Knowledge Representation and Information Systems

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Dagstuhl Perspectives Workshop 22282 on
Current and Future Challenges in Knowledge Representation and Reasoning

11–15 July 2022 – Dagstuhl, Germany

Information systems

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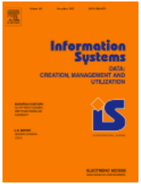
An **information system** can be defined as an integration of components for collection, storage and **processing of data** of which the **data** is used to provide information, contribute to **knowledge** as well as digital products that facilitate **decision making**.

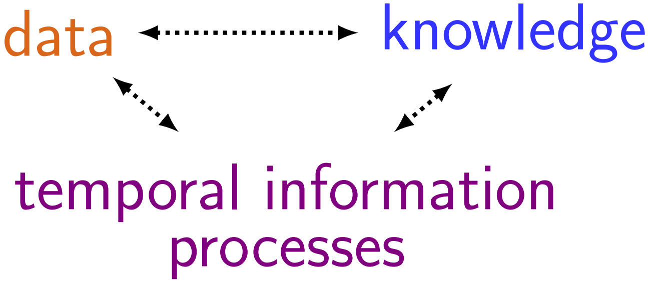


Information Systems
DATA: CREATION, MANAGEMENT AND UTILIZATION

Information systems are the software and hardware systems that support **data-intensive** applications. The journal Information Systems publishes articles concerning the design and implementation of languages, **data models**, **process models**, algorithms, software and hardware for information systems.

Dealing with information systems

This requires to deal at the same time with



KR has contributed to the requirements of **modeling** these three components, and **inferring** relevant properties about them.

Outline

1. Information systems
2. Processes and data
3. Capturing structural aspects through description logics
4. Capturing dynamic aspects
5. Conclusions

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Processes and data

They constitute the information assets of an organization:

- **data**: determine the information of interest
- **processes**: determine how data change and evolve over time

Conceptual Modeling

Both aspects can be modelled at the conceptual level, but traditionally this has been done:

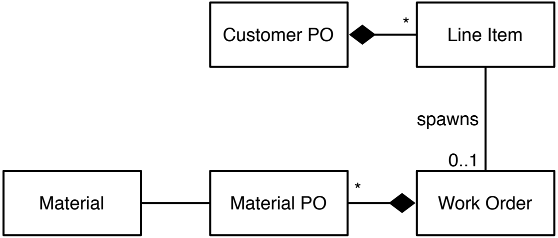
- using different modeling tools,
- by different teams with different competences, and
- their connection is NOT modelled conceptually, but it should!

Consequence

Automated inference (e.g., for verification) combining both processes and data, is not possible!

Conventional data modeling

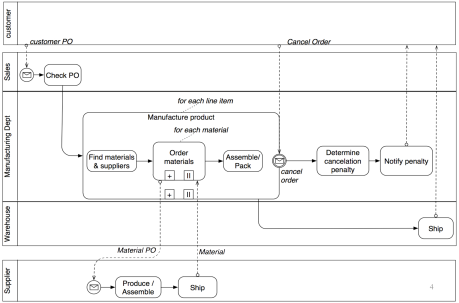
- Produce a structural model of the domain of interest
- Focus: entities, relations, and static constraints that are relevant for the domain of interest.
- Formalisms: UML, ER, ORM, . . .
- Result: conceptual model of a database schema



But how do data evolve?

Conventional process modeling

- Produce a model of the dynamics of the domain of interest
- Focus: control flow of activities realizing the business objectives
- Formalisms: BPMN, UML AD, ...
- Result: executable process model



But how are data manipulated?

Consequences of the dichotomy

Survey by Forrester: Which of the two aspects should be given priority from the point of view of IT management? [Karel et al. 2009]:

- Business process management professionals: view data as subsidiary to processes manipulating them, and neglect importance of data quality.
- Data management experts: consider data as the driver of the organizational processes and are concerned about data quality only.

Dichotomy in the relative perception of importance **has a negative impact**:

- Little collaboration between the teams
  - running the master data management initiatives, and
  - managing the business processes.

  Forrester: 83% … no interaction at all
- Little attention on the side of tool vendors to address the combined requirements:
  - Data management tools consider only the processes directly affecting the data in the tools, but not the actual business processes using the data,
  - Business process modeling suites do not allow for direct connection of data.

However, data and processes are tightly coupled together!

Overcoming the dichotomy – The role of KR

Strong need for:

- Suitable modeling formalisms supporting the **integrated management** of processes and data **at the conceptual level**.
- A clear understanding of semantic and **computational properties** of such formalisms, so as to enable their **analysis**.

KR to the rescue

Traditionally, KR has studied different types of formalisms / logics that are able to capture both structural aspects and dynamic aspects of a domain of interest.

Outline

Description Logics

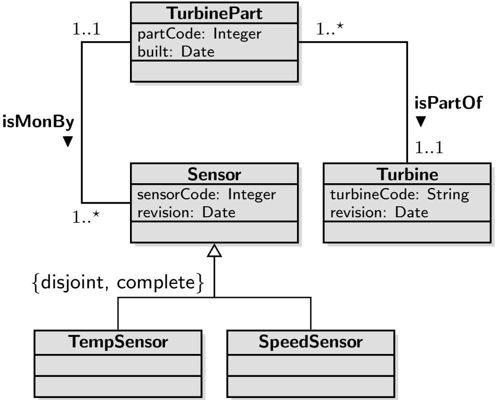
- **Description Logics (DLs)** stem from early days (1970') KR formalisms, and assumed their current form in the late 1980's & 1990's.
- Are logics specifically designed to represent and reason on **structured knowledge**.
- Technically they can be considered as well-behaved (i.e., decidable) **fragments of first-order logic**.
- Semantics given in terms of first-order interpretations.
- Come in hundreds of variations, with different semantic and computational properties.
- Provide the formal foundations for the W3C standard **Web Ontology Language** OWL.

DLs vs. conceptual modeling formalisms

There is a close correspondence between DL constructs and the typical constructs used in conceptual modeling formalisms (such as UML class diagrams, ER schemas, ORM):

Modeling construct	DL axiom	FOL formalization
ISA on classes	$A_1 \sqsubseteq A_2$	$\forall x(A_1(x) \rightarrow A_2(x))$
. . . and on relations	$R_1 \sqsubseteq R_2$	$\forall x, y(R_1(x, y) \rightarrow R_2(x, y))$
Disjointness of classes	$A_1 \sqsubseteq \neg A_2$	$\forall x(A_1(x) \rightarrow \neg A_2(x))$
. . . and of relations	$R_1 \sqsubseteq \neg R_2$	$\forall x, y(R_1(x, y) \rightarrow \neg R_2(x, y))$
Domain of relations	$\exists P \sqsubseteq A_1$	$\forall x(\exists y(P(x, y)) \rightarrow A_1(x))$
Range of relations	$\exists P^- \sqsubseteq A_2$	$\forall x(\exists y(P(y, x)) \rightarrow A_2(x))$
Mandatory participation *(min card = 1)*	$A_1 \sqsubseteq \exists P$ $A_2 \sqsubseteq \exists P^-$	$\forall x(A_1(x) \rightarrow \exists y(P(x, y)))$ $\forall x(A_2(x) \rightarrow \exists y(P(y, x)))$
Functionality of relations *(max card = 1)*	$A_1 \sqsubseteq \leq 1\, P$ $A_2 \sqsubseteq \leq 1\, P^-$	$\forall x, y, y'(A_1(x) \wedge P(x, y) \wedge P(x, y') \rightarrow y = y')$ $\forall x, x', y(A_2(y) \wedge P(x, y) \wedge P(x', y) \rightarrow x = x')$
. . .	. . .	. . .

DLs capture UML class diagrams



$$\begin{array}{rcl}
\mathsf{TempSensor} & \sqsubseteq & \mathsf{Sensor} \\
\mathsf{SpeedSensor} & \sqsubseteq & \mathsf{Sensor} \\
\mathsf{TempSensor} & \sqsubseteq & \neg \mathsf{SpeedSensor} \\
\mathsf{Sensor} & \sqsubseteq & \mathsf{TempSensor} \sqcup \mathsf{SpeedSensor} \\
\mathsf{Turbine} & \sqsubseteq & \forall \mathsf{turbineCode}.\mathsf{String} \sqcap \\
 & & \exists \mathsf{turbineCode} \sqcap \leq 1\, \mathsf{turbineCode} \\
\exists \mathsf{isMonBy} & \sqsubseteq & \mathsf{TurbinePart} \\
\exists \mathsf{isMonBy}^- & \sqsubseteq & \mathsf{Sensor} \\
\mathsf{TurbinePart} & \sqsubseteq & \exists \mathsf{isMonBy} \\
\mathsf{Sensor} & \sqsubseteq & \exists \mathsf{isMonBy}^- \\
\exists \mathsf{isPartOf} & \sqsubseteq & \mathsf{TurbinePart} \\
\exists \mathsf{isPartOf}^- & \sqsubseteq & \mathsf{Turbine}
\end{array}$$

$$(\mathbf{funct}\ \mathsf{isMonBy}^-)$$
$$(\mathbf{funct}\ \mathsf{isPartOf})$$
$$\ldots$$

DLs for conceptual modeling

DLs have been used to formalize different variants of conceptual modeling formalisms, and to provide automated reasoning in such formalisms (see also [Borgida & Brachman 2003]).

- ER schemas with cardinality constraints (but no hierarchies) [Lenzerini & Nobili 1990]
- Acyclic ER schemas with hierarchies [Bergamaschi & Sartori 1992]
- Arbitrary (possibly cyclic) ER schemas with hierarchies [C., Lenzerini, et al. 1994, 1999]
- UML Class Diagrams [Berardi et al. 2005], with OCL constraints [Queralt et al. 2012]
- ORM [Franconi, Mosca, et al. 2012; Fillottrani, Keet, et al. 2015; Sportelli & Franconi 2016]

In this way, DL reasoning can be used to provide support for various conceptual modeling activities.

While most of the work has been theoretical, also some prototype systems that provide reasoning support for conceptual modeling have been developed:

- ICOM conceptual modeling tool [Franconi & Ng 2000; Fillottrani, Franconi, et al. 2006, 2012]

Capturing distributed and contextualized knowledge

- Interschema knowledge, distinguishing *intensional* from *extensional* interschema assertions [Catarci & Lenzerini 1993]
- Distributed DLs [Borgida & Serafini 2003; Serafini, Borgida, et al. 2005; Homola & Serafini 2010]
- Contextualized knowledge-bases [Serafini & Homola 2012], with bridge rules [Joseph et al. 2016]
- Contextualized Knowledge Repository (CKR) framework with global and local contexts [Bozzato, Serafini, et al. 2017; Bozzato, Eiter, et al. 2018]

Beyond conceptual modeling – Ontology-mediated query answering

Compute the **certain answers** to a (database like) query over (incomplete) data in the presence of ontology axioms.

Since late 1990's, hundreds of results for variants of ontology-mediated query answering:

- Ontology language: lightweight DLs (*DL-Lite*-family, $\mathcal{EL}$-family), Horn-DLs, very expressive DLs (OWL 2), Guarded TGDs, . . .
- Query language: ontology language itself (instance checking/retrieval), conjunctive queries, positive queries, variants of (conjunctive) regular path queries, queries with counting, . . .
- Variations: uniform and non-uniform variants of the problem, closed vs. open predicates, finite vs. unrestricted models, . . .

For an early overview of various data management tasks accomplished through DLs, see also [Borgida 1995].

Sample of complexity results for conjunctive query answering in DLs

	Combined complexity	**Data complexity**
Plain databases	NP-complete	in AC^0 (1)
DL-Lite family	NP-complete (2)	in AC^0 (2)
$\mathcal{EL}$, $\mathcal{ELH}$	NP-complete (3)	PTIME-complete (3)
$\mathcal{ALCI}$, $\mathcal{SH}$, $\mathcal{SHIQ}$, ...	2EXPTIME-complete (4)	coNP-complete (5)
OWL 2 (and even less)	3EXPTIME-hard	coNP-hard

(1) This is what we need to scale with the data.

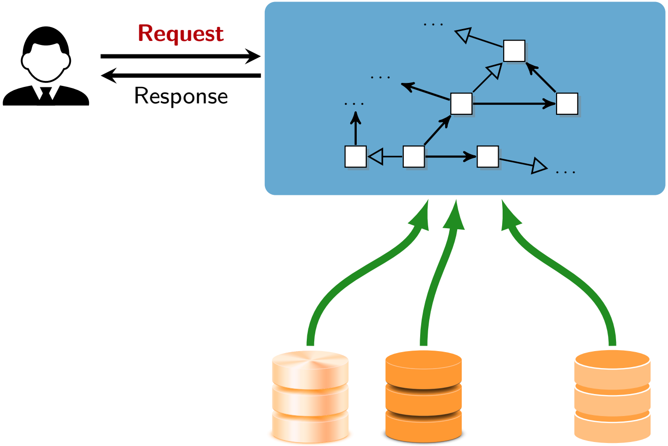
(2) [C., De Giacomo, Lembo, Lenzerini, et al. 2007, 2013; Artale, C., et al. 2009].

(3) [Krisnadhi & Lutz 2007; Rosati 2007]. Becomes undecidable for $\mathcal{EL}^+$

(4) Hardness by [Lutz 2008; Eiter, Lutz, et al. 2009].
Tight upper bounds obtained for a variety of expressive DLs [Lutz 2008; C., De Giacomo & Lenzerini 1998; Levy & Rousset 1998; C., Eiter, et al. 2007; C., De Giacomo & Lenzerini 2008; Glimm, Horrocks & Sattler 2008; Glimm, Lutz, et al. 2008; Eiter, Gottlob, et al. 2008; C., Eiter, et al. 2014].

(5) coNP-hard already for a TBox with a single disjunction [C., De Giacomo, Lembo, Lenzerini, et al. 2013
In coNP for very expressive DLs [Levy & Rousset 1998; M. M. Ortiz et al. 2006; Glimm, Horrocks, Lutz

Ontology-based data management



Request

Response

Ontology $\mathcal{O}$

conceptual view of data,
convenient vocabulary

Mapping $\mathcal{M}$

how to populate
the ontology
from the data

Data Sources $\mathcal{S}$

autonomous and
heterogeneous

Simplifies the access to information, and allows one to abstract away the precise structure of data sources.

Topics in ontology-based data management (OBDM) [Lenzerini 2011]

- Ontology-based data access (or query answering) (OBDA)
- Ontology-based data integration (OBDI)
- Ontology-based data quality (OBDQ)
- Ontology-based data governance (OBDG)
- Ontology-based data restructuring (OBDR)
- Ontology-based business intelligence (OBBI)
- Ontology-based data exchange and coordination (OBDE)
- Ontology-based data update (OBDU)
- Ontology-based service and process management (OBSP)
- Ontology-based open data publishing (OBOD)

. . . under the general requirement

- of being able to deal with large data collections
- while staying efficient with respect to the size of data (data complexity).

Ontology-based data access and integration (OBDA/I) [Poggi et al. 2008]

- OBDA and OBDI are the most well investigated tasks within OBDM.
- Rely on lightweight ontology languages with AC^0 data complexity (*DL-Lite* family)
- Theoretical foundations are well understood.
- Practical systems have been developed and are deployed in industrial settings.
- For the integration layer, one possibility is to rely on commercial data federation technology (e.g., Denodo, Dremio, Teiid).

Outline

DLs and processes

Work in DLs has mainly been concerned with studying static/structural aspects.

However, it is also essential to capture the dynamic aspects of Information Systems

- This requires a **high-level descriptions of computations** abstracting from the technological issues of the actual programs that realize them.
- **Dynamic aspects** to deal with: action effects, change, knowledge evolution, . . .

Combining data and processes

- Is critical to correctly and "completely" capture Information Systems.
- Many attempts both in the Semantic Web community (e.g., OWL-S, SWSO, . . .) and in DLs.
- But the combination has resisted automated reasoning . . . for good reasons.

(A partial) history of DLs and processes

- Early 1990s: Starting point
  - [Baader 1991]: Extends $\mathcal{ALC}$ with regular expressions on roles ($\mathcal{ALC}_{reg}$)
  - [Schild 1991]: DLs ↔ PDLs/Modal Logic: $\mathcal{ALC}_{reg} =$ PDL
- Mid 1990s: High hopes
  - [Schild 1993]: DLs + temporal logics (for processes – point based)
  - [De Giacomo & Lenzerini 1994a; Schild 1994]: DLs ↔ μ-calculus
  - [De Giacomo & Lenzerini 1994a,b, 1995a, 1996; C., De Giacomo & Lenzerini 1995]: DLs as rich modal logics, ExpTime-complete
  - [De Giacomo & Lenzerini 1995b]: Use knowledge in DLs to capture Reiter's Propositional Situation Calculus
- End of 1990: Everything collapses
  - [Baader & Laux 1995]: DLs+modal logics = Multi-Dimensional Modal Logics
  - [Baader & Ohlbach 1995] Multi-dimensional description logics
  - [Wolter & Zakharyaschev 1998, 1999a,b,c; Gabbay et al. 2003]: Multi-Dimensional Modal Logics are computationally nasty

Satisfiability of a KB where a role extension persists is undecidable!

Deep undecidability of DLs + Actions Theory

Result [C., De Giacomo & Soutchanski 2015]

DLs + Action theories are undecidable even in the simplest cases.

Some attempts to regain decidability:

- Allow changes only of concepts (not roles)
  e.g., [Gabbay et al. 2003; Artale & Franconi 1999; Gutiérrez-Basulto et al. 2012; Jamroga 2012]
- Drop TBox (or make it acyclic)
  e.g., [Baader, Lutz, et al. 2005; Gu & Soutchanski 2007]
- Drop persistence of TBox (ontology is not maintained by actions)
  e.g., [Gu & Soutchanski 2010]

However, these restrictions are too strong and unsuitable for conceptual models of data and processes in Information Systems!

Alternative combinations of DLs with temporal information

- Integration of DLs with action formalisms, relying on acyclic TBox and conditional actions [Milicic 2008] (and different co-authors)
  - Decidability and complexity of projection and executability for DLs from $\mathcal{ALC}$ to $\mathcal{ALCQIO}$
- Combining LTL and DLs
  - We are in a case of logics with a two-dimensional semantics (objects and time)
  - The problem has different **dimensions**:
    - temporal operators applied to concept expressions and/or TBox axioms and/or ABox assertions;
    - no rigid symbols vs. rigid concepts and/or rigid roles

Combining LTL and DLs

Already many results on the combinations of DLs and LTL:

- Rich settings, combining (extensions of) $\mathcal{ALC}$ with LTL, with rigid concepts, but no rigid roles:
  - temporal operators on concepts only: satisfiability is ExpTime-complete [Schild 1993]
  - temporal operators on concept expressions and (TBox + ABox) axioms: satisfiability is ExpSpace-complete [Wolter & Zakharyaschev 1999a; Gabbay et al. 2003].

  Satisfiability becomes undecidable with rigid roles [Gabbay et al. 2003].
- With rigid roles, decidability can be obtained by strongly restricting:
  - the temporal component (S5, instead of LTL) [Artale, Lutz, et al. 2007], or
  - the DL component (*DL-Lite*, instead of $\mathcal{ALC}$) [Artale, Kontchakov, et al. 2007]
- LTL over $\mathcal{ALC}$ axioms
  - Temporal operators only on (TBox + ABox) axioms, but not on concept constructors
  - Satisfiability is from ExpTime-complete (without rigid symbols) to 2ExpTime-complete (with rigid symbols) [Baader, Ghilardi, et al. 2012]
  - Tight complexity bounds also for runtime verification (i.e., check whether all traces of a transition system satisfy a given formula) [Baader & Lippmann 2014]

Adopting Levesque's functional approach

Assume a **functional view of ontologies** [Levesque 1984]

View KB as a system that allows for two kinds of operations:

- $\textsc{ask}(q, \mathcal{K})$, which returns the answers to a query q that are logically implied by the KB $\mathcal{K}$
- $\textsc{tell}(a, \mathcal{K})$, which produces a new KB $\mathcal{K}'$ as a result applying an action a to the KB $\mathcal{K}$

- **Advantage:** strong decoupling of reasoning on the static knowledge from reasoning on the dynamics $\rightsquigarrow$ We can lift to DLs results developed in Reasoning about Actions, Process Modeling, and Verification
- **Disadvantage:** no single theory for representing and reasoning on actions over ontologies

Decidability of verification

Decidability of verification of variants of μ-calculus and LTL under suitable restrictions of state-boundedness for the evolving system.

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Ontology-based data management (OBDM) [Lenzerini 2011]

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Semantically-Governed Information Systems (SGISs)

The data layer in a dynamic system constituted of evolving data elements (artifacts) might be very complex, and difficult to interact with.

Hence we can resort to ontology-based technology and ontology-based data access techniques to support users:

- We install "on top" of an information system an ontology, capturing the domain of interest at a higher level of abstraction.
- We connect the ontology to the underlying system via declarative mappings.

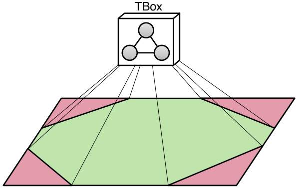
Such a setting gives rise to a very rich and still largely unexplored framework, in which we have various choices for:

- the language used to express the ontology;
- the form of the mappings, and the language used to express them;
- the assumptions we make about the dynamics of the system;
- the kind of analysis tasks we want to perform.

Some initial results were reported in [C., De Giacomo, Lembo, Montali, et al. 2012].

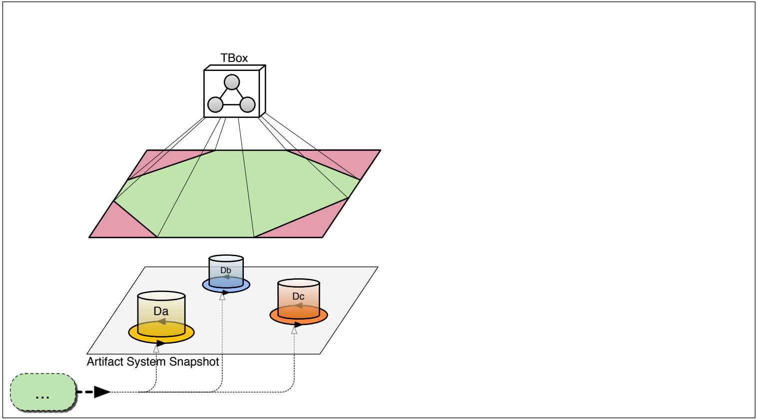
Semantically-Governed Information Systems (SGISs)

The system's conceptual schema (TBox) is composed of semantic constraints that define the "data boundaries" of the underlying information system.



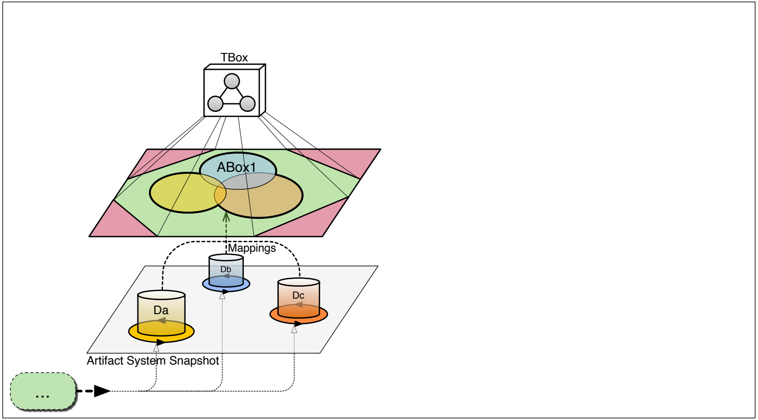
Semantic layer and snapshots

Actual data are concretely maintained by the information system.
Snapshot: database instances of the involved artifacts.



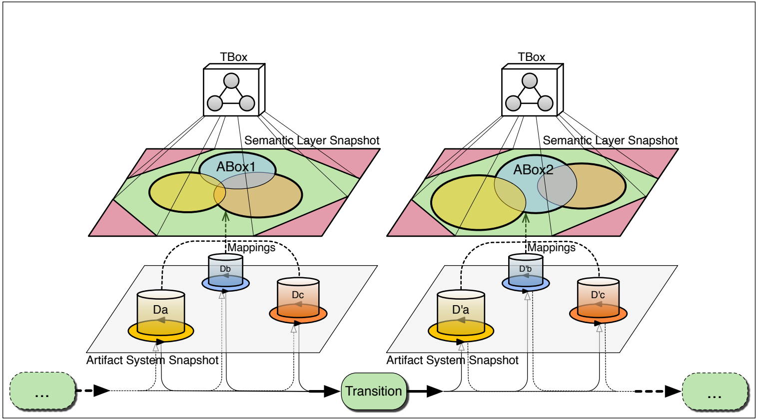
Mappings

Each snapshot is conceptualized in the ontology as instance data.
Mappings define how to obtain a virtual ABox from the source data.



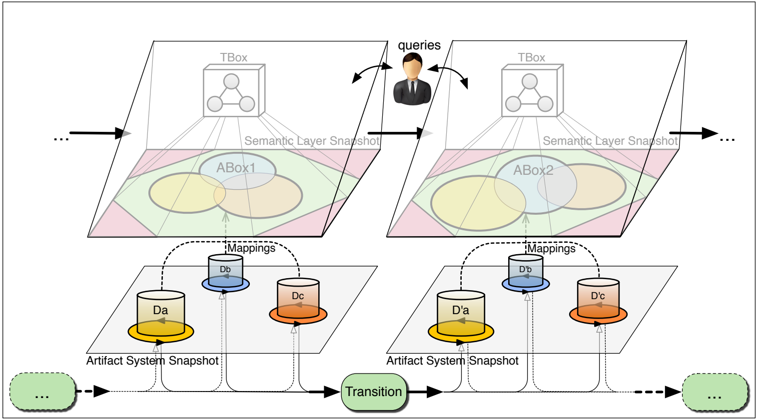
Action execution to evolve the system

The system evolves due to actions/process executed over the artifact layer, possibly invoking external services to inject new data.



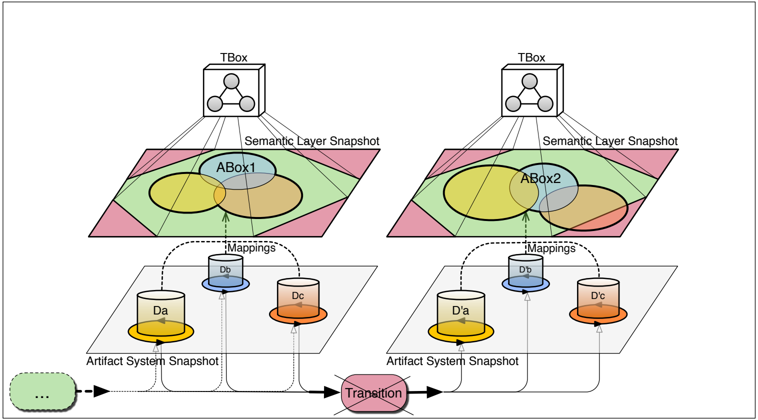
Understanding the evolution

Semantic layer used to **understand** the evolution at the conceptual level, by posing queries over the ontology.



Semantic governance

Semantic layer used to regulate the execution of actions at the artifact layer by **rejecting actions that lead to violations of constraints** in the ontology.



Temporal verification over semantic layer

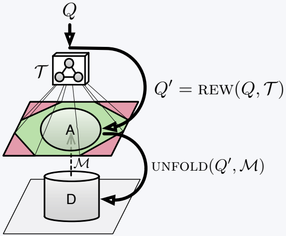
Temporal properties expressed as:

- queries over the ontology combined with
- temporal operators to talk about the dynamics of the system.

System evolves at the Information System level.

Rewriting of temporal properties

- The temporal part is maintained unaltered, because the system evolves at the level of the Information System.
- Faithful transformation of a temporal property over Semantic Layer:
  - ① **Rewriting** of ontology queries to compile away the TBox.
  - ② **Unfolding** of temporal property wrt mappings to obtain a corresponding temporal property over the underlying data.



Hence, verification of temporal properties expressed over the ontology is reduced to verification over the underlying evolving data.

Conclusions – Managing SGISs

- We obtain that the verification of (restricted first-order) temporal properties is decidable, provided the transition system of the underlying Information System satisfies suitable boundedness conditions.
- In principle, we would like to carry out all OBDM tasks by operating directly over the ontology, abstracting away the underlying Information System.
- This poses several challenges that are currently not well understood, but for which we can build on results and proposals coming from KR:
  - view-update problem
  - privacy
  - personalization and contextualization
  - security
  - dealing with inconsistency

Thank you for your attention!

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