Ontology-based Access to Temporal Data

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Free University of Bozen-Bolzano, Italy

RuleML Webinar

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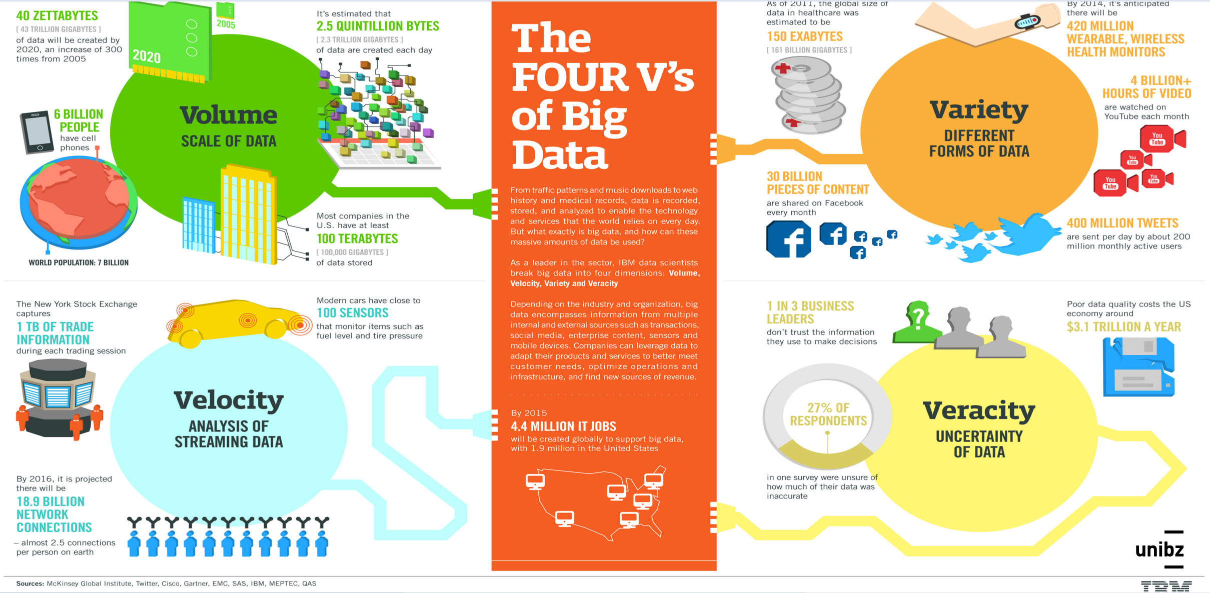
Challenges in the Big Data era



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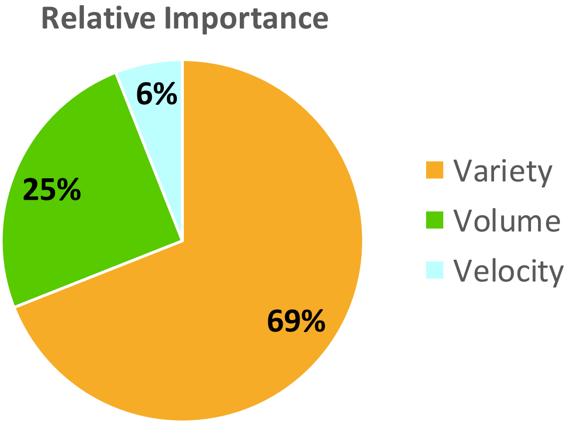
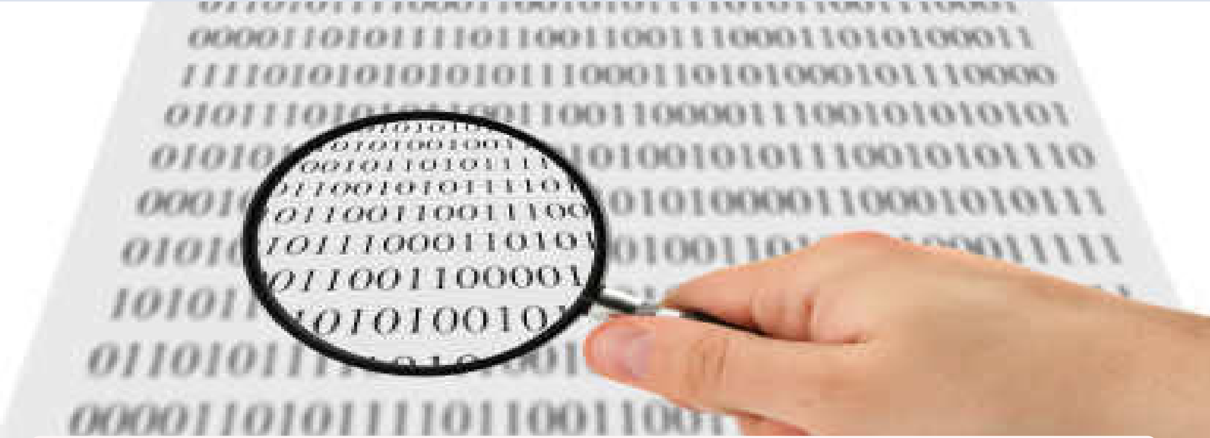
Variety, not volume, is driving Big Data initiatives

MIT Sloan Management Review (28 March 2016)



http://sloanreview.mit.edu/article/variety-not-volume-is-driving-big-data-initiatives/

How much time is spent searching for the right data?



Important problem: searching for data and establishing its quality

Example: in oil&gas, engineers spend 30–70% of their time on this (Crompton, 2008)

Solution: Ontology-based data access (OBDA)

Data Sources $\mathcal{S}$
autonomous and heterogeneous

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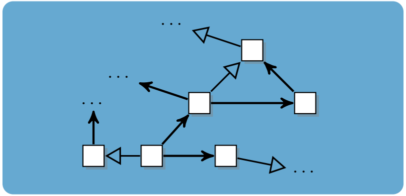

Ontology $\mathcal{O}$
conceptual view of data, convenient vocabulary

Data Sources $\mathcal{S}$
autonomous and heterogeneous

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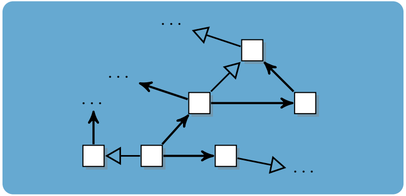
Solution: Ontology-based data access (OBDA)

Query



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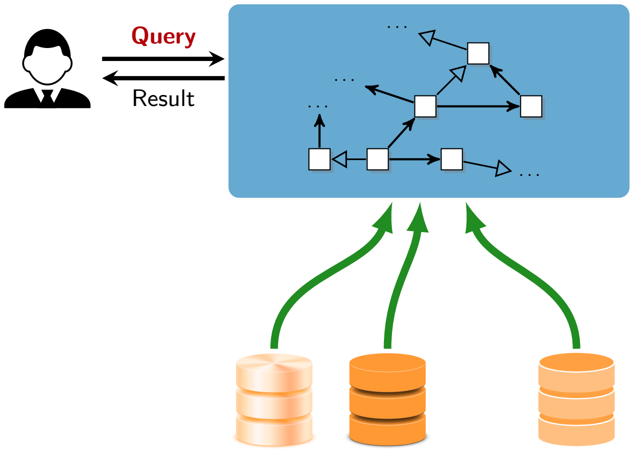

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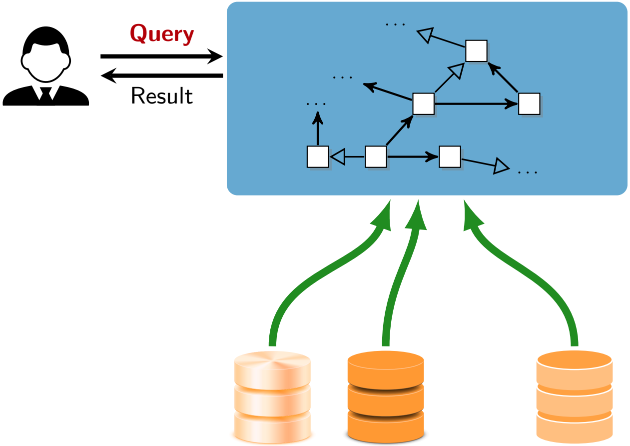

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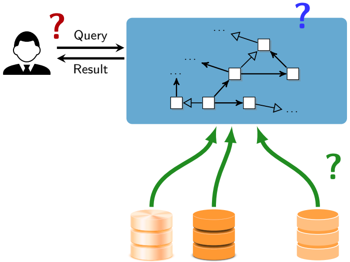
Reduces the time for translating information needs into queries from days to minutes.

OBDA framework – Which languages to use?

The choice of the right languages needs to take into account the tradeoff between expressive power and efficiency of query answering.



Note: We are in a setting where data plays a prominent role, so **efficiency with respect to the data** is the key factor.

The W3C has standardized languages that are suitable for OBDA:

1. Ontology $\mathcal{O}$: expressed in **OWL 2 QL** [W3C Rec. 2012]
2. Query: expressed in **SPARQL** [W3C Rec. 2013] (v1.1)
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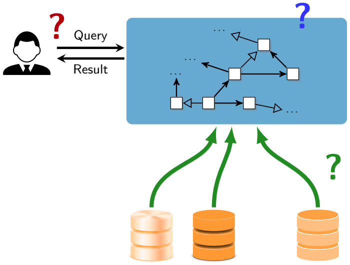

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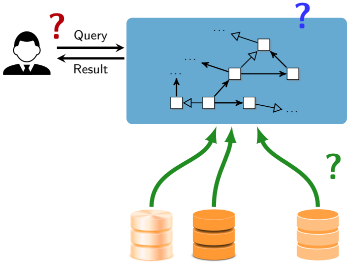

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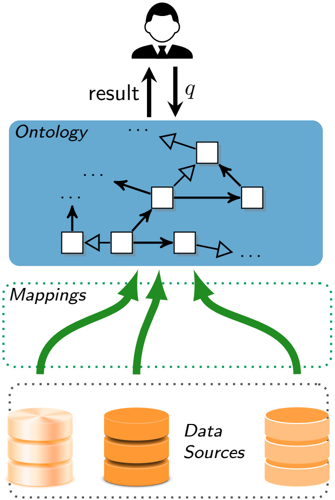
Query answering by query rewriting



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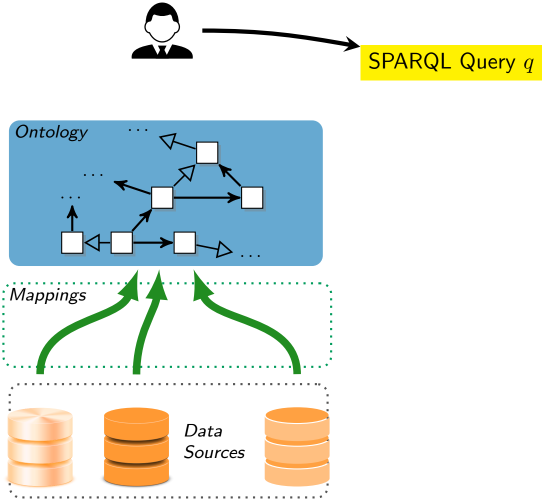

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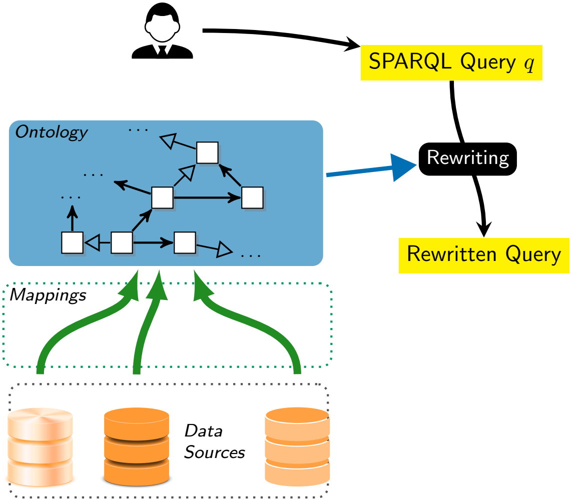

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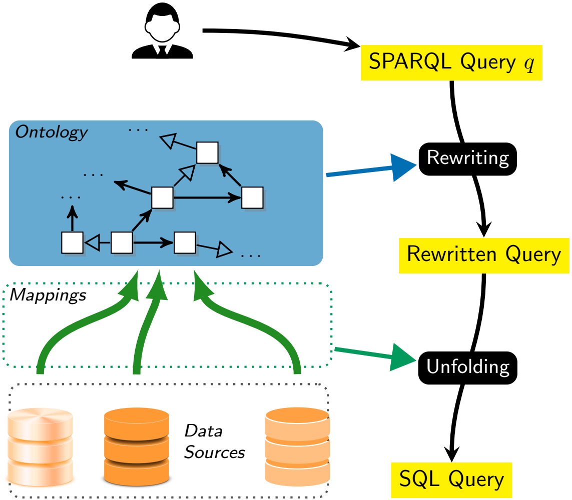

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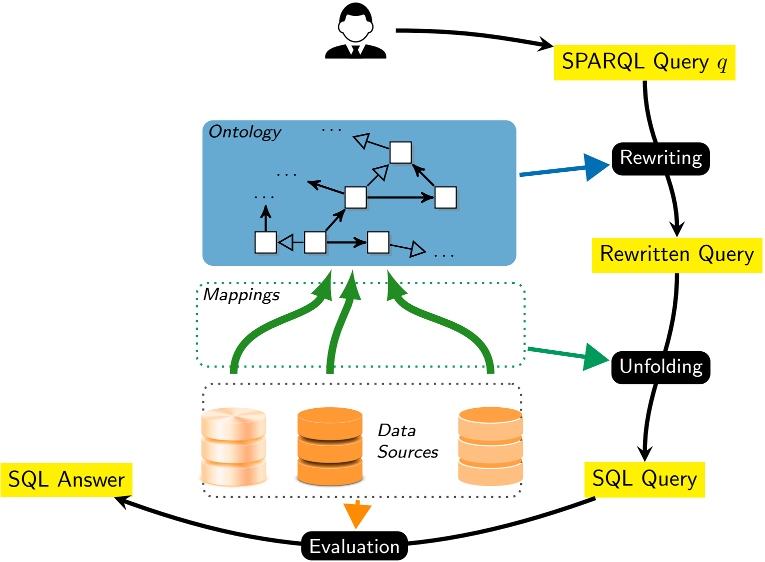

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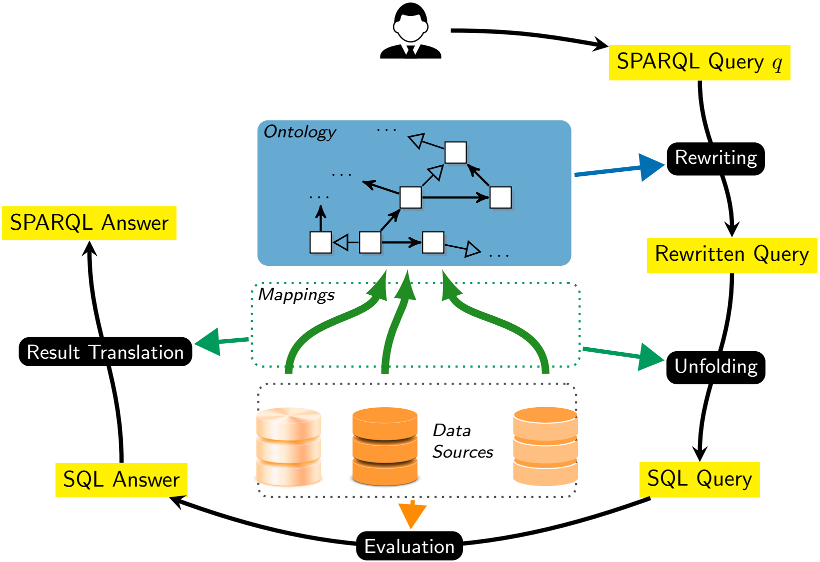

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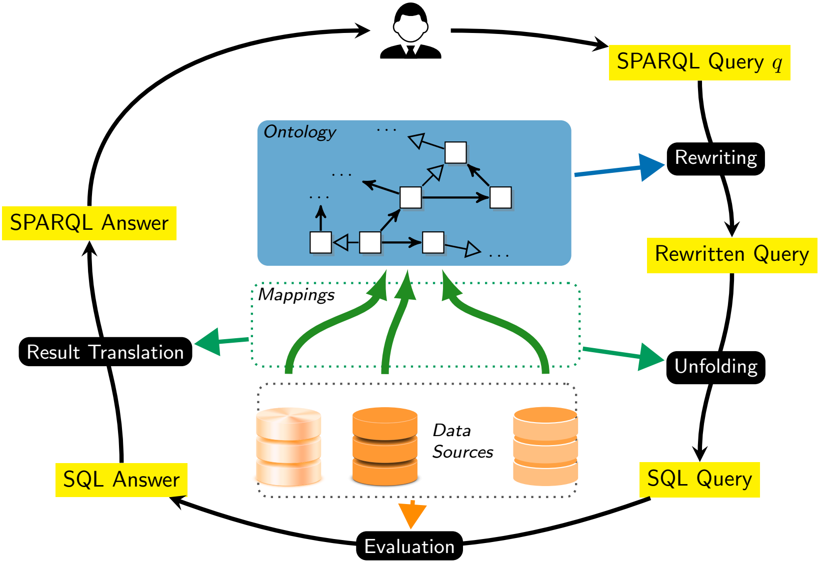
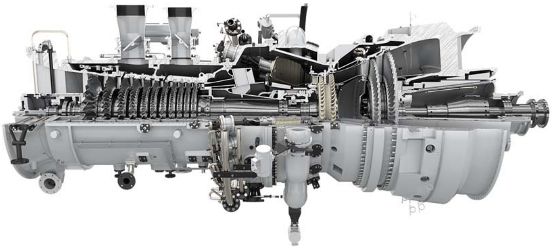


Outline

1. Motivation
2. Temporal OBDA Framework
3. Ontology Layer
4. Mapping Layer
5. Query Answering for Temporal OBDA
6. Summary and Future Work

Siemens Energy Services

- Monitor gas and steam turbines.
- Collect data from 50 remote diagnostic centers around the world.
- Centers linked to a common central DB.
- Turbines are highly complex, with 5 000–50 000 sensors each.
- Engineers compute KPIs, and extract data from maintenance reports using ETL tools.



Objective: retrospective diagnostics

i.e., detect abnormal or potentially dangerous events.

Events

- Involve a number of sensor measurements.
- Have a certain temporal duration.
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Example request

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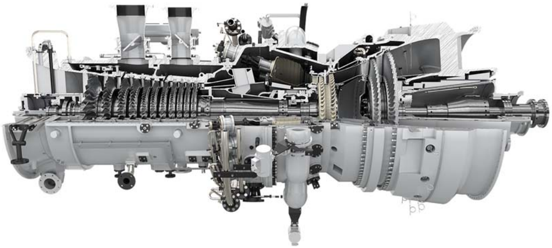

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To capture such a complex scenario . . .

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Approaches proposed in the literature:

1. Use standard ontologies and extend queries with temporal operators

[Gutiérrez-Basulto and Klarman 2012; Baader, Borgwardt, and Lippmann 2013; Klarman and Meyer 2014; Özçep and Möller 2014; Kharlamov et al. 2016]

However:

- Query language gets significantly more complicated.
- Effort is shifted from design time to query time.

2. Extend both query and ontology with linear temporal logic (LTL) operators

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We propose a different approach to temporal OBDA

- At the ontology level, we have both **static** and **temporal predicates**:
  - Static predicates to represent ordinary facts.
    E.g., Burner(b01), isMonitoredBy(b01, mf01)
  - Temporal predicates to represent temporal facts with a validity interval
    E.g., HighRotorSpeed(rs01)@[2017-06-06 12:22:50, 2017-06-06 12:23:40)

    We consider both open and closed intervals:
    $A(d)@(t_1, t_2)$, $A(d)@[t_1, t_2)$, $A(d)@(t_1, t_2]$, $A(d)@[t_1, t_2]$
- The ontology is expressed in OWL 2 QL $\rightsquigarrow$ First-order rewritability.
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Formal framework for temporal OBDA

A **traditional OBDA specification** is a triple $\mathcal{P} = \langle \mathcal{O}, \mathcal{M}, \mathcal{S} \rangle$

- $\mathcal{O}$ is an ontology.
- $\mathcal{M}$ is a set of mapping assertions between ontology and data sources.
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Temporal OBDA builds on traditional OBDA.

A **temporal OBDA specification** is a tuple $\mathcal{P}_t = \langle \Sigma_s, \Sigma_t, \mathcal{O}, \mathcal{R}_s, \mathcal{R}_t, \mathcal{M}_s, \mathcal{M}_t, \mathcal{S} \rangle$

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Static ontology – Example

We use an **ontology** to model the **static knowledge** about

- machines and their deployment profiles
- component hierarchies
- sensor configurations
- functional profiles

We still use **OWL 2 QL** as the static ontology language.

Devices consist of parts, and these are monitored by many different kinds of sensors (temperature, pressure, vibration etc.).

$$\begin{aligned}
\mathsf{GasTurbine} &\sqsubseteq \mathsf{Turbine} & \exists\mathsf{isDeployedIn} &\sqsubseteq \mathsf{Turbine}\\
\mathsf{SteamTurbine} &\sqsubseteq \mathsf{Turbine} & \exists\mathsf{isDeployedIn}^- &\sqsubseteq \mathsf{Train}\\
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Static rules

However, OWL 2 QL is not able to capture all the static knowledge required, e.g., in the Siemens use case.

We complement this ontology with **nonrecursive Datalog static rules**.

Example: turbine parts monitored by different co-located sensors (e.g., temperature, rotation speed)

$$\begin{aligned}\mathsf{ColocSensors}(tb, ts, rs) \leftarrow\ & \mathsf{Turbine}(tb),\ \mathsf{isPartOf}(pt, tb),\\ & \mathsf{isMonitoredBy}(pt, ts),\ \mathsf{TemperatureSensor}(ts),\\ & \mathsf{isMonitoredBy}(pt, rs),\ \mathsf{RotationSpeedSensor}(rs).\end{aligned}$$

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Temporal rules

Siemens is interested in detecting abnormal situations, and monitoring running tasks.

"Purging is Over" is a complex event of a turbine

We model this situation with metric temporal rules:

$$
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\mathsf{PurgingIsOver}(tb) \;\leftarrow\;& \boxminus_{[0s,10s]}\mathsf{MainFlameOn}(ts) \land \\
& \diamondminus_{(0,10m]}\big(\boxminus_{(0,30s]}\mathsf{HighRotorSpeed}(rs) \land \\
& \qquad \diamondminus_{(0,2m]}\boxminus_{(0,1m]}\mathsf{LowRotorSpeed}(rs)\big) \land \\
& \mathsf{ColocTempRotSensors}(tb, ts, rs).\\
\mathsf{HighRotorSpeed}(tb) \;\leftarrow\;& \mathsf{rotorSpeed}(tb, v) \land v > 1260.\\
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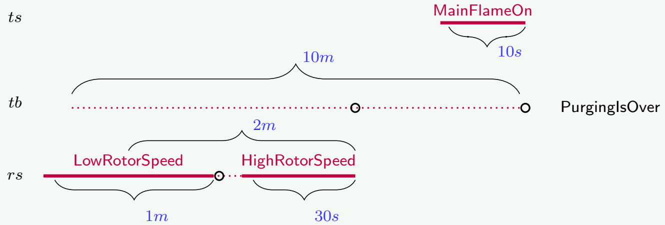

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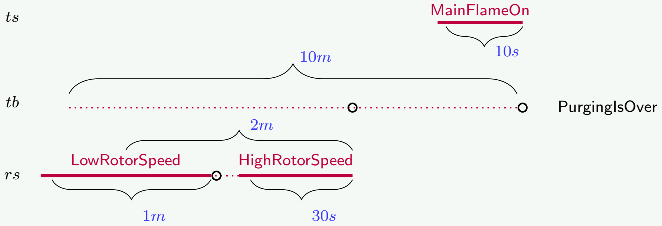

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We use *DatalogMTL*

DatalogMTL is a Horn fragment of Metric Temporal Logic (MTL).

A *DatalogMTL program* is a finite set of rules of the form

$$A^+ \leftarrow A_1 \land \cdots \land A_k \qquad \text{or} \qquad \bot \leftarrow A_1 \land \cdots \land A_k,$$

where

- each A_i is either $\tau \neq \tau'$, or defined by the grammar

$$A \ ::= \ P(\tau_1, \ldots, \tau_m) \ \mid \ \boxplus_\varrho A \ \mid \ \boxminus_\varrho A \ \mid \ \diamondplus_\varrho A \ \mid \ \diamondminus_\varrho A$$

  where ϱ denotes a (left/right open or closed) interval with non-negative endpoints,
- A^+ does not contain $\diamondplus_\varrho$ or $\diamondminus_\varrho$ (since this would lead to undecidability).

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Query evaluation in *DatalogMTL*

[Brandt, Kalayci, et al. 2017; Brandt, Güzel Kalayci, et al. 2018]

Theorem

Answering *DatalogMTL*queries is ExpSpace-complete in combined complexity.

We consider the **nonrecursive fragment** $Datalog_{nr}MTL$ of *DatalogMTL*:

- sufficient expressive power for many real-world situations
- computationally well-behaved

Answering $Datalog_{nr}MTL$ queries:

- Is PSpace-complete in combined complexity.
- Is in AC^0 in data complexity.
- Can be **reduced to SQL query evaluation**.

Hence, $Datalog_{nr}MTL$ is well suited as a temporal rule language for OBDA.

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Data sources: schema and data

Data sources often contain temporal information in the form of time-stamps.

Example data schema $\mathcal{S}$ for the Siemens data

It includes time-stamped sensor measurements and deployment details:

tb_measurement(timestamp, sensor_id, value),
tb_sensors(sensor_id, sensor_type, mnted_part, mnted_tb),
tb_components(turbine_id, component_id, component_type).

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A corresponding data instance $\mathcal{D}_0$:

tb_measurement

timestamp	*sensor_id*	*value*
2017-06-06 12:20:00	rs01	570
2017-06-06 12:22:50	rs01	1278
2017-06-06 12:23:40	rs01	1310
...	...	...
2017-06-06 12:32:30	mf01	2.3
2017-06-06 12:32:50	mf01	1.8
2017-06-06 12:33:40	mf01	0.9
...	...	...

tb_sensors

sensor_id	*sensor_type*	*mnted_part*	*mnted_tb*
rs01	0	pt01	tb01
mf01	1	b01	tb01
...	...	...	...

tb_components

turbine_id	*component_id*	*component_type*
tb01	pt01	0
tb01	b01	1
...	...	...

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...	...	...	...

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turbine_id	*component_id*	*component_type*
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...	...	...

Outline

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Static mapping assertions in $\mathcal{M}_s$

Static mapping assertions: $\Phi(\vec{x}) \rightsquigarrow \Psi(\vec{x})$

- $\Phi(\vec{x})$ is a query over the source schema $\mathcal{S}$
- $\Psi(\vec{x})$ is an atom with predicate in Σ_s

Example

```
SELECT sensor_id AS X FROM tb_sensors
WHERE sensor_type = 1                                ⇝ TemperatureSensor(X)

SELECT component_id AS X FROM tb_components
WHERE component_type = 1                             ⇝ Burner(X)

SELECT mnted_part AS X, sensor_id AS Y FROM tb_sensors ⇝ isMonitoredBy(X, Y)
```

These mappings retrieve from the database ordinary facts.

$$\mathsf{Burner}(\mathtt{b01}),\quad \mathsf{TemperatureSensor}(\mathtt{mf01}),$$
$$\mathsf{isMonitoredBy}(\mathtt{pt01},\mathtt{rs01}),\quad \mathsf{isMonitoredBy}(\mathtt{b01},\mathtt{mf01}).$$

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These mappings retrieve from the database ordinary facts.

Burner(b01), TemperatureSensor(mf01),
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Temporal mapping assertions in $\mathcal{M}_t$

Temporal mapping assertions: $\Phi(\vec{x}, \mathtt{begin}, \mathtt{end}) \rightsquigarrow \Psi(\vec{x})@\langle t_{\mathtt{begin}}, t_{\mathtt{end}}\rangle$

- begin and end are variables returning a date/time.
- '$\langle$' is either '(' or '[', and similarly for '$\rangle$'.
- $\Psi(\vec{x})$ is an atom with predicate in Σ_t.
- $t_{\mathtt{begin}}$ is either begin or a date-time constant, and similarly for $t_{\mathtt{end}}$.

Example

```
SELECT * FROM (
  SELECT sensor_id, value, timestamp AS begin,
         LEAD(timestamp,1) OVER W AS end
  FROM tb_measurement, tb_sensors
  WINDOW W AS (PARTITION BY sensor_id ORDER BY timestamp)
  WHERE tb_measurement.sensor_id = tb_sensors.sensor_id AND sensor_type = 0
) SUBQ WHERE value > 1260                    ⇝ HighRotorSpeed(sensor_id)@[begin,end)
```

These mappings retrieve from the database temporal facts.

$$\mathsf{HighRotorSpeed}(\mathtt{rs01})@[\mathtt{2017\text{-}06\text{-}06\ 12:22:50}, \mathtt{2017\text{-}06\text{-}06\ 12:23:40})$$

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SELECT * FROM (
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```

$\rightsquigarrow$ HighRotorSpeed(sensor_id)@[begin,end)

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HighRotorSpeed(rs01)@[2017-06-06 12:22:50, 2017-06-06 12:23:40)

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```
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Outline

Concrete syntax for temporal OBDA specifications

Temporal OBDA specification $\mathcal{P}_t = \langle \Sigma_s, \Sigma_t, \mathcal{O}, \mathcal{R}_s, \mathcal{R}_t, \mathcal{M}_s, \mathcal{M}_t, \mathcal{S} \rangle$

- Σ_s is a static vocabulary,
- Σ_t is a temporal vocabulary,
- $\mathcal{O}$ is an ontology,
- $\mathcal{R}_s$ is a set of static rules,
- $\mathcal{R}_t$ is a set of temporal rules,
- $\mathcal{M}_s$ is a set of static mapping assertions,
- $\mathcal{M}_t$ is a set of temporal mapping assertions,
- $\mathcal{S}$ is a database schema.

Component	defines predicates in	in terms of predicates in	Adopted language
$\mathcal{O}$	Σ_s	Σ_s	OWL 2 QL
$\mathcal{R}_s$	Σ_s	Σ_s	non-recursive Datalog
$\mathcal{R}_t$	Σ_t	$\Sigma_s \cup \Sigma_t$	$Datalog_{nr}MTL$
$\mathcal{M}_s$	Σ_s	$\mathcal{S}$	R2RML / Ontop
$\mathcal{M}_t$	Σ_t	$\mathcal{S}$	R2RML / Ontop

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Ontop mapping syntax

```
[PrefixDeclaration]
st:      http://siemens.com/temporal/ns#
xsd:     http://www.w3.org/2001/XMLSchema#
obda:    https://w3id.org/obda/vocabulary#

[MappingDeclaration] @collection [[
mappingId mappingRSA1260
target    st:HighRotorSpeed/{sensor_id} obda:hasStatus
            st:HighRotorSpeed.
interval  [ {begin}^^xsd:dateTimeStamp, {end}^^xsd:dateTimeStamp )
source
  SELECT sensor_id, begin, end FROM (
    SELECT sensor_id, value, timestamp AS begin,
           LEAD(timestamp, 1) OVER W AS end
    FROM MEASUREMENT
    WINDOW W AS (PARTITION BY sensor_id ORDER BY timestamp)) SUBQ
  WHERE value > 1260
]]
```

Temporal OBDA instance

A **temporal OBDA instance** is a pair $\mathcal{J} = \langle \mathcal{P}_t, \mathcal{D} \rangle$

- $\mathcal{P}_t$ is a temporal OBDA specification,
- $\mathcal{D}$ is a database instance compliant with the database schema $\mathcal{S}$ in $\mathcal{P}_t$.

To represent the facts generated by $\mathcal{J}$, we use **RDF Datasets**.

(We follow the model proposed by the W3C RSP Community Group.)

The temporal fact $\quad \mathsf{HighRotorSpeed}(\mathtt{rs01})@[\mathtt{2017\text{-}06\text{-}06\ 12{:}22{:}50}, \mathtt{2017\text{-}06\text{-}06\ 12{:}23{:}40})$

is modeled as the **named graph** $\quad \mathsf{GRAPH}\ g_0\ \{(\mathtt{rs01}, \mathsf{a}, \mathtt{HighRotorSpeed})\}$

and a set of triples in the default graph, to model the time interval:

$$
\begin{array}{l}
(g_0, \mathsf{a}, \mathtt{time{:}Interval}),\\
(g_0, \mathtt{time{:}isBeginningInclusive}, \mathtt{true}),\ (g_0, \mathtt{time{:}isEndInclusive}, \mathtt{false}),\\
(g_0, \mathtt{time{:}hasBeginning}, b_0),\ (g_0, \mathtt{time{:}hasEnd}, e_0),\\
(b_0, \mathtt{time{:}inXSDDateTimeStamp}, \text{`}\mathtt{2017\text{-}06\text{-}06\ 12{:}22{:}50}\text{'}),\\
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Query answering

Example query

"Find the gas turbines deployed in the train with the ID T001 and the time periods of their accomplished purgings".

This corresponds to the query: $Q(tb)@\iota$, where $Q(tb)$ is defined as

$$\begin{aligned} \mathsf{Q}(tb) \leftarrow\ & \mathsf{Train}(\mathtt{T001}),\ \mathsf{GasTurbine}(tb),\\ & \mathsf{isDeployedIn}(tb, \mathtt{T001}),\ \mathsf{PurgingIsOver}(tb). \end{aligned}$$

In "temporal" SPARQL syntax:

```
PREFIX ss: <http://siemens.com/ns#>
PREFIX st: <http://siemens.com/temporal/ns#>

SELECT ?tb ?left_edge ?begin ?end ?right_edge
WHERE {
  ?tb a ss:GasTurbine ;
      ss:isDeployedIn ss:train_T001 .
  {?tb a st:PurgingIsOver}@<?left_edge,?begin,?end,?right_edge>
}
```

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Equivalent standard SPARQL query

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}
```

... is translated into the following standard SPARQL query:

```
PREFIX time: <http://www.w3.org/2006/time#>
...
SELECT ?tb ?left_edge ?begin ?end ?right_edge
WHERE {
  ?tb a ss:GasTurbine ;  ss:isDeployedIn ss:train_T001 .
  GRAPH ?g { ?tb a st:PurgingIsOver . }
  ?g a time:Interval ;
     time:isBeginningInclusive ?left_edge ;
     time:hasBeginning [ time:inXSDDateTimeStamp ?begin ] ;
     time:hasEnd [ time:inXSDDateTimeStamp ?end ] ;
     time:isEndInclusive ?right_edge .
}
```

Equivalent standard SPARQL query

```
PREFIX ss: <http://siemens.com/ns#>
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}
```

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The Ontop-temporal system

We have implemented the temporal OBDA framework in the **Ontop-temporal** system [Güzel Kalayci et al. 2018], as an extension of *Ontop*.

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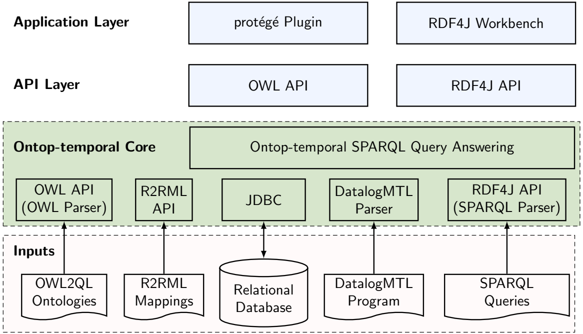

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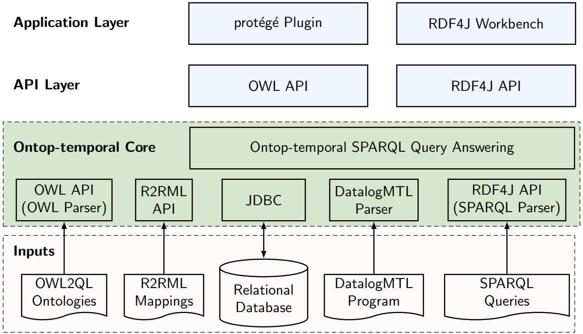

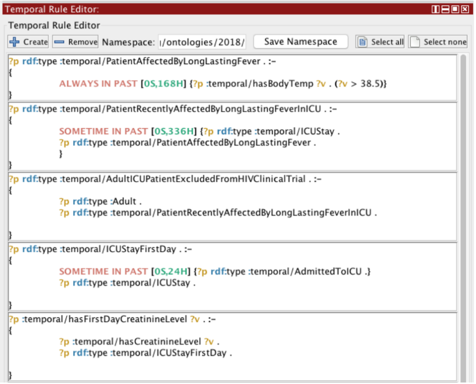

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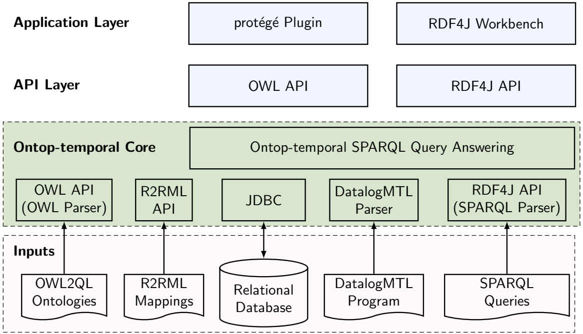
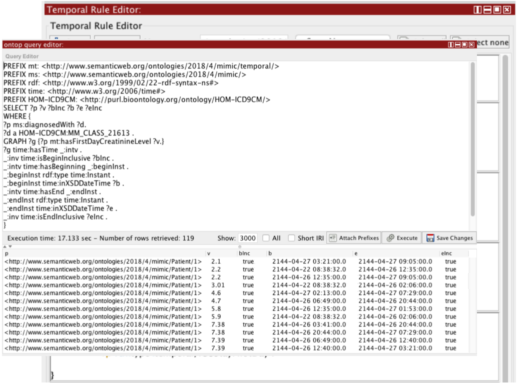


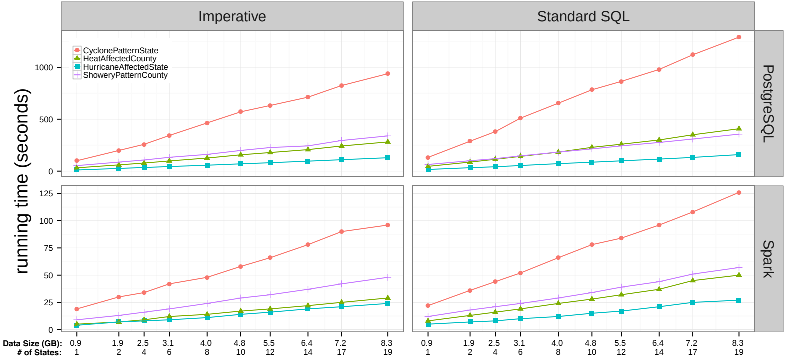


Evaluation [Brandt, Güzel Kalayci, et al. 2018; Güzel Kalayci et al. 2018]

Done on three real-world use cases from different domains: MesoWest, MIMIC-III, and Siemens.

Evaluation with respect to two aspects:

- **utility evaluation** over MIMIC-III, MesoWest, and Siemens use-cases
- **scalability evaluation** over MesoWest and Siemens use-cases



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Outline

Summary and future work

Contributions

- A novel **temporal OBDA framework**.
- A **temporal rule language** for modeling complex temporal events.
- Implementation of the framework in the **Ontop-temporal** system.
- Extensive **evaluation** of the system over real-world data from different domains.

Future work

- Extension of temporal OBDA with temporal aggregates.
- Support for streaming data.
- Optimization and support for parallel processing

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Thanks

Thank you for your attention!

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- Elem Güzel Kalayci (unibz)
- Roman Kontchakov (Birkbeck)
- Vladislav Ryzhikov (unibz, Birkbeck)
- Guohui Xiao (unibz)
- Michael Zakharyaschev (Birkbeck)

OBDA framework developed in Bolzano

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