Getting to the CORE of Complex Event Recognition

Stijn Vansummeren
UHasselt, Data Science Institute

My goal for this talk

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1. Present a logic for CER.
2. Introduce CEA, an automaton model for CER.
3. Explain our algorithm for processing CEA in constant-time per event.
4. Discuss limitations and open questions.

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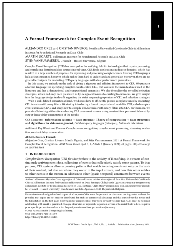
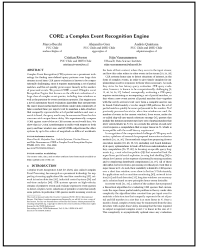


A Formal Framework for Complex Event Recognition

A Formal Framework for Complex Event Recognition
ACM TODS 46(4), 2021



CORE: a Complex Event Recognition Engine

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VLDB 2022

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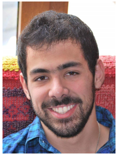
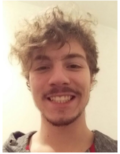


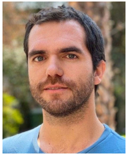
Marco Bucchi



Alejandro Grez

Andrés Quintana

Cristian Riveros



Martin Ugarte

PUC Chile, IMFD

Outline

A logic for CER

An automaton model for CER

Evaluation algorithm

The CORE complex event recognition engine

Open questions

"[...] CEP languages are often oversimplified, providing only a small set of operators, insufficient to express a number of desirable patterns and the rules to combine incoming information to produce new knowledge. Even worse, the semantics of such languages is usually given only informally, *which leads to ambiguities and makes it difficult compare the different proposals."*

G. Cugola and A. Margara

"TESLA: A formally defined event specification language", DEBS 2010.

"[...] CEP languages are often oversimplified, providing only a small set of operators, insufficient to express a number of desirable patterns and the rules to combine incoming information to produce new knowledge. Even worse, the semantics of such languages is usually given only informally*, which leads to ambiguities and makes it difficult compare the different proposals."*

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"TESLA: A formally defined event specification language", DEBS 2010.

See also [1] and [2].

[1] D. Zimmer and R. Unland
"On the semantics of complex events in active database management systems." ICDE 1999.

[2] N. Giatrakos, E. Alevizos, A. Artikis, A. Deligiannakis, M. N. Garofalakis
"Complex event recognition in the Big Data era: a survey." VLDB J. 29(1), 2020.

What do we expect for a query language for CER?

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1. Formal syntax and semantics.

   "For every query and stream, the output will be defined precisely."

2. Declarative, denotational semantics.

   "The semantics will specify what the output is, but not how to compute it."

3. Composable language.

   "The language operators can be combined as free as possible."

What do we expect for a query language for CER?

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   "The language operators can be combined as free as possible."

Complex Event Logic (CEL) is our proposal for a CER query language with these properties.

Data model for complex event recognition

Data model for complex event recognition

"A stream is a sequence of events where each event is represented as a tuple."

Event:

Buy (`vol` : 25, `stock` : 'amz')

Event type — Attribute name — Attribute value

Data model for complex event recognition

"A stream is a sequence of events where each event is represented as a tuple."

Event:

B (25, amz)

Event type

Attribute value

Data model for complex event recognition

"A stream is a sequence of events where each event is represented as a tuple."

Stream:

$\boxed{\mathrm{B}(16, a)}$ $\boxed{\mathrm{B}(23, c)}$ $\boxed{\mathrm{S}(16, b)}$ $\boxed{\mathrm{B}(25, a)}$ $\boxed{\mathrm{S}(11, c)}$ $\boxed{\mathrm{S}(12, d)}$ $\cdots$

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Data model for complex event recognition

"A stream is a sequence of events where each event is represented as a tuple."

Stream:

$\mathrm{B}_0(16, a)$ $\mathrm{B}_1(23, c)$ $\mathrm{S}_2(16, b)$ $\mathrm{B}_3(25, a)$ $\mathrm{S}_4(11, c)$ $\mathrm{S}_5(12, d)$ $\cdots$

Data model for complex event recognition

"A stream is a sequence of events where each event is represented as a tuple."

Stream:

B_0 B_1 S_2 B_3 S_4 S_5 $\cdots$

Data model for complex event recognition

Definition

A **complex event** is a pair $([i, j], C)$ where

- $[i, j]$ is an interval that denotes the start and end of the complex event;
- $C \subseteq \{i, i+1, \ldots, j\}$ is a finite set of selected events.

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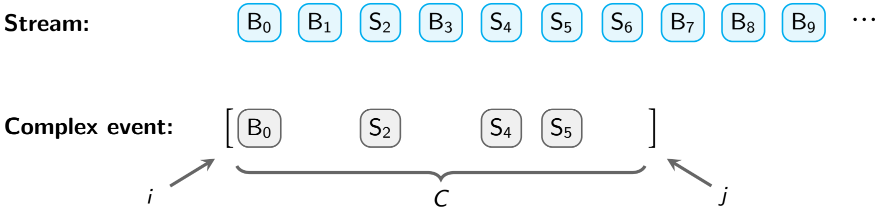

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Complex event: $[\ B_0 \quad S_2 \quad S_4 \quad S_5\ ]$

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Complex event: $[$ B_3 S_4 S_6 $]$

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" Complex Event Recognition (CER) *is the act of recognizing complex events in a stream of primitive events."*

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Output:

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Output: $[\,B_0 \quad S_2 \quad S_4\,]$

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Output: $\left[B_0 \quad S_2 \quad S_4 \right]$

$\left[B_3 \quad S_4 \right]$

Data model for complex event recognition

> *"Complex Event Recognition (CER) is the act of recognizing complex events in a stream of primitive events."*

Input: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

Output: $[B_0 \; S_2 \; S_4]$

$[B_3 \; S_4]$

$[B_1 \; S_2 \; S_5 \; S_6]$

$\cdots$

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"Complex Event Recognition (CER) *is the act of recognizing complex events in a stream of primitive events.*"

Input: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

Output:

$$\left\{ \begin{array}{c} [\,B_0 \;\; S_2 \;\; S_4\,] \\ [\,B_3 \;\; S_4\,] \\ [\,B_1 \;\; S_2 \;\; S_5 \;\; S_6\,] \\ \cdots \end{array} \right\}$$

CER queries recognize **complex events** and extract them

Complex event logic (CEL)

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CEL syntax

$$\varphi \quad := \quad R$$

- R is an event type.

Complex event logic (CEL)

CEL syntax

$$\varphi \quad := \quad R \;\mid\; \varphi\,;\,\varphi \;\mid\; \varphi \;\texttt{OR}\; \varphi \;\mid\; \varphi+$$

- R is an event type.

Complex event logic (CEL)

CEL syntax

$$\varphi \quad := \quad R \;\mid\; \varphi \,;\, \varphi \;\mid\; \varphi \;\texttt{OR}\; \varphi \;\mid\; \varphi + \;\mid\; \varphi \;\texttt{AS}\; X$$

- R is an event type.
- X is a variable.

Complex event logic (CEL)

CEL syntax

$$\varphi \quad := \quad R \;\mid\; \varphi \,;\, \varphi \;\mid\; \varphi \;\texttt{OR}\; \varphi \;\mid\; \varphi+ \;\mid\; \varphi \;\texttt{AS}\; X \;\mid\; \varphi \;\texttt{FILTER}\; P(\overline{X})$$

- R is an event type.
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- $P(\overline{X})$ is a predicate over variables $\overline{X} = X_1, \ldots, X_k$.

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Example of a CEL formula

$$\varphi = (B\,;\,(S+ \;\texttt{AS}\; X)\,;\,B) \;\; \texttt{FILTER} \;\; \texttt{SameStock}(X)$$

Complex event logic (CEL)

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Example of a CEL formula

$$\varphi = (B \,;\, (S+ \;\texttt{AS}\; X) \,;\, B) \;\; \texttt{FILTER} \;\; \texttt{SameStock}(X)$$

Variables in CEL represent **sets of events** (i.e. complex events)

Complex event logic: semantics

Definition

Given a set of variables $\mathcal{X}$, a **valuation** V is a pair $([i,j],\mu)$ with $\mu : \mathcal{X} \to 2^{\mathbb{N}}$ a function that maps each variable $X \in \mathcal{X}$ to a finite set $\mu(X) \subseteq \{i,\ldots,j\}$.

Complex event logic: semantics

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$$\boxed{B_0} \; \boxed{B_1} \; \boxed{S_2} \; \boxed{B_3} \; \boxed{S_4} \; \boxed{S_5} \; \boxed{S_6} \; \boxed{B_7} \; \boxed{B_8} \; \boxed{B_9} \; \cdots$$

$$\Big[\underset{X}{\boxed{B_0}} \qquad \underset{Z}{\boxed{S_2}} \qquad \underset{X,\,Y}{\boxed{S_4}}\Big]$$

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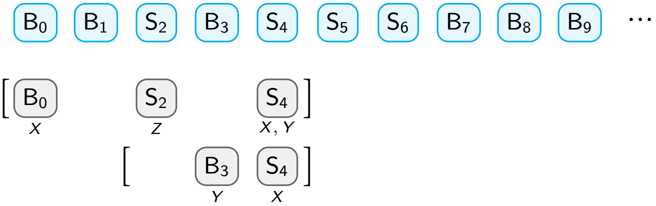

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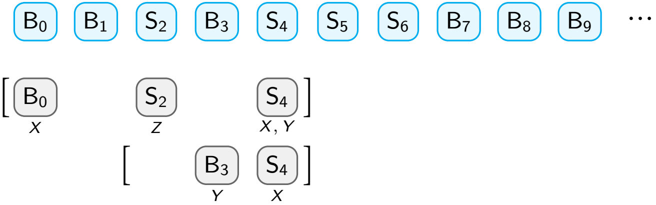

CEL auxiliary semantics (informally)

The **valuation semantics** of CEL formula φ is a function $[\![\varphi]\!]$ that maps a **stream** $\mathcal{S}$ to a set of **valuations**.

Complex event logic: semantics

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Input: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

Output:

$\left[\underset{X}{B_0} \quad \underset{Z}{S_2} \quad \underset{X,Y}{S_4} \right]$

$\left[\underset{Y}{B_3} \quad \underset{X}{S_4} \right]$

CEL semantics

The **complex event** semantics $[\![\varphi]\!]$ of CEL formula φ is obtained from $\llbracket\varphi\rrbracket$ by returning all events in the image of μ.

Complex event logic: semantics

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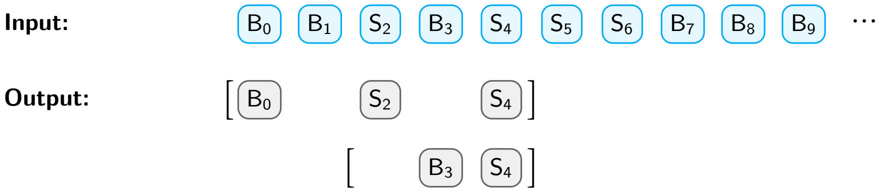

CEL semantics

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Complex event logic: semantics

$\boxed{R}$ $\quad \varphi \,;\, \varphi \quad \varphi \ \texttt{OR} \ \varphi \quad \varphi+ \quad \varphi \ \texttt{AS} \ X \quad \varphi \ \texttt{FILTER} \ P(\overline{X}) \quad \pi_{\overline{X}}(\varphi)$

Complex event logic: semantics

R $\qquad \varphi \,;\, \varphi \qquad \varphi \texttt{ OR } \varphi \qquad \varphi+ \qquad \varphi \texttt{ AS } X \qquad \varphi \texttt{ FILTER } P(\overline{X}) \qquad \pi_{\overline{X}}(\varphi)$

$$\begin{aligned}[\![R]\!](\mathcal{S}) \quad = \; \{V \mid\; & V(\text{time}) = [i,i] \;\wedge\; \text{type}(\mathcal{S}[i]) = R \\ & \wedge\; V(R) = \{i\} \;\wedge\; \forall X \neq R.\; V(X) = \varnothing\;\}\end{aligned}$$

Complex event logic: semantics

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\end{aligned}
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Example: $\varphi = B$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

Complex event logic: semantics

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Example: $\varphi = B$

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$[\![\varphi]\!](\mathcal{S})$: $\quad \big[\, \underset{B}{B_0} \,\big]$

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$\llbracket \varphi \rrbracket(\mathcal{S})$: $\left[\underset{B}{B_0}\right]$

$\left[\underset{B}{B_1}\right]$

Complex event logic: semantics

R $\varphi\,;\,\varphi$ φ OR φ $\varphi+$ φ AS X φ FILTER $P(\overline{X})$ $\pi_{\overline{X}}(\varphi)$

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Example: $\varphi = B$

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$\llbracket \varphi \rrbracket(\mathcal{S})$: $\Big[\underbrace{\boxed{B_0}}_{B}\Big]$ $\Big[\underbrace{\boxed{B_1}}_{B}\Big]$ $\Big[\underbrace{\boxed{B_3}}_{B}\Big]$

Complex event logic: semantics

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Complex event logic: semantics

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\wedge \quad & V(\text{time}) = [V_1(\text{start}), V_2(\text{end})] \\
\wedge \quad & \forall X.\ V(X) = V_1(X) \cup V_2(X)\ \}
\end{aligned}
$$

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$$
\begin{aligned}
[\![\varphi_1 \,;\, \varphi_2]\!](\mathcal{S}) \quad = \quad \{V \mid \; & \text{there exist } V_1 \in [\![\varphi_1]\!](\mathcal{S}), V_2 \in [\![\varphi_2]\!](\mathcal{S}) \text{ s.t. } V_1(\text{end}) < V_2(\text{start}) \\
& \wedge \quad V(\text{time}) = [V_1(\text{start}), V_2(\text{end})] \\
& \wedge \quad \forall X.\; V(X) = V_1(X) \cup V_2(X) \; \}
\end{aligned}
$$

Example: $\varphi = B \,;\, S$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

Complex event logic: semantics

R $\quad$ $\boxed{\varphi\,;\,\varphi}$ $\quad$ φ `OR` φ $\quad$ $\varphi+$ $\quad$ φ `AS` X $\quad$ φ `FILTER` $P(\overline{X})$ $\quad$ $\pi_{\overline{X}}(\varphi)$

$$\begin{aligned}
[\![\varphi_1\,;\,\varphi_2]\!](\mathcal{S}) \quad = \{V \mid \text{ there exist } V_1 \in [\![\varphi_1]\!](\mathcal{S}), V_2 \in [\![\varphi_2]\!](\mathcal{S}) \text{ s.t. } V_1(\text{end}) < V_2(\text{start}) \\
\wedge \quad V(\text{time}) = [V_1(\text{start}), V_2(\text{end})] \\
\wedge \quad \forall X.\ V(X) = V_1(X) \cup V_2(X) \}
\end{aligned}$$

Example: $\varphi = B\,;\,S$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$: $[\underset{B}{B_0} \quad \underset{S}{S_2}]$

Complex event logic: semantics

R | $\varphi \,;\, \varphi$ | φ `OR` φ | $\varphi+$ | φ `AS` X | φ `FILTER` $P(\overline{X})$ | $\pi_{\overline{X}}(\varphi)$

$$
\begin{aligned}
[\![\varphi_1 \,;\, \varphi_2]\!](\mathcal{S}) \quad = \quad \{ V \mid\ & \text{there exist } V_1 \in [\![\varphi_1]\!](\mathcal{S}), V_2 \in [\![\varphi_2]\!](\mathcal{S}) \text{ s.t. } V_1(\text{end}) < V_2(\text{start}) \\
\wedge \quad & V(\text{time}) = [V_1(\text{start}), V_2(\text{end})] \\
\wedge \quad & \forall X.\ V(X) = V_1(X) \cup V_2(X) \ \}
\end{aligned}
$$

Example: $\varphi = B \,;\, S$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

$[\underset{B}{B_0} \quad \underset{S}{S_2}]$

$[\underset{B}{B_0} \quad \underset{S}{S_4}]$

Complex event logic: semantics

R $\quad \varphi ; \varphi \quad \varphi\ \texttt{OR}\ \varphi \quad \varphi+ \quad \varphi\ \texttt{AS}\ X \quad \varphi\ \texttt{FILTER}\ P(\overline{X}) \quad \pi_{\overline{X}}(\varphi)$

$$\begin{aligned}
[\![\varphi_1 ; \varphi_2]\!](\mathcal{S}) \quad = \{V \mid\ & \text{there exist } V_1 \in [\![\varphi_1]\!](\mathcal{S}), V_2 \in [\![\varphi_2]\!](\mathcal{S}) \text{ s.t. } V_1(\text{end}) < V_2(\text{start}) \\
\wedge\ & V(\text{time}) = [V_1(\text{start}), V_2(\text{end})] \\
\wedge\ & \forall X.\ V(X) = V_1(X) \cup V_2(X)\ \}
\end{aligned}$$

Example: $\varphi = B ; S$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

$[\underset{B}{B_0} \quad \underset{S}{S_2}]$

$[\underset{B}{B_0} \quad \underset{S}{S_4}]$

$[\underset{B}{B_1} \quad \underset{S}{S_4}]$

Complex event logic: semantics

R $\quad\quad \varphi \,;\, \varphi \quad\quad \boxed{\varphi \texttt{ OR } \varphi} \quad\quad \varphi+ \quad\quad \varphi \texttt{ AS } X \quad\quad \varphi \texttt{ FILTER } P(\overline{X}) \quad\quad \pi_{\overline{X}}(\varphi)$

Complex event logic: semantics

R $\qquad \varphi \,;\, \varphi$ $\qquad \boxed{\varphi \ \texttt{OR}\ \varphi}$ $\qquad \varphi+$ $\qquad \varphi \ \texttt{AS}\ X$ $\qquad \varphi \ \texttt{FILTER}\ P(\overline{X})$ $\qquad \pi_{\overline{X}}(\varphi)$

$$[\![\varphi_1 \ \texttt{OR}\ \varphi_2]\!](\mathcal{S}) \quad = \quad [\![\varphi_1]\!](\mathcal{S}) \ \cup \ [\![\varphi_2]\!](\mathcal{S})$$

Complex event logic: semantics

R $\quad \varphi \,;\, \varphi$ $\quad \varphi$ OR φ $\quad \boxed{\varphi+}$ $\quad \varphi$ AS X $\quad \varphi$ FILTER $P(\overline{X})$ $\quad \pi_{\overline{X}}(\varphi)$

Complex event logic: semantics

R $\varphi \,;\, \varphi$ φ OR φ $\boxed{\varphi+}$ φ AS X φ FILTER $P(\overline{X})$ $\pi_{\overline{X}}(\varphi)$

$$[\![\varphi+]\!](\mathcal{S}) = \bigcup_{k=1}^{\infty} [\![\varphi^k]\!](\mathcal{S}) \text{ where } \varphi^k = \varphi \,;\, \cdots \,;\, \varphi \;\; k\text{-times}$$

Complex event logic: semantics

R $\qquad$ $\varphi\,;\,\varphi$ $\qquad$ φ `OR` φ $\qquad$ $\boxed{\varphi+}$ $\qquad$ φ `AS` X $\qquad$ φ `FILTER` $P(\overline{X})$ $\qquad$ $\pi_{\overline{X}}(\varphi)$

$$[\![\varphi+]\!](\mathcal{S}) = \bigcup_{k=1}^{\infty} [\![\varphi^k]\!](\mathcal{S}) \quad \text{where } \varphi^k = \varphi\,;\,\cdots\,;\,\varphi \;\; k\text{-times}$$

Example: $\varphi = B\,;\,S{+}\,;\,B$

$\mathcal{S}$: $\quad B_0 \quad B_1 \quad S_2 \quad B_3 \quad S_4 \quad S_5 \quad S_6 \quad B_7 \quad B_8 \quad B_9 \quad \cdots$

$[\![\varphi]\!](\mathcal{S})$:

Complex event logic: semantics

R $\varphi\,;\,\varphi$ φ OR φ $\boxed{\varphi+}$ φ AS X φ FILTER $P(\overline{X})$ $\pi_{\overline{X}}(\varphi)$

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Example: $\varphi = B\,;\,S+\,;\,B$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$: $\left[\underset{B}{B_0}\quad \underset{S}{S_2}\ \underset{B}{B_3}\right]$

Complex event logic: semantics

R $\qquad \varphi\,;\,\varphi$ $\qquad \varphi$ OR φ $\qquad \boxed{\varphi+}$ $\qquad \varphi$ AS X $\qquad \varphi$ FILTER $P(\overline{X})$ $\qquad \pi_{\overline{X}}(\varphi)$

$$[\![\varphi+]\!](\mathcal{S}) = \bigcup_{k=1}^{\infty} [\![\varphi^k]\!](\mathcal{S}) \quad \text{where } \varphi^k = \varphi\,;\,\cdots\,;\,\varphi \;\; k\text{-times}$$

Example: $\varphi = B\,;\,S+\,;\,B$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

$$\big[\, \underset{B}{B_0} \;\; \underset{S}{S_2} \;\; \underset{B}{B_3} \,\big]$$

$$\big[\, \underset{B}{B_0} \;\; \underset{S}{S_2} \;\; \underset{S}{S_4} \;\; \underset{S}{S_5} \;\; \underset{S}{S_6} \;\; \underset{B}{B_7} \,\big]$$

Complex event logic: semantics

R $\quad\varphi\,;\,\varphi$ $\quad\varphi\ \texttt{OR}\ \varphi$ $\quad\boxed{\varphi+}$ $\quad\varphi\ \texttt{AS}\ X$ $\quad\varphi\ \texttt{FILTER}\ P(\overline{X})$ $\quad\pi_{\overline{X}}(\varphi)$

$$[\![\varphi+]\!](\mathcal{S}) \quad = \bigcup_{k=1}^{\infty} [\![\varphi^k]\!](\mathcal{S}) \quad \text{where } \varphi^k = \varphi\,;\,\cdots\,;\,\varphi \ \ k\text{-times}$$

Example: $\varphi = B\,;\,S+\,;\,B$

$\mathcal{S}$: $\quad \mathrm{B}_0 \quad \mathrm{B}_1 \quad \mathrm{S}_2 \quad \mathrm{B}_3 \quad \mathrm{S}_4 \quad \mathrm{S}_5 \quad \mathrm{S}_6 \quad \mathrm{B}_7 \quad \mathrm{B}_8 \quad \mathrm{B}_9 \quad \cdots$

$[\![\varphi]\!](\mathcal{S})$:

$$\Big[\underset{B}{\mathrm{B}_0}\quad \underset{S}{\mathrm{S}_2}\quad \underset{B}{\mathrm{B}_3}\Big]$$

$$\Big[\underset{B}{\mathrm{B}_0}\quad \underset{S}{\mathrm{S}_2}\quad \underset{S}{\mathrm{S}_4}\quad \underset{S}{\mathrm{S}_5}\quad \underset{S}{\mathrm{S}_6}\quad \underset{B}{\mathrm{B}_7}\Big]$$

$$\Big[\underset{B}{\mathrm{B}_0}\quad \underset{S}{\mathrm{S}_2}\quad \underset{S}{\mathrm{S}_5}\quad \underset{B}{\mathrm{B}_7}\Big]$$

Complex event logic: semantics

R $\varphi \,;\, \varphi$ φ OR φ $\varphi+$ $\boxed{\varphi \texttt{ AS } X}$ φ FILTER $P(\overline{X})$ $\pi_{\overline{X}}(\varphi)$

Complex event logic: semantics

R $\qquad \varphi\,;\,\varphi$ $\qquad \varphi$ OR φ $\qquad \varphi+$ $\qquad \boxed{\varphi \text{ AS } X}$ $\qquad \varphi$ FILTER $P(\overline{X})$ $\qquad \pi_{\overline{X}}(\varphi)$

$$
\begin{aligned}
[\![\varphi \text{ AS } X]\!](\mathcal{S}) \quad = \{V \mid \exists\, V' \in [\![\varphi]\!](\mathcal{S}).\ & V(\text{time}) = V'(\text{time}) \\
\wedge\ & V(X) = \textstyle\bigcup_Y V'(Y) \\
\wedge\ & \forall Z \neq X.\ V(Z) = V'(Z)\ \}
\end{aligned}
$$

Complex event logic: semantics

R $\qquad \varphi\,;\,\varphi$ $\qquad \varphi$ **OR** φ $\qquad \varphi+$ $\qquad \boxed{\varphi \textbf{ AS } X}$ $\qquad \varphi$ **FILTER** $P(\overline{X})$ $\qquad \pi_{\overline{X}}(\varphi)$

$$\begin{aligned} [\![\varphi \text{ AS } X]\!](\mathcal{S}) \quad = \{V \mid \exists\, V' \in [\![\varphi]\!](\mathcal{S}).\ & V(\text{time}) = V'(\text{time}) \\ \wedge\ & V(X) = \cup_Y V'(Y) \\ \wedge\ & \forall Z \neq X.\ V(Z) = V'(Z) \ \} \end{aligned}$$

Example: $\varphi = (B\,;\,S+) \qquad ;\,B$

$\mathcal{S}$:	B_0	B_1	S_2	B_3	S_4	S_5	S_6	B_7	B_8	B_9	$\cdots$
$[\![\varphi]\!](\mathcal{S})$:	[B_0 (B)		S_2 (S)	B_3 (B)]							
	[B_0 (B)		S_2 (S)		S_4 (S)	S_5 (S)	S_6 (S)	B_7 (B)]			
	[B_0 (B)		S_2 (S)			S_5 (S)		B_7 (B)]			

Complex event logic: semantics

R $\qquad \varphi \,;\, \varphi$ $\qquad \varphi \;\texttt{OR}\; \varphi$ $\qquad \varphi+$ $\qquad \boxed{\varphi \;\texttt{AS}\; X}$ $\qquad \varphi \;\texttt{FILTER}\; P(\overline{X})$ $\qquad \pi_{\overline{X}}(\varphi)$

$$
\begin{aligned}
[\![\varphi \;\text{AS}\; X]\!](\mathcal{S}) \quad = \quad \{V \mid \exists\, V' \in [\![\varphi]\!](\mathcal{S}).\;\; & V(\text{time}) = V'(\text{time}) \\
\wedge \;\; & V(X) = \textstyle\bigcup_Y V'(Y) \\
\wedge \;\; & \forall Z \neq X.\; V(Z) = V'(Z) \;\}
\end{aligned}
$$

Example: $\varphi = (B \,;\, S+)\;\; \text{AS} \;\; X \,;\, B$

$\mathcal{S}$: B_0 B_1 S_2 B_3 S_4 S_5 S_6 B_7 B_8 B_9 $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

B_0 (B, X)	S_2 (S, X)	B_3 (B)					
B_0 (B, X)	S_2 (S, X)		S_4 (S, X)	S_5 (S, X)	S_6 (S, X)	B_7 (B)
B_0 (B, X)	S_2 (S, X)			S_5 (S, X)		B_7 (B)

Complex event logic: semantics

R $\varphi \, ; \, \varphi$ $\varphi \texttt{ OR } \varphi$ $\varphi+$ $\varphi \texttt{ AS } X$ $\boxed{\varphi \texttt{ FILTER } P(\overline{X})}$ $\pi_{\overline{X}}(\varphi)$

Complex event logic: semantics

R $\varphi \,;\, \varphi$ $\varphi \texttt{ OR } \varphi$ $\varphi+$ $\varphi \texttt{ AS } X$ $\varphi \texttt{ FILTER } P(\overline{X})$ $\pi_{\overline{X}}(\varphi)$

Definition

Consider universal predicates $P(X_1, \ldots X_n)$ of the form:

$$P(X_1, \ldots X_n) \;:=\; \forall t_1 \in X_1 \ldots \forall t_n \in X_n.\; P_E(t_1, \ldots, t_n)$$

where $P_E(t_1, \ldots, t_n)$ is a **first-order predicate over tuples**.

Complex event logic: semantics

R | $\varphi \,;\, \varphi$ | φ `OR` φ | $\varphi+$ | φ `AS` X | φ `FILTER` $P(\overline{X})$ | $\pi_{\overline{X}}(\varphi)$

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Examples

- `Stock=a`$(X) := \forall t \in X.\; t[\text{stock}] = \text{‘a‘}$

Complex event logic: semantics

R $\varphi\,;\,\varphi$ φ OR φ $\varphi+$ φ AS X φ FILTER $P(\overline{X})$ $\pi_{\overline{X}}(\varphi)$

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Examples

- Stock=a$(X) := \forall t \in X.\ t[\text{stock}] = \text{`a`}$
- SameStock$(X_1, X_2) := \forall t_1 \in X_1 . \forall t_2 \in X_2.\ t_1[\text{stock}] = t_2[\text{stock}]$

Complex event logic: semantics

R $\varphi\,;\,\varphi$ φ OR φ $\varphi+$ φ AS X **φ FILTER $P(\overline{X})$** $\pi_{\overline{X}}(\varphi)$

Definition

Consider universal predicates $P(X_1, \ldots X_n)$ of the form:

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Examples

- $\texttt{Stock=a}(X) := \forall t \in X.\; t[\text{stock}] = \text{`a`}$
- $\texttt{SameStock}(X_1, X_2) := \forall t_1 \in X_1. \forall t_2 \in X_2.\; t_1[\text{stock}] = t_2[\text{stock}]$

The definition of CEL considers **any predicate over tuples of sets of events** but we restrict to **universal predicates** to fit our purposes.

Complex event logic: semantics

R $\quad$ $\varphi \,;\, \varphi$ $\quad$ $\varphi \texttt{ OR } \varphi$ $\quad$ $\varphi+$ $\quad$ $\varphi \texttt{ AS } X$ $\quad$ $\varphi \texttt{ FILTER } P(\overline{X})$ $\quad$ $\pi_{\overline{X}}(\varphi)$

Complex event logic: semantics

R $\quad \varphi \,;\, \varphi$ $\quad \varphi \ \texttt{OR}\ \varphi$ $\quad \varphi+$ $\quad \varphi \ \texttt{AS}\ X$ $\quad \boxed{\varphi \ \texttt{FILTER}\ P(\overline{X})}$ $\quad \pi_{\overline{X}}(\varphi)$

$$[\![\varphi \ \texttt{FILTER}\ P(\overline{X})]\!](\mathcal{S}) \quad = \quad \{ V \mid V \in [\![\varphi]\!](\mathcal{S}) \wedge V(\overline{X}) \in P \}$$

Complex event logic: semantics

R $\quad\quad$ $\varphi\,;\,\varphi$ $\quad\quad$ φ OR φ $\quad\quad$ $\varphi+$ $\quad\quad$ φ AS X $\quad\quad$ $\boxed{\varphi \texttt{ FILTER } P(\overline{X})}$ $\quad\quad$ $\pi_{\overline{X}}(\varphi)$

$$[\![\varphi \texttt{ FILTER } P(\overline{X})]\!](\mathcal{S}) \quad = \{V \mid V \in [\![\varphi]\!](\mathcal{S}) \wedge V(\overline{X}) \in P\}$$

Example: $\varphi = ((B\,;\,S+) \text{ AS } X)\,;\,B)$

$\mathcal{S}$: $\boxed{B(a)_0}$ $\boxed{B(b)_1}$ $\boxed{S(a)_2}$ $\boxed{B(c)_3}$ $\boxed{S(c)_4}$ $\boxed{S(a)_5}$ $\boxed{S(b)_6}$ $\boxed{B(a)_7}$ $\boxed{B(b)_8}$ $\boxed{B(c)_9}$ $\cdots$

$[\![\varphi]\!](\mathcal{S})$:

Complex event logic: semantics

R $\quad$ $\varphi \,;\, \varphi$ $\quad$ $\varphi \texttt{ OR } \varphi$ $\quad$ $\varphi+$ $\quad$ $\varphi \texttt{ AS } X$ $\quad$ $\boxed{\varphi \texttt{ FILTER } P(\overline{X})}$ $\quad$ $\pi_{\overline{X}}(\varphi)$

$$[\![\varphi \texttt{ FILTER } P(\overline{X})]\!](\mathcal{S}) \quad = \; \{ V \mid V \in [\![\varphi]\!](\mathcal{S}) \wedge V(\overline{X}) \in P \}$$

Example: $\varphi = ((B \,;\, S+) \text{ AS } X) \,;\, B)$

$\mathcal{S}$:	$\mathrm{B(a)}_0$	$\mathrm{B(b)}_1$	$\mathrm{S(a)}_2$	$\mathrm{B(c)}_3$	$\mathrm{S(c)}_4$	$\mathrm{S(a)}_5$	$\mathrm{S(b)}_6$	$\mathrm{B(a)}_7$	$\mathrm{B(b)}_8$	$\mathrm{B(c)}_9$	$\cdots$
$[\![\varphi]\!](\mathcal{S})$:	[$\underset{B,X}{\mathrm{B(a)}_0}$		$\underset{S,X}{\mathrm{S(a)}_2}$	$\underset{B}{\mathrm{B(c)}_3}$]							
	[$\underset{B,X}{\mathrm{B(a)}_0}$		$\underset{S,X}{\mathrm{S(a)}_2}$		$\underset{S,X}{\mathrm{S(c)}_4}$	$\underset{S,X}{\mathrm{S(a)}_5}$	$\underset{S,X}{\mathrm{S(b)}_6}$	$\underset{B}{\mathrm{B(a)}_7}$]			
	[$\underset{B,X}{\mathrm{B(a)}_0}$		$\underset{S,X}{\mathrm{S(a)}_2}$		$\underset{S,X}{\mathrm{S(c)}_4}$			$\underset{B}{\mathrm{B(a)}_7}$]			

Complex event logic: semantics

R $\qquad$ $\varphi\,;\,\varphi$ $\qquad$ φ `OR` φ $\qquad$ $\varphi+$ $\qquad$ φ `AS` X $\qquad$ **φ `FILTER` $P(\overline{X})$** $\qquad$ $\pi_{\overline{X}}(\varphi)$

$$[\![\varphi\ \texttt{FILTER}\ P(\overline{X})]\!](\mathcal{S}) \quad = \ \{ V \mid V \in [\![\varphi]\!](\mathcal{S}) \wedge V(\overline{X}) \in P \}$$

Example: $\varphi = ((B\,;\,S+)\ \text{AS}\ X)\,;\,B)\ \texttt{FILTER Stock=a}(X)$

$\mathcal{S}$: $\quad \text{B(a)}_0 \quad \text{B(b)}_1 \quad \text{S(a)}_2 \quad \text{B(c)}_3 \quad \text{S(c)}_4 \quad \text{S(a)}_5 \quad \text{S(b)}_6 \quad \text{B(a)}_7 \quad \text{B(b)}_8 \quad \text{B(c)}_9 \quad \cdots$

$[\![\varphi]\!](\mathcal{S})$:

$$\Big[\ \underset{B,X}{\text{B(a)}_0} \quad \underset{S,X}{\text{S(a)}_2} \quad \underset{B}{\text{B(c)}_3}\ \Big]$$

$$\cancel{\Big[\ \underset{B,X}{\text{B(a)}_0} \quad \underset{S,X}{\text{S(a)}_2} \quad \underset{S,X}{\text{S(c)}_4} \quad \underset{S,X}{\text{S(a)}_5} \quad \underset{S,X}{\text{S(b)}_6} \quad \underset{B}{\text{B(a)}_7}\ \Big]}$$

$$\cancel{\Big[\ \underset{B,X}{\text{B(a)}_0} \quad \underset{S,X}{\text{S(a)}_2} \quad \underset{S,X}{\text{S(c)}_4} \quad \underset{B}{\text{B(a)}_7}\ \Big]}$$

Complex event logic: semantics

R $\quad \varphi\,;\,\varphi$ $\quad \varphi$ $\texttt{OR}$ φ $\quad \varphi+$ $\quad \varphi$ $\texttt{AS}$ X $\quad \varphi$ $\texttt{FILTER}$ $P(\overline{X})$ $\quad \boxed{\pi_{\overline{X}}(\varphi)}$

Complex event logic: semantics

R $\qquad \varphi \,;\, \varphi$ $\qquad \varphi \ \mathtt{OR}\ \varphi$ $\qquad \varphi+$ $\qquad \varphi\ \mathtt{AS}\ X$ $\qquad \varphi\ \mathtt{FILTER}\ P(\overline{X})$ $\qquad \boxed{\pi_{\overline{X}}(\varphi)}$

$$
\begin{aligned}
[\![\, \pi_{\overline{X}}(\varphi)]\!](\mathcal{S}) \quad = \quad \{V \mid\ & \exists\, V' \in [\![\varphi]\!](\mathcal{S}).\ V(\text{time}) = V'(\text{time}) \\
& \wedge\ \forall Y \in \overline{X}.\ V(Y) = V'(Y) \\
& \wedge\ \ \forall Y \notin \overline{X}.\ V(Y) = \varnothing\}
\end{aligned}
$$

Complex event logic: semantics

R $\quad \varphi \,;\, \varphi \quad \varphi \texttt{ OR } \varphi \quad \varphi+ \quad \varphi \texttt{ AS } X \quad \varphi \texttt{ FILTER } P(\overline{X}) \quad \boxed{\pi_{\overline{X}}(\varphi)}$

$$\llbracket \pi_{\overline{X}}(\varphi) \rrbracket(\mathcal{S}) = \{V \mid \exists\, V' \in \llbracket \varphi \rrbracket(\mathcal{S}).\ V(\text{time}) = V'(\text{time}) \\ \wedge\ \forall Y \in \overline{X}.\ V(Y) = V'(Y) \\ \wedge\ \forall Y \notin \overline{X}.\ V(Y) = \varnothing\}$$

Example: $\varphi = \quad ((B\,;\,S+)\ \text{AS}\ X)\,;\,B)\ \texttt{FILTER}\ \texttt{Stock=a}(X)$

$\mathcal{S}$: B(a)$_0$ B(b)$_1$ S(a)$_2$ B(c)$_3$ S(c)$_4$ S(a)$_5$ S(b)$_6$ B(a)$_7$ B(b)$_8$ B(c)$_9$ $\cdots$

$\llbracket \varphi \rrbracket(\mathcal{S})$:

Complex event logic: semantics

R $\qquad \varphi \,;\, \varphi$ $\qquad \varphi \texttt{ OR } \varphi$ $\qquad \varphi+$ $\qquad \varphi \texttt{ AS } X$ $\qquad \varphi \texttt{ FILTER } P(\overline{X})$ $\qquad \boxed{\pi_{\overline{X}}(\varphi)}$

$$\begin{aligned}
[\![\, \pi_{\overline{X}}(\varphi)]\!](\mathcal{S}) \quad = \quad \{V \mid\ & \exists\, V' \in [\![\varphi]\!](\mathcal{S}).\ V(\text{time}) = V'(\text{time}) \\
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& \wedge\ \forall Y \notin \overline{X}.\ V(Y) = \varnothing\}
\end{aligned}$$

Example: $\varphi = \quad ((B\,;\, S+)\ \text{AS}\ X)\,;\, B)\ \texttt{FILTER Stock=a}(X)$

$\mathcal{S}$: B(a)$_0$ B(b)$_1$ S(a)$_2$ B(c)$_3$ S(c)$_4$ S(a)$_5$ S(b)$_6$ B(a)$_7$ B(b)$_8$ B(c)$_9$ $\cdots$

$[\![\varphi]\!](\mathcal{S})$: $\Big[\underset{B,X}{\text{B(a)}_0}\quad \underset{S,X}{\text{S(a)}_2}\quad \underset{S,X}{\text{S(a)}_5}\quad \underset{B}{\text{B(a)}_7}\Big]$

Complex event logic: semantics

R $\quad \varphi\,;\,\varphi$ $\quad \varphi\ \texttt{OR}\ \varphi$ $\quad \varphi+$ $\quad \varphi\ \texttt{AS}\ X$ $\quad \varphi\ \texttt{FILTER}\ P(\overline{X})$ $\quad \boxed{\pi_{\overline{X}}(\varphi)}$

$$
\begin{aligned}
[\![\,\pi_{\overline{X}}(\varphi)]\!](\mathcal{S}) \;=\; \{V \mid\ & \exists\, V' \in [\![\varphi]\!](\mathcal{S}).\ V(\text{time}) = V'(\text{time}) \\
& \wedge\ \forall Y \in \overline{X}.\ V(Y) = V'(Y) \\
& \wedge\ \forall Y \notin \overline{X}.\ V(Y) = \varnothing\}
\end{aligned}
$$

Example: $\varphi = \pi_X\,[((B\,;\,S+)\ \text{AS}\ X)\,;\,B)\ \texttt{FILTER}\ \texttt{Stock=a}(X)]$

$\mathcal{S}$: $\boxed{\text{B(a)}_0}\ \boxed{\text{B(b)}_1}\ \boxed{\text{S(a)}_2}\ \boxed{\text{B(c)}_3}\ \boxed{\text{S(c)}_4}\ \boxed{\text{S(a)}_5}\ \boxed{\text{S(b)}_6}\ \boxed{\text{B(a)}_7}\ \boxed{\text{B(b)}_8}\ \boxed{\text{B(c)}_9}\ \cdots$

$[\![\varphi]\!](\mathcal{S})$: $\Big[\ \underset{X}{\boxed{\text{B(a)}_0}}\quad \underset{X}{\boxed{\text{S(a)}_2}}\quad \underset{X}{\boxed{\text{S(a)}_5}}\ \Big]$

Complex event logic: semantics

CEL semantics (final)

The **output** of a CEL formula φ over a stream $\mathcal{S}$ **at position** n is defined as:

$$[\![\varphi]\!]_n(\mathcal{S}) = \left\{ \left(V(\text{time}), \bigcup_X V(X) \right) \mid V \in [\![\varphi]\!](\mathcal{S}), V(\text{end}) = n \right\}$$

Complex event logic: semantics

CEL semantics (final)

The **output** of a CEL formula φ over a stream $\mathcal{S}$ **at position** n is defined as:

$$[\![\varphi]\!]_n(\mathcal{S}) = \left\{ \left(V(\text{time}), \bigcup_X V(X) \right) \mid V \in [\![\varphi]\!](\mathcal{S}), V(\text{end}) = n \right\}$$

All complex events that satisfy the formula are given as output

Selection strategies

CER systems includes operations to filter complex events:

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usually defined by an algorithm.

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> *"a further relaxation is to remove the contiguity requirements:*
> *all irrelevant events will be skipped until the next relevant event is read." [1]*

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"a further relaxation is to remove the contiguity requirements: all irrelevant events will be skipped until the next relevant event is read." [1]

In CEL we declaratively formalize existing selection strategies, and propose new ones [2].

[1] D. Gyllstrom, J. Agrawal, Y. Diao, and N. Immerman
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[2] A. Grez, C. Riveros, M. Ugarte, and S. Vansummeren
"A Formal Framework for Complex Event Recognition", ACM TODS 46(4), 2021.

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Complex event automata

Let P_1 be the set of all **unary predicates** over tuples.

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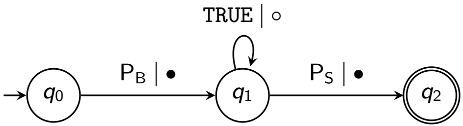
Definition

A **complex event automata** (CEA) is a tuple $\mathcal{A} = (Q, \Delta, I, F)$ where:

1. Q is a finite set of **states**,
2. I and F are the sets of **initial** and **final** states, and
3. $\Delta \subseteq Q \times \mathrm{P}_1 \times \{\bullet, \circ\} \times Q$ is the **transition relation**.



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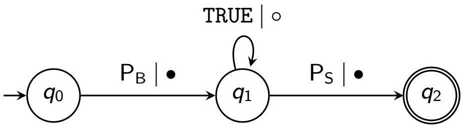
Complex event automata: semantics



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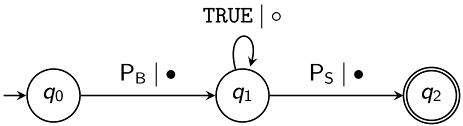

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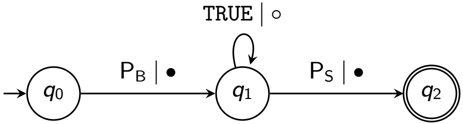

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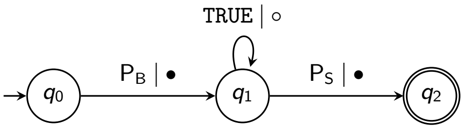

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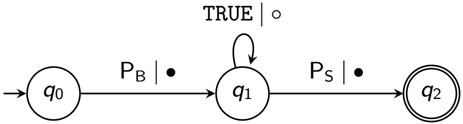

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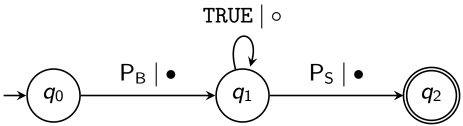

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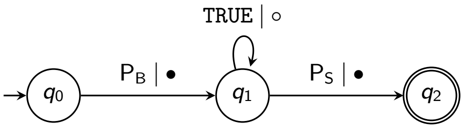

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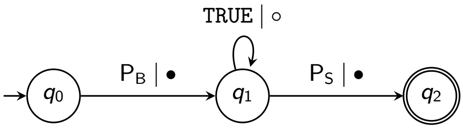

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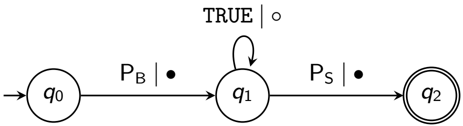

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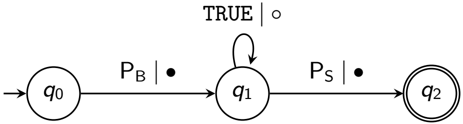

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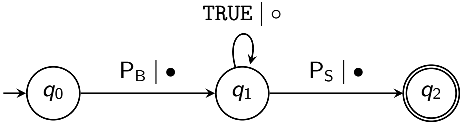

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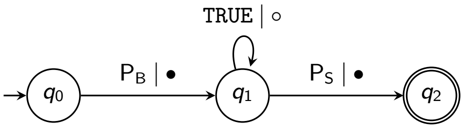

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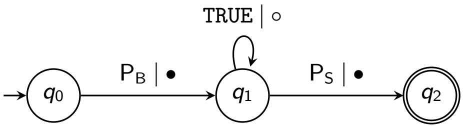

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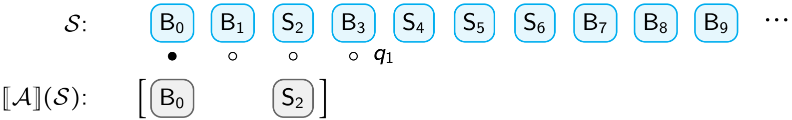

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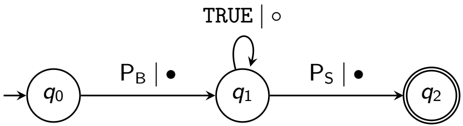

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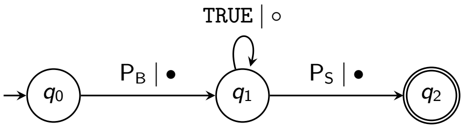

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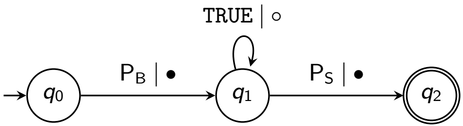

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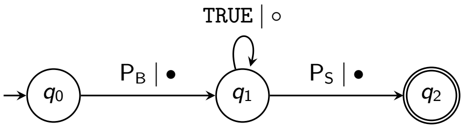

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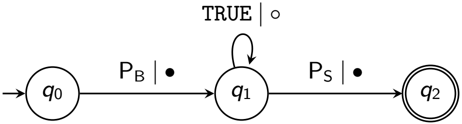

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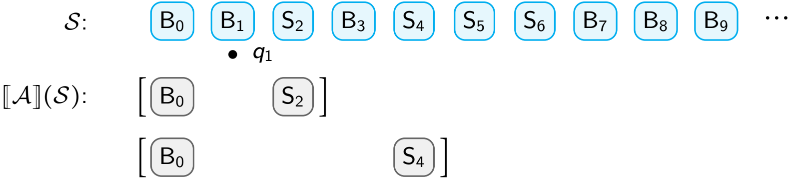

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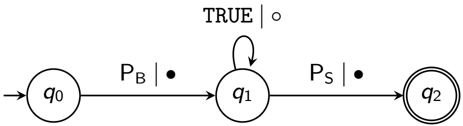

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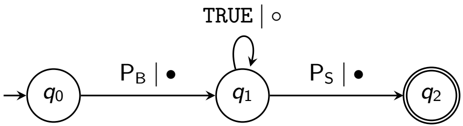

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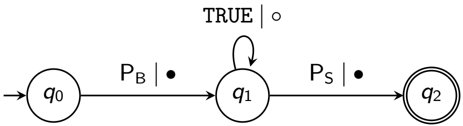

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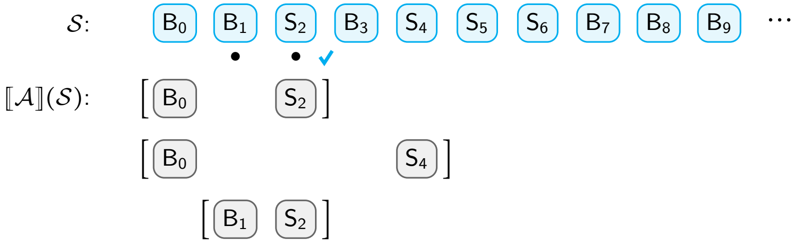

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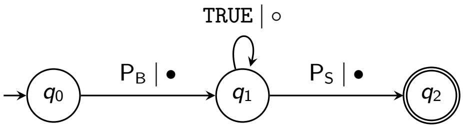

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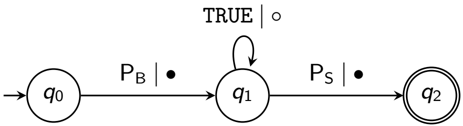

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Theorem

For every CEL-formula φ with **unary predicate** filters we can construct a CEA $\mathcal{A}$ of size linear in φ s.t.

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- CEL can be extended to capture the expressive power of CEA, see [1].

[1] A. Grez, C. Riveros, M. Ugarte, and S. Vansummeren
"A Formal Framework for Complex Event Recognition", ACM TODS 46(4), 2021.

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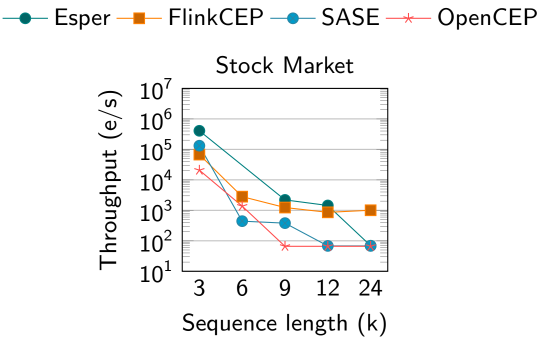

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   "Users do not see any difference compared to naively storing all outputs"

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   "Same guarantee as a streaming algorithm."

2. **Enumeration of outputs** (output-linear delay enumeration)

   "Users do not see any difference compared to naively storing all outputs"

If an evaluation algorithm E satisfies 1. and 2.,
we say that E has **output-linear delay** evaluation.

CEA evaluation strategy

Definition

Let $\epsilon \in \mathbb{N} \cup \{\infty\}$, let $\mathcal{A}$ be a CEA and $\mathcal{S}$ a stream. We define

$$[\![\mathcal{A} \texttt{ WITHIN } \epsilon]\!](\mathcal{S}) := \{C \in [\![\mathcal{A}]\!](\mathcal{S}) \mid C(\mathsf{end}) - C(\mathsf{start}) \leq \epsilon\}.$$

CEA evaluation strategy

Theorem

$[\![\mathcal{A}\ \texttt{WITHIN}\ \epsilon]\!]$ can be evaluated with **output-linear delay**, for every CEA $\mathcal{A}$ and every ϵ.

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Main ideas of the algorithm:

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Main ideas of the algorithm:

1. A notion of **I/O deterministic** CEA.
2. A **timed Enumerable Compact Set** (tECS) for compactly representing complex events and enumerating all outputs with window-size ϵ.

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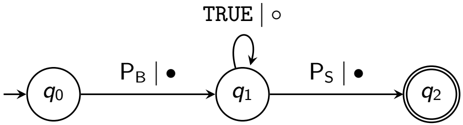
Main ideas of the algorithm:

1. A notion of **I/O deterministic** CEA.
2. A **timed Enumerable Compact Set** (tECS) for compactly representing complex events and enumerating all outputs with window-size ϵ.
3. An evaluation algorithm for incrementally building tECS given active states of I/O deterministic CEA.

I/O determinism

Definition

A CEA is **I/O deterministic** if for every pair of transitions $q \xrightarrow{P_1/m_1} q_1$ and $q \xrightarrow{P_2/m_2} q_2$ from the same state q, if $P_1 \cap P_2 \neq \emptyset$ then $m_1 \neq m_2$.



$\mathrm{P_B} := \{\, t \mid \mathrm{type}(t) = B \}$ $\quad$ $\mathrm{P_S} := \{\, t \mid \mathrm{type}(t) = S \}$

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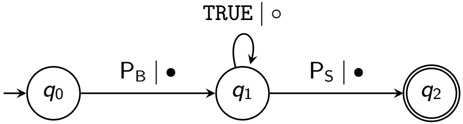

$\mathrm{P}_{\mathrm{B}} := \{\ t \mid \mathrm{type}(t) = B\}$ $\quad$ $\mathrm{P}_{\mathrm{S}} := \{\ t \mid \mathrm{type}(t) = S\}$

"Every recognized complex event has only one run that defines it."

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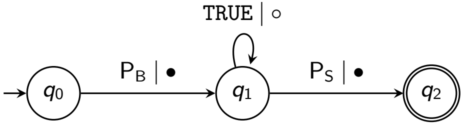

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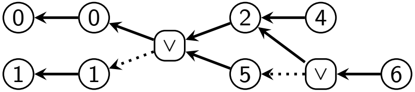
Proposition

CEA can be I/O-determinized in exponential time.

Timed Enumerable Compact Sets

Definition

A **timed Enumerable Compact Set** (tECS) is a DAG with three kinds of nodes: **bottom** nodes, **position** nodes, and **union** nodes, with out-degree 0, 1, and 2, respectively.



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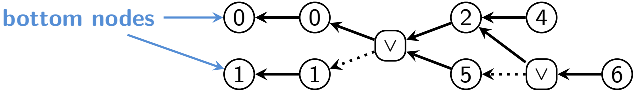

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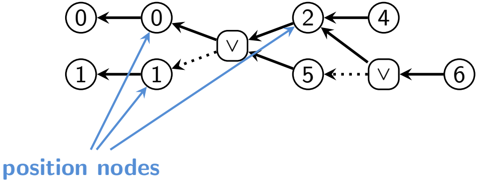

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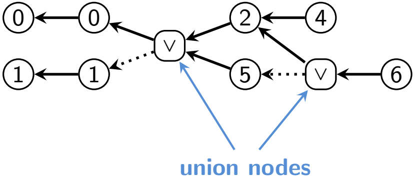

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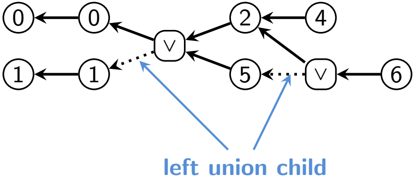

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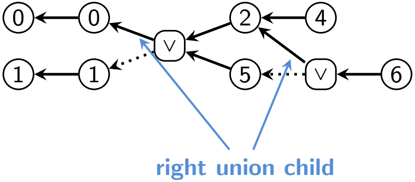

Timed Enumerable Compact Sets: semantics

Definition

A **open complex event** is a pair (i, C) with $i \in \mathbb{N}$ and $C \subseteq \mathbb{N}$ finite.

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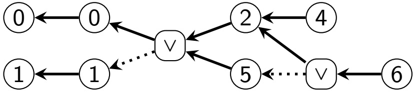
- Every path from a node to a bottom node defines an open complex event.
- A node n hence encodes a set $[\![n]\!]$ of open complex events.



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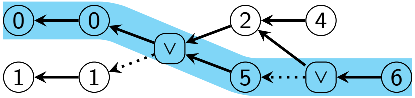

Open complex event: $(0, \{0, 5, 6\})$

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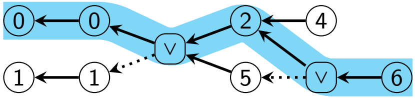

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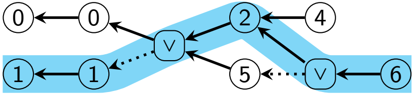

Open complex event: $(1, \{1, 2, 6\})$

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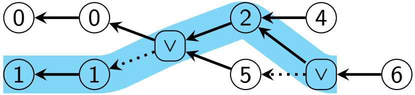

Open complex event: $(1, \{1, 2\})$

Timed Enumerable Compact Sets: enumeration

For each position node n, window size ϵ and $j \in \mathbb{N}$ we want to be able to enumerate

$$[\![n]\!]^{\epsilon}(j) := \{ \qquad \mid (i, C) \in [\![n]\!] \qquad \}$$

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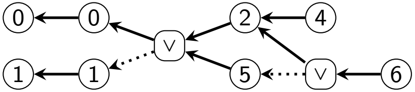

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- For every node n, distinct paths starting at n encode distinct open complex events.
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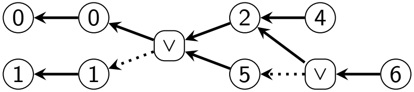

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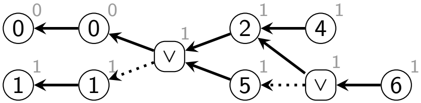

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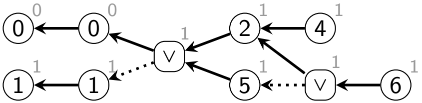
- The children of union nodes u are max-start sorted: $\max(\text{left}(u)) \geq \max(\text{right}(u))$.



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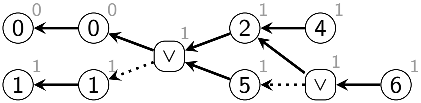
- There is a constant bounding the length of chains of union left-child paths.



Timed Enumerable Compact Sets: enumeration

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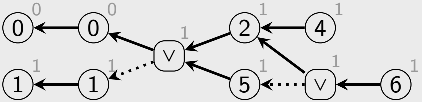
Example: $n = 6$, $\epsilon = 5$, $j = 6$



Enumeration algorithm:

- Do depth-first search, starting from n.
- Visit left-children of union nodes before right-children.
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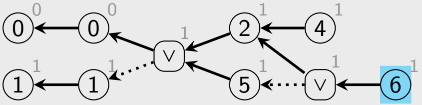

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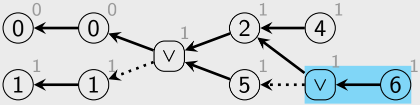

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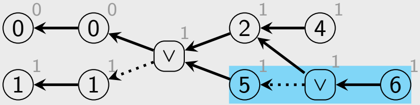

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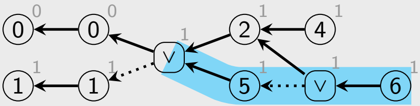

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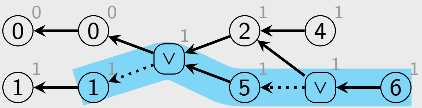

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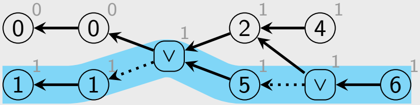
output $([1,6],\{1,5,6\})$



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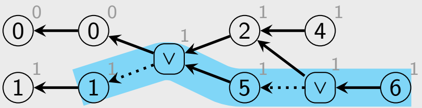

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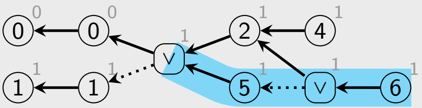

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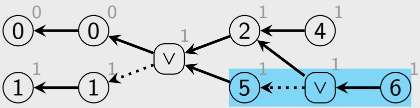

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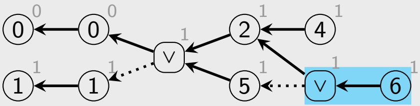
Example: $n = 6$, $\epsilon = 5$, $j = 6$



Enumeration algorithm:

- Do depth-first search, starting from n.
- Visit left-children of union nodes before right-children.
- Before moving to a child c, check that $j - \max(c) \leq \epsilon$.

Timed Enumerable Compact Sets: enumeration

Theorem

Under the previous conditions, we may enumerate

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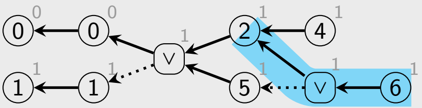

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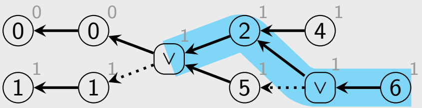

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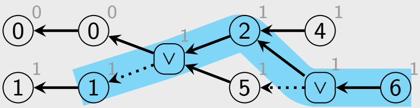

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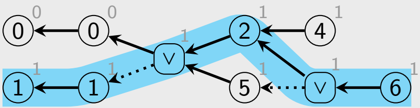
output $([1,6], \{1,2,6\})$



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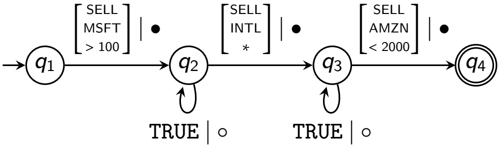
Evaluation Algorithm by Example

Evaluation Algorithm by Example

CEA:

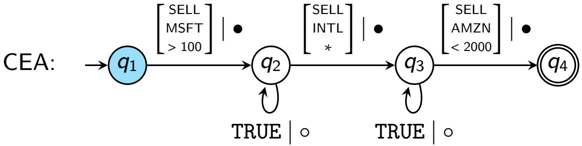


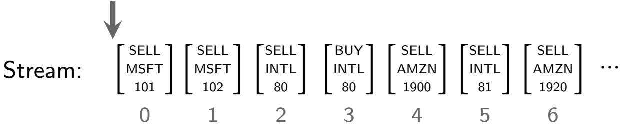
Stream:

$$\underset{0}{\begin{bmatrix}\text{SELL}\\ \text{MSFT}\\ 101\end{bmatrix}} \underset{1}{\begin{bmatrix}\text{SELL}\\ \text{MSFT}\\ 102\end{bmatrix}} \underset{2}{\begin{bmatrix}\text{SELL}\\ \text{INTL}\\ 80\end{bmatrix}} \underset{3}{\begin{bmatrix}\text{BUY}\\ \text{INTL}\\ 80\end{bmatrix}} \underset{4}{\begin{bmatrix}\text{SELL}\\ \text{AMZN}\\ 1900\end{bmatrix}} \underset{5}{\begin{bmatrix}\text{SELL}\\ \text{INTL}\\ 81\end{bmatrix}} \underset{6}{\begin{bmatrix}\text{SELL}\\ \text{AMZN}\\ 1920\end{bmatrix}} \cdots$$

Evaluation Algorithm by Example

tECS:

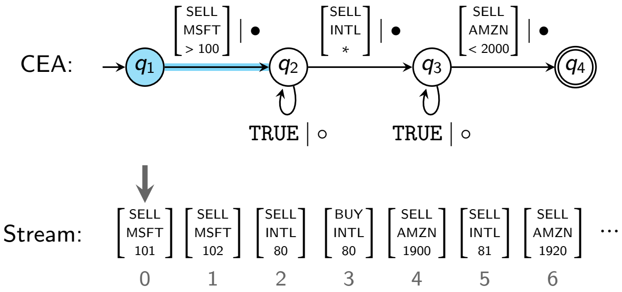




Algorithm crux:

- Incrementally build the (well-structured) tECS to represents all open complex events up to the current event.

Evaluation Algorithm by Example



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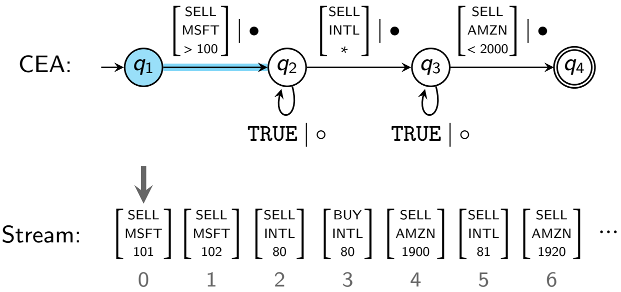

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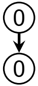

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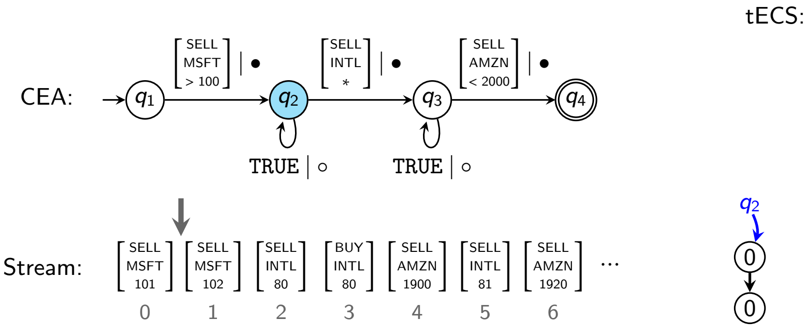

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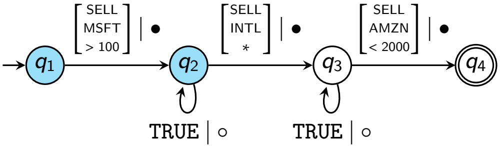

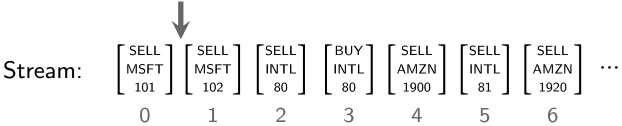

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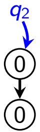

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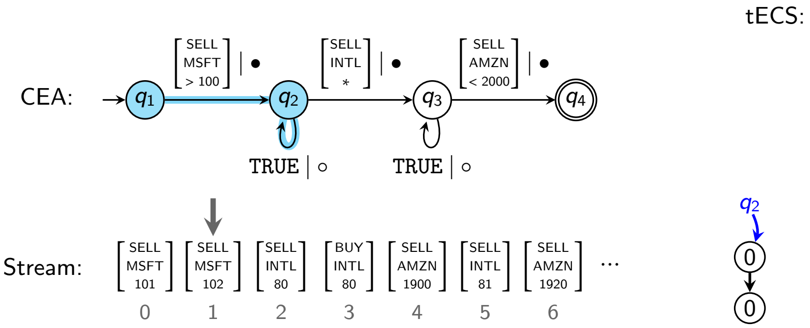

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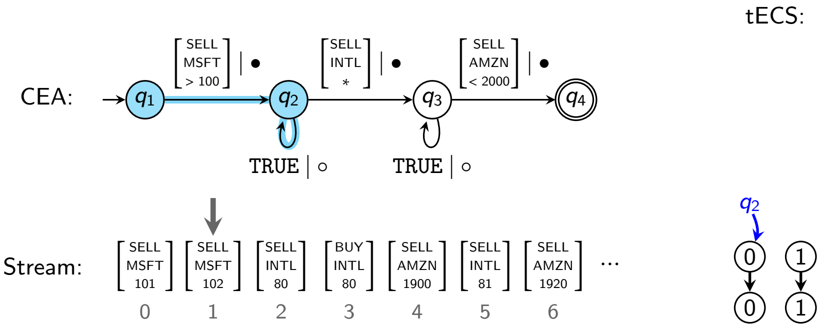

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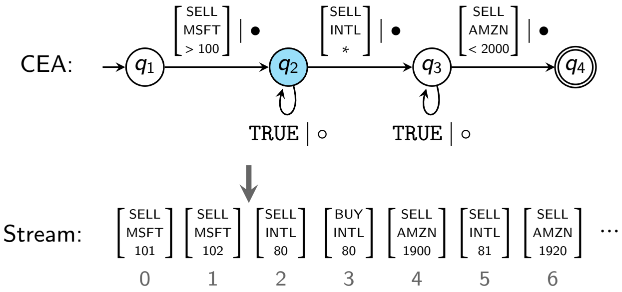

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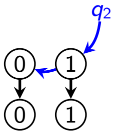

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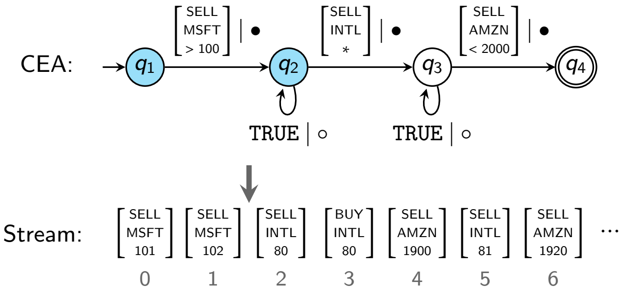

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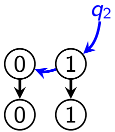

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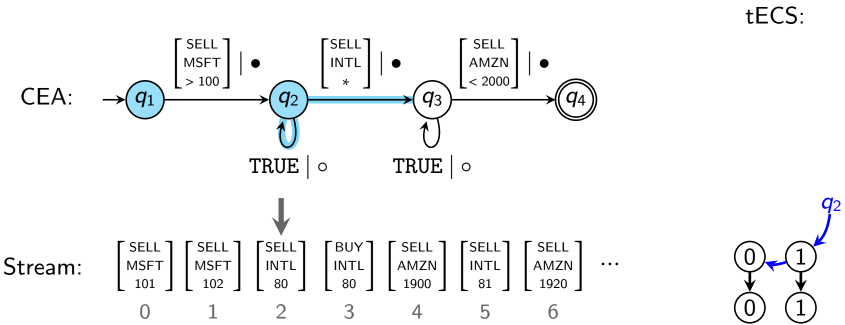

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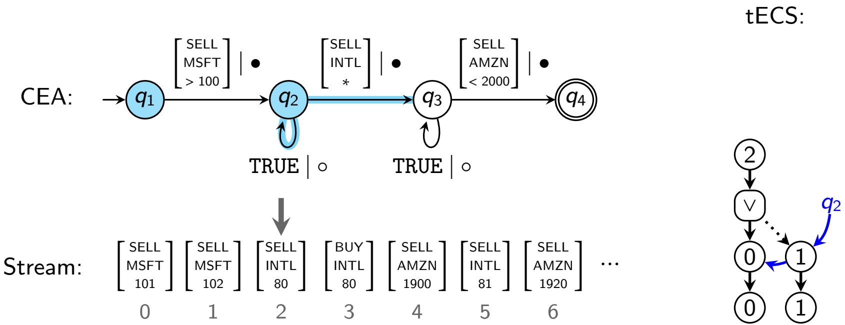

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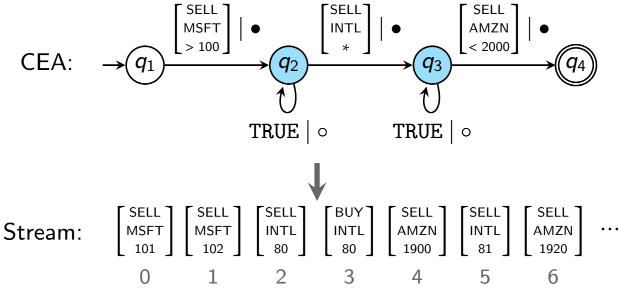

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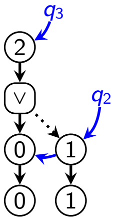

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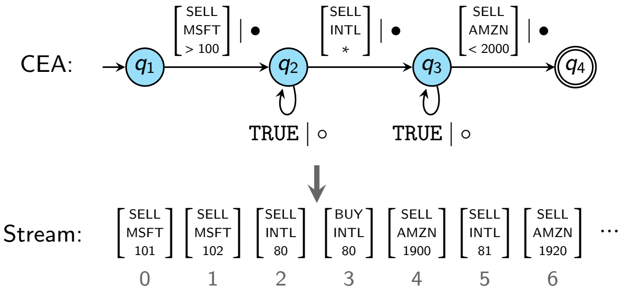

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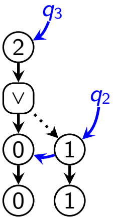

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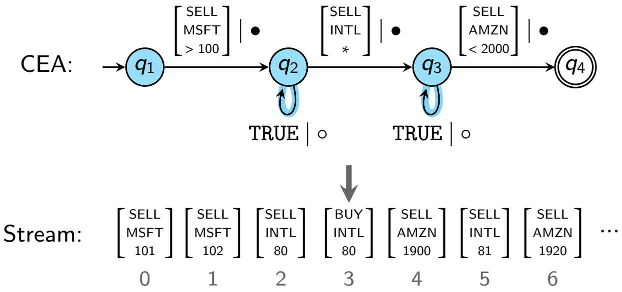

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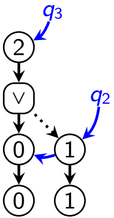

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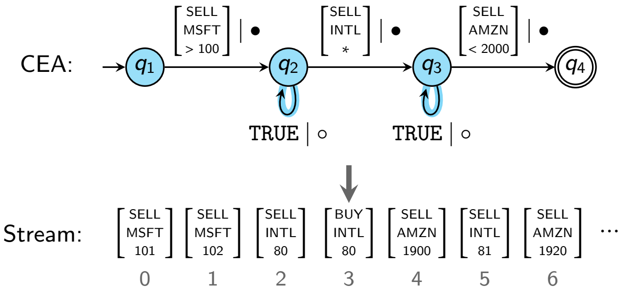

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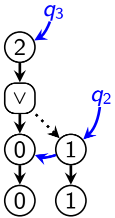

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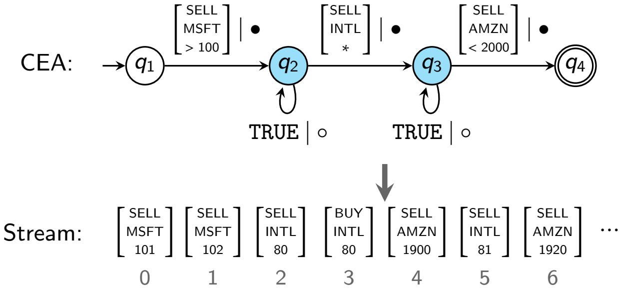

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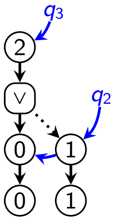

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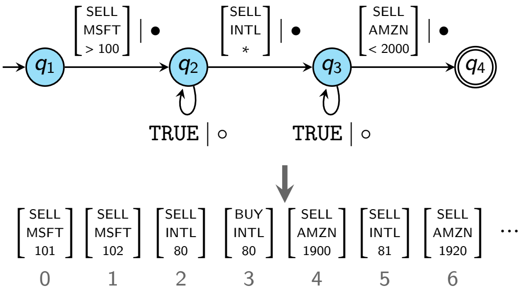
Evaluation Algorithm by Example

CEA:

Stream:



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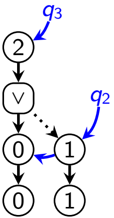

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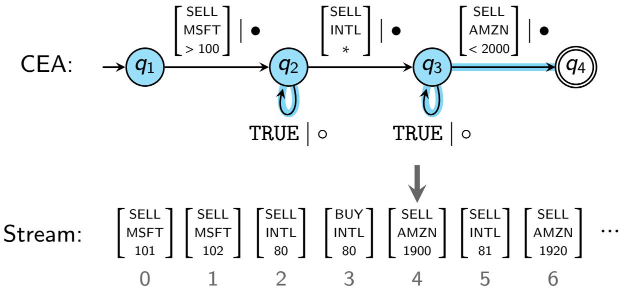

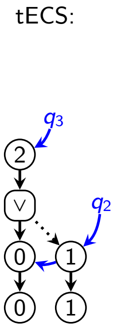

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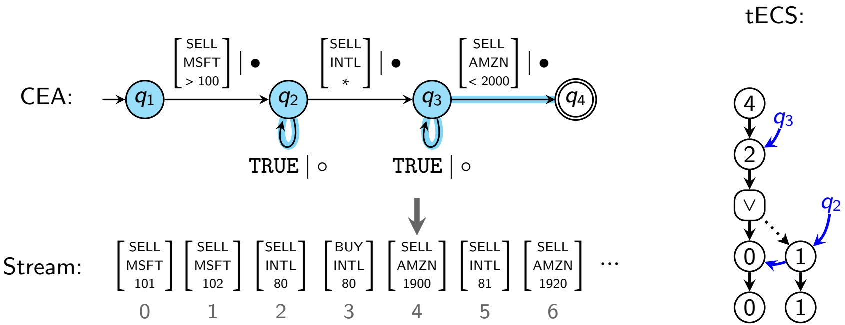

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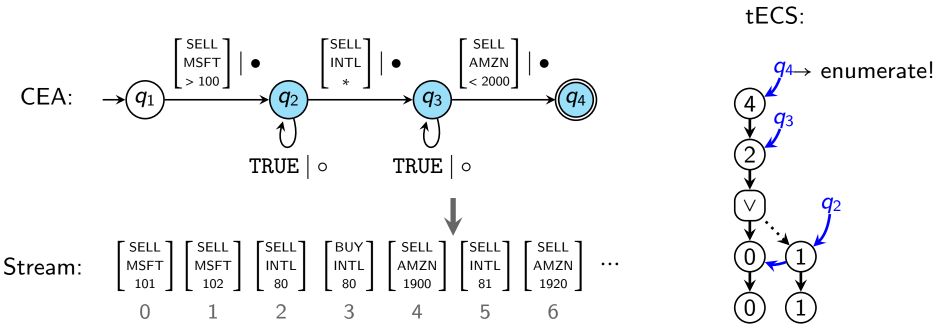

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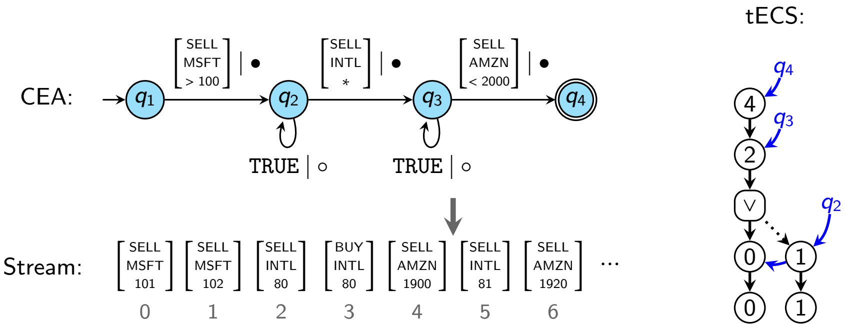

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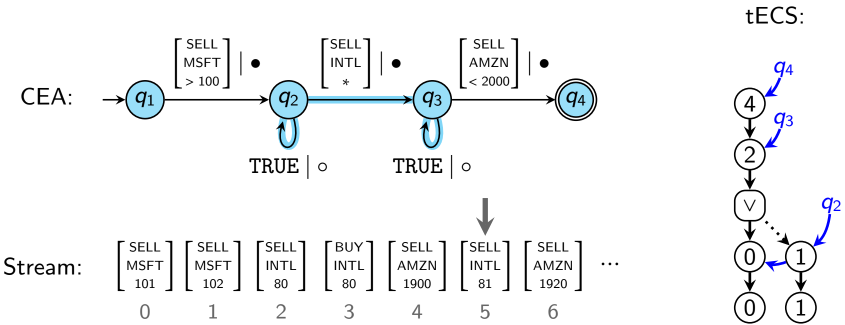

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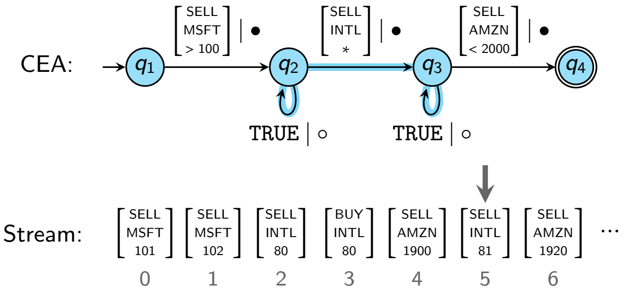

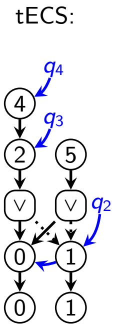

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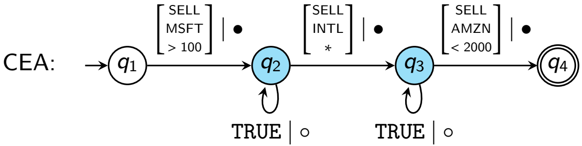

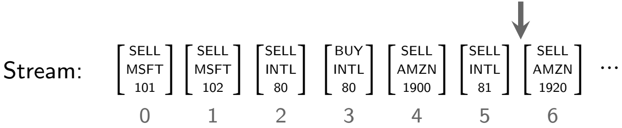

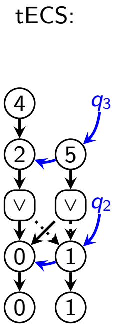

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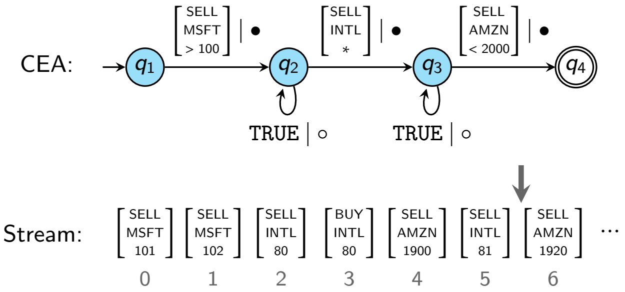
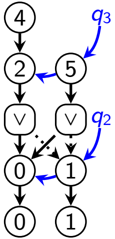


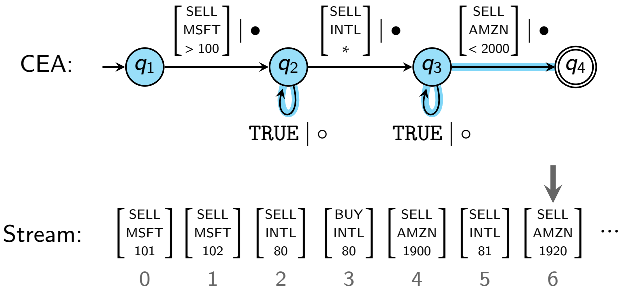
tECS:



Algorithm crux:

- Incrementally build the (well-structured) tECS to represents all open complex events up to the current event.
- Maintain the set of *active* CEA states, and the open complex events they correspond to.
- Crucially, all bookkeeping is $\mathcal{O}(|\mathrm{CEA}|)$, implying that we only take time $\mathcal{O}(|\mathrm{CEA}|)$ per event. This is constant in data complexity.

Evaluation Algorithm by Example



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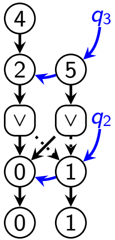

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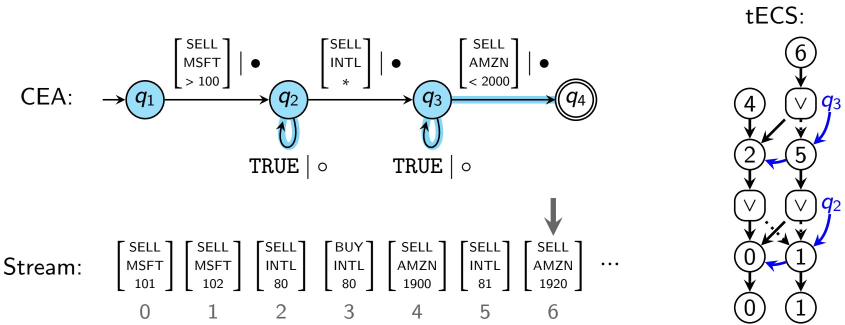

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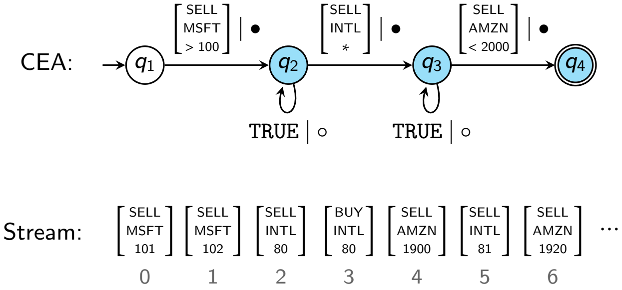

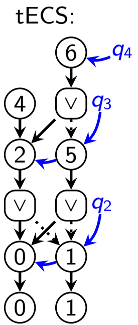

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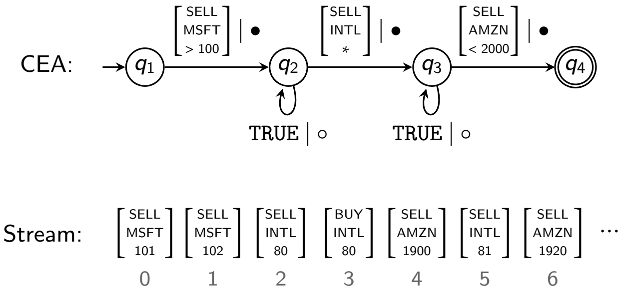

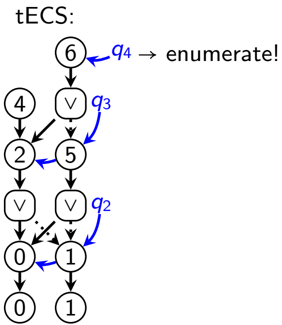

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CORE: **CO**mplex event **R**ecognition **E**ngine

An **open-source implementation** [1] of our approach.

[1] `https://github.com/CORE-cer/CORE`

CORE: **CO**mplex event **R**ecognition **E**ngine

An **open-source implementation** [1] of our approach.

1. Practical query language (CEQL) based on unary CEL.
2. Evaluation in constant update-time and output-linear delay, based on CEA.
3. CORE's performance is stable w.r.t query and time-window size.
4. CORE outperforms existing systems by up to 5 orders of magnitude.

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CEQL: Complex Event Query language

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SELECT	< list-of-variables >
FROM	< list-of-streams >
WHERE	< CEL-formula >
FILTER	< list-of-filters >
[PARTITION BY	< list-of-attributes >]
[WITHIN	< time-value >]

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Examples (Stock Market)

1.
```
SELECT   * FROM Stocks
WHERE    SELL as msft; SELL as intel; SELL as amzn
FILTER   msft[name="MSFT"] AND msft[price > 100]
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Stream: $\begin{bmatrix} \text{SELL} \\ \text{MSFT} \\ 101 \end{bmatrix} \begin{bmatrix} \text{SELL} \\ \text{MSFT} \\ 102 \end{bmatrix} \begin{bmatrix} \text{SELL} \\ \text{INTL} \\ 80 \end{bmatrix} \begin{bmatrix} \text{BUY} \\ \text{INTL} \\ 80 \end{bmatrix} \begin{bmatrix} \text{SELL} \\ \text{AMZN} \\ 1900 \end{bmatrix} \begin{bmatrix} \text{BUY} \\ \text{INTL} \\ 81 \end{bmatrix} \begin{bmatrix} \text{BUY} \\ \text{AMZN} \\ 1920 \end{bmatrix} \cdots \quad \begin{matrix} \text{(type)} \\ \text{(name)} \\ \text{(price)} \end{matrix}$

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101	102	**80**	80	**1900**	81	1920		(price)

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MSFT	MSFT	INTL	INTL	AMZN	INTL	AMZN		(name)
101	102	80	80	1900	81	1920		(price)
10:00	10:02	10:10	10:14	10:25	10:30	10:33		(time)

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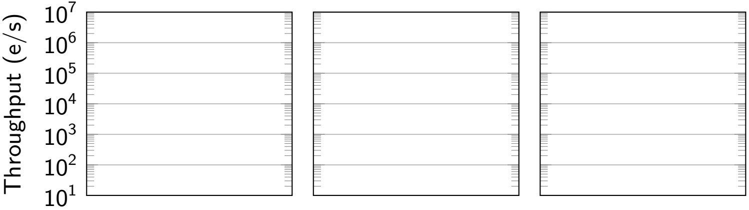
Experiments: Sequence queries



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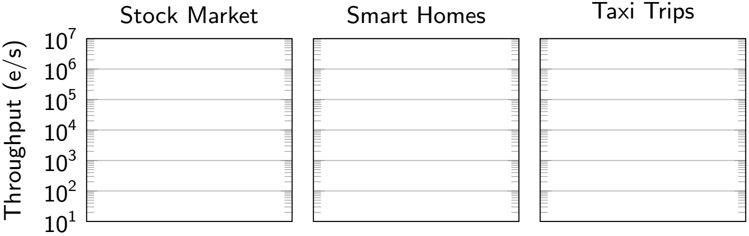

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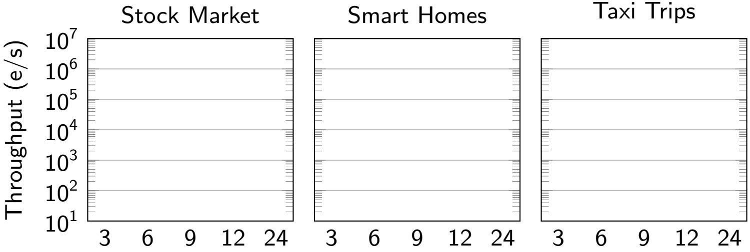


```
SELECT   * FROM Dataset
WHERE    A1 ; A2 ; ...  ; An
FILTER   A1[filter_1] AND ...  AND An[filter_n]
WITHIN   T
```

Experiments: Sequence queries


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SELECT   * FROM Dataset
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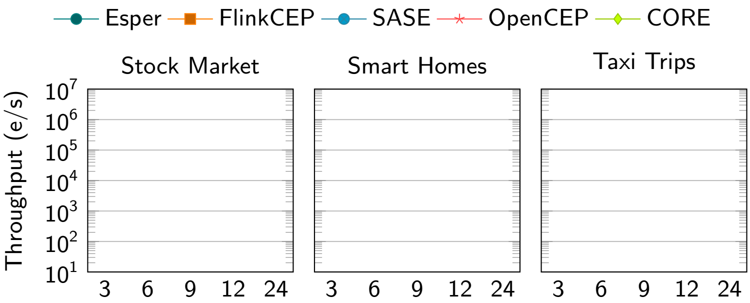
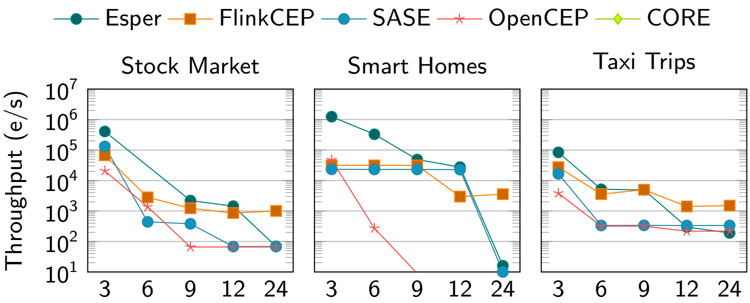
We use sequences of length $n = 3, 6, 9, 12, 24$.

Experiments: Sequence queries



1. Esper (*industry*)
2. FlinkCEP (*industry*)
3. SASE (*academy*)
4. OpenCEP (*academy*)
5. CORE

Experiments: Sequence queries



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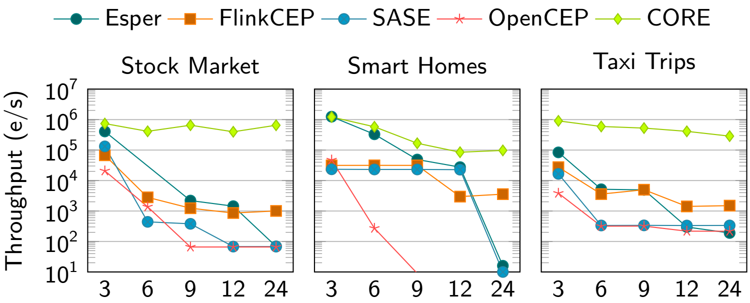

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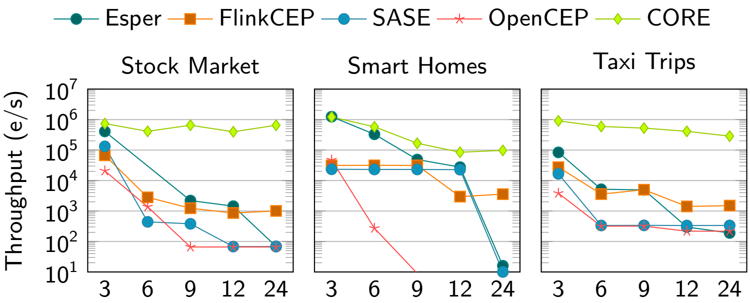
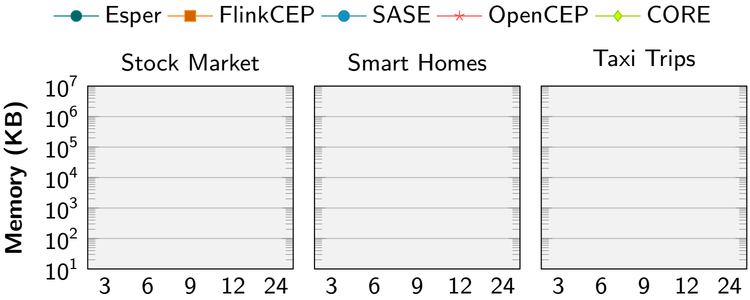


CORE is up to **4 orders of magnitude faster** than other systems

Experiments: Sequence queries (memory)



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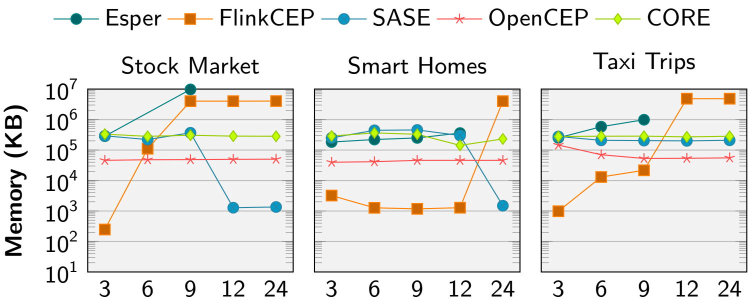

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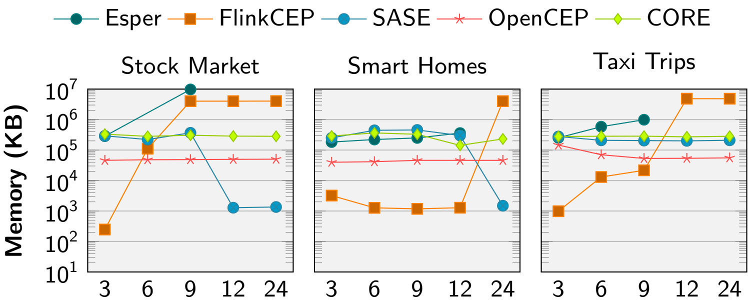
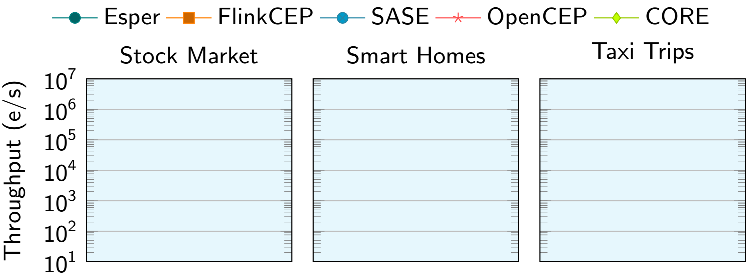


CORE is **stable** in the memory usage

Experiments: Window queries



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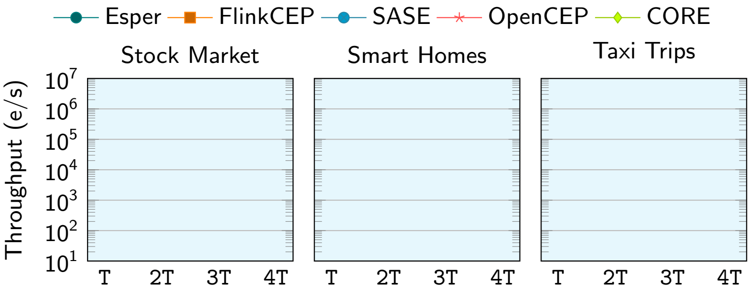


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SELECT   * FROM Dataset
WHERE    A1 ; A2 ; A3
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WITHIN   X
```
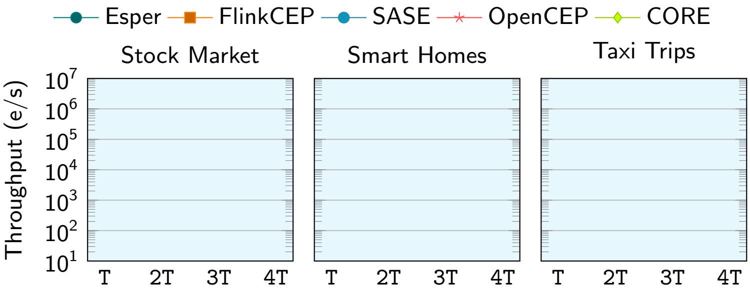

Experiments: Window queries

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We use time-windows **size** `X` = `T`, `2T`, `3T`, `4T`.

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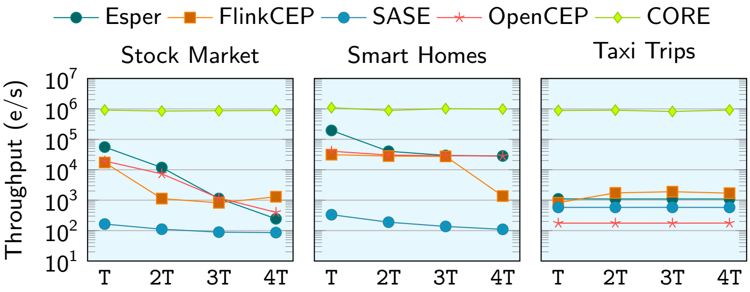

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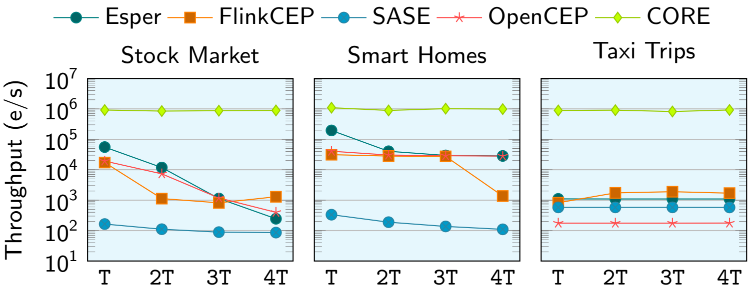

Conclusions

1. CORE is orders of magnitude faster than other systems.

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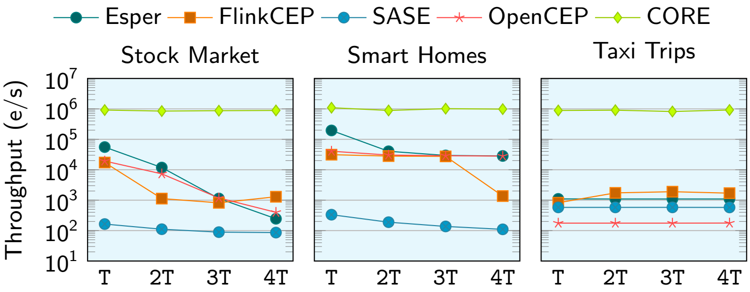
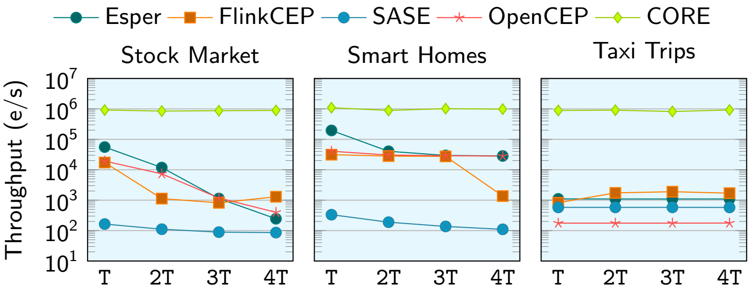


Conclusions

1. CORE is orders of magnitude faster than other systems.
2. CORE is **not affected** by the **query** or **time-windows** size.

Experiments: Window queries



In the paper [1], we show similar results with other query workloads

[1] M. Bucchi, A. Grez, A. Quintana, C. Riveros, and S. Vansummeren
"CORE: a Complex Event Recognition Engine", VLDB 2022.

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An automaton model for CER

Evaluation algorithm

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Open questions

Time Model

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Limitation: No out-of-order events

- Time is implicit, given by arrival order
- Crucial property for CEA evaluation:
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Open question: What is the impact of out-of-order events on

- Language design and expressiveness ?
- Evaluation model (CEA) and complexity ?

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Limitation: CORE and CEQL are based on **unary** CEL

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- Unary CEL does not allow event **correlation**.

Example: unsupported

$$\varphi = (B \, ; \, S) \; \texttt{FILTER} \; B[\mathrm{id}] = S[\mathrm{id}] \wedge B[\mathit{volume}] > S[\mathit{volume}]$$

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Open questions:

- What is the impact of moving to k-ary predicates, $k > 1$ on Language expressiveness ?
- What is the right computational model (à la CEA) with binary predicates ?
- How does this affect complexity?

Processing versus recognition

Limitation: CORE, CEQL, and CEL focus on complex event **recognition**

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Other features in the literature that focus on *processing* of complex events are not supported:

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- parallel or distributed execution

Open questions:

- What is the right language for CER + aggregation?
- What is the right computational model (à la CEA) in the presence of aggregation?
- How does aggregation affect evaluation complexity?

Getting to the CORE of Complex Event Recognition

Stijn Vansummeren
UHasselt, Data Science Institute