Data Repair of Inconsistent DL-Programs

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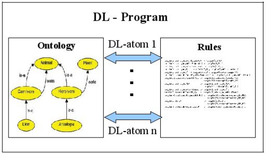
Motivation

- DL-program: ontology + rules (loose coupling combination approach);
- DL-atoms serve as query interfaces to ontology;
- Possibility to add information from the rule part to ontology prior to querying it allows for bidirectional information flow.



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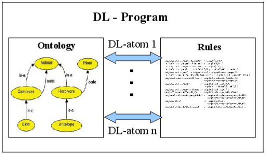

However, information exchange between rules and ontology can have unforeseen effects and cause **inconsistency** of the DL-program (absence of answer sets).

In this work: Repair data part of the ontology ($DL\text{-}Lite_{\mathcal{A}}$), i.e. change ontology ABox s.t. the resulting DL-program is consistent.

Overview

DL-Lite$_{\mathcal{A}}$

- Lightweight Description Logic for accessing large data sources.
- Concepts and roles model sets of objects and their relationships.

$$C \rightarrow A \mid \exists R \qquad R \rightarrow P | P^{-}$$

- A *DL-Lite*$_{\mathcal{A}}$ ontology $\mathcal{O} = \langle \mathcal{T}, \mathcal{A} \rangle$ consists of:
  - TBox $\mathcal{T}$ specifying constraints at the conceptual level.

    $$C_1 \sqsubseteq C_2, \qquad C_1 \sqsubseteq \neg C_2,$$
    $$R_1 \sqsubseteq R_2, \qquad R_1 \sqsubseteq \neg R_2, \qquad (funct\ R).$$

  - ABox $\mathcal{A}$ specifying the facts that hold in the domain.

    $$A(b) \qquad P(a, b)$$

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Example

$$\mathcal{T} = \left\{ \begin{array}{l} Child \sqsubseteq \exists hasParent \\ Female \sqsubseteq \neg Male \end{array} \right\} \qquad \mathcal{A} = \left\{ \begin{array}{l} hasParent(john, pat) \\ Male(john) \end{array} \right\}$$

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Conjunctive query answering in *DL-Lite*$_{\mathcal{A}}$ is tractable [Calvanese *et al.*, 2007].

Example: DL-program

$\Pi = \langle \mathcal{O}, P \rangle$ is a DL-program.

$$\mathcal{O} = \left\{ \begin{array}{ll} (1)\ \mathit{Child} \sqsubseteq \exists \mathit{hasParent} & (4)\ \mathit{Male}(\mathit{pat}) \\ (2)\ \mathit{Adopted} \sqsubseteq \mathit{Child} & (5)\ \mathit{Male}(\mathit{john}) \\ (3)\ \mathit{Female} \sqsubseteq \neg \mathit{Male} & (6)\ \mathit{hasParent}(\mathit{john}, \mathit{pat}) \end{array} \right\}$$

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$$P = \left\{ \begin{array}{l} (7)\ \mathit{ischildof}(\mathit{john}, \mathit{alex}); \quad (8)\ \mathit{boy}(\mathit{john}); \\ (9)\ \mathit{hasfather}(\mathit{john}, \mathit{pat}) \leftarrow \mathit{DL}[\mathit{Male} \uplus \mathit{boy}; \mathit{Male}](\mathit{pat}), \\ \qquad \mathit{DL}[; \mathit{hasParent}](\mathit{john}, \mathit{pat}) \end{array} \right\}$$

- interpretation: $I = \{\mathit{ischildof}(\mathit{john}, \mathit{alex}), \mathit{boy}(\mathit{john}), \mathit{hasfather}(\mathit{john}, \mathit{pat})\}$;
- satisfaction relation: $I \models^{\mathcal{O}} \mathit{boy}(\mathit{john})$; $I \models^{\mathcal{O}} \mathit{DL}[; \mathit{hasParent}](\mathit{john}, \mathit{pat})$;
- semantics is given in terms of answer sets, which are x-founded models;
- *flp* and *weak* semantics are relevant in this work;
- I is both *weak*- and *flp*-founded model.

Example: Inconsistent DL-program

$$\Pi = \langle \mathcal{O}, P \rangle$$

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Example: Inconsistent DL-program

$\Pi = \langle \mathcal{O}, P \rangle$ is inconsistent!

$$\mathcal{O} = \left\{ \begin{array}{ll} (1)\ Child \sqsubseteq \exists hasParent & (4)\ Male(pat) \\ (2)\ Adopted \sqsubseteq Child & (5)\ Male(john) \\ (3)\ Female \sqsubseteq \neg Male & (6)\ hasParent(john, pat) \end{array} \right\}$$

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No answer sets.

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$I_1 = \{\mathit{ischildof}(\mathit{john}, \mathit{alex}), \mathit{boy}(\mathit{john})\}$

Example: Inconsistent DL-program

$\Pi = \langle \mathcal{O}, P \rangle$ is consistent!

$$\mathcal{O} = \left\{ \begin{array}{ll} (1)\ Child \sqsubseteq \exists hasParent & (4)\ Female(pat) \\ (2)\ Adopted \sqsubseteq Child & (5)\ Male(john) \\ (3)\ Female \sqsubseteq \neg Male & (6)\ hasParent(john, pat) \end{array} \right\}$$

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$I_1 = \{ischildof(john, alex), boy(john)\}$

Repair Answer Sets

Definition

Let $\Pi = \langle \mathcal{O}, P \rangle$, $\mathcal{O} = \langle \mathcal{T}, \mathcal{A} \rangle$ be a DL-program,

- an ABox $\mathcal{A}'$ is an *x-repair* of Π if
  - $\mathcal{O}' = \langle \mathcal{T}, \mathcal{A}' \rangle$ is consistent;
  - $\Pi' = \langle \mathcal{O}', P \rangle$ has some x-answer set.

$rep_x(\Pi)$ is the set of all x-repairs of Π.

- I is an *x-repair answer set* of Π, if $I \in AS_x(\Pi')$, where $\Pi' = \langle \mathcal{O}', P \rangle, \mathcal{O}' = \langle \mathcal{T}, \mathcal{A}' \rangle$, and $\mathcal{A}' \in rep_x(\Pi)$.

$RAS_x(\Pi)$ is the set of all x-repair AS of Π.

$rep^I_x(\Pi)$ is the set of all $\mathcal{A}'$ under which I is an x-repair answer set of Π.

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$rep_x^I(\Pi)$ is the set of all $\mathcal{A}'$ under which I is an x-repair answer set of Π.

Example

$I_1 = \{ischildof(john, alex), boy(john)\}$ is an *flp*-repair answer set with repair $\mathcal{A}'_1 = \{Male(pat), Male(john)\}$; $\mathcal{A}'_1 \in rep^I_{flp}(\Pi)$.

Complexity of Repair Answer Sets

Theorem

Deciding $AS_x(\Pi) \neq \emptyset$ and deciding $RAS_x(\Pi) \neq \emptyset$ have in all cases the same complexity.

Π	$RAS_{FLP}(\Pi) \neq \emptyset$	$RAS_{weak}(\Pi) \neq \emptyset$
normal	Σ_2^P-complete	NP-complete
disjunctive	Σ_2^P-complete	Σ_2^P-complete

Membership:

- guess repair $\mathcal{A}'$ together with I and proceed with the check as usual;
- deciding $I \models^{\mathcal{O}} a$ is feasible in polynomial time if $\mathcal{O}$ is in $DL\text{-}Lite_{\mathcal{A}}$;

Hardness: for normal FLP AS hardness proof of ordinary disjunctive LP can be adapted, for other cases hardness is inherited from ordinary ASP.

DL-program Evaluation

Algorithm 1: $AnsSet$: Compute $AS_x(\Pi)$

Input: A DL-program Π, $x \in \{weak, flp\}$
Output: $AS_x(\Pi)$
for $\hat{I} \in AS(\hat{\Pi})$ **do**
  if $CMP(\hat{I}, \Pi) \wedge xFND(\hat{I}, \Pi)$ **then**
    output $\hat{I}|_{\Pi}$
  end
end

- $\hat{\Pi}$ is Π with all DL-atoms a substituted by ordinary atoms e_a plus additional guess rules for values of e_a;
- $CMP(\hat{I}, \Pi)$ is a compatibility check, i.e. check whether the values of DL-atoms coincide with the values of their replacement atoms in $\hat{I}$;
- $xFND(\hat{I}, \Pi)$ is x-foundedness check;
- $\hat{I}|_{\Pi}$ is a restriction of $\hat{I}$ to original language of Π.

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```
(1)     for Î ∈ AS(Π̂) do
(2a,b)      if CMP(Î, Π) ∧ xFND(Î, Π) then
                output Î|Π
            end
        end
```

Reasons for inconsistency:

1. $\hat{\Pi}$ does not have any answer sets;

2. for all $\hat{I} \in AS(\Pi)$:

- **a.** compatibility check failed or
- **b.** *x*-foundedness check failed.

Ontology Repair Problem

To address the compatibility check issue we introduce:

Definition

A ontology repair problem (ORP) is a triple $\mathcal{P} = \langle \mathcal{O}, D_1, D_2 \rangle$, where $\mathcal{O} = \langle \mathcal{T}, \mathcal{A} \rangle$ is an ontology and $D_i = \{\langle U^i_j, Q^i_j \rangle | 1 \leq j \leq m_i\},\ i = 1, 2$ are sets of pairs where U^i_j is any ABox and each Q^i_j is a DL-query.

A repair (solution) for $\mathcal{P}$ is any ABox $\mathcal{A}'$ s.t.

- $\mathcal{O}' = \langle \mathcal{T}, \mathcal{A}' \rangle$ is consistent;
- $\tau(\langle \mathcal{T}, \mathcal{A}' \cup U^1_k \rangle) \models Q^1_j$ holds for $1 \leq j \leq m_1$;
- $\tau(\langle \mathcal{T}, \mathcal{A}' \cup U^2_k \rangle) \not\models Q^2_j$ holds for $1 \leq j \leq m_2$.

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Example

$$\Pi = \langle \mathcal{O}, P \rangle, \text{ where } P = \left\{ \begin{array}{l} p(c);\ \ r(c);\ \ q(c) \leftarrow \underbrace{DL[C \uplus r; D](c)}_{a_1}; \\ \bot \leftarrow \underbrace{DL[D \uplus p, E \uplus r; \neg C](c)}_{a_2} \end{array} \right\}.$$

- $\hat{I} = \{p(c), r(c), q(c), e_{a_1}\}$: a_1 is guessed true, a_2 is guessed false;
- $\mathcal{P} = \langle \mathcal{O}, D_1, D_2 \rangle$, where
  - $D_1 = \{\langle \{\neg C(c)\}; D(c) \rangle\}$;
  - $D_2 = \{\langle \{D(c), \neg E(c)\}; \neg C(c) \rangle\}$.

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Example

Let $\mathcal{O} = \langle \overbrace{E \sqsubseteq D, A \sqsubseteq D}^{\mathcal{T}}, \overbrace{\neg C(c)}^{\mathcal{A}} \rangle$;

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$\mathcal{A}' = \{A(c)\}$ is a solution for $\mathcal{P}$.

ORP is *NP*-complete in general, even if $\mathcal{O} = \emptyset$.

Selection Preferences

Consider a set $\mathcal{AB}$ of all possible ABoxes.
Function $\sigma : 2^{\mathcal{AB}} x \mathcal{AB} \rightarrow 2^{\mathcal{AB}}$ is a selection function.
$\sigma(S, \mathcal{A}) \subseteq S$ is a set of preferred ABoxes.

A selection $\sigma : 2^{\mathcal{AB}} x \mathcal{AB} \rightarrow 2^{\mathcal{AB}}$ is independent if
$\sigma(S, \mathcal{A}) = \sigma(S', \mathcal{A}) \cup \sigma(S \backslash S', \mathcal{A})$, whenever $S' \subseteq S$.

Example

- deletion repair is independent;
- set-minimal change repair is not independent;
- cardinality minimal change repair is not independent.

Tractable Cases of ORP

C1. bounded $\delta^{\pm}$-change: $\sigma_{\delta^{\pm},k}(S, \mathcal{A}) = \{\mathcal{A}' \mid |\mathcal{A}' \Delta \mathcal{A}| \leq k\}$, for some k;

C2. deletion repair: $\sigma_{del}(S, \mathcal{A}) = \{\mathcal{A}' \mid \mathcal{A}' \subseteq \mathcal{A}\}$;

C3. deletion δ^{+}: first apply σ_{del} and get $\mu(\mathcal{O})$ s.t. for all $1 \leq j \leq m_2$ $\tau(\langle \mathcal{T}, \mathcal{A}' \cup U_j^2 \rangle) \not\models Q_j^2$, then further compute $\sigma_{\delta^+}(S, \mu(\mathcal{O}))$;

C4. addition under bounded opposite polarity: $\sigma_{bop}(S, \mathcal{A}) = \{\mathcal{A}' \supseteq \mu(\mathcal{O}) || \mathcal{A}'^{+} \backslash \mathcal{A}| \leq k \text{ or } |\mathcal{A}'^{-} \backslash \mathcal{A}| \leq k\}$

C1 - C4 are independent.

Applicability of results for independent selections:

- deciding whether repair $\mathcal{A}'$ is selected by σ does not require looking at other repairs;
- without major complexity increase σs can be combined with
  - DB-style factorization and localization techniques;
  - local search.

Repair Answer Set Computation

Algorithm 2: $RepAns$: Compute $rep^{\hat{I}|_\Pi}_{(\sigma,x)}(\Pi)$

Input: $\Pi = \langle \mathcal{O}, P \rangle$, $\mathcal{O} = \langle \mathcal{T}, \mathcal{A} \rangle$, $\hat{I} \in AS(\hat{\Pi})$, σ, $x \in \{weak, flp\}$
Output: $rep^{\hat{I}|_\Pi}_{(\sigma,x)}(\Pi)$

for $\mathcal{A}' \in ORP(\hat{I}, \Pi, \sigma)$ **do**
  if $CMP(\hat{I}, \langle \mathcal{T}, \mathcal{A}', P \rangle) \wedge xFND(\hat{I}, \langle \mathcal{T}, \mathcal{A}', P \rangle)$ **then**
    output $\mathcal{A}'$
  end
end

- *ORP*$(\hat{I}, \Pi, \sigma)$ computes σ repairs for $\hat{I}, \Pi$;
- *CMP*$(\hat{I}, \langle \mathcal{T}, \mathcal{A}', P \rangle)$ checks whether $\hat{I}$ is compatible w.r.t. Π';
- *xFND*$(\hat{I}, \langle \mathcal{T}, \mathcal{A}', P \rangle)$ checks whether $\hat{I}$ is x-founded w.r.t. Π'.

RepAnsSet outputs $\hat{I}$ if the result of *RepAns* is nonempty.

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Output: $rep^{\hat{I}|_{\Pi}}_{(\sigma,x)}(\Pi)$
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  end
end

- $ORP(\hat{I}, \Pi, \sigma)$ computes σ repairs for $\hat{I}, \Pi$;
- $CMP(\hat{I}, \langle \mathcal{T}, \mathcal{A}', P \rangle)$ checks whether $\hat{I}$ is compatible w.r.t. Π';
- $xFND(\hat{I}, \langle \mathcal{T}, \mathcal{A}', P \rangle)$ checks whether $\hat{I}$ is x-founded w.r.t. Π'.

RepAnsSet outputs $\hat{I}$ if the result of *RepAns* is nonempty.

RepAns and *RepAnsSet* are sound and complete for independent σ.

Related Work

- Repairing ontologies
  - consistent query answering over *DL-Lite* ontologies based on repair technique [Lembo *et al.*, 2010], [Bienvenu, 2012];
  - QA to $DL\text{-}Lite_{\mathcal{A}}$ ontologies that miss expected tuples (abductive explanations corresponding to repairs) [Calvanese *et al.*, 2012].

- Repairing nonmonotonic logic programs
  - extended abduction for deleting minimal sets of rules (in reality addition is also possible) [Sakama and Inoue, 2003].
- Repairing inconsistent combination of rules and ontologies
  - paraconsistent semantics, based on the HT logic [Fink, 2012];
  - inconsistency tolerance in DL-programs [Pührer *et al.*, 2010].

Conclusion and Future Work

Conclusions:

- consideration of repair answer sets (RAS);
- same complexity as ordinary AS (for $\mathcal{O}$ in *DL-Lite*$_{\mathcal{A}}$);
- RAS computation by extending the existing evaluation algorithm;
- involvement of a generalized ontology repair problem (ORP);
- tractable cases for independent selections.

Future work:

- extending the work to other DLs ($\mathcal{EL}$++, RL);
- DL-programs with richer queries (unions of conjunctive queries);
- further σ-selections;
- optimization and implementation.

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DL-program: syntax

Signature: $\Sigma = \langle \mathcal{C}, \mathbf{I}, \mathcal{P}, \mathbf{C}, \mathbf{R} \rangle$, where

- $\Sigma_0 = \langle \mathbf{I}, \mathbf{C}, \mathbf{R} \rangle$ is a DL signature;
- $\mathcal{C} \supseteq \mathbf{I}$ is a set of constant symbols;
- $\mathcal{P}$ is a finite set of predicate symbols of arity ≥ 0, s.t. $\mathcal{P} \cap \{\mathbf{C} \cup \mathbf{R}\} = \emptyset$.

DL-atom is of the form $DL[S_1 op_1 p_1, \ldots, S_m op_m p_m; Q](\mathbf{t})$, $m \geq 0$, where

- $S_i \in \mathbf{C} \cup \mathbf{R}$;
- $op_i \in \{\uplus, \cupdot, \Cap\}$;
- $p_i \in \mathcal{P}$ (unary or binary);
- $Q(\mathbf{t})$ is a DL-query:
  - $C(t_1)$, $\neg C(t_1)$, $\mathbf{t} = t_1$, where $C \in \mathbf{C}$;
  - $R(t_1, t_2)$, $\neg R(t_1, t_2)$, $\mathbf{t} = t_1, t_2$, where $R \in \mathbf{R}$.
  - $C \sqsubseteq D$, $C \not\sqsubseteq D$, $\mathbf{t} = \epsilon$, where $C, D \in \mathbf{C} \cup \{\top, \bot\}$;

DL-program: $\Pi = \langle \mathcal{O}, P \rangle$, $\mathcal{O}$ is a DL ontology, P is a set of DL-rules:

$$a_1 \vee \ldots \vee a_n \leftarrow b_1, \ldots b_k, not\ b_{k+1}, \ldots, not\ b_m,$$

$m \geq k \geq 0$, a_i is a classical literal; b_i is a classical literal or a DL-atom.

DL-program: semantics

Consider grounding $grd(\Pi)= \langle \mathcal{O}, grd(P)\rangle$ of $\Pi = \langle \mathcal{O}, P\rangle$ over $\mathcal{C}$ and $\mathcal{P}$.

Interpretation I is a consistent set of ground literals over $\mathcal{C}$ and $\mathcal{P}$.

- for ground literal ℓ: $I \models^{\mathcal{O}} \ell$ iff $\ell \in I$;
- for ground DL-atom $a = DL[S_1 op_1 p_1, \ldots, S_m op_m p_m; Q](\mathbf{c})$:

$$I \models^{\mathcal{O}} a$$

iff $\tau(\langle \mathcal{T}, \mathcal{A} \cup \lambda^I(a)\rangle) \models Q(\mathbf{c})$, where $\tau(\mathcal{O})$ is a modular translation of $\mathcal{O}$ to FOL, $\lambda^I(a) = \bigcup_{i=1}^m A_i(I)$ is a DL-update of $\mathcal{O}$ under I by a:

- $A_i(I) = \{S_i(t) \mid p_i(t) \in I\}$, for $op_i = \uplus$;
- $A_i(I) = \{\neg S_i(t) \mid p_i(t) \in I\}$, for $op_i = \cup\!\!\!-$;
- $A_i(I) = \{\neg S_i(t) \mid p_i(t) \notin I\}$, for $\cap\!\!\!-$.

FLP-reduct $\rho_{flp}P^I$ of P is a set of ground DL-rules r s.t. $I \models b^+(r),\ I \not\models b^-(r)$.

Weak-reduct $\rho_{weak}P^I$ of P: removes all DL-atoms b_i, $1 \leq i \leq k$ and all *not* b_j, $k < j \leq m$ from the rules of $\rho_{flp}P^I$.

I is an x-answer set of P iff I is a minimal model of its x-reduct.