Can Computers Understand What is Happening?
Probabilistic Complex Event Recognition

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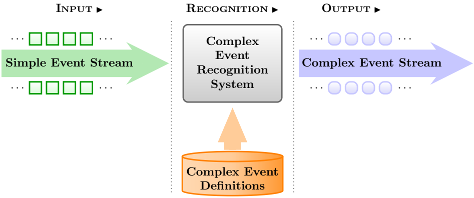
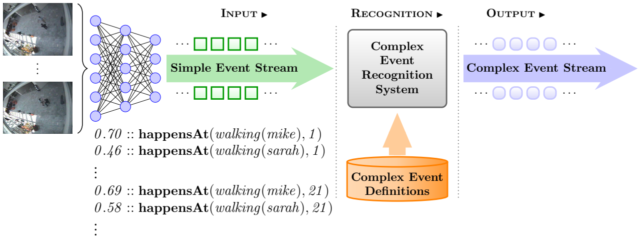
https://cer.iit.demokritos.gr

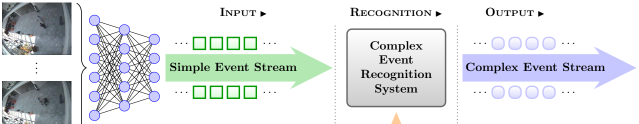
Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty

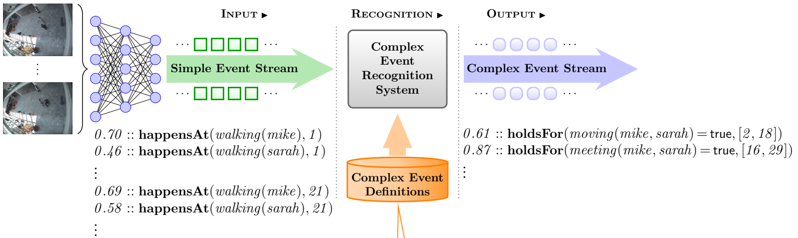


0.70 :: **happensAt**$(\textit{walking}(\textit{mike}), 1)$
0.46 :: **happensAt**$(\textit{walking}(\textit{sarah}), 1)$
$\vdots$
0.69 :: **happensAt**$(\textit{walking}(\textit{mike}), 21)$
0.58 :: **happensAt**$(\textit{walking}(\textit{sarah}), 21)$
$\vdots$

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

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

Complex Event Recognition under Uncertainty



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

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

$\vdots$

Human Activity Recognition

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

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.

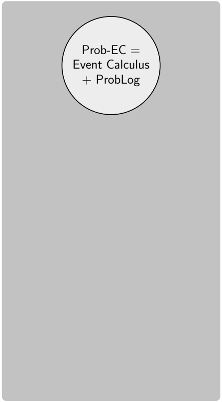
*Kowalski and Sergot, A Logic-based Calculus of Events. New Generation Computing, 1986.

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.

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

Online Probabilistic Interval-Based Event Calculus



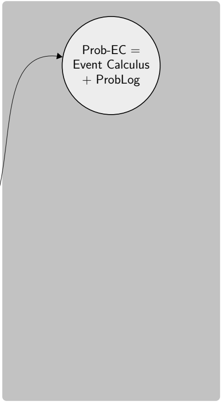
Online Probabilistic Interval-Based Event Calculus

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 Interval-Based 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).
  ⋮

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).
  ⋮

Prob-EC =
Event Calculus
+ ProbLog

Online Probabilistic Interval-Based Event Calculus

Application-Specific Rules

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

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

$\vdots$

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$(F = V, T_s, T)$.

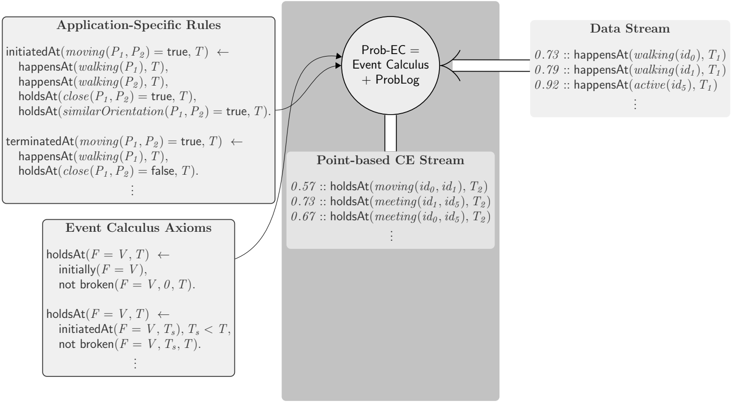
$\vdots$

Prob-EC = Event Calculus + ProbLog

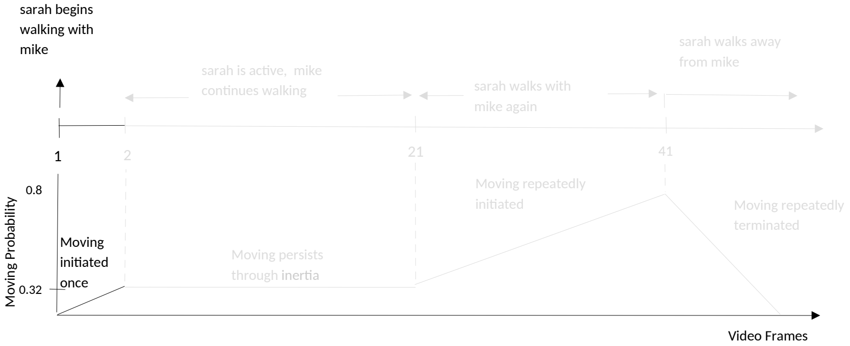
Data Stream

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

Online Probabilistic Interval-Based Event Calculus



Instantaneous Recognition

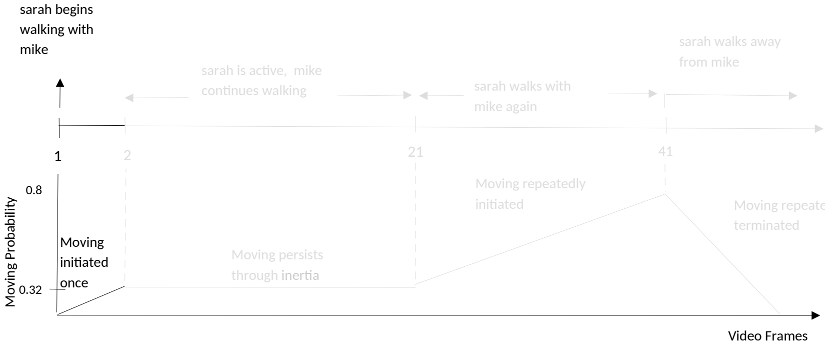


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



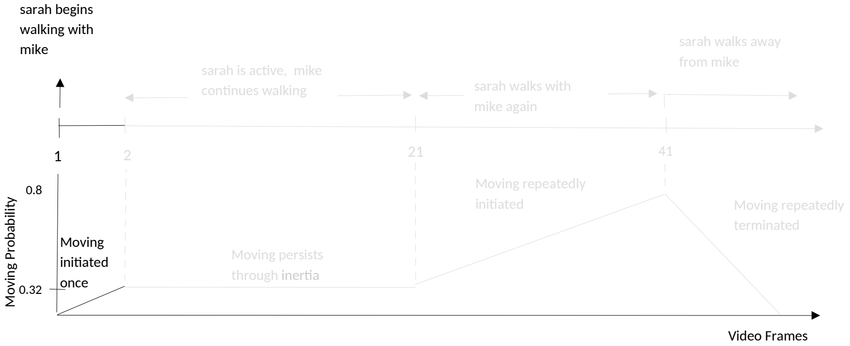
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$
\begin{aligned}
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1)) =\\
&\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{mike}), 1)) \times\\
&\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{sarah}), 1)) \times\\
&\quad P(\textbf{holdsAt}(\mathit{close}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1)) \times\\
&\quad P(\textbf{holdsAt}(\mathit{orientation}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1))\\
&\quad = 0.7 \times 0.46 \times 1 \times 1 = 0.32
\end{aligned}
$$

Instantaneous Recognition



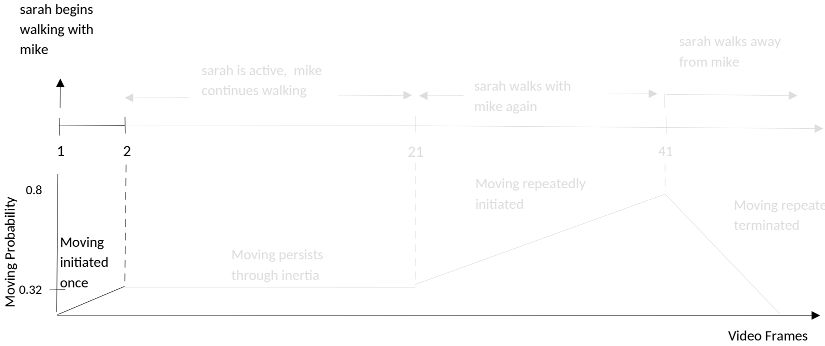
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$
\begin{aligned}
&P(\textbf{holdsAt}(CE = \text{true}, t)) = \\
&\quad P(\textbf{initiatedAt}(CE = \text{true}, t-1) \lor \\
&\qquad (\textbf{holdsAt}(CE = \text{true}, t-1) \land \\
&\qquad \neg\ \textbf{terminatedAt}(CE = \text{true}, t-1)))
\end{aligned}
$$

Instantaneous Recognition



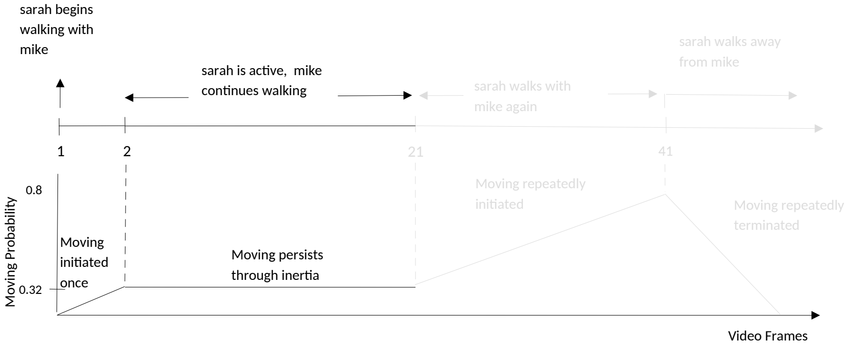
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$
\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{2})) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{1}) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{1}) \wedge \\
&\quad \neg \textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{1}))) \\
&= \mathit{0.32} + \mathit{0} \times \mathit{1} - \mathit{0.32} \times \mathit{0} \times \mathit{1} = \mathit{0.32}
\end{aligned}
$$

Instantaneous Recognition



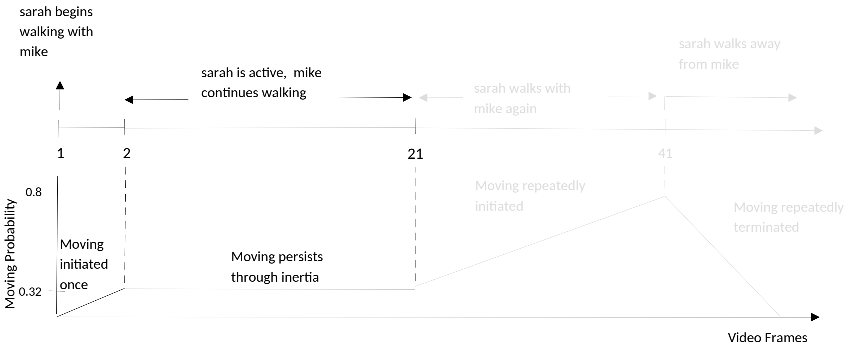
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 3)) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 2) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 2) \wedge \\
&\quad \neg \textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 2))) \\
&= 0 + 0.32 \times 1 - 0 \times 0.32 \times 1 = 0.32
\end{aligned}$$

Instantaneous Recognition



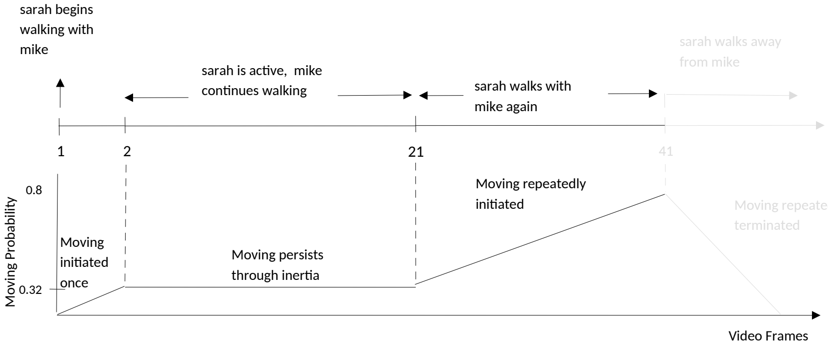
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \mathrm{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \mathrm{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \mathrm{true}, 21)) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \mathrm{true}, 20) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \mathrm{true}, 20) \wedge \\
&\quad \neg \textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \mathrm{true}, 20))) \\
&= 0 + 0.32 \times 1 - 0 \times 0.32 \times 1 = 0.32
\end{aligned}$$

Instantaneous Recognition



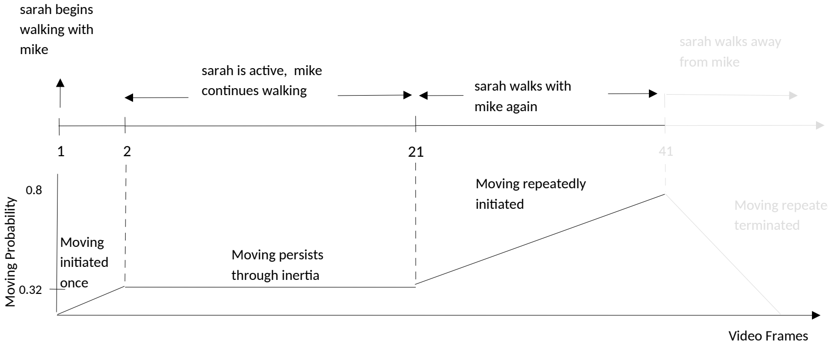
$$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \mathrm{true},\ T) \leftarrow$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \mathrm{true},\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



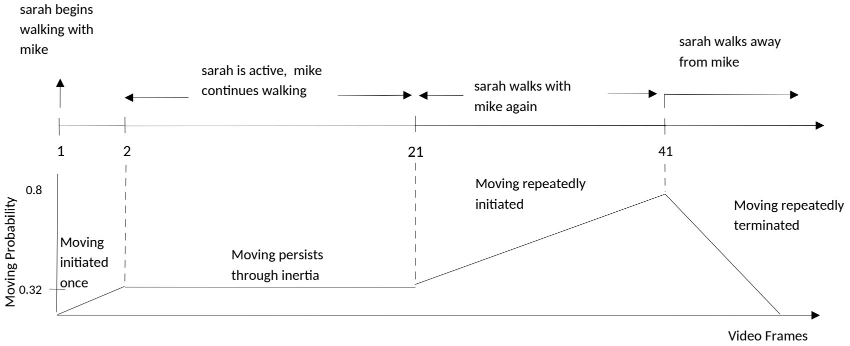
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$
\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 22)) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21) \wedge \\
&\quad \neg\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21))) \\
&= 0.11 + 0.32 \times 1 - 0.11 \times 0.32 \times 1 = 0.39
\end{aligned}
$$

Instantaneous Recognition



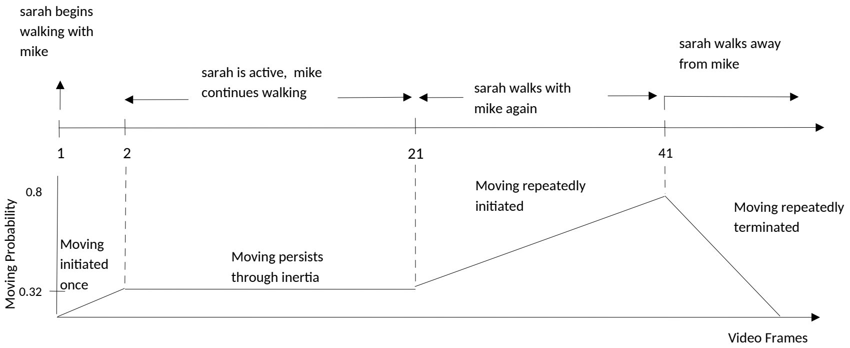
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



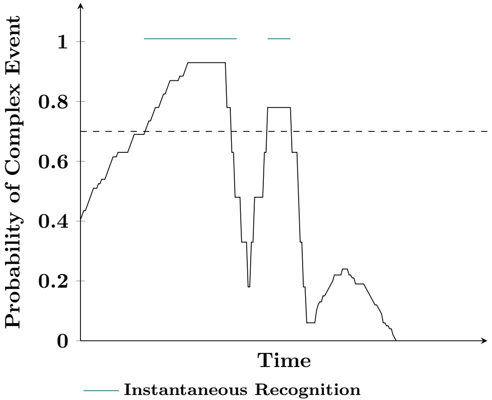
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

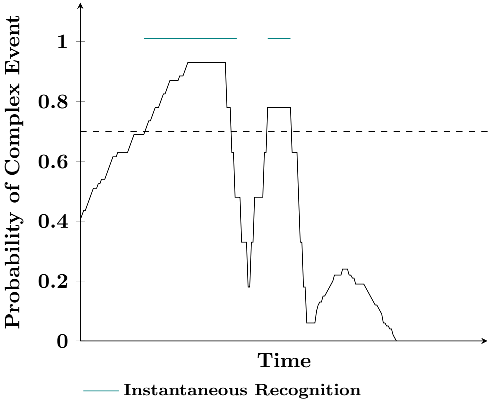
$$
\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{42})) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, \mathit{41}) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) =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

Instantaneous Recognition*



*Skarlatidis et al, A Probabilistic Logic Programming Event Calculus. Theory & Practice of Logic Programming, 2015.

Instantaneous Recognition*

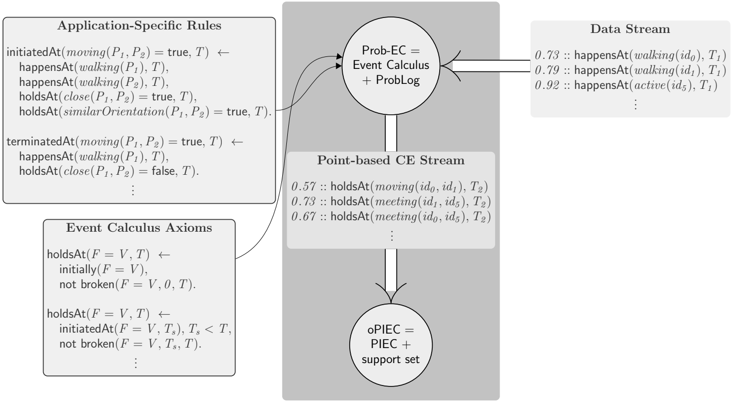


Higher accuracy than crisp reasoning in the presence of:

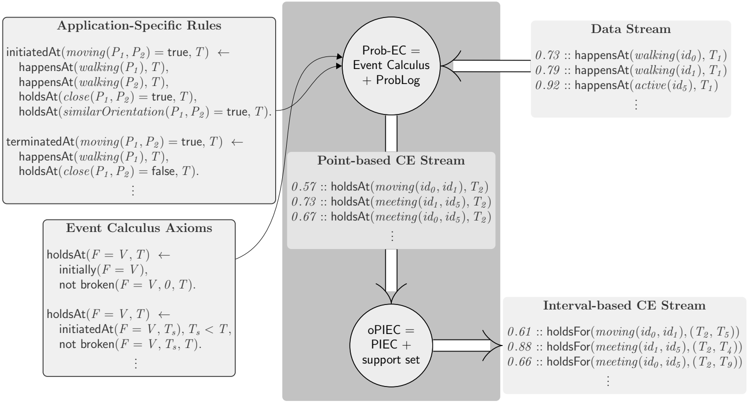
- several initiations and terminations;
- few probabilistic conjuncts.

*Skarlatidis et al, A Probabilistic Logic Programming Event Calculus. Theory & Practice of Logic Programming, 2015.

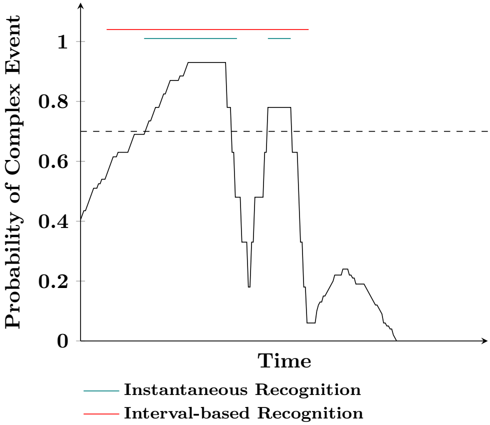
Online Probabilistic Interval-Based Event Calculus



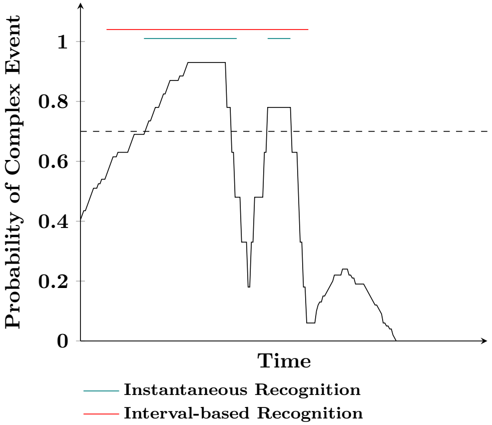
Online Probabilistic Interval-Based Event Calculus



Instantaneous vs Interval-based Recognition

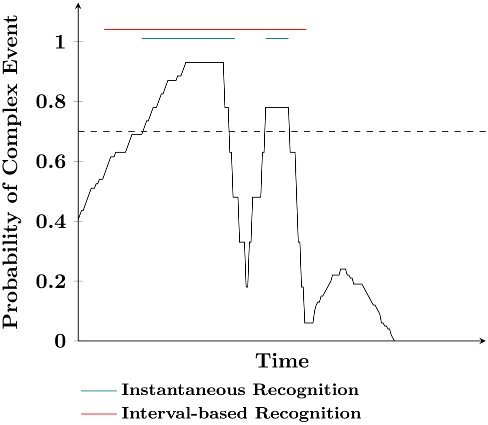


Instantaneous vs Interval-based Recognition



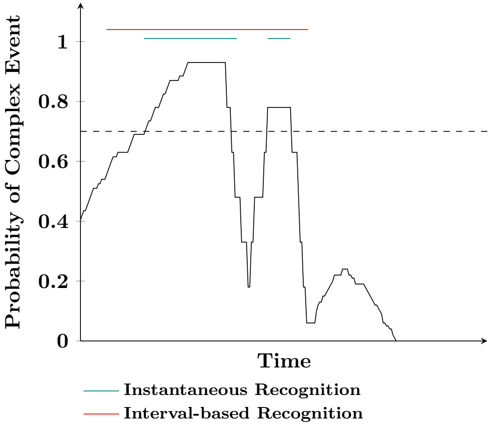
- Interval Probability: average probability of the time-points it contains.

Instantaneous vs Interval-based Recognition



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

Instantaneous vs Interval-based Recognition



- 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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

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

	$\Uparrow\Downarrow$									
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

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

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

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

Interval-based Recognition*

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, 2021.

Interval-based Recognition*

Interval Computation Correctness

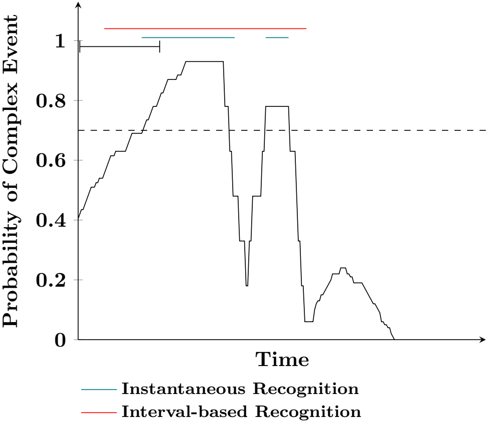
An interval is computed iff it is a probabilistic maximal interval.

Complexity

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

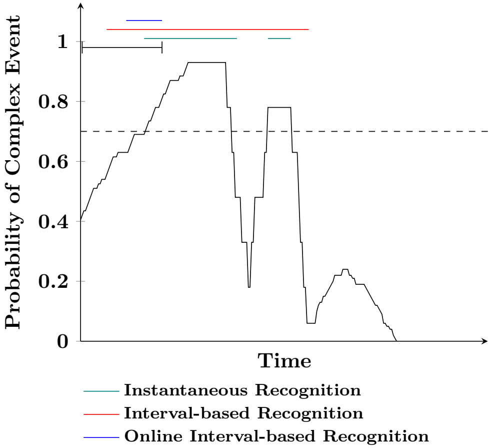
*Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Annals of Mathematics and Artificial Intelligence, 2021.

Online Interval-based Recognition



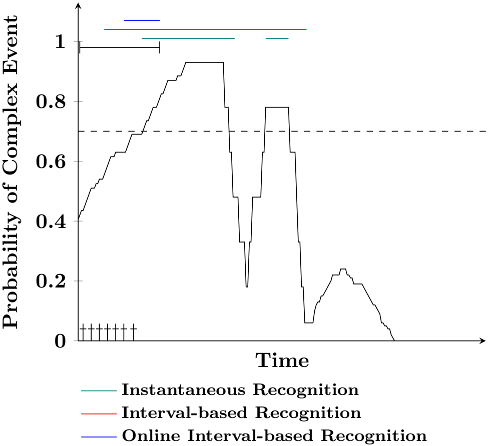
- Windowing.

Online Interval-based Recognition



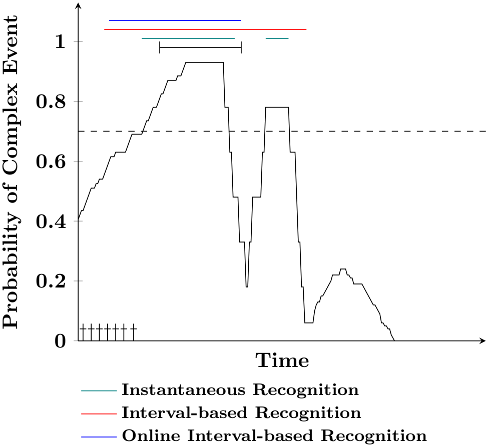
- Windowing.
- Probabilistic maximal interval computation.

Online Interval-based Recognition



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

Online Interval-based Recognition



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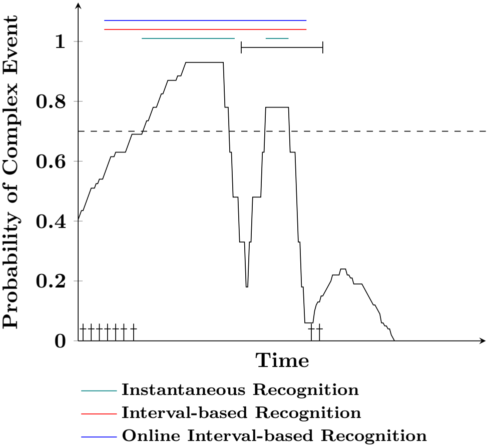

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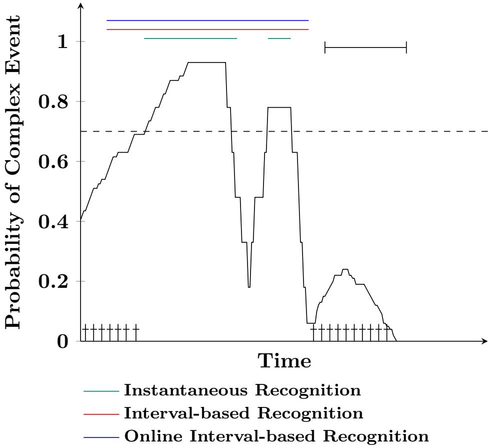

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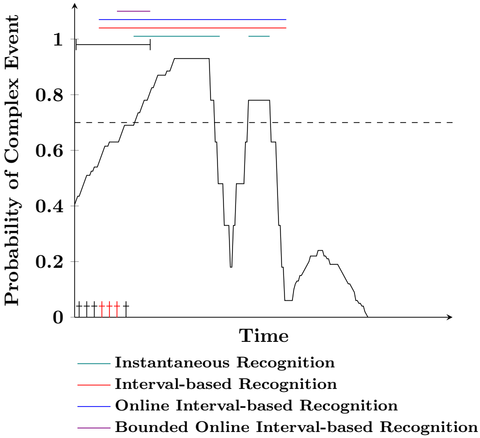
Complexity

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 Event Recognition over Noisy Data Streams. International Journal of Approximate Reasoning, 2023. https://github.com/Periklismant/oPIEC

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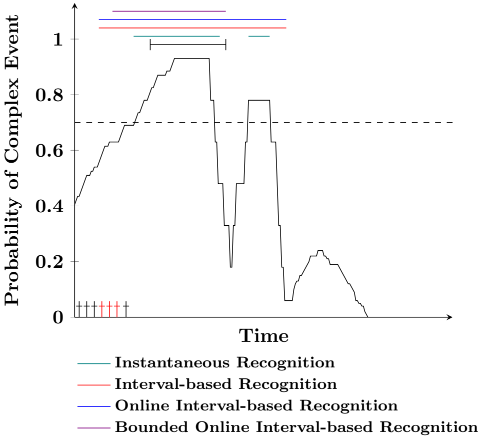

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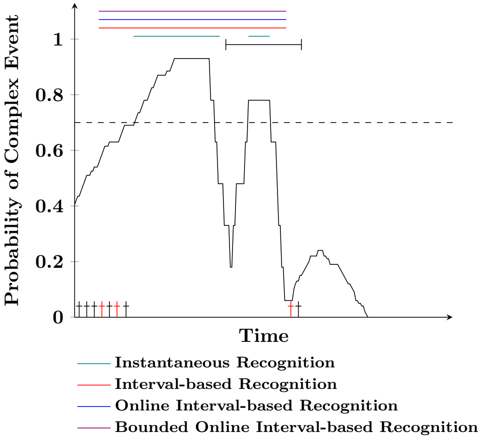

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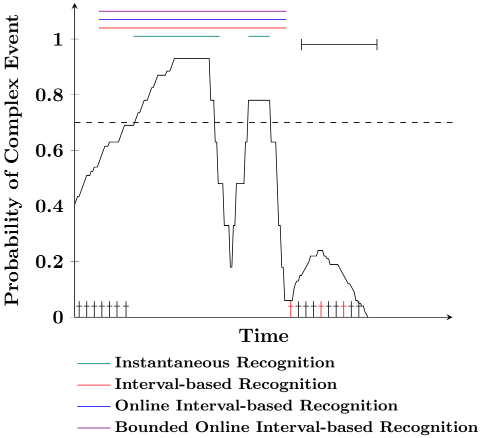

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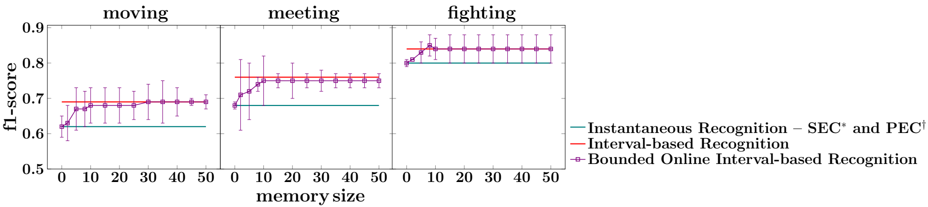
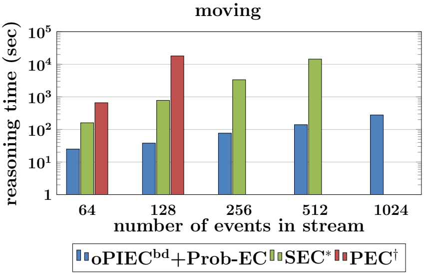
Indicative Experimental Results





*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.

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Next:

- Forecast complex events.