Online Reasoning under Uncertainty with the Event Calculus

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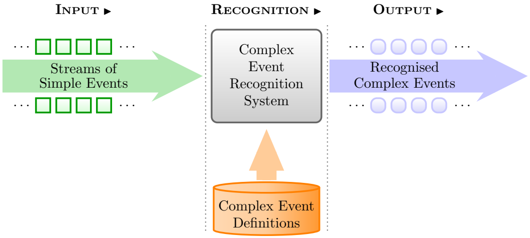
http://cer.iit.demokritos.gr/

Complex Event Recognition (Event Pattern Matching)



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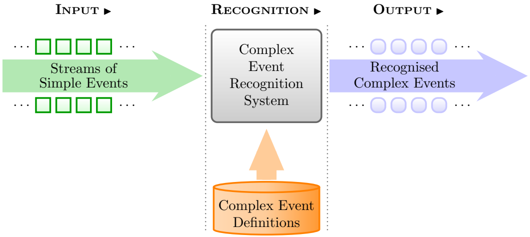

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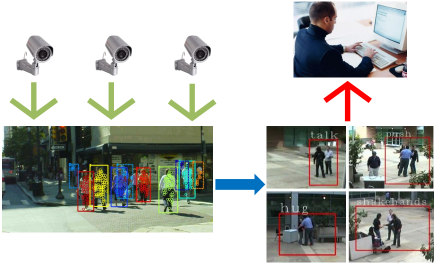
https://rdcu.be/cNkQE

Human Activity Recognition



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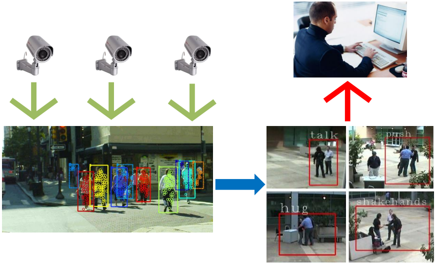

https://cer.iit.demokritos.gr (activity recognition)

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- Expressive representation
    - to capture complex relationships between the events that stream into the system.

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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.

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

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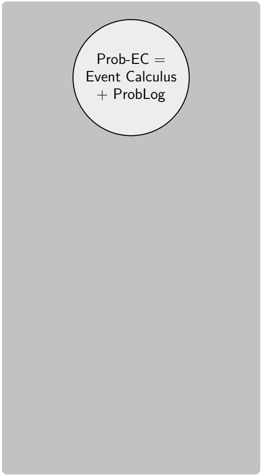
Online Probabilistic Event Calculus



Online Probabilistic Event Calculus

Prob-EC =
Event Calculus
+ ProbLog

Event Calculus Axioms

holdsAt$(F = V, T) \leftarrow$
  initially$(F = V)$,
  not broken$(F = V, 0, T)$.

holdsAt$(F = V, T) \leftarrow$
  initiatedAt$(F = V, T_s)$, $T_s < T$,
  not broken$(F = V, T_s, T)$.

$\vdots$

Online Probabilistic Event Calculus

Application-Specific Rules

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($similarOrientation(P_1, P_2)$ = true, T).

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

Event Calculus Axioms

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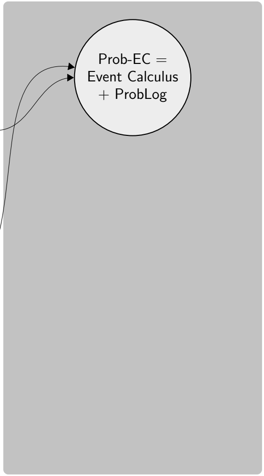

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$\mathsf{initiatedAt}(moving(P_1, P_2) = \mathsf{true}, T) \leftarrow$
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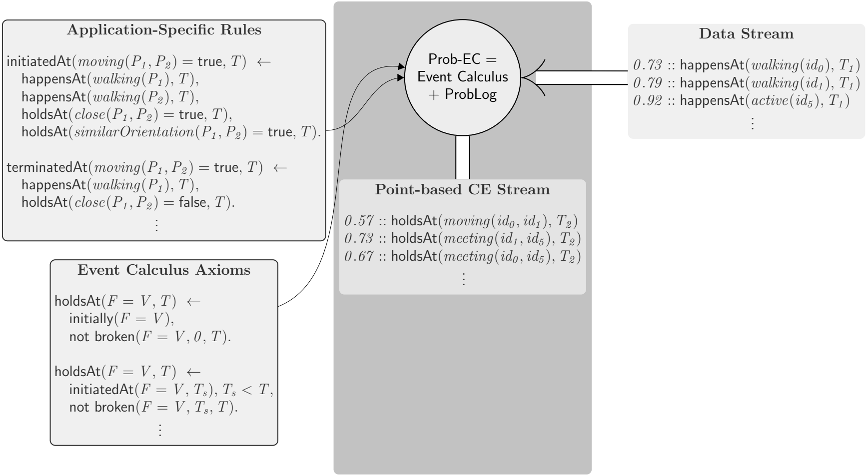
$\vdots$

Prob-EC = Event Calculus + ProbLog

Data Stream

$0.73 :: \mathsf{happensAt}(walking(id_0), T_1)$
$0.79 :: \mathsf{happensAt}(walking(id_1), T_1)$
$0.92 :: \mathsf{happensAt}(active(id_5), T_1)$
$\vdots$

Online Probabilistic Event Calculus



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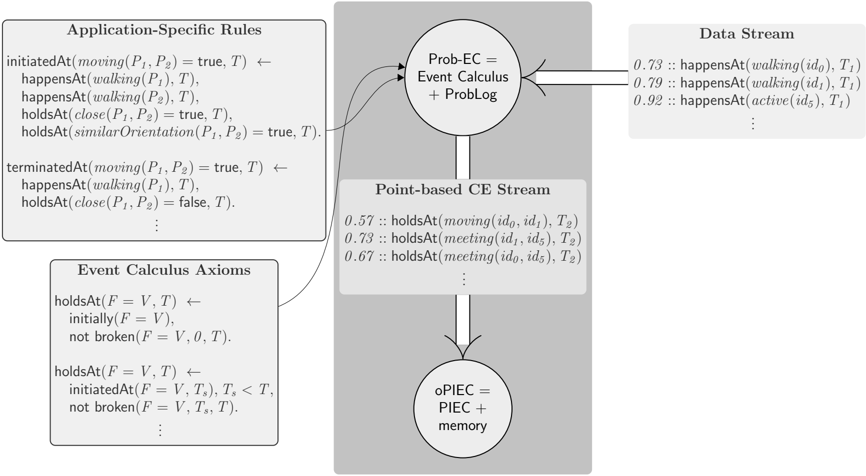

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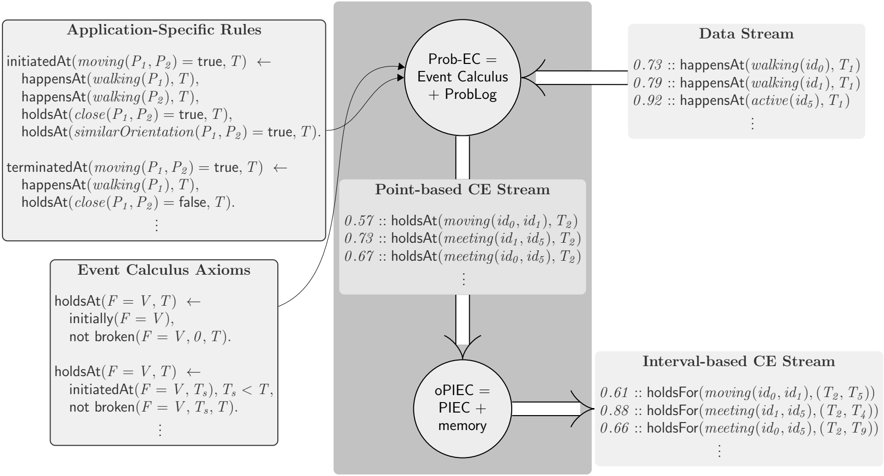
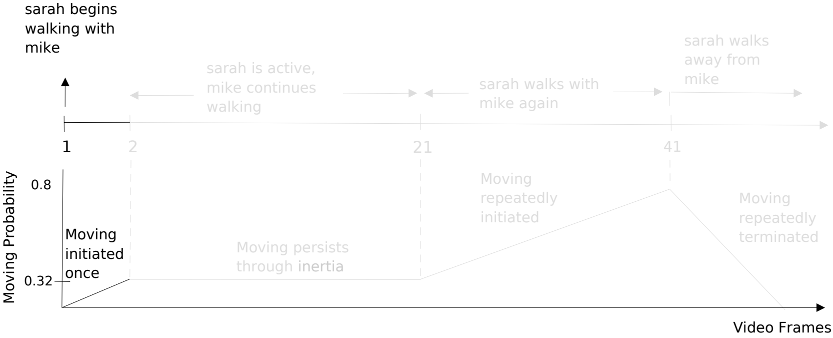


Instantaneous Recognition

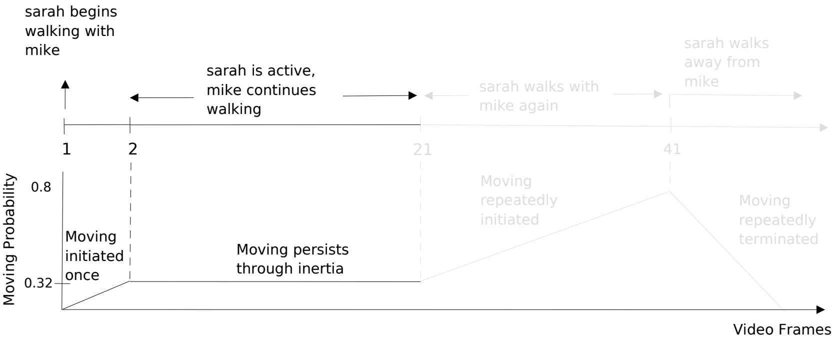


$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\ &\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\ &\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\ &\quad \textbf{holdsAt}(\mathit{similarOrientation}(P_1,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

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

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

Instantaneous Recognition



$$
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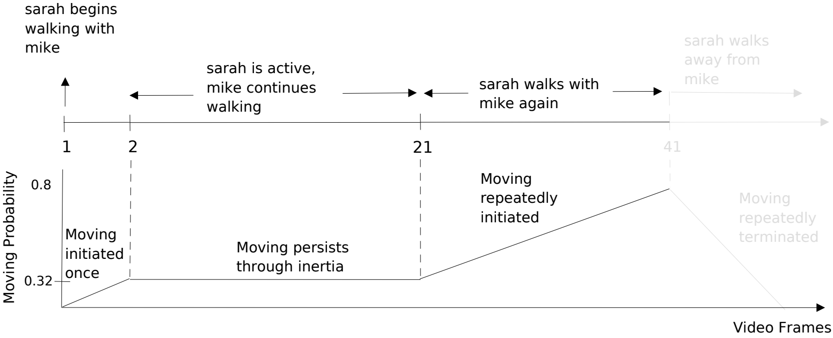

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&0.55 :: \textbf{happensAt}(\mathit{active}(\mathit{sarah}),\ 2).\ \cdots \\
&0.69 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 21). \\
&0.58 :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 21).\ \cdots
\end{aligned}$$

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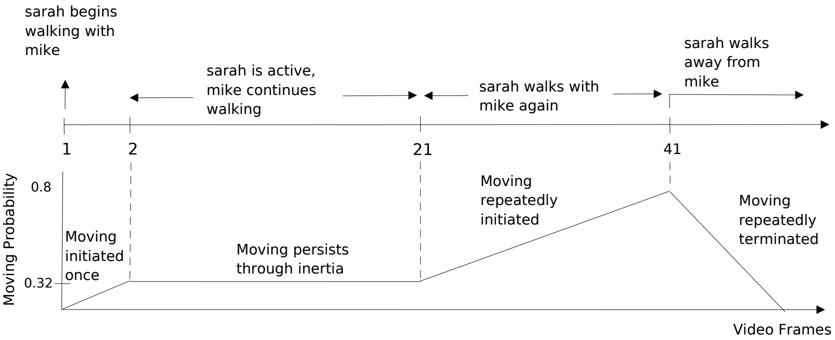

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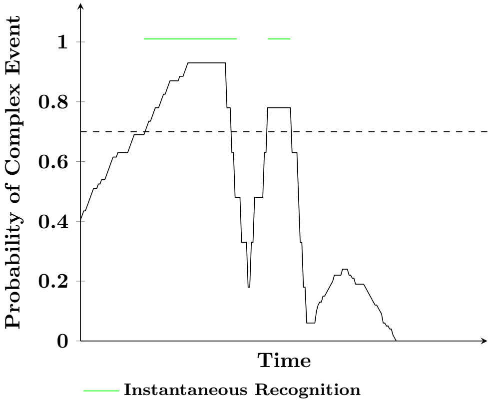
&0.69 :: \textbf{happensAt}(\mathit{walking}(\mathit{mike}),\ 21). \\
&0.58 :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 21).\ \cdots \\
&0.82 :: \textbf{happensAt}(\mathit{inactive}(\mathit{mike}),\ 41). \\
&0.79 :: \textbf{happensAt}(\mathit{walking}(\mathit{sarah}),\ 41).\ \cdots
\end{aligned}$$

Instantaneous Recognition



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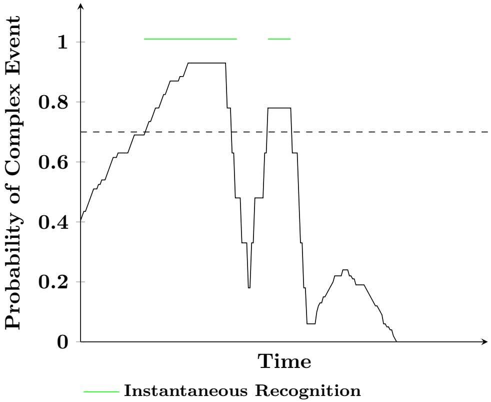

Higher accuracy than crisp reasoning in the presence of:

- several initiations and terminations;
- few probabilistic conjuncts.

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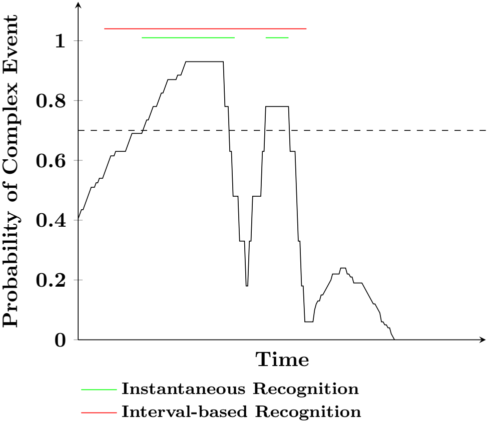
Instantaneous vs Interval-based Recognition



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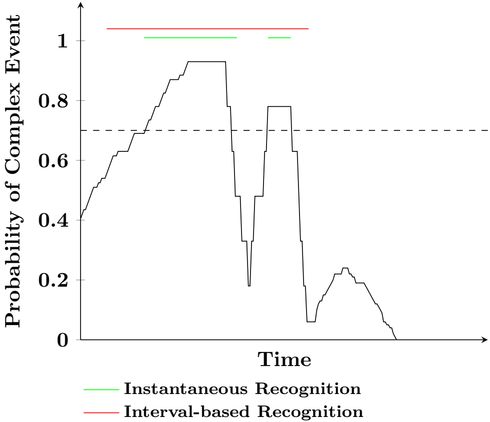
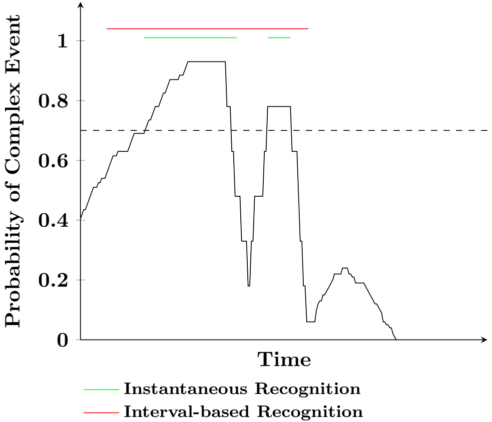


- Interval Probability: average probability of the time-points it contains.

Instantaneous vs Interval-based Recognition



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

Interval-based Recognition

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

Interval-based Recognition

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

Interval-based Recognition

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

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

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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
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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

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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

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In	0	0.5	0.7	0.9	0.4	0.1	0	0	0.5	1
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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

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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
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

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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

$\Uparrow\Downarrow$

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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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

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

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

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

Interval-based Recognition

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

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

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
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Interval Computation Correctness

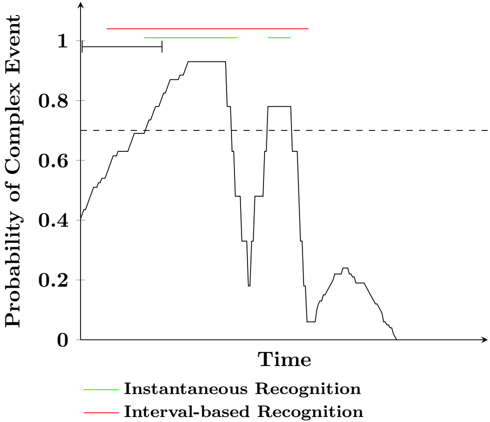
An interval is computed iff it is a probabilistic maximal interval.

Complexity

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

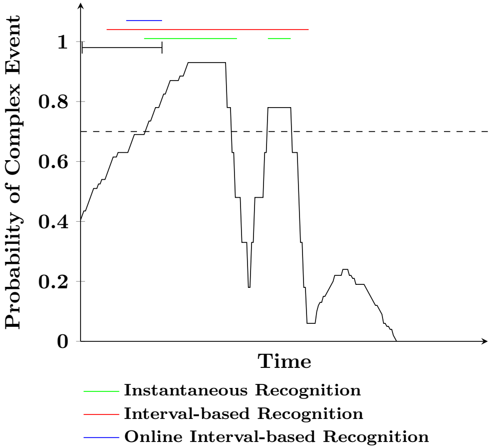
Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Ann. Math. Artif. Intell., 2020.

Online Interval-based Recognition



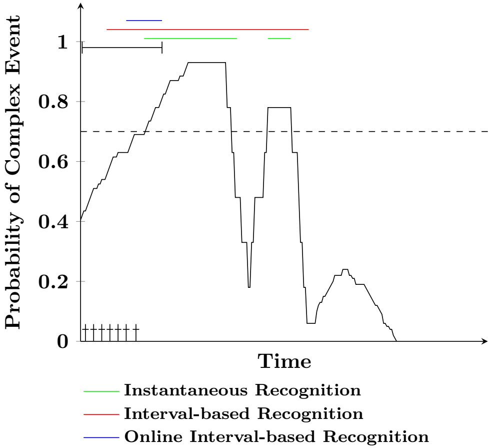
- Windowing.

Online Interval-based Recognition



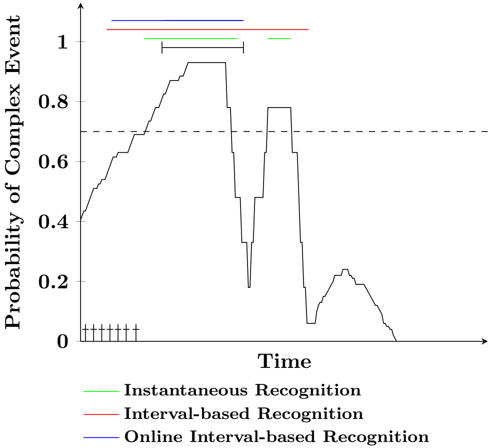
- Windowing.
- Probabilistic maximal interval computation.

Online Interval-based Recognition



- Windowing.
- Probabilistic maximal interval computation.
- Caching potential starting points.

Online Interval-based Recognition



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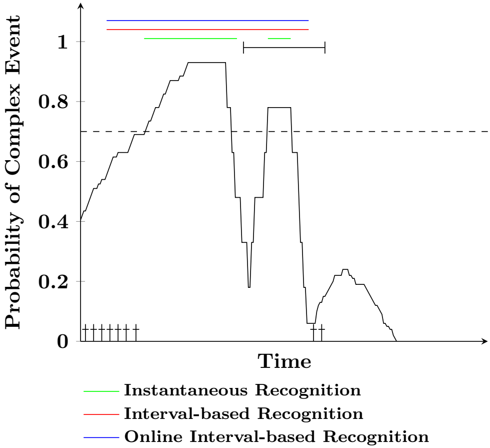

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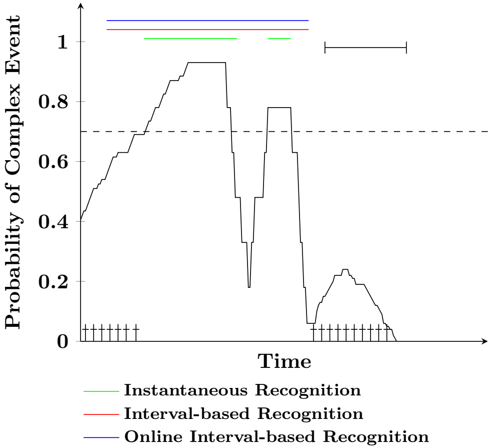
Online Interval-based Recognition



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Online Interval-based Recognition: Properties

Memory Minimality

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

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An interval is computed iff it is a probabilistic maximal interval given the data seen so far.

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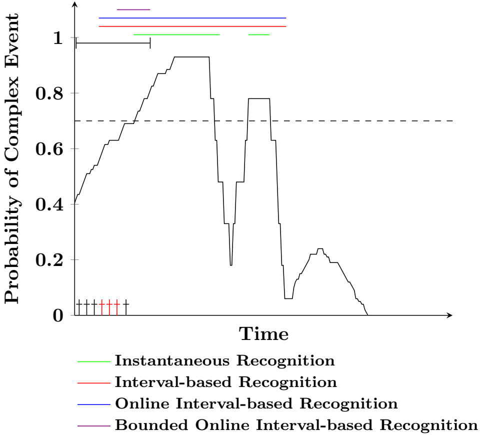
Complexity

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

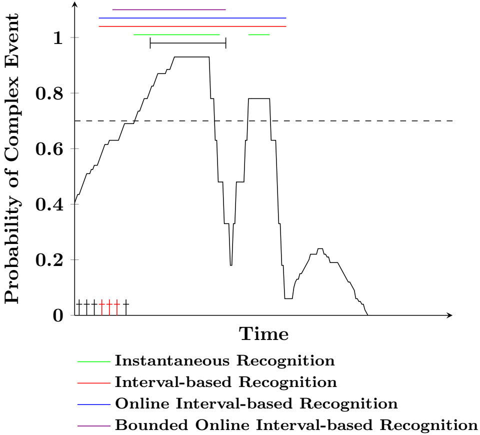
Bounded Online Interval-based Recognition



- 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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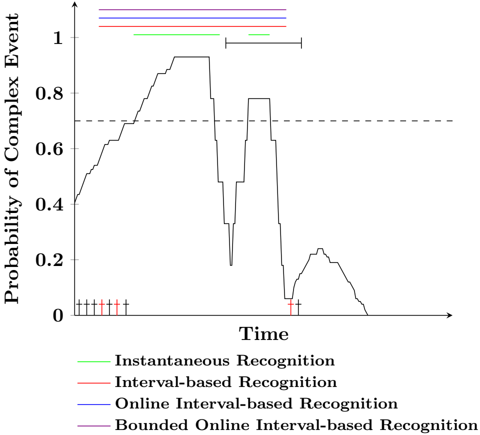

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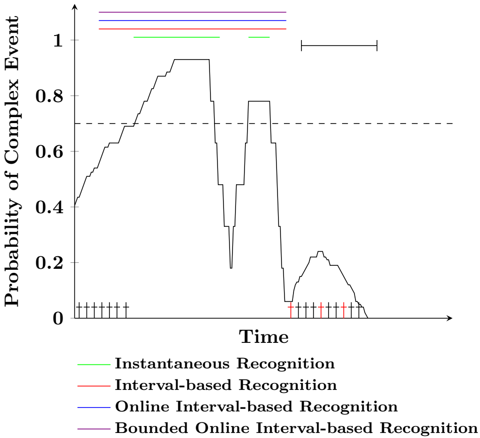
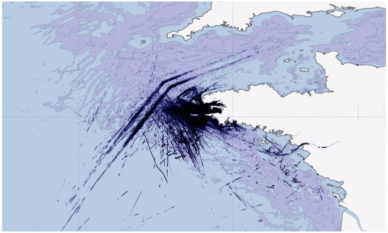


- Complex event duration statistics favor more recent potential starting points.
- Comparable accuracy to batch reasoning.

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

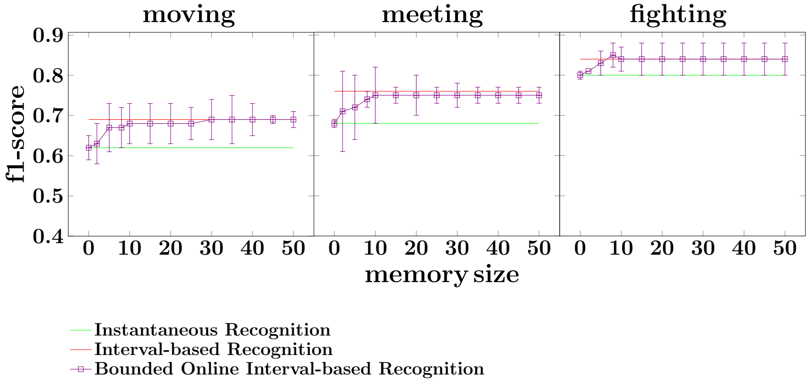
Experimental Setup



- 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

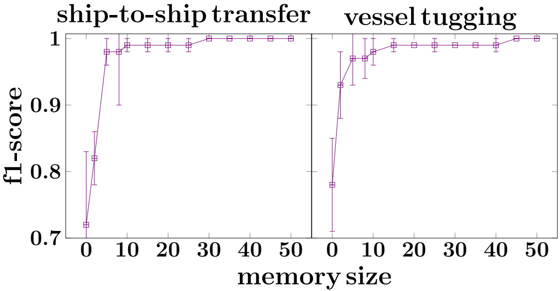
Experimental Results: Human Activity Recognition

Comparison against ground truth



Experimental Results: Maritime Situational Awareness

Performance of bounded online recognition against batch recognition



Summary & Topics not Covered

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- Online reasoning over noisy streams.
- Optimal history compression for correct interval computation.
- Reproducible evaluation on benchmark, real data.

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[∇] *Alevizos et al, Complex Event Forecasting with Prediction Suffix Trees. VLDB Journal, 2022.*