An Event Calculus for Run-Time Reasoning

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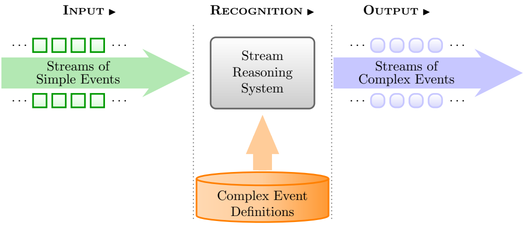
http://cer.iit.demokritos.gr/

Stream Reasoning



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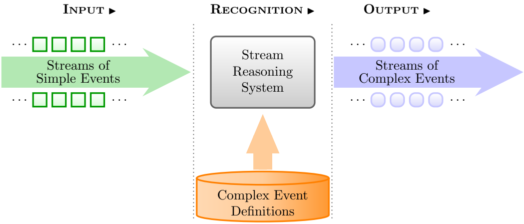

https://cer.iit.demokritos.gr (maritime)

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 R., Sergot M., A Logic-based Calculus of Events. New Gener. Comput. 4(1): 67-95, 1986.

Event Calculus

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

Kowalski R., Sergot M., A Logic-based Calculus of Events. New Gener. Comput. 4(1): 67-95, 1986.

Run-Time Event Calculus (RTEC): Fluent Specification

Simple Fluents:

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

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

where conditions:
$^{0-K}[\text{not}]\ \textbf{happensAt}(E_k, T),$
$^{0-M}[\text{not}]\ \textbf{holdsAt}(F_m = V_m, T),$
$^{0-N}\text{atemporal-constraint}_n$

Artikis A., Sergot M., Paliouras G., An Event Calculus for Event Recognition. In IEEE Transactions on Knowledge and Data Engineering (TKDE), 27(4), 895–908, 2015.

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Statically Determined Fluents:

$\textbf{holdsFor}(F = V, I) \leftarrow$
$\quad \textbf{holdsFor}(F_1 = V_1, I_1)[,$
$\quad \textbf{holdsFor}(F_2 = V_2, I_2), \ldots$
$\quad \textbf{holdsFor}(F_n = V_n, I_n),$
$\quad \text{intervalOperation}(L_1, I_{n+1}), \ldots$
$\quad \text{intervalOperation}(L_m, I)].$

where intervalOperation:

union_all or
intersect_all or
relative_complement_all

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Simple Fluent: 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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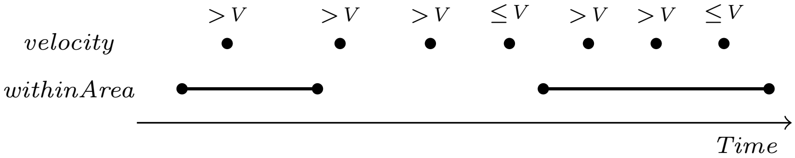
Reasoning: $\textbf{holdsFor}(\mathit{highSpeedNC}(\mathit{Vessel}) = \text{true},\ I)$



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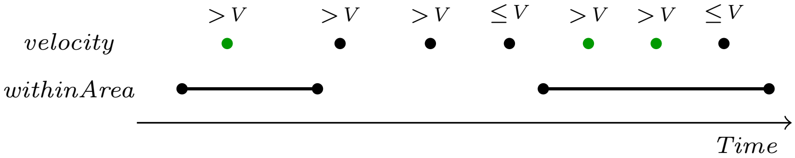

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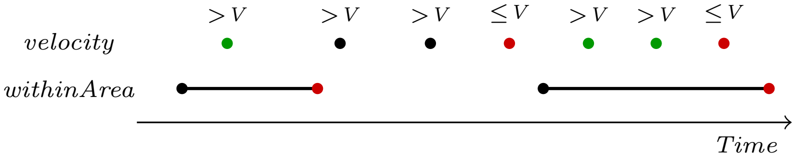

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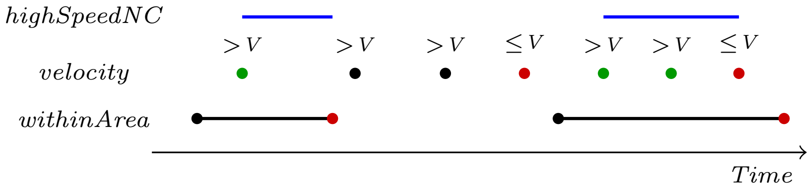

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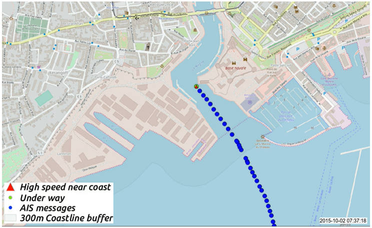

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Statically Determined Fluent: Anchored or Moored

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&\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).
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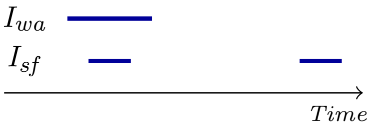

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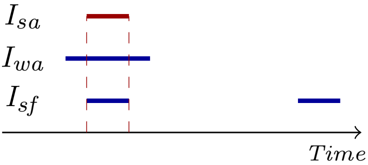

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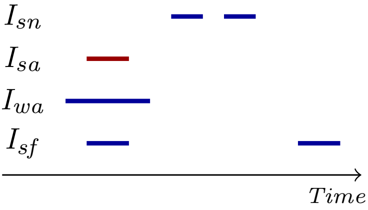

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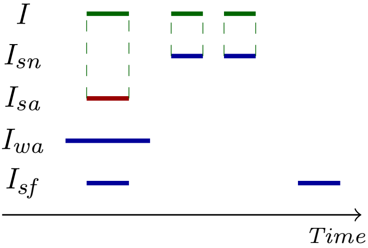

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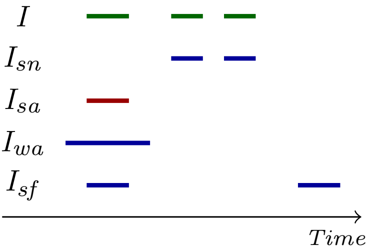

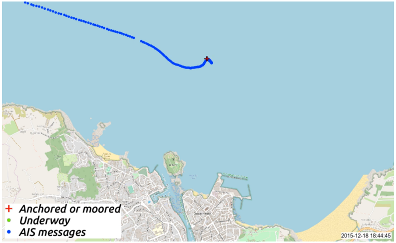

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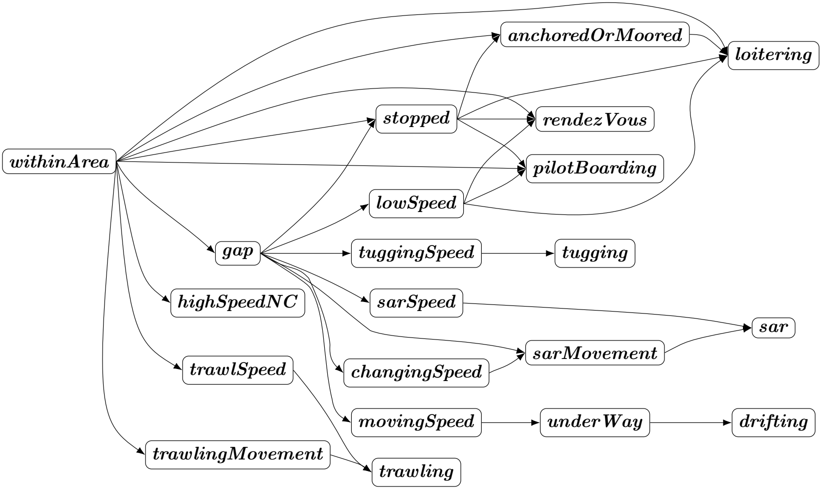
Maritime Knowledge Base



Pitsikalis E. et al., Composite Event Recognition for Maritime Monitoring. In International Conference on Distributed and Event-Based Systems (DEBS), 163–174, 2019.

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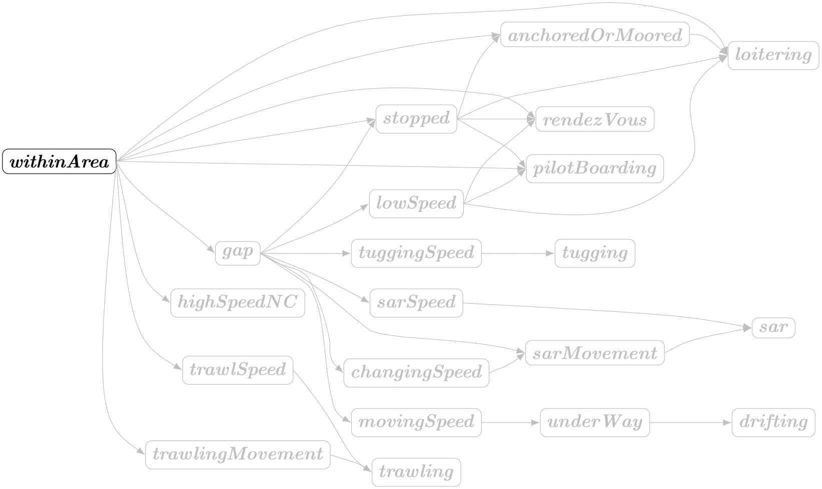

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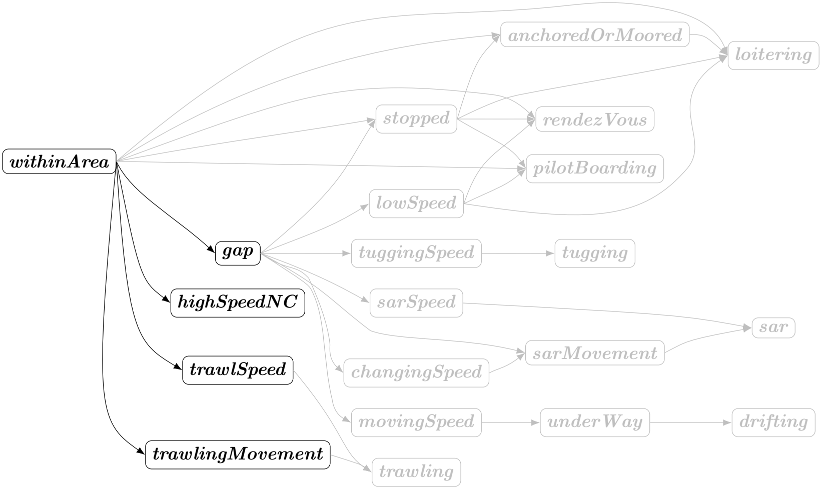

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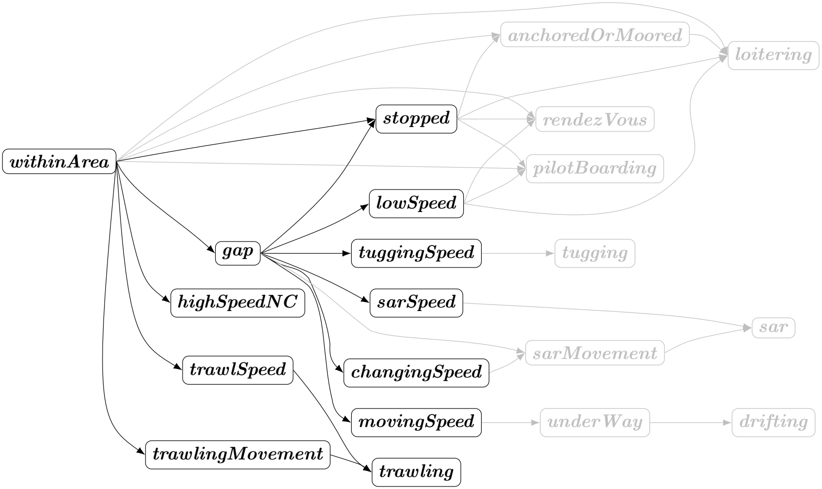

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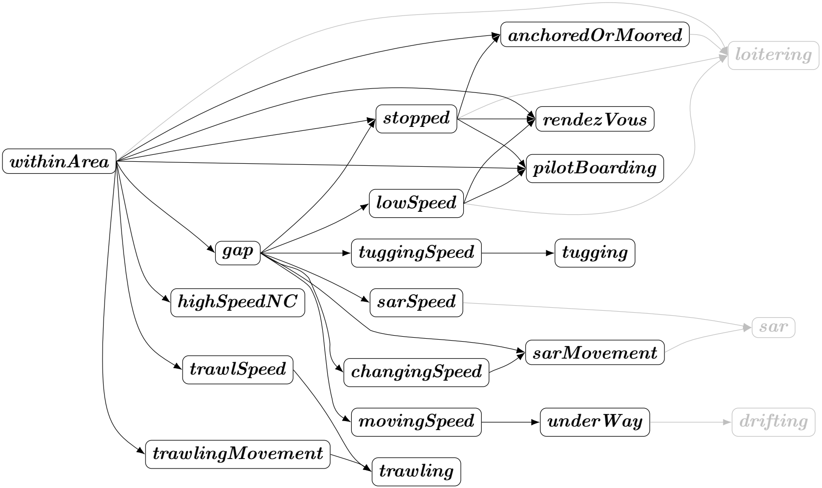

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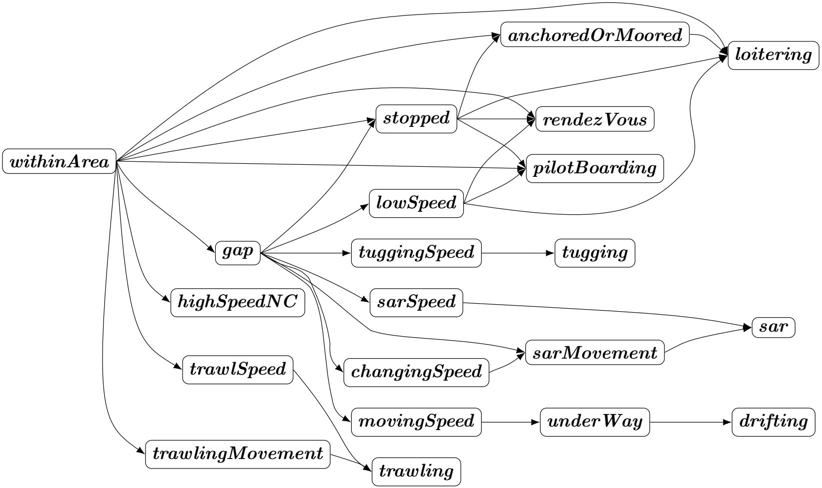

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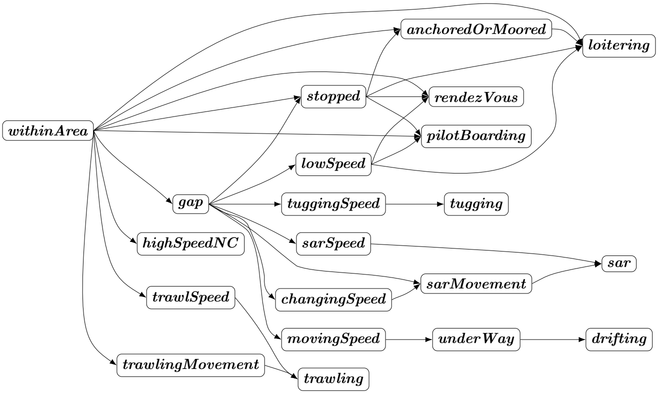
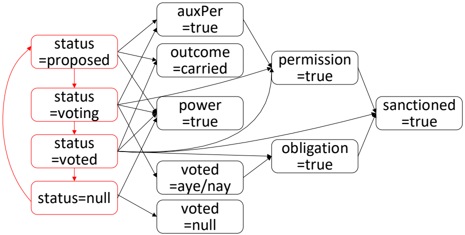


Semantics

An event description of RTEC is a locally stratified logic program.

Cyclic Dependencies in Temporal Specifications



Mantenoglou P., Pitsikalis E., Artikis A., Stream Reasoning with Cycles. In International Conference on Principles of Knowledge Representation and Reasoning (KR), 544–553, 2022.

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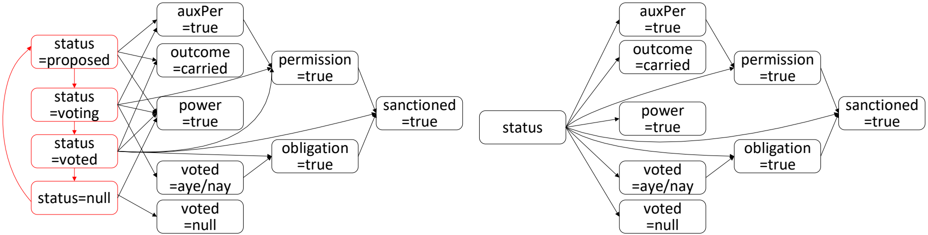

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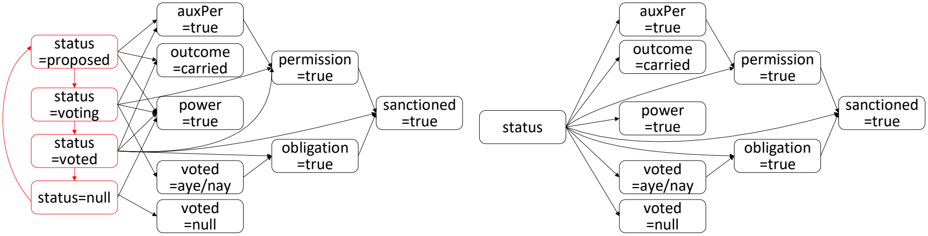

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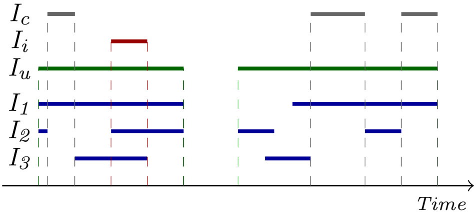
Interval Operations & Allen Relations

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

Mantenoglou P., Kelesis D., Artikis A., Complex Event Recognition with Allen Relations. In International Conference on Principles of Knowledge Representation and Reasoning (KR), 502–511, 2023.

RTEC with Allen Relations

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&\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel}) = \mathit{farFromPorts}, \mathcal{T}), \\
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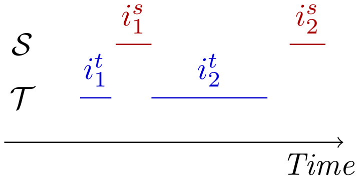

Mantenoglou P., Kelesis D., Artikis A., Complex Event Recognition with Allen Relations. In International Conference on Principles of Knowledge Representation and Reasoning (KR), 502–511, 2023.

RTEC with Allen Relations

$$
\begin{aligned}
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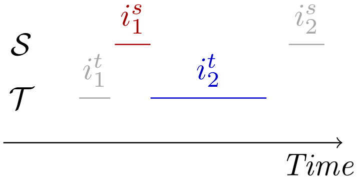

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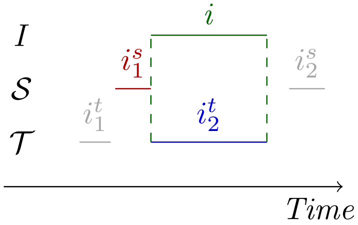

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Multi-Agent Systems: Voting & NetBill

- Compute, e.g., normative positions of agents.

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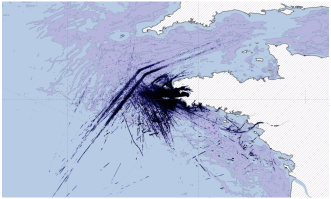

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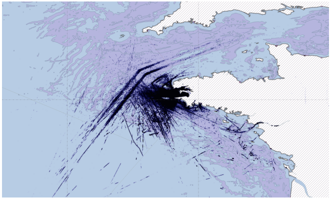


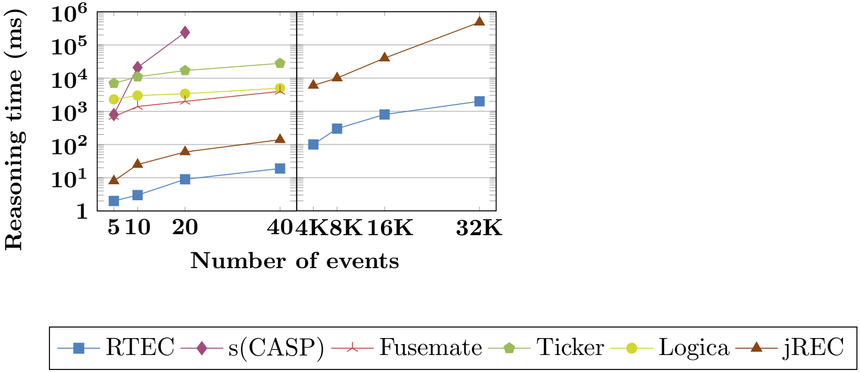
Code, Data & Temporal Specifications

https://github.com/aartikis/RTEC

https://github.com/aartikis/RTEC/tree/allen

Experimental Results

NetBill: monitoring active quotes



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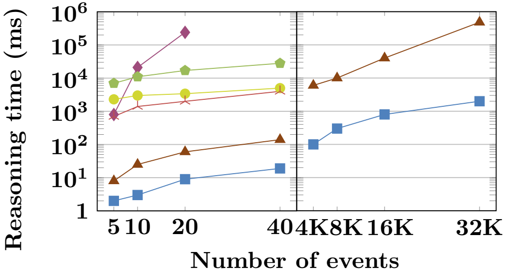
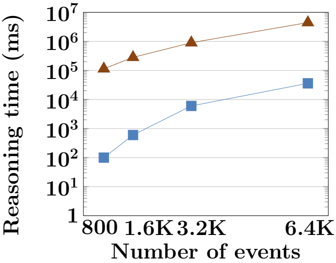
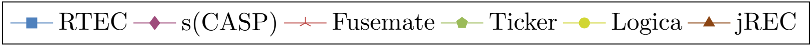


Voting: monitoring the status of motions (cycles)





Experimental Results

Monitoring maritime activities with Allen relations

Window size		Reasoning Time (ms)		Output Intervals	
Days	Input Intervals	RTEC	D^2IA	RTEC	D^2IA
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

Summary & Further Work

RTEC:

- An open-source stream reasoning framework.
- Locally stratified specifications.
- Efficient treatment of cyclic dependencies.
- Support for Allen relations in event patterns.
- Reproducible empirical evaluation on large data streams.

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Further Work:

- Compare expressive power with event sequencing operators.
- Support events with delayed effects.

Appendix

Run-Time Event Calculus (RTEC)

Predicate	Meaning
happensAt(E, T)	Event E occurs at time T
initiatedAt$(F = V, T)$	At time T a period of time for which $F = V$ is initiated
terminatedAt$(F = V, T)$	At time T a period of time for which $F = V$ is terminated
holdsFor$(F = V, I)$	I is the list of the maximal intervals for which $F = V$ holds continuously
holdsAt$(F = V, T)$	The value of fluent F is V at time T
union_all$([J_1, \ldots, J_n],\ I)$	$I = (J_1 \cup \ldots \cup J_n)$
intersect_all$([J_1, \ldots, J_n],\ I)$	$I = (J_1 \cap \ldots \cap J_n)$
relative_complement_all $(I',\ [J_1, \ldots, J_n],\ I)$	$I = I' \setminus (J_1 \cup \ldots \cup J_n)$

Artikis A., Sergot M. and Paliouras G., An Event Calculus for Event Recognition. In IEEE Transactions on Knowledge and Data Engineering (TKDE), 27(4), 895–908, 2015.

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Fluent-Value Pair Computation

Definition:

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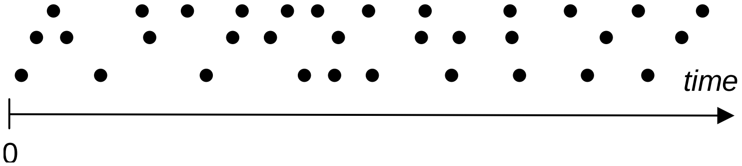

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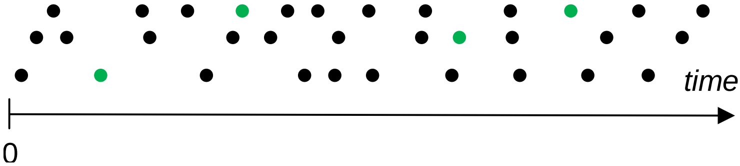

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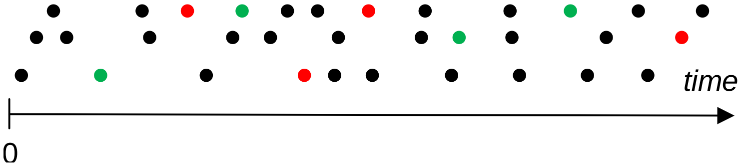

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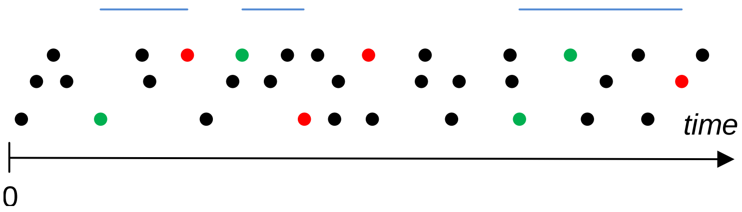
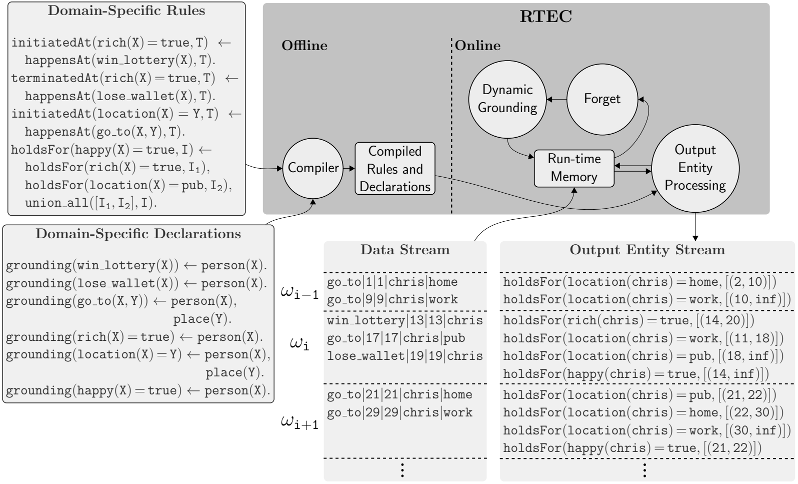
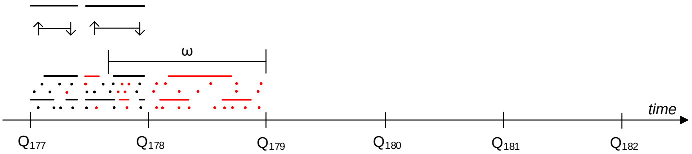
Reasoning: $\textbf{holdsFor}(F = V,\ I)$



RTEC Architecture



RTEC: Windowing



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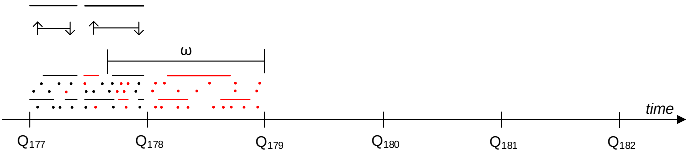

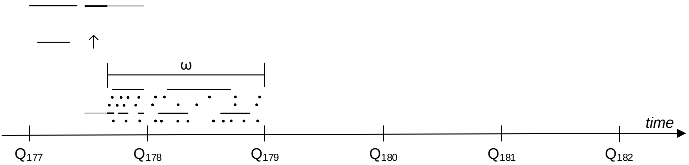

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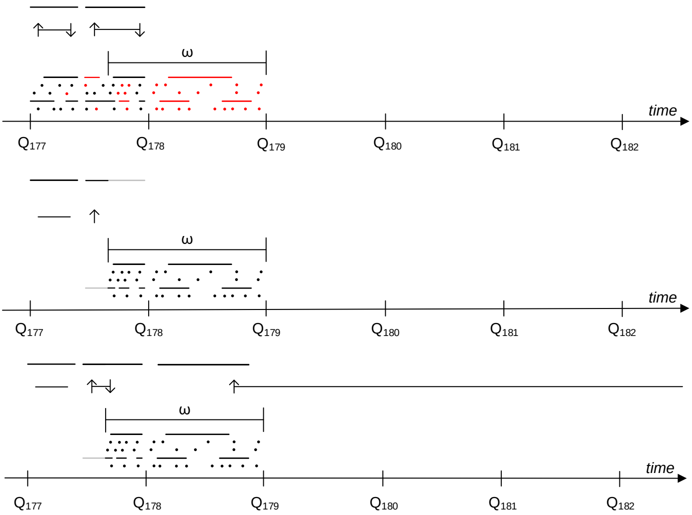

Cyclic Dependencies in Temporal Specifications

$$
\begin{aligned}
&\mathbf{initiatedAt}(\mathit{status}(M) = \mathit{proposed}, T) \leftarrow \\
&\quad \mathbf{happensAt}(\mathit{propose}(P, M), T), \\
&\quad \mathbf{holdsAt}(\mathit{status}(M) = \mathit{null}, T). \\
&\mathbf{initiatedAt}(\mathit{status}(M) = \mathit{voting}, T) \leftarrow \\
&\quad \mathbf{happensAt}(\mathit{second}(S, M), T), \\
&\quad \mathbf{holdsAt}(\mathit{status}(M) = \mathit{proposed}, T). \\
&\mathbf{initiatedAt}(\mathit{status}(M) = \mathit{voted}, T) \leftarrow \\
&\quad \mathbf{happensAt}(\mathit{close\_ballot}(C, M), T), \\
&\quad \mathbf{holdsAt}(\mathit{status}(M) = \mathit{voting}, T). \\
&\mathbf{initiatedAt}(\mathit{status}(M) = \mathit{null}, T) \leftarrow \\
&\quad \mathbf{happensAt}(\mathit{declare}(C, M, \mathit{Res}), T), \\
&\quad \mathbf{holdsAt}(\mathit{status}(M) = \mathit{voted}, T).
\end{aligned}
$$

RTEC$_\mathsf{A}$: Windowing

$$\begin{aligned}
&\textbf{holdsFor}(\mathit{disappearedInArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{withinArea}(\mathit{Vessel}, \mathit{AreaType}) = \text{true}, \mathcal{S}), \\
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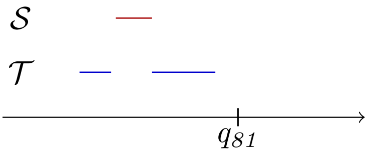
\end{aligned}$$

Query time: q_{81}



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

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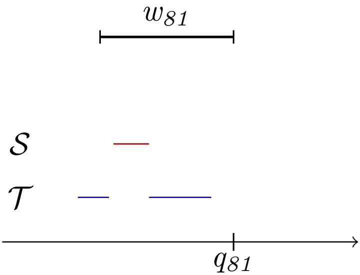

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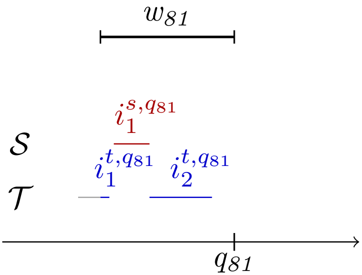

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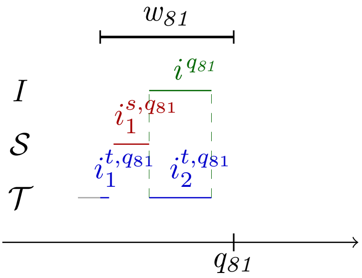
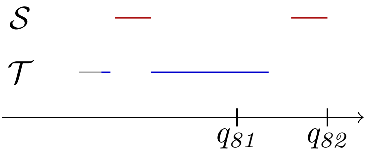


RTEC_{A}: Windowing

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

Query time: q_{82}



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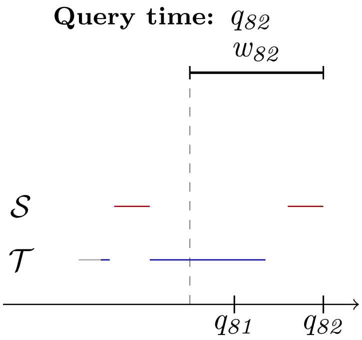

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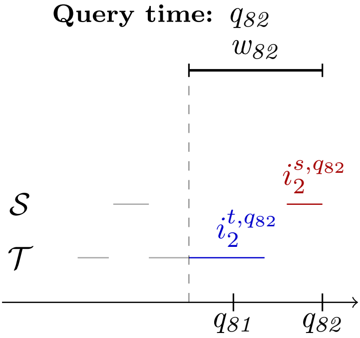

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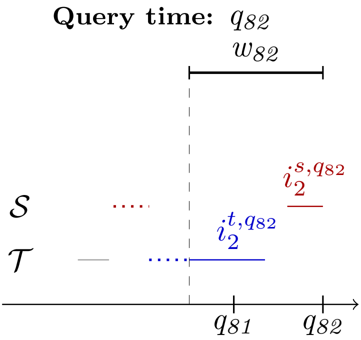
$$



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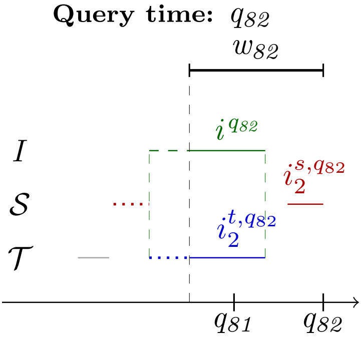


RTEC_A: Correctness & Complexity

Correctness of RTEC_A

RTEC_A computes all maximal intervals of a fluent defined in terms of an Allen relation, and no other interval.

RTEC$_A$: Correctness & Complexity

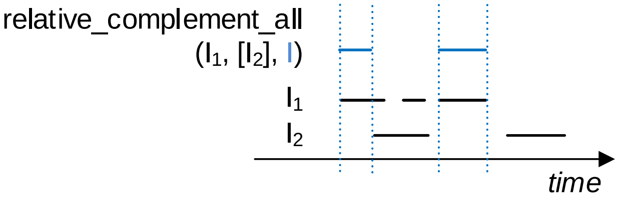
Correctness of RTEC$_A$

RTEC$_A$ computes all maximal intervals of a fluent defined in terms of an Allen relation, and no other interval.

Complexity of RTEC$_A$

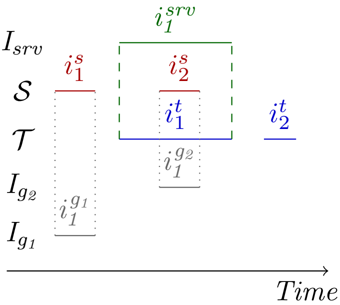
The cost of computing the maximal intervals of a fluent defined in terms of an Allen relation is $\mathcal{O}(n)$, where n is the number of input intervals.

Interval Manipulation: Relative Complement



RTEC$_A$: RTEC with Allen Relations

$$\begin{aligned}
&\textbf{holdsFor}(\mathit{suspiciousRendezVous}(\mathit{Vessel_1}, \mathit{Vessel_2}) = \mathrm{true}, I) \leftarrow \\
&\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel_1}) = \mathit{farFromPorts}, I_{g_1}), \\
&\quad \textbf{holdsFor}(\mathit{gap}(\mathit{Vessel_2}) = \mathit{farFromPorts}, I_{g_2}), \\
&\quad \textbf{holdsFor}(\mathit{proximity}(\mathit{Vessel_1}, \mathit{Vessel_2}) = \mathrm{true}, \mathcal{T}), \\
&\quad \textbf{union_all}([I_{g_1}, I_{g_2}], \mathcal{S}), \\
&\quad \textbf{allen}(\mathrm{during}, \mathcal{S}, \mathcal{T}, \mathrm{target}, I).
\end{aligned}$$



Experimental Evaluation

Batch setting.

Batch size	Reasoning Time		
Input Intervals	$RTEC_A$	AEGLE	D^2IA
200	**1**	980	2K
2K	**14**	4K	6K
20K	**154**	71.5K	395K
200K	**1.8K**	MEM	$>$3.6M

Streaming setting.

Window size		Reasoning Time		Output Interval Pairs	
Days	Input Intervals	$RTEC_A$	D^2IA	$RTEC_A$	D^2IA
1	125	**1**	48	5K	5K
2	250	**2**	164	19K	18K
4	500	**4**	568	72K	71K
8	1K	**8**	1.7K	237K	236K
16	2K	**15**	7.8K	878K	874K