Making Sense of Streaming Data: Probabilistic CER

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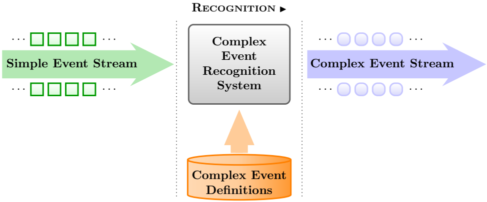
Slides, Papers, Code & Data

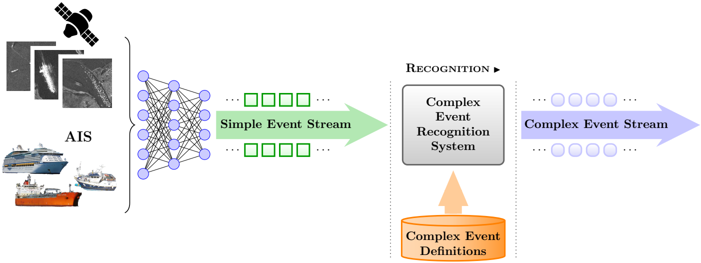
Making Sense of Streaming Data

Complex Event Recognition lab

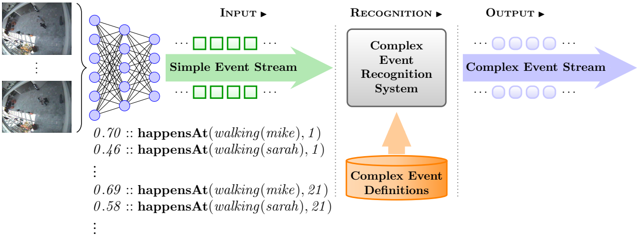
Complex Event Recognition (CER)



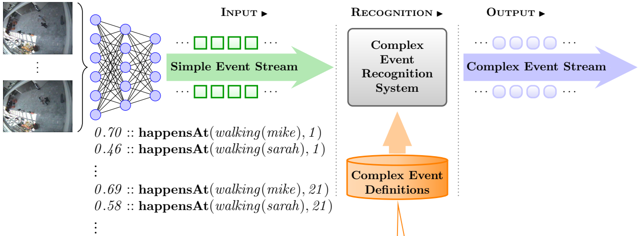
Complex Event Recognition (CER)



Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty

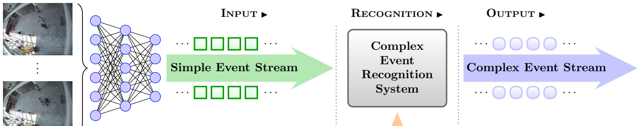


$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \mathsf{true},\ T) \leftarrow$
$\quad \mathbf{happensAt}(\mathit{walking}(P_1),\ T),$
$\quad \mathbf{happensAt}(\mathit{walking}(P_2),\ T),$
$\quad \mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \mathsf{true},\ T),$
$\quad \mathbf{holdsAt}(\mathit{orientation}(P_1,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

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

$\vdots$

Complex Event Recognition under Uncertainty



0.70 :: **happensAt**(*walking*(*mike*), *1*)
0.46 :: **happensAt**(*walking*(*sarah*), *1*)
⋮
0.69 :: **happensAt**(*walking*(*mike*), *21*)
0.58 :: **happensAt**(*walking*(*sarah*), *21*)
⋮

0.61 :: **holdsFor**(*moving*(*mike*, *sarah*) = true, [*2*, *18*])
0.87 :: **holdsFor**(*meeting*(*mike*, *sarah*) = true, [*16*, *29*])
⋮

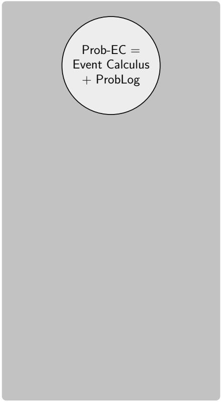
initiatedAt(*moving*(P_1, P_2) = true, T) ←
  happensAt(*walking*(P_1), T),
  happensAt(*walking*(P_2), T),
  holdsAt(*close*(P_1, P_2) = true, T),
  holdsAt(*orientation*(P_1, P_2) = true, T).

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

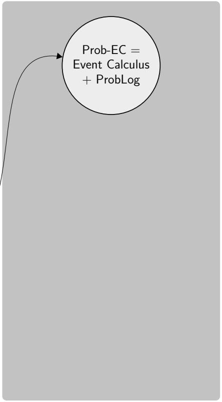
Activity Recognition

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

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

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

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

$\vdots$

Event Calculus Axioms

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

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

$\vdots$

Prob-EC =
Event Calculus
+ ProbLog

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).

$\vdots$

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

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

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)
$\vdots$

Point-based CE Stream

0.57 :: holdsAt($moving(id_0, id_1)$, T_2)
0.73 :: holdsAt($meeting(id_1, id_5)$, T_2)
0.67 :: holdsAt($meeting(id_0, id_5)$, T_2)
$\vdots$

Instantaneous Recognition

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

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

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

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

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

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

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

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

Instantaneous Recognition

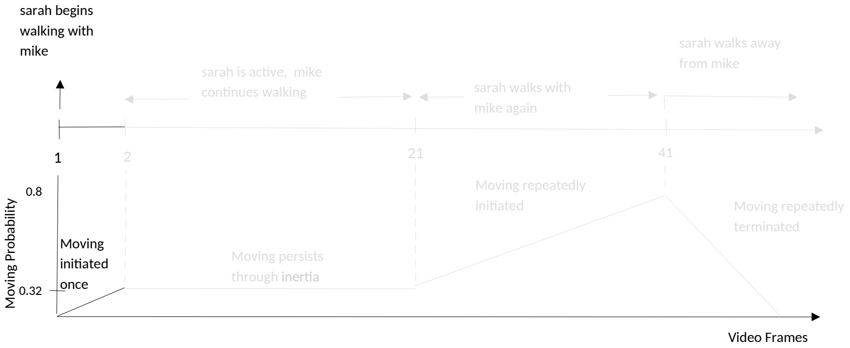
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



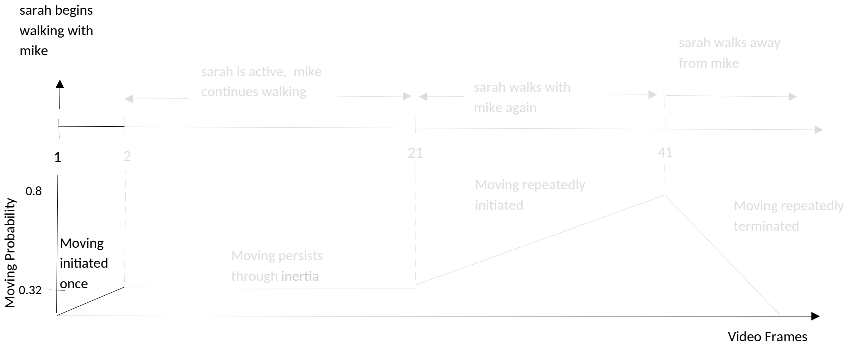
$$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

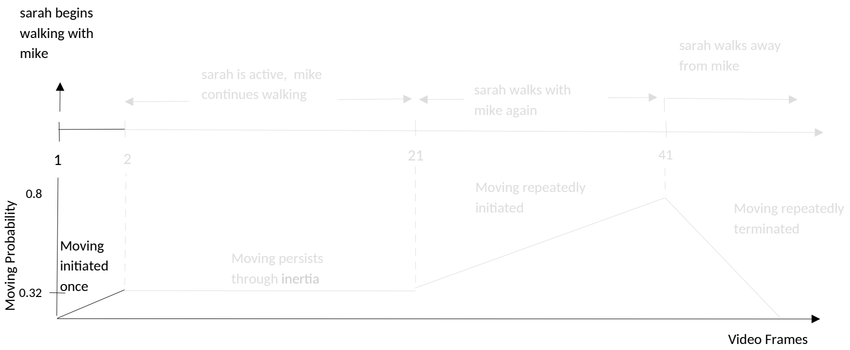


$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\ &\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\ &\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\ &\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



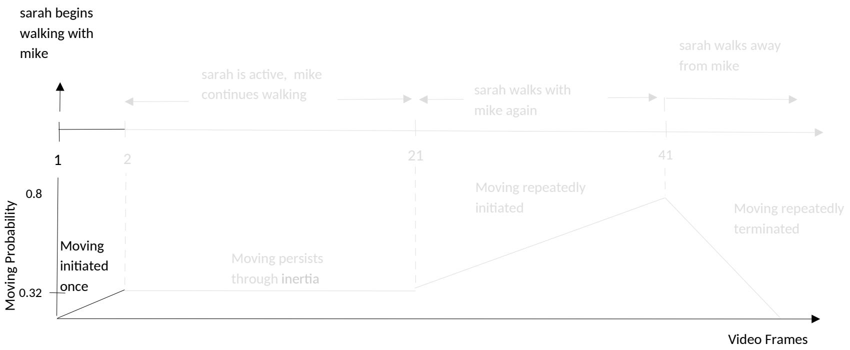
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

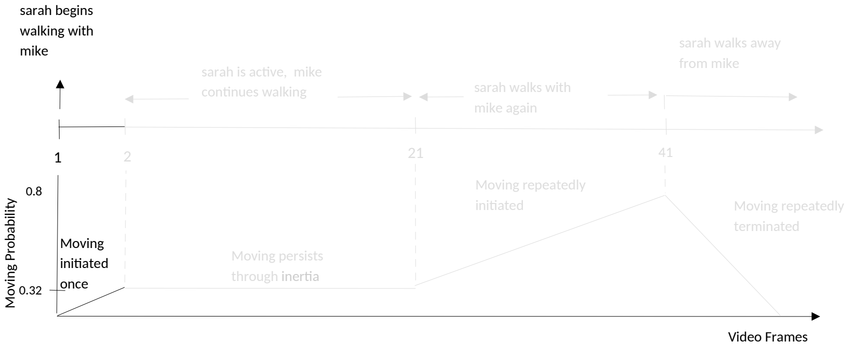


$$\begin{aligned}
&\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\textit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\textit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

$$\begin{aligned}
&\mathit{0.45} :: \textbf{happensAt}(\textit{walking}(\textit{mike}),\ \mathit{20}). \\
&\mathit{0.14} :: \textbf{happensAt}(\textit{active}(\textit{sarah}),\ \mathit{20}).
\end{aligned}$$

Instantaneous Recognition



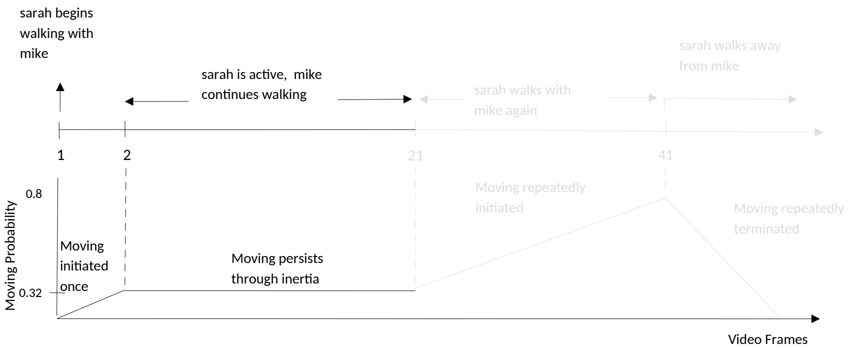
$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \mathrm{true},\ T) \leftarrow\\&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \mathrm{true},\ T),\\&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



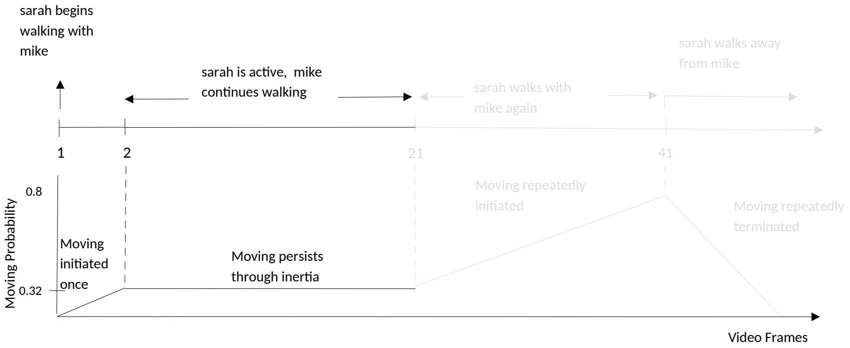
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

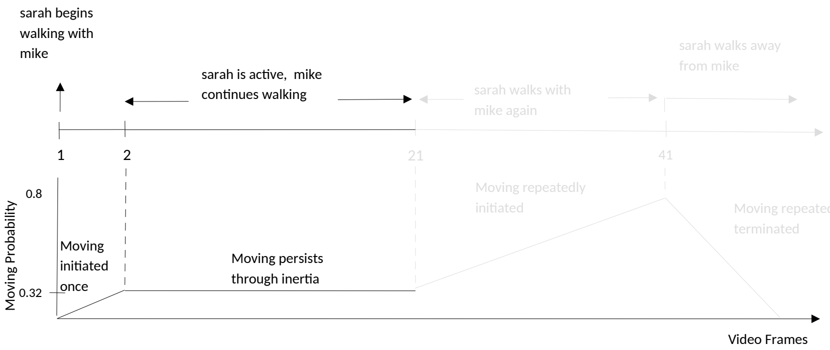


$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



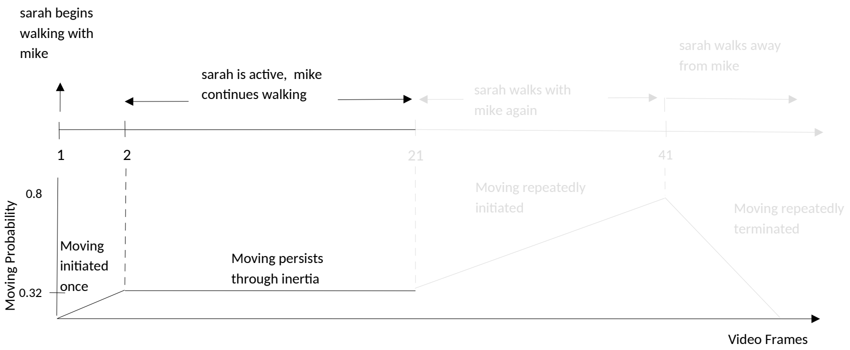
$$\begin{aligned}&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\ &\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\ &\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\ &\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

$$\begin{aligned}&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21)) =\\ &\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{mike}), 21)) \times\\ &\quad P(\textbf{happensAt}(\mathit{walking}(\mathit{sarah}), 21)) \times\\ &\quad P(\textbf{holdsAt}(\mathit{close}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21)) \times\\ &\quad P(\textbf{holdsAt}(\mathit{orientation}(\mathit{mike}, \mathit{sarah}) = \text{true}, 21))\\ &\quad = 0.39 \times 0.28 \times 1 \times 1 = 0.11\end{aligned}$$

Instantaneous Recognition



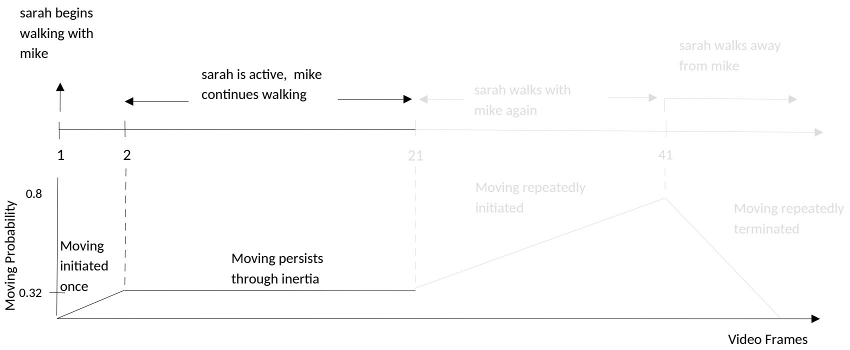
$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

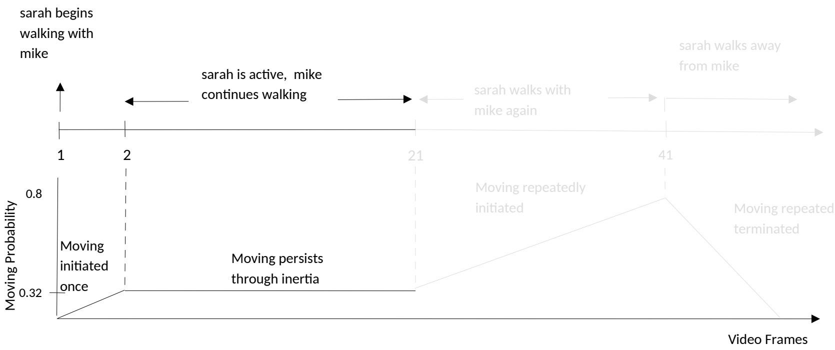


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



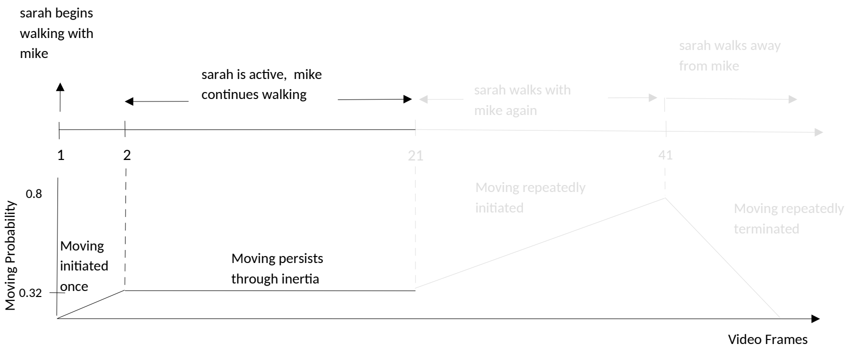
$$\begin{aligned}
&\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ \ T) \leftarrow \\
&\quad \textbf{happensAt}(walking(P_1),\ \ T), \\
&\quad \textbf{happensAt}(walking(P_2),\ \ T), \\
&\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ \ T), \\
&\quad \textbf{holdsAt}(orientation(P_1, P_2)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

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

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

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

Instantaneous Recognition



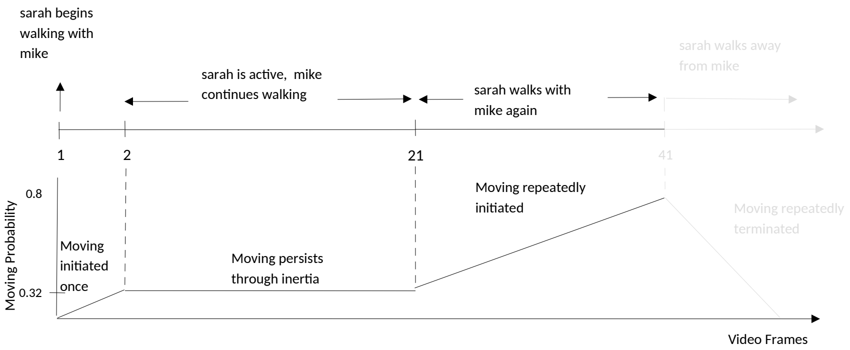
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



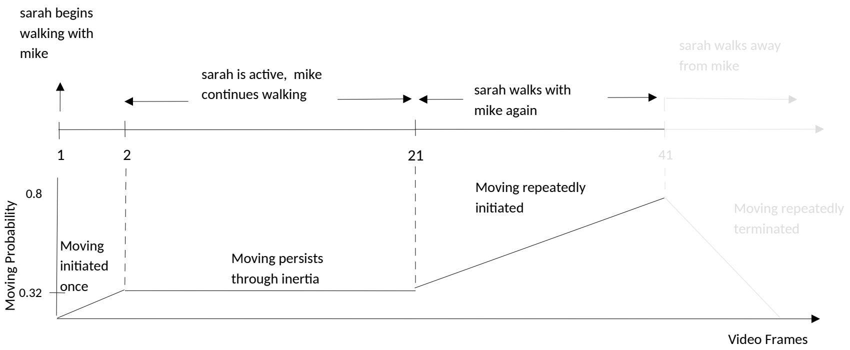
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

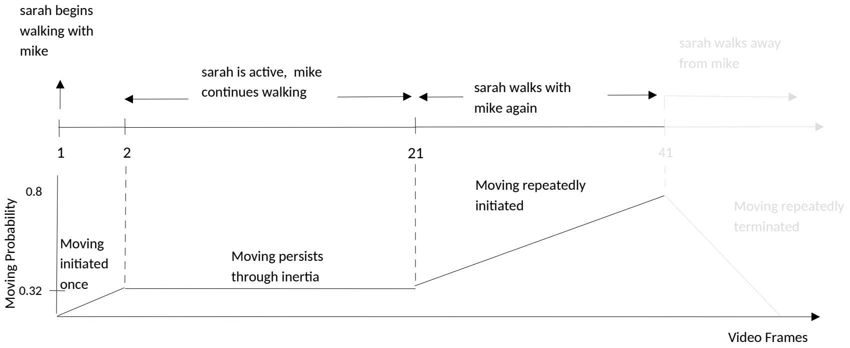


$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



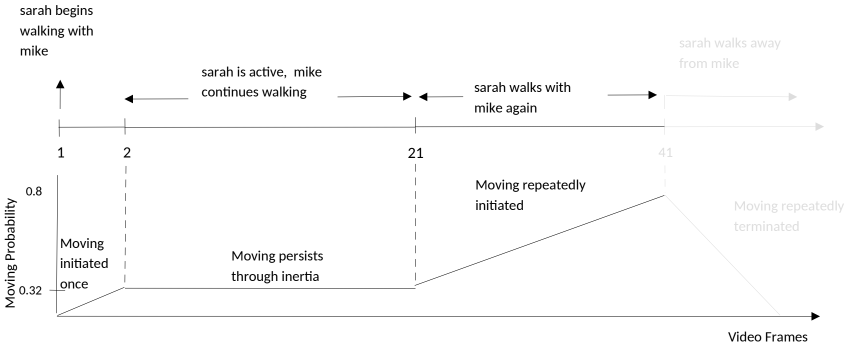
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



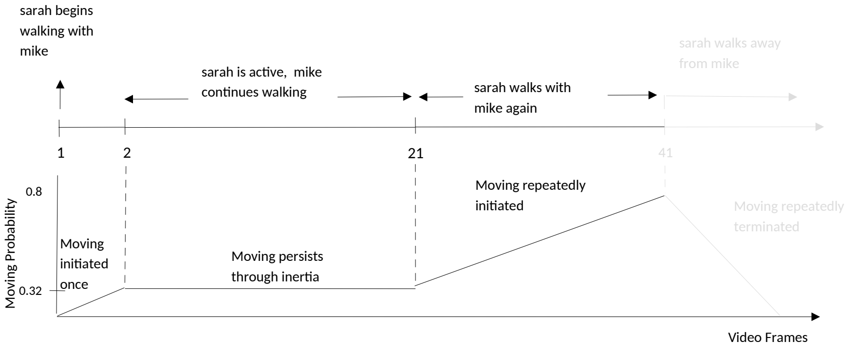
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

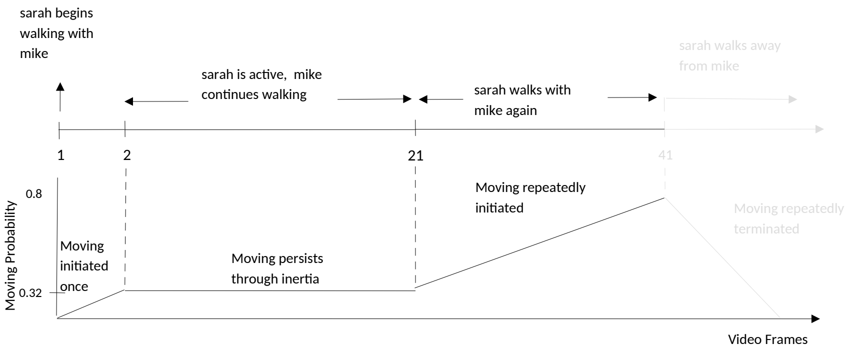


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

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

Instantaneous Recognition



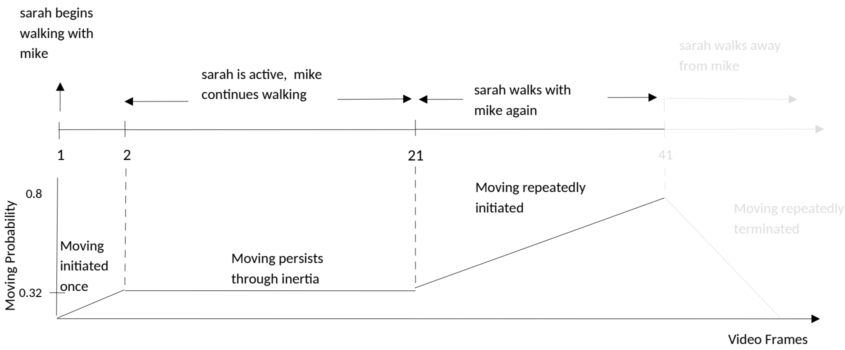
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



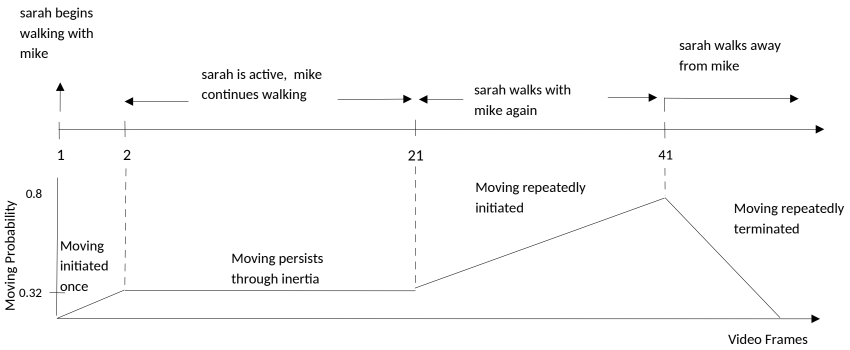
$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



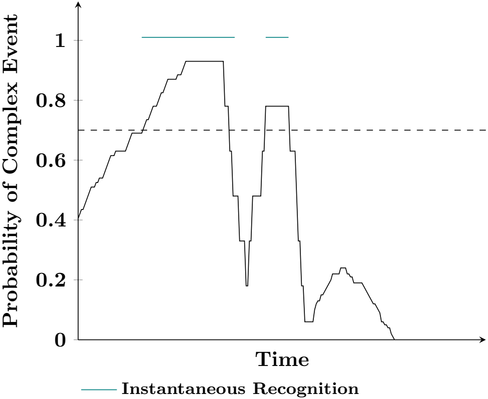
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

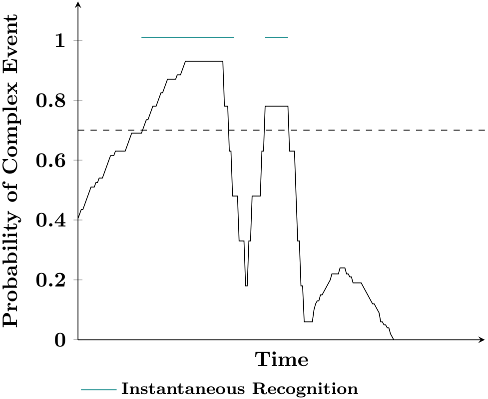
$$
\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 50)) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \wedge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

Instantaneous Recognition*



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

Instantaneous Recognition*

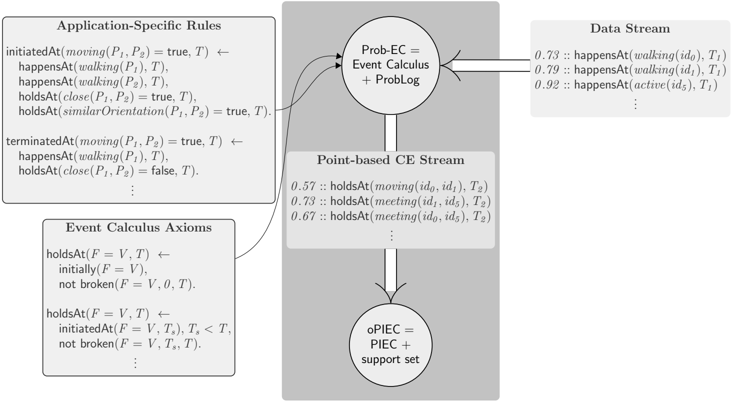


Higher accuracy than crisp reasoning in the presence of:

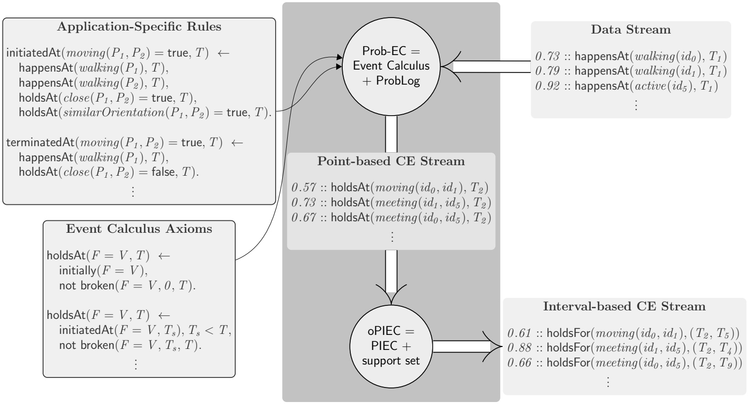
- several initiations and terminations;
- few probabilistic conjuncts.

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

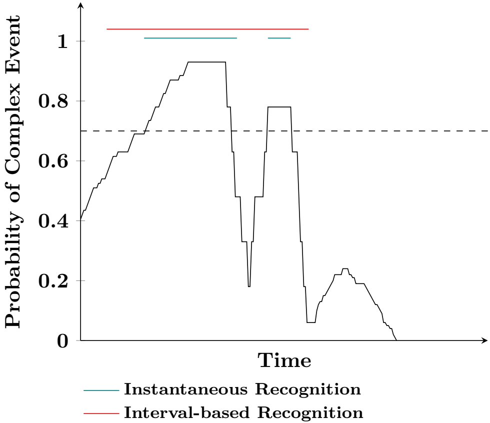
Online Probabilistic Interval-Based Event Calculus



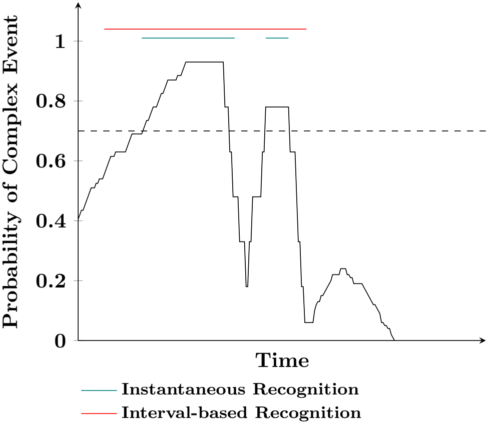
Online Probabilistic Interval-Based Event Calculus



Instantaneous vs Interval-based Recognition

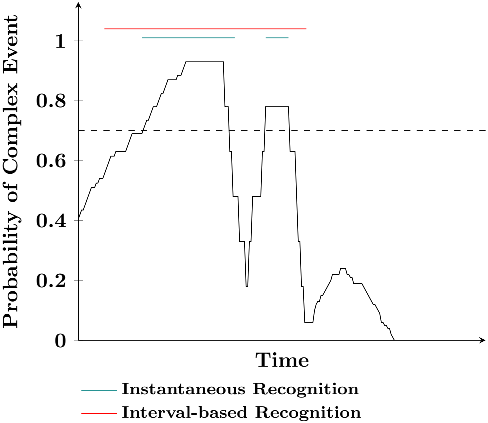


Instantaneous vs Interval-based Recognition



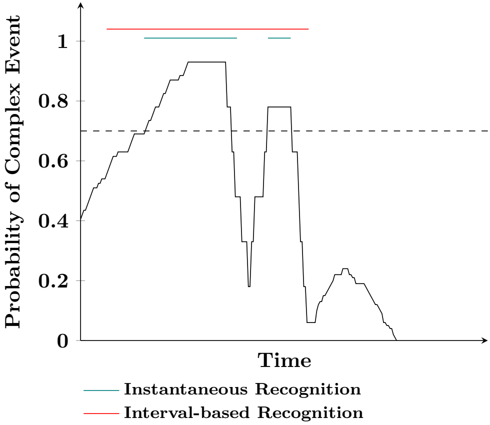
- Interval Probability: average probability of the time-points it contains.

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										

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

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

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

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

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

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

Time	$\Uparrow$ 1	$\Downarrow$ 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

		$\Uparrow$				$\Downarrow$				
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

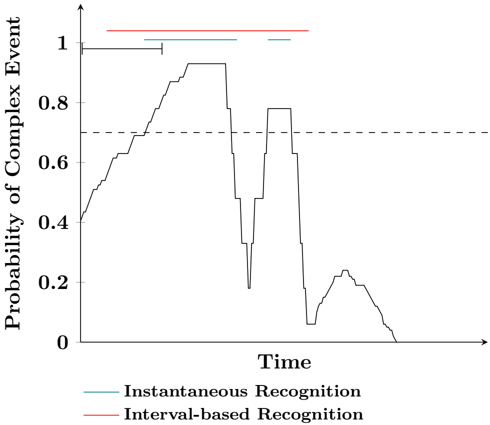
An interval is computed iff it is a probabilistic maximal interval.

Complexity

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

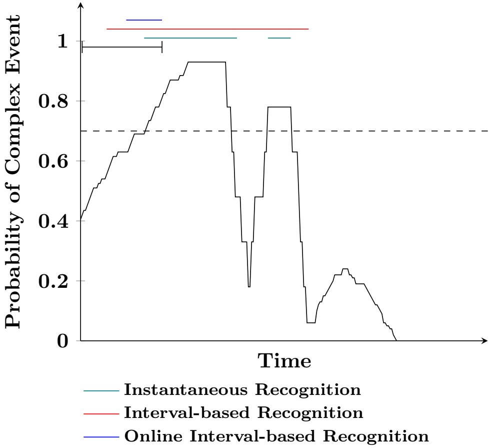
*Artikis et al, A Probabilistic Interval-based Event Calculus for Activity Recognition. Annals of Mathematics and Artificial Intelligence, 2021.

Online Interval-based Recognition



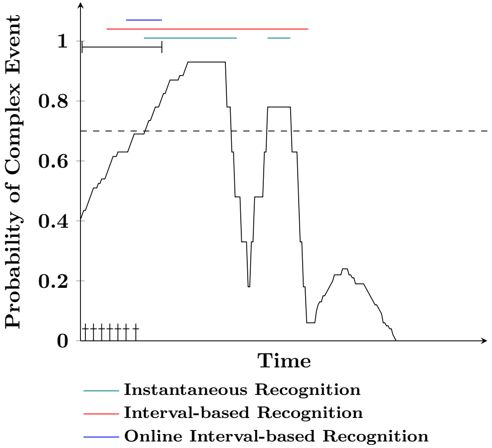
- Windowing.

Online Interval-based Recognition



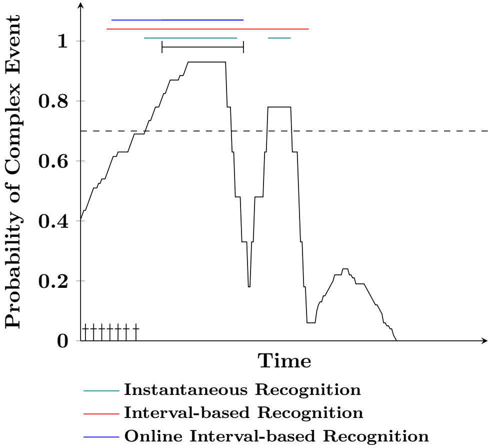
- Windowing.
- Probabilistic maximal interval computation.

Online Interval-based Recognition



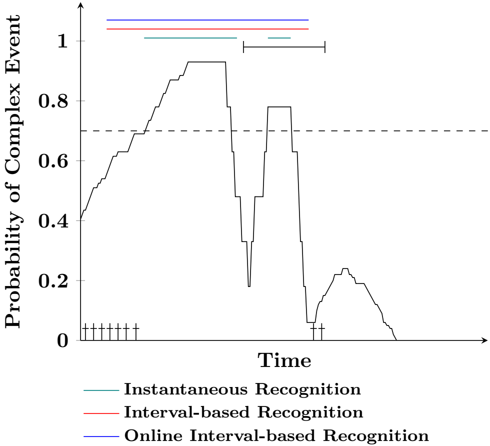
- Windowing.
- Probabilistic maximal interval computation.
- Caching potential starting points.
  - Discard time-point t iff there is a $t' < t$ that can be the starting point of a probabilistic maximal interval including t.

Online Interval-based Recognition



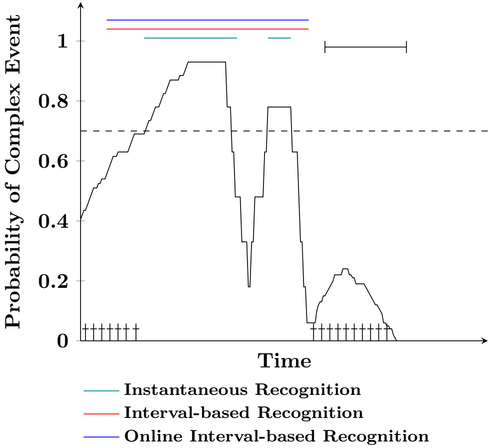
- Windowing.
- Probabilistic maximal interval computation.
- Caching potential starting points.
  - Discard time-point t iff there is a $t' < t$ that can be the starting point of a probabilistic maximal interval including t.

Online Interval-based Recognition



- 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



- 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: Properties

Memory Minimality

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

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.

Interval Computation Correctness

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

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.

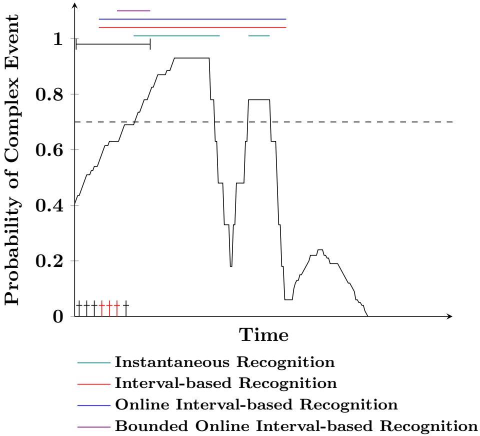
Interval Computation Correctness

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

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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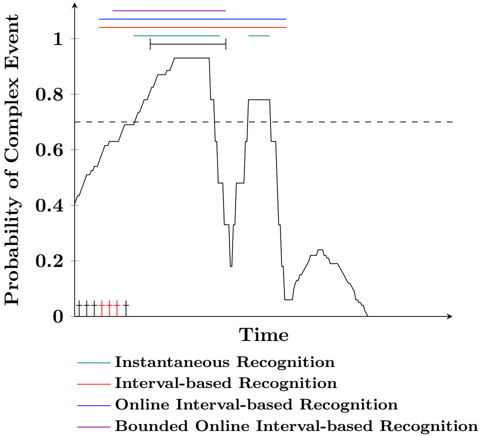

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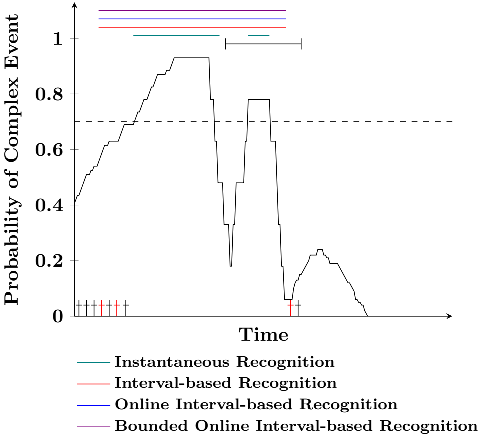

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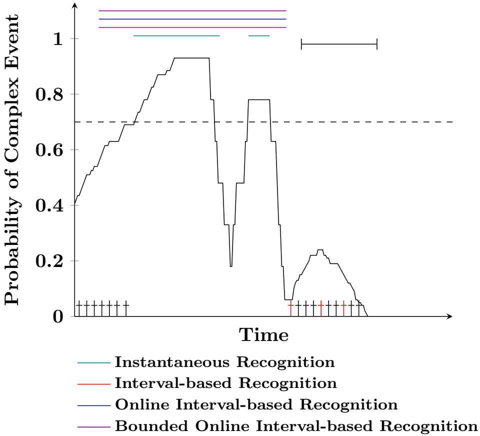

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- Comparable accuracy to batch reasoning.

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

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Complex event recognition over noisy streams:

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- Probabilistic reasoning $\rightarrow$ robust complex event recognition.
- Interval-based reasoning $\rightarrow$ improved predictive accuracy.
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- Optimal stream compression $\rightarrow$ correct complex event recognition.
- Direct routes to neuro-symbolic learning $\rightarrow$ end-to-end optimisation of simple and complex event recognition.

Computing the probability of holdsAt

- Consider the initiation and termination probabilities for "$moving(mike, sarah) = \text{true}$" below. $P(x)$ denotes the probability of x.

Time	1	2	3	...	25
P(initiatedAt(moving(mike,sarah)=true, T))	0.4	0.5	0	0	0
P(terminatedAt(moving(mike,sarah)=true, T))	0	0	0	0	0.7

- What is the probability of:
  - $\text{holdsAt}(moving(mike, sarah) = \text{true}, 3)$?
  - $\text{holdsAt}(moving(mike, sarah) = \text{true}, 21)$?
  - $\text{holdsAt}(moving(mike, sarah) = \text{true}, 26)$?

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- Introduction to Complex Event Recognition (CER).
- Formal Models for CER
- Probabilistic CER.

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- Topics not covered.