Complex Event Recognition

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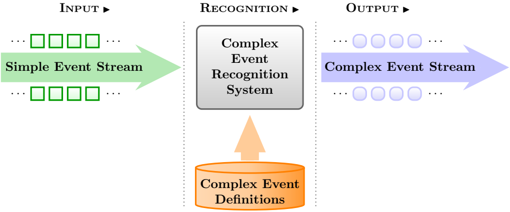
[2]University of Piraeus, Greece

https://cer.iit.demokritos.gr

Complex Event Recognition (Event Pattern Matching)*,†



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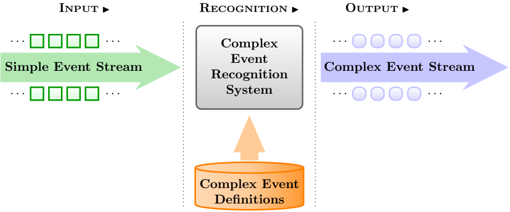

https://rdcu.be/cNkQE

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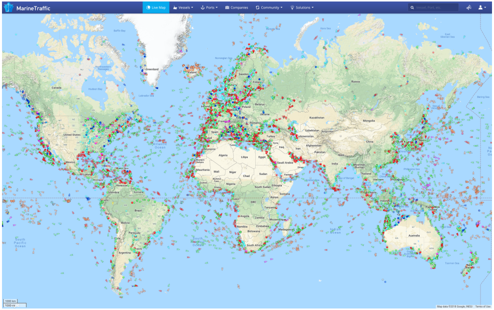
Maritime Situational Awareness*



http://www.marinetraffic.com

*Artikis and Zissis, Guide to Maritime Informatics, Springer, 2021.

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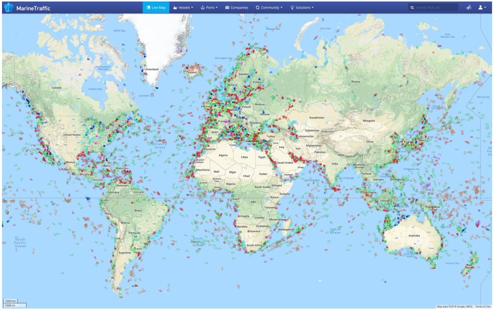

http://www.marinetraffic.com

https://cer.iit.demokritos.gr (fishing vessel)

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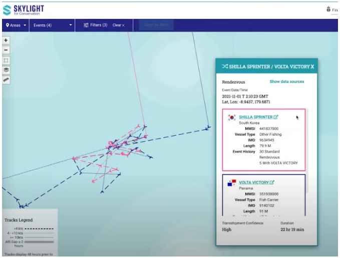
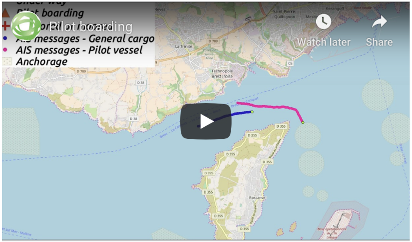
Maritime Situational Awareness*

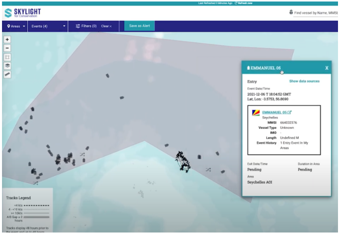
https://cer.iit.demokritos.gr (tugging)



https://www.skylight.global (rendez-vous)



https://cer.iit.demokritos.gr (pilot boarding)



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Data Challenges

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- ... and static information
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- Lack of Veracity: GPS manipulation, vessels reporting false identity, communication gaps.
- Distribution: Vessels operating across the globe.

Many Other Applications

- Cardiac arrhythmia recognition.
- Financial fraud detection.
- Human activity recognition.
- Intrusion detection in computer networks.
- Traffic congestion recognition and forecasting in smart cities.

Requirements

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  - to avoid the time-consuming, error-prone manual CE definition development.
- Reasoning under uncertainty
  - to deal with various types of noise.
- Complex event forecasting
  - to support proactive decision-making.

Complex Event Recognition vs Database Management Systems*

Complex event recognition systems:

- Process data without storing them.

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- Users install standing/continuous queries:
  - Queries deployed once and executed continuously until removed.
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- No assumption can be made on data arrival order.
- Users install standing/continuous queries:
  - Queries deployed once and executed continuously until removed.
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- Latency requirements are very strict.

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Complex Event Recognition vs Deep Learning

We have Deep Learning and it seems to work. Can we go home?

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Complex event recognition:

- Formal semantics* for trustworthy models.
- Explanation — why did we detect a complex event?
- Machine Learning is necessary. But:
  - Complex events are rare.
  - Supervision is scarce.
- More often than not, background knowledge is available — let's use it!

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Event Calculus*

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

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

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Run-Time Event Calculus (RTEC)*

$$\begin{aligned}&\textbf{initiatedAt}(F=V,\ T) \leftarrow\\ &\quad \textbf{happensAt}(E_{In_1},\ T),\\ &\quad [\text{conditions}]\\ &\ldots\\ &\textbf{initiatedAt}(F=V,\ T) \leftarrow\\ &\quad \textbf{happensAt}(E_{In_i},\ T),\\ &\quad [\text{conditions}]\end{aligned}$$

$$\begin{aligned}&\textbf{terminatedAt}(F=V,\ T) \leftarrow\\ &\quad \textbf{happensAt}(E_{T_1},\ T),\\ &\quad [\text{conditions}]\\ &\ldots\\ &\textbf{terminatedAt}(F=V,\ T) \leftarrow\\ &\quad \textbf{happensAt}(E_{T_j},\ T),\\ &\quad [\text{conditions}]\end{aligned}$$

where

$$\text{conditions:}\quad \begin{aligned}&{}^{0-K}\textbf{happensAt}(E_k,\ T),\\ &{}^{0-M}\textbf{holdsAt}(F_m=V_m,\ T),\\ &{}^{0-N}\text{atemporal-constraint}_n\end{aligned}$$

*Artikis et al, An Event Calculus for Event Recognition. IEEE TKDE, 2015.
https://github.com/aartikis/RTEC

Run-Time Event Calculus (RTEC)

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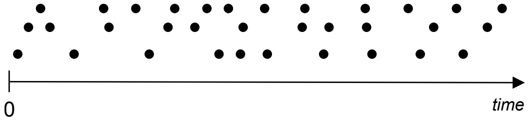

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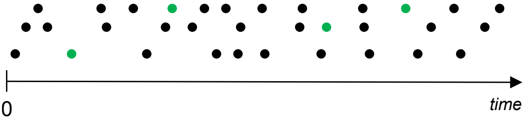

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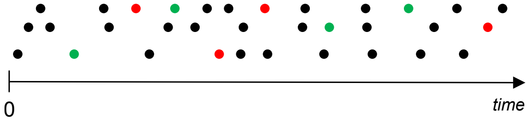

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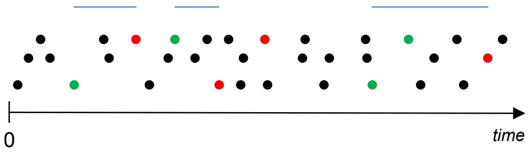
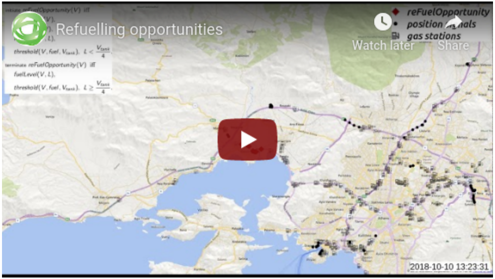
$\textbf{holdsFor}(F = V,\ I)$



Fleet Management*



https://cer.iit.demokritos.gr (refuelling opportunities)

*Tsilionis et al, Online Event Recognition from Moving Vehicles. Theory and Practice of Logic Programming, 2019.

RTEC: Interval-based Reasoning

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{anchoredOrMoored}(\mathit{Vessel}) = \mathrm{true},\ I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{farFromPorts},\ I_{sf}), \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{anchorage}) = \mathit{true},\ I_{wa}), \\
&\quad \textbf{intersect\_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
&\quad \textbf{holdsFor}(\mathit{stopped}(\mathit{Vessel}) = \mathit{nearPorts},\ I_{sn}), \\
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\end{aligned}
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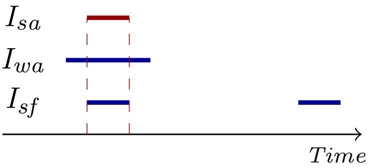

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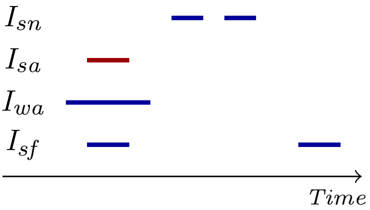

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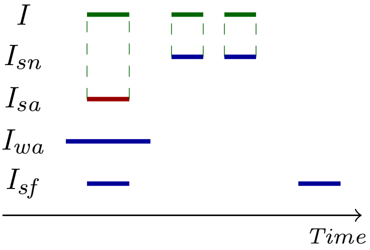

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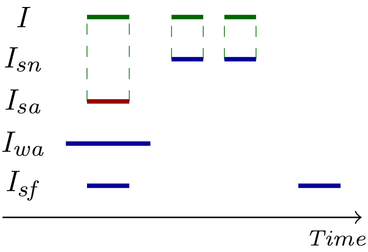
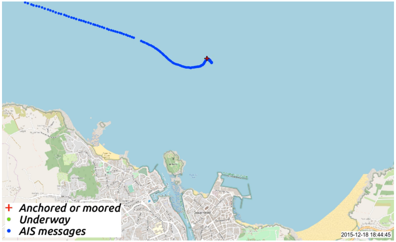
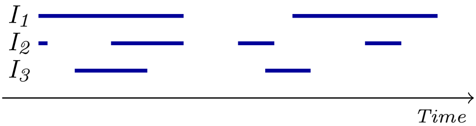




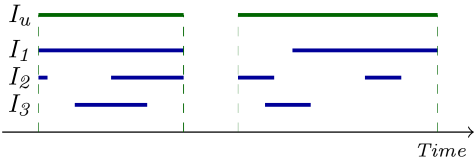
https://cer.iit.demokritos.gr (anchored or moored)

RTEC: Interval-based Reasoning



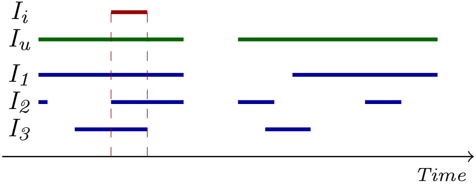
RTEC: Interval-based Reasoning

union_all$([I_1, I_2, I_3], I_u)$



RTEC: Interval-based Reasoning

intersect_all$([I_1, I_2, I_3], I_i)$
union_all$([I_1, I_2, I_3], I_u)$

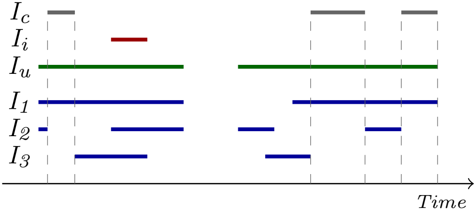


RTEC: Interval-based Reasoning

relative_complement_all$(I_1, [I_2, I_3], I_c)$

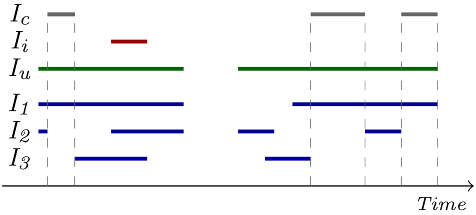
intersect_all$([I_1, I_2, I_3], I_i)$

union_all$([I_1, I_2, I_3], I_u)$

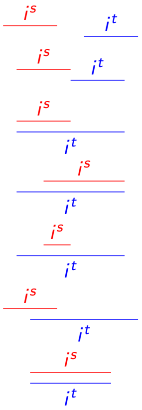


RTEC: Interval-based Reasoning & Allen Relations*

relative_complement_all$(I_1, [I_2, I_3], I_c)$
intersect_all$([I_1, I_2, I_3], I_i)$
union_all$([I_1, I_2, I_3], I_u)$

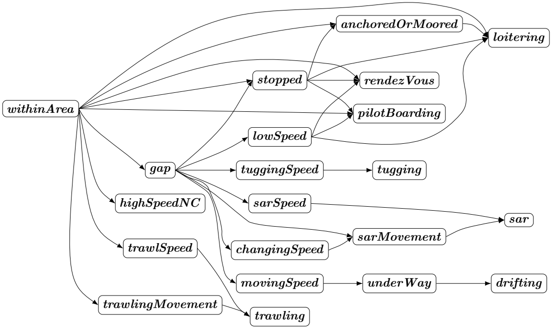


Relation	Illustration
before(i^s, i^t)	
meets(i^s, i^t)	
starts(i^s, i^t)	
finishes(i^s, i^t)	
during(i^s, i^t)	
overlaps(i^s, i^t)	
equal(i^s, i^t)	



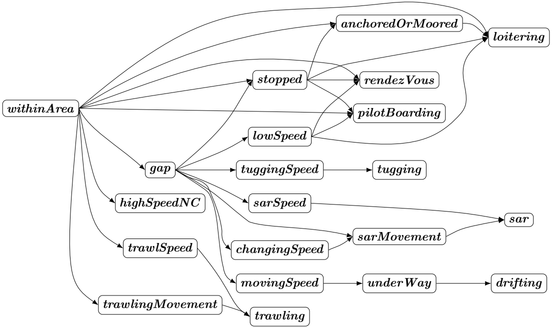
*Mantenoglou et al, Complex Event Recognition with Allen Relations. Knowledge Representation and Reasoning (KR), 2023.

Semantics

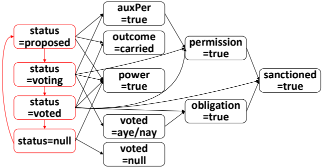


anchoredOrMoored
loitering
stopped
rendezVous
withinArea
pilotBoarding
lowSpeed
gap
tuggingSpeed
tugging
highSpeedNC
sarSpeed
sar
sarMovement
trawlSpeed
changingSpeed
movingSpeed
underWay
drifting
trawlingMovement
trawling

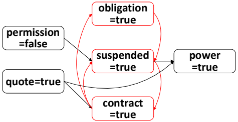
Semantics



withinArea
anchoredOrMoored
loitering
stopped
rendezVous
pilotBoarding
lowSpeed
gap
tuggingSpeed
tugging
highSpeedNC
sarSpeed
sar
sarMovement
trawlSpeed
changingSpeed
movingSpeed
underWay
drifting
trawlingMovement
trawling

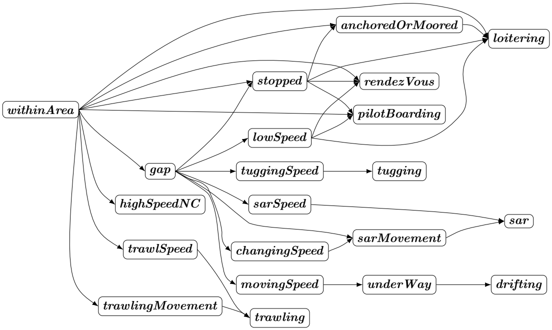


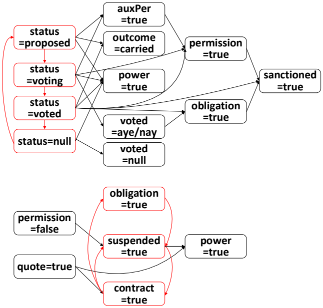
auxPer =true
status =proposed
outcome =carried
permission =true
status =voting
power =true
sanctioned =true
status =voted
obligation =true
voted =aye/nay
status=null
voted =null



obligation =true
permission =false
suspended =true
power =true
quote=true
contract =true

Semantics



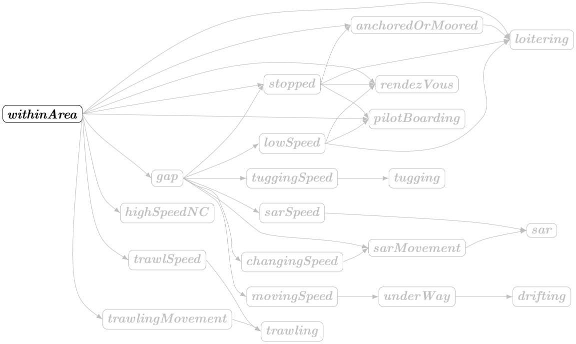


Proposition

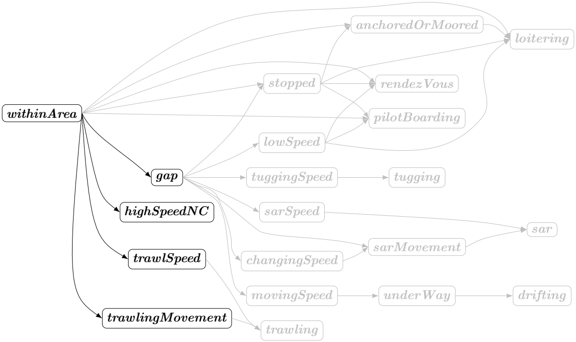
An event description in RTEC is a locally stratified logic program*.

*Mantenoglou et al, Stream Reasoning with Cycles. Knowledge Representation and Reasoning (KR), 2022.

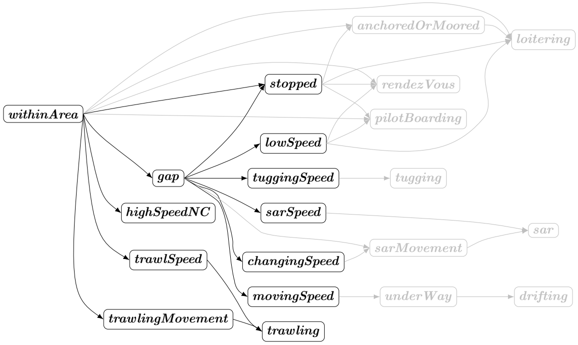
Stratification & Reasoning



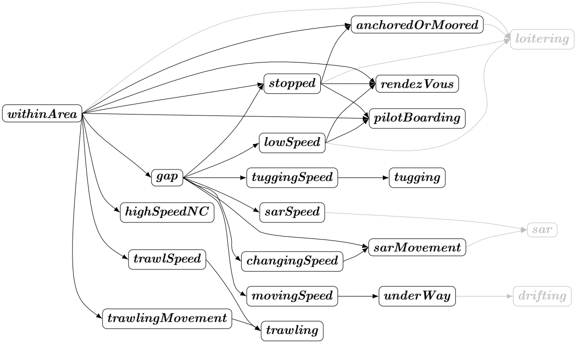
Stratification & Reasoning



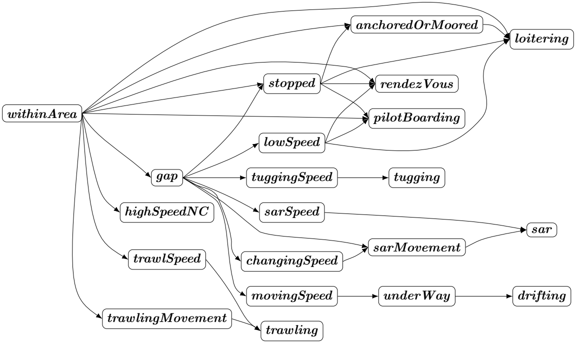
Stratification & Reasoning



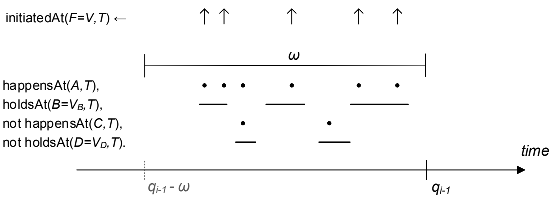
Stratification & Reasoning



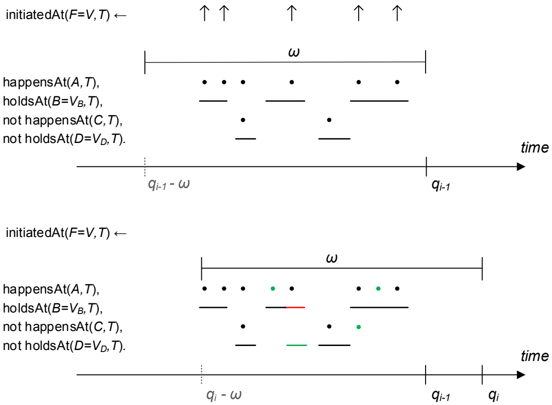
Stratification & Reasoning



Windowing


initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i-1 - ω
q_i-1

Windowing



initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i-1 - ω
q_i-1
initiatedAt(F=V,T) ←
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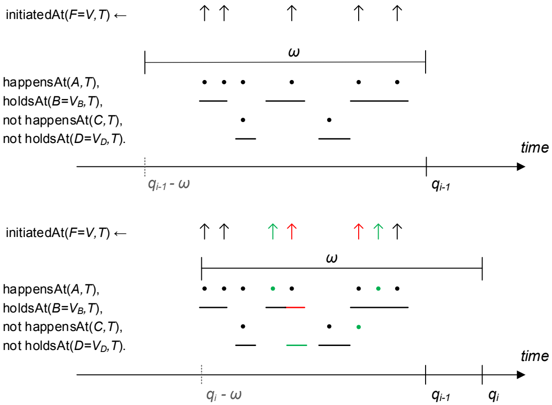
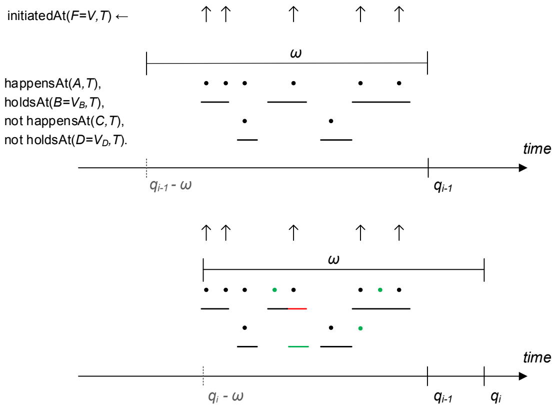
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i - ω
q_i-1
q_i

Windowing



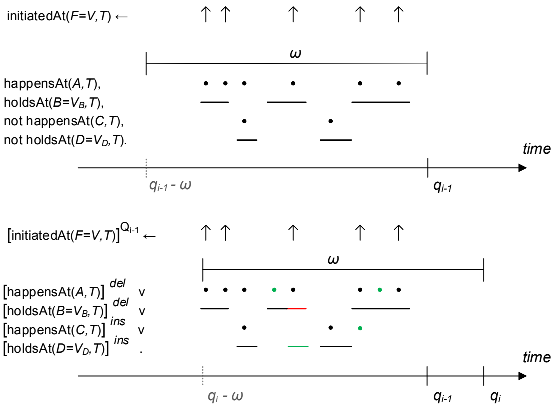
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_{i-1} - ω
q_{i-1}
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i - ω
q_{i-1}
q_i

Incremental Reasoning: Deletion Phase*



*Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

Incremental Reasoning: Deletion Phase*



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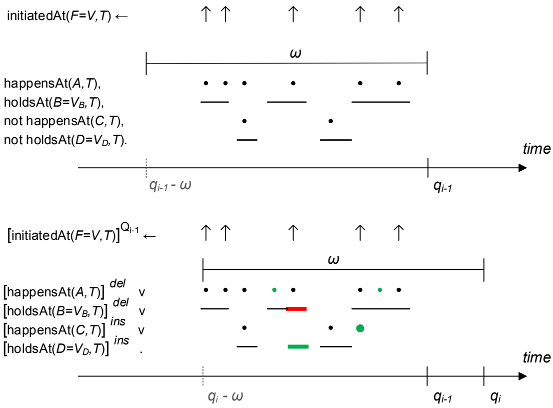

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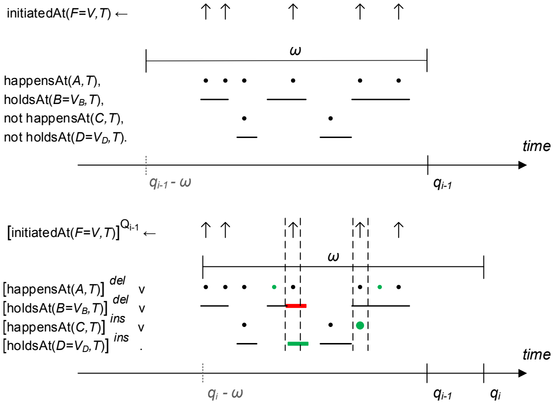

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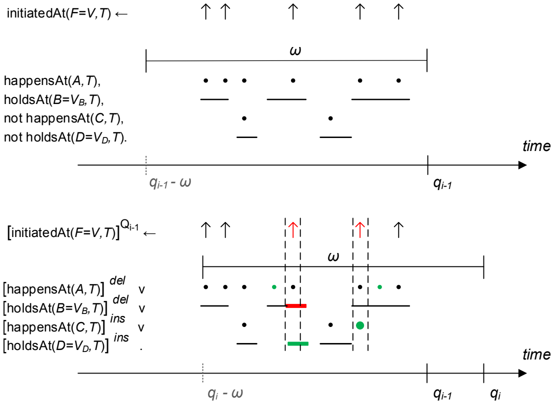

*Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

RTEC: Correctness and Complexity

Correctness

RTEC computes all maximal intervals of a fluent, and no other interval, provided that interval delays/retractions, if any, are tolerated by the window size.

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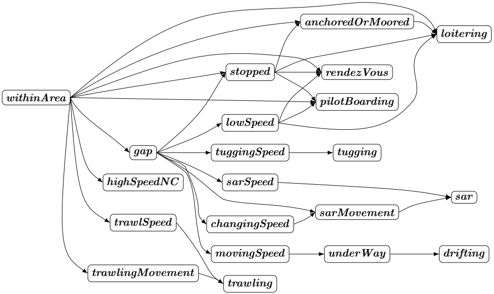
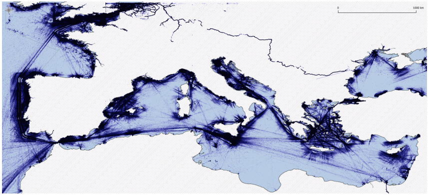
RTEC computes all maximal intervals of a fluent, and no other interval, provided that interval delays/retractions, if any, are tolerated by the window size.

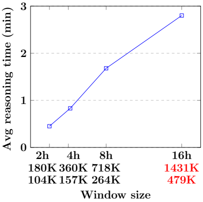
Complexity

The time to compute the maximal intervals of a fluent is linear to the window size.

Performance: Indicative Results







Summary

Run-Time Event Calculus (RTEC):

- Interval-based reasoning $\rightarrow$ avoid unintended semantics.

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- Incremental reasoning $\rightarrow$ handle out-of-order streams.

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- Various implementation routes*.

*Tsilionis et al, A Tensor-based Formalisation of the Event Calculus. IJCAI, 2024.

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- Various implementation routes*.
- Direct routes to machine learning → automated complex event definition construction†.

---

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†Michelioudakis et al, Online Semi-Supervised Learning of Composite Event Rules by Combining Structure and Mass-based Predicate Similarity. Machine Learning, 2024.

Summary

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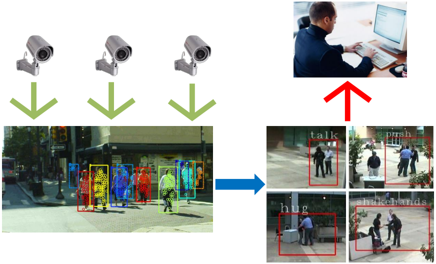
- Expressive language → *n*-ary constraints.
- Incremental reasoning → handle out-of-order streams.
- Caching → real-time performance.
- Various implementation routes*.
- Direct routes to machine learning → automated complex event definition construction†.
- Direct routes to probabilistic reasoning → handle the lack of veracity of data streams.

---

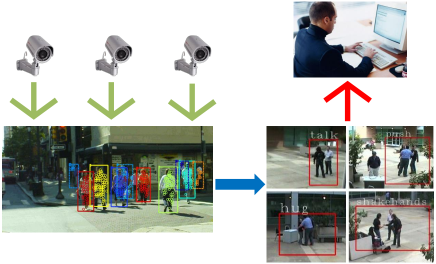
*Tsilionis et al, A Tensor-based Formalisation of the Event Calculus. IJCAI, 2024.

†Michelioudakis et al, Online Semi-Supervised Learning of Composite Event Rules by Combining Structure and Mass-based Predicate Similarity. Machine Learning, 2024.

Human Activity Recognition

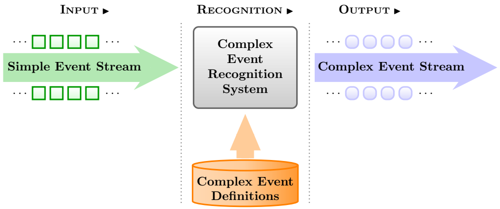


Human Activity Recognition

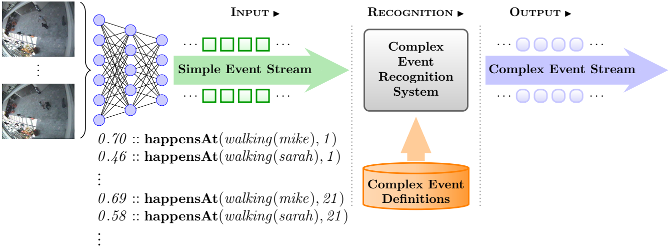


https://cer.iit.demokritos.gr (activity recognition)

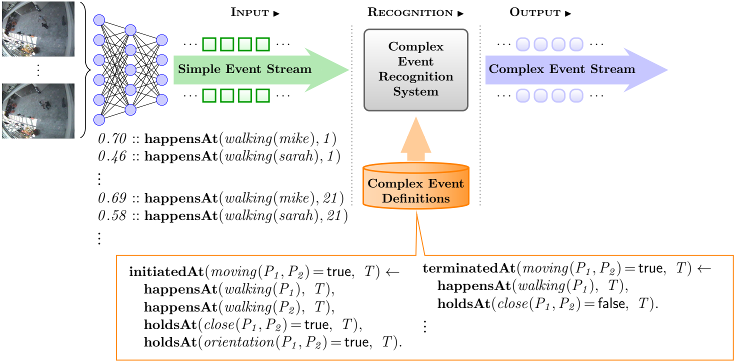
Complex Event Recognition under Uncertainty



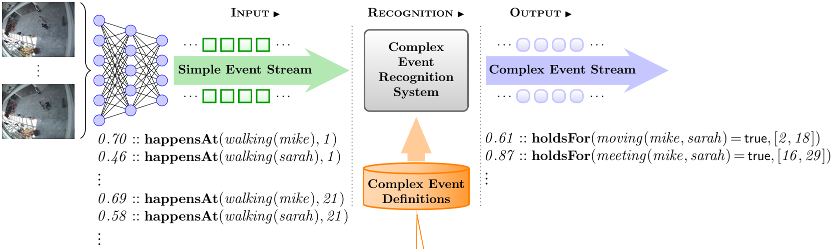
Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty



Complex Event Recognition under Uncertainty

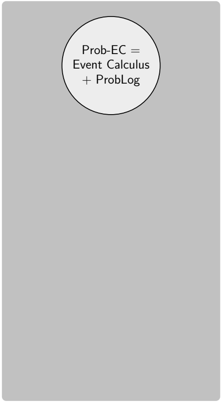


$\mathbf{initiatedAt}(moving(P_1, P_2) = \mathsf{true},\ T) \leftarrow$
$\quad \mathbf{happensAt}(walking(P_1),\ T),$
$\quad \mathbf{happensAt}(walking(P_2),\ T),$
$\quad \mathbf{holdsAt}(close(P_1, P_2) = \mathsf{true},\ T),$
$\quad \mathbf{holdsAt}(orientation(P_1, P_2) = \mathsf{true},\ T).$

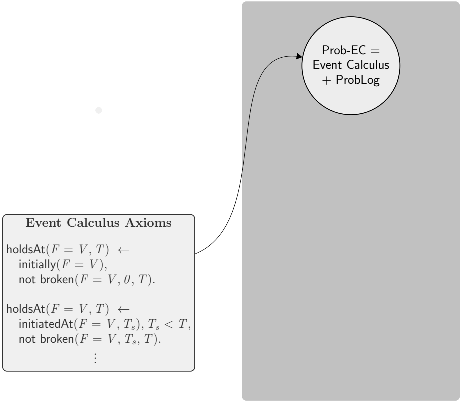
$\mathbf{terminatedAt}(moving(P_1, P_2) = \mathsf{true},\ T) \leftarrow$
$\quad \mathbf{happensAt}(walking(P_1),\ T),$
$\quad \mathbf{holdsAt}(close(P_1, P_2) = \mathsf{false},\ T).$

⋮

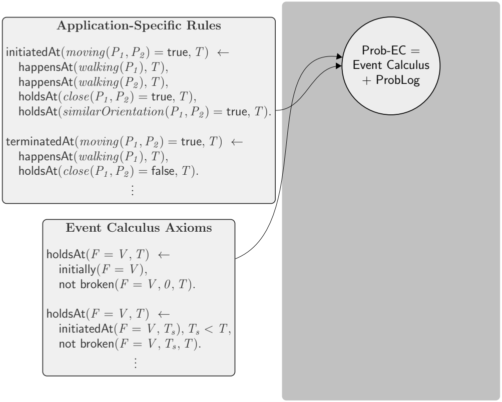
Online Probabilistic Interval-Based Event Calculus



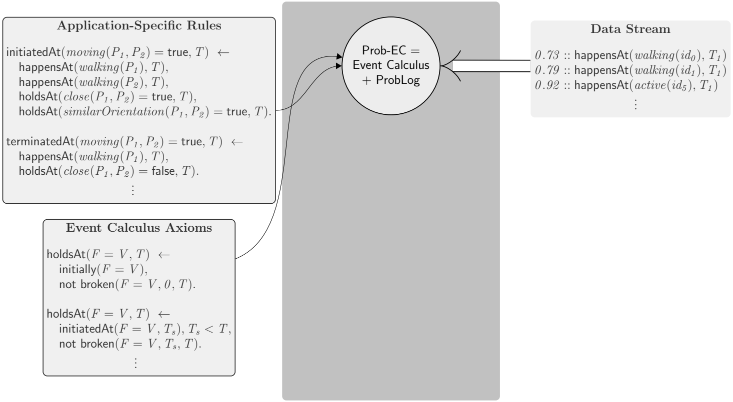
Online Probabilistic Interval-Based Event Calculus



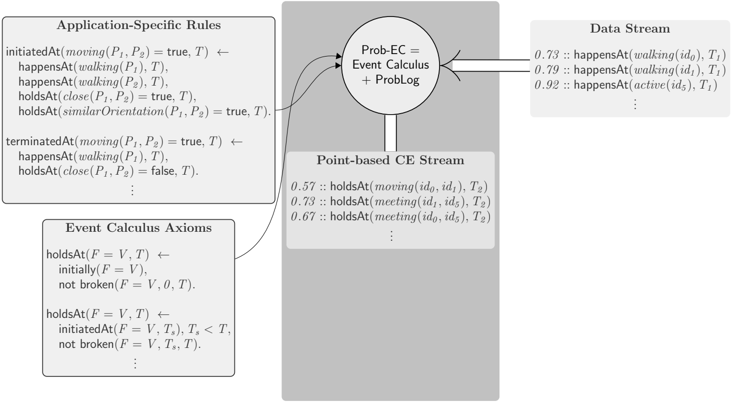
Online Probabilistic Interval-Based Event Calculus



Online Probabilistic Interval-Based Event Calculus



Online Probabilistic Interval-Based Event Calculus



Instantaneous Recognition

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

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

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

Instantaneous Recognition

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

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

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

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

Instantaneous Recognition

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

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

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

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

Instantaneous Recognition

$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
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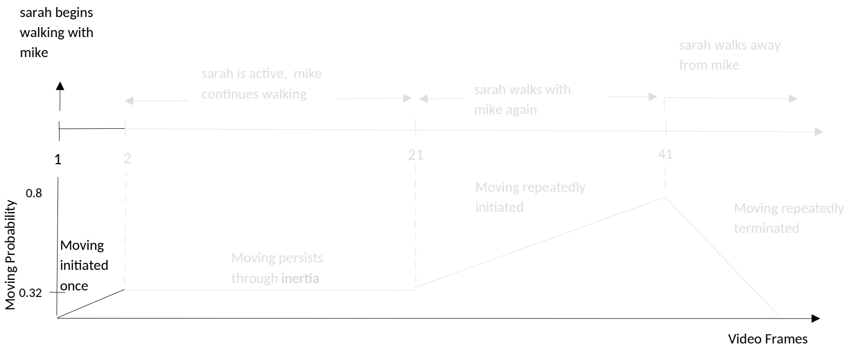
$0.46 :: \textbf{happensAt}(\textit{walking}(\textit{sarah}),\ 1).$

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

Instantaneous Recognition



$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
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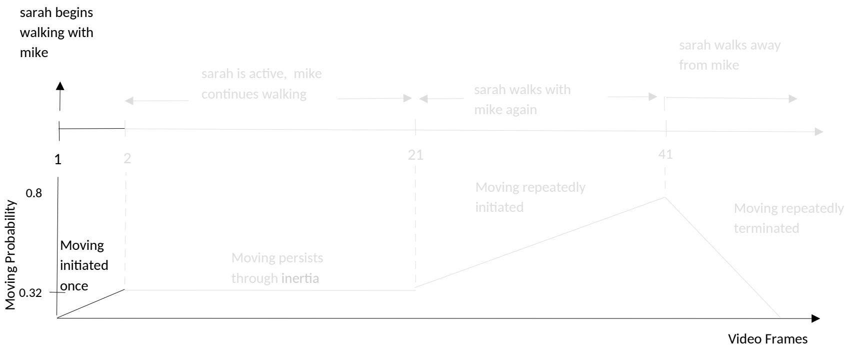
$$P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1) \vee$$
$$(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1) \wedge$$
$$\neg\textbf{terminatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 1)))$$
$$= 0.322 + 0 \times 1 - 0.322 \times 0 \times 1 = 0.322$$

Instantaneous Recognition

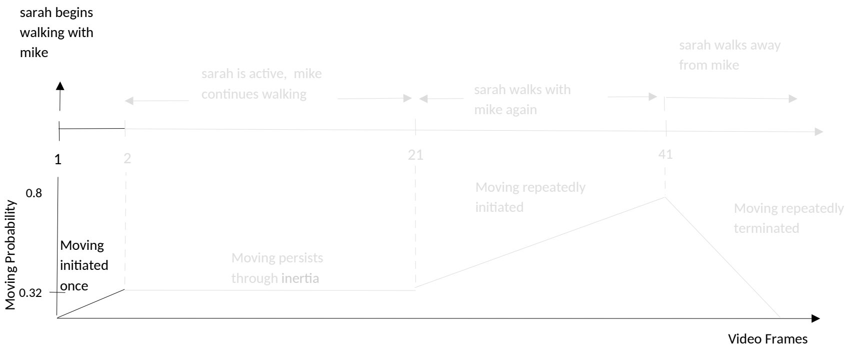


$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

Instantaneous Recognition



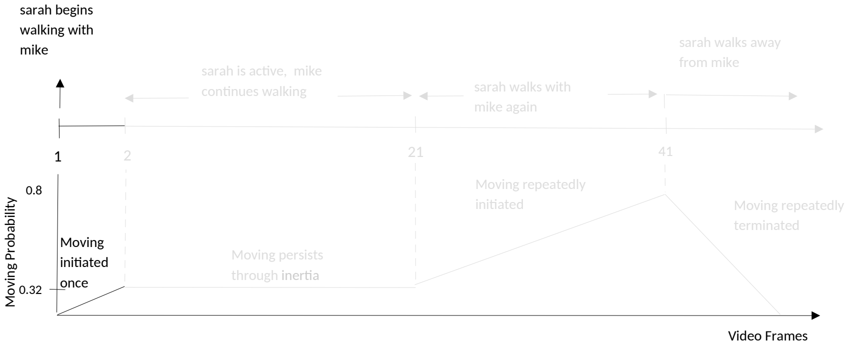
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition

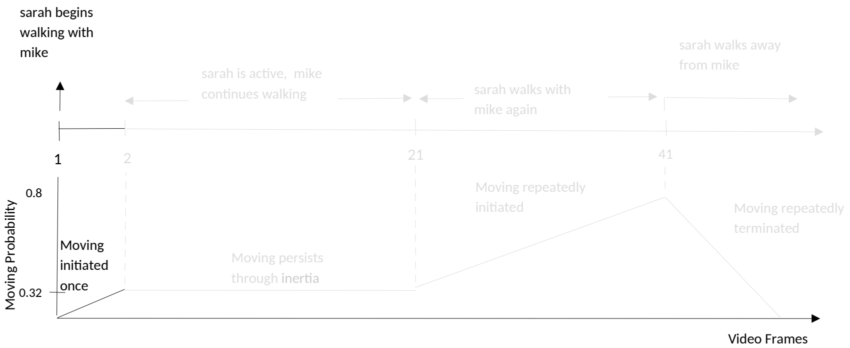


$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
$\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),$
$\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),$
$\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),$
$\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

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

Instantaneous Recognition



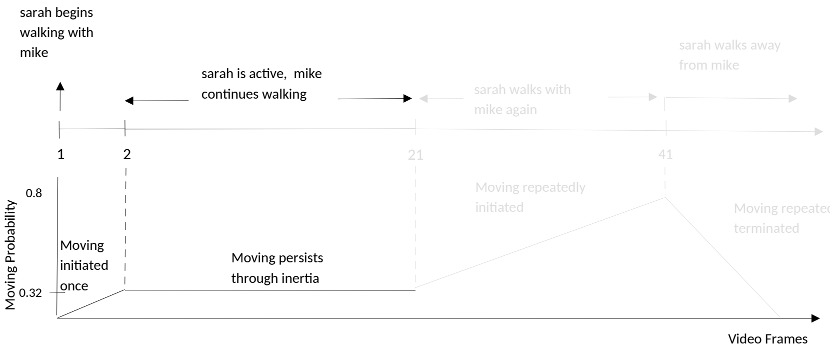
$$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



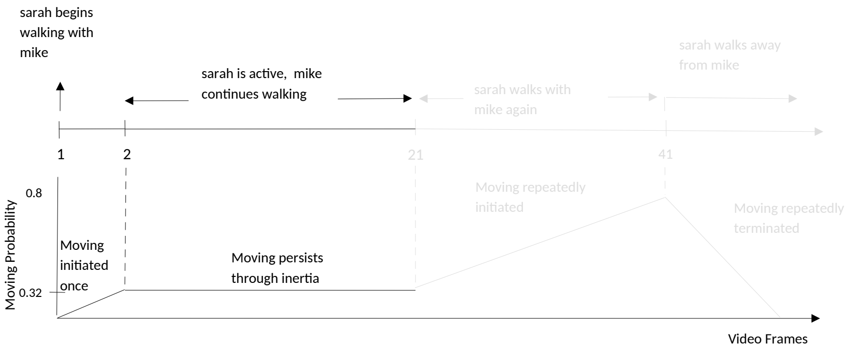
$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

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

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

Instantaneous Recognition

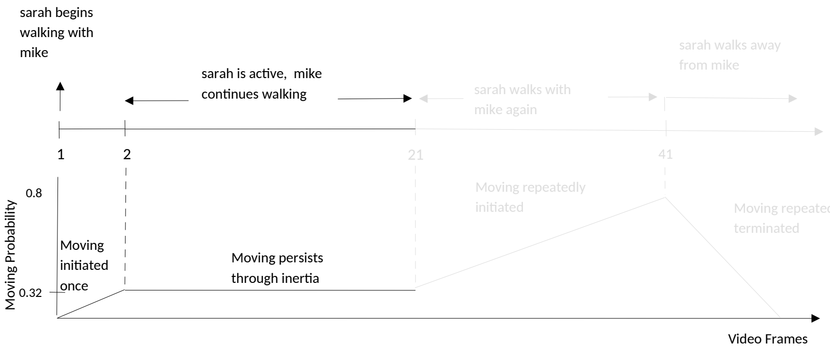


$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$
$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$
$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$
$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$
$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



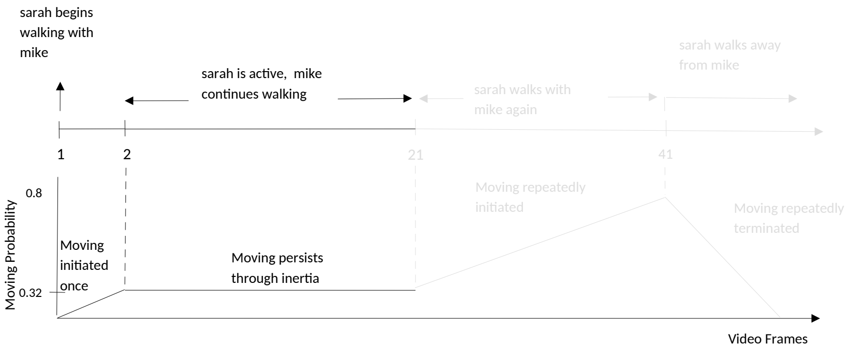
$$\mathbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \mathbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \mathbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



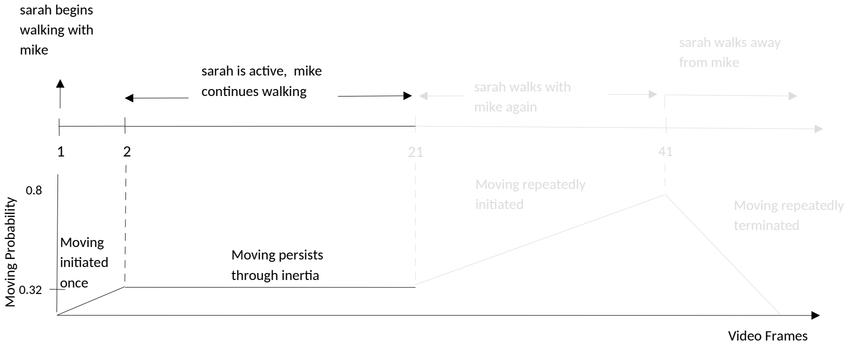
$$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\textit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\textit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\textit{orientation}(P_1, P_2) =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

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

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

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

Instantaneous Recognition

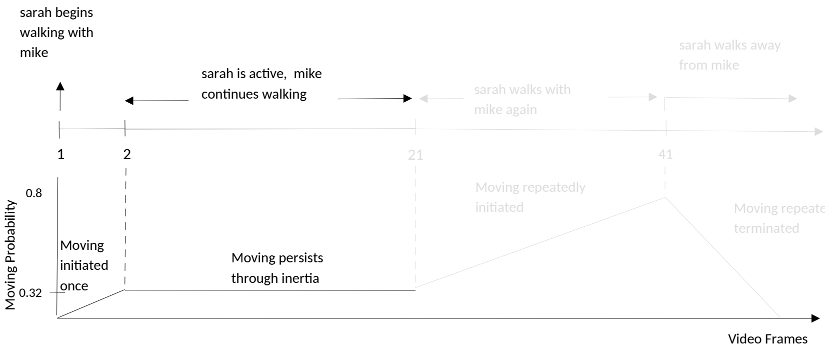


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

Instantaneous Recognition



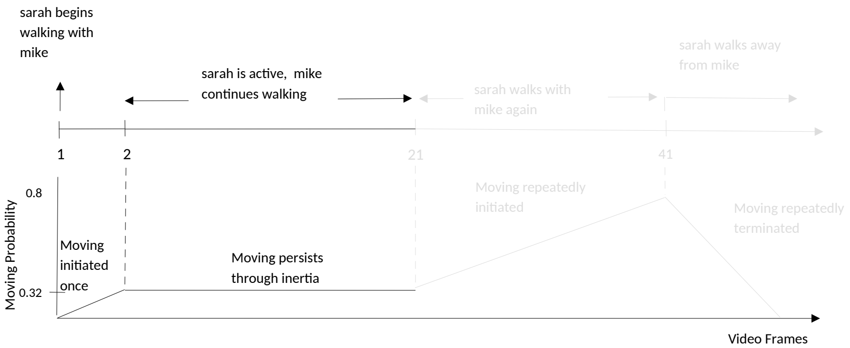
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition



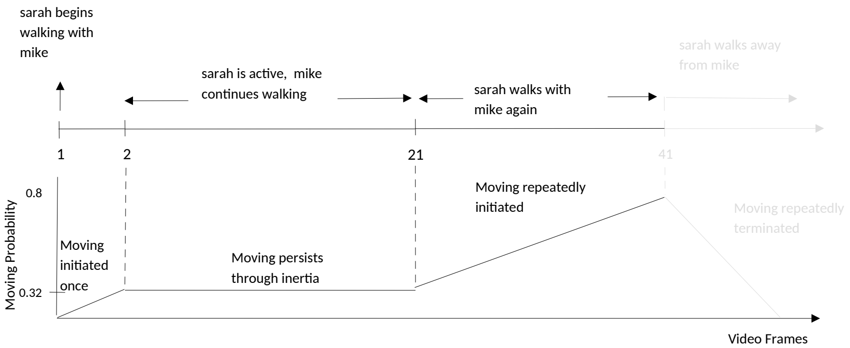
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition



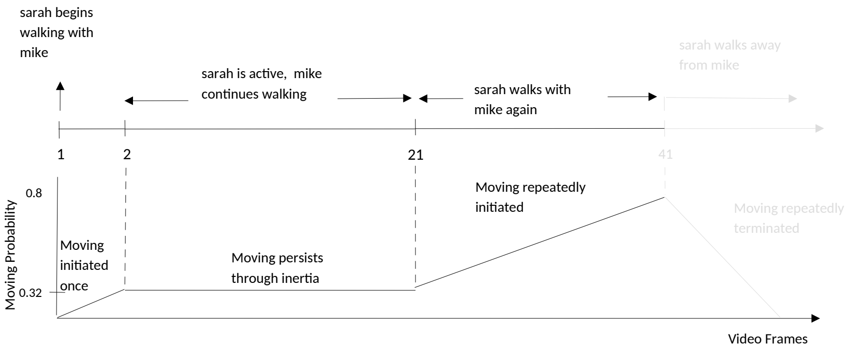
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(walking(P_1),\ T),$$
$$\textbf{happensAt}(walking(P_2),\ T),$$
$$\textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition

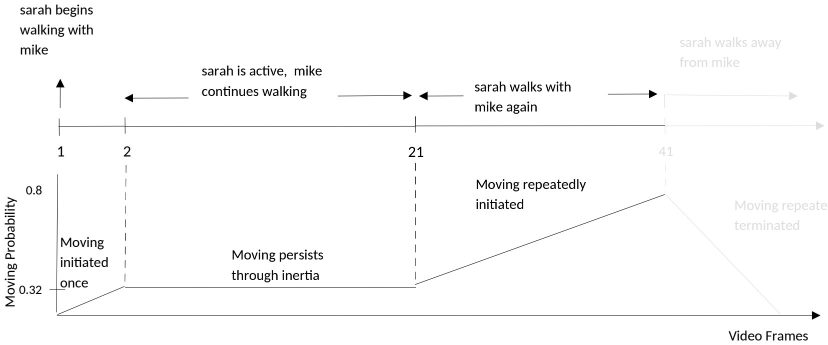


$$\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\textbf{happensAt}(\mathit{walking}(P_1),\ T),$$
$$\textbf{happensAt}(\mathit{walking}(P_2),\ T),$$
$$\textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),$$
$$\textbf{holdsAt}(\mathit{orientation}(P_1, P_2) =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

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

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

Instantaneous Recognition



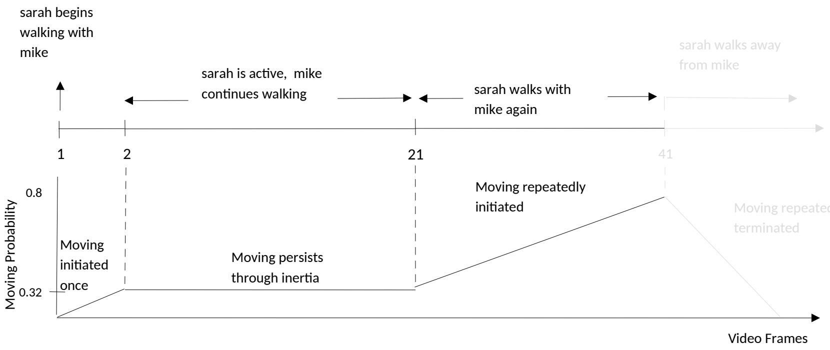
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow\\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T),\\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T),\\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T),\\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



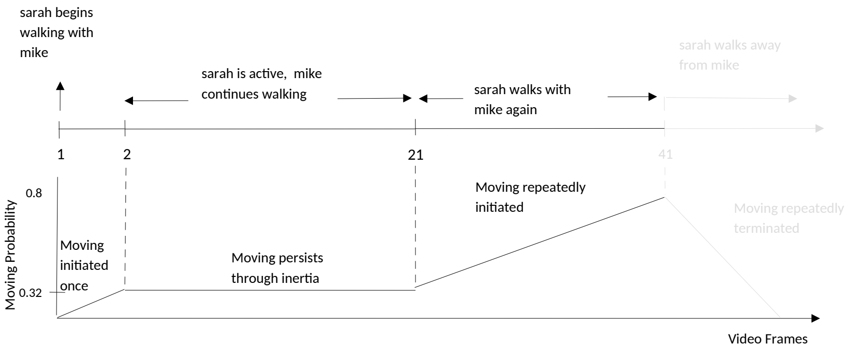
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition

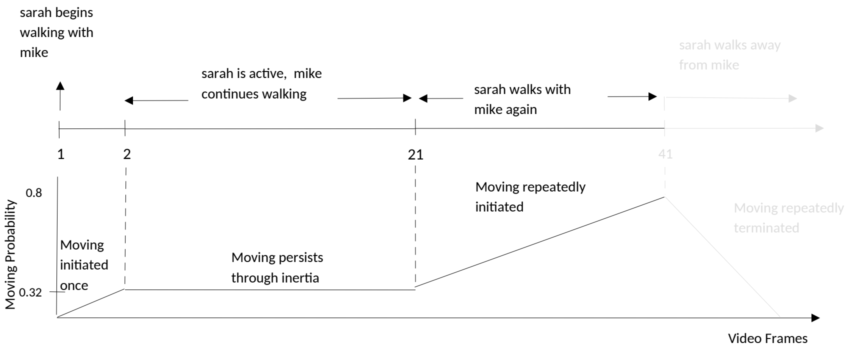


$$\textbf{initiatedAt}(\textit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(\textit{walking}(P_1),\ T),$$
$$\quad \textbf{happensAt}(\textit{walking}(P_2),\ T),$$
$$\quad \textbf{holdsAt}(\textit{close}(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(\textit{orientation}(P_1,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

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

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

Instantaneous Recognition



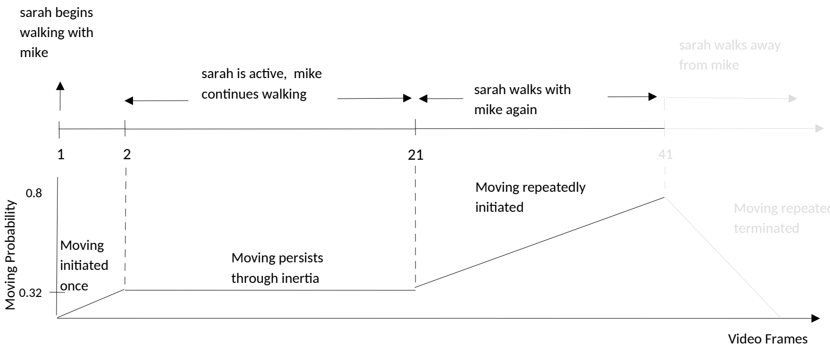
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

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

Instantaneous Recognition



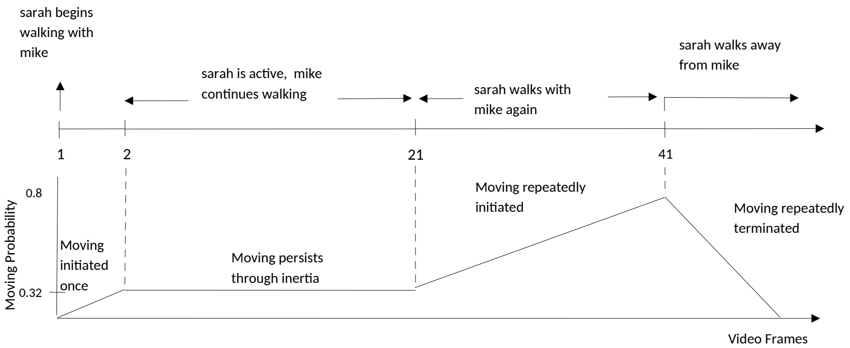
$$\textbf{initiatedAt}(moving(P_1, P_2) = \text{true},\ T) \leftarrow$$
$$\quad \textbf{happensAt}(walking(P_1),\ T),$$
$$\quad \textbf{happensAt}(walking(P_2),\ T),$$
$$\quad \textbf{holdsAt}(close(P_1, P_2) = \text{true},\ T),$$
$$\quad \textbf{holdsAt}(orientation(P_1, P_2) = \text{true},\ T).$$

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

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

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

Instantaneous Recognition



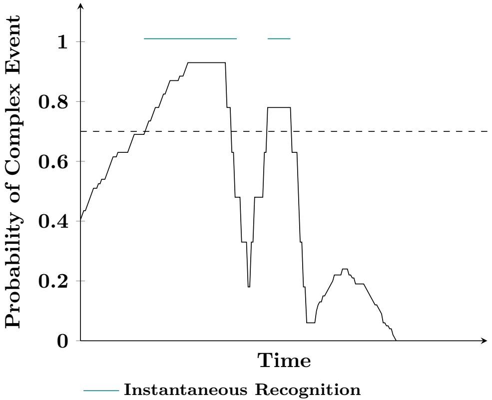
$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{moving}(P_1, P_2) = \text{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{walking}(P_1),\ T), \\
&\quad \textbf{happensAt}(\mathit{walking}(P_2),\ T), \\
&\quad \textbf{holdsAt}(\mathit{close}(P_1, P_2) = \text{true},\ T), \\
&\quad \textbf{holdsAt}(\mathit{orientation}(P_1,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

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

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

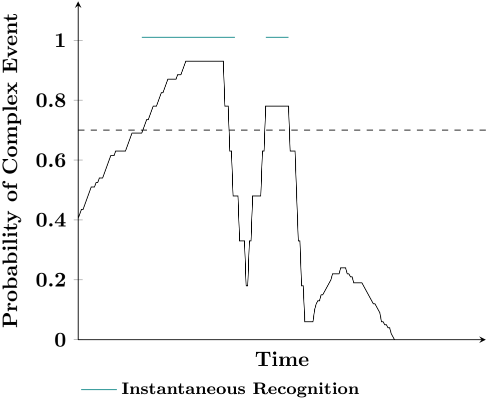
$$
\begin{aligned}
&P(\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 50)) = \\
&P(\textbf{initiatedAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \vee \\
&\quad (\textbf{holdsAt}(\mathit{moving}(\mathit{mike}, \mathit{sarah}) = \text{true}, 49) \wedge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

Instantaneous Recognition*



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

Instantaneous Recognition*

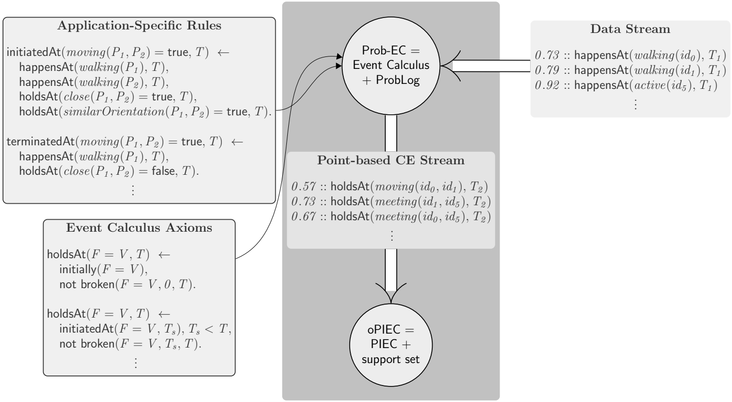


Higher accuracy than crisp reasoning in the presence of:

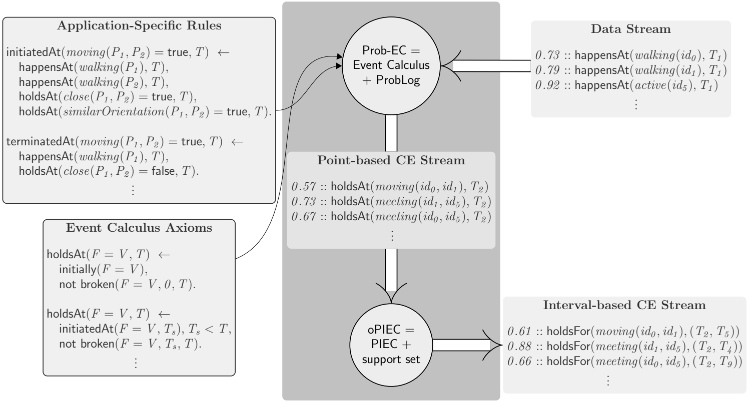
- several initiations and terminations;
- few probabilistic conjuncts.

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

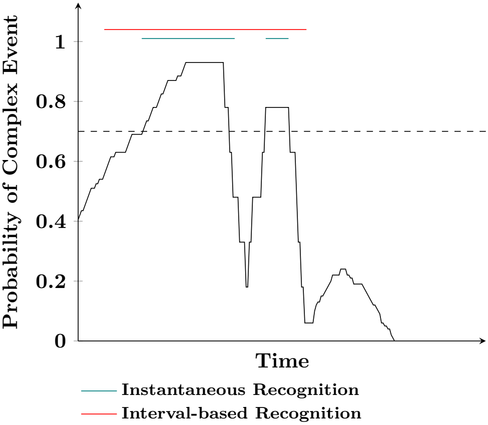
Online Probabilistic Interval-Based Event Calculus



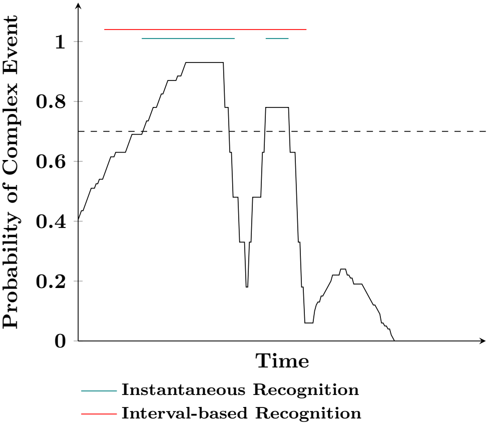
Online Probabilistic Interval-Based Event Calculus



Instantaneous vs Interval-based Recognition

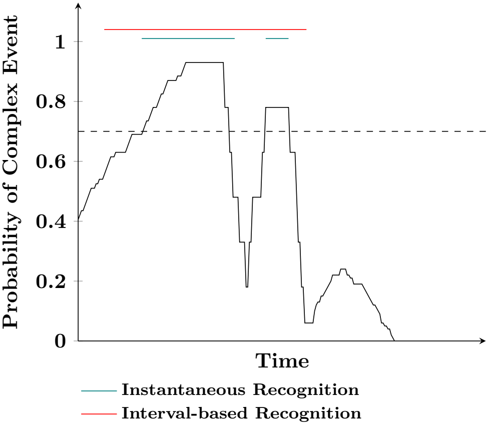


Instantaneous vs Interval-based Recognition



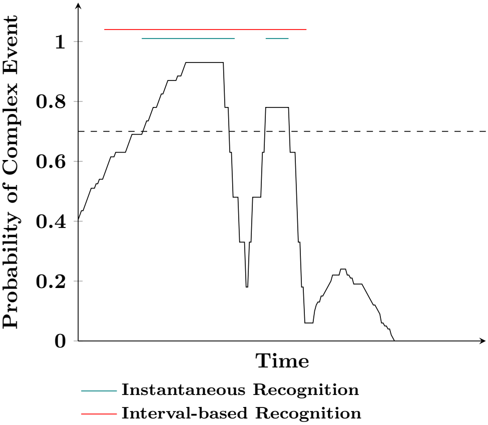
- Interval Probability: average probability of the time-points it contains.

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										

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

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

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

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								-0.9	-0.9	-0.9

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

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							-0.9	-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

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

Interval-based Recognition

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

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

Interval-based Recognition

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

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

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

Interval-based Recognition

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

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

Interval-based Recognition

		⇑				⇓				
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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Complexity

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

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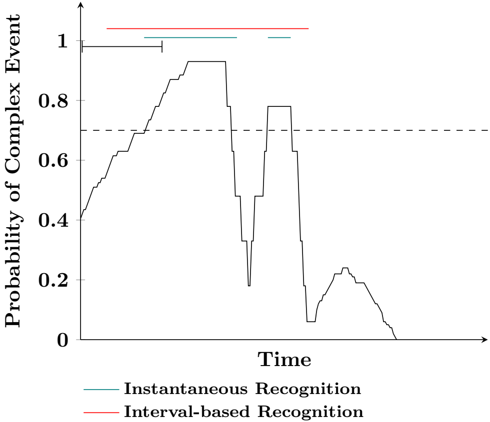
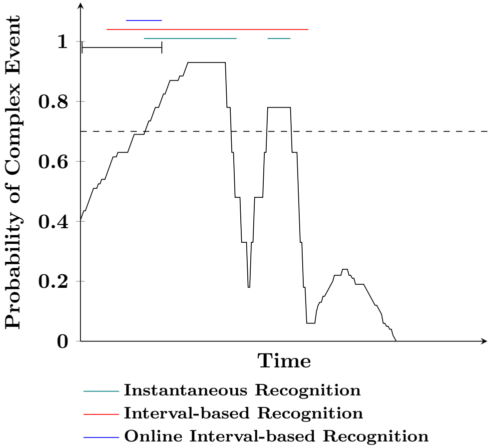
Online Interval-based Recognition



- Windowing.

Online Interval-based Recognition



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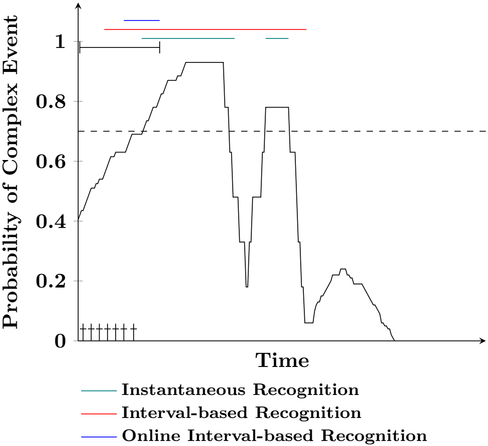

- Windowing.
- Probabilistic maximal interval computation.
- Caching potential starting points.
  - Discard time-point t iff there is a $t' < t$ that can be the starting point of a probabilistic maximal interval including t.

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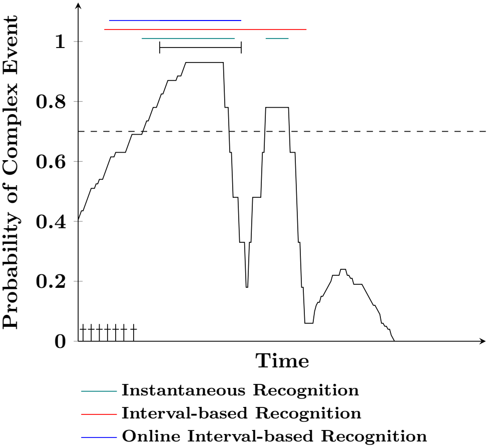

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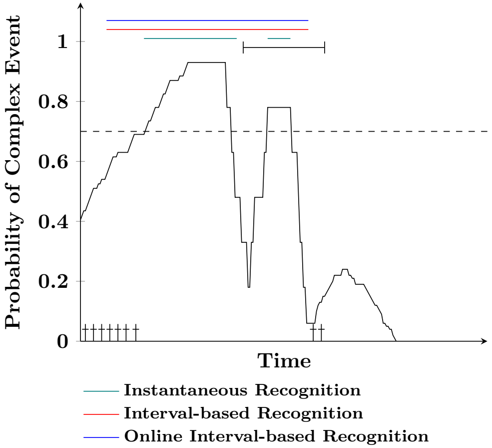

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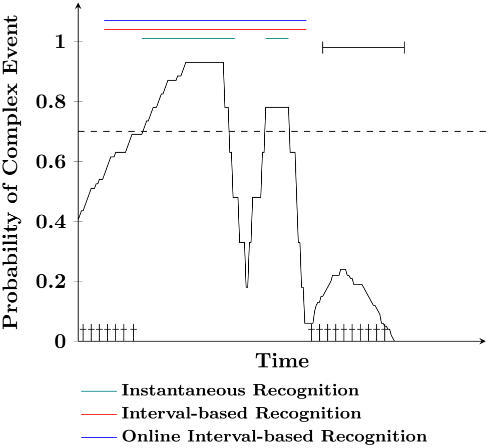

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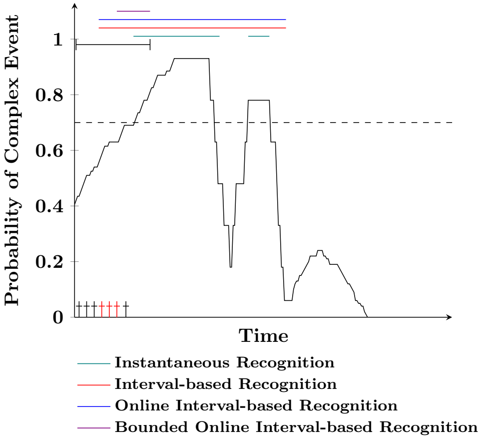
The computation of probabistic maximal intervals is linear to the window and memory size.

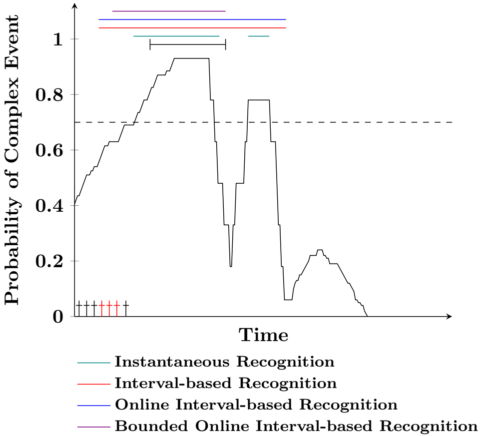
Bounded Online Interval-based Recognition*



- 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

Bounded Online Interval-based Recognition*



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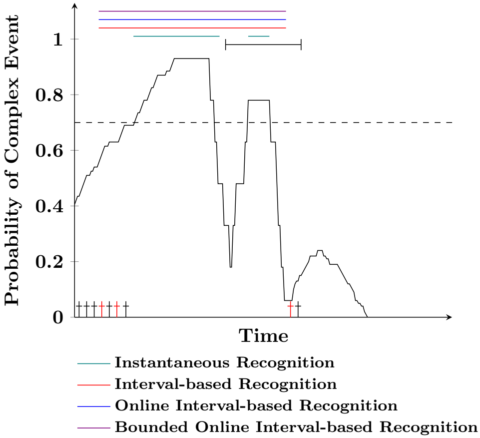

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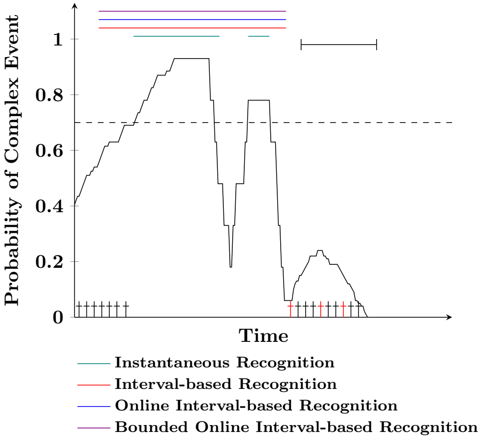
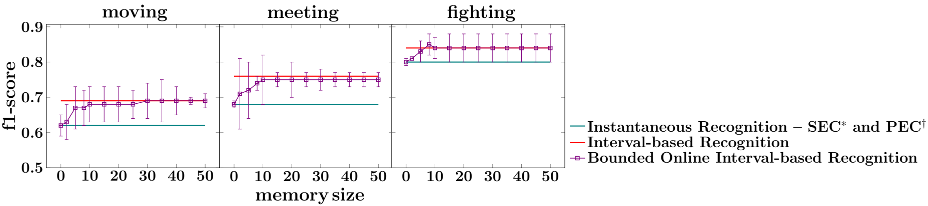
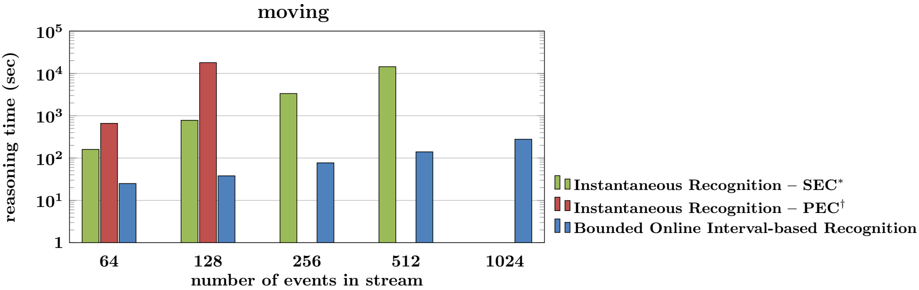


- Complex event duration statistics favor more recent potential starting points.
- Comparable accuracy to batch reasoning.

*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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Summary

Complex event recognition over noisy streams:

- 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.

Topics not covered

- Formal models of CER
  - Other approaches on formal complex event recognition*,†.

*Bucchi et al, CORE: a COmplex event Recognition Engine. VLDB Endowment, 2022.
https://github.com/CORE-cer/CORE

†Alevizos et al, Complex Event Recognition with Symbolic Register Transducers. VLDB, 2024.
https://github.com/ElAlev/Wayeb

Topics not covered

- Formal models of CER
  - Other approaches on formal complex event recognition[*,†].
  - Comparison in terms of expressive power, complexity and performance[‡].

[*] Bucchi et al, CORE: a COmplex event Recognition Engine. VLDB Endowment, 2022. https://github.com/CORE-cer/CORE

[†] Alevizos et al, Complex Event Recognition with Symbolic Register Transducers. VLDB, 2024. https://github.com/ElAlev/Wayeb

[‡] Grez et al, A Formal Framework for Complex Event Recognition. ACM TODS, 2021.

Topics not covered

- Formal models of CER
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  - Uncertainty in the complex event definitions[§,¶].

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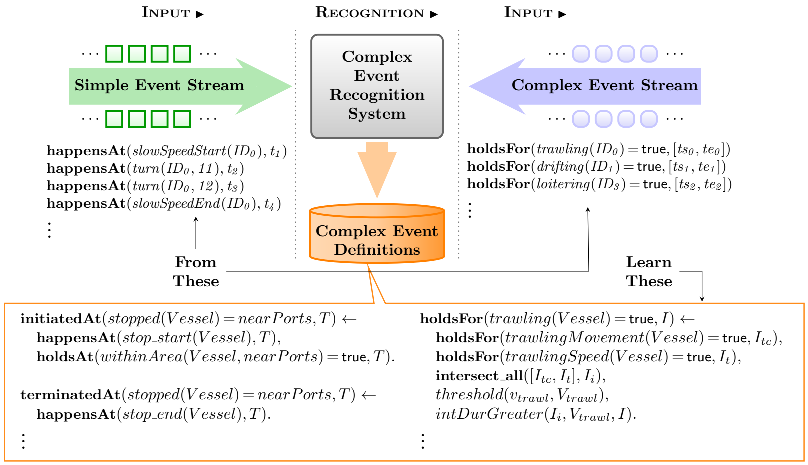
[†] Alevizos et al, Complex Event Recognition with Symbolic Register Transducers. VLDB, 2024. https://github.com/ElAlev/Wayeb

[‡] Grez et al, A Formal Framework for Complex Event Recognition. ACM TODS, 2021.

[§] Skarlatidis et al, Probabilistic Event Calculus for Event Recognition. ACM TOCL, 2015.

[¶] Alevizos et al, Probabilistic Complex Event Recognition: A Survey. ACM Computing Surveys, 2017.

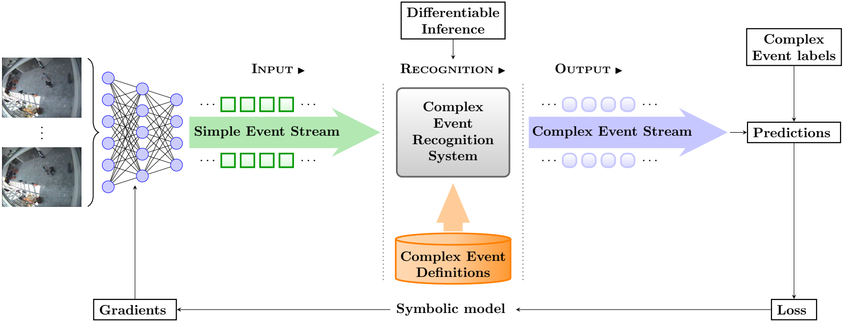
Machine Learning for Complex Event Recognition*,†



*Katzouris et al, Online Learning Probabilistic Event Calculus Theories in Answer Set Programming. Theory and Practice of Logic Programming, 2023.

†Michelioudakis et al, Online semi-supervised learning of composite event rules by combining structure and mass-based predicate similarity. Machine Learning, 2024.

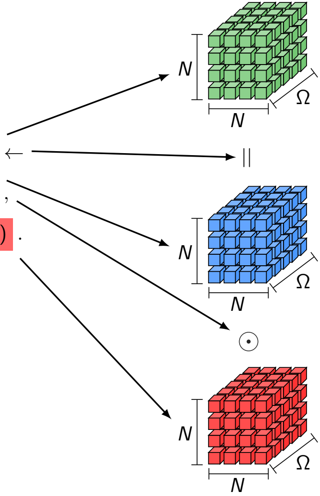
Neuro-Symbolic Complex Event Recognition*



*Marra et al, From statistical relational to neurosymbolic artificial intelligence: A survey. Artificial Intelligence, 2024.

Tensor-Based Complex Event Recognition*

initiatedAt($fl(X, Y){=}v,\ T$) ←
happensAt($e(X, Y),\ T$) ,
holdsAt($d(X, Y){=}v_d,\ T$) .



*Tsilionis et al, A Tensor-Based Formalization of the Event Calculus. IJCAI, 2024.

Tutorial Resources

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

- Slides: http://cer.iit.demokritos.gr/talks
- Code: http://cer.iit.demokritos.gr/software
- Data: http://cer.iit.demokritos.gr/datasets
- Opportunities for (funded) collaboration: job openings and topics for BSc/MSc theses and internships