NeuroSymbolic AI for Making Sense of Streaming Data: Formal Models for CER

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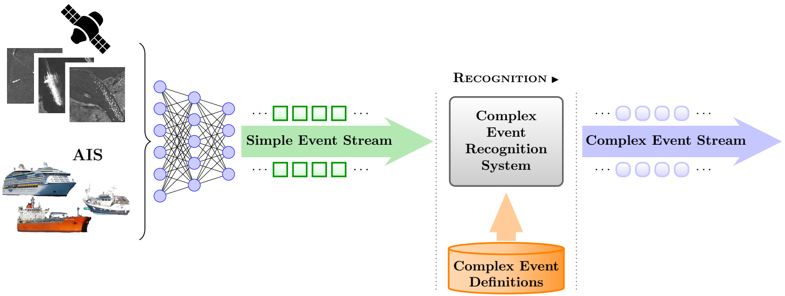
DEMOKRITOS
ÖREBRO UNIVERSITY

Slides, Papers, Code & Data

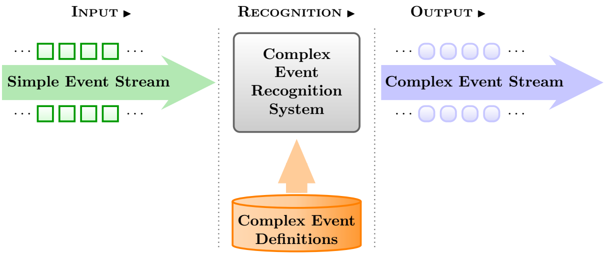
StreamingNeSy

Complex Event Recognition lab

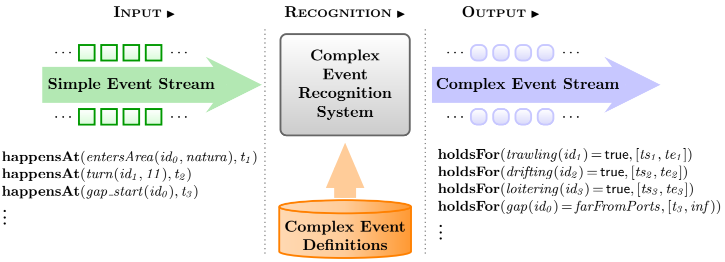
Complex Event Recognition



Complex Event Recognition



Complex Event Recognition



$\mathbf{initiatedAt}(\mathit{gap}(\mathit{Vessel}) = \mathit{nearPorts},\ T) \leftarrow$
  $\mathbf{happensAt}(\mathit{gap\_start}(\mathit{Vessel}),\ T),$
  $\mathbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearPorts}) = \mathsf{true},\ T).$

$\mathbf{initiatedAt}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts},\ T) \leftarrow$
  $\mathbf{happensAt}(\mathit{gap\_start}(\mathit{Vessel}),\ T),$
  $\mathsf{not}\ \mathbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearPorts}) = \mathsf{true},\ T).$

$\mathbf{terminatedAt}(\mathit{gap}(\mathit{Vessel}) = \mathit{PortStatus},\ T) \leftarrow$
  $\mathbf{happensAt}(\mathit{gap\_end}(\mathit{Vessel}),\ T).$

$\mathbf{holdsFor}(\mathit{trawling}(\mathit{Vessel}) = \mathsf{true},\ I) \leftarrow$
  $\mathbf{holdsFor}(\mathit{trawlingMovement}(\mathit{Vessel}) = \mathsf{true},\ I_{tc}),$
  $\mathbf{holdsFor}(\mathit{trawlingSpeed}(\mathit{Vessel}) = \mathsf{true},\ I_t),$
  $\mathbf{intersect\_all}([I_{tc}, I_t], I_i),$
  $\mathit{threshold}(v_{trawl}, V_{trawl}),$
  $\mathit{intDurGreater}(I_i, V_{trawl}, I).$

Deductive Databases*: 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.

* Ramamohanarao and Harland. An Introduction to Deductive Database Languages and Systems. VLDB Journal, 1994.

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

Deductive Databases*: Event Calculus†

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

*Ramamohanarao and Harland. An Introduction to Deductive Database Languages and Systems. VLDB Journal, 1994.

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

Run-Time Event Calculus (RTEC)*,†

$$
\begin{array}{ll}
\textbf{initiatedAt}(F=V,\ T) \leftarrow & \textbf{terminatedAt}(F=V,\ T) \leftarrow \\
\quad \textbf{happensAt}(E_{In_1},\ T), & \quad \textbf{happensAt}(E_{T_1},\ T), \\
\quad [\text{conditions}] & \quad [\text{conditions}] \\
\ldots & \ldots \\
\textbf{initiatedAt}(F=V,\ T) \leftarrow & \textbf{terminatedAt}(F=V,\ T) \leftarrow \\
\quad \textbf{happensAt}(E_{In_i},\ T), & \quad \textbf{happensAt}(E_{T_j},\ T), \\
\quad [\text{conditions}] & \quad [\text{conditions}]
\end{array}
$$

where

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

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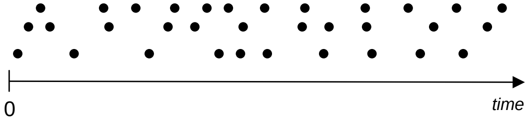
* Artikis et al, An Event Calculus for Event Recognition. IEEE TKDE, 2015.

† Mantenoglou et al, Stream Reasoning with Cycles. KR, 2022. https://github.com/aartikis/RTEC

Run-Time Event Calculus (RTEC)

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

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



Run-Time Event Calculus (RTEC)

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&\textbf{initiatedAt}(F = V,\ T) \leftarrow\\
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&\qquad [\text{conditions}]
\end{aligned}$$

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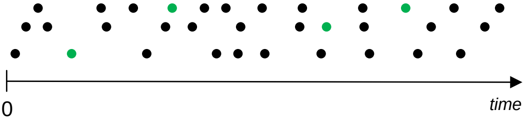
&\qquad \textbf{happensAt}(E_{T_j},\ T),\\
&\qquad [\text{conditions}]
\end{aligned}$$



Run-Time Event Calculus (RTEC)

$\mathbf{initiatedAt}(F = V,\ T) \leftarrow$
$\quad \mathbf{happensAt}(E_{In_1},\ T),$
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$\ldots$

$\mathbf{initiatedAt}(F = V,\ T) \leftarrow$
$\quad \mathbf{happensAt}(E_{In_i},\ T),$
$\quad [\text{conditions}]$

$\mathbf{terminatedAt}(F = V,\ T) \leftarrow$
$\quad \mathbf{happensAt}(E_{T_1},\ T),$
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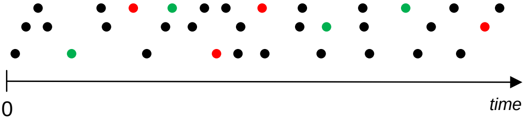

Run-Time Event Calculus (RTEC)

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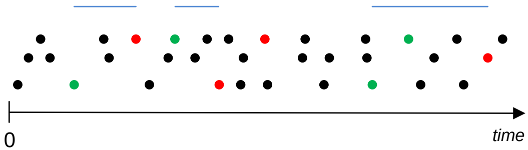
$\textbf{holdsFor}(F = V,\ I)$



High Speed Near Coast

$$
\begin{aligned}
&\textbf{initiatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}, \_\mathit{CoG}, \_\mathit{TrueHeading}), T), \\
&\quad \textbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \text{true}, T), \\
&\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} > V.
\end{aligned}
$$

High Speed Near Coast

$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true},\ T) \leftarrow \\
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&\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}),\ T), \\
&\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} \leq V.
\end{aligned}$$

$$\begin{aligned}
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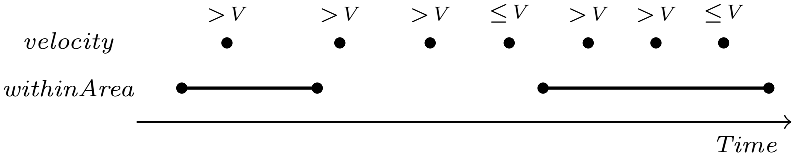

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$$\begin{aligned}
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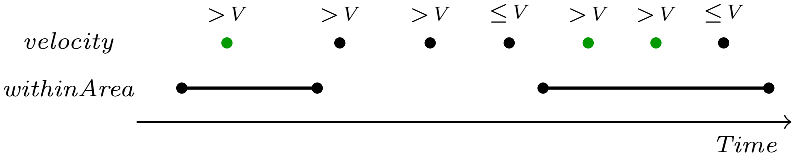

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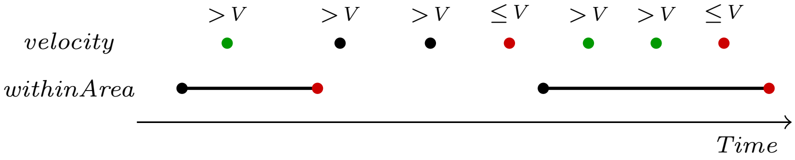

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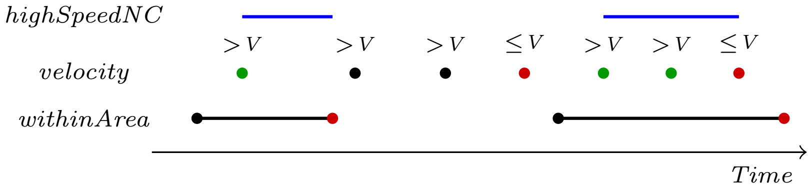
\end{aligned}
$$



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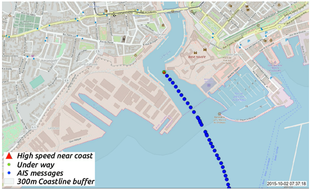
\end{aligned}
$$

$$
\begin{aligned}
&\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true},\ T) \leftarrow \\
&\qquad \textbf{happensAt}(\mathit{end}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \text{true}), T).
\end{aligned}
$$

https://cer.iit.demokritos.gr (high speed near coast (a))



https://cer.iit.demokritos.gr (high speed near coast (b))

DIY: High Speed Near Coast

$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true}, T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}, _\mathit{CoG}, _\mathit{TrueHeading}), T), \\
&\quad \textbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \text{true}, T), \\
&\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} > V.
\end{aligned}$$

$$\begin{aligned}
&\textbf{happensAt}(\mathit{velocity}(v1, 7.5, 124, 130), 13), \\
&\textbf{happensAt}(\mathit{velocity}(v1, 5.2, 180, 178), 24), \\
&\textbf{happensAt}(\mathit{velocity}(v1, 5.1, 212, 212), 32), \\
&\textbf{happensAt}(\mathit{velocity}(v1, 4, 210, 212), 36), \\
&\textbf{happensAt}(\mathit{velocity}(v1, 6, 200, 199), 52), \\
&\textbf{happensAt}(\mathit{velocity}(v1, 4, 189, 189), 56).
\end{aligned}$$

Which are the initiation points of $\mathit{highSpeedNC}(v1) = \text{true}$?

** $\mathit{withinArea}(v1, \mathit{nearCoast}) = \mathit{true}$ holds continuously in the intervals [10,21) and [40,61) and the threshold for v_{hs} is 5 knots.

DIY: High Speed Near Coast

$$
\begin{array}{l}
\textbf{initiatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true}, T) \leftarrow \\
\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}, \_\mathit{CoG}, \_\mathit{TrueHeading}), T), \\
\quad \textbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \text{true}, T), \\
\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} > V.
\end{array}
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\textbf{happensAt}(\mathit{velocity}(v1, 7.5, 124, 130), 13), \\
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\textbf{happensAt}(\mathit{velocity}(v1, 4, 210, 212), 36), \\
\textbf{happensAt}(\mathit{velocity}(v1, 6, 200, 199), 52), \\
\textbf{happensAt}(\mathit{velocity}(v1, 4, 189, 189), 56).
\end{array}
$$

Which are the initiation points of $\mathit{highSpeedNC}(v1) = \text{true}$?

Initiations: 13 and 52

** $\mathit{withinArea}(v1, \mathit{nearCoast}) = \mathit{true}$ holds continuously in the intervals [10,21) and [40,61) and the threshold for v_{hs} is 5 knots.

DIY: High Speed Near Coast

$$\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true}, T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}), T),$$
$$\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} \leq V.$$

$$\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true}, T) \leftarrow$$
$$\quad \textbf{happensAt}(\mathit{end}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \mathrm{true}), T).$$

$\textbf{happensAt}(\mathit{velocity}(v1, 7.5, 124, 130), 13),$
$\textbf{happensAt}(\mathit{velocity}(v1, 5.2, 180, 178), 24),$
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$\textbf{happensAt}(\mathit{velocity}(v1, 4, 210, 212), 36),$
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Which are the termination points of $\mathit{highSpeedNC}(v1) = \mathrm{true}$?

** $\mathit{withinArea}(v1, \mathit{nearCoast}) = \mathit{true}$ holds continuously in the intervals [10,21) and [40,61) and the threshold for v_{hs} is 5 knots.

DIY: High Speed Near Coast

$$\begin{aligned}&\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true}, T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}), T),\\ &\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} \leq V.\end{aligned}$$

$$\begin{aligned}&\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true}, T) \leftarrow\\ &\quad \textbf{happensAt}(\mathit{end}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \mathrm{true}), T).\end{aligned}$$

$\textbf{happensAt}(\mathit{velocity}(v1, 7.5, 124, 130), 13)$,
$\textbf{happensAt}(\mathit{velocity}(v1, 5.2, 180, 178), 24)$,
$\textbf{happensAt}(\mathit{velocity}(v1, 5.1, 212, 212), 32)$,
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Which are the termination points of $\mathit{highSpeedNC}(v1) = \mathrm{true}$?
Terminations : 20, 36, 56 and 60

** $\mathit{withinArea}(v1, \mathit{nearCoast}) = \mathit{true}$ holds continuously in the intervals [10,21) and [40,61) and the threshold for v_{hs} is 5 knots.

DIY: High Speed Near Coast

$$\begin{aligned}
&\textbf{initiatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}, _\mathit{CoG}, _\mathit{TrueHeading}), T), \\
&\quad \textbf{holdsAt}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \mathrm{true},\ T), \\
&\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} > V.
\end{aligned}$$

$$\begin{aligned}
&\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{velocity}(\mathit{Vessel}, \mathit{Speed}), T), \\
&\quad \mathit{threshold}(v_{hs}, V), \mathit{Speed} \leq V.
\end{aligned}$$

$$\begin{aligned}
&\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \mathrm{true},\ T) \leftarrow \\
&\quad \textbf{happensAt}(\mathit{end}(\mathit{withinArea}(\mathit{Vessel}, \mathit{nearCoast}) = \mathrm{true}), T).
\end{aligned}$$

Initiations: 13 and 52

Terminations : 20, 36, 56 and 60

What are the maximal intervals of $\mathit{highSpeedNC}(\mathit{v1}) = \mathrm{true}$?

DIY: High Speed Near Coast

$$\begin{aligned}
&\textbf{initiatedAt}(\textit{highSpeedNC}(\textit{Vessel}) = \text{true}, T) \leftarrow \\
&\quad \textbf{happensAt}(\textit{velocity}(\textit{Vessel}, \textit{Speed}, _\textit{CoG}, _\textit{TrueHeading}), T), \\
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\end{aligned}$$

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\end{aligned}$$

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&\quad \textbf{happensAt}(\textit{end}(\textit{withinArea}(\textit{Vessel}, \textit{nearCoast}) = \text{true}), T).
\end{aligned}$$

Initiations: 13 and 52
Terminations : 20, 36, 56 and 60

What are the maximal intervals of $\textit{highSpeedNC}(\textit{v1}) = \text{true}$?

Answer: [14, 21) and [53, 57)

RTEC: Interval-based Reasoning

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

RTEC: Interval-based Reasoning

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

RTEC: Interval-based Reasoning

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\begin{aligned}
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&\quad \textbf{intersect\_all}([I_{sf}, I_{wa}],\ I_{sa}), \\
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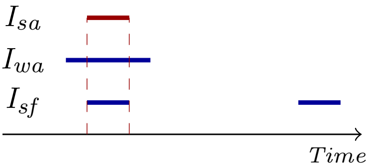
&\quad \textbf{union\_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}
$$



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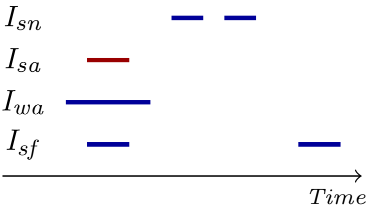

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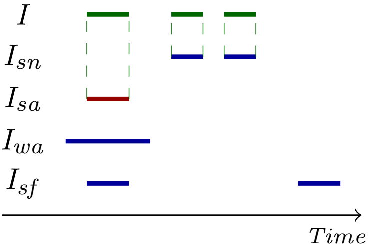
&\quad \textbf{union_all}([I_{sa}, I_{sn}],\ I).
\end{aligned}$$



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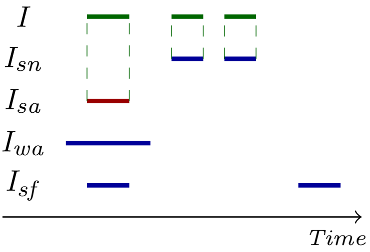
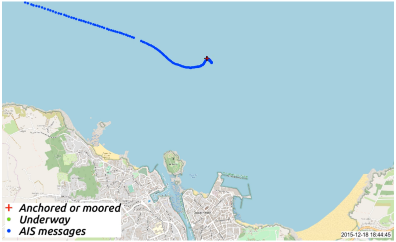
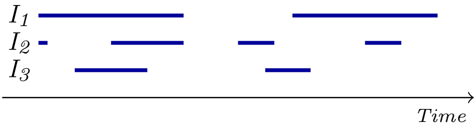




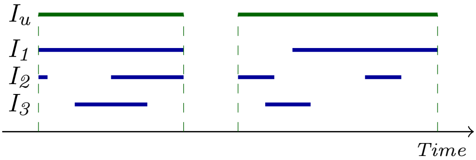
https://cer.iit.demokritos.gr (anchored or moored)

RTEC: Interval-based Reasoning



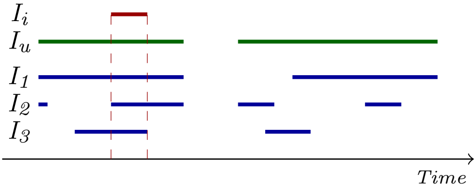
RTEC: Interval-based Reasoning

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

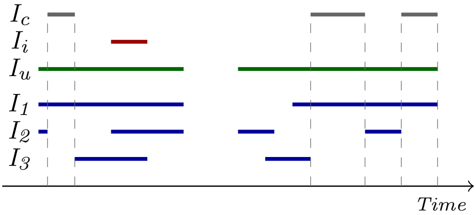


RTEC: Interval-based Reasoning

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

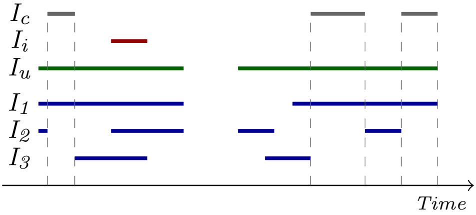
intersect_all$([I_1, I_2, I_3], I_i)$

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

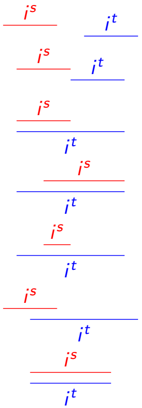


RTEC: Interval-based Reasoning & Allen Relations*

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. KR, 2023.

RTEC: Interval-based Reasoning & Allen Relations*

$$
\begin{aligned}
&\textbf{holdsFor}(\mathit{disappearedInArea}(\mathit{Vessel}, \mathit{AreaType}) = \mathrm{true}, I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{AreaType}) = \mathrm{true}, \mathcal{S}), \\
&\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}), \\
&\quad \textbf{allen}(\mathrm{meets}, \mathcal{S}, \mathcal{T}, \mathrm{target}, I).
\end{aligned}
$$

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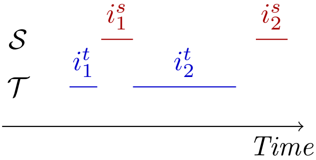
\end{aligned}$$



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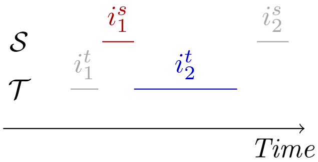
\end{aligned}
$$



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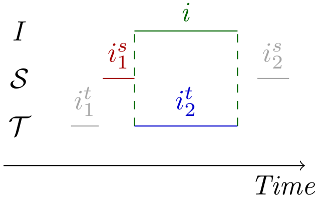
RTEC: Interval-based Reasoning & Allen Relations*

holdsFor(*disappearedInArea*(*Vessel*, *AreaType*) = true, *I*) ←
holdsFor(*withinArea*(*Vessel*, *AreaType*) = true, $\mathcal{S}$),
holdsFor(*gap*(*Vessel*) = *farFromPorts*, $\mathcal{T}$),
allen(meets, $\mathcal{S}$, $\mathcal{T}$, target, *I*).



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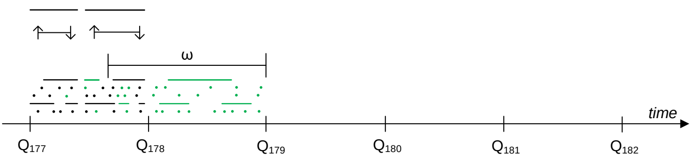
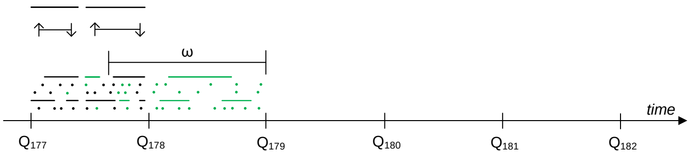
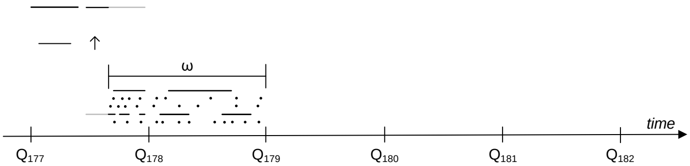
Windowing



Windowing

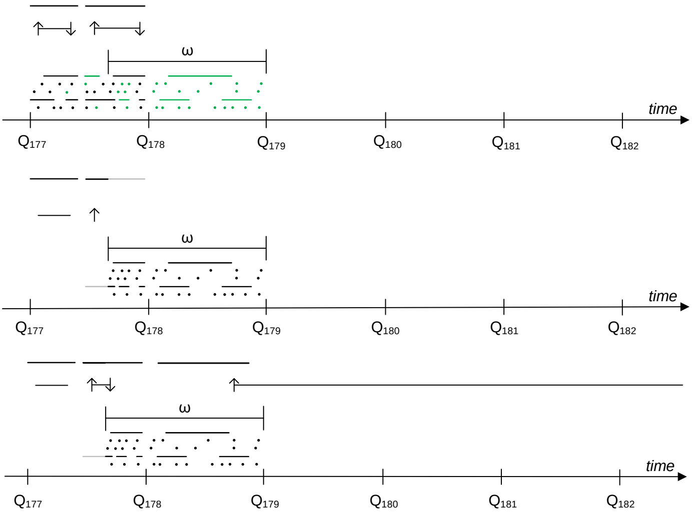


ω
time
Q177
Q178
Q179
Q180
Q181
Q182

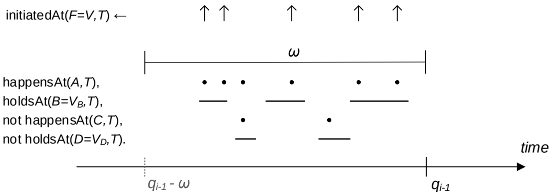


ω
time
Q177
Q178
Q179
Q180
Q181
Q182

Windowing

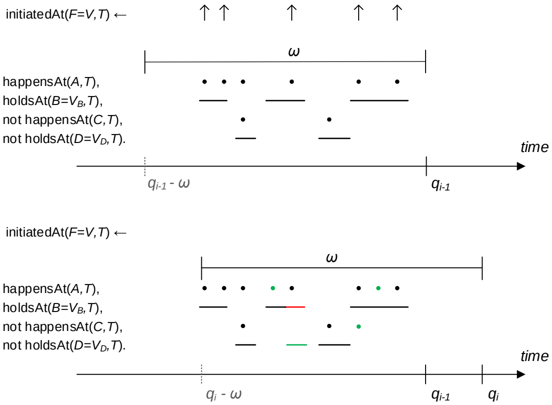

ω
time
Q177
Q178
Q179
Q180
Q181
Q182
ω
time
Q177
Q178
Q179
Q180
Q181
Q182
ω
time
Q177
Q178
Q179
Q180
Q181
Q182

Windowing



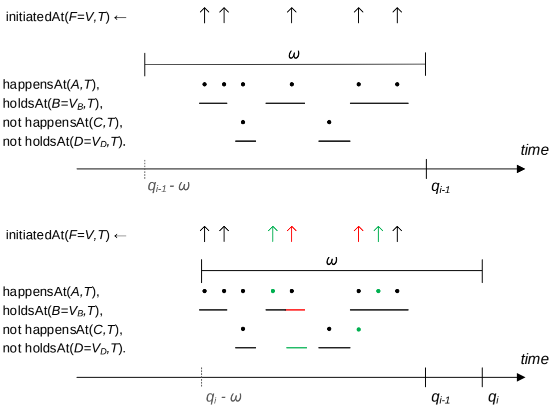
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i-1 - ω
q_i-1

Windowing



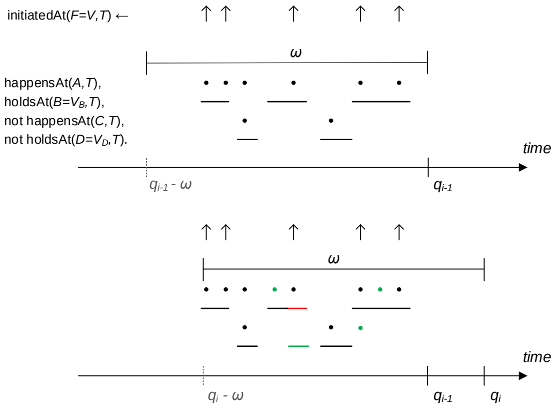
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i-1 - ω
q_i-1
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i - ω
q_i-1
q_i

Windowing



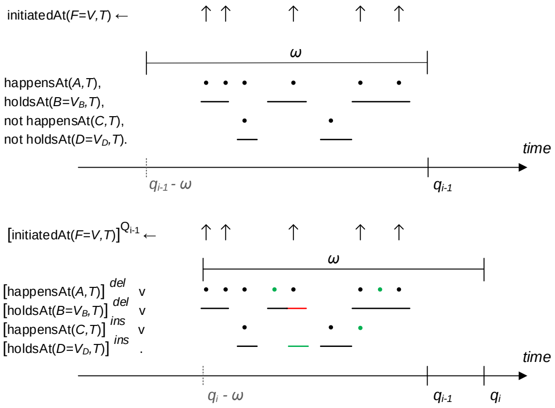
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_{i-1} - ω
q_{i-1}
initiatedAt(F=V,T) ←
ω
happensAt(A,T),
holdsAt(B=V_B,T),
not happensAt(C,T),
not holdsAt(D=V_D,T).
time
q_i - ω
q_{i-1}
q_i

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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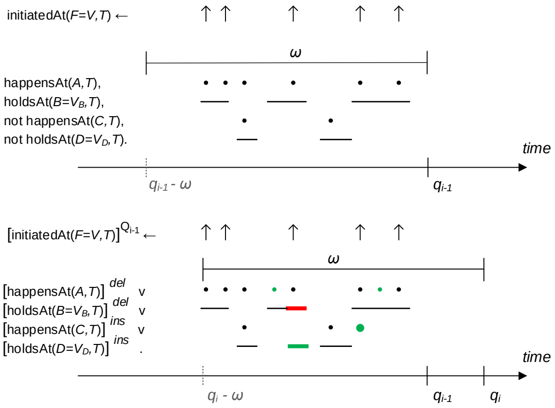

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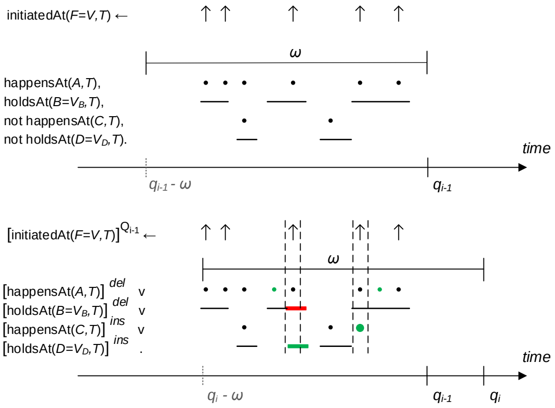

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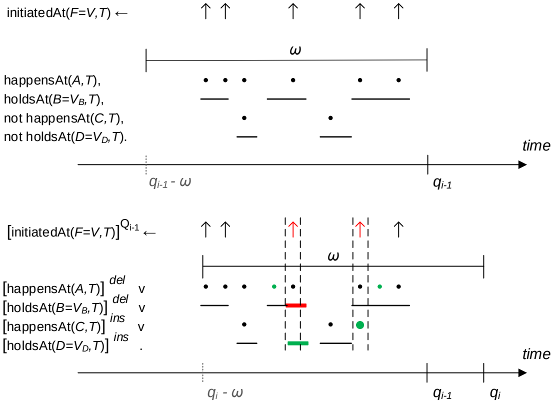

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RTEC: Correctness and Complexity

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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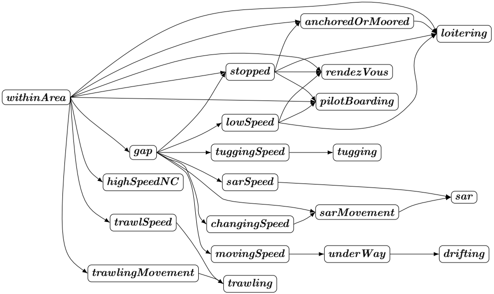
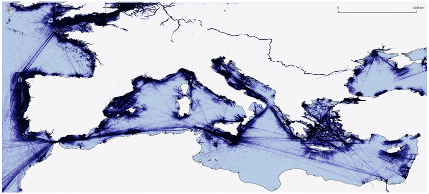
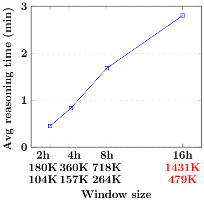
Complexity

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.

*Mantenoglou et al, Complex Event Recognition with Allen Relations. KR, 2023.

Summary

Run-Time Event Calculus (RTEC):

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- Formal, declarative semantics $\rightarrow$ robust/trustworthy CER.

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- Direct routes to probabilistic reasoning‡ $\rightarrow$ real-time performance. $\rightarrow$ handle the lack of veracity of data streams.

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‡Mantenoglou et al, Online Event Recognition over Noisy Data Streams. IJAR, 2023.

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Course Structure

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

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- Introduction to Complex Event Recognition (CER).
- Formal Models for CER
- Probabilistic CER.
- Tensor-based CER.
- Topics not covered.