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hypothetical answers to continuous queries over data streams

 $\frac{\text{luís cruz-filipe}^1}{\text{(joint work with graça gaspar}^2 \& \text{ isabel nunes}^2)}$

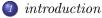
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days in logic january 30th, 2020

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denotational semantics

operational semantics

Integration





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	the conte	ext			
	continuo	us queries over data	streams		
	 modern-day distributed systems 				
	• information pouring in from e.g. sensors				
	• queries need to be answered in real-time				
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• answers are output as information arrives

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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

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

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current contribution

online algorithm with offline pre-processing outputting partial information

• information that an answer may be output in the future

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• fundamentation for such hypothetical answers

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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

practical relevance

partial information allows for preventive measures to be taken

 \bullet an action might be required \leadsto 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

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detecti	ng malfunctions in u	vind turbines		
	T ()		(-)	

 $\mathsf{Temp}(X,\mathsf{high},T) o \mathsf{Flag}(X,T)$ $\mathsf{Flag}(X,T) \wedge \mathsf{Flag}(X,T+1) \to \mathsf{Cool}(X,T+1)$ $\mathsf{Cool}(X,T) \wedge \mathsf{Flag}(X,T+1) \to \mathsf{Shdn}(X,T+1)$ $\mathsf{Shdn}(X,T) \to \mathsf{Malf}(X,T-2)$

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

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$$\mathsf{Temp}(X,\mathsf{high},T) \to \mathsf{Flag}(X,T)$$

 $\mathsf{Flag}(X,T) \land \mathsf{Flag}(X,T+1) \to \mathsf{Cool}(X,T+1)$
 $\mathsf{Cool}(X,T) \land \mathsf{Flag}(X,T+1) \to \mathsf{Shdn}(X,T+1)$
 $\mathsf{Shdn}(X,T) \to \mathsf{Malf}(X,T-2)$

query:
$$Q = Malf(X, T)$$

if:

$$\mathsf{Temp}(\mathsf{wt25},\mathsf{high},i) \qquad i=0,1,2$$

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all arrive at the data stream, then $\{X:=\mathsf{wt25},\,\mathcal{T}:=\mathsf{0}\}$ is an answer to Q

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$$\mathsf{Temp}(X,\mathsf{high},T) \to \mathsf{Flag}(X,T)$$

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query:
$$Q = Malf(X, T)$$

but: once

Temp(wt25, high, 0)

arrives, we already know that $\{X:=\mathsf{wt25},\, T:=0\}$ might become an answer to Q

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$$\mathsf{Temp}(X, \mathsf{high}, T) o \mathsf{Flag}(X, T)$$

 $\mathsf{Flag}(X, T) \wedge \mathsf{Flag}(X, T+1) \to \mathsf{Cool}(X, T+1)$
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query:
$$Q = Malf(X, T)$$

and since

Temp(wt42, high, 0)

does not arrive, we know that $\{X := wt42, T := 0\}$ cannot become an answer to Q

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$$\begin{array}{c} \mathsf{Temp}(X,\mathsf{high},\,T) \to \mathsf{Flag}(X,\,T) \\ \mathsf{Flag}(X,\,T) \land \mathsf{Flag}(X,\,T+1) \to \mathsf{Cool}(X,\,T+1) \\ \mathsf{Cool}(X,\,T) \land \mathsf{Flag}(X,\,T+1) \to \mathsf{Shdn}(X,\,T+1) \\ & \mathsf{Shdn}(X,\,T) \to \mathsf{Malf}(X,\,T-2) \end{array}$$

assumption

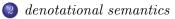
we assume that the data stream D is complete at each time point, i.e. at time t it contains all facts with timestamps $\leq t$ we call this set of facts the τ -history D_{τ}

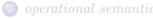
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extensional predicates

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 au' > au
- $\Pi \cup D_{\tau} \cup H \models Q\theta$
- H is minimal with respect to set inclusion

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our example program

$$\begin{array}{l} \mathsf{Temp}(X,\mathsf{high},\,T) \to \mathsf{Flag}(X,\,T) \\ \mathsf{Flag}(X,\,T) \land \mathsf{Flag}(X,\,T+1) \to \mathsf{Cool}(X,\,T+1) \\ \mathsf{Cool}(X,\,T) \land \mathsf{Flag}(X,\,T+1) \to \mathsf{Shdn}(X,\,T+1) \\ & \mathsf{Shdn}(X,\,T) \to \mathsf{Malf}(X,\,T-2) \end{array}$$

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Q = Malf(X, T)

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our example program

$$\mathsf{Temp}(X,\mathsf{high},T) \to \mathsf{Flag}(X,T)$$
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$$\mathsf{Shdn}(X,T) \to \mathsf{Malf}(X,T-2)$$

query

 $Q = \mathsf{Malf}(X, T)$

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

 $\langle \{X := wt25, T := 0\}, H \rangle$ is a hypothetical answer to Q for $H = \{\text{Temp}(wt25, \text{high}, i) \mid i = 1, 2\}$

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our example program

$$\begin{array}{c} \mathsf{Temp}(X,\mathsf{high},\,T) \to \mathsf{Flag}(X,\,T) \\ \mathsf{Flag}(X,\,T) \land \mathsf{Flag}(X,\,T+1) \to \mathsf{Cool}(X,\,T+1) \\ \mathsf{Cool}(X,\,T) \land \mathsf{Flag}(X,\,T+1) \to \mathsf{Shdn}(X,\,T+1) \\ & \mathsf{Shdn}(X,\,T) \to \mathsf{Malf}(X,\,T-2) \end{array}$$

query

 $Q = \mathsf{Malf}(X, T)$

$Temp(wt42, high, 0) \notin D_0$

 $\langle \{X:=\mathsf{wt42},\, T:=0\}, H\rangle$ is not a hypothetical answer to Q for any H

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supported answers

- a non-empty set of facts E ⊆ D_τ is *evidence* supporting a hypothetical answer ⟨θ, H⟩ if E is a minimal set
 s.t. Π ∪ E ∪ H ⊨ Pθ
- a supported answer to Q over D_τ is a triple (θ, H, E) where E is evidence supporting (θ, H)

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supported answers

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 s.t. Π ∪ E ∪ H ⊨ Pθ
- a supported answer to Q over D_τ is a triple (θ, H, E) where E is evidence supporting (θ, H)

in our example program

the fact

```
\mathsf{Temp}(\mathsf{wt25},\mathsf{high},0) \in D_0
```

is evidence that $\langle \{X:=\mathsf{wt25},\, \mathcal{T}:=0\}, \mathcal{H}\rangle$ is a hypothetical answer to Q for

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

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③ operational semantics





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future atom

an atom $P(t_1, \ldots, t_n)$ 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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future atom

an atom $P(t_1, \ldots, t_n)$ 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 $t_n > \tau$

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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future atom

an atom $P(t_1, \ldots, t_n)$ 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 $t_n > \tau$

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

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 var(Q), then $\langle \theta, \wedge_i \alpha_i \rangle$ is a *computed answer with premises* to Q over D_{τ}

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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_τ in temporal order

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conclusions

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_τ in temporal order

$key \ idea$

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

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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

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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

online step

to compute $S_{\tau+1}$ from 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 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 $\mathcal{S}_{\tau+1}$

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under suitable assumptions, the pre-processing step terminates

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under suitable assumptions, the pre-processing step terminates

termination (ii)

the online step terminates in polynomial time in the size of $\mathcal{S}_{ au}$, \mathcal{P}_Q and $D_{ au+1}\setminus D_{ au}$

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under suitable assumptions, the pre-processing step terminates

termination (ii)

the online step terminates in polynomial time in the size of $\mathcal{S}_{ au}$, \mathcal{P}_Q and $D_{ au+1}\setminus D_{ au}$

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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under suitable assumptions, the pre-processing step terminates

termination (ii)

the online step terminates in polynomial time in the size of $\mathcal{S}_{ au}$, \mathcal{P}_Q and $D_{ au+1}\setminus D_{ au}$

soundness

every instantiation of an element of \mathcal{S}_{τ} is a supported answer to Q over Π and D_{τ}

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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safe negation

we can add (safe) negation in the usual way to our framework

• most results go through (but complexity increases)

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safe negation

we can add (safe) negation in the usual way to our framework

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• most results go through (but complexity increases)

stratification

stronger results in presence of stratified negation

- more complex notion
- possibly infinitely many strata
- not necessarily temporally ordered

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our contribution

- new notion of stratification
- decision procedure + algorithm returning a finite representation of the strata

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our contribution

- new notion of stratification
- decision procedure + algorithm returning a finite representation of the strata

results

- fixed-parameter tractability for the online step
- soundness and completeness wrt well-founded semantics (wip)

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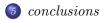
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main achievements

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...

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thank you!

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