Data Exchange beyond Complete Data

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Outline

- The need for a more general data exchange framework
  - Two important scenarios: Incomplete databases and knowledge bases
- Formalism for exchanging representations systems
- Applications to incomplete databases
- Applications to metadata management
- Concluding remarks

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Data exchange: Some lessons learned

Key steps in the development of the area:

- Definition of schema mapping: Precise syntax and semantics
- Definition of the notion of solution
- Identification of good solutions
  - Universal solutions
- Polynomial time algorithms for materializing good solutions
  - Based on the chase procedure

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Creating schema mappings is a time consuming and expensive process

- Manual or semi-automatic process in general

Ongoing project: Reusing schema mappings

$$\mathbf{S} \xrightarrow[\Sigma_{\mathbf{ST}}]{} \mathbf{T}$$

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$$\mathbf{S} \xrightarrow[\Sigma_{\mathbf{ST}}]{} \mathbf{T} \xrightarrow[\Sigma_{\mathbf{TU}}]{} \mathbf{U}$$

Ongoing project: Reusing schema mappings

$$
\begin{tikzcd}
\mathbf{S} \arrow[r, "\Sigma_{\mathbf{ST}}"'] \arrow[rr, bend right, "\Sigma_{\mathbf{SU}}\,?"'] & \mathbf{T} \arrow[r, "\Sigma_{\mathbf{TU}}"'] & \mathbf{U}
\end{tikzcd}
$$

Ongoing project: Reusing schema mappings

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\begin{tikzcd}[column sep=huge]
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We need some operators for schema mappings

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$$\Sigma_{\mathbf{SU}} = \Sigma_{\mathbf{ST}} \circ \Sigma_{\mathbf{TU}}$$

We need some operators for schema mappings

- **Composition** in the above case

Metadata management

This has motivated the need for the development of a general infrastructure for managing schema mappings.

The problem of managing schema mappings is called **metadata management.**

High-level algebraic operators, such as compose, are used to manipulate mappings.

- What other operators are needed?

An inverse operator is also needed

$$\mathbf{S} \xrightarrow[\Sigma_{\mathbf{ST}}]{} \mathbf{T}$$

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\mathbf{S} \arrow[r, "\Sigma_{\mathbf{ST}}"'] \arrow[d, "\Sigma_{\mathbf{SV}}"] & \mathbf{T} \\
\mathbf{V} &
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Composition and inverse operators have to be combined

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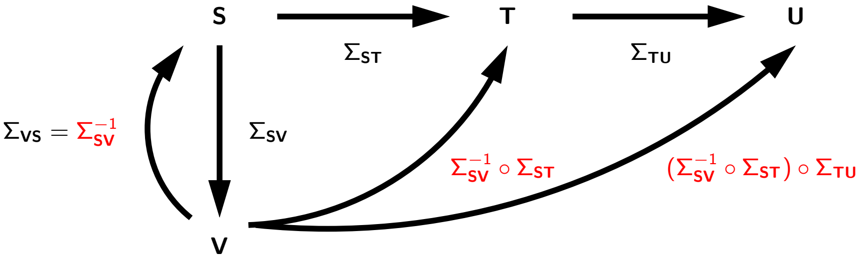

Composition and inverse operators have to be combined

Metadata management: A more general data exchange framework is needed

Composition and inverse operators have been extensively studied in the relational world.

- Semantics, computation, ...

Combining these operators is an open issue.

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- Sources instances may contain null values

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- Sources instances may contain null values

There is a need for a data exchange framework that can handle databases with incomplete information.

Data exchange in the RDF world

There is an increasing interest in publishing relational data as RDF

- Resulted in the creation of the W3C RDB2RDF Working Group

The problem of translating relational data into RDF can be seen as a data exchange problem

- Schema mappings can be used to describe how the relational data is to be mapped into RDF

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- Schema mappings can be used to describe how the relational data is to be mapped into RDF

But there is a mismatch here: A relational database under a closed-world semantics is to be translated into an RDF graph under an open-world semantics

- There is a need for a data exchange framework that can handle both databases with complete and incomplete information

Data exchange in the RDF world

An issue discussed at the W3C RDB2RDF Working Group: Is a mapping information preserving?

- In particular: For the default mapping defined by this group

How can we address this issue?

- Metadata management can help us

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Question to answer: Is a mapping invertible?

- This time an RDF graph is to be translated into a relational database!
- We want to have a unifying framework for all these cases

But these are not the only reasons . . .

Nowadays several applications use knowledge bases to represent data.

- A knowledge base has not only data but also rules that allows to infer new data
- In the Semantics Web: RDFS and OWL ontologies

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> The input is a mapping and a source specification including data and rules, and the output is a target specification also including data and rules

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There is a need for a data exchange framework that can handle knowledge bases.

One can exchange more than complete data

- In data exchange one starts with a database instance (with complete information).
- What if we have an initial object that has several interpretations?
  - A representation of a set of possible instances
- We propose a new general formalism to exchange representations of possible instances
  - We apply it to the problems of exchanging instances with incomplete information and exchanging knowledge bases

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Representation systems

A representation system $\mathcal{R} = (\mathbf{W}, \mathrm{rep})$ consists of:

- a set $\mathbf{W}$ of *representatives*
- a function rep that assigns a set of instances to every element in $\mathbf{W}$

$$\mathrm{rep}(\mathcal{V}) = \{I_1, I_2, I_3, \ldots\} \text{ for every } \mathcal{V} \in \mathbf{W}$$

Uniformity assumption: For every $\mathcal{V} \in \mathbf{W}$, there exists a relational schema $\mathbf{S}$ (the type of $\mathcal{V}$) such that $\mathrm{rep}(\mathcal{V}) \subseteq \mathrm{Inst}(\mathbf{S})$

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Incomplete instances and knowledge bases are representation systems

In classical data exchange we consider only *complete* data

$\mathcal{M}$ is a mapping from **S** to **T** if $\mathcal{M} \subseteq \text{Inst}(\mathbf{S}) \times \text{Inst}(\mathbf{T})$

- Given instances I of **S** and J of **T**: J is a solution for I under $\mathcal{M}$ if **S** if $(I, J) \in \mathcal{M}$

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$\mathcal{M}$ is defined by a set Σ of dependencies (e.g., st-tgds) if: $(I, J) \in \mathcal{M}$ iff $(I, J) \models \Sigma$.

- Notation: $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$

Extending the definition to representation systems

$\text{Sol}_{\mathcal{M}}(I)$: Set of solutions for I under $\mathcal{M}$

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This can be extended to set of instances. Given $\mathcal{X} \subseteq \text{Inst}(\mathbf{S})$:

$$\text{Sol}_{\mathcal{M}}(\mathcal{X}) \;=\; \bigcup_{I \in \mathcal{X}} \text{Sol}_{\mathcal{M}}(I)$$

Extending the definition to representation systems

Given:

- a mapping $\mathcal{M}$ from $\mathbf{S}$ to $\mathbf{T}$
- a representation system $\mathcal{R} = (\mathbf{W}, \text{rep})$
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Definition (APR11)

$\mathcal{V}$ is an $\mathcal{R}$*-solution* of $\mathcal{U}$ under $\mathcal{M}$ if

$$\text{rep}(\mathcal{V}) \quad \subseteq \quad \text{Sol}_{\mathcal{M}}(\text{rep}(\mathcal{U}))$$

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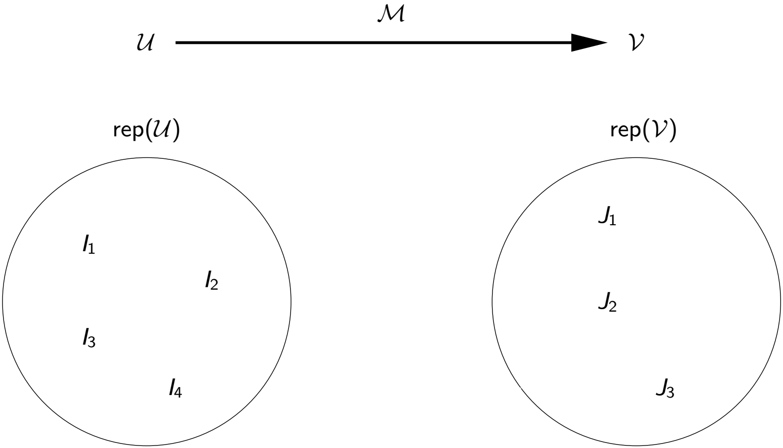
Or equivalently: $\mathcal{V}$ is an $\mathcal{R}$-*solution* of $\mathcal{U}$ if for every $J \in \text{rep}(\mathcal{V})$, there exists $I \in \text{rep}(\mathcal{U})$ such that $J \in \text{Sol}_{\mathcal{M}}(I)$.

Extending the definition to representation systems

$$\mathcal{U} \xrightarrow{\mathcal{M}} \mathcal{V}$$

Extending the definition to representation systems



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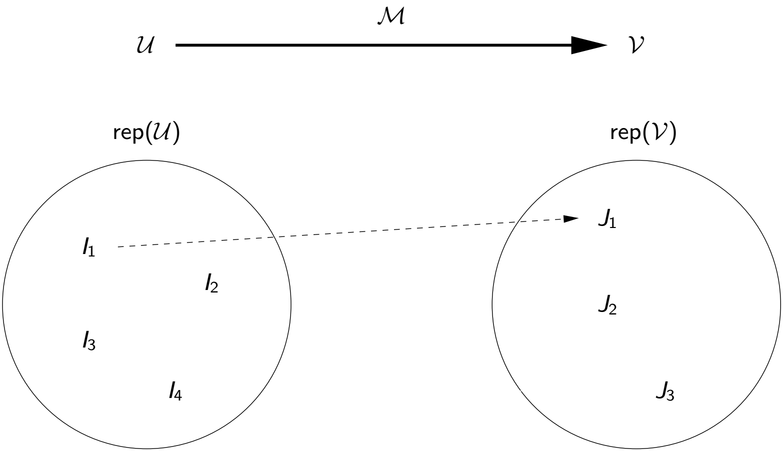

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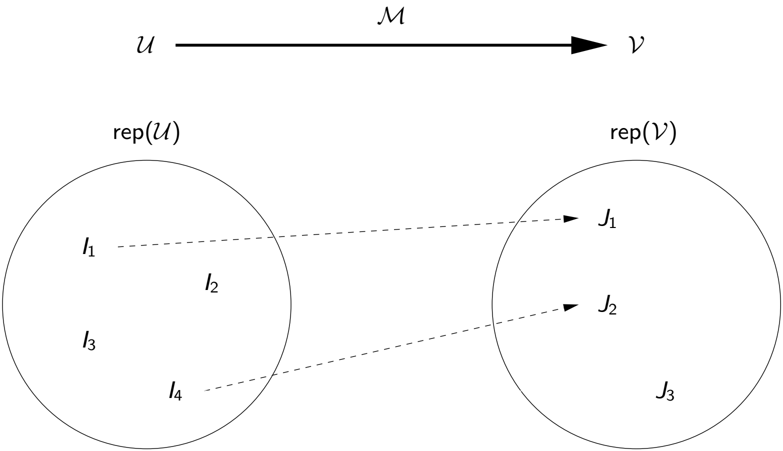

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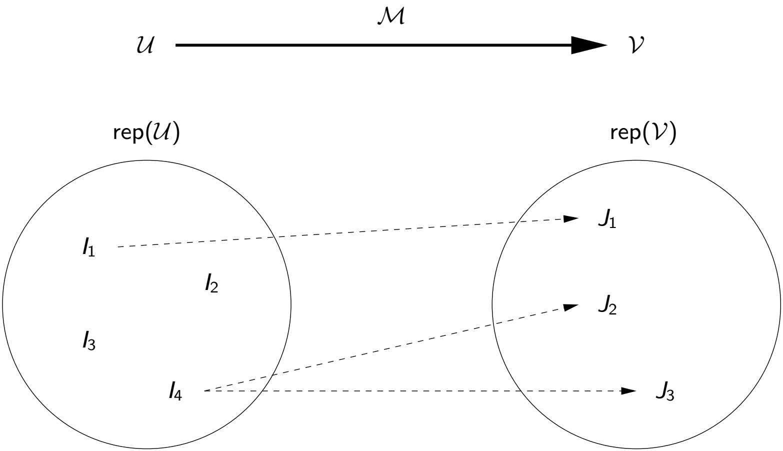

Universal solutions

What is a good solution in this framework?

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$\mathcal{V}$ is an *universal $\mathcal{R}$-solution* of $\mathcal{U}$ under $\mathcal{M}$ if

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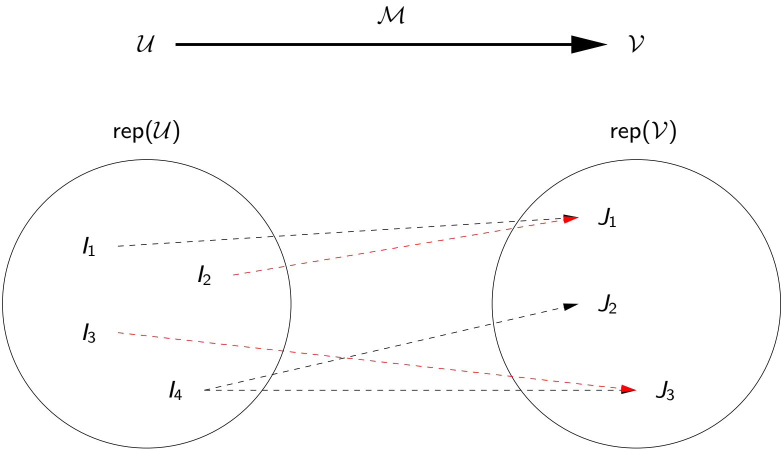
Universal solutions in a figure



Strong representation systems

Let $\mathcal{C}$ be a class of mappings.

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Definition (APR11)

$\mathcal{R} = (\mathbf{W}, \text{rep})$ is a *strong representation system* for $\mathcal{C}$ if for every $\mathcal{M} \in \mathcal{C}$ and for every $\mathcal{U} \in \mathbf{W}$, there exists a $\mathcal{V} \in \mathbf{W}$:

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If $\mathcal{R} = (\mathbf{W}, \text{rep})$ is a strong representation system, then the universal solutions for the representatives in **W** can be represented in the same system.

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Motivating questions

What is a strong representation system for the class of mappings specified by st-tgds?

- Are instances including nulls enough?

Can the fundamental data exchange problems be solved in polynomial time in this setting?

- Computing (universal) solutions

Naive instances

We have already considered naive instances: Instances with null values

- Example: Universal solutions

A naive instance $\mathcal{I}$ has labeled nulls:

$$
\begin{array}{c}
R(1, n_1) \\
R(n_1, 2) \\
R(1, n_2)
\end{array}
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A naive instance $\mathcal{I}$ has labeled nulls:

$$R(1, n_1)$$
$$R(n_1, 2)$$
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The interpretations of $\mathcal{I}$ are constructed by replacing nulls by constants:

$$\text{rep}(\mathcal{I}) \quad = \quad \{K \mid \mu(\mathcal{I}) \subseteq K \text{ for some valuation } \mu\}$$

Are naive instances expressive enough?

Naive instances have been extensively used in data exchange:

Proposition (FKMP03)

Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$, where Σ is a set of st-tgds. Then for every instance I of $\mathbf{S}$, there exists a naive instance $\mathcal{J}$ of $\mathbf{T}$ such that:

$$rep(\mathcal{J}) \quad = \quad \mathrm{Sol}_{\mathcal{M}}(I)$$

In fact, every universal solution satisfies the property mentioned above.

Are naive instances expressive enough?

But naive instances are not expressive enough to deal with incomplete information in the source instances:

Proposition (APR11)

Naive instances are not a strong representation system for the class of mappings specified by st-tgds

Are naive instances expressive enough?

Example

Consider a mapping $\mathcal{M}$ specified by:

$$\begin{array}{rcl} \texttt{Manager}(x, y) & \rightarrow & \texttt{Reports}(x, y) \\ \texttt{Manager}(x, x) & \rightarrow & \texttt{SelfManager}(x) \end{array}$$

The *canonical* universal solution for $\mathcal{I} = \{\texttt{Manager}(n, \text{Peter})\}$ under $\mathcal{M}$:

$$\mathcal{J} \quad = \quad \{\texttt{Reports}(n, \text{Peter})\}$$

But $\mathcal{J}$ is not a *good* solution for $\mathcal{I}$.

- It cannot represent the fact that if n is given value Peter, then $\texttt{SelfManager}(\text{Peter})$ should hold in the target.

Conditional instances

What should be added to naive instances to obtain a strong representation system?

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- Answer from database theory: Conditions on the nulls

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Conditional instances: Naive instances plus *tuple conditions*

A tuple condition is a positive Boolean combinations of:

- equalities and inequalities between nulls, and between nulls and constants

Conditional instances

Example

$$\begin{array}{l|l} R(1, n_1) & n_1 = n_2 \\ R(n_1, n_2) & n_1 \neq n_2 \ \vee \ n_2 = 2 \end{array}$$

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$\underline{\mu(n_1) = \mu(n_2) = 2}$ $\quad$ $\underline{\mu(n_1) = \mu(n_2) = 3}$ $\quad$ $\underline{\mu(n_1) = 2, \mu(n_2) = 3}$

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Semantics:

$$\frac{\mu(n_1) = \mu(n_2) = 2}{\begin{array}{c} R(1,2) \\ R(2,2) \end{array}} \qquad \frac{\mu(n_1) = \mu(n_2) = 3}{R(1,3)} \qquad \frac{\mu(n_1) = 2, \mu(n_2) = 3}{}$$

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Interpretations of a conditional instance $\mathcal{I}$:

$$\text{rep}(\mathcal{I}) \quad = \quad \{K \mid \mu(\mathcal{I}) \subseteq K \text{ for some valuation } \mu\}$$

Positive conditional instances

Many problems are intractable over conditional instances.

- We also consider a restricted class of conditional instances

Positive conditional instances: Conditional instances without inequalities

(Positive) conditional instances are enough

Theorem (APR11)

Both conditional instances and positive conditional instances are strong representation systems for the class of mappings specified by st-tgds.

Example

Consider again the mapping $\mathcal{M}$ specified by:

$$\begin{array}{rcl} \texttt{Manager}(x, y) & \rightarrow & \texttt{Reports}(x, y) \\ \texttt{Manager}(x, x) & \rightarrow & \texttt{SelfManager}(x) \end{array}$$

The following is a universal solution for $\mathcal{I} = \{\texttt{Manager}(n, \text{Peter})\}$

$$\begin{array}{l|l} \texttt{Reports}(n, \text{Peter}) & \textit{true} \\ \texttt{SelfManager}(\text{Peter}) & n = \text{Peter} \end{array}$$

Positive conditional instances are *exactly* the needed representation system

Theorem (APR11)

All the following are needed to obtain a strong representation system for the class of mappings specified by st-tgds:

Positive conditional instances are *exactly* the needed representation system

Theorem (APR11)

All the following are needed to obtain a strong representation system for the class of mappings specified by st-tgds:

- *equalities between nulls*

Positive conditional instances are *exactly* the needed representation system

Theorem (APR11)

All the following are needed to obtain a strong representation system for the class of mappings specified by st-tgds:

- *equalities between nulls*
  - *There exists a mapping $\mathcal{M}$ given by st-tgds and a source naive instance $\mathcal{I}$ such that for every target positive conditional $\mathcal{J}$ not mentioning equalities between nulls:* $rep(\mathcal{J}) \neq \mathrm{Sol}_{\mathcal{M}}(rep(\mathcal{I}))$

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- *equalities between constant and nulls*

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- *equalities between constant and nulls*
- *conjunctions and disjunctions*

Positive conditional instances are *exactly* the needed representation system

Theorem (APR11)

All the following are needed to obtain a strong representation system for the class of mappings specified by st-tgds:

- *equalities between nulls*
  - *There exists a mapping $\mathcal{M}$ given by st-tgds and a source naive instance $\mathcal{I}$ such that for every target positive conditional $\mathcal{J}$ not mentioning equalities between nulls: $rep(\mathcal{J}) \neq \mathrm{Sol}_{\mathcal{M}}(rep(\mathcal{I}))$*
- *equalities between constant and nulls*
- *conjunctions and disjunctions*

Conditional instances are enough but not minimal.

Positive conditional instance can be used in practice!

Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$, where Σ is a set of st-tgds.

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There exists a polynomial time algorithm that, given a positive conditional instance $\mathcal{I}$ over $\mathbf{S}$, computes a positive conditional instance $\mathcal{J}$ over $\mathbf{T}$ that is a universal solution for $\mathcal{I}$ under $\mathcal{M}$.

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Remark

They are also appropriate for query answering in data exchange.

- Same polynomial-time cases as in the usual setting

Outline

- The need for a more general data exchange framework
  - Two important scenarios: Incomplete databases and knowledge bases
- Formalism for exchanging representations systems
- Applications to incomplete databases
- Applications to metadata management
- Concluding remarks

The composition operator

Definition (FKPT04)

Let $\mathcal{M}_{12}$ be a mapping from $\mathbf{S}_1$ to $\mathbf{S}_2$, and $\mathcal{M}_{23}$ a mapping from $\mathbf{S}_2$ to $\mathbf{S}_3$:

$$\mathcal{M}_{12} \circ \mathcal{M}_{23} = \{(I_1, I_3) \mid \exists I_2 : (I_1, I_2) \in \mathcal{M}_{12} \text{ and } (I_2, I_3) \in \mathcal{M}_{23}\}$$

Expressing the composition of mappings

Question

What is the right language for expressing the composition?

- st-tgds?

Example (FKPT04)

Consider the mappings $\mathcal{M}_{12}$:

$$\begin{aligned} node(x) &\rightarrow \exists y\, coloring(x, y) \\ edge(x, y) &\rightarrow edge'(x, y) \end{aligned}$$

and $\mathcal{M}_{23}$:

$$\begin{aligned} edge'(x, y) \wedge coloring(x, u) \wedge coloring(y, u) &\rightarrow error(x, y) \\ coloring(x, y) &\rightarrow color(y) \end{aligned}$$

SO tgds: The right language for expressing the composition of mappings

Example (Cont'd)

The following dependency defines the composition:

$$\exists f \Big[\forall x (node(x) \rightarrow color(f(x))) \wedge \\ \forall x \forall y (edge(x,y) \wedge f(x) = f(y) \rightarrow error(x,y)) \Big]$$

SO tgds: The right language for expressing the composition of mappings

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$$\left. \forall x \forall y (edge(x,y) \wedge f(x) = f(y) \rightarrow error(x,y)) \right]$$

This example shows the main ingredients of SO tgds:

- Predicates including terms: $color(f(x))$
- Equality between terms: $f(x) = f(y)$

SO tgds: The right language for expressing the composition of mappings

SO tgds were introduced in [FKPT04]

- They have good properties regarding composition

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If $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$ are specified by SO tgds, then $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ can be specified by an SO tgd

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If $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$ are specified by SO tgds, then $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ can be specified by an SO tgd

- *There exists an exponential time algorithm that computes such SO tgds*

SO tgds: The right language for expressing the composition of mappings

Corollary (FKPT04)

The composition of a finite number of mappings, each defined by a finite set of st-tgds, is defined by an SO tgd

SO tgds: The right language for expressing the composition of mappings

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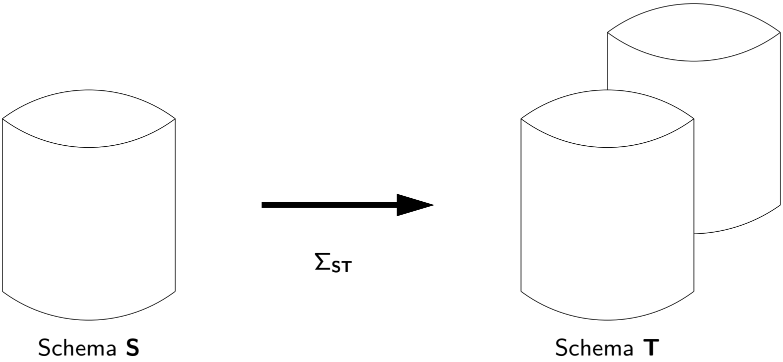
The composition of a finite number of mappings, each defined by a finite set of st-tgds, is defined by an SO tgd

But not only that, SO tgds are *exactly* the right language:

Theorem (FKPT05)

Every SO tgd defines the composition of a finite number of mappings, each defined by a finite set of st-tgds.

The inverse operator



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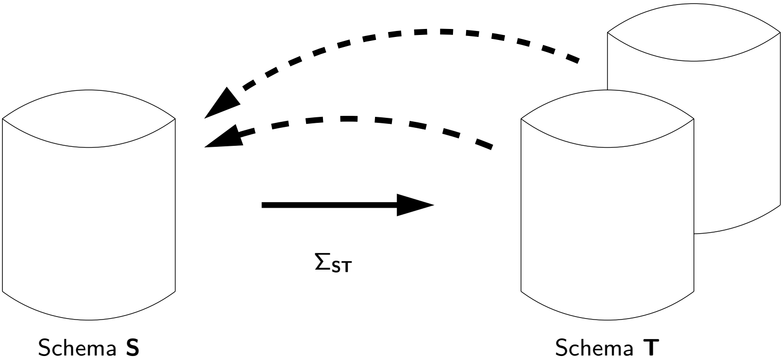

The inverse operator

Question

What is the semantics of the inverse operator?

This turns out to be a very difficult question.

Several notions of inverse have been considered:

- Fagin-inverse [F06]
- Quasi-inverse [FKPT07]
- Maximum recovery [APR08]
- Maximum extended recovery [FKPT09]
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Recovery: specifies how to recover sound information

Data may be lost in the exchange through a mapping $\mathcal{M}$

- We would like to find a mapping $\mathcal{M}^\star$ that at least recovers sound data w.r.t. $\mathcal{M}$
  - $\mathcal{M}^\star$ is called a recovery of $\mathcal{M}$

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Consider a mapping $\mathcal{M}$ specified by:

$$emp(x, y, z) \wedge y \neq z \quad \rightarrow \quad shuttle(x, z)$$

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Maximum recovery: The *most informative* recovery

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We would like to find a recovery of $\mathcal{M}$ that is better than any other recovery: Maximum recovery

The notion of recovery: Formalization

Definition (APR08)

Let $\mathcal{M}$ be a mapping from $\mathbf{S}_1$ to $\mathbf{S}_2$ and $\mathcal{M}^\star$ a mapping from $\mathbf{S}_2$ to $\mathbf{S}_1$. Then $\mathcal{M}^\star$ is a recovery of $\mathcal{M}$ if:

for every instance I of $\mathbf{S}_1$: $(I, I) \in \mathcal{M} \circ \mathcal{M}^\star$

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Example

Consider again mapping $\mathcal{M}$ specified by:

$$emp(x, y, z) \wedge y \neq z \quad \rightarrow \quad shuttle(x, z)$$

This mapping is not a recovery of $\mathcal{M}$:

$$\mathcal{M}_3^\star: \quad shuttle(x, z) \quad \rightarrow \quad \exists u \, emp(x, z, u)$$

The notion of recovery: Formalization

Example (Cont'd)

On the other hand, these mappings are recoveries of $\mathcal{M}$:

$$\begin{array}{llcl}
\mathcal{M}_1^\star: & \mathit{shuttle}(x,z) & \rightarrow & \exists u \exists v\, \mathit{emp}(x,u,v) \\
\mathcal{M}_2^\star: & \mathit{shuttle}(x,z) & \rightarrow & \exists u\, \mathit{emp}(x,u,z) \\
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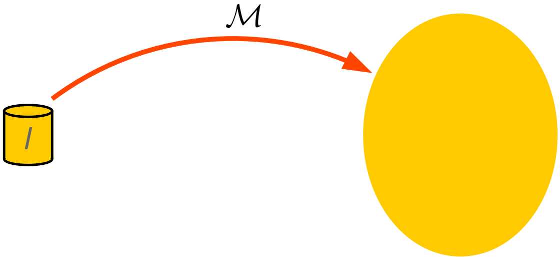
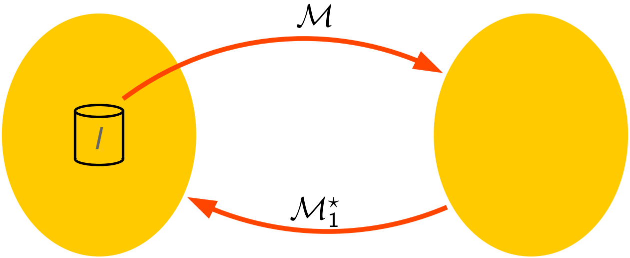
The notion of maximum recovery



The notion of maximum recovery



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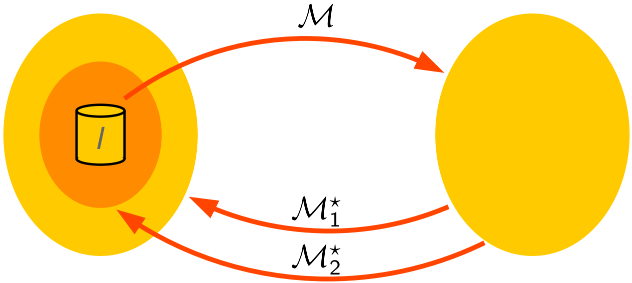

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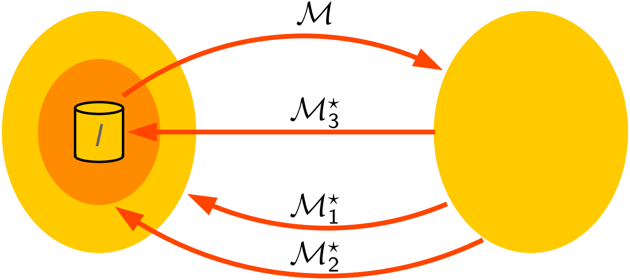

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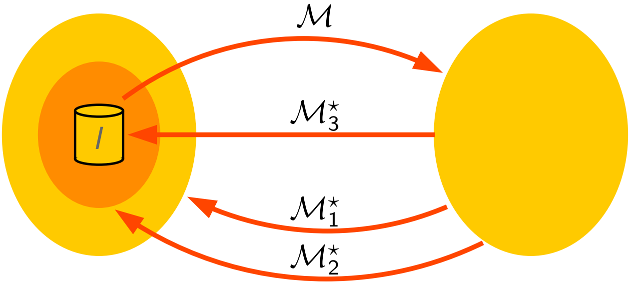

Definition (APR08)

$\mathcal{M}^\star$ is a maximum recovery of $\mathcal{M}$ if:

- $\mathcal{M}^\star$ is a recovery of $\mathcal{M}$
- for every recovery $\mathcal{M}'$ of $\mathcal{M}$: $\mathcal{M} \circ \mathcal{M}^\star \subseteq \mathcal{M} \circ \mathcal{M}'$

On the existence of maximum recoveries

Theorem (APR08)

Every mapping specified by a finite set of st-tgds has a maximum recovery.

On the existence of maximum recoveries

Theorem (APR08)

Every mapping specified by a finite set of st-tgds has a maximum recovery.

But this does not hold if one also considers naive instances in the source.

- Maximum extended recovery was introduced to overcome this limitation

We need to combine the operators

Can we combine the composition and inverse operators?

- Is there a good language for both operators?

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- Is there a good language for both operators?

Bad news:

Theorem (APR11)

There exists a mapping specified by an SO tgd that does not have a maximum recovery.

We need to combine the operators

Even worse:

- Previous mapping has neither a Fagin-inverse nor a quasi-inverse nor a $\mathcal{C}$-maximum recovery ($\mathbf{CQ} \subseteq \mathcal{C}$)
- Semantics of maximum extended recovery is appropriate for st-tgds.

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Do we need yet another notion of inverse?

- No, we need to revisit the semantics of mappings

What went wrong?

Key observation: A target instance of a mapping can be the source instance of another mapping.

- Sources instances may contain null values

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Theorem (APR11)

Positive conditional instances are a strong representation system for the class of mappings specified by SO tgds.

A solution to the problem

Theorem (APR11)

If (usual) instances are replaced by positive conditional instances:

- *SO tgds are still the right language for the composition of mappings given by st-tgds*
- *Every mapping specified by an SO tgd admits a maximum recovery*

Outline

- The need for a more general data exchange framework
  - Two important scenarios: Incomplete databases and knowledge bases
- Formalism for exchanging representations systems
- Applications to incomplete databases
- Applications to metadata management
- Concluding remarks

We can exchange more than complete data

We propose a general formalism to exchange *representation systems*

- Applications to incomplete instances
- Applications to metadata management
- Applications to knowledge bases

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Next step: Apply our general setting to the Semantic Web

- Semantic Web data has *nulls* (blank nodes)
- Semantic Web specifications have rules (RDFS, OWL)

Thank you!

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