Can Computers Understand What is Happening? Probabilistic Complex Event Recognition

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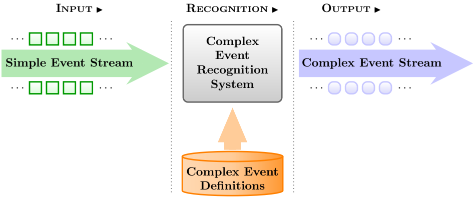
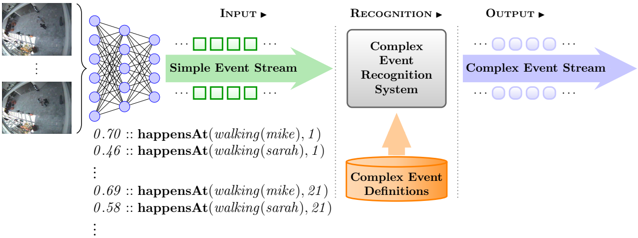
https://cer.iit.demokritos.gr

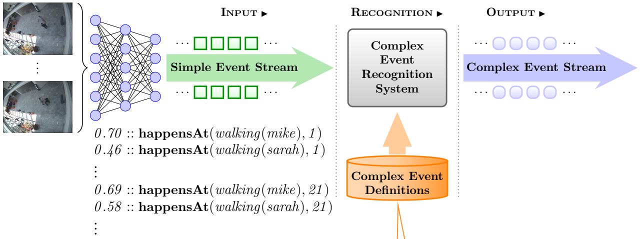
Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty

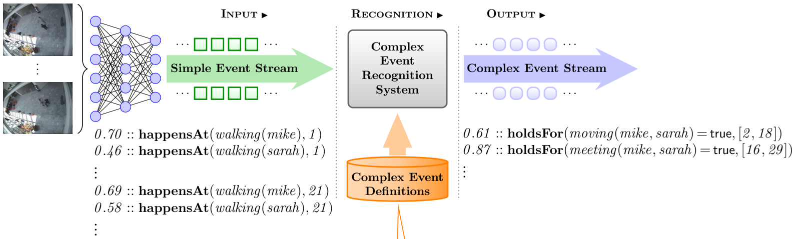


$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \mathsf{true},\ T) \leftarrow$
$\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),$
$\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),$
$\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \mathsf{true},\ T),$
$\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

⋮

Complex Event Recognition under Uncertainty



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

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

⋮

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.

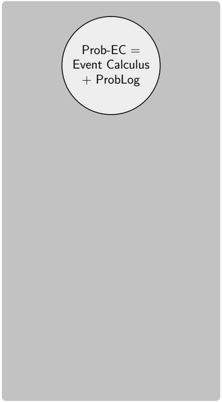
*Kowalski and Sergot, A Logic-based Calculus of Events. New Generation Computing, 1986.

Event Calculus*

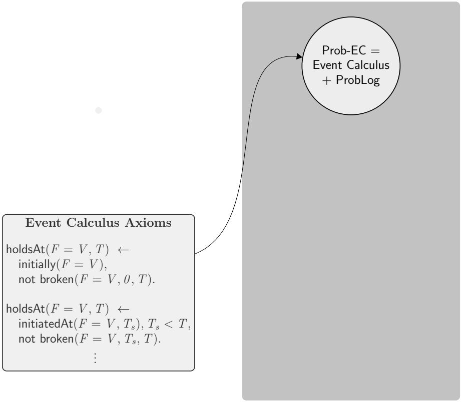
- A logic programming language for representing and reasoning about events and their effects.
- Key components:
  - event (typically instantaneous).
  - fluent: a property that may have different values at different points in time.
- Built-in representation of inertia:
  - $F = V$ holds at a particular 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



Online Probabilistic Interval-Based Event Calculus

Application-Specific Rules

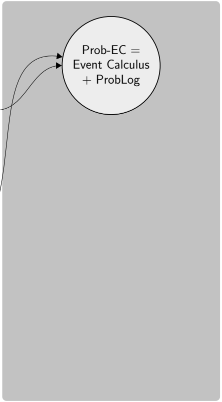
initiatedAt($moving(P_1, P_2)$ = true, T) $\leftarrow$
  happensAt($walking(P_1)$, T),
  happensAt($walking(P_2)$, T),
  holdsAt($close(P_1, P_2)$ = true, T),
  holdsAt($similarOrientation(P_1, P_2)$ = true, T).

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

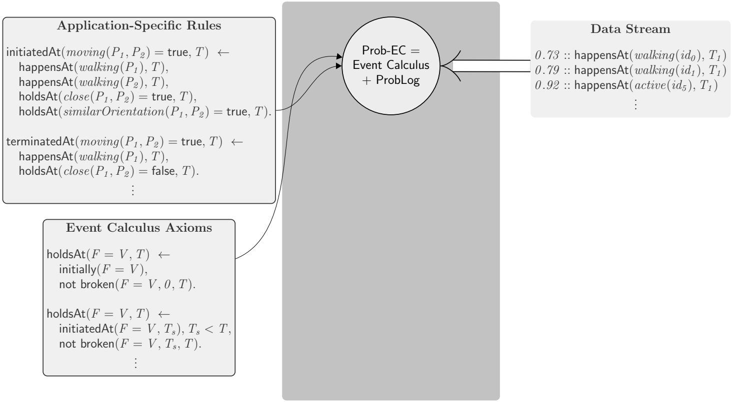
Event Calculus Axioms

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

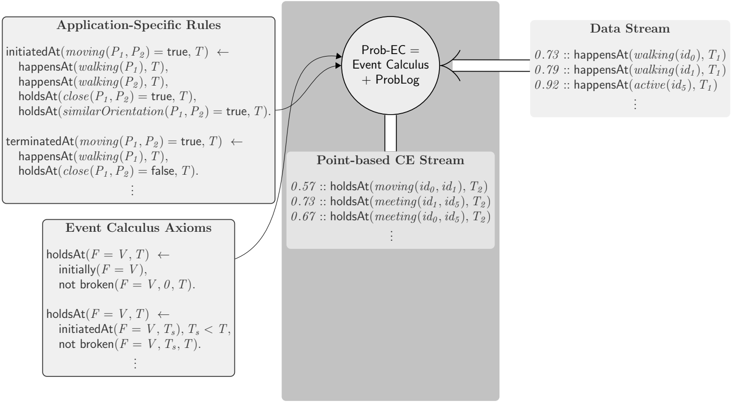
holdsAt($F = V$, T) $\leftarrow$
  initiatedAt($F = V$, T_s), $T_s < T$,
  not broken($F = V$, T_s, T).
  ⋮



Online Probabilistic Interval-Based Event Calculus



Online Probabilistic Interval-Based Event Calculus



Instantaneous Recognition

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

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

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

Instantaneous Recognition

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

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

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

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

Instantaneous Recognition

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

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

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

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

Instantaneous Recognition

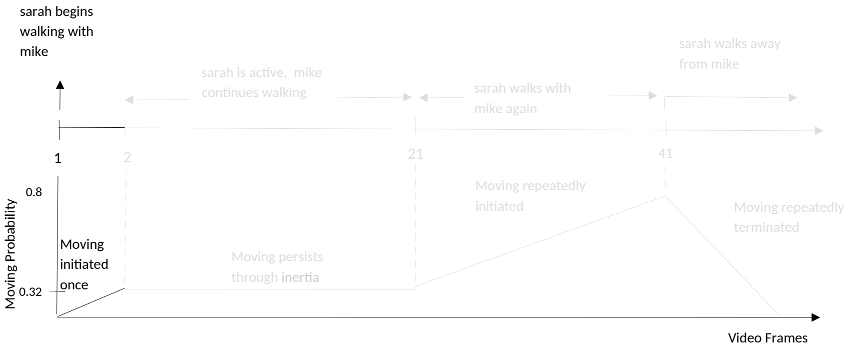
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



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

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

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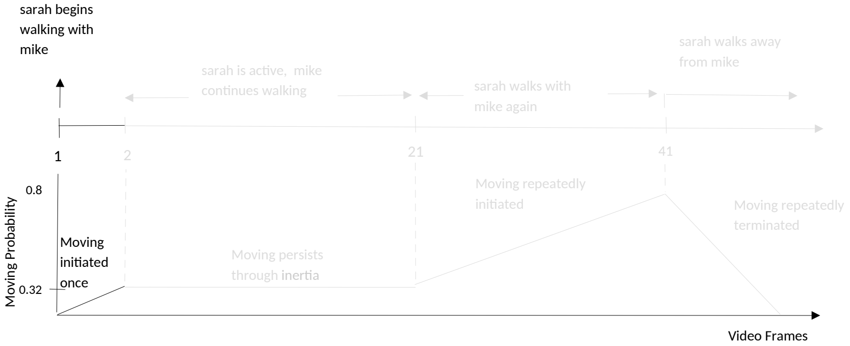
\end{aligned}$$

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

Instantaneous Recognition

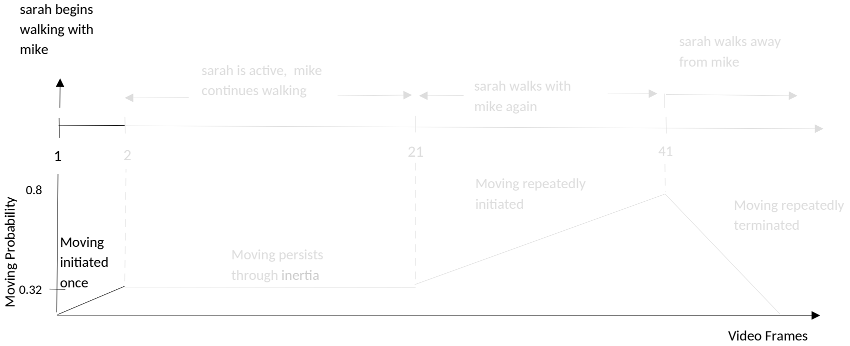


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

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

Instantaneous Recognition



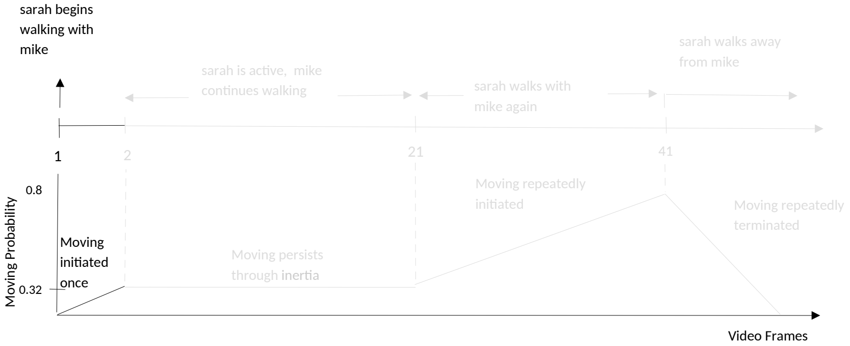
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition

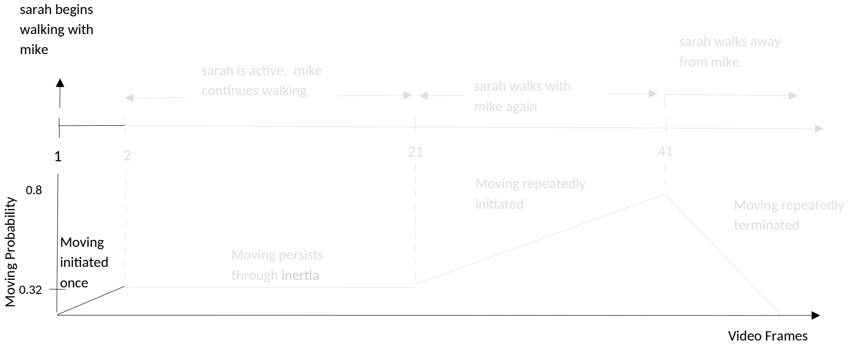


$$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\textit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\textit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\textit{orientation}(P_1, P_2) =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

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

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

Instantaneous Recognition



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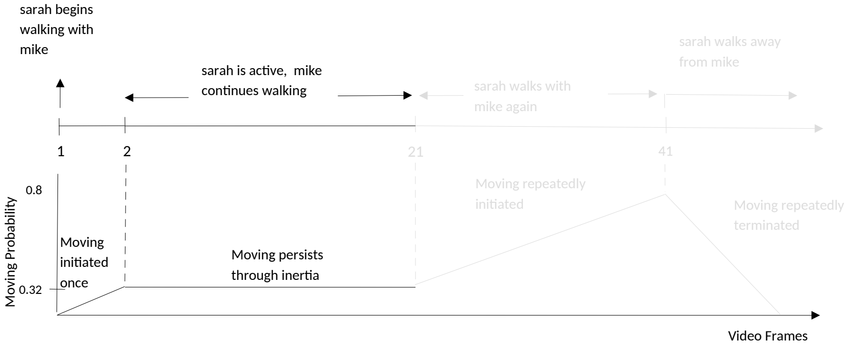
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition



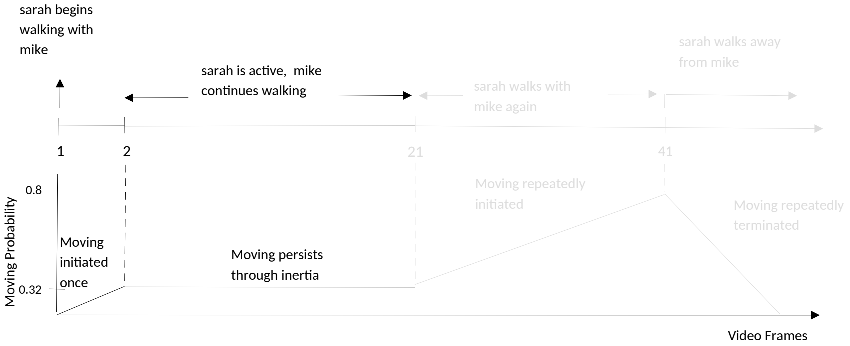
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition

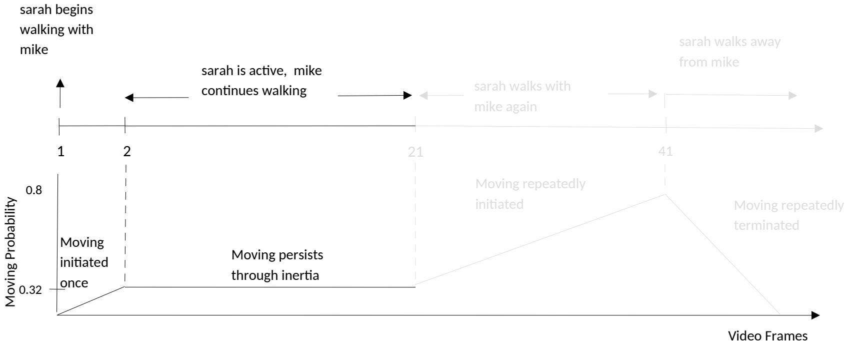


$$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

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

Instantaneous Recognition



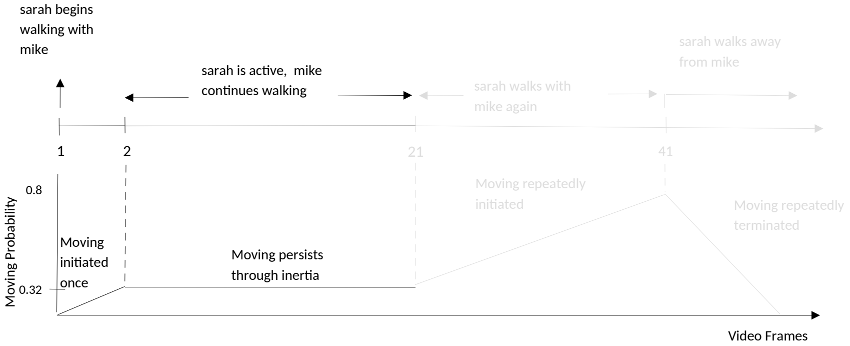
$$\mathbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \mathbf{happensAt}(walking(P_1),\ T),$$
$$\quad \mathbf{happensAt}(walking(P_2),\ T),$$
$$\quad \mathbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \mathbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition



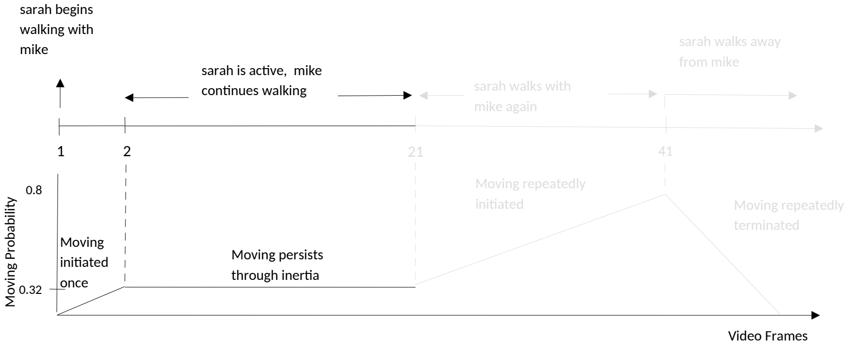
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition

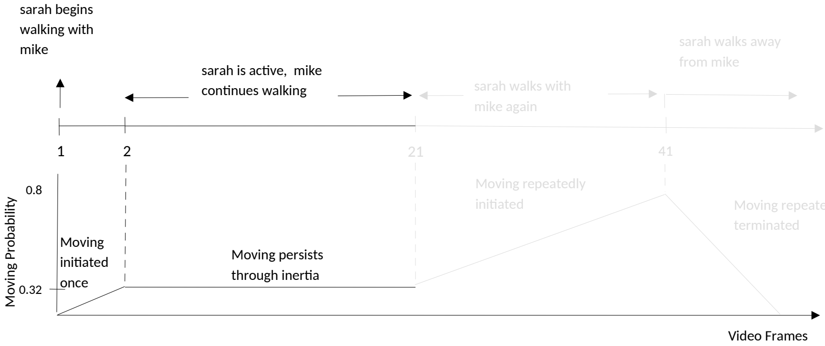


$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



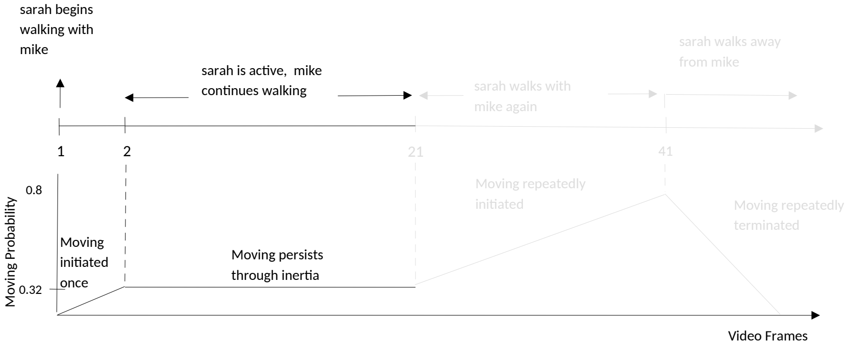
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition



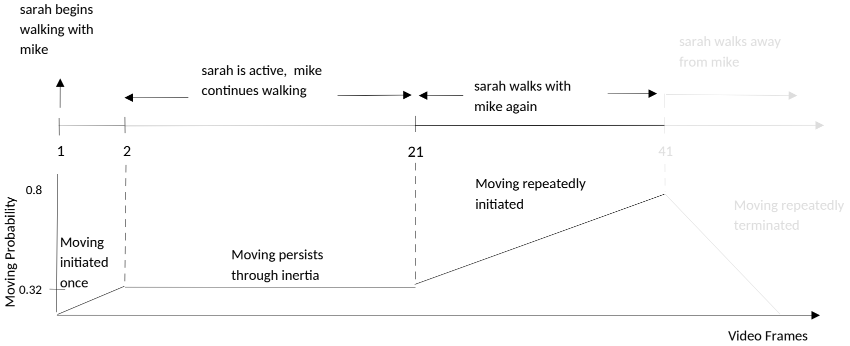
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



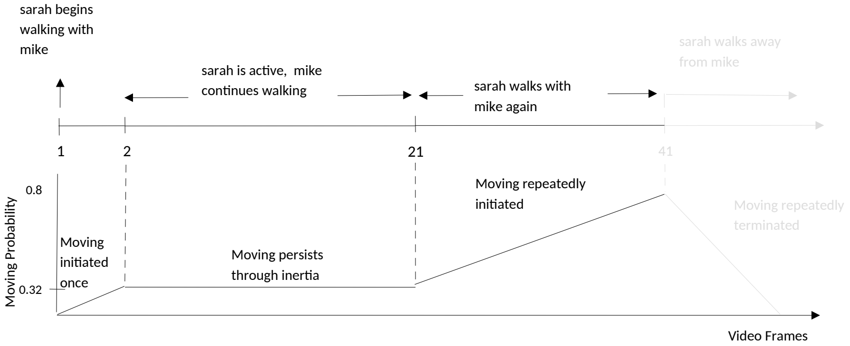
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

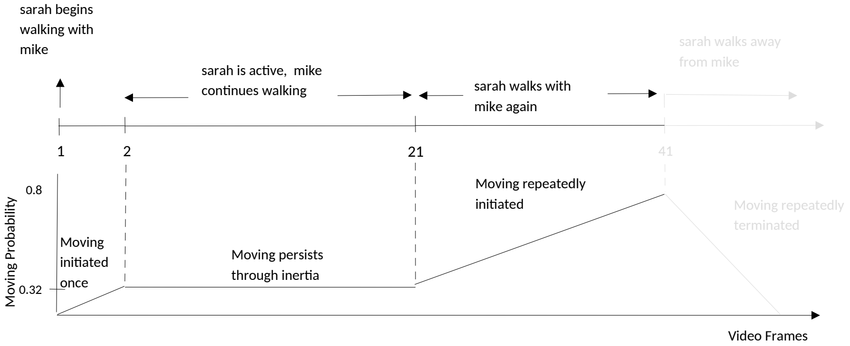


$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



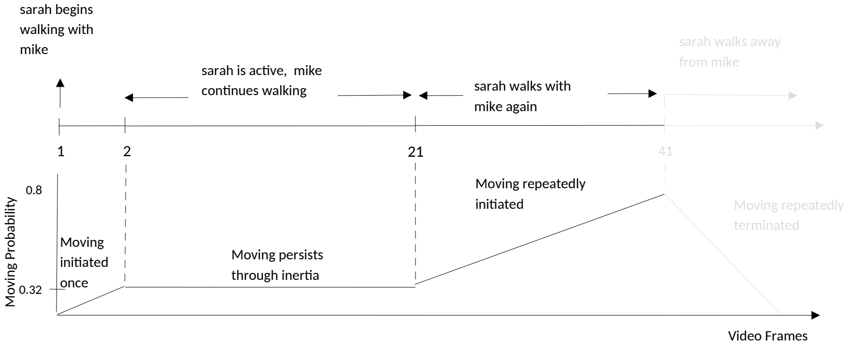
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



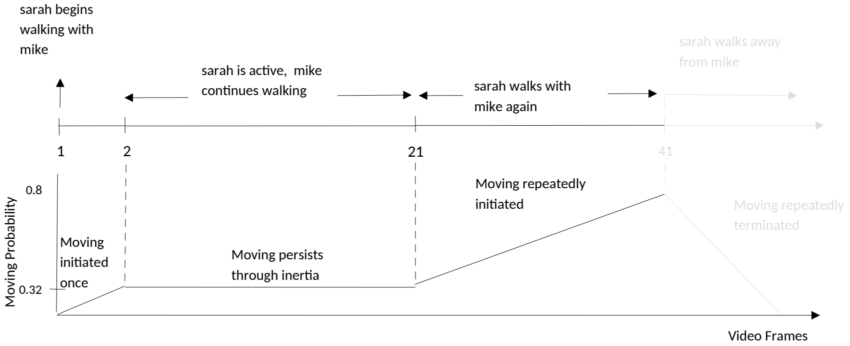
$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

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

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

Instantaneous Recognition

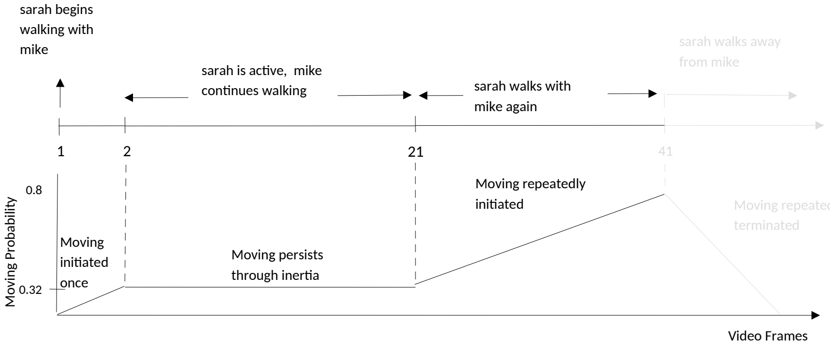


$$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\mathbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\mathbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\mathbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

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

Instantaneous Recognition



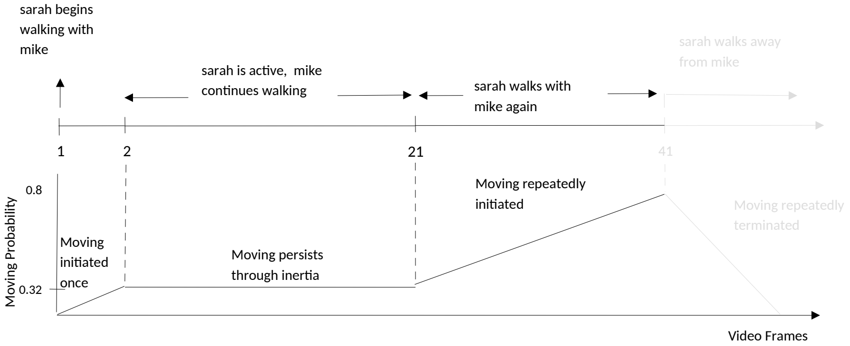
$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\ &\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\ &\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\ &\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



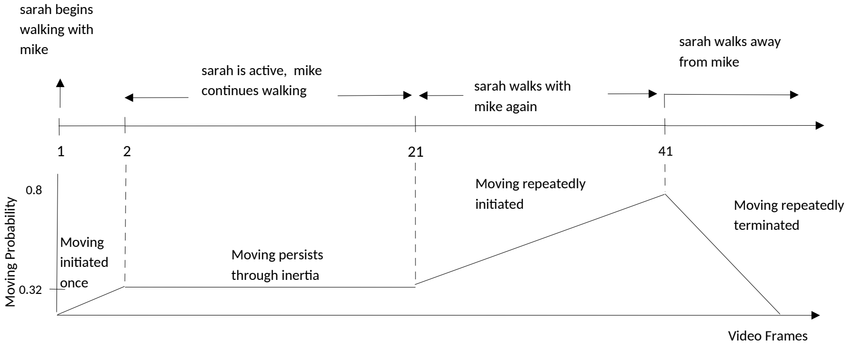
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



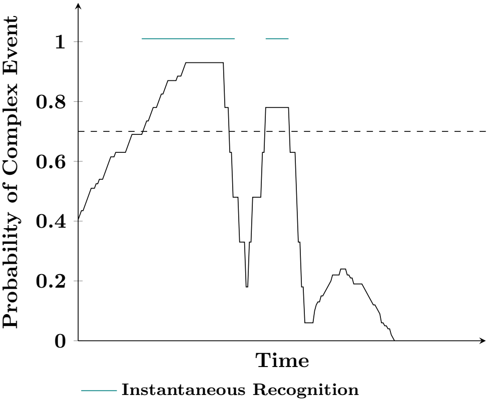
$$
\begin{aligned}
&\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

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

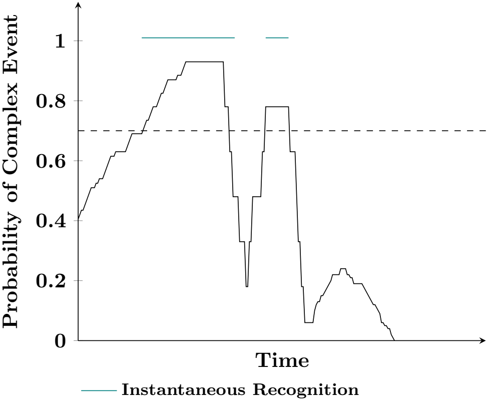
$$
\begin{aligned}
&P(\textbf{holdsAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 50)) =\\
&P(\textbf{initiatedAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 49) \vee\\
&\quad (\textbf{holdsAt}(\textit{moving}(\textit{mike}, \textit{sarah}) = \text{true}, 49) \wedge\\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

Instantaneous Recognition*



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

Instantaneous Recognition*

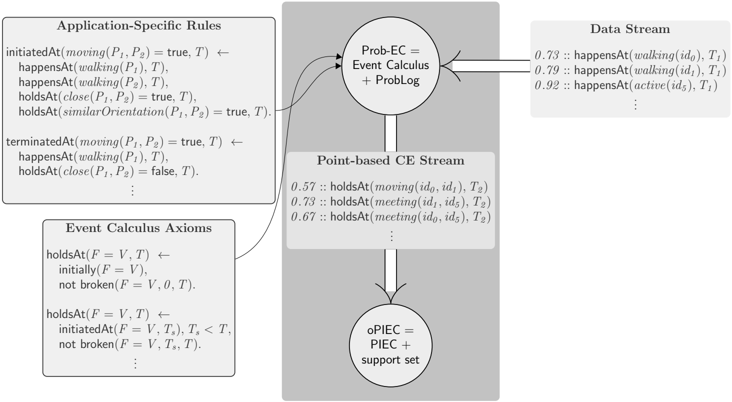


Higher accuracy than crisp reasoning in the presence of:

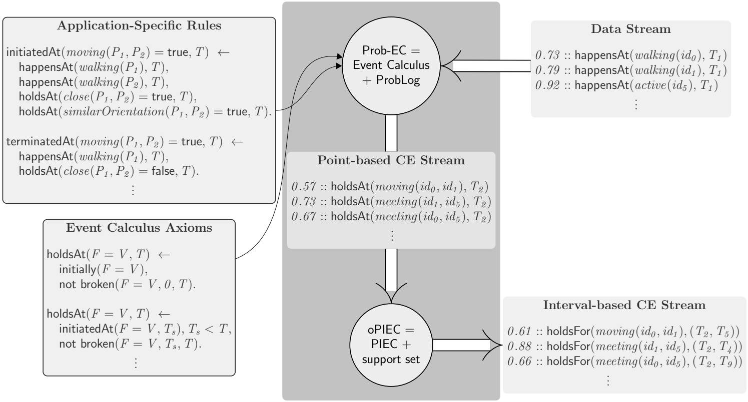
- several initiations and terminations;
- few probabilistic conjuncts.

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

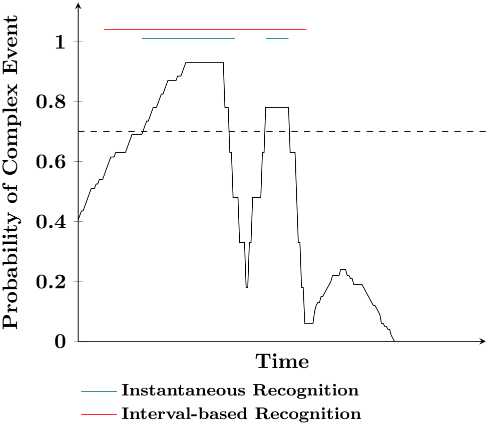
Online Probabilistic Interval-Based Event Calculus



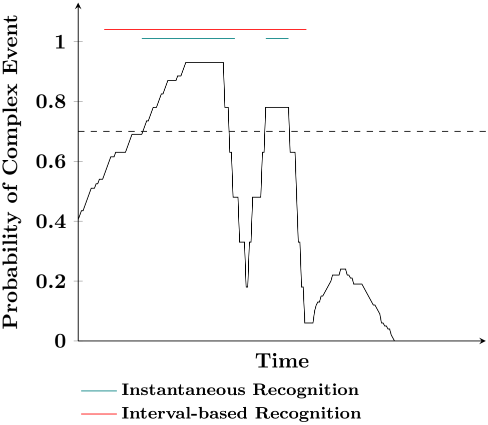
Online Probabilistic Interval-Based Event Calculus



Instantaneous vs Interval-based Recognition

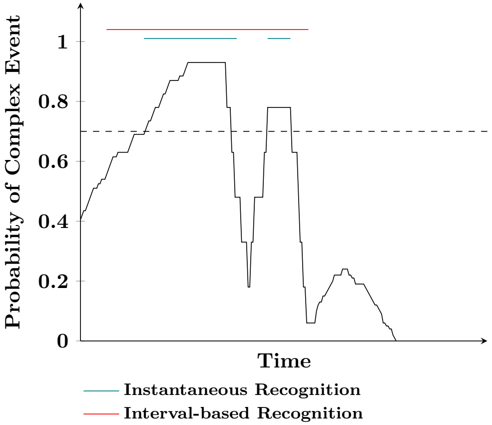


Instantaneous vs Interval-based Recognition



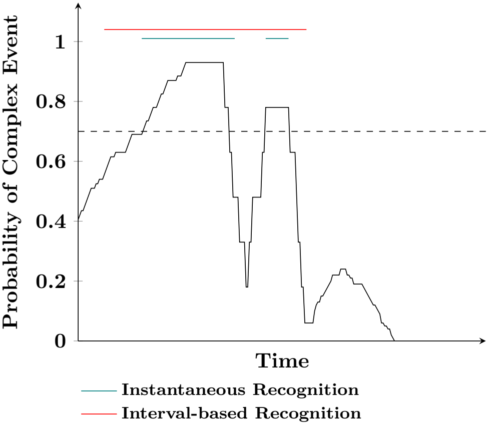
- Interval Probability: average probability of the time-points it contains.

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										

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

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

	⇑⇓									
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

	$\Uparrow$	$\Downarrow$								
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

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

Interval-based Recognition

	$\Uparrow$					$\Downarrow$				
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

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

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.

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

Complexity

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

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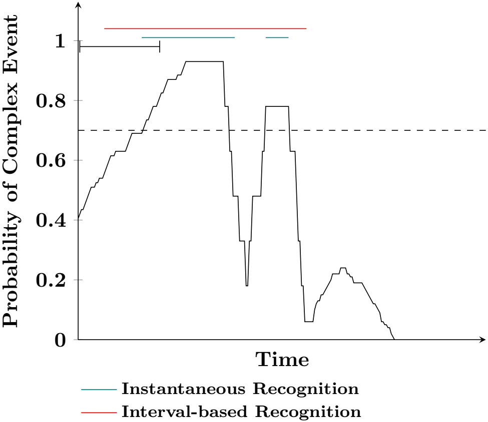
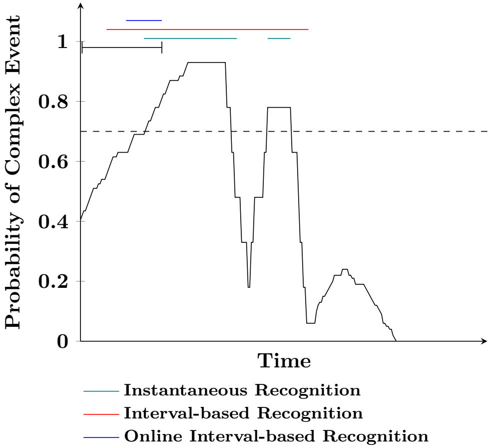
Online Interval-based Recognition



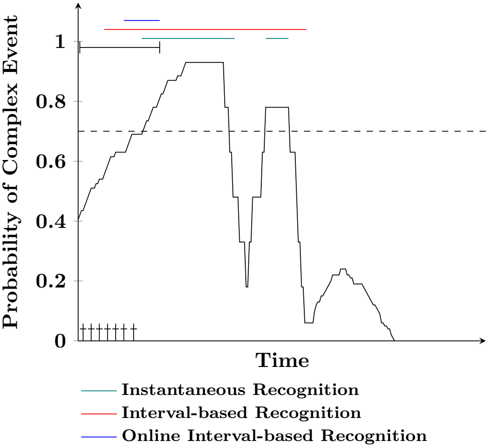
- Windowing.

Online Interval-based Recognition



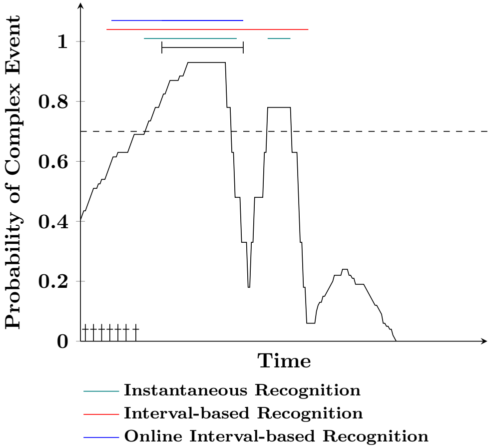
- Windowing.
- Probabilistic maximal interval computation.

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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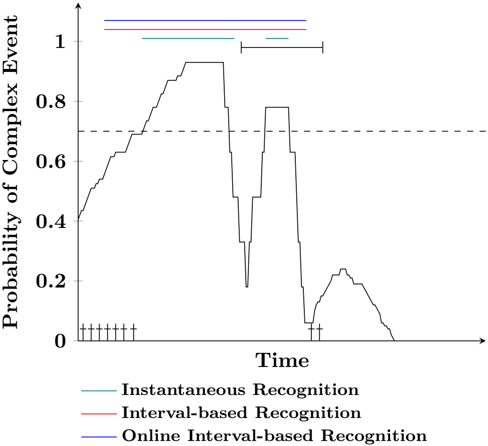

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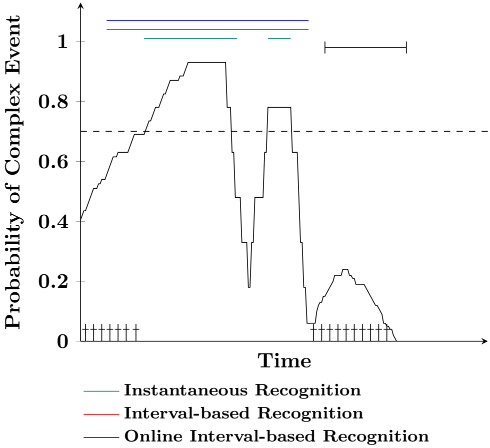

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Online Interval-based Recognition: Properties

Memory Minimality

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

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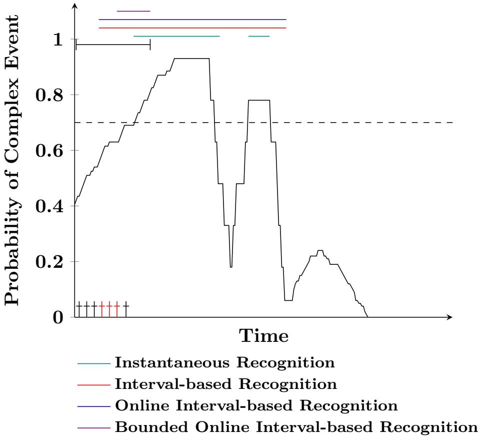
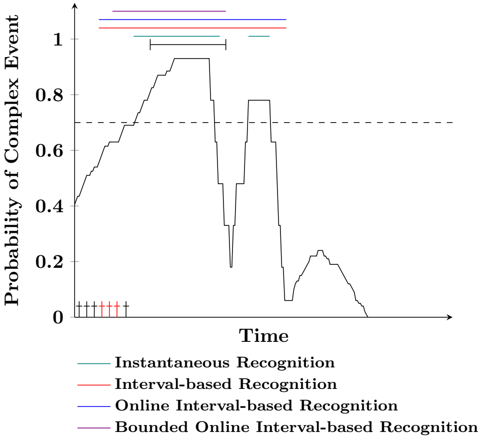
Bounded Online Interval-based Recognition*



- 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

Bounded Online Interval-based Recognition*



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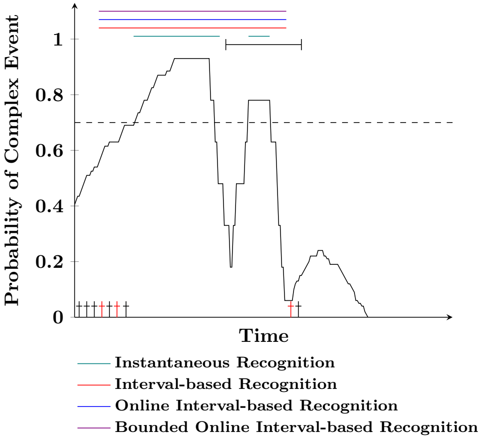

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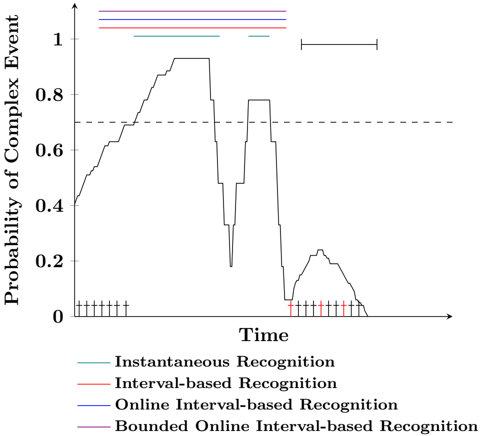
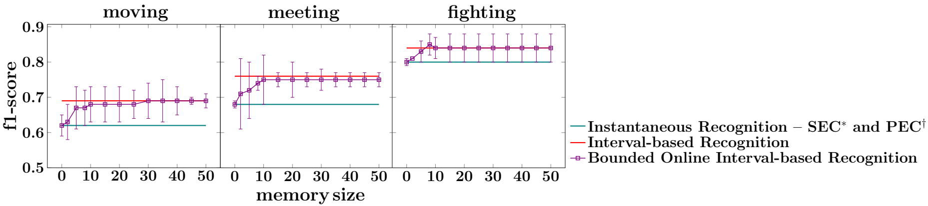
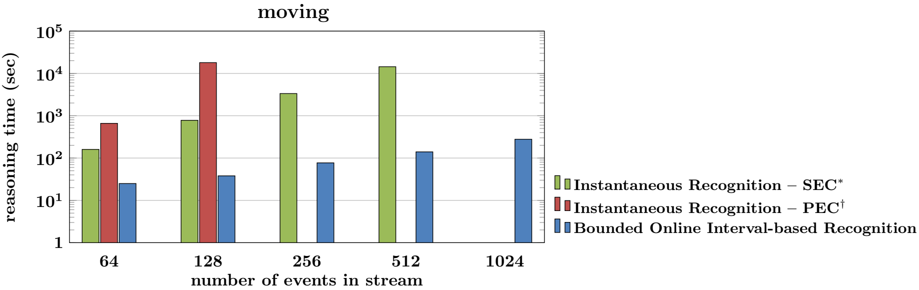


- Complex event duration statistics favor more recent potential starting points.
- Comparable accuracy to batch reasoning.

*Mantenoglou et al, Online Event Recognition over Noisy Data Streams. International Journal of Approximate Reasoning, 2023. https://github.com/Periklismant/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

Complex event recognition over noisy streams:

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- Probabilistic reasoning $\rightarrow$ robust complex event recognition.
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Complex event recognition over noisy streams:

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Next:

- Forecast complex events.