Can Computers Understand what is Happening? The Run-Time Event Calculus

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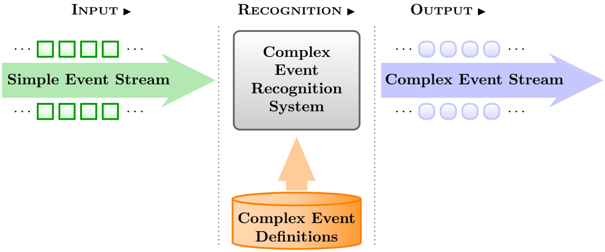
[3]NKUA, Greece

https://cer.iit.demokritos.gr

Complex Event Recognition



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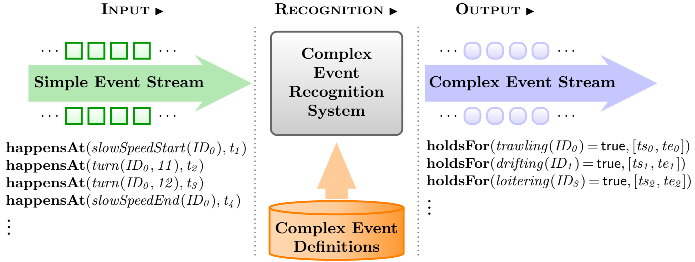

$\mathbf{initiatedAt}(stopped(Vessel) = nearPorts, T) \leftarrow$
$\quad \mathbf{happensAt}(stop\_start(Vessel), T),$
$\quad \mathbf{holdsAt}(withinArea(Vessel, nearPorts) = \mathsf{true}, T).$

$\mathbf{terminatedAt}(stopped(Vessel) = nearPorts, T) \leftarrow$
$\quad \mathbf{happensAt}(stop\_end(Vessel), T).$

$\vdots$

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

$\vdots$

Event Calculus*

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

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

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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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Features of the Event Calculus

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

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- Direct routes to probabilistic reasoning → handle the lack of veracity of data streams.
- Direct routes to machine learning → automated complex event definition construction*.

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

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- Direct routes to probabilistic reasoning → handle the lack of veracity of data streams.
- Direct routes to machine learning → automated complex event definition construction*.
- Various implementation routes†.

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

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

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

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

Run-Time Event Calculus (RTEC)

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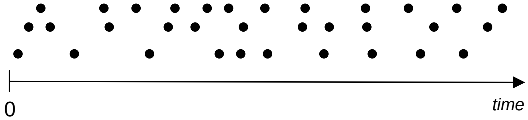

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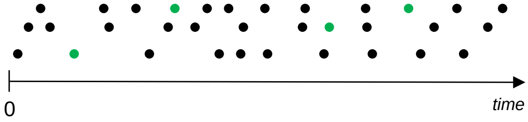

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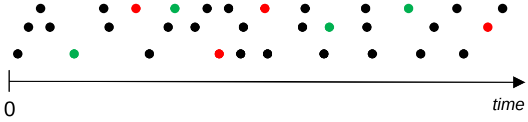

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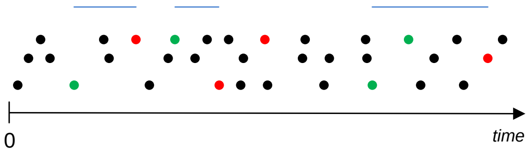
$\textbf{holdsFor}(F = V,\ I)$



High Speed Near Coast

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

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&\textbf{terminatedAt}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true},\ T) \leftarrow\\
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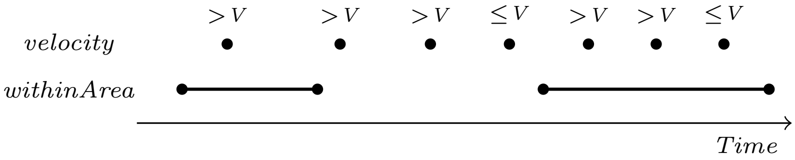

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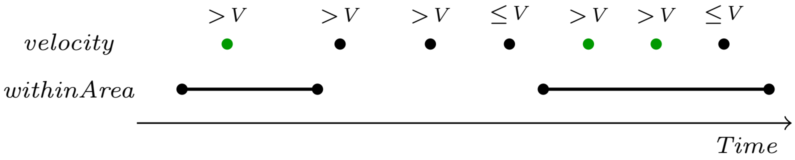

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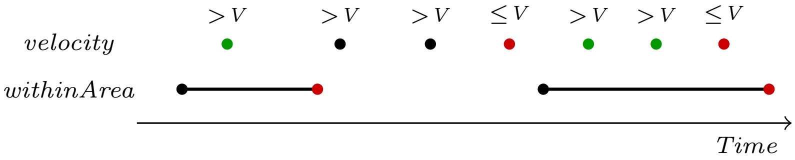

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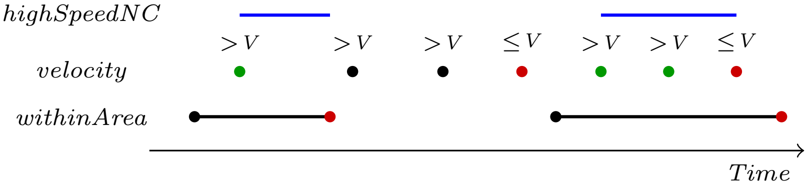

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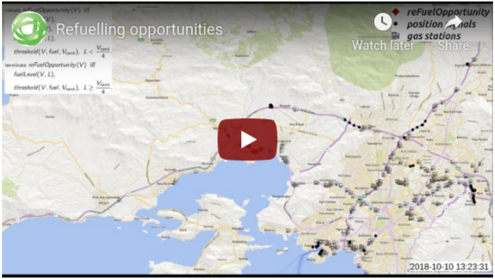
https://cer.iit.demokritos.gr (high speed near coast)

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

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\begin{aligned}
&\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}), \\
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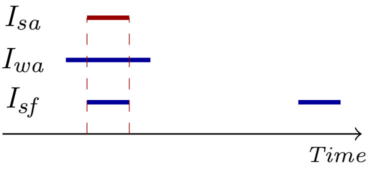

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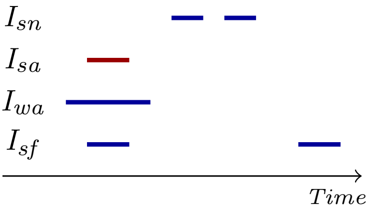

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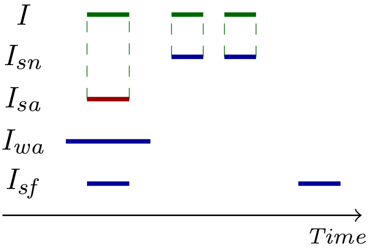

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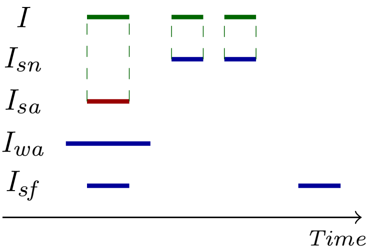

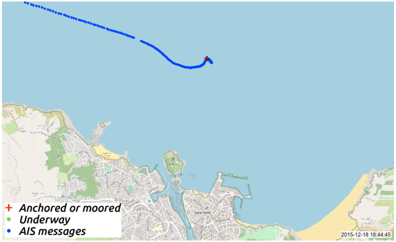

https://cer.iit.demokritos.gr (anchored or moored)

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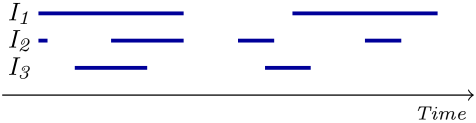
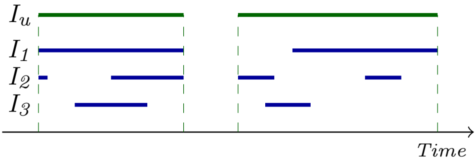


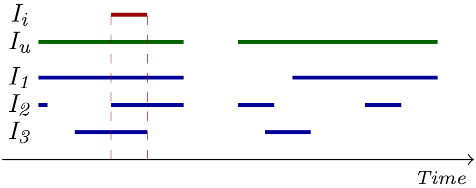
RTEC: Interval-based Reasoning

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

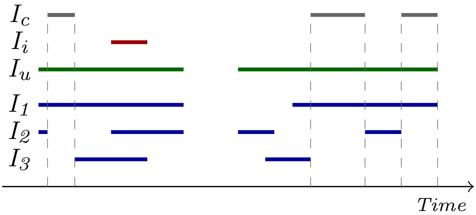


RTEC: Interval-based Reasoning

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

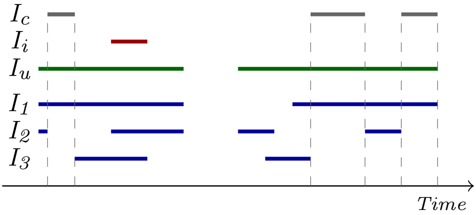
intersect_all$([I_1, I_2, I_3], I_i)$

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

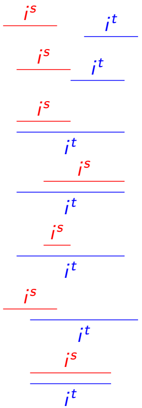


RTEC: Interval-based Reasoning & Allen Relations*

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.

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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RTEC: Interval-based Reasoning & Allen Relations*

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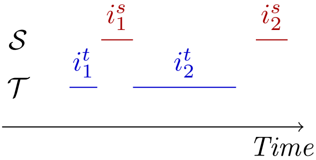
&\quad \textbf{allen}(\mathrm{meets}, \mathcal{S}, \mathcal{T}, \mathrm{target}, I).
\end{aligned}
$$



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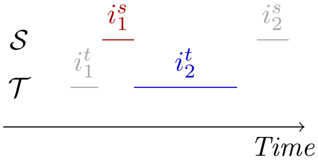
&\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}),\\
&\quad \textbf{allen}(\mathrm{meets}, \mathcal{S}, \mathcal{T}, \mathrm{target}, I).
\end{aligned}
$$



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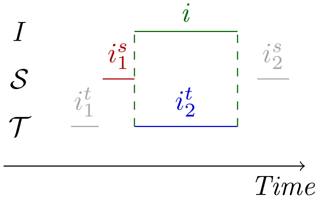
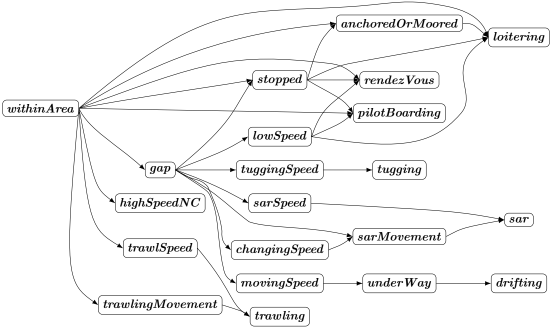
RTEC: Interval-based Reasoning & Allen Relations*

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

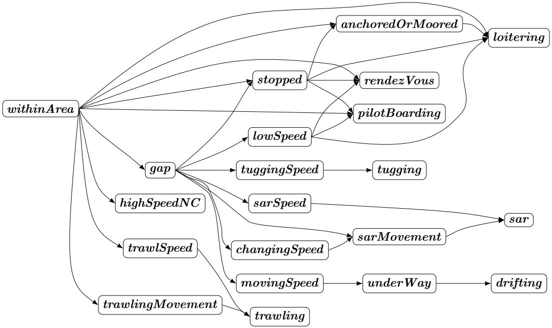


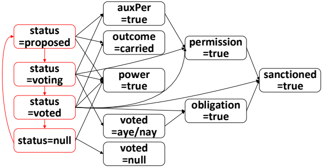
*Mantenoglou et al, Complex Event Recognition with Allen Relations. Knowledge Representation and Reasoning (KR), 2023.

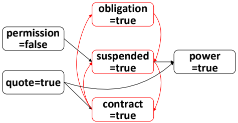
Semantics


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

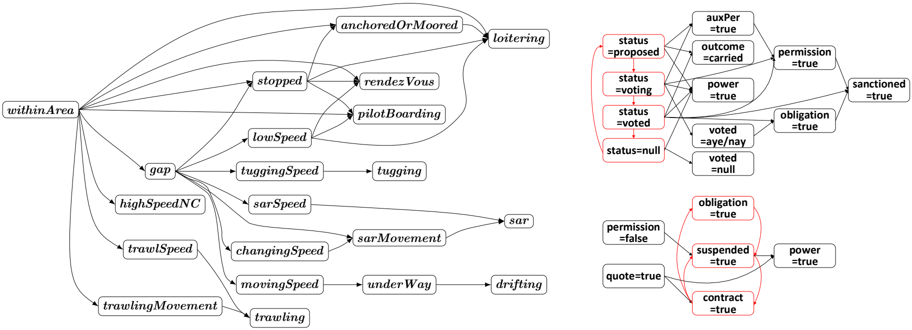
Semantics


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


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


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

Semantics



Proposition

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

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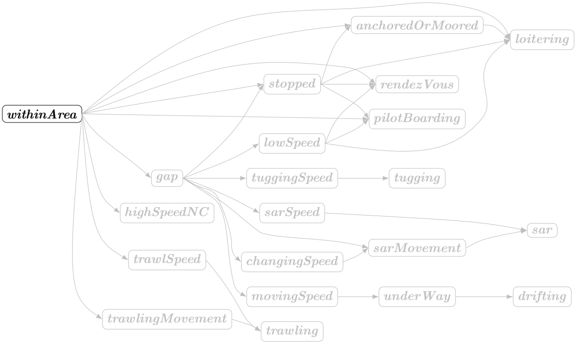
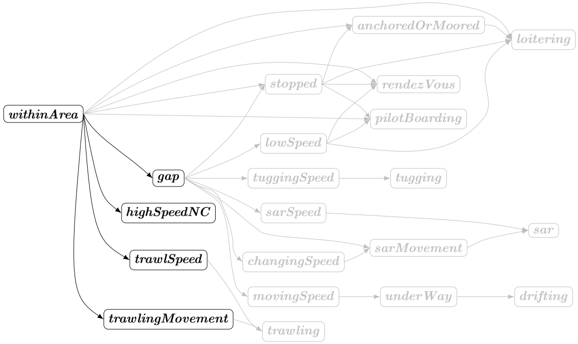
*Mantenoglou et al, Stream Reasoning with Cycles. Knowledge Representation and Reasoning (KR), 2022.

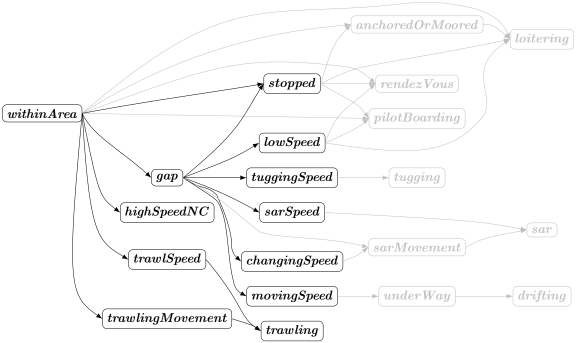
Stratification & Reasoning



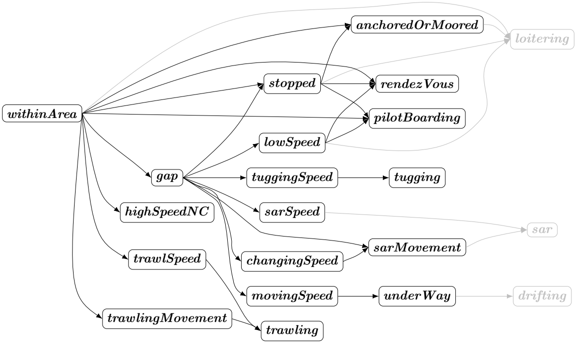
Stratification & Reasoning



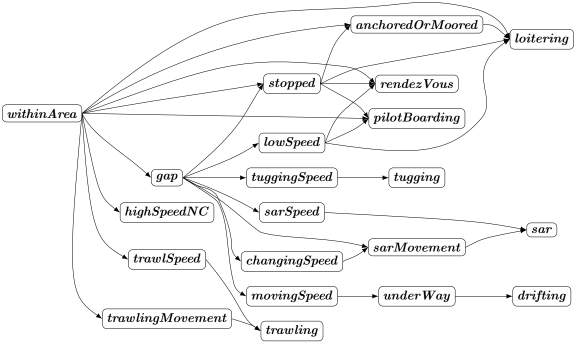
Stratification & Reasoning



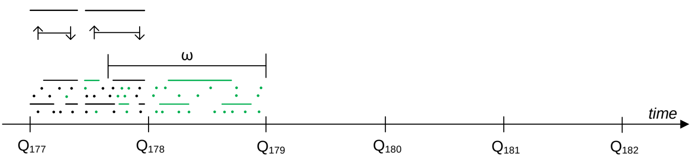
Stratification & Reasoning



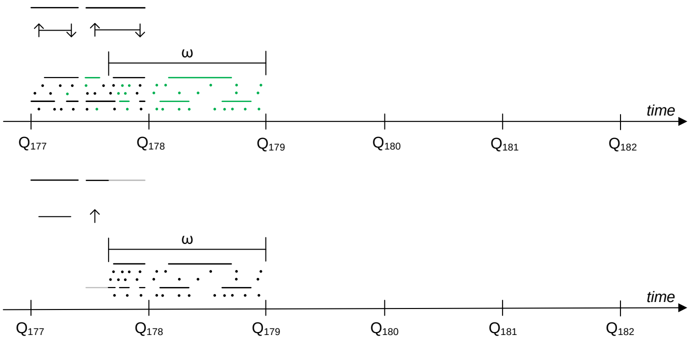
Stratification & Reasoning



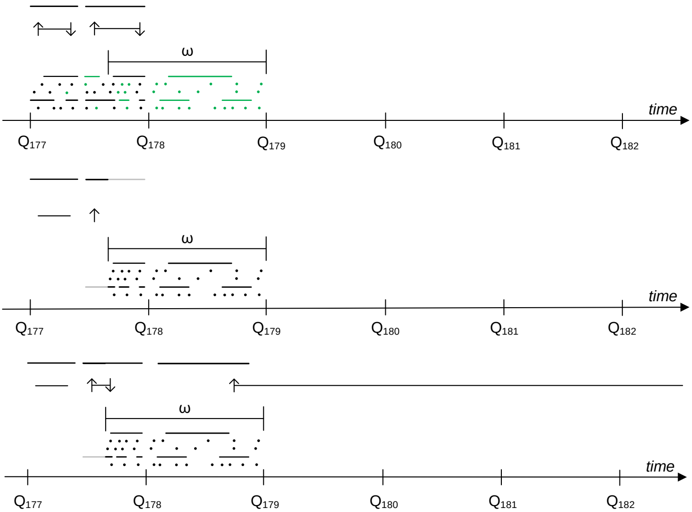
Windowing



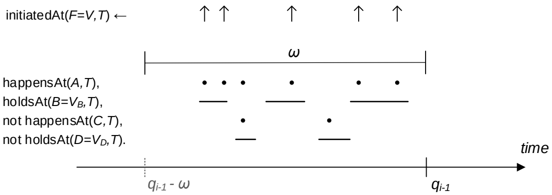
Windowing


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

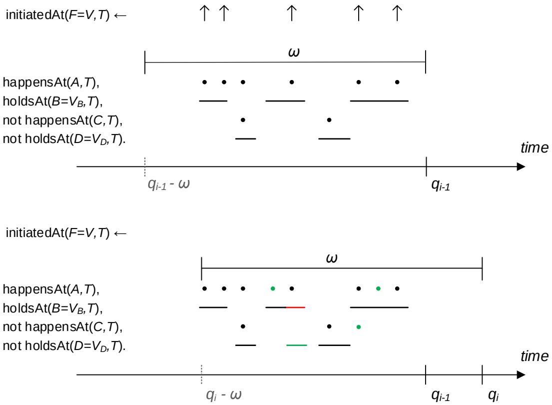
Windowing


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

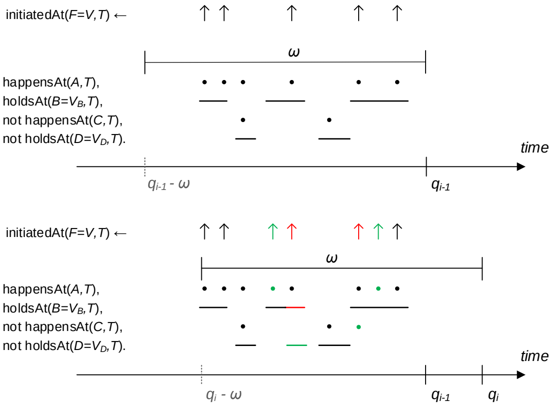
Windowing: Delayed Additions and Deletions



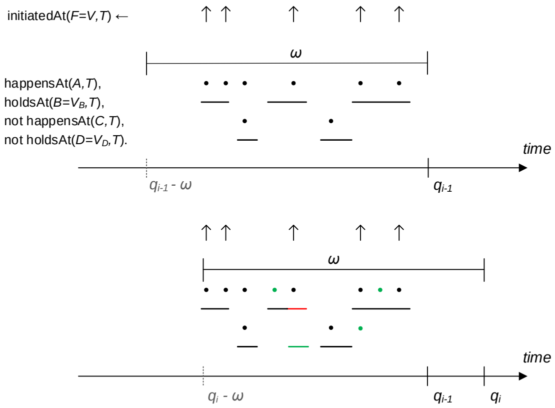
Windowing: Delayed Additions and Deletions



Windowing: Delayed Additions and Deletions

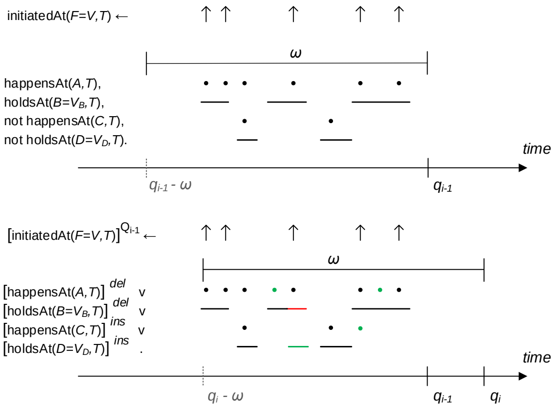


Incremental Reasoning: Deletion Phase*



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

Incremental Reasoning: Deletion Phase*



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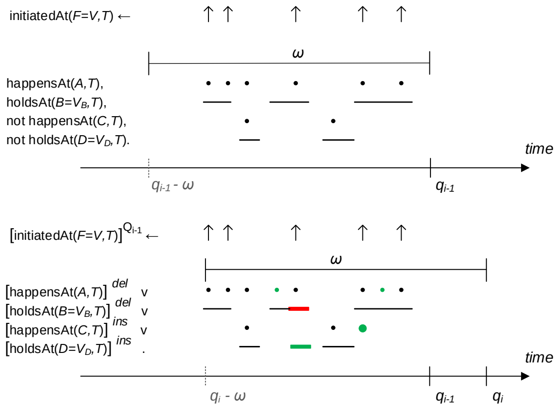

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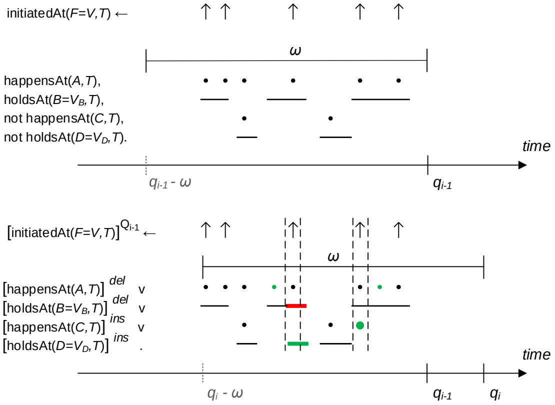
Incremental Reasoning: Deletion Phase*



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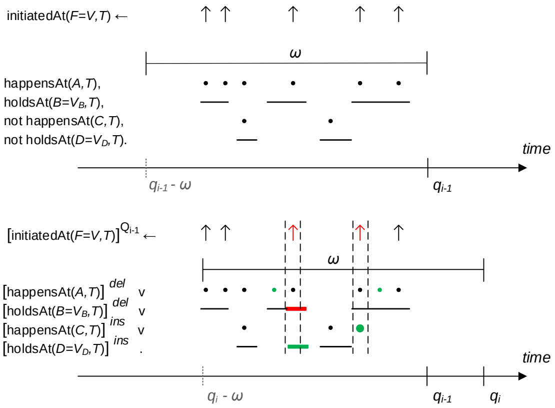

*Tsilionis et al, Incremental Event Calculus for Run-Time Reasoning. Journal of AI Research (JAIR), 2022.

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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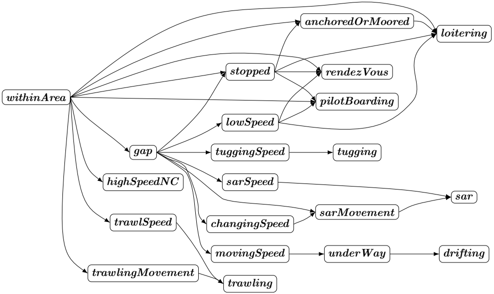
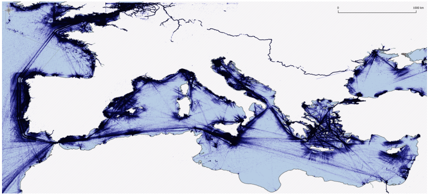
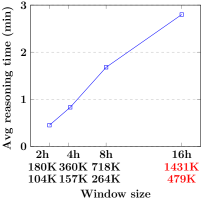
Complexity

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

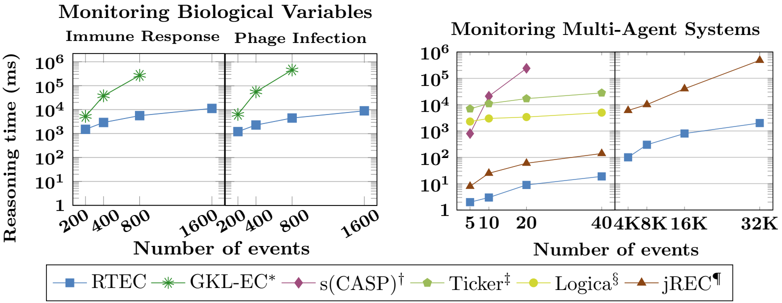
Performance: Indicative Results







Indicative Comparative Analysis



*Srinivasan et al., Learning explanations for biological feedback with delays using an event calculus. Machine Learning, 2022.

†Arias et al., Modeling and reasoning in event calculus using goal-directed constraint answer set programming. Theory and Practice of Logic Programming, 2022.

‡Beck et al., Ticker: A system for incremental asp-based stream reasoning. Theory and Practice of Logic Programming, 2017.

§Logica: Language of Big Data, `https://github.com/EvgSkv/logica`.

¶Falcionelli et al., Indexing the event calculus: Towards practical human-readable personal health systems. Artificial Intelligence in Medicine, 2019.

Indicative Comparative Analysis

Monitoring maritime activities with Allen relations

Window size		Reasoning Time (ms)		Output Intervals	
Days	Input Intervals	RTEC	D^{2}IA*	RTEC	D^{2}IA
1	19K	**40**	410	6K	6K
2	37K	**65**	592	9K	9K
4	74K	**99**	1.1K	16K	16K
8	148K	**156**	1.6K	32K	31K
16	297K	**285**	2.7K	77K	76K

* Awad et al, D^{2}IA: User-defined interval analytics on distributed streams. Information Systems, 2022.

Summary

RTEC:

- Interval-based reasoning $\rightarrow$ avoid unintended semantics.
- Formal, declarative semantics $\rightarrow$ robust/trustworthy CER.
- White-box model $\rightarrow$ explainability.
- Expressive language $\rightarrow$ n-ary constraints.

Summary

RTEC:

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- Formal, declarative semantics $\rightarrow$ robust/trustworthy CER.
- White-box model $\rightarrow$ explainability.
- Expressive language $\rightarrow$ *n*-ary constraints.
- Incremental reasoning $\rightarrow$ handle out-of-order streams.
- Caching $\rightarrow$ real-time performance.
- Direct routes to machine learning $\rightarrow$ automated complex event definition construction.
- Direct routes to probabilistic reasoning.

Summary

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- Direct routes to probabilistic reasoning.

Next: Handle the lack of veracity of data streams.