

hypothetical answers to continuous queries over data streams

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Outline

- 1 *introduction*
- 2 *denotational semantics*
- 3 *operational semantics*
- 4 *conclusions*

the context

continuous queries over data streams

- modern-day distributed systems
- information pouring in from e.g. sensors
- queries need to be answered in real-time
- answers are output as information arrives

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several models

common approach: rule-based reasoning

- usually based on variants of datalog
- set of facts dynamically obtained from a data stream D
- common problems: blocking queries, unbound wait

current contribution

online algorithm with offline pre-processing outputting partial information

- information that an answer may be output in the future
- fundamentation for such hypothetical answers

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practical relevance

partial information allows for preventive measures to be taken

- an action might be required \rightsquigarrow maybe prepare for it
- a failure might occur \rightsquigarrow steps may be taken to prevent it

the justification for *why* the hypothetical answer is output can be used to evaluate its likelihood

detecting malfunctions in wind turbines
$$\text{Temp}(X, \text{high}, T) \rightarrow \text{Flag}(X, T)$$
$$\text{Flag}(X, T) \wedge \text{Flag}(X, T + 1) \rightarrow \text{Cool}(X, T + 1)$$
$$\text{Cool}(X, T) \wedge \text{Flag}(X, T + 1) \rightarrow \text{Shdn}(X, T + 1)$$

- a data center managing a set of wind turbines receives temperature readings $\text{Temp}(\text{Device}, \text{Level}, \text{Time})$ from sensors in each turbine
- the data centre tracks activation of cooling measures in each turbine, recording shutdowns by means of a program in temporal datalog

detecting malfunctions in wind turbines

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$$\text{Cool}(X, T) \wedge \text{Flag}(X, T + 1) \rightarrow \text{Shdn}(X, T + 1)$$

query: $Q = \text{Shdn}(X, T)$

if:

$$\text{Temp}(\text{wt25}, \text{high}, i) \quad i = 0, 1, 2$$

all arrive at the data stream, then $\{X := \text{wt25}, T := 2\}$ is an answer to Q

detecting malfunctions in wind turbines

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query: $Q = \text{Shdn}(X, T)$

but: once

$$\text{Temp}(\text{wt25}, \text{high}, 0)$$

arrives, we already know that $\{X := \text{wt25}, T := 2\}$ *might* become an answer to Q

detecting malfunctions in wind turbines

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query: $Q = \text{Shdn}(X, T)$

and since

$$\text{Temp}(\text{wt42}, \text{high}, 0)$$

does *not* arrive, we know that $\{X := \text{wt42}, T := 2\}$ *cannot* become an answer to Q

detecting malfunctions in wind turbines

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assumption

we assume that the data stream D is complete at each time point, i.e. at time τ it contains all facts with timestamps $\leq \tau$

we call this set of facts the τ -history D_τ

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extensional predicates

we assume that the predicate symbols occurring in D do not appear in heads of rules in Π – these are *extensional* predicates

hypothetical answers

a *hypothetical answer* to a query Q over a program Π and a history D_τ is a pair $\langle \theta, H \rangle$, where θ is a substitution and H is a finite set of ground extensional atoms (the hypotheses) such that:

- θ only instantiates variables free in Q
- H only contains atoms with time stamp $\tau' > \tau$
- $\Pi \cup D_\tau \cup H \models Q\theta$
- H is minimal with respect to set inclusion

our example program

$$\begin{aligned} & \text{Temp}(X, \text{high}, T) \rightarrow \text{Flag}(X, T) \\ & \text{Flag}(X, T) \wedge \text{Flag}(X, T + 1) \rightarrow \text{Cool}(X, T + 1) \\ & \text{Cool}(X, T) \wedge \text{Flag}(X, T + 1) \rightarrow \text{Shdn}(X, T + 1) \end{aligned}$$

query

$$Q = \text{Shdn}(X, T)$$

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query
$$Q = \text{Shdn}(X, T)$$
$$\text{Temp}(\text{wt25}, \text{high}, 0) \in D_0$$

$\langle \{X := \text{wt25}, T := 2\}, H \rangle$ is a hypothetical answer to Q for
 $H = \{\text{Temp}(\text{wt25}, \text{high}, i) \mid i = 1, 2\}$

our example program
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query
$$Q = \text{Shdn}(X, T)$$
$$\text{Temp}(\text{wt42}, \text{high}, 0) \notin D_0$$

$\langle \{X := \text{wt42}, T := 2\}, H \rangle$ is not a hypothetical answer to Q for any H

supported answers

- a non-empty set of facts $E \subseteq D_\tau$ is *evidence* supporting a hypothetical answer $\langle \theta, H \rangle$ if E is a minimal set s.t. $\Pi \cup E \cup H \models P\theta$
- a *supported answer* to Q over D_τ is a triple $\langle \theta, H, E \rangle$ where E is evidence supporting $\langle \theta, H \rangle$

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in our example program

the fact

$$\text{Temp}(\text{wt25}, \text{high}, 0) \in D_0$$

is evidence that $\langle \{X := \text{wt25}, T := 2\}, H \rangle$ is a hypothetical answer to Q for

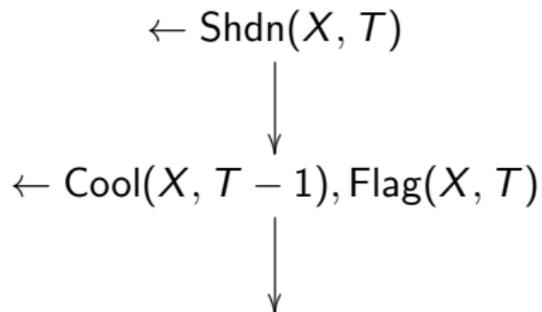
$$H = \{\text{Temp}(\text{wt25}, \text{high}, i) \mid i = 1, 2\}$$

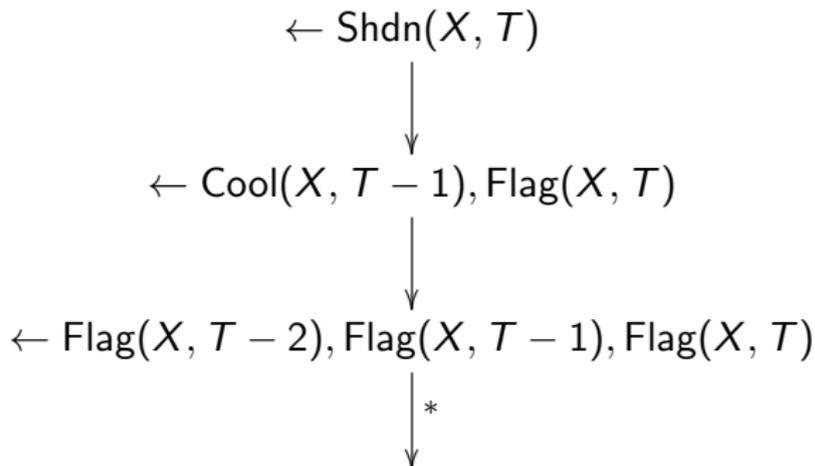
Outline

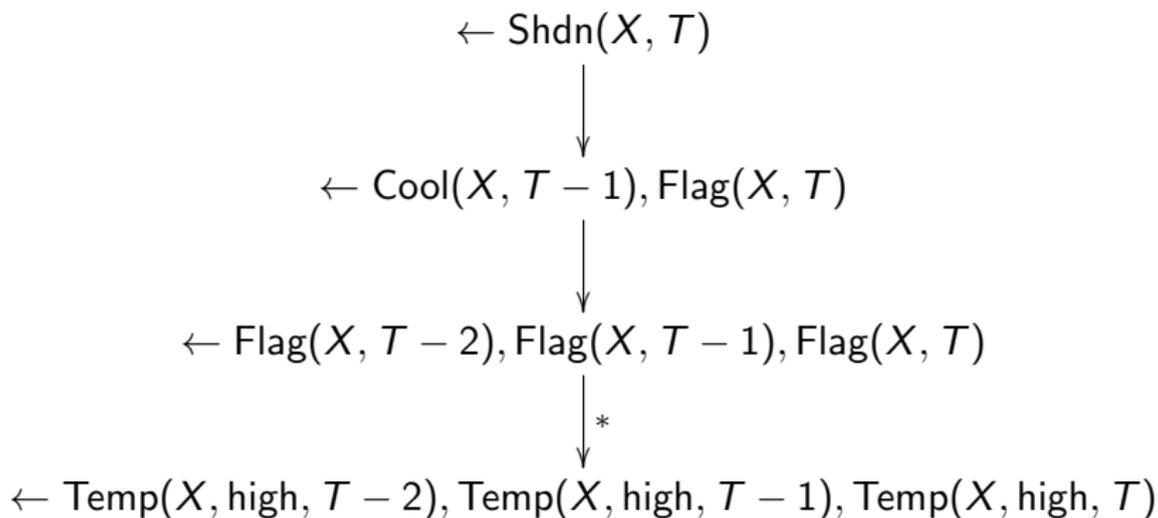
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intuition

intuition $\leftarrow \text{Shdn}(X, T)$ 

intuition

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intuition

future atom

an atom $P(t_1, \dots, t_n)$ is a *future atom wrt* τ if P is a temporal predicate and the time term t_n either contains a temporal variable or is a time instant $t_n > \tau$

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sld-refutation, revisited

an *sld-refutation with future premises* of Π and Q over D_τ is a finite sld-derivation of $P \cup D_\tau \cup \{\neg Q\}$ whose last goal only contains extensional future atoms wrt τ

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computed answer with premises

if \mathcal{D} is an sld-refutation with future premises of Q over D_τ with last goal $G = \neg \wedge_i \alpha_i$ and θ is the restriction of the composition of the substitutions in \mathcal{D} to $\text{var}(Q)$, then $\langle \theta, \wedge_i \alpha_i \rangle$ is a *computed answer with premises* to Q over D_τ

independence of the computation rule

from classical results about sld-resolution, we can reorder the steps of any sld-refutation with future premises to use the facts from D_T in temporal order

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key idea

this simple observation gives us an incremental algorithm

- at each step, update any “ongoing” derivations with the new facts
- any derivations expecting facts that did not arrive are forgotten
- some pre-processing allows us to identify relevant facts

a two-stage algorithm

pre-processing step

we compute answers with premises to Q over D_{-1}

- we store the minimal answers wrt set inclusion in a set \mathcal{P}_Q
- we initialize the set \mathcal{S}_{-1} of *schematic supported answers* to \emptyset

a two-stage algorithm

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online step

to compute $\mathcal{S}_{\tau+1}$ from \mathcal{S}_τ and $D_{\tau+1} \setminus D_\tau$:

- for each answer in \mathcal{P}_Q , we perform sld-resolution between its set of elements with minimal timestamps and $D_{\tau+1} \setminus D_\tau$
- for each element of \mathcal{S}_τ , we perform sld-resolution between its set of elements with timestamp $\tau + 1$ and $D_{\tau+1} \setminus D_\tau$

each refutation yields an element in $\mathcal{S}_{\tau+1}$

termination (i)

under suitable assumptions, the pre-processing step terminates

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termination (ii)

the online step terminates in polynomial time in the size of \mathcal{S}_τ , \mathcal{P}_Q
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soundness

every instantiation of an element of \mathcal{S}_τ is a supported answer to Q over Π and D_τ

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completeness

every supported answer to Q over Π and D_τ is an instantiation of an element of \mathcal{S}_τ

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main achievements

our contribution

- denotational semantics for hypothetical answers
- notion of evidence for hypothetical answers
- operational semantics based on sld-resolution
- online algorithm with offline pre-processing outputting partial information
- parallel computation of answers (bypasses some usual problems)
- more expressive negation in the language
- new (decidable) notion of stratification with computable strata

future work

- an implementation. . .

thank you!