Stream Reasoning with Sequencing

Manolis Pitsikalis[1] **and Alexander Artikis**[2,1]

[1]NCSR Demokritos, [2] University of Piraeus, Greece



LPAR 2026

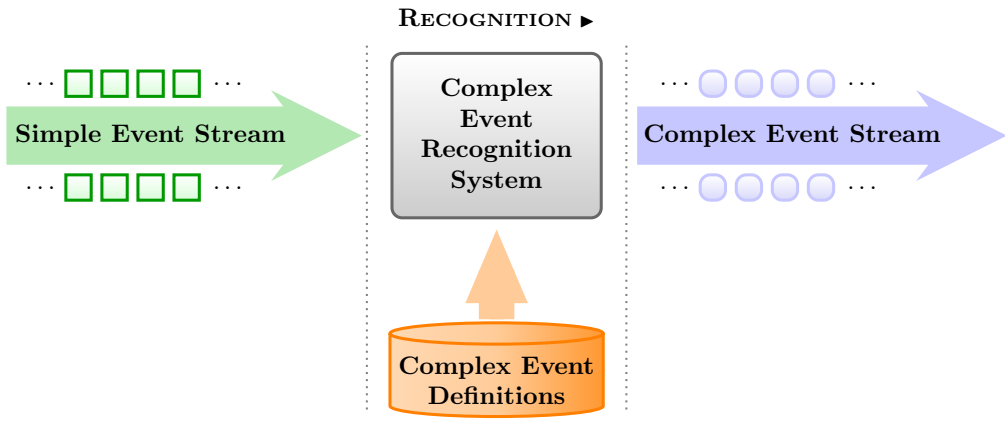




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UNIVERSITY OF PIRAEUS

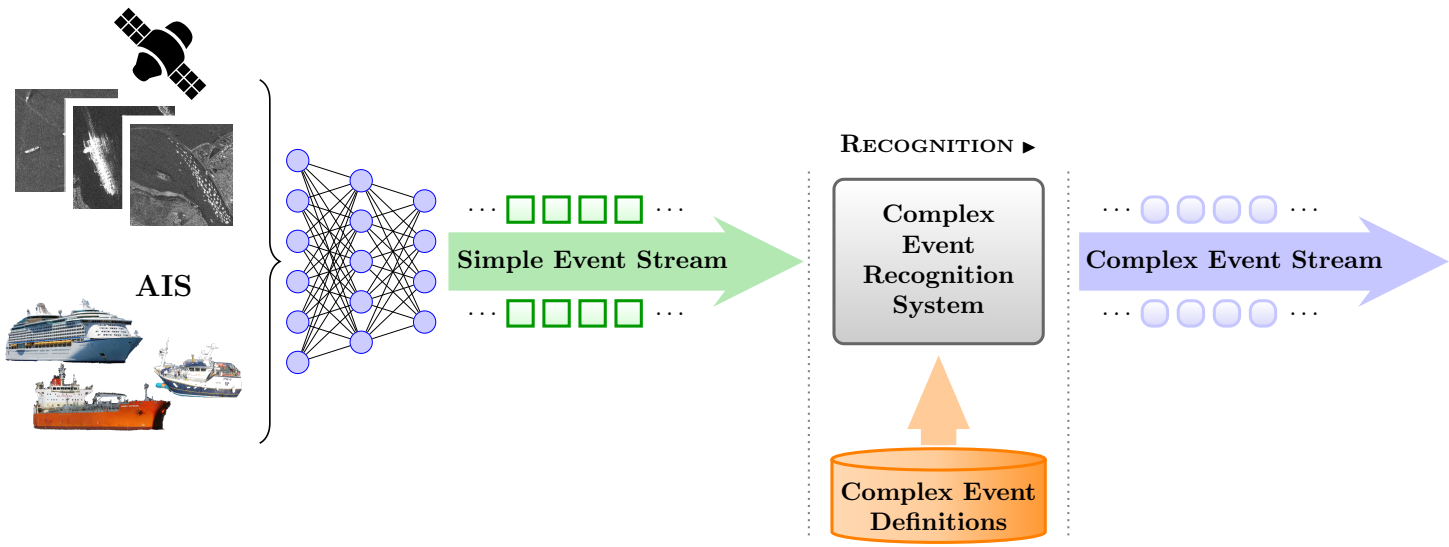
Complex Event Recognition*,†



*Giatrakos et al, Complex Event Recognition in the Big Data Era: A Survey. VLDB Journal, 2020.

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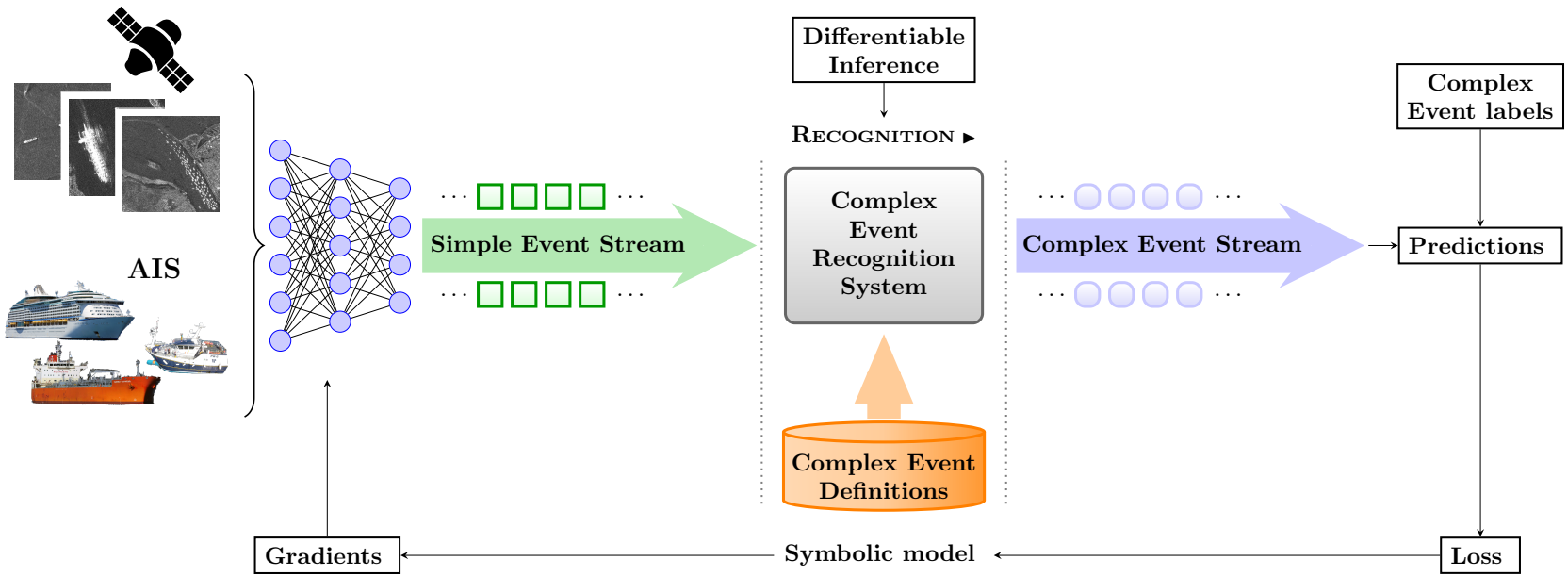
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Complex Event Recognition for Maritime Situational Awareness*



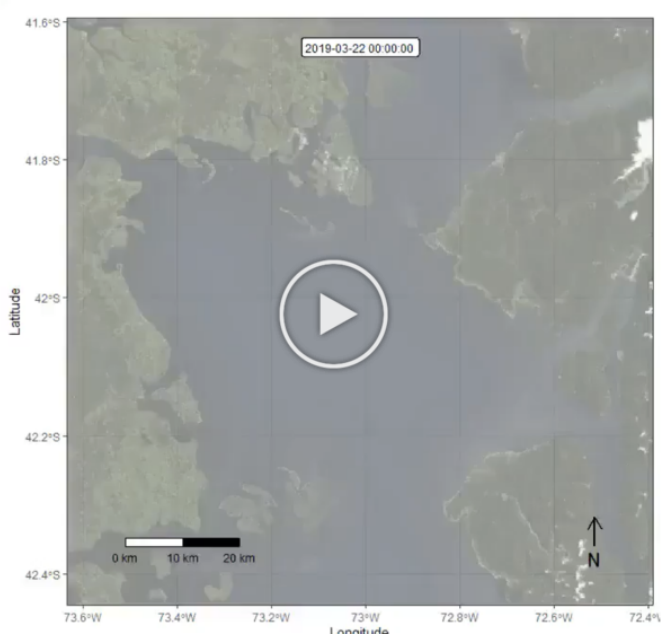
https://cer.iit.demokritos.gr (fishing vessel)

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

Complex Event Recognition for Maritime Situational Awareness*



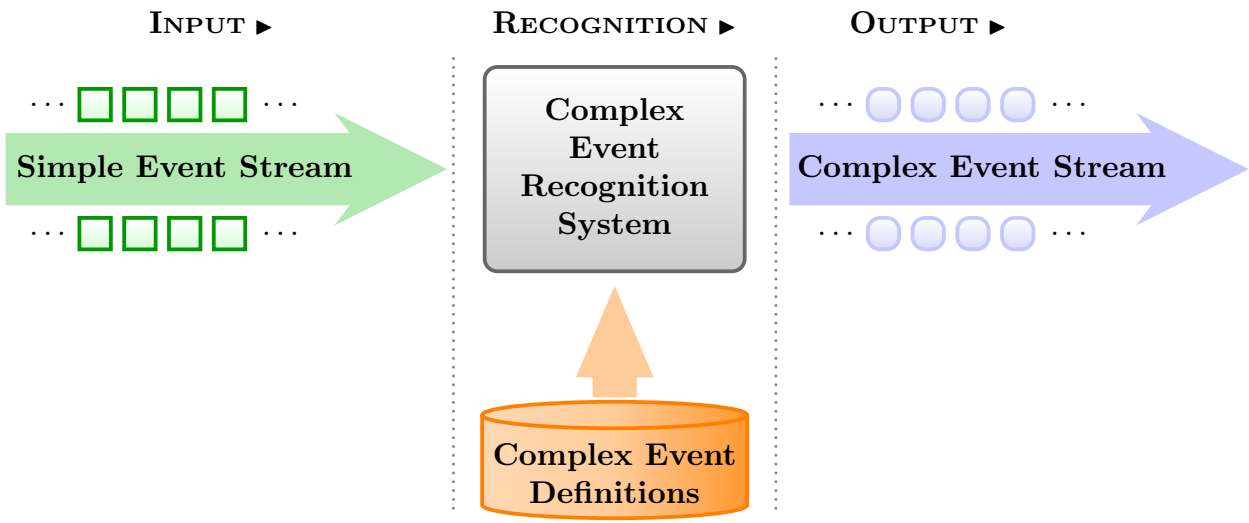
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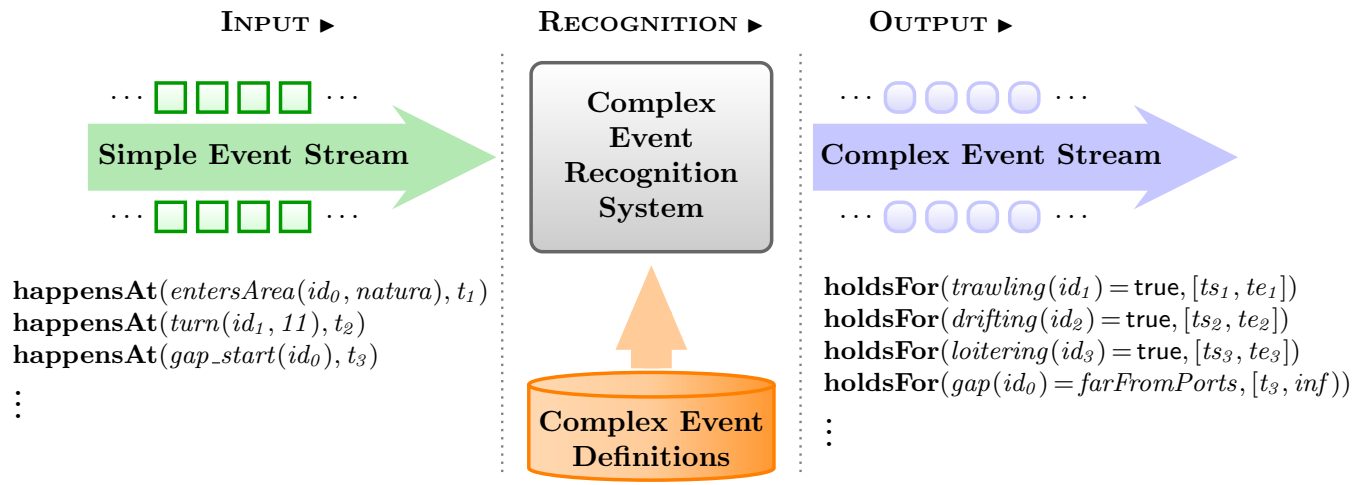
https://rdcu.be/cNkQE

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

Complex Event Recognition



Complex Event Recognition with the Run-Time Event Calculus (RTEC)*



initiatedAt$(gap(Vessel) = nearPorts, T) \leftarrow$
  happensAt$(gap_start(Vessel), T)$,
  holdsAt$(withinArea(Vessel, nearPorts) = \text{true}, T)$.

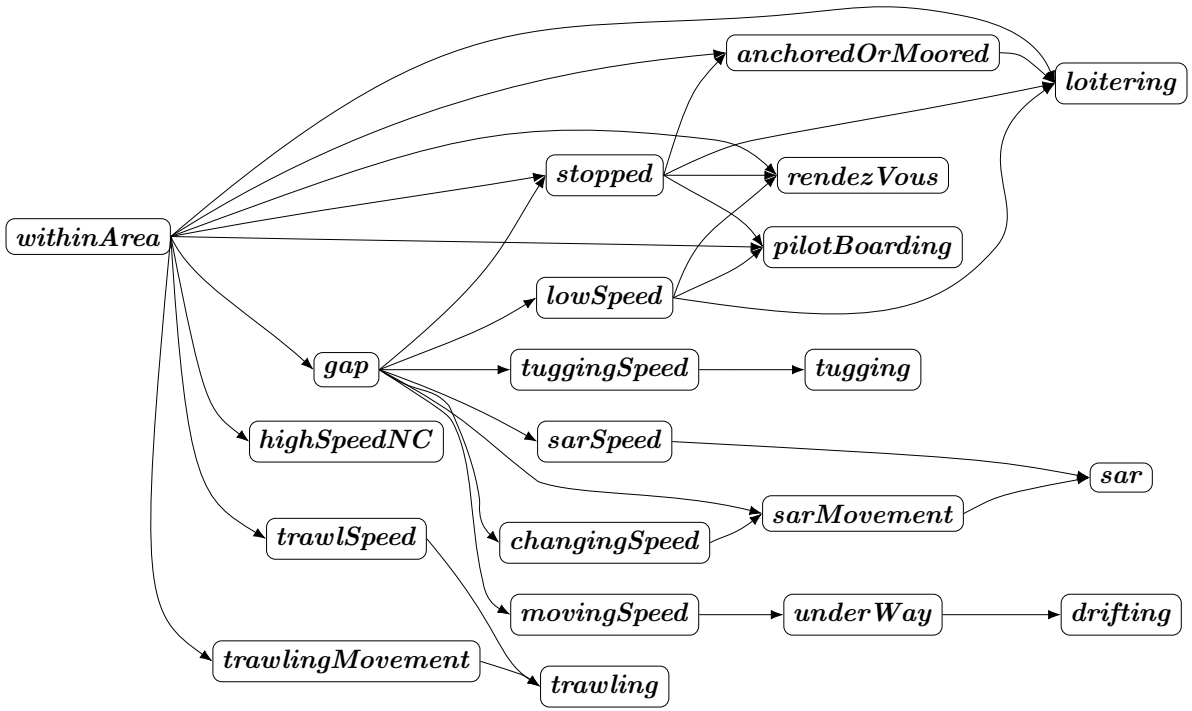
initiatedAt$(gap(Vessel) = farFromPorts, T) \leftarrow$
  happensAt$(gap_start(Vessel), T)$,
  not **holdsAt**$(withinArea(Vessel, nearPorts) = \text{true}, T)$.

terminatedAt$(gap(Vessel) = PortStatus, T) \leftarrow$
  happensAt$(gap_end(Vessel), T)$.

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

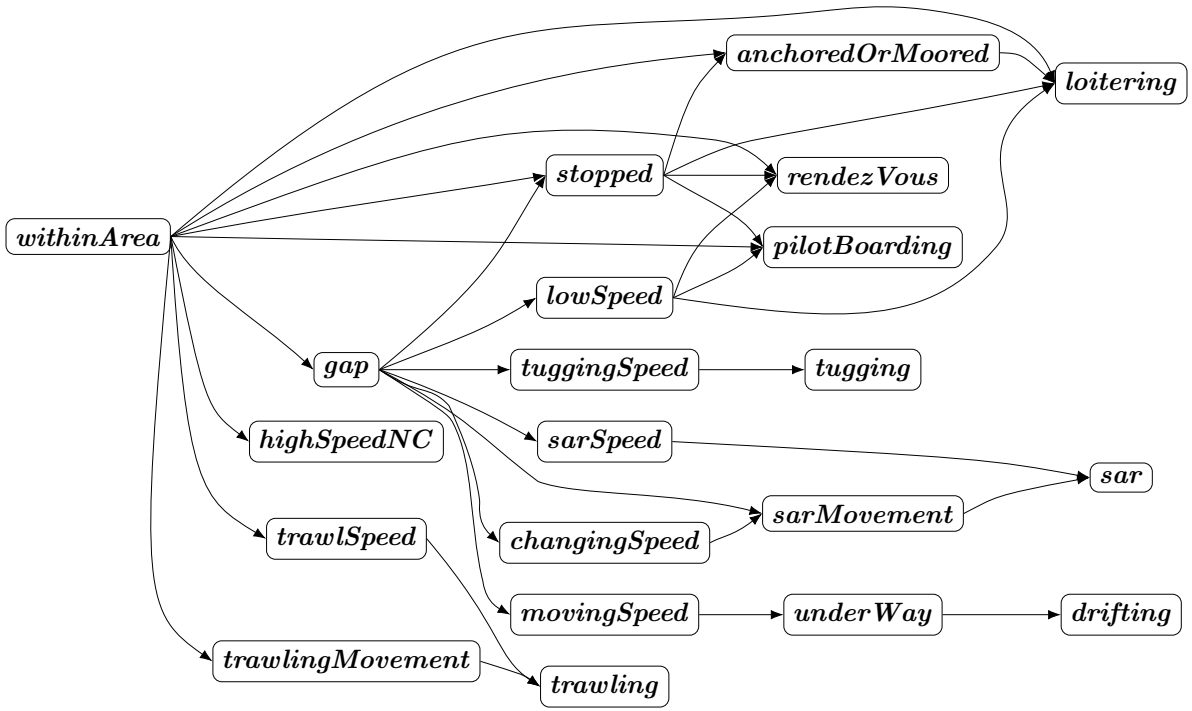
*Mantenoglou et al, Reasoning over Streams of Events with Delayed Effects. JAIR, 2025.
https://github.com/aartikis/RTEC

Dependency Graph & Semantics*



*Mantenoglou et al, Stream Reasoning with Cycles. KR, 2022.

Dependency Graph & Semantics*



Semantics

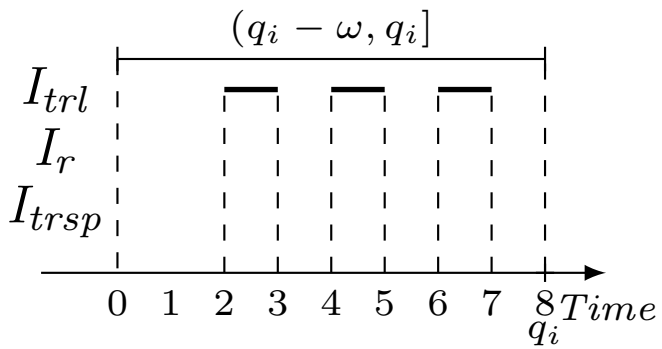
An event description in RTEC is a locally stratified logic program.

*Mantenoglou et al, Stream Reasoning with Cycles. KR, 2022.

RTEC$_s$: Sequencing in RTEC*

RTEC$_s$: RTEC with associative and compositional interval-based sequencing.

$$\textbf{holdsFor}(\mathit{transhipment}(\mathit{Vessel}_a, \mathit{Vessel}_b) = \text{true},\ I_{trsp}) \leftarrow$$
$$\textbf{holdsFor}(\mathit{trawling}(\mathit{Vessel}_a) = \text{true},\ I_{trl}),$$
$$\textbf{holdsFor}(\mathit{rendezVous}(\mathit{Vessel}_a, \mathit{Vessel}_b) = \text{true},\ I_r),$$
$$\textbf{seq}(I_{trl},\ I_r,\ I_{trsp}).$$

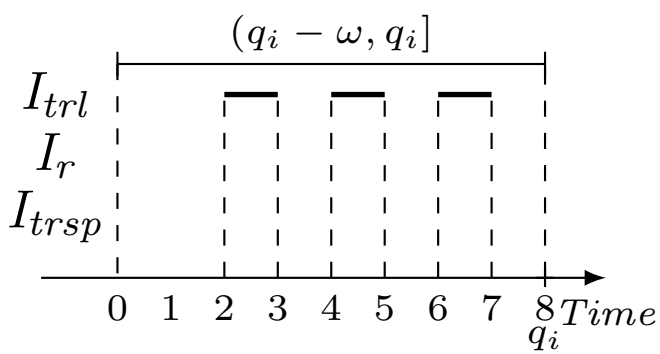


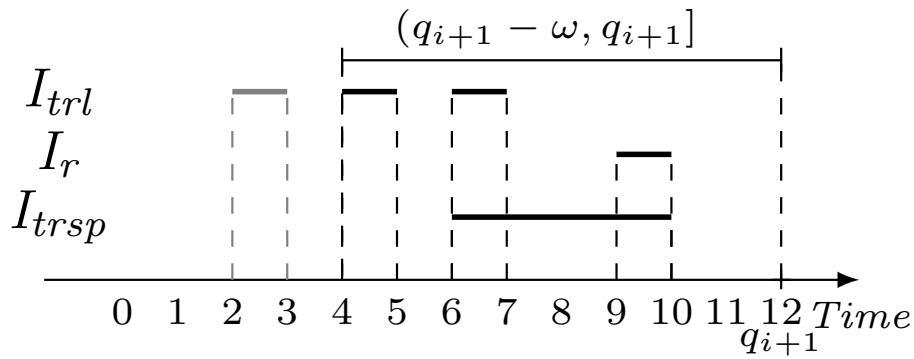
*Mantenoglou P. and Artikis A., Sequencing in the Run-Time Event Calculus. In ECAI 2025.

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*Mantenoglou P. and Artikis A., Sequencing in the Run-Time Event Calculus. In ECAI 2025.

$\text{RTEC}_s^{\text{RCT}}$: Monotonic & Efficient Stream Reasoning with Sequencing

$\text{RTEC}_s^{\text{RCT}}$

- Monotonic output for monotonic input.

$\text{RTEC}_s^{\text{RCT}}$: Monotonic & Efficient Stream Reasoning with Sequencing

$\text{RTEC}_s^{\text{RCT}}$

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- Identify the largest prefix of the output that will remain invariant under any possible evolution of the input.

$\text{RTEC}_s^{\text{RCT}}$: Monotonic & Efficient Stream Reasoning with Sequencing

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- Stateful windowing with minimal bookkeeping.

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$\text{RTEC}_s^{\text{RCT}}$

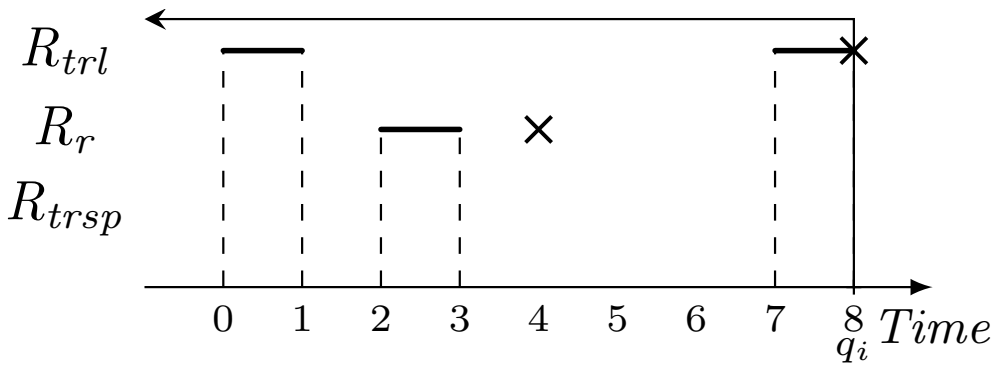
- Monotonic output for monotonic input.
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- Stateful windowing with minimal bookkeeping.

Key strucuture: Reasoning Cut-off Tuples (RCTs), denoted as $R_o = \langle I_o, T_o \rangle$.

- I_o: a list of maximal intervals
- T_o: a cut-off point expressing a 'stability horizon'
- The intervals in I_o end no later than T_o

Cut-off point computation

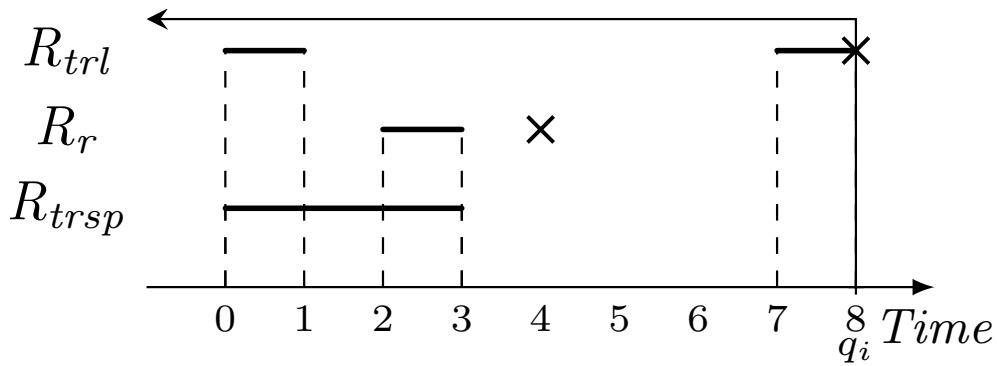
$$\textbf{holdsFor}^{\bullet}(\mathit{transhipment}(\mathit{Vessel}_a, \mathit{Vessel}_b) = \text{true},\ R_{trsp}) \leftarrow$$
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$$\textbf{seq}^{\bullet}(R_{trl},\ R_r,\ R_{trsp}).$$



$\times$: cut-off point

Cut-off point computation

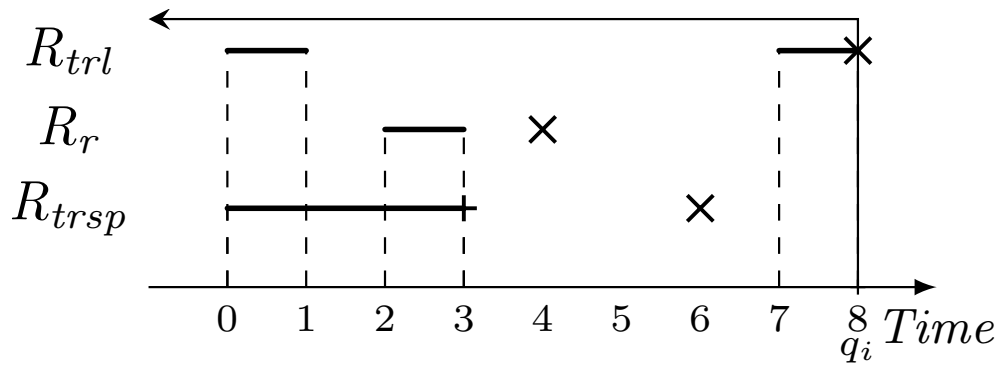
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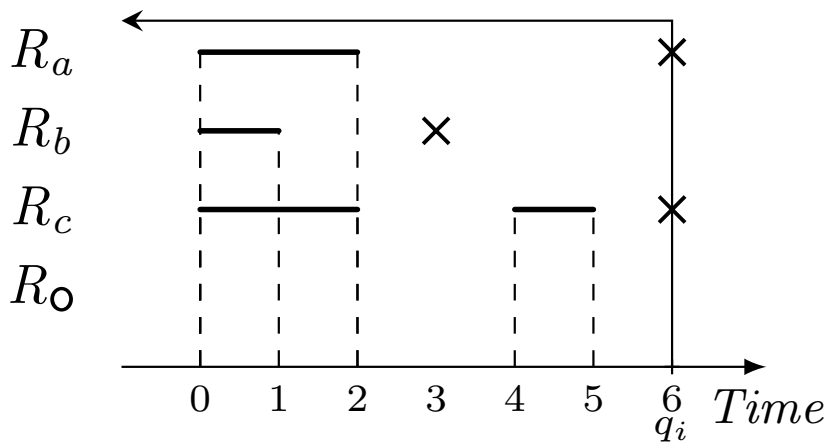


$\times$: cut-off point

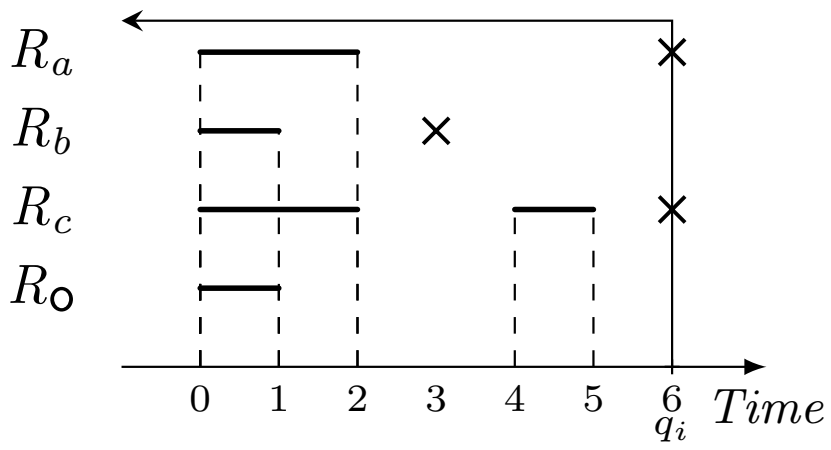
Cut-off point computation: Hierarchal knowledge bases

$$\begin{aligned}
&\textbf{holdsFor}^{\bullet}(\mathit{suspiciousAnchored}(\mathit{Vessel}) = \text{true},\ R_{sa}) \leftarrow \\
&\quad \textbf{holdsFor}^{\bullet}(\mathit{transhipment}(_, \mathit{Vessel}) = \text{true},\ R_{trsp}), \\
&\quad \textbf{holdsFor}^{\bullet}(\mathit{withinArea}(\mathit{Vessel}, \mathit{anchorage}) = \text{true},\ R_a), \\
&\quad \textbf{seq}^{\bullet}(R_{trsp},\ R_a,\ R_{aux}), \\
&\quad \textbf{holdsFor}^{\bullet}(\mathit{stopped}(\mathit{Vessel}) = \mathit{farFromPorts},\ R_{sf}), \\
&\quad \textbf{intersect_all}^{\bullet}([R_a, R_{aux}, R_{sf}],\ R_{sa}).
\end{aligned}$$

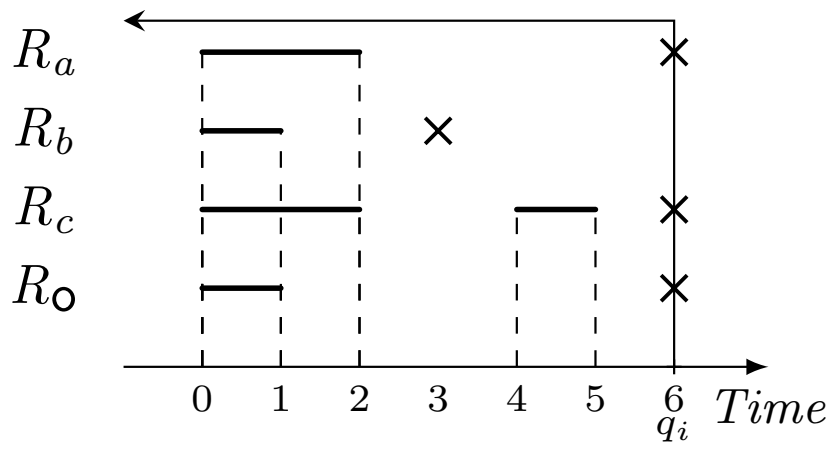
Cut-off point computation: intersection



Cut-off point computation: intersection



Cut-off point computation: intersection



$\text{RTEC}_s^{\text{RCT}}$: Monotonic reasoning & cut-off optimality

Monotonic reasoning

The interval list I_o computed by means of $\textbf{holdsFor}^{\bullet}(F = V, \langle I_o, T_o \rangle)$ at query-time q_i will never be revised at a future query-time.

$\text{RTEC}_s^{\text{RCT}}$: Monotonic reasoning & cut-off optimality

Monotonic reasoning

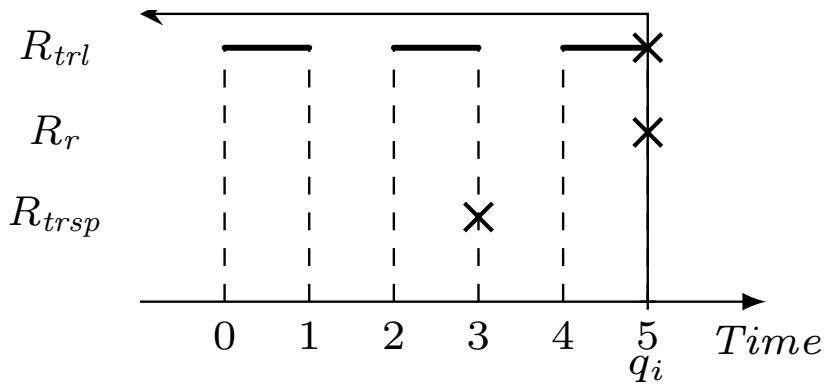
The interval list I_o computed by means of $\textbf{holdsFor}^\bullet(F = V, \langle I_o, T_o \rangle)$ at query-time q_i will never be revised at a future query-time.

Cut-off point optimality

The cut-off point T_o computed by means of $\textbf{holdsFor}^\bullet(F = V, \langle I_o, T_o \rangle)$ at query-time q_i is the latest time-point that guarantees monotonic output.

Stateful Windowing

$$\textbf{holdsFor}^{\bullet}(\mathit{transhipment}(\mathit{Vessel}_a, \mathit{Vessel}_b) = \text{true},\ R_{trsp}) \leftarrow$$
$$\quad \textbf{holdsFor}^{\bullet}(\mathit{trawling}(\mathit{Vessel}_a) = \text{true},\ R_{trl}),$$
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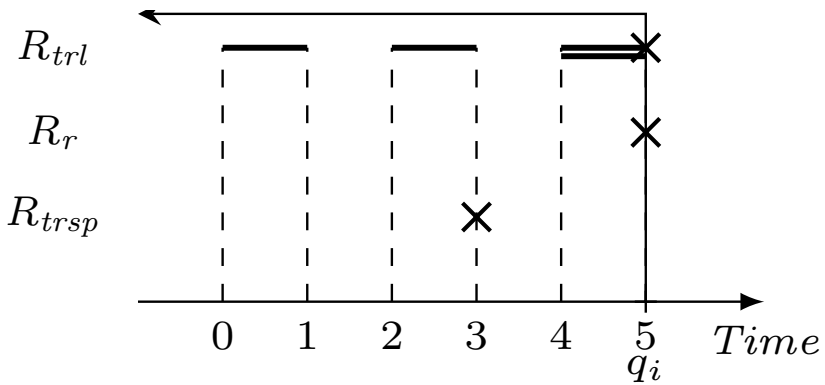
× : cut-off point

$\Longrightarrow$: interval caching

$\Longrightarrow$: interval retrieval

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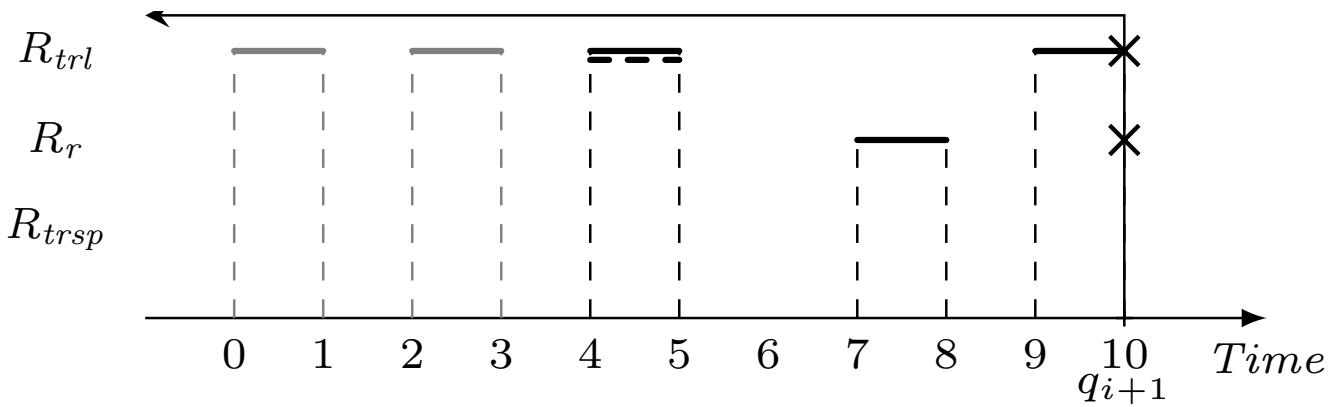
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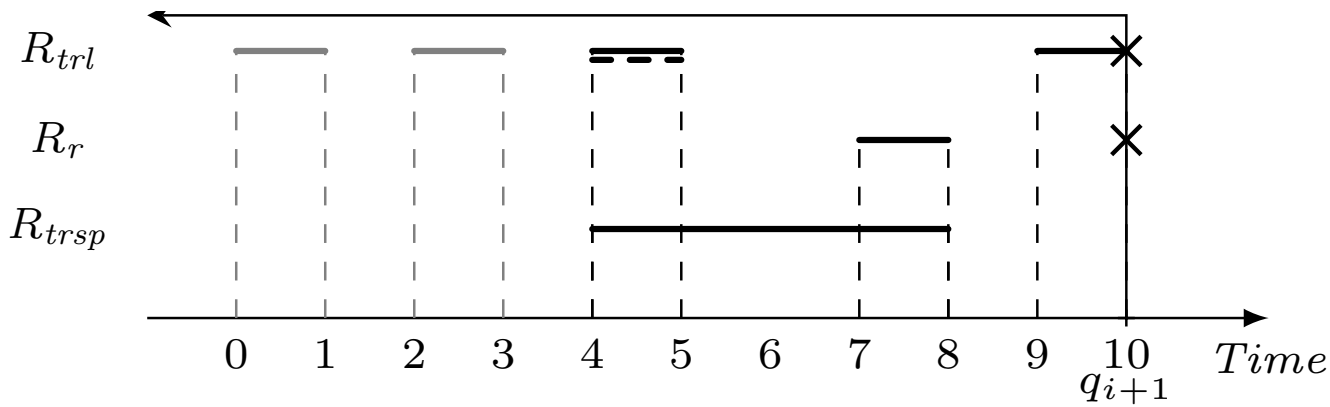
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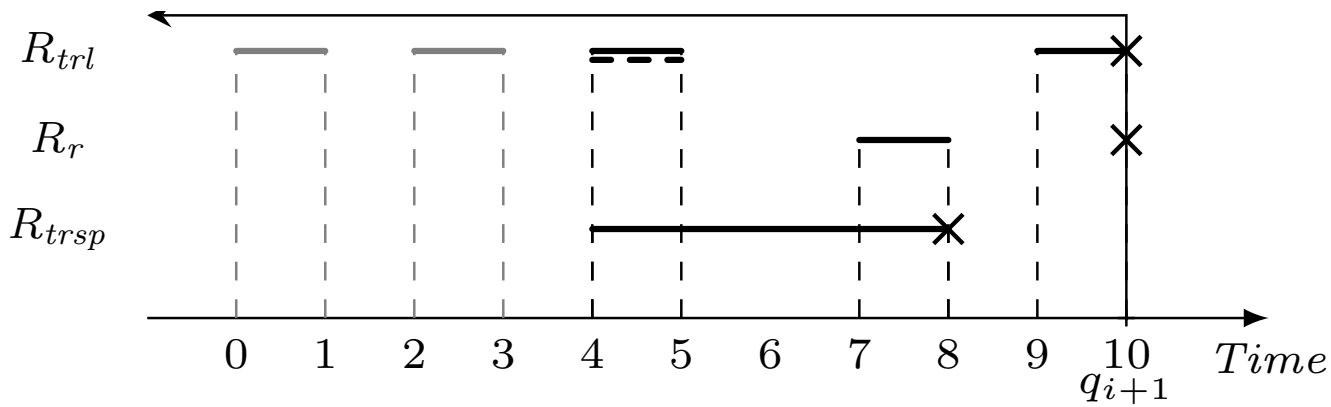
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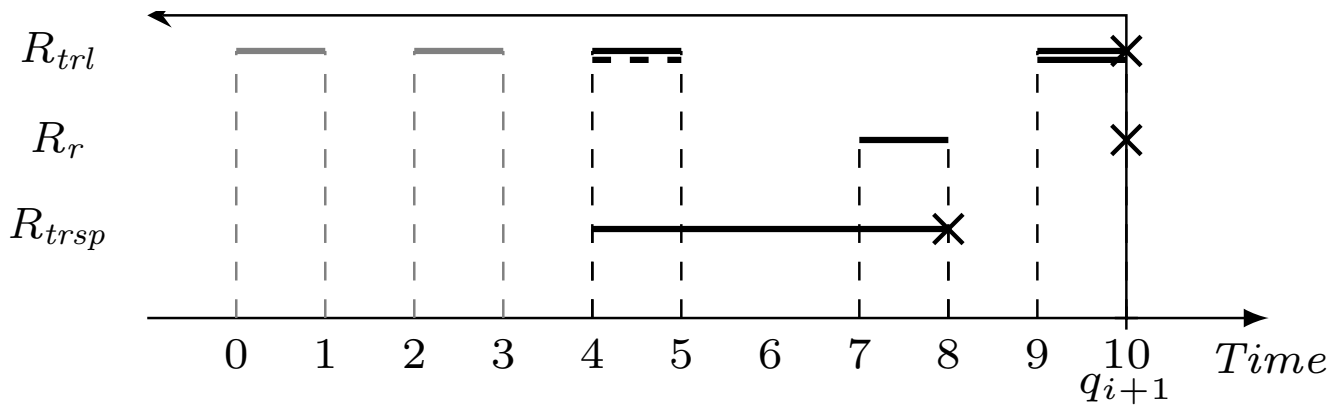
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$\text{RTEC}_s^{\text{RCT}}$: Bookkeeping minimality & correctness

Soundness and completeness of bookkeeping

The bookkeeping policy of $\text{RTEC}_s^{\text{RCT}}$ caches all intervals that may be necessary at a future query-time, and no other interval.

$\text{RTEC}_s^{\text{RCT}}$: Bookkeeping minimality & correctness

Soundness and completeness of bookkeeping

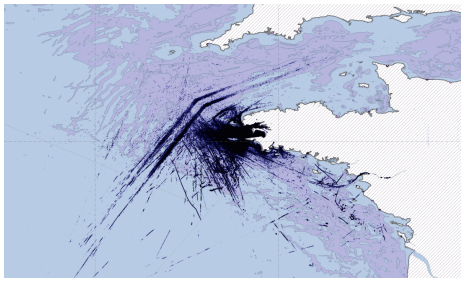
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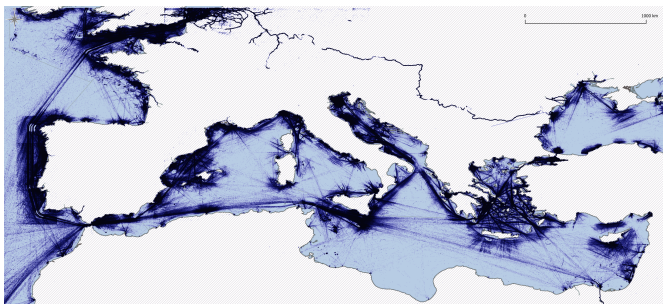
Correctness of $\text{RTEC}_s^{\text{RCT}}$

At each query-time, $\text{RTEC}_s^{\text{RCT}}$ computes the same intervals for $F = V$ as RTEC_s, up to the cut-off point T_o of $\textbf{holdsFor}^{\bullet}(F = V, \langle I_o, T_o \rangle)$, provided that the window of RTEC_s is large enough so that no sequence is missed.

Empirical analysis

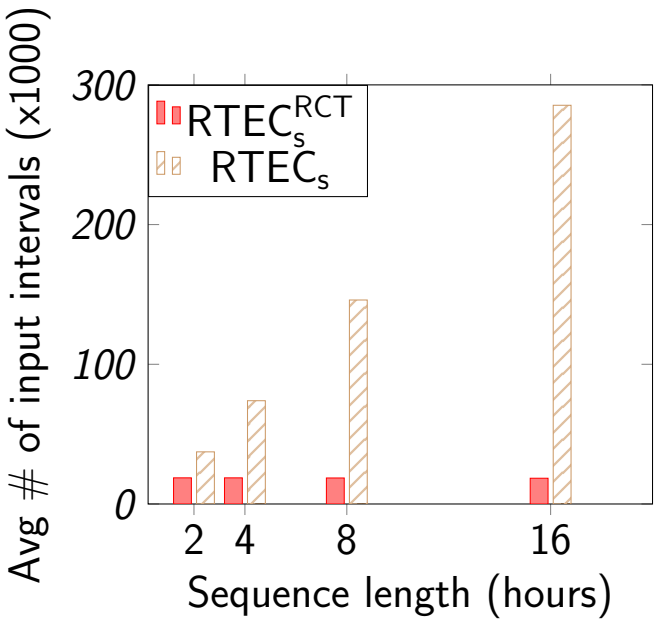
- Maritime Situational Awareness (MSA)
  - 18M signals, 5K vessels
  - 55M signals, 34K vessels
- Commercial Fleet Management (CFM)
  - 70M signals, 6K vehicles

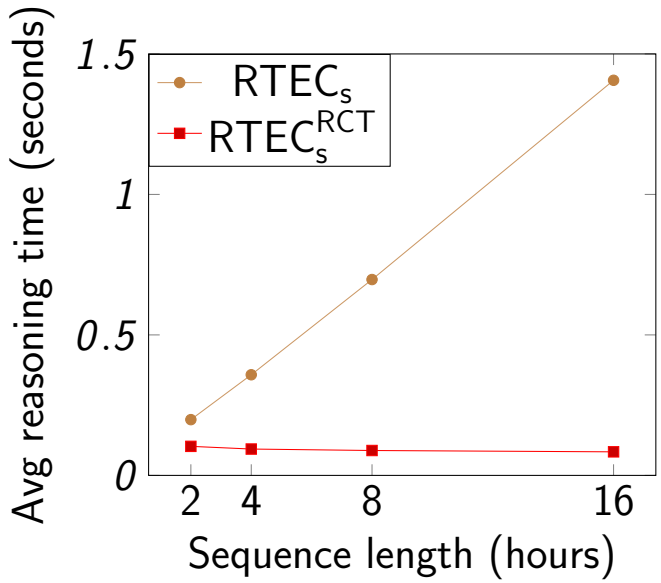






Effect of sequence length





Operational setting

	MSA: Brest		MSA: European seas		CFM	
	input	**time**	**input**	**time**	**input**	**time**
RTEC_s	411K	10.2 sec	N/A	N/A	N/A	N/A
$\text{RTEC}_s^{\text{RCT}}$	7.5K	1.3 sec	130K	34.6 sec	101K	2.5 sec

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	input	**time**	**input**	**time**	**input**	**time**
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$\text{RTEC}_s^{\text{RCT}}$ remains monotonic 8–37 hours after the last computed interval.

Summary & Future Work

Summary:

- Monotonic stream reasoning with sequencing
  - for longer horizons.
- Minimal bookkeeping for stateful windowing.
- Reproducible empirical analysis
  - Real and synthetic data.
  - Three application domains.

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- Minimal bookkeeping for stateful windowing.
- Reproducible empirical analysis
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Further Work:

- Tensor-based stream reasoning.
- Neuro-symbolic stream reasoning.
- Sequencing over non-monotonic input.