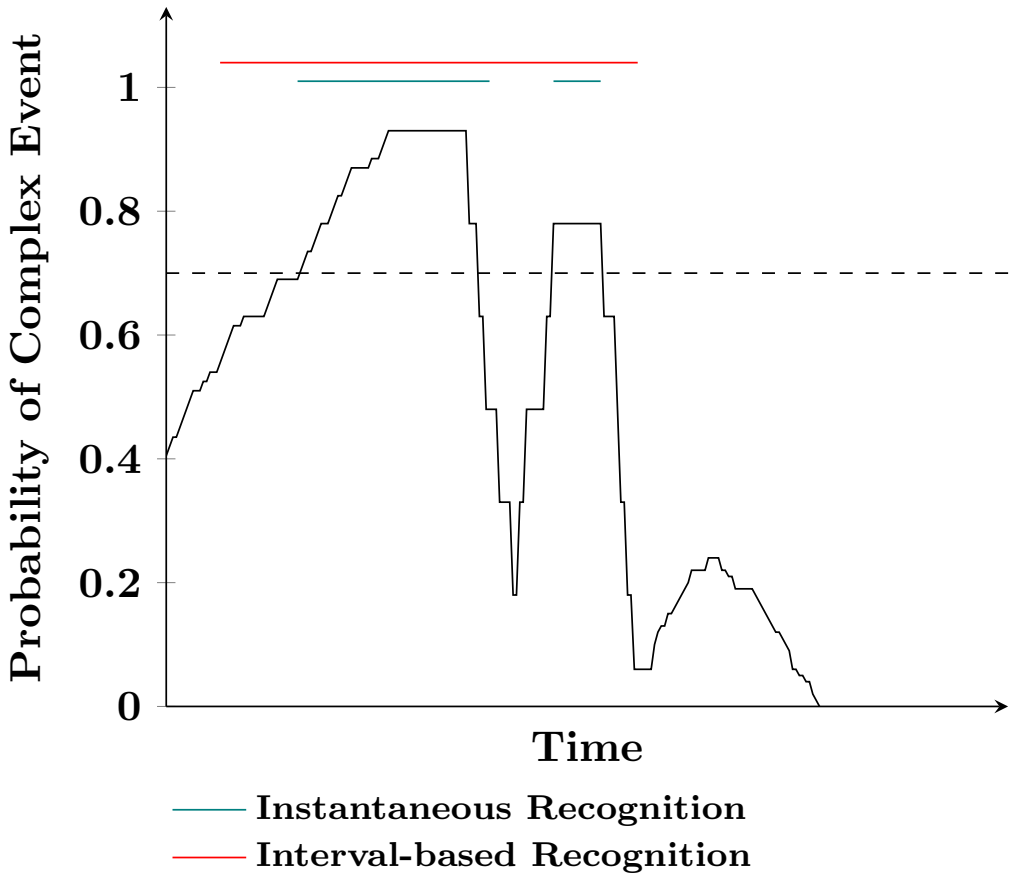
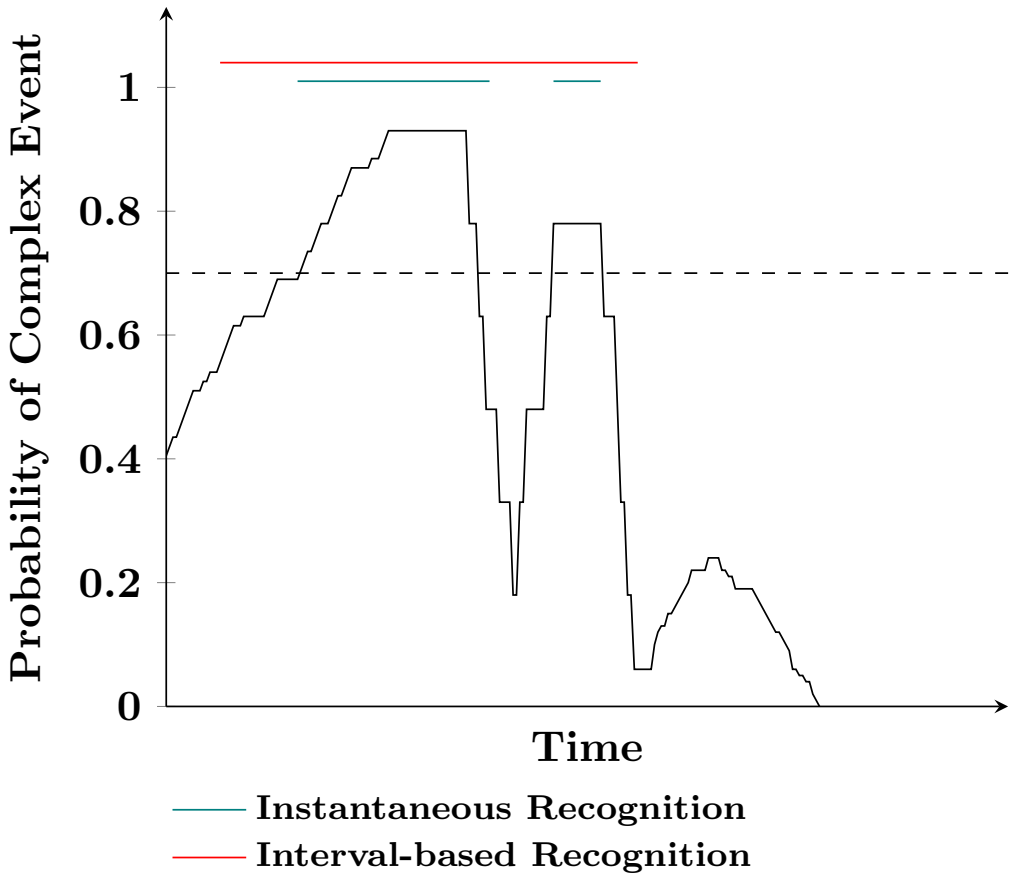


- Interval Probability: average probability of the time-points it contains.

Instantaneous vs Interval-based Recognition



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  - interval probability above a given threshold;
  - no super-interval with probability above the threshold.

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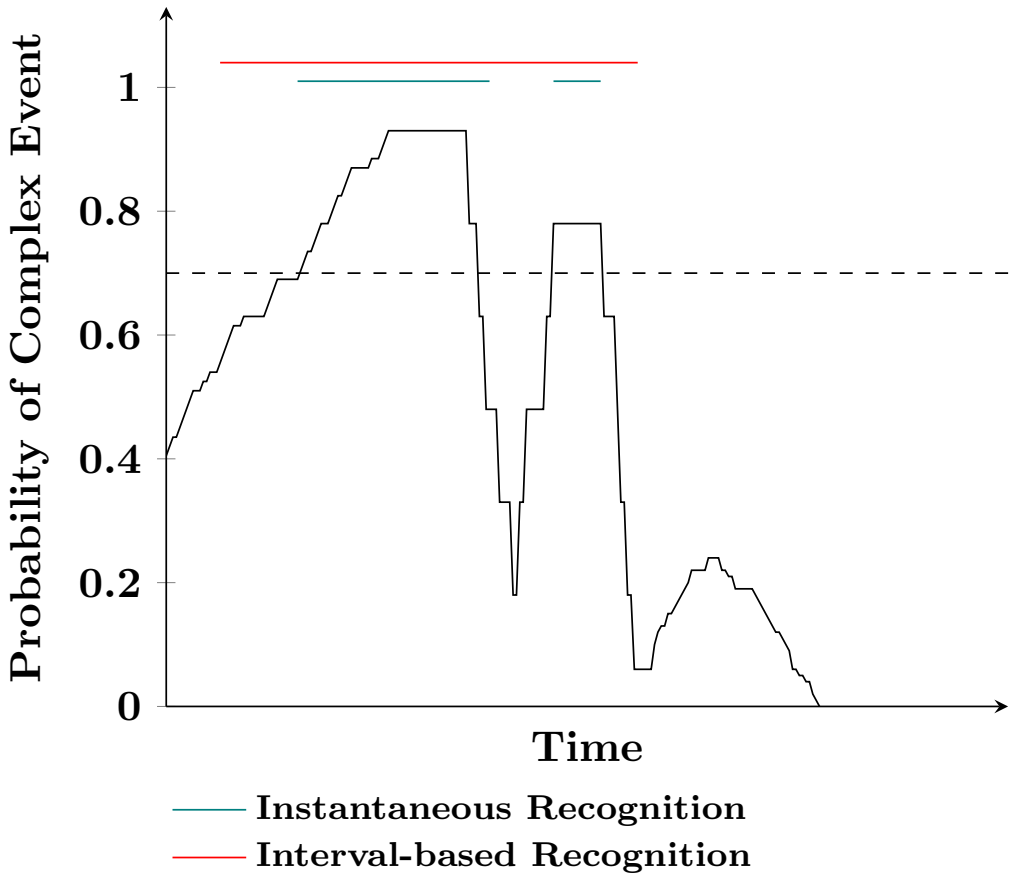

- Interval Probability: average probability of the time-points it contains.
- Probabilistic Maximal Interval:
  - interval probability above a given threshold;
  - no super-interval with probability above the threshold.
- Probabilistic maximal interval computation via maximal non-negative sum interval computation.

Interval-based Recognition*

Interval Computation Correctness

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

*Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Annals of Mathematics and Artificial Intelligence, 2020.

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Complexity

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

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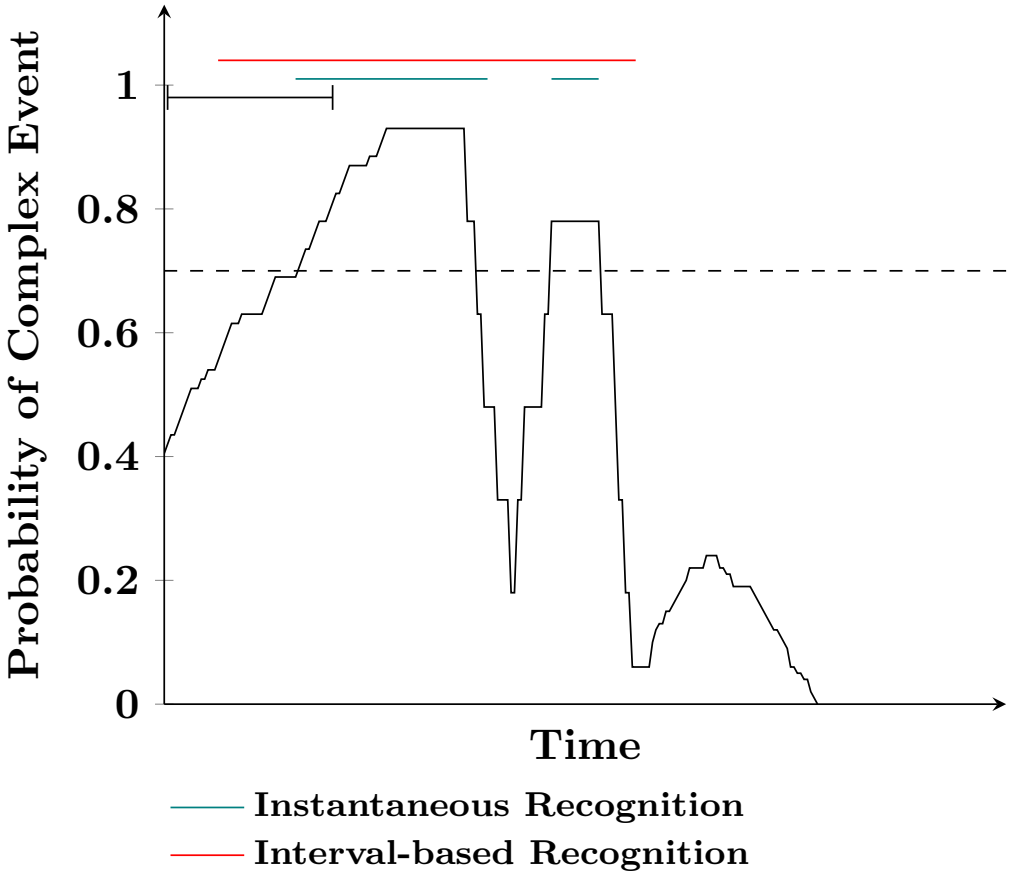
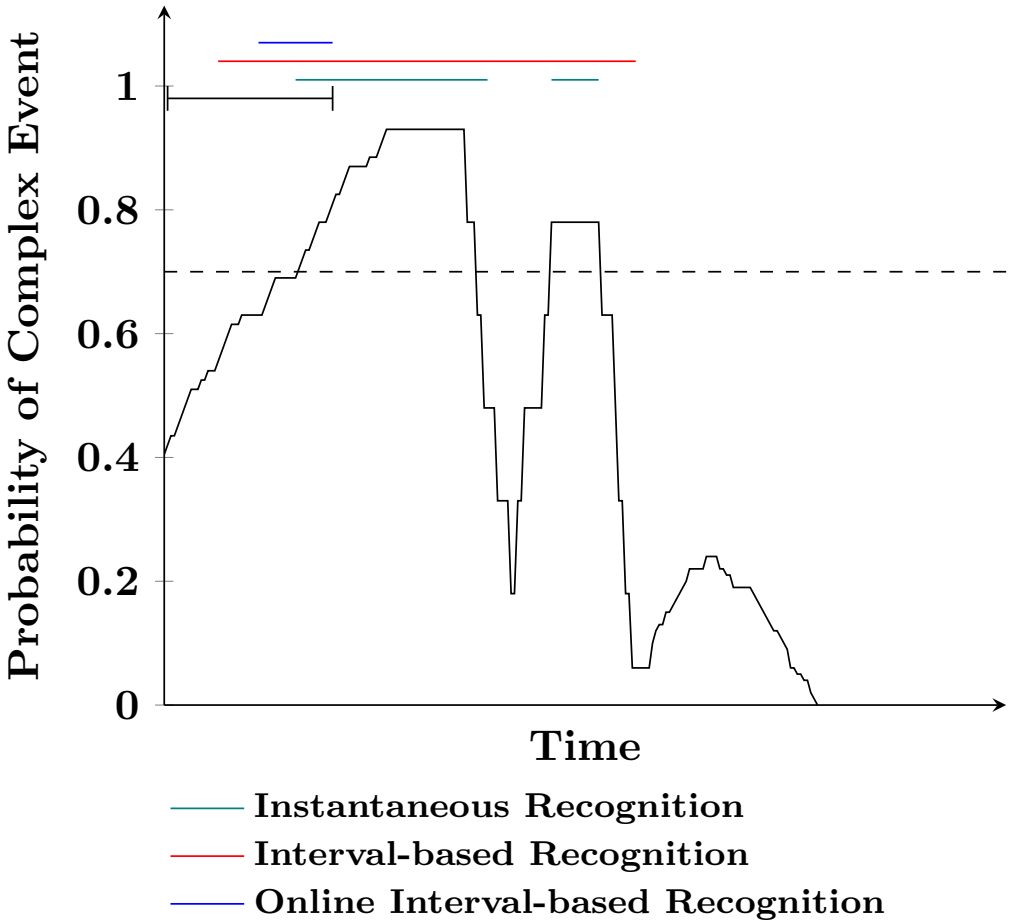
Online Interval-based Recognition



- Windowing.

Online Interval-based Recognition



- Windowing.
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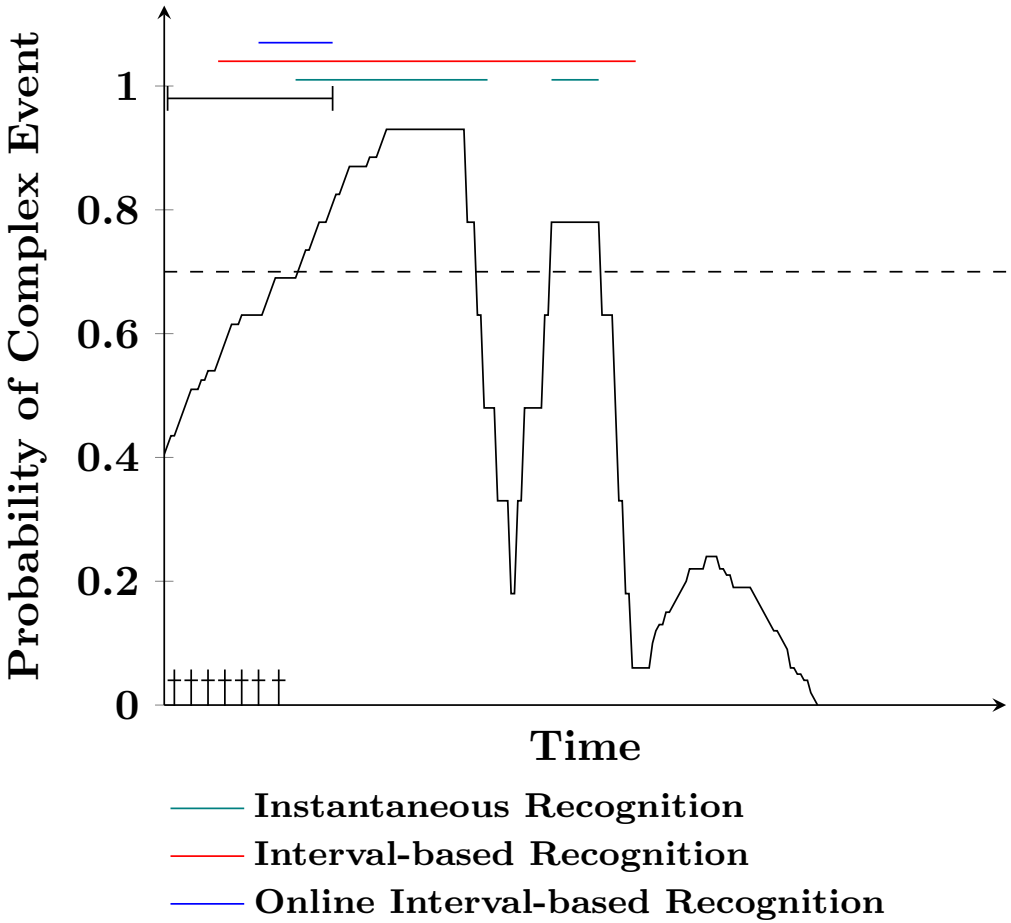
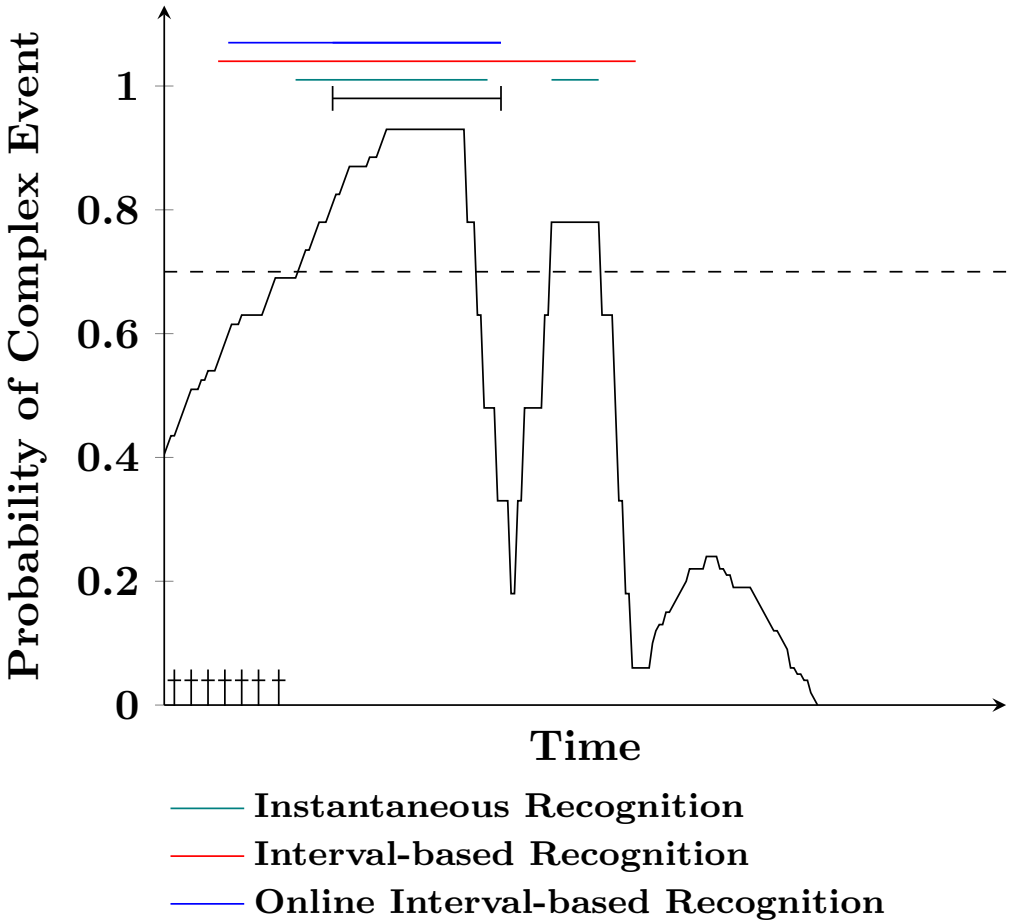


- Windowing.
- Probabilistic maximal interval computation.
- Caching potential starting points.
  - Caches time-point t iff the probability of an interval starting at t cannot be increased by extending it to the left.

Online Interval-based Recognition



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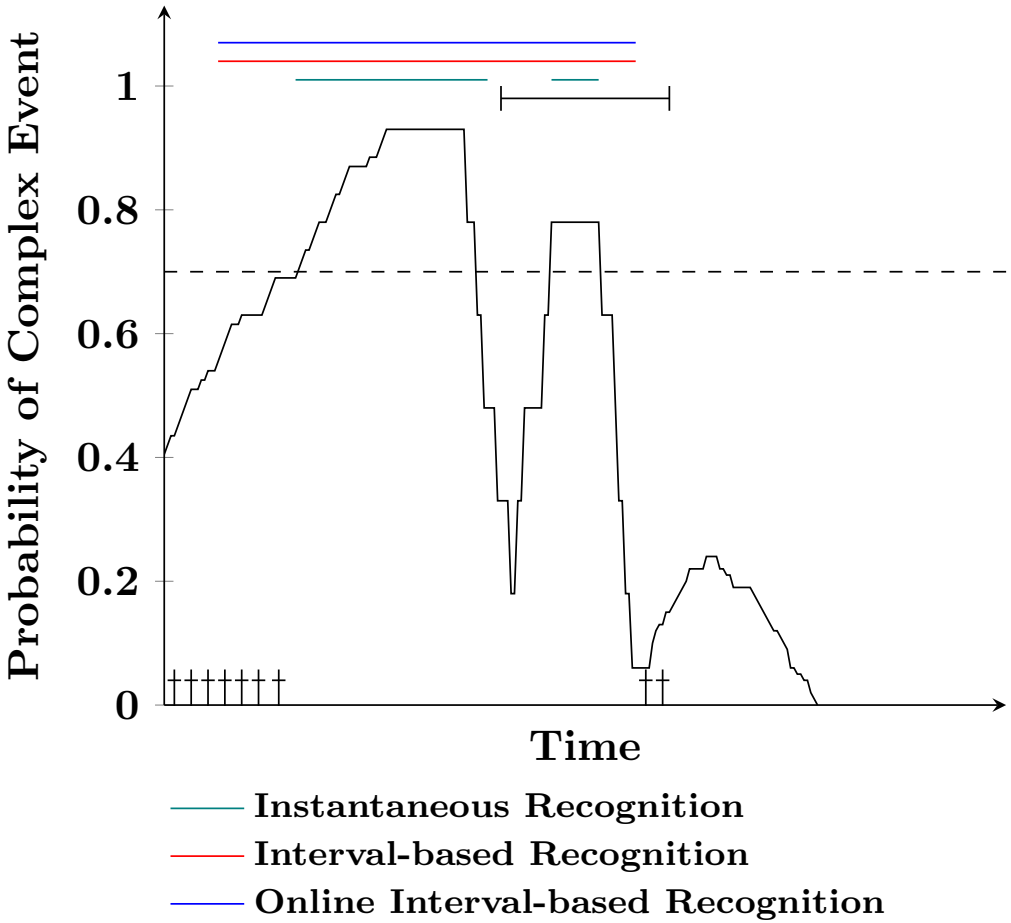

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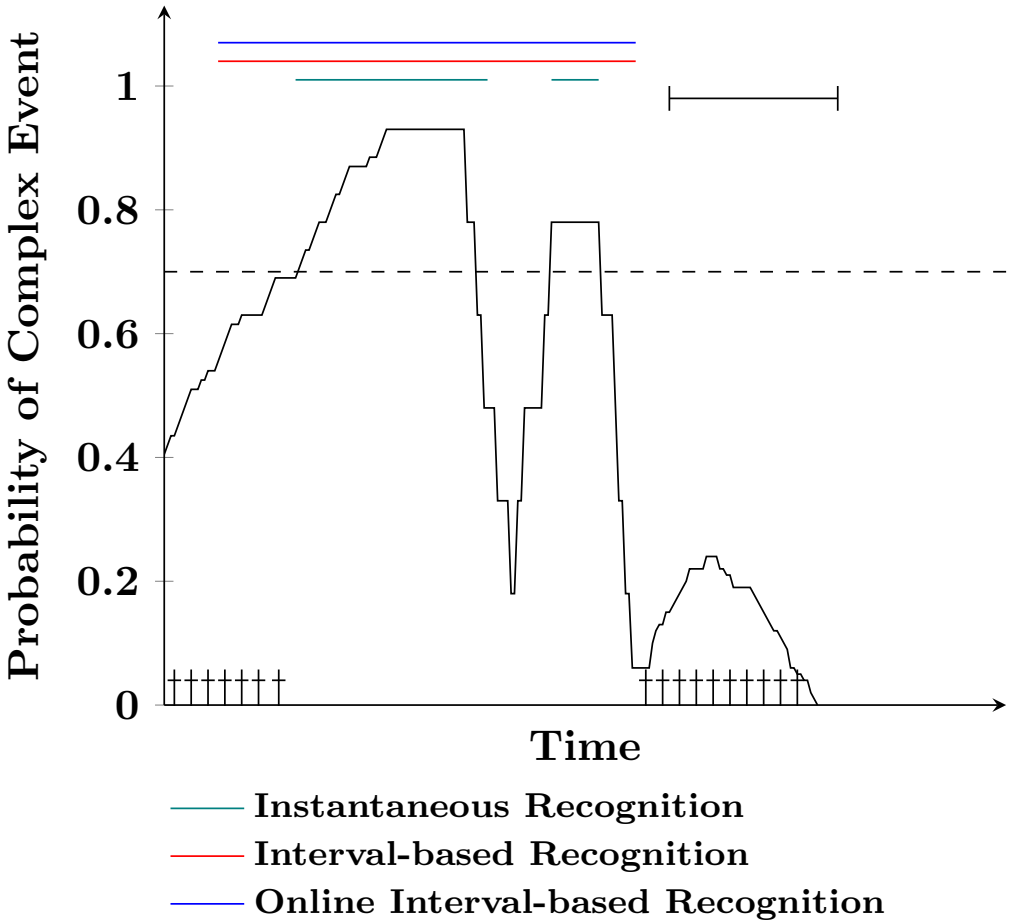

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Online Interval-based Recognition: Properties

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Interval Computation Correctness

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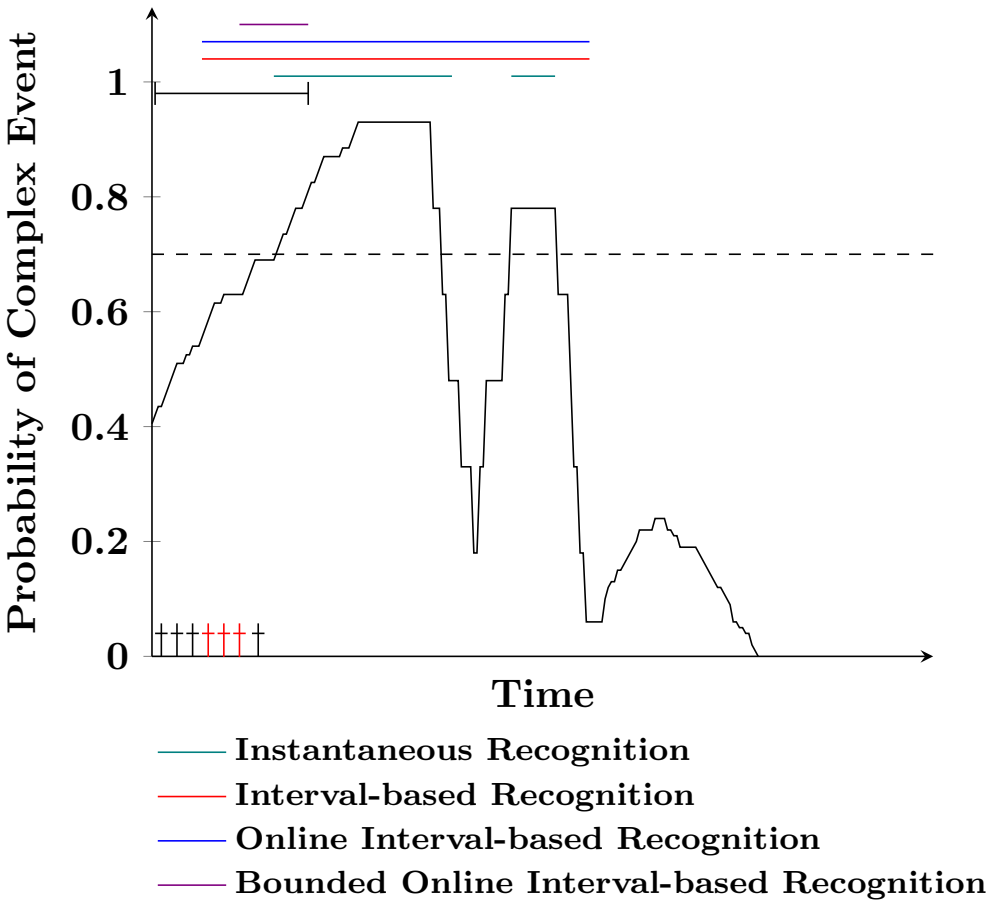
Complexity

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

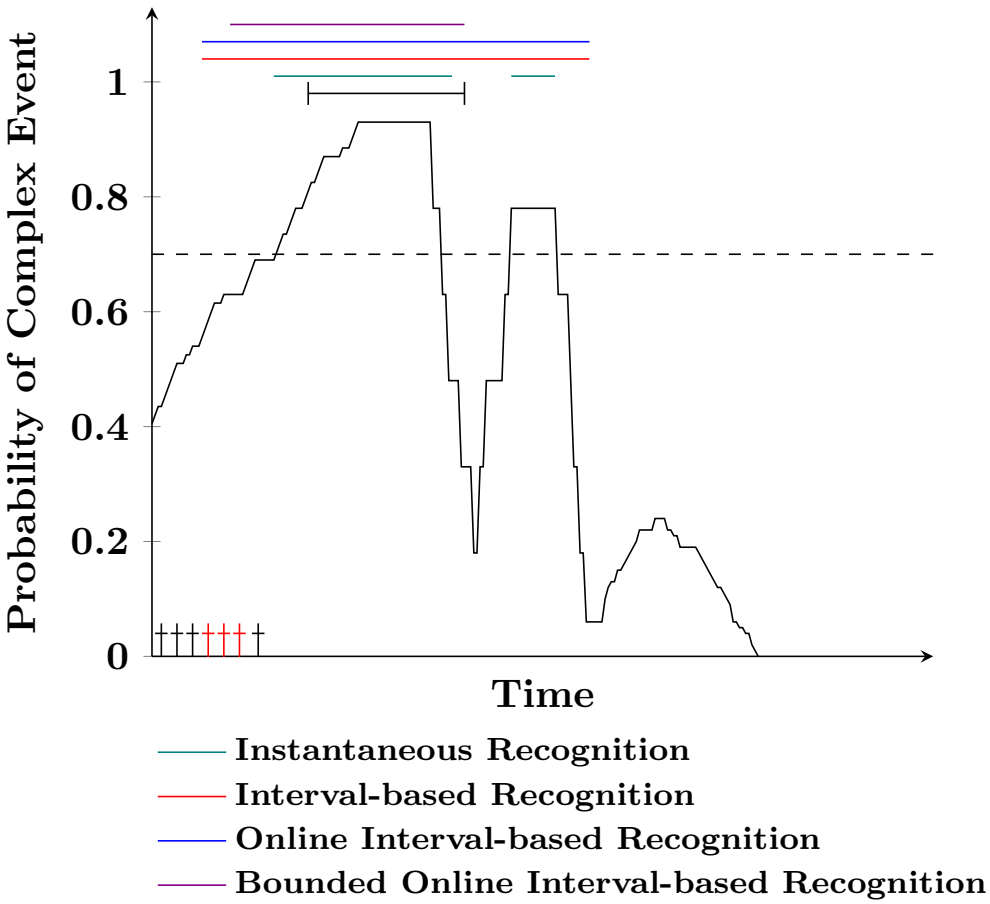
Bounded Online Interval-based Recognition*



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

*Mantenoglou et al, Online Probabilistic Interval-Based Event Calculus. ECAI, 2020.

Bounded Online Interval-based Recognition*



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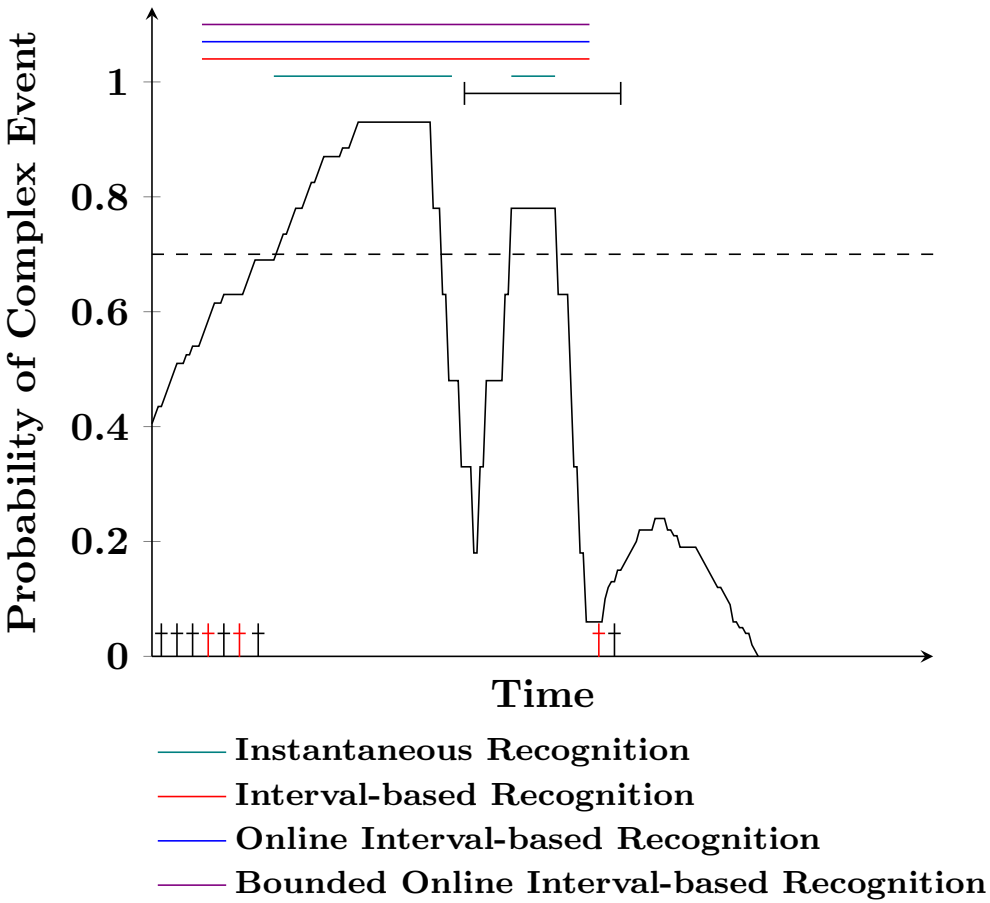

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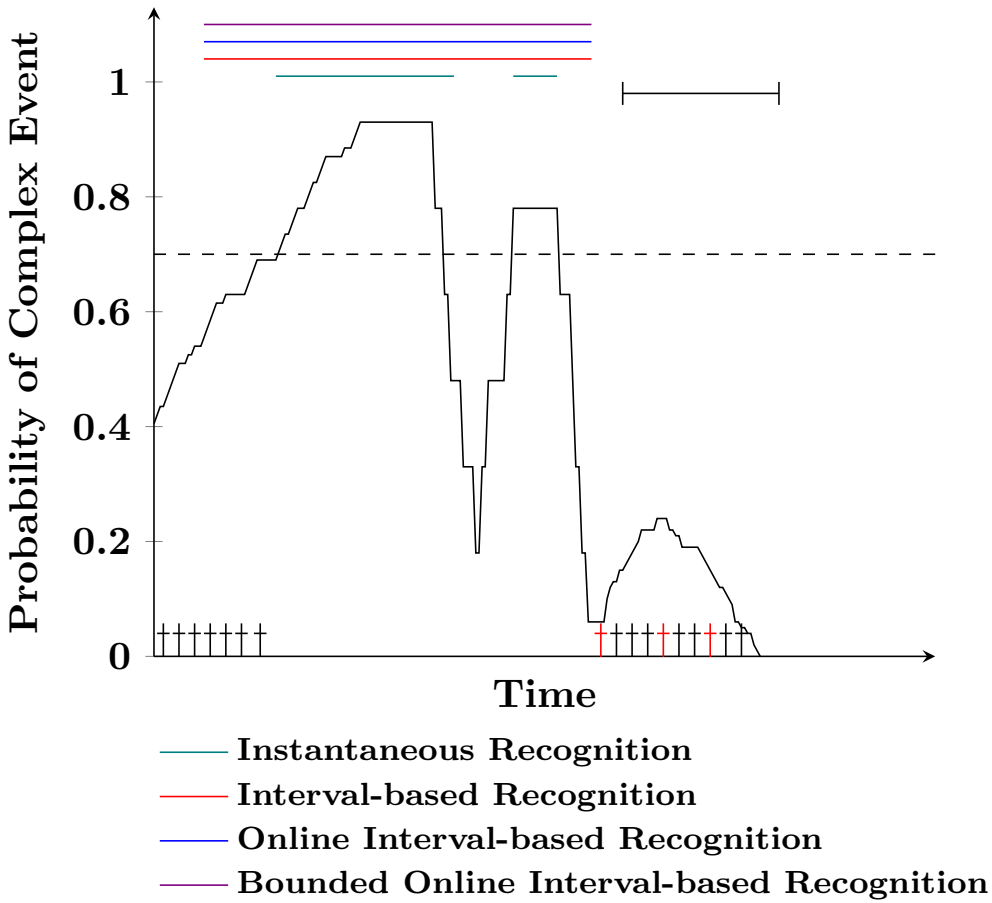

- Complex event duration statistics favor more recent potential starting points.
- Comparable accuracy to batch reasoning.

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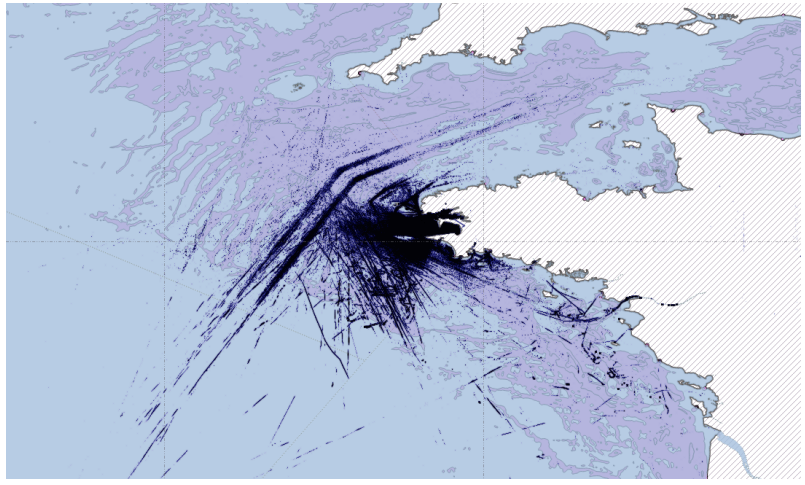
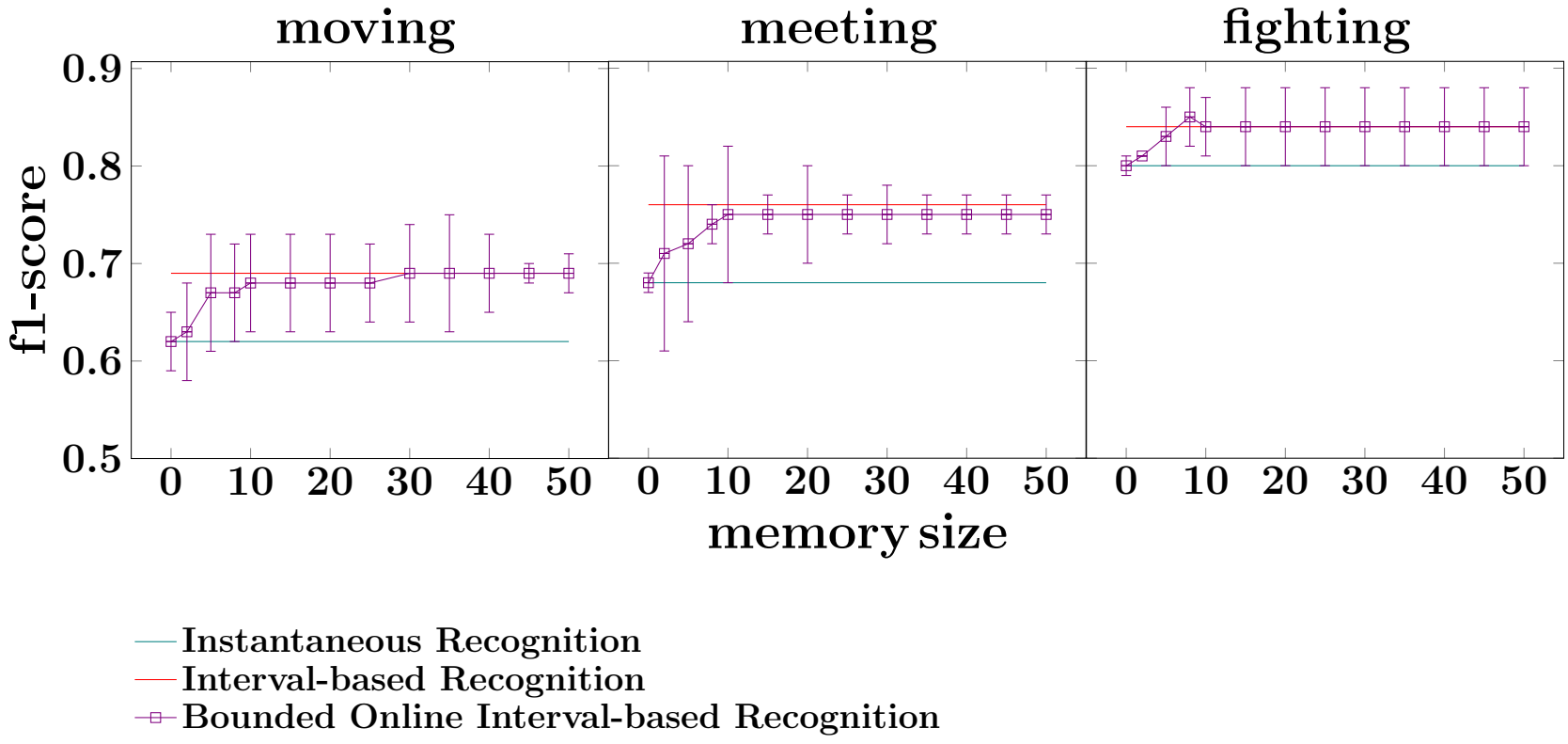
Experimental Setup



- Human Activity Recognition:
  - Input: manually annotated simple activities on individual video frames.
  - Output: maximal intervals of complex activities.
- Maritime Situational Awareness:
  - Input: vessel position signals from the area of Brest, France.
  - Output: maximal intervals of complex vessel activities.
- https://github.com/Periklismant/oPIEC

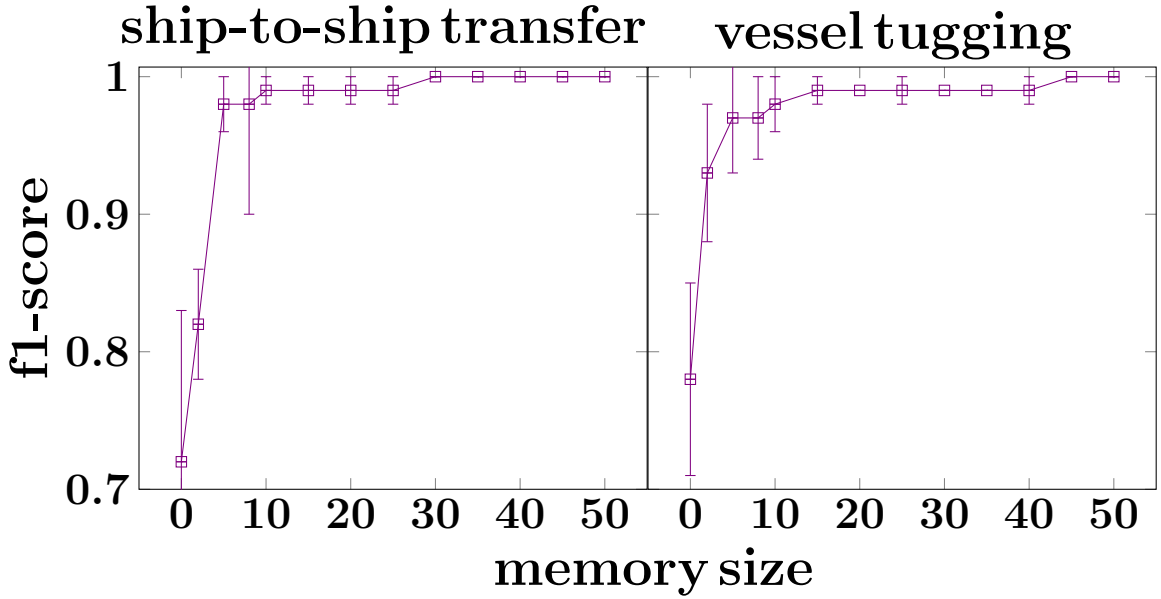
Experimental Results: Human Activity Recognition

Comparison against ground truth



Experimental Results: Maritime Situational Awareness

Performance of bounded online recognition against batch recognition



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- Online reasoning over noisy streams.
- Optimal history compression for correct interval computation.
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- Symbolic 'simple events' are required.
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- Support uncertainty in complex event definitions.

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Resources

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https://cer.iit.demokritos.gr

Appendix

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

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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*

Interval-based Recognition

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

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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

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

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**
In	*0*	*0.5*	*0.7*	*0.9*	*0.4*	*0.1*	*0*	*0*	*0.5*	*1*
L	*−0.5*	*0*	*0.2*	*0.4*	*−0.1*	*−0.4*	*−0.5*	*−0.5*	*0*	*0.5*
prefix	*−0.5*	*−0.5*	*−0.3*	*0.1*	*0*	*−0.4*	*−0.9*	*−1.4*	*−1.4*	*−0.9*
dp	*0.1*	*0.1*	*0.1*	*0.1*	*0*	*−0.4*	*−0.9*	*−0.9*	*−0.9*	*−0.9*

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

Interval-based Recognition

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

Interval-based Recognition

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

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

Interval-based Recognition

	⇑		⇓						
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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

	⇑					⇓				
Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
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**
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

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

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

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

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 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 Computation Correctness

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

Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Ann. Math. Artif. Intell., 2020.

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 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.

Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Ann. Math. Artif. Intell., 2020.