Locally Consistent Transformations and Query Answering in Data Exchange

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Data exchange settings

Data Exchange Setting: $(\mathbf{S}, \mathbf{T}, \Sigma_{st})$

$\mathbf{S}$: Source schema.

$\mathbf{T}$: Target schema.

Σ_{st}: Set of source-to-target dependencies.

- Source-to-target dependency: FO sentence of the form

$$\forall \bar{x} \, (\varphi_{\mathbf{S}}(\bar{x}) \rightarrow \exists \bar{y} \, \psi_{\mathbf{T}}(\bar{x}, \bar{y})).$$

- $\varphi_{\mathbf{S}}(\bar{x})$: FO formula over $\mathbf{S}$.

- $\psi_{\mathbf{T}}(\bar{x}, \bar{y})$: conjunction of FO atomic formulas over $\mathbf{T}$.

Data exchange settings: Example

$$\mathbf{S} = \langle Employee(\cdot) \rangle$$

$$\mathbf{T} = \langle Dept(\cdot, \cdot) \rangle$$

$$\Sigma_{st} = \{\forall x \, (Employee(x) \rightarrow \exists y \; Dept(x, y))\}.$$

Data exchange problem

Given a source instance I, find a target instance J such that (I, J) satisfies Σ_{st}.

- J is called a solution for I.

Example: Possible solutions for $I = \{Employee(peter)\}$:

- $J_1 = \{Dept(peter, 1)\}$.
- $J_2 = \{Dept(peter, 1), Dept(peter, 2)\}$.
- $J_3 = \{Dept(peter, 1), Dept(john, 1)\}$.
- $J_4 = \{Dept(peter, X)\}$.
- $J_5 = \{Dept(peter, X), Dept(peter, Y)\}$.

Query answering

Q: Query over the target schema.

- What does it mean to answer Q?

$$\underline{\textit{certain}}(Q, I) \;=\; \bigcap_{J \text{ is a solution for } I} Q(J)$$

Example:

- $\underline{\textit{certain}}(\exists y\, Dept(x, y),\ I) = \{peter\}$.
- $\underline{\textit{certain}}(Dept(x, y),\ I) = \emptyset$.

Query rewriting

How can we compute $\underline{\textit{certain}}(Q, I)$?

- Naïve algorithm does not work: infinitely many solutions.

Approach proposed in [FKMP03]: **Query Rewriting**

Look for some specific $\mathcal{F} : \text{inst}(\mathbf{S}) \rightarrow \text{inst}(\mathbf{T})$, and find conditions under which $\underline{\textit{certain}}(Q, I) = Q'(\mathcal{F}(I))$ for every source instance I.

What is a good alternative for $\mathcal{F}$?

Outline

- Query rewriting over the canonical solution.
- Locality in data exchange.
  - Proving inexpressibility results.
- Query rewriting over the core.
  - Canonical solution versus core.
- Extensions.
  - Other semantics.
- Conclusions.

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Canonical solution

Input: $(\mathbf{S}, \mathbf{T}, \Sigma_{st})$ and a source instance I

Output: Canonical solution J for I

Algorithm:

for every $\forall \bar{x}\, (\varphi_{\mathbf{S}}(\bar{x}) \rightarrow \exists y\, \psi_{\mathbf{T}}(\bar{x}, \bar{y})) \in \Sigma_{st}$ do

for every $\bar{a}$ such that I satisfies $\varphi_{\mathbf{S}}(\bar{a})$ do

create a fresh tuple of null values $\overline{X}$

insert $\psi_{\mathbf{T}}(\bar{a}, \overline{X})$ into J

Canonical solution: Example

$\Sigma_{st} = \{\forall x\,(Employee(x) \rightarrow \exists y\, Dept(x,y))\}$ and
$I = \{Employee(peter), Employee(john)\}$.

- For $a = peter$ do

  Create a fresh null value X

  Insert $Dept(peter, X)$ into J

- For $a = john$ do

  Create a fresh null value Y

  Insert $Dept(john, Y)$ into J

Canonical solution:

$$\{Dept(peter, X),\; Dept(john, Y)\}$$

Query rewriting over the canonical solution

$\mathcal{F}_{\text{can}}(I)$: canonical solution for I.

- Can be computed in polynomial time (data complexity).

Theorem [FKMP03]: For every data exchange setting and union of conjunctive queries Q, there exists Q' such that for every source instance I, *certain*$(Q, I) = Q'(\mathcal{F}_{\text{can}}(I))$.

- $C(x)$: holds whenever x is a constant.
- $Q'(x_1, \ldots, x_m) = C(x_1) \wedge \cdots \wedge C(x_m) \wedge Q(x_1, \ldots, x_m)$.

Query rewriting over the canonical solution

Can the theorem be extended to other classes of queries?

Theorem [FKMP03]: There exists a data exchange setting and a conjunctive query Q with one inequality such that Q is not FO-rewritable over $\mathcal{F}_{\mathrm{can}}$.

- For every FO query Q', there exists an instance I such that $\underline{\textit{certain}}(Q, I) \neq Q'(\mathcal{F}_{\mathrm{can}}(I))$.

We would like to study the query rewriting problem.

- We need some tools: How can we prove that a query is not FO-rewritable?

Query rewriting: Some facts

The problem of deciding whether an FO formula is FO-rewritable over $\mathcal{F}_{\mathrm{can}}$ is undecidable.

There exists other classes of queries that are FO-rewritable over the canonical solution.

- Every boolean query Q whose asymptotic probability is 0 is FO-rewritable: <u>*certain*</u>$(Q, I) = \mathit{false}$.

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Locality in data exchange: Notation

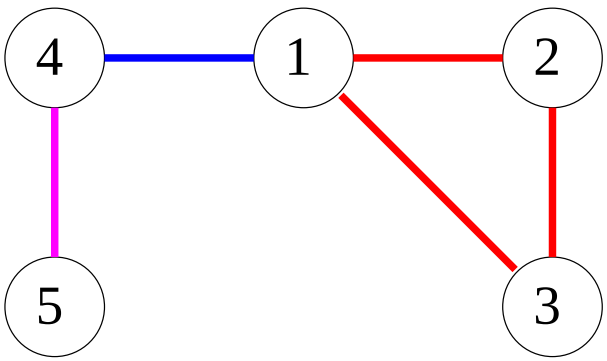
I: source instance.

Gaifman graph $\mathcal{G}(I)$ of I:

- adom(I) is the set of nodes of $\mathcal{G}(I)$.
- There exists an edge between a and b iff a and b belong to the same tuple of a relation in I.

Example: $I(R) = \{(1,2,3)\}$ and $I(T) = \{(1,4),\ (4,5)\}$.

$\mathcal{G}(I)$:



Locality in data exchange: Notation

$d_I(a,b)$: distance between a and b in $\mathcal{G}(I)$.

$d_I(\bar{a},b)$: minimum value of $d_I(a,b)$, where a is in $\bar{a}$.

$N_d^I(\bar{a})$: restriction of I to the elements at distance at most d from $\bar{a}$.

- Example: $\text{adom}(N_2^I(5)) = \{1,4,5\}$, $N_2^I(5)(R) = \emptyset$ and $N_2^I(5)(T) = \{(1,4),(4,5)\}$.

$N_d^I(\bar{a}) \cong N_d^I(\bar{b})$: members of $\bar{a}$ and $\bar{b}$ are treated as distinguished elements.

- $\bar{a} = (a_1,\ldots,a_m)$ and $\bar{b} = (b_1,\ldots,b_m)$.
- There is an isomorphism $f : N_d^I(\bar{a}) \to N_d^I(\bar{b})$ such that $f(a_i) = b_i$ ($1 \leq i \leq m$).

Locality in data exchange: Definition

Given: $(\mathbf{S}, \mathbf{T}, \Sigma_{st})$ and m-ary query Q over $\mathbf{T}$.

Definition: Q is **locally source-dependent** if there is $d \geq 0$ such that for every instance I of $\mathbf{S}$ and m-tuples $\bar{a}, \bar{b}$ in I,

$$N_d^I(\bar{a}) \cong N_d^I(\bar{b}) \quad \Longrightarrow \quad \begin{array}{c} \bar{a} \in \underline{\textit{certain}}(Q, I) \\ \text{iff} \\ \bar{b} \in \underline{\textit{certain}}(Q, I) \end{array}$$

Locality in data exchange: Main theorem

Theorem: If Q is FO-rewritable over the canonical solution, then Q is locally source-dependent.

This theorem can be used to prove inexpressibility results.

- If a query is not locally source-dependent, then it is not FO-rewritable.

Example: Proving inexpressibility

Data exchange setting:

$$\mathbf{S} = \langle G(\cdot,\cdot),\ R(\cdot),\ S(\cdot)\rangle$$

$$\mathbf{T} = \langle G'(\cdot,\cdot),\ R'(\cdot),\ S'(\cdot)\rangle$$

$$\begin{aligned}\Sigma_{st} = \ & \forall x \forall y\, (G(x,y) \rightarrow G'(x,y)),\\ & \forall x\, (R(x) \rightarrow R'(x)),\\ & \forall x\, (S(x) \rightarrow S'(x)).\end{aligned}$$

Query:

$$Q(x) = R'(x) \ \vee \ S'(x) \wedge \exists y \exists z (R'(y) \wedge G'(y,z) \wedge \neg R'(z))$$

Example: Proving inexpressibility

Assume that Q is FO-rewritable over the canonical solution.

Then there exists $d \geq 0$ such that

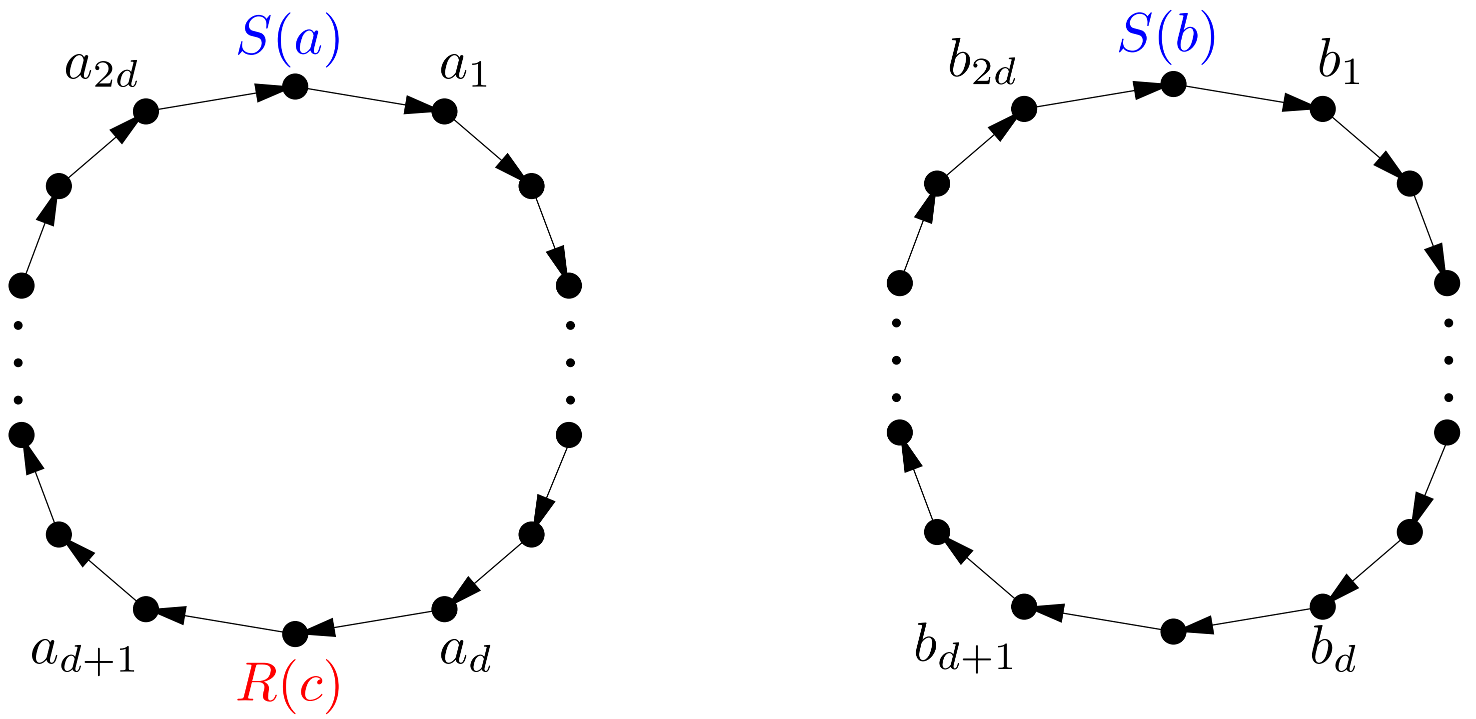
$$N_d^I(a) \cong N_d^I(b) \quad \Longrightarrow \quad a \in \underline{\textit{certain}}(Q, I) \text{ iff } b \in \underline{\textit{certain}}(Q, I).$$

Contradiction: find a source instance I such that

$$N_d^I(a) \cong N_d^I(b), \;\; a \in \underline{\textit{certain}}(Q, I) \;\text{ and }\; b \notin \underline{\textit{certain}}(Q, I).$$

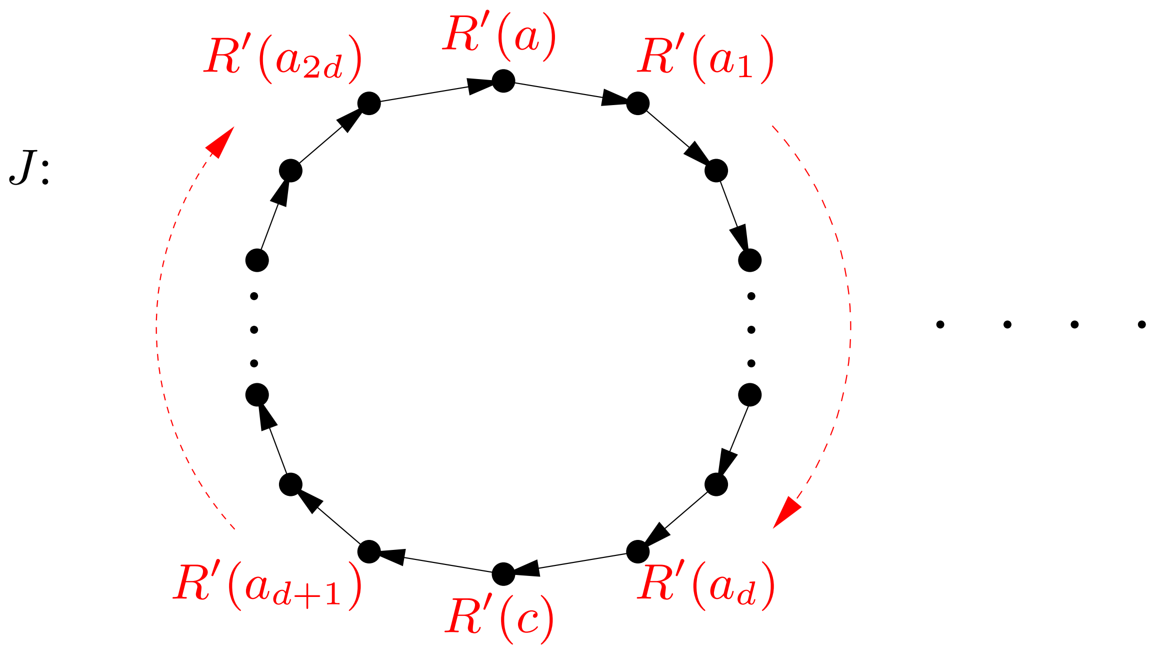
Example: Defining instance I

I:



Example: $a \in \underline{certain}(Q, I)$

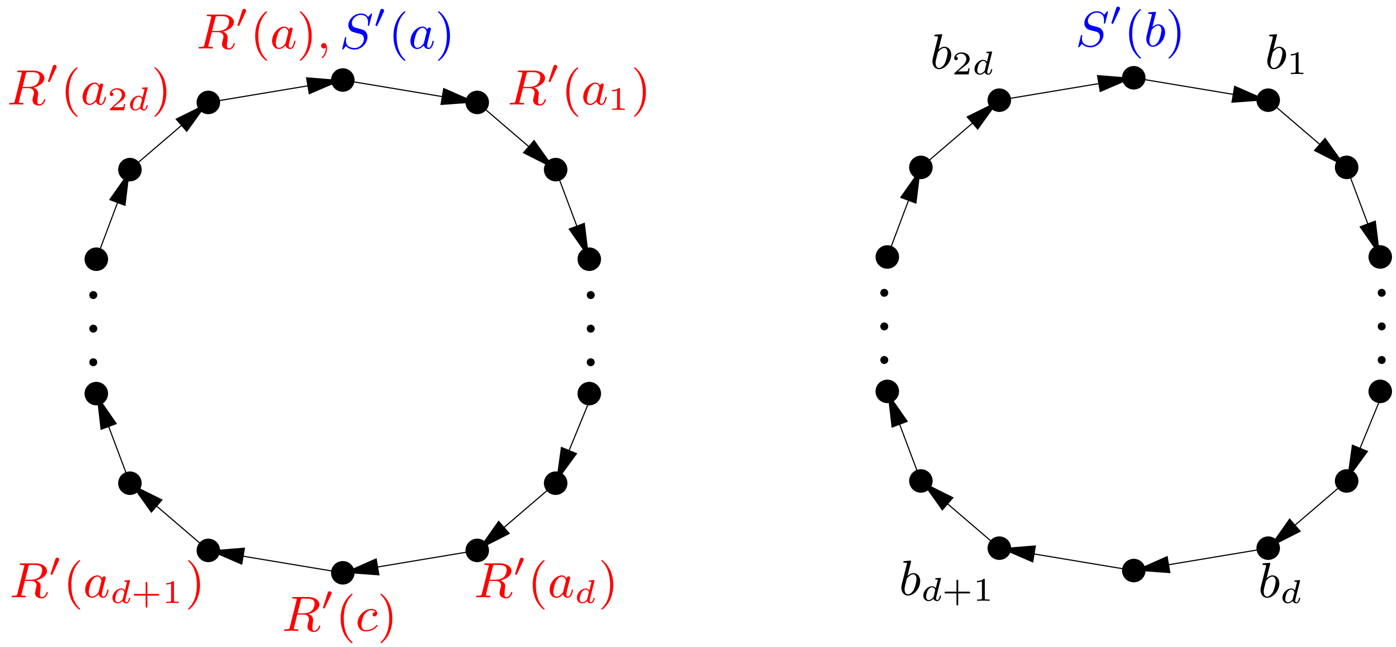
If J does not satisfy $S'(a) \wedge \exists y \exists z (R'(y) \wedge G'(y,z) \wedge \neg R'(z))$:



Then: J satisfies $R'(a)$.

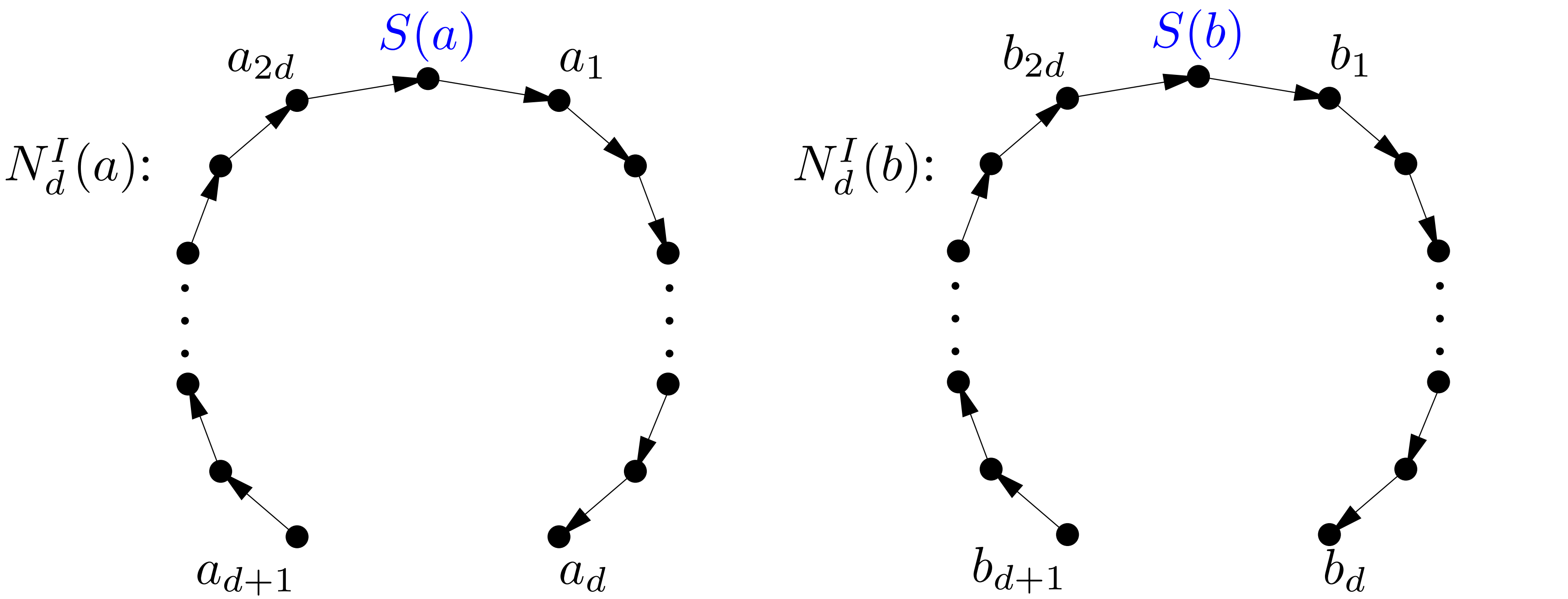
Example: $b \notin \underline{certain}(Q, I)$

J:



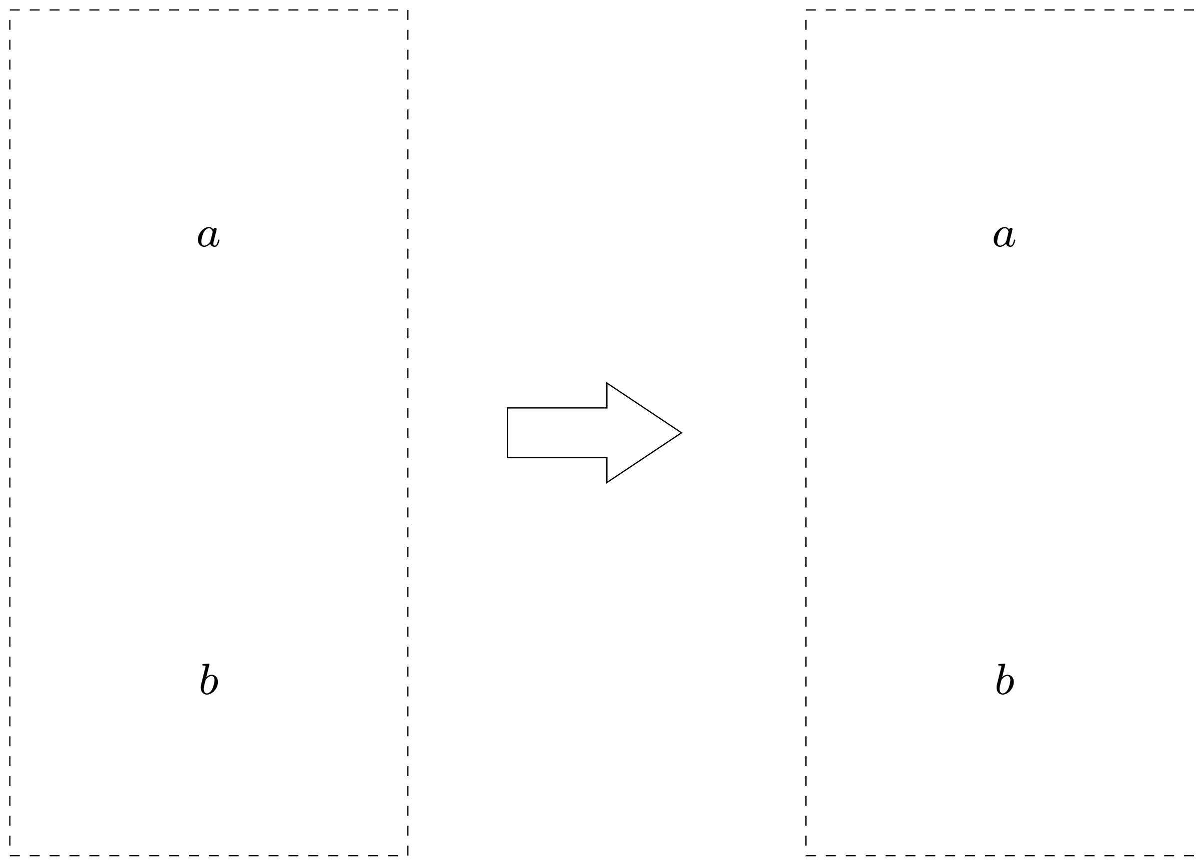
J does not satisfy $R'(b) \ \vee \ S'(b) \wedge \exists y \exists z (R'(y) \wedge G'(y, z) \wedge \neg R'(z))$.

Example: Getting a contradiction



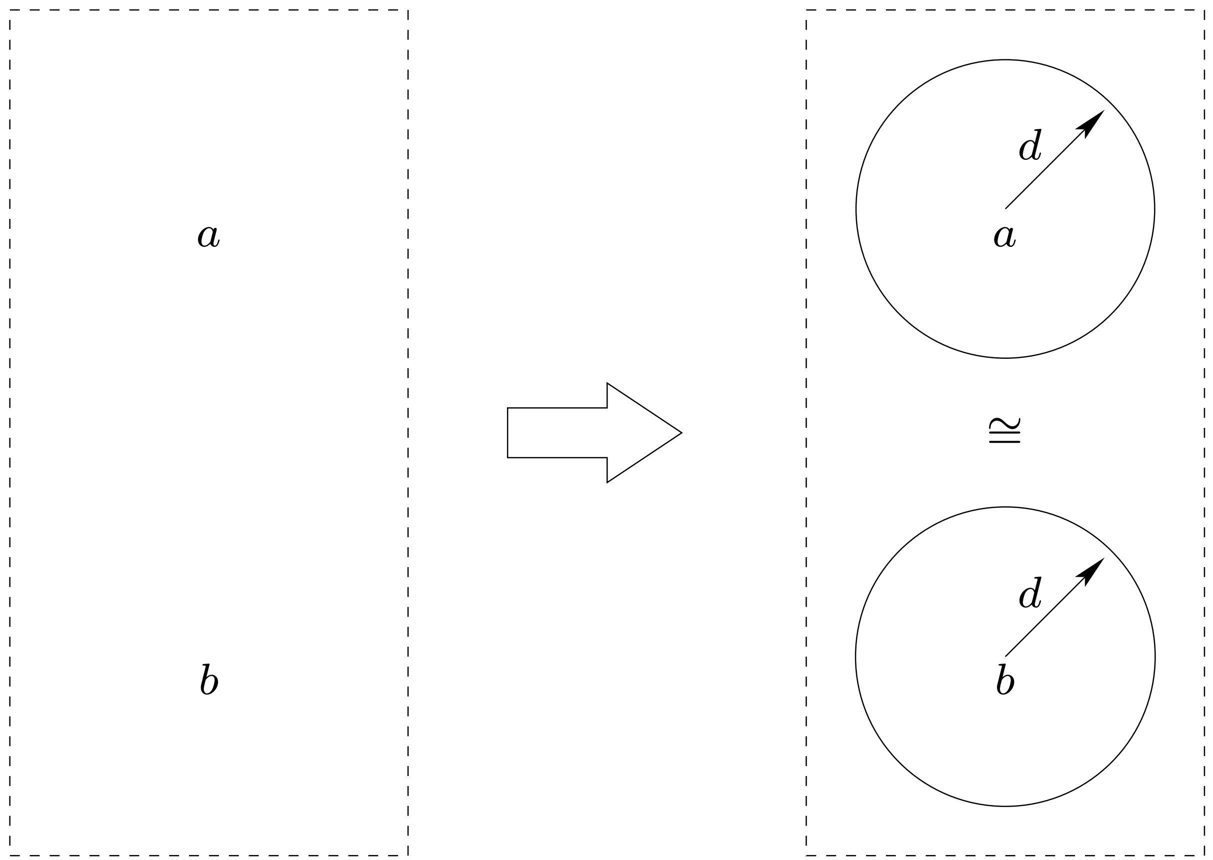
Conclusion: Q is **not** FO-rewritable over the canonical solution.

How do we prove the theorem?



source | canonical solution

How do we prove the theorem?



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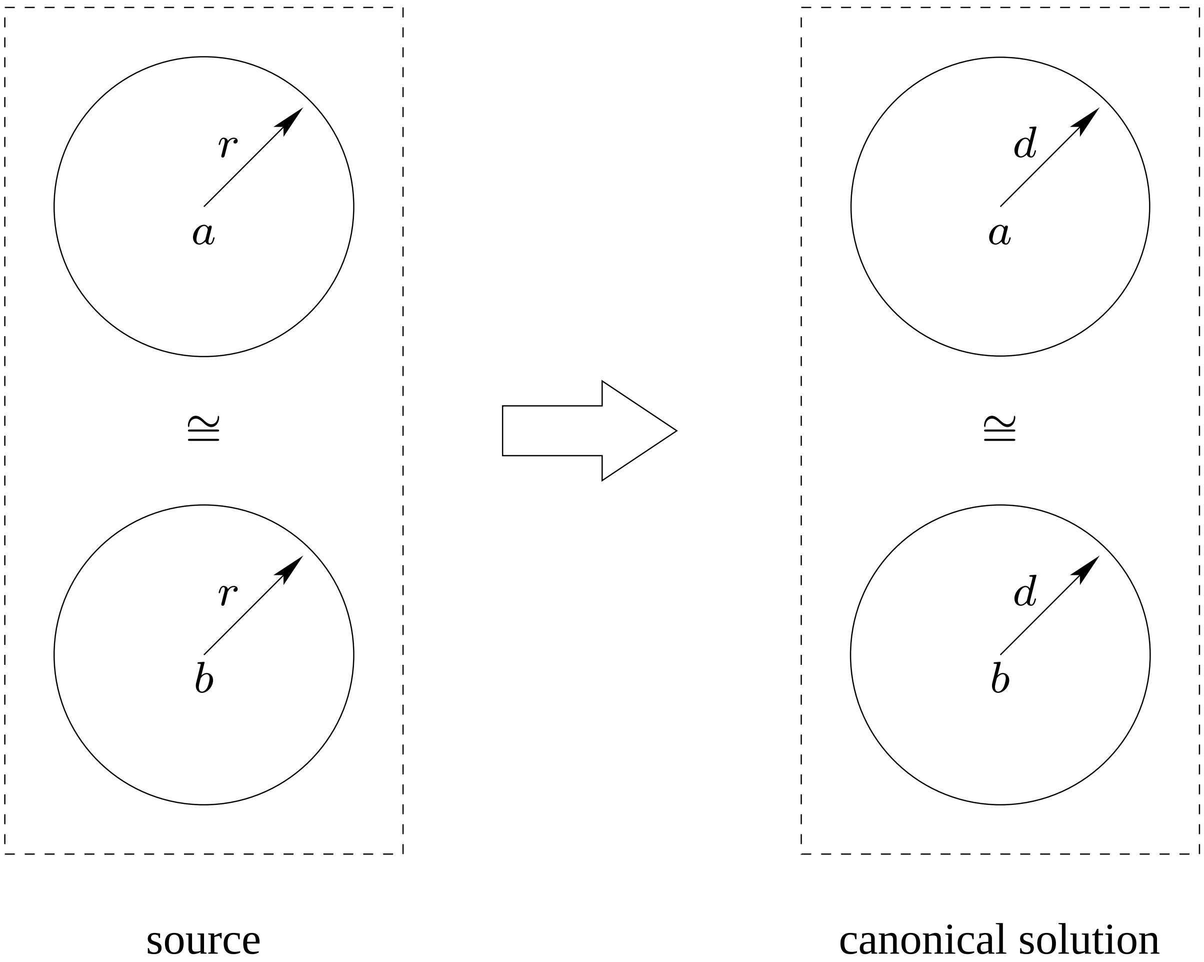

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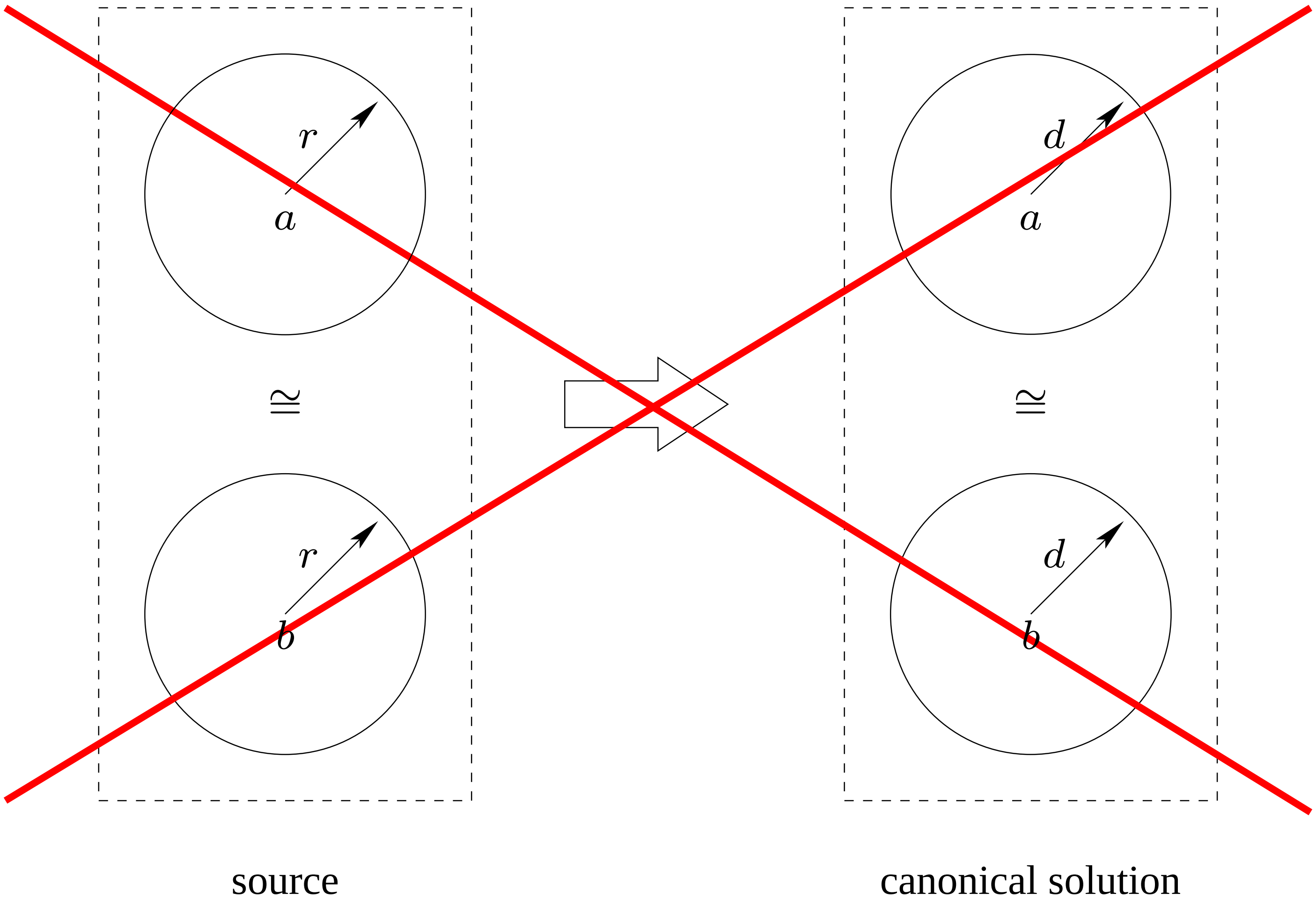

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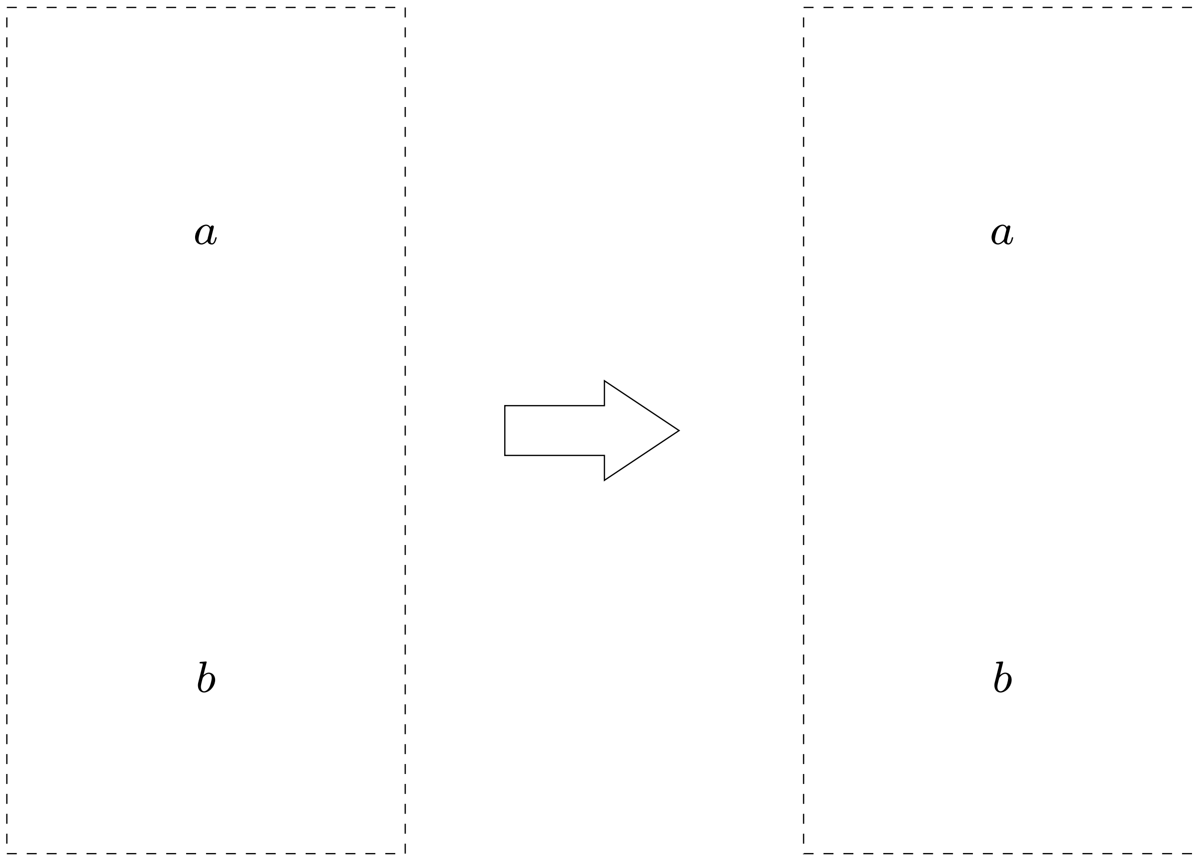

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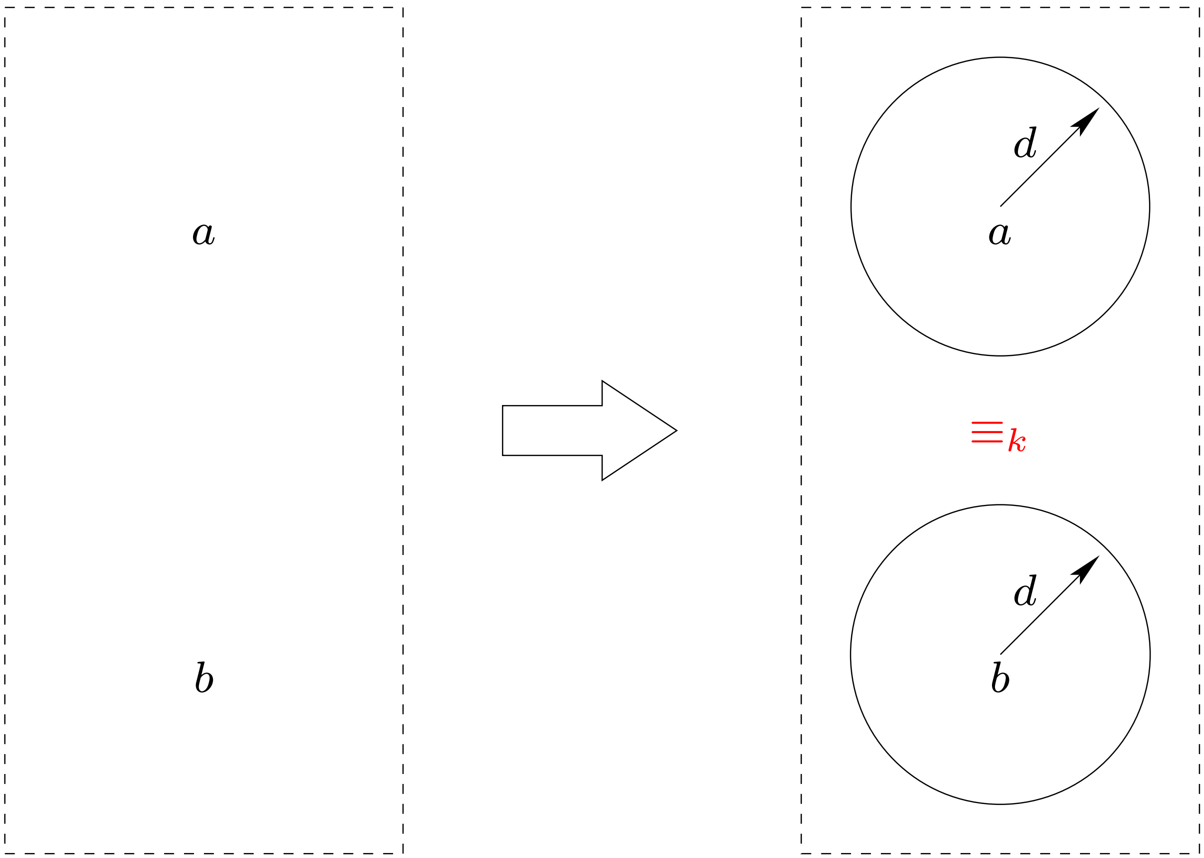

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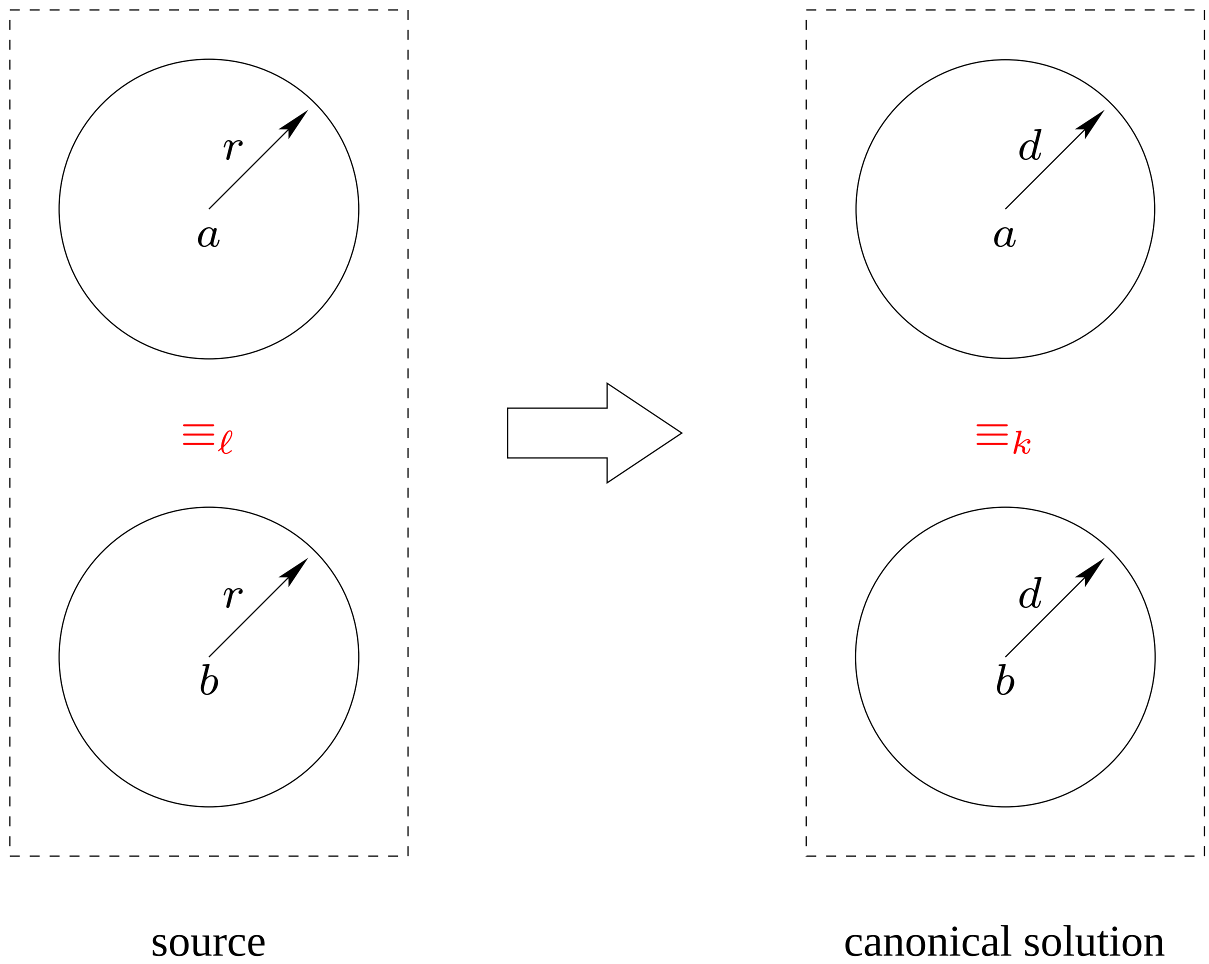

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What about other transformations?

Core of canonical solution J: Substructure $J^\star$ of J such that there is a homomorphism from J to $J^\star$ and there is no homomorphism from J to a proper substructure of $J^\star$.

- Homomorphism $h : J \rightarrow J'$: mapping from $\mathrm{adom}(J)$ to $\mathrm{adom}(J')$ such that $h(c) = c$ for all constant c, and $\bar{t} \in J(R)$ implies $h(\bar{t}) \in J'(R)$.

Core is the smallest solution that is *homomorphically equivalent* to the canonical solution.

- It can be computed in polynomial time [FKP03].

Query rewriting over the core

$\mathcal{F}_{\text{core}}(I)$: core of the canonical solution for I.

Theorem [FKMP03]: For every data exchange setting and union conjunctive queries Q, there exists Q' such that for every source instance I, *certain*$(Q, I) = Q'(\mathcal{F}_{\text{core}}(I))$.

- Certain answers can be computed more efficiently by using the core.

Rewritability over the core: Can we use locality?

Canonical solution versus core: First attempt

Proposition: There exists a data exchange setting $\mathcal{A} = (\mathbf{S}, \mathbf{T}, \Sigma_{st})$ such that for every data exchange setting $\mathcal{B} = (\mathbf{S}, \mathbf{T}, \Gamma_{st})$, there exists instance I of $\mathbf{S}$ such that:

$$\mathcal{F}^{\mathcal{A}}_{\text{core}}(I) \quad \not\cong \quad \mathcal{F}^{\mathcal{B}}_{\text{can}}(I).$$

We need a different approach ...

Expressiveness: Canonical solution versus core

Theorem: If Q is FO-rewritable over the core, then Q is also FO-rewritable over the canonical solution.

- There is a PTIME algorithm that, given a rewriting of Q over the core, finds a rewriting of Q over the canonical solution.

Corollary: If Q is FO-rewritable over the core, then Q is locally source-dependent.

Proof sketch

Assume $\varphi(\bar{x}) = \exists u \forall v \, \psi(\bar{x}, u, v)$ is a rewriting of Q over the core, where $\psi(\bar{x}, u, v)$ is quantifier-free.

- For every source instance I and tuple of constants $\bar{a}$: $\bar{a} \in$ *certain*(Q, I) iff $\mathcal{F}_{\text{core}}(I) \models \varphi(\bar{a})$.

Assume that:

$\alpha_1(x)$	:	holds if there is a core of $\mathcal{F}_{\text{can}}(I)$ containing null x.
$\alpha_2(x, y)$	:	holds if there is a core of $\mathcal{F}_{\text{can}}(I)$ containing nulls x and y.

Proof sketch

If $\alpha_1(x)$ and $\alpha_2(x, y)$ are FO-definable, then Q is FO-rewritable over the canonical solution:

$$\bar{a} \in \underline{\textit{certain}}(Q, I) \quad \text{iff} \quad \mathcal{F}_{\text{core}}(I) \models \exists u \forall v\, \varphi(\bar{a}, u, v)$$
$$\text{iff} \quad \mathcal{F}_{\text{can}}(I) \models \exists u\, (\alpha_1(u) \wedge \forall v\, (\alpha_2(u, v) \rightarrow \varphi(\bar{a}, u, v))).$$

How can we define $\alpha_1(x)$ and $\alpha_2(x, y)$ in FO?

- We show how to define $\alpha_1(x)$.

Proof sketch

Notation:

$\mathsf{nulls}(X, J)$	:	$\{Y \mid Y$ is a null of J and X, Y are in the same connected component of the graph induced from $\mathcal{G}(J)$ by the nulls of $J\}$
$\mathsf{block}(X, J)$	:	$\{t \mid t$ is a tuple in J containing a null in $\mathsf{nulls}(X, J)\}$

If J is a canonical solution: $|\mathsf{nulls}(X, J)|$ and $|\mathsf{block}(X, J)|$ are bounded.

Defining $\alpha_1(x)$

Lemma: Let J be the canonical solution for I and X a null value of J. There exists a core of J containing X iff for every pair of target structures J', J'' satisfying the following conditions:

- $J' \subseteq J$ and $|J'| \leq |\mathsf{block}(X, J)|$,
- there exists a homomorphism $h : \mathsf{block}(X, J) \rightarrow J'$ such that X is not a null of $h(\mathsf{block}(X, J))$,
- and $J' \subseteq J'' \subseteq \left(J' \cup \bigcup_{\{X \,|\, X \text{ is a null of } J'\}} \mathsf{block}(X, J)\right)$,

it is the case that there exists a homomorphism $h' : J'' \rightarrow J$ such that X is a null of $h'(J'')$.

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Is this definable in FO?

- and $J' \subseteq J'' \subseteq \left(J' \cup \bigcup_{\{X \mid X \text{ is a null of } J'\}} \text{block}(X, J)\right)$,

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Expressiveness: Canonical solution versus core

Theorem: There exists an FO query that is FO-rewritable over the canonical solution but not over the core.

Expressiveness point of view: Canonical solution is better than the core.

- Canonical solution contains more information than the core.

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What about other semantics?

Usual certain answers semantics sometimes exhibit counterintuitive behavior.

Good solutions: Universal solutions.

- Homomorphically equivalent to the canonical solution.

May be more meaningful to consider semantics based on universal solutions:

$$\underline{\textit{u-certain}}(Q, I) = \bigcap_{J \text{ is a universal solution for } I} Q(J).$$

Query rewriting under the universal solutions semantics

Given query Q, we want to find Q' such that
u-certain$(Q, I) = Q'(\mathcal{F}(I))$ for every source instance I.

Theorem [FKP03]: For every data exchange setting and existential query Q, there exists Q' such that for every source instance I,
u-certain$(Q, I) = Q'(\mathcal{F}_{\mathrm{core}}(I))$.

Query rewriting under the universal solutions semantics

Definition: Q is locally source-dependent under the universal solution semantics if there is $d \geq 0$ such that:

$$N_d^I(\bar{a}) \cong N_d^I(\bar{b}) \quad \Longrightarrow \quad \begin{array}{c} \bar{a} \in \underline{\textit{u-certain}}(Q, I) \\ \text{iff} \\ \bar{b} \in \underline{\textit{u-certain}}(Q, I) \end{array}$$

Theorem: All the previous results hold for the universal solution semantics.

- If Q is FO-rewritable over the canonical solution (core) under the universal solutions semantics, then Q is locally source-dependent under the universal solutions semantics.

What about target constraints?

Locality is no longer valid.

tgd: Even with a single full tgd.

$$\forall x \forall y \forall z \, (R(x, y) \wedge R(y, z) \rightarrow R(x, z)).$$

egd: Even for key dependencies.

Except for GAV settings: $\forall \bar{x} \, (\varphi_{\mathbf{S}}(\bar{x}) \rightarrow T(\bar{x}))$.

Conclusions

- Common data exchange transformations map similar neighborhoods into similar neighborhoods.

- This propertity can be used to formulate a locality notion for the canonical solution and the core.

- Locality can be used to prove that a query is not FO-rewritable.
  - Holds for other semantics.

- Expressiveness point of view: Canonical solution is better than the core.