Constant-delay Enumeration for Lorem Ipsum

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Abstract

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2012 ACM Subject Classification Theory of computation → Database theory

Keywords and phrases Streams, query evaluation, enumeration algorithms.

1 Introduction

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2 Preliminaries

Sets and intervals. Given a set A, we denote by 2^A the *powerset* of A. We denote by $\mathbb{N}$ the natural numbers. Given $n, m \in \mathbb{N}$ with $n \leq m$, we denote by $[n]$ the set $\{1, \ldots, n\}$ and by $[n..m]$ the interval $\{n, n+1, \ldots, m\}$ over $\mathbb{N}$.

Events and streams. We fix a set $\mathbf{T}$ of *event types*, a set $\mathbf{A}$ of *attributes names*, and a set $\mathbf{D}$ of *data values* (e.g., integers, floats, strings). An *event* e is a partial mapping $e : \mathbf{A} \to \mathbf{D}$ that maps attributes names in $\mathbf{A}$ to data values in $\mathbf{D}$. We denote att(e) the domain of e, called the attributes of e, and we assume that att(e) is finite. We denote by $e(A)$ the data value of the attribute $A \in \mathbf{A}$ whenever $A \in att(e)$. Further, each event e has a type in $\mathbf{T}$ denoted by type(e). We write $\mathbf{E}$ to denote the set of all events over event types $\mathbf{T}$, attributes names $\mathbf{A}$, and data values $\mathbf{D}$. A *stream* is an (arbitrary long) sequence $\bar{S} = e_1 e_2 \ldots e_n$ of events where $|S| = n$ is the length of the stream.

Complex events. Fix a finite set $\mathbf{X}$ of variables and assume that $\mathbf{T} \subseteq \mathbf{X}$, where $\mathbf{T}$ is the set of event types as defined earlier, this is to say that all event types are a variable. Let $\bar{S}$ be a stream of length n. A complex event of $\bar{S}$ is a triple (i, j, μ) where $i, j \in [n]$, $i \leq j$, and $\mu : \mathbf{X} \to 2^{[i..j]}$ is a function with finite domain. Intuitively, i and j marks the beginning and end of the interval where the complex event happens, and μ stores the events in the interval $[i..j]$ that fired the complex event. In the following, we will usually use C to denote a complex event (i, j, μ) of $\bar{S}$ and omit $\bar{S}$ if the stream is clear from the context. We will use interval(C), start(C), and end(C) to denote the interval $[i..j]$, the start i, and the end j

$$
\begin{aligned}
[\![R]\!](\bar{S}) &= \{\, (i,i,\mu) \mid \text{type}(e_i) = R \wedge \mu(R) = \{i\} \wedge \forall X \neq R.\ \mu(X) = \varnothing \,\} \\
[\![\varphi \text{ AS } X]\!](\bar{S}) &= \{\, C \mid \exists C' \in [\![\varphi]\!](\bar{S}).\ \text{interval}(C) = \text{interval}(C') \wedge C(X) = \textstyle\bigcup_Y C'(Y) \\
&\qquad \wedge \forall Z \neq X.\ C(Z) = C'(Z) \,\} \\
[\![\varphi \text{ FILTER } X[P]]\!](\bar{S}) &= \{\, C \mid C \in [\![\varphi]\!](\bar{S}) \wedge C(X) \vDash P \,\} \\
[\![\varphi_1 \text{ OR } \varphi_2]\!](\bar{S}) &= [\![\varphi_1]\!](\bar{S}) \cup [\![\varphi_2]\!](\bar{S}) \\
[\![\varphi_1 \text{ AND } \varphi_2]\!](\bar{S}) &= [\![\varphi_1]\!](\bar{S}) \cap [\![\varphi_2]\!](\bar{S}) \\
[\![\varphi_1 ; \varphi_2]\!](\bar{S}) &= \{\, C_1 \cup C_2 \mid C_1 \in [\![\varphi_1]\!](\bar{S}) \wedge C_2 \in [\![\varphi_2]\!](\bar{S}) \wedge \text{end}(C_1) < \text{start}(C_2) \,\} \\
[\![\varphi_1 : \varphi_2]\!](\bar{S}) &= \{\, C_1 \cup C_2 \mid C_1 \in [\![\varphi_1]\!](\bar{S}) \wedge C_2 \in [\![\varphi_2]\!](\bar{S}) \wedge \text{end}(C_1) + 1 = \text{start}(C_2) \,\} \\
[\![\varphi^{+}]\!](\bar{S}) &= [\![\varphi]\!](\bar{S}) \cup [\![\varphi ; \varphi^{+}]\!](\bar{S}) \\
[\![\varphi^{\oplus}]\!](\bar{S}) &= [\![\varphi]\!](\bar{S}) \cup [\![\varphi : \varphi^{\oplus}]\!](\bar{S}) \\
[\![\pi_L(\varphi)]\!](\bar{S}) &= \{\, \pi_L(C) \mid C \in [\![\varphi]\!](\bar{S}) \,\}
\end{aligned}
$$

Figure 1: The semantics of CEL formulas defined over a stream $\bar{S} = e_1 e_2 \dots e_n$ where each e_i is an event.

of C, respectively. Further, by some abuse of notation we will also use C(X) for $X \in \mathbf{X}$ to denote the set $\mu(X)$ of C.

The following operations on complex events will be useful throughout the paper. We define the union of complex events C_1 and C_2, denoted by $C_1 \cup C_2$, as the complex event C' such that start(C') = min{start(C_1),start(C_2)}, end(C') = max{end(C_1), end(C_2)}, and C'(X) = $C_1(X) \cup C_2(X)$ for every $X \in \mathbf{X}$. Further, we define the *projection over* L of a complex event C, denoted by π_L(C), as the complex event C' such that interval(C') = interval(C) and C'(X) = C(X) whenever $X \in L$, and C'(X) = $\varnothing$, otherwise. Finally, we denote by $(i, j, \mu_\varnothing)$ the complex event with trivial mapping $\mu_\varnothing$ such that $\mu_\varnothing$(X) = $\varnothing$ for every $X \in \mathbf{X}$.

Predicate of events. A *predicate* is a possibly infinite set $\mathbf{P}$ of events. We say that an event e satisfies predicate P, denoted $e \vDash P$, if, and only if, $e \in P$. We generalize this notation from events to a set of events E such that $E \vDash P$ if, and only if, $e \vDash P$ for every $e \in E$. We assume a fixed set of predicates $\mathbf{P}$. Further, we assume that there is a basic set of predicates P_basic $\subseteq P$ and $\mathbf{P}$ is the closure of P_basic under intersection and negation (i.e., $P_1 \cap P_2 \in \mathbf{P}$ and $\mathbf{E}$ $P \in \mathbf{P}$ for every $P, P_1, P_2 \in \mathbf{P}$) where $\mathbf{E}$ is a predicate in $\mathbf{P}$, that we usually denote by true.

Complex event logic. In this work, we use the Complex Event Logic (CEL) introduced in [21] and implemented in CORE [11] as our basic query language for CER. The syntax of a CEL formula φ is given by the grammar:

$$\varphi := R \mid \varphi \text{ AS } X \mid \varphi \text{ FILTER } X[P] \mid \varphi \text{ OR } \varphi \mid \varphi \text{ AND } \varphi \mid \varphi ; \varphi \mid \varphi : \varphi \mid \varphi + \mid \varphi \oplus \mid \pi_L(\varphi)$$

where $R \in \mathbf{T}$ is an event type, $X \in \mathbf{X}$ is a variable, $P \in \mathbf{P}$ is a predicate, and $L \subseteq \mathbf{X}$ is a set of variables. We define the semantics of a CEL formula φ over a stream $\bar{S}$, recursively, as a set of complex events over $\bar{S}$ In Figure 1, we define the semantics of each CEL operator like in [11, 21].

3 Main results

In this section we introduce an extension to the semantics of CEL, namely we introduce a new operator using [allen interval algebra] *overlap*. We then extend the formal computational model for evaluating CEL formulas and prove its correctness. We start by recalling the notion of a CEA to later extend the proof.

Fernando: this intro is just to get the point a cross, not polished

Complex Event Automata. A *Complex Event Automata* (CEA) is a tuple $\mathcal{A} = (Q,\mathbf{P},\mathbf{X},\Delta,q_0,F)$ where Q is a finite set of states, $\mathbf{P}$ is the set of predicates, $\mathbf{X}$ is a finite set of variables, $\Delta \subseteq Q \times \mathbf{P} \times 2^{\mathbf{X}} \times Q$ is a finite relation (called the transition relation), $q_0 \in Q$ is the inital state, and F is the set of final states. A run ρ of $\mathcal{A}$ over the stream $\bar{S} = e_1e_2\dots e_n$ from position i to j is a sequence:

$$\rho := p_i \xrightarrow{P_i,L_i} p_{i+1} \xrightarrow{P_{i+1},L_{i+1}} p_{i+2} \xrightarrow{P_{i+2},L_{i+2}} \dots \xrightarrow{P_j,L_j} p_{j+1}$$

where $p_i = q_0, (p_k,P_k,L_k,p_{k+1}) \in \Delta$, and $e_k \vDash P_k$ for all $k \in [i..j]$. We say that the run is accepting if $p_{j+1} \in F$. A run ρ from positions i to j like above defines the complex event $C_\rho = (i,j,\mu_\rho)$ such that $\mu_\rho(X) = k \in [i..j] \mid X \in L_k$ for every $X \in \mathbf{X}$. Note that the starting and ending positions i,j of the run define the interval of the complex event, and the labels $L_k \subseteq \mathbf{X}$ define the mapping μ_ρ of C_ρ. We define the set of all complex events of $\mathcal{A}$ over $\bar{S}$ as:

$$[\![\mathcal{A}]\!](\bar{S}) = \{C_\rho \mid \rho \text{ is an accepting run of } \mathcal{A} \text{ over } \bar{S}\}$$

We present then the overlap operator for CEL as with the following definition:

$$\begin{aligned}[\![\varphi_1 :\!o\ \varphi_2]\!](\bar{S}) = \{C_1 \cup C_2 \mid C_1 \in [\![\varphi_1]\!](\bar{S}) \wedge C_2 \in [\![\varphi_2]\!](\bar{S})\\ \wedge\, \mathit{start}(C_1) \le \mathit{start}(C_2) \le \mathit{end}(C_1) \le \mathit{end}(C_2)\}\end{aligned}$$

We also know from [11,22] the following theorem:

▶ **Theorem 1** (CEA and CEL equivalence). *For every CEL formula φ there exists a CEA $\mathcal{A}_\varphi$ such that $[\![\varphi]\!](\bar{S}) = [\![\mathcal{A}_\varphi]\!](\bar{S})$ for every stream $\bar{S}$*

To maintain the correctness of it true, we extend the induction proof [11,22] by adding an extra case for this operator.
Lets assume then that there exists an automaton that satisfies the previous property for φ_1 and φ_2, therefore we know there exists $\mathcal{A}_{\varphi_1} = (Q_1,\mathbf{P}_1,\mathbf{X}_1,q_0,F_1)$ and $\mathcal{A}_{\varphi_2} = (Q_2,\mathbf{P}_2,\mathbf{X}_2,p_0,F_2)$

Then the construction for the operator will be $\mathcal{A}_{:o}$ be a CEA such that $\mathcal{A}_{:o} = ()$

4 Conclusions

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A Proofs from Section 2

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B Proofs of Section 3

B.1 Proof of Lemma ??

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B.2 Proof of Theorem 1

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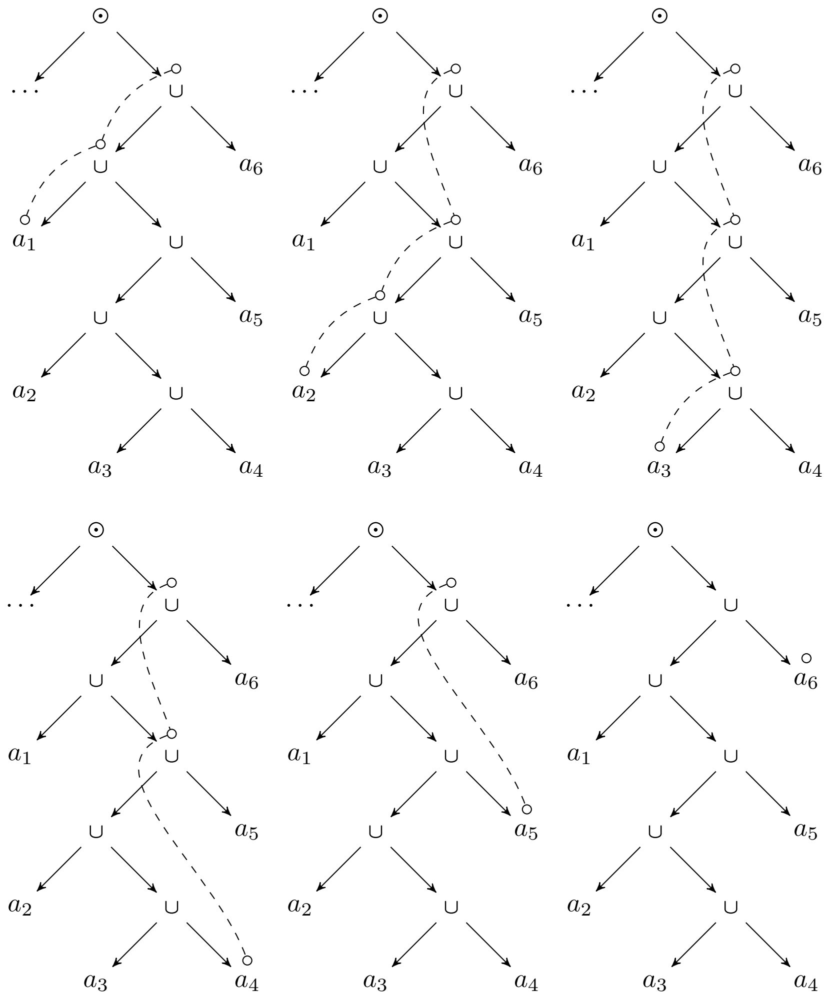

■ **Figure 1** An example iteration of `trav` and `move`. The sequences of nodes joined by dashed lines represent a stack `St`, where the first one was obtained after calling `trav` over the topmost union node, and the following five are obtained by repeated applications of `move(St)`.

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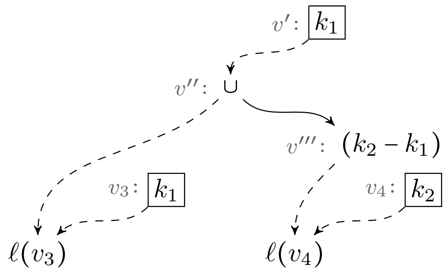

Figure 2 Gadget used in Theorem 1.

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B.3 Proof of Proposition ??

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▷ Claim 2. Fix $k \in \mathbb{N}$. Let $\mathcal{C}_k$ be the class of all duplicate-free and k-bounded D that satisfy the ϵ condition. Then one can solve the problem $\texttt{Enum}[\mathcal{C}_k]$ with output-linear delay and without preprocessing (i.e. constant preprocessing time).

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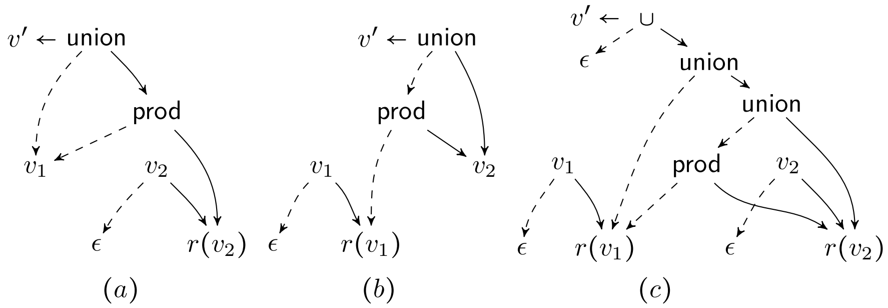

Figure 3 Gadgets for product as defined for an $\mathcal{D}$ with the ϵ-node.

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