Incremental Event Calculus for Run-Time Reasoning

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Motivation for Incremental CER

- Delayed events (e.g., satellite GPS messages)
- Overlapping temporal windows
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- Propagation of changes
Event Calculus

- A logic programming language for representing and reasoning about events and their effects.
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- 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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- 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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  - 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.

- RTEC is a CER system based on the Event Calculus formalism
Problem Statement

\[
\text{initiatedAt}(F\equiv V, T) \leftarrow \\
\text{happensAt}(A, T), \\
\text{holdsAt}(B\equiv V_B, T), \\
\text{not happensAt}(C, T), \\
\text{not holdsAt}(D\equiv V_D, T).
\]
Problem Statement

- \happensAt(A, T)
- \holdsAt(B=V_B, T)
- \not \happensAt(C, T)
- \not \holdsAt(D=V_D, T)

\initiatedAt(F=V, T) ←
Problem Statement

\[
\text{initiatedAt}(F=V, T) \leftarrow \quad \uparrow \quad \uparrow \quad \uparrow \quad \uparrow \quad \uparrow \\
\text{happensAt}(A, T), \quad \text{holdsAt}(B=V_B, T), \quad \text{not happensAt}(C, T), \quad \text{not holdsAt}(D=V_D, T).
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\[ \text{not holdsAt}(D=V_D, T). \]
Problem Statement: Inefficiency
Incremental RTEC

initiatedAt(F=V, T) ←

↑ ↑

↑ ↑

↑ ↑

↑ ↑

time

ω

happensAt(A, T),
holdsAt(B=V_B, T),
not happensAt(C, T),
not holdsAt(D=V_D, T).

not happensAt(C, T),
not holdsAt(D=V_D, T).

qi_i-1

initiatedAt(F=V, T) ←

↑ ↑

↑ ↑

↑ ↑

↑ ↑

time

ω

happensAt(A, T),
holdsAt(B=V_B, T),
not happensAt(C, T),
not holdsAt(D=V_D, T).

initiatedAt(F=V, T) ←
Incremental RTEC

\[ S_{F_i}^Q = S_{F_i-1}^Q + \Delta s_F(Q_{i-1}\{\text{ins,del}\}) \]

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Incremental RTEC

\[ S_F^Q = S_{F_{i-1}} + \Delta S_F(Q_{i-1}, \{\text{ins, del}\}) \]
Incremental RTEC

\[
\text{initiatedAt}(F=V, T) \leftarrow \begin{array}{c}
\uparrow \uparrow \\
\uparrow \\
\uparrow \\
\uparrow \\
\uparrow
\end{array}
\]

\[\omega\]

\[\begin{array}{c}
\text{happensAt}(A, T), \\
\text{holdsAt}(B=V_B, T), \\
\text{not happensAt}(C, T), \\
\text{not holdsAt}(D=V_D, T).
\end{array}\]

\[\text{initiatedAt}(F=V, T) \leftarrow \begin{array}{c}
\uparrow \uparrow \\
\uparrow \\
\uparrow \\
\uparrow \\
\uparrow
\end{array}
\]

\[\omega\]

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\text{happensAt}(A, T), \\
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\text{not happensAt}(C, T), \\
\text{not holdsAt}(D=V_D, T).
\end{array}\]

\[S_F^{Q_i} = S_F^{Q_{i-1}} + \Delta s_F(Q_{i-1}, \{\text{ins}, \text{del}\})\]
Incremental RTEC

$$s_{F_q} = s_{F_{q-1}} + \Delta s_F(Q_{i-1}, \{ins, del\})$$

initiatedAt($F=V, T$) ←

happensAt($A, T$),
holdsAt($B=V_B, T$),
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happensAt($A, T$),
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Incremental RTEC

\[ \text{initiatedAt}(F=V, T) \leftarrow \]

\[ \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \omega \]

\[ \text{happensAt}(A, T), \]
\[ \text{holdsAt}(B=V_B, T), \]
\[ \text{not happensAt}(C, T), \]
\[ \text{not holdsAt}(D=V_D, T). \]

\[ \text{time} \]

\[ q_{i-1} - \omega \]

\[ q_i \]

\[ S_F^{Q_i} = S_F^{Q_{i-1}} + \Delta S_F(Q_{i-1}, \{\text{ins, del}\}) \]
Incremental RTEC

\[ s_F^{Q_i} = s_F^{Q_{i-1}} + \Delta s_F(Q_{i-1}, \{\text{ins, del}\}) \]
**Incremental RTEC**

\[
\text{initiatedAt}(F=V, T) \leftarrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow
\]

\[
\text{happensAt}(A, T), \quad \text{holdsAt}(B=V_B, T), \quad \text{not happensAt}(C, T), \quad \text{not holdsAt}(D=V_D, T).
\]

\[
q_i \rightarrow \omega \rightarrow q_{i-1}
\]

\[
S^Q_i = S^Q_{i-1} + \Delta S_F(Q_{i-1}, \{\text{ins, del}\})
\]
Incremental RTEC

\[
\text{initiatedAt}(F=V, T) \leftarrow \uparrow \uparrow \uparrow \uparrow \uparrow
\]

\[
\text{happensAt}(A, T),
\text{holdsAt}(B=V_B, T),
\text{not happensAt}(C, T),
\text{not holdsAt}(D=V_D, T).
\]

\[
\omega \quad \omega \quad \omega \quad \omega
\]

\[
\text{time}
\]

\[
s_{F_i} = s_{F_{i-1}} + \Delta s_{F_i}(Q_{i-1}, \{\text{ins, del}\})
\]
Incremental RTEC

\[
S^Q_i = S^Q_{i-1} + \Delta S_F(Q_{i-1}, \{\text{ins, del}\})
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Incremental RTEC

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S^Q_i = S^Q_{i-1} + \Delta S_F(Q_{i-1}, \{ins, del\})
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Incremental RTEC

\[ s_{FQ_i} = s_{FQ_{i-1}} + \Delta s_F(Q_{i-1}, \{ins, del\}) \]

Two phases:
- Deletion phase
- Addition phase
Incremental RTEC - Deletion phase

\[
\text{initiatedAt}(F=V, T) \leftarrow \uparrow \uparrow \uparrow \uparrow \uparrow \\
\text{happensAt}(A, T), \quad \text{holdsAt}(B=V_B, T), \quad \text{not happensAt}(C, T), \quad \text{not holdsAt}(D=V_D, T).
\]
Incremental RTEC - Deletion phase

\[ q_{i-1} - \omega \]

\[ q_i \]

\[ \text{initiatedAt}(F=V, T) \leftarrow \]

\[ \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \omega \]

\[ \text{happensAt}(A, T), \]
\[ \text{holdsAt}(B=V_B, T), \]
\[ \text{not happensAt}(C, T), \]
\[ \text{not holdsAt}(D=V_D, T). \]

\[ \text{time} \]
Incremental RTEC - Deletion phase

initiatedAt(F=V, T) ←

↑↑↑↑↑

ω

happensAt(A, T),
holdsAt(B=V_B, T),
not happensAt(C, T),
not holdsAt(D=V_D, T).

[q_i-1 - ω]

[i initiatedAt(F=V, T)]^{Q_i-1} ←

↑↑↑↑↑

ω

[happensAt(A, T)]^{del}
[holdsAt(B=V_B, T)]^{del}
[happensAt(C, T)]^{v}
[holdsAt(D=V_D, T)]^{ins}

[q_i - ω]

[q_i-1]

[q_i]
Incremental RTEC - Deletion phase

\[\text{initiatedAt}(F = V, T) \leftarrow \]

\[\text{happensAt}(A, T),\]

\[\text{holdsAt}(B = V_B, T),\]

\[\text{not happensAt}(C, T),\]

\[\text{not holdsAt}(D = V_D, T).\]

\[\text{[initiatedAt}(F = V, T)\text{]}^{Q_i} \leftarrow \]

\[\text{[happensAt}(A, T)\text{]}^{del} \]

\[\text{[holdsAt}(B = V_B, T)\text{]}^{del} \]

\[\text{[happensAt}(C, T)\text{]}^{ins} \]

\[\text{[holdsAt}(D = V_D, T)\text{]}^{ins}.\]
Incremental RTEC - Deletion phase

\[ \text{initiatedAt}(F=V, T) \leftarrow \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \text{happensAt}(A, T), \]
\[ \text{holdsAt}(B=V_B, T), \]
\[ \text{not happensAt}(C, T), \]
\[ \text{not holdsAt}(D=V_D, T). \]

\[ \text{initiatedAt}(F=V, T)^{Q_i-1} \leftarrow \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \text{happensAt}(A, T)^{del}, \]
\[ \text{holdsAt}(B=V_B, T)^{del}, \]
\[ \text{happensAt}(C, T)^{v}, \]
\[ \text{holdsAt}(D=V_D, T)^{ins}. \]
Incremental RTEC - Deletion phase

\[ \text{initiatedAt}(F=V,T) \leftarrow \]

\[ \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \omega \]

\[ \text{happensAt}(A,T), \]
\[ \text{holdsAt}(B=V_B,T), \]
\[ \text{not happensAt}(C,T), \]
\[ \text{not holdsAt}(D=V_D,T). \]

\[ q_{i-1} - \omega \]

\[ q_i \]

\[ \text{initiatedAt}(F=V,T) \]
\[ \left[ \text{happensAt}(A,T) \right]^{Q_{i-1}} \]
\[ \left[ \text{holdsAt}(B=V_B,T) \right]^{del} \]
\[ \left[ \text{happensAt}(C,T) \right]^{del} \]
\[ \left[ \text{holdsAt}(D=V_D,T) \right]^{ins} \]

\[ \uparrow \uparrow \uparrow \uparrow \uparrow \]

\[ \omega \]

\[ \text{time} \]

\[ q_{i-1} \]

\[ q_i \]

\[ q_{i-1} - \omega \]
Incremental RTEC - Addition phase

\[ q_i - \omega \]

\[ q_{i-1} \]

\[ q_i \]
Incremental RTEC - Addition phase

\[ \text{happensAt}(A, T) \]
\[ \text{holdsAt}(B=V_B, T) \]
\[ \text{not happensAt}(C, T) \]
\[ \text{not holdsAt}(D=V_D, T) \]
Incremental RTEC - Addition phase

\[
\begin{align*}
\text{[happensAt}(A, T) & \text{]}_{\text{ins}}^{Q_i}, \\
\text{[holdsAt}(B=V_B, T) & \text{]}^{Q_i}, \\
\text{[not happensAt}(C, T) & \text{]}_{\text{not}}^{Q_i}, \\
\text{[not holdsAt}(D=V_D, T) & \text{]}_{\text{not}}^{Q_i}.
\end{align*}
\]
Incremental RTEC - Addition phase

\[
\text{[happensAt}(A, T) \text{]}^{ins}, \\
\text{[holdsAt}(B=V_B, T) \text{]}^{Q_i}, \\
\text{[not happensAt}(C, T) \text{]}^{\dot{Q}_i}, \\
\text{[not holdsAt}(D=V_D, T) \text{]}^{Q_i}.
\]
Incremental RTEC - Addition phase

\[ \text{happensAt}(A, T) \quad \text{ins} \quad \]  
\[ \text{holdsAt}(B = V_B, T) \quad Q_i \quad \]  
\[ \text{not happensAt}(C, T) \quad Q_i \quad \]  
\[ \text{not holdsAt}(D = V_D, T) \quad Q_i \quad . \]
Incremental RTEC - Addition phase

\[ \text{happensAt}(A, T) \]

\[ \text{holdsAt}(B = V_B, T) \]

\[ \text{not happensAt}(C, T) \]

\[ \text{not holdsAt}(D = V_D, T) \]
Incremental RTEC - Addition phase

\[ \text{ins}(A, T) \]

\[ \text{holdsAt}(B=V_B, T) \]

\[ \text{not happensAt}(C, T) \]

\[ \text{not holdsAt}(D=V_D, T) \]
Incremental RTEC - Addition phase

\[ \text{[happensAt}(A, T)\text{]}^{ins} \]
\[ \text{[holdsAt}(B=V_B, T)\text{]}^{Q_i} \]
\[ \text{[not happensAt}(C, T)\text{]}^{Q_i} \]
\[ \text{[not holdsAt}(D=V_D, T)\text{]}^{Q_i} \]
Incremental RTEC - Evaluation

- Delays up to 16 hours
- $17M$ position signals, $34K$ vessels
- European seas
- January 2016
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(Left) Average recognition time and (Right) average number of input and complex events. Sliding step of 1 hour.
Summary

- Properties of the algorithm:
  - Evaluation of small sets early
  - Optimal rule rewriting
  - Can handle retractions in the input
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  - Evaluation of small sets early
  - Optimal rule rewriting
  - Can handle rejections in the input

- We have performed a complexity analysis of the incremental version and have discovered the conditions that lead to better performance

- Future work:
  - Probabilistic version of the incremental algorithm