Managing and Communicating Object Identities in Knowledge Representation and Information Systems

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IDENTIFYING AND COMMUNICATING REFERENCES

(TO OBJECTS/ENTITIES)

(Real world) Entities vs. (Computer) Representation(s)

Problem

- Information systems store information about *entities*
- Computers store (arrays of) `ints` and `strings`

How do we bridge the GAP?

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2. Keys (proxying entity *identity* by a unique combination of values (local))
   $\Rightarrow$ typically declared/managed by user (Relational DBMS).

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Performance: The PROTEL2 Case

every object WILL have an OID (say 64 bits)

⇒ storage/performance overhead (need to be generated/managed)

can we proxy by (storage) *address*?

what about memory/storage reuse and/or garbage collection??

what about data replication??

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What happens to an *object* stored in *different ORBs*??

$\Rightarrow$ what does `CORBA::Object::is_equivalent(in Object)` do??

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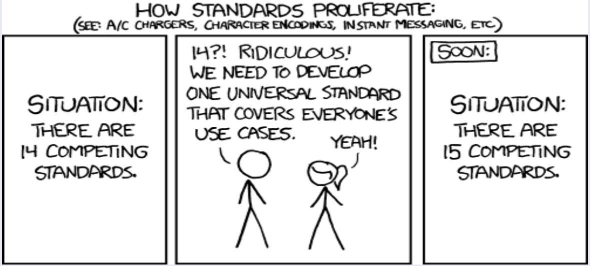
… and before someone mentions URL/URI/IRIs:



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Unintuitive Answers: RDF/Freebase/... Cases

Freebase The (object id of the) “Synchronicity” album by “The Police” is `/guid/9202a8c04000641f8000000002f9e349`

(as of April, 2015.)

W3C URI/IRI/... do not improve the situation

$\Rightarrow$ and RDF *introduces* additional internal identifiers!

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Missing (implied) Answers: The OBDA Case

In the presence of *background knowledge* we may *know* that certain objects exist, but we cannot identify/report them due to lack of an *explicit identifier*

(example later)

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Alternative Preferred Answers

Internal (computer) addresses vs. physical locations of equipment

⇒ programs need electronic address (to route the electric signals)
⇒ technicians need physical address (to find the equipmant in a data centre)

Goal of the Tutorial

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Introduce *referring expressions* as an uniform approach to identification of entities in information systems.

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Outline

- Referring Expressions in Philosophy/Linguistics
- Logical Foundations: Single Interpretations vs. Models of Theories
- Use of Referring Expressions in Information Systems
  1. Referring Expressions in Answers to Queries over Knowledge Bases
  2. Referring Expressions for Ground Knowledge
  3. Referring Expressions in Conceptual Design
- Summary and Open Problems

REFERRING EXPRESSIONS

(BACKGROUND)

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Russell: "On Denoting," Mind, New Series, Vol.14, No.56, pp. 479–493, 1905.

A *definite description* "the F is a G" is understood to have the form

$$\exists x.F(x) \wedge \forall y(F(y) \rightarrow x = y) \wedge G(x)$$

A definite description is a denoting phrase in the form of "the F" where F is a noun-phrase or a singular common noun. The definite description is proper if F applies to a unique individual or object.

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The discussion of *definite* and *indefinite* descriptions (in English, phrases of the form ‘the F’ and ‘an F’) has been at the centre of analytic philosophy for over a century (so we won’t go there today!).

Issues and Criticisms

Referring to Non-existing Object:

"The King of Kentucky (is. . .)" [Strawson]

(object does NOT exist in this interpretation? or *in principle*?)

Referring to Object in Context:

"The table (is covered with books)"

(non-unique reference without assuming additional context)

Multiple Reference:

"The Morning Star" vs. "The Evening Star" [Frege]

(multiple distinct references to the same object)

Rigidity:

Should referring expressions identify the same object in *all* possible worlds? [Kripke, S.: Identity and Necessity, In Identity and Individuation. NYU Press, pp. 135-164 (1971)]

. . .

Referring Expressions and (Logical) Theories

Referring to Objects

How do we *communicate* Results of Queries?

Typical solution: tuples of *constant symbols* that, when substituted for free variables, make a query *logically implied* by the Knowledge Base.

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Referring Expressions

More answers (e.g., objects *without* explicit name), and/or more informative/*preferred* answers, e.g.:

$$ALBUM \sqcap (title = \text{“Synchronicity”}) \sqcap (band = \text{“The Police”})$$

Single Interpretations vs. (non-trivial) Logical Theories

Russell's *Definite Descriptions* . . . denote exactly *one* object

What happens if we consider *logical theories* rather than a *particular model*?

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$\Rightarrow$ (standard) constants don't quite satisfy Russell's/Kripke's requirements

Rigidity and Genericity: DB Theory Way

Why not require constants to be *rigid designators*?

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Database (theory) Approach

- Database Instances (aka models) *use rigid constants*, but
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  $\Rightarrow$ invariant under permutations of the underlying domain

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Certain Answers (to $\varphi\{x\}$ in $\mathcal{K}$)

1. Logical Definition: $\{a \mid \mathcal{K} \models \varphi[a/x]\}$
2. DB Definition: $\bigcap_{I \models K} \{a \mid \mathcal{I}, [x \mapsto a] \models \varphi\}$

   (conflates constants with domain elements)

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   (conflates constants with domain elements)

... for generic (and domain-independent) queries the result is *the same*!

Bottom Line

Referring Expressions

Formulæ $\phi\{x\}$ (in the language of the Knowledge Base)

1. with *exactly one free variable* (x) that are
2. *singular* with respect to a Knowledge Base $\mathcal{K}$, i.e.,

$$|\{o \mid \mathcal{I}, [x \mapsto o] \models \phi\}| = 1$$

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Why not *terms*?

Terms (with the standard FO semantics) suffer from *totality*

$\Rightarrow$ must denote *something* in *every* interpretation

Referring to Objects (fine print)

The rest of the presentation is based on

KR16 Alexander Borgida, David Toman, and Grant E. Weddell: On Referring Expressions in Query Answering over First Order Knowledge Bases. Proc. *International Conference on Principles of Knowledge Representation and Reasoning* KR 2016, 319-328, 2016.

ER16 Alexander Borgida, David Toman, and Grant Weddell: On Referring Expressions in Information Systems Derived from Conceptual Modelling. Proc, *International Conference on Conceptual Modeling* ER 2016, 183-197, 2016.

AI16 David Toman, and Grant Weddell: Ontology Based Data Access with Referring Expressions for Logics with the Tree Model Property. Proc. *Australasian Joint Conference on Artificial Intelligence*, 2016.

EKAW18 Weicong Ma, C. Maria Keet, Wayne Oldford, David Toman, and Grant Weddell: The Utility of the Abstract Relational Model and Attribute Paths in SQL. Proc. *International Conference on Knowledge Engineering and Knowledge Management*, 195-211, EKAW 2018.

DL18 David Toman and Grant E. Weddell: Identity Resolution in Conjunctive Querying over DL-based Knowledge Bases. Proc. *Description Logics* DL 2018, 2018 (to appear in PRICAI 2019).

DL19 David Toman, Grant E. Weddell: Exhaustive Query Answering via Referring Expressions. Proc. *Description Logics* DL 2019, 2019 (under review).

Ontology Based Data Access

(Better query answers when querying Knowledge Bases)

Queries and Ontologies

Ontology-based Data Access

Enriches (query answers over) *explicitly represented data* using *background knowledge* (captured using an *ontology*.)

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Example

- Bob is a BOSS (explicit data)
- Every BOSS is an EMPloyee (ontology)

List all EMPloyees $\Rightarrow \{\text{Bob}\}$ (query)

Goal: compute all *certain answers*

$\Rightarrow$ answers *common* in all models of KB (aka. answers *logically implied* by KB)

Approaches to Ontology-based Data Access

Main Task

INPUT: $\underbrace{\text{Ontology } (\mathcal{T}), \text{ Data } (\mathcal{A})}_{\text{Knowledge Base}(\mathcal{K})}$, and a Query ($Q$)

OUTPUT: $\{a \mid \mathcal{K} \models Q[a]\}$

1. Reduction to *standard reasoning* (e.g., satisfiability)
2. Reduction to *querying a relational database*

   $\Rightarrow$ *very* good at $\{a \mid \mathcal{A} \models Q[a]\}$ for range restricted Q

   $\Rightarrow$ what to do with $\mathcal{T}$??

   1. incorporate into Q (perfect rewriting for DL-Lite et al. (AC^0 logics)); or
   2. incorporate into $\mathcal{A}$ (combined approach for $\mathcal{EL}$ (PTIME-complete logics));

   or sometimes both ($\mathcal{CFDI}$ logics).

Issues with the Standard Definition of Answers

“David is a UWaterloo Employee” and “every Employee has a Phone”

Question: Does David have a Phone?

Answer: YES

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Better Answers (possibly)

1. it is a phone *with phone # +1(519) 888-4567x34447*;
2. it is a *UWaterloo* phone *with an extension x34447*;
3. it is a phone *in the Davis Centre, Office 3344*;
4. it is a *Waterloo* phone *attached to port* `0x0123abcd`;
5. it is a *Waterloo CS* phone *with inventory # 100034447*;
6. it is *David's* phone (??)

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7. it is the *red phone* ; ×

Referring Expressions (revisited)

Definition (Singular Referring Expression)

... is a unary formula that, when used as a query answer, identifies *a particular* object in this query answer.

"David is a UWaterloo Employee" and "every Employee has a Phone"

1. it is a phone x s.t. PhoneNo(x, "+1(519) 888-4567x34447") holds; ✓
2. it is a phone x s.t. UWPhone(x) $\wedge$ PhoneExt(x, "x34447") holds; ✓
3. it is a phone x s.t. UWRoom(x, "DC3344") holds; ✓
4. it is a phone x s.t. UWPhone(x) $\wedge$ PhonePort(x, `0x0123abcd`) holds; ✓
5. it is a phone x s.t. UWCSPhone(x) $\wedge$ InvNo(x, "100034447") holds; ✓
6. it is a phone x s.t. IsOwner("David", x) holds; ×
7. it is the phone x s.t. Colour(x, "red") holds; ×

From Query Answers to Referring Expressions [KR16]

(Certain) Query Answers

Given a query $\psi\{x_1, \ldots, x_k\}$ and a KB $\mathcal{K}$;

- Classical answers: *substitutions*

$$\theta = \{x_1 \mapsto a_1, \ldots, x_k \mapsto a_k\}$$

that map free variables of ψ to constants *that appear in* $\mathcal{K}$ and $\mathcal{K} \models \psi\theta$.

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- Referring Expression-based answers: *R-substitutions*

$$\theta = \{x_1 \mapsto \phi_1\{x_1\}, \ldots, x_k \mapsto \phi_k\{x_k\}\}$$

  where $\phi_i\{x_i\}$ are *unary formulæ in the language of $\mathcal{K}$* such that

  1. $\forall x_1, \ldots, x_k.(\phi_1 \wedge \ldots \wedge \phi_k) \rightarrow \psi$ (soundness)
  2. $\exists x_1, \ldots, x_k.(\phi_1 \wedge \ldots \wedge \phi_k) \wedge \psi$ (existence)
  3. $\forall x_1, \ldots, x_k, y_i.\phi_1 \wedge \ldots \wedge \phi_k \wedge \psi \wedge \phi_i[x_i/y_i] \wedge \psi[x_i/y_i] \rightarrow x_i = y_i$ (singularity)

  ... are logically implied by $\mathcal{K}$.

Infinite number of Answers

$$\mathcal{T} = \{ \text{fatherof}(x, y) \rightarrow (\text{Father}(x) \wedge \text{Person}(y)),$$
$$\text{Father}(x) \rightarrow \text{Person}(x),$$
$$\text{Father}(x) \rightarrow \exists y.\text{fatherof}(x, y),$$
$$\text{Person}(x) \rightarrow \exists y.\text{fatherof}(y, x)$$
$$\}$$

$$\mathcal{A} = \{ \text{Father}(\text{fred}), \text{Person}(\text{mary}) \}$$

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Query: $\text{Father}(x)$?

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Query: $\text{Father}(x)$?

Answers: $x = \text{fred}, \text{fatherof}(x, \text{mary})$

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Answers: $x = \text{fred}, \text{fatherof}(x, \text{mary}), \exists y.\text{fatherof}(x,y) \wedge \text{fatherof}(y, \text{mary}), \ldots$
$\text{fatherof}(x, \text{fred}), \exists y.\text{fatherof}(x,y) \wedge \text{fatherof}(y, \text{fred}), \ldots$

Infinite number of Answers

$$\mathcal{T} = \{\ \text{fatherof}(x,y) \rightarrow (\text{Father}(x) \wedge \text{Person}(y)),$$
$$\text{Father}(x) \rightarrow \text{Person}(x),$$
$$\text{Father}(x) \rightarrow \exists y.\text{fatherof}(x,y),$$
$$\text{Person}(x) \rightarrow \exists y.\text{fatherof}(y,x)$$
$$\text{fatherof}(x,z) \wedge \text{fatherof}(y,z) \rightarrow x = y \quad \}$$

$$\mathcal{A} = \{\ \text{Father}(\text{fred}), \text{Person}(\text{mary})\ \}$$

Query: $\text{Father}(x)$?

Answers: $x = \text{fred}$, $\text{fatherof}(x,\text{mary})$, $\exists y.\text{fatherof}(x,y) \wedge \text{fatherof}(y,\text{mary})$, ...
$\text{fatherof}(x,\text{fred})$, $\exists y.\text{fatherof}(x,y) \wedge \text{fatherof}(y,\text{fred})$, ...

Query: $\text{Person}(x)$?

Infinite number of Answers

$$\mathcal{T} = \{\ \text{fatherof}(x, y) \rightarrow (\text{Father}(x) \wedge \text{Person}(y)),$$
$$\text{Father}(x) \rightarrow \text{Person}(x),$$
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Query: $\text{Father}(x)$?

Answers: $x = \text{fred}$, $\text{fatherof}(x, \text{mary})$, $\exists y.\text{fatherof}(x, y) \wedge \text{fatherof}(y, \text{mary})$, ...
$\text{fatherof}(x, \text{fred})$, $\exists y.\text{fatherof}(x, y) \wedge \text{fatherof}(y, \text{fred})$, ...

Query: $\text{Person}(x)$?

Answers: $x = \text{mary}$, $x = \text{fred}$

Infinite number of Answers

$$\mathcal{T} = \{ \text{fatherof}(x, y) \rightarrow (\text{Father}(x) \wedge \text{Person}(y)),$$
$$\text{Father}(x) \rightarrow \text{Person}(x),$$
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$$\text{fatherof}(x, z) \wedge \text{fatherof}(y, z) \rightarrow x = y \quad \}$$

$$\mathcal{A} = \{ \text{Father}(\text{fred}), \text{Person}(\text{mary}) \}$$

Query: $\text{Father}(x)$?

Answers: $x = \text{fred}$, $\text{fatherof}(x, \text{mary})$, $\exists y.\text{fatherof}(x, y) \wedge \text{fatherof}(y, \text{mary})$, ...
$\text{fatherof}(x, \text{fred})$, $\exists y.\text{fatherof}(x, y) \wedge \text{fatherof}(y, \text{fred})$, ...

Query: $\text{Person}(x)$?

Answers: $x = \text{mary}$, $x = \text{fred}$, $\text{fatherof}(\text{fred}, x)$ (NO!)

Infinite number of Answers

$$\mathcal{T} = \{ \text{fatherof}(x, y) \rightarrow (\text{Father}(x) \land \text{Person}(y)),$$
$$\text{Father}(x) \rightarrow \text{Person}(x),$$
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Query: $\text{Father}(x)$?

Answers: $x = \text{fred}$, $\text{fatherof}(x, \text{mary})$, $\exists y.\text{fatherof}(x, y) \land \text{fatherof}(y, \text{mary})$, ...
$\text{fatherof}(x, \text{fred})$, $\exists y.\text{fatherof}(x, y) \land \text{fatherof}(y, \text{fred})$, ...

Query: $\text{Person}(x)$?

Answers: $x = \text{mary}$, $x = \text{fred}$, $\text{fatherof}(\text{fred}, x)$ (NO!)
$\text{fatherof}(x, \text{mary})$, $\text{fatherof}(x, \text{fred})$, ...

Infinite number of Answers II

$$\mathcal{T} = \{ \text{spouse}(x, y) \rightarrow \text{spouse}(y, x),$$
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$$\mathcal{A} = \{\ \text{spouse}(\text{mary}, \text{fred})\ \}$$

Query: $\text{spouse}(x, \text{mary})$?

Answers: $x = \text{fred}$

Infinite number of Answers II

$$\mathcal{T} = \{ \text{spouse}(x, y) \rightarrow \text{spouse}(y, x),$$
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$$\mathcal{A} = \{ \text{spouse}(\text{mary}, \text{fred}) \}$$

Query: $\text{spouse}(x, \text{mary})$?

Answers: $x = \text{fred}$, $\text{spouse}(x, \text{mary})$

Infinite number of Answers II

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Query: $\text{spouse}(x, \text{mary})$?

Answers: $x = \text{fred}$, $\text{spouse}(x, \text{mary})$, $\exists y.\text{spouse}(x, y) \wedge \text{spouse}(y, \text{fred})$, ...

How many *distinct* answers to $\exists y.\text{spouse}(x, y)$?

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$\text{fred} = \text{spouse}(x, \text{mary}) = \exists y.\text{spouse}(x, y) \wedge \text{spouse}(y, \text{fred}) = \ldots$

Infinite number of Answers II

$$\mathcal{T} = \{ \text{spouse}(x, y) \to \text{spouse}(y, x),$$
$$\text{spouse}(x, z) \wedge \text{spouse}(y, z) \to x = y$$
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$\text{mary} = \text{spouse}(x, \text{fred}) = \exists y.\text{spouse}(x, y) \wedge \text{spouse}(y, \text{mary}) = \ldots$

Infinite number of Answers II

$$\mathcal{T} = \{ \text{spouse}(x, y) \rightarrow \text{spouse}(y, x), \\ \text{spouse}(x, z) \wedge \text{spouse}(y, z) \rightarrow x = y \\ \text{spouse}(x, y) \rightarrow x \neq y \}$$

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$\text{mary} \neq \text{fred}$ (last constraint!)

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How many *distinct* answers to $\exists y.\text{spouse}(x, y)$?

$\text{fred} = \text{spouse}(x, \text{mary}) = \exists y.\text{spouse}(x, y) \wedge \text{spouse}(y, \text{fred}) = \ldots$
$\text{mary} = \text{spouse}(x, \text{fred}) = \exists y.\text{spouse}(x, y) \wedge \text{spouse}(y, \text{mary}) = \ldots$
$\text{mary} \neq \text{fred}$ (last constraint!) $\Rightarrow$ exactly 2 distinct certain answers

Infinite number of Answers: Finite Representation

How do we deal with multiple referring expression answers/preferences/. . . ?

- potentially too many implied answers (infinitely many!)
- potentially too many ways to refer to the same object

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Can we (somehow) get *ALL* answers to Q over $\mathcal{K}$?

Yes (for logics with *recursively enumerable* logical consequence):

for all (tuples of) unary formulas $\varphi(x)$
do test if $\varphi(x)$ is a singular certain answer to Q in $\mathcal{K}$.

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for all (tuples of) unary formulas $\varphi(x)$

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$\Rightarrow$ but is there a *finite representation*?

Example: Horn Logics with Tree Models [DL19]

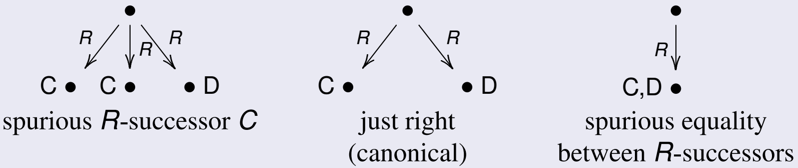
What to do $\mathcal{EL}^{\bot}$ (and Horn-$\mathcal{ALC}$)?

- *singularity* requires *role functionality* (not expressible in $\mathcal{EL}^{\bot}$/Horn-$\mathcal{ALC}$)

Example: Horn Logics with Tree Models [DL19]

What to do $\mathcal{EL}^\perp$ (and Horn-$\mathcal{ALC}$)?

- *singularity* requires *role functionality* (not expressible in $\mathcal{EL}^\perp$/Horn-$\mathcal{ALC}$)
- (Tree) Models of $a : \exists R.C \sqcap \exists R.D$:



$\Rightarrow$ *singular **certain** answers*: singular in a canonical model

How Does it Work?

Base Case: Instance Retrieval $B(x)$ over $\mathcal{T}$ and $\mathcal{A} = \{a : A\}$

Looping automaton-like construction

$\Rightarrow$ only non-redundant successors in matching tuples
$\Rightarrow$ preserves complexity bounds for both logics

How Does it Work?

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Generalizations&Limitations

1. General ABoxes and Conjunctive Queries
   $\Rightarrow$ lots of case analysis followed by existing approaches
2. Finite representation of answers (succinctness??)
3. More Expressive Logics
   $\Rightarrow$ this will NOT work with *at-least* restrictions (*functionality* is fine)
4. Non-Horn Logics
   $\Rightarrow$ non-unique canonical models
   $\Rightarrow$ disjunctions in referring expressions (questionable)

Infinite number of Answers: Typing Restrictions

How do we deal with multiple referring expression answers/preferences/…?

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Referring Expression Types and Typed Queries

Types: $Rt ::= Pd = \{?\} \mid Rt_1 \wedge Rt_2 \mid T \rightarrow Rt \mid Rt_1; Rt_2$

$\Rightarrow$ each type induces a set of unary formulæ;

Queries: **select** $x_1 : Rt_1, \ldots, x_k : Rt_k$ **where** ψ

$\Rightarrow$ $x_1 : Rt_1, \ldots, x_k : Rt_k$ is called the head, ψ is the body.

Examples of Typed Queries

Reference via a Single-Attribute Key

"The ssn# of any person with phone 1234567"

$$\textbf{select } x : \mathit{ssn\#} = \{?\}$$
$$\textbf{where } \mathit{Person}(x) \land \mathit{phone\#}(x, 1234567)$$

Examples of Typed Queries

Reference via a Single-Attribute Key

Reference by a Multi-Attribute Key

"The title and publisher of any journals"

$$\textbf{select } x : \textit{title} = \{?\} \wedge \textit{publishedBy} = \{?\}$$
$$\textbf{where } \textit{Journal}(x)$$

Examples of Typed Queries

Reference via a Single-Attribute Key

Reference by a Multi-Attribute Key

Choice of Identification in a Heterogeneous Set

"Any legal entity"

$$\textbf{select } x : \textit{Person} \rightarrow \textit{ssn\#} = \{?\} \; ; \; \textit{Company} \rightarrow \textit{tickerSymbol} = \{?\} \quad \textbf{where } \textit{LegalEntity}(x)$$

answers: $\{x \mapsto \textit{Person}(x) \wedge \textit{ssn\#}(x, 7654)\}$
$\{x \mapsto \textit{Company}(x) \wedge \textit{tickerSymbol}(x, \text{“IBM”})\}$.

Examples of Typed Queries

Reference via a Single-Attribute Key

Reference by a Multi-Attribute Key

Choice of Identification in a Heterogeneous Set

Preferred Identification

"Any publication, identified by its most specific identifier, when available."

$$\begin{array}{l} \textbf{select } x : \textit{Journal} \rightarrow (\textit{title} = \{?\} \land \textit{publisher} = \{?\}); \\ \quad\quad\quad \textit{EditedCollection} \rightarrow \textit{isbn\#} = \{?\} \ ; \ \{?\} \\ \textbf{where } \textit{Publication}(x) \end{array}$$

answers:

$$\{x \mapsto \textit{Journal}(x) \land \textit{title}(x, \text{"AIJ"}) \land \textit{publisher}(x, \text{"Elsevier"})\}$$
$$\{x \mapsto \textit{EditedCollection}(x) \land \textit{isbn\#}(x, 123456789)\}$$
$$\{x \mapsto x = \texttt{/guid/9202a8c04000641f8000000...}\}.$$

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Desiderata: only Referring Expressions that Conform to a certain

Given
1. a KB $\mathcal{K}$ (the "background knowledge"),
2. a query $\psi\{x_1, \ldots, x_k\}$, and
3. (specifications of) sets of unary formulæ $S_1, \ldots, S_k$

We ask whether, for *every* $\mathcal{K}'$ (the "data") consistent with $\mathcal{K}$ and an *answer*

$$\theta = \{x_1 \mapsto \phi_1\{x_1\}, \ldots, x_k \mapsto \phi_k\{x_k\}\}$$

to ψ with respect to $\mathcal{K} \cup \mathcal{K}'$ such that $\phi_i \in S_i$, *it is the case that θ is singular*.

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Theorem (Weak Identification; paraphrased)

Given a query ψ with a head H and a KB $\mathcal{K}$, the question

"are all answers to ψ conforming to H over any $\mathcal{K} \cup \mathcal{K}'$ singular?"

reduces to logical implication in the underlying logic of $\mathcal{K}$.

REQA (Referring Expression-based QA)

GOAL: reduce REQA to standard OBDA (used as an *oracle*)

REQA (outline, unary queries only)

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Input: $\mathcal{K}$ (background knowledge), $\mathcal{K}'$ (data), $\psi\{x\}$ (query), H (query head)

1. Normalize H to $H_1; \ldots; H_\ell$, each of the form
$$T_i \rightarrow Pd_{i,1} = \{?\} \wedge \ldots \wedge Pd_{i,k_i} = \{?\};$$
2. Create queries $\psi_i\{x, y_1, \ldots, y_{k_i}\}$ as
$$\psi \wedge T_i(x) \wedge Pd_{i,1}(x, y_1) \wedge \ldots \wedge Pd_{i,k_i}(x, y_{k_i});$$
3. Create $\mathcal{K}_i$ with a witnesses for x when no such witness exists;
4. Evaluate $\mathcal{K} \cup \mathcal{K}' \cup \mathcal{K}_i \models \psi_i$ (OBDA oracle);
5. Resolve preferences (based on value of x); and
6. Reconstruct a referring expression from the values of $y_1, \ldots, y_{k_i}$.

... extends naturally to higher arity queries: (more) messy

The Tractable (practical) Cases

DL-Lite$^{\mathcal{F}}_{core}(idc)$:

- Weak identification $\longrightarrow$ sequence of KB consistency tests
- Query answering $\longrightarrow$ REQA
  + Witnesses for x w.r.t. H + Perfect Reformulation

$\mathcal{CFDI}^{\forall}_{nc}$:

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- Query answering $\longrightarrow$ REQA
  + Combined Combined Approach

Logics with Tree Models (outside an ABox) [AI16]

The witnesses for anonymous objects (step (3))
$\longrightarrow$ *last* named individual on a path *towards* the anonymous object

RECORDING/REPRESENTING FACTUAL DATA

Referring Expressions for Ground Knowledge

Standard approach: constant symbols $\sim$ objects (and values!)

$\Rightarrow$ needs a constant symbol for *every individual* (Skolems?)

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How are *external* objects identified in a KB?

- Two PERSON objects, o_1 and o_2, identified by their *ssn* value:

$$\text{PERSON} \sqcap \exists \mathit{ssn}.\{123\} \text{ and } \text{PERSON} \sqcap \exists \mathit{ssn}.\{456\}.$$

- Role (feature) assertions of the form $\mathit{mother}(o_1) = o_2$ can then be captured as:

$$\text{PERSON} \sqcap \exists \mathit{ssn}.\{123\} \sqcap \exists \mathit{mother}.(\text{PERSON} \sqcap \exists \mathit{ssn}.\{345\}).$$

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$$\text{PERSON} \sqcap \exists ssn.\{123\} \sqcap \exists mother.(\text{PERSON} \sqcap \exists ssn.\{345\}).$$

Issues:

- admissibility: what descriptions qualify here? $\Rightarrow$ singularity!
- minimality: is the description succinct? (similar to keys/superkeys issues)

Referring Expressions for Ground Knowledge

Example

JSON fragment describing persons, hypothetically occurring in a MongoDB document source:

```
{"fname" : "John", "lname" : "Smith", "age" : 25,
  "phoneNum" : [
    {"loc" : "home", "dialnum" : "212 555-1234"},
    {"loc" : "work", "dialnum" : "212 555-4567"}
  ]}
```

can be naturally and directly represented as a CBox assertion of the form

$$\begin{aligned}&\text{PERSON} \sqcap (\exists \mathit{fname}.\{\text{“John”}\}) \sqcap (\exists \mathit{lname}.\{\text{“Smith”}\}) \sqcap \exists \mathit{age}.\{25\}\\ &\quad \sqcap \exists \mathit{phoneNumFor}^{-1}.((\exists \mathit{loc}.\{\text{“home”}\}) \sqcap (\exists \mathit{dialnum}.\{\text{“212 555-1234”}\}))\\ &\quad \sqcap \exists \mathit{phoneNumFor}^{-1}.((\exists \mathit{loc}.\{\text{“work”}\}) \sqcap (\exists \mathit{dialnum}.\{\text{“212 555-4567”}\}))\end{aligned}$$

This assertion is admissible, e.g., whenever the combination of *fname* and *lname* identifies PERSONs.

Heterogeneous Data Integration (example)

Example

- TBox $\mathcal{T} = \{ \quad \text{FRIEND} \sqsubseteq \text{PERSON},$
  $\text{FRIEND} \sqsubseteq \text{PERSON} : \mathit{fname} \rightarrow \mathit{id},$
  $\text{MATRIARCH} \sqsubseteq \text{PERSON},$
  $\text{MATRIARCH} \sqsubseteq \text{PERSON} : \mathit{lname} \rightarrow \mathit{id},$
  $\text{PERSON} \sqsubseteq \text{PERSON} : \mathit{fname}, \mathit{lname} \rightarrow \mathit{id}, \ldots \quad \}$
- CBox $\mathcal{C} = \{ \quad \text{FRIEND} \sqcap \exists \mathit{fname}.\{\text{“Mary”}\},$
  $\text{PERSON} \sqcap (\exists \mathit{fname}.\{\text{“Mary”}\}) \sqcap (\exists \mathit{lname}.\{\text{“Smith”}\}),$
  $\text{MATRIARCH} \sqcap \exists \mathit{lname}.\{\text{“Smith”}\}, \ldots \quad \}$

Heterogeneous Data Integration (example)

Example

- TBox $\mathcal{T} = \{$ FRIEND $\sqsubseteq$ PERSON,
  FRIEND $\sqsubseteq$ PERSON : *fname* $\rightarrow$ *id*,
  MATRIARCH $\sqsubseteq$ PERSON,
  MATRIARCH $\sqsubseteq$ PERSON : *lname* $\rightarrow$ *id*,
  PERSON $\sqsubseteq$ PERSON : *fname*, *lname* $\rightarrow$ *id*, ... $\}$
- CBox $\mathcal{C} = \{$ FRIEND $\sqcap$ $\exists$*fname*.{"Mary"},
  PERSON $\sqcap$ ($\exists$*fname*.{"Mary"}) $\sqcap$ ($\exists$*lname*.{"Smith"}),
  MATRIARCH $\sqcap$ $\exists$*lname*.{"Smith"}, ... $\}$

Heterogeneous Identification

"FRIEND $\sqcap$ $\exists$*fname*.{"Mary"}" identifies *the same object* as "PERSON $\sqcap$ ($\exists$*fname*.{"Mary"}) $\sqcap$ ($\exists$*lname*.{"Smith"})" and in turn as "MATRIARCH $\sqcap$ $\exists$*lname*.{"Smith"}"

Heterogeneous Data Integration (example)

Example

- TBox $\mathcal{T} = \{ \quad \text{FRIEND} \sqsubseteq \text{PERSON}, \\ \text{FRIEND} \sqsubseteq \text{PERSON} : \mathit{fname} \rightarrow \mathit{id}, \\ \text{MATRIARCH} \sqsubseteq \text{PERSON}, \\ \text{MATRIARCH} \sqsubseteq \text{PERSON} : \mathit{lname} \rightarrow \mathit{id}, \\ \text{PERSON} \sqsubseteq \text{PERSON} : \mathit{fname}, \mathit{lname} \rightarrow \mathit{id}, \ldots \quad \}$
- CBox $\mathcal{C} = \{ \quad \text{FRIEND} \sqcap \exists \mathit{fname}.\{\text{“Mary”}\}, \\ \text{PERSON} \sqcap (\exists \mathit{fname}.\{\text{“Mary”}\}) \sqcap (\exists \mathit{lname}.\{\text{“Smith”}\}), \\ \text{MATRIARCH} \sqcap \exists \mathit{lname}.\{\text{“Smith”}\}, \ldots \quad \}$

Heterogeneous Identification

“$\text{FRIEND} \sqcap \exists \mathit{fname}.\{\text{“Mary”}\}$” identifies *the same object* as “$\text{PERSON} \sqcap (\exists \mathit{fname}.\{\text{“Mary”}\}) \sqcap (\exists \mathit{lname}.\{\text{“Smith”}\})$” and in turn as “$\text{MATRIARCH} \sqcap \exists \mathit{lname}.\{\text{“Smith”}\}$”

. . . and thus is an answer to $\{x \mid \text{MATRIARCH}(x)\}$.

Minimality

IDEA: minimal referring expressions (ala Candidate Keys)

C is a referring expression singular w.r.t. a TBox $\mathcal{T}$ (e.g., a *superkey*)

- C's subconcepts A, $\{a\}$, $\exists f.\top$, $\exists f^{-1}.\top$, and $\top \sqcap \top$ are *leaves* of C.
- $C[L \mapsto \top]$ is a description C in which a leaf L was replaced by $\top$.
- "first-leaf" and "next-leaf" successively enumerate all leaves of C.

1. $L :=$ first-leaf(C);
2. **while** $C[L \mapsto \top]$ is singular w.r.t. $\mathcal{T}$ **do**
3. $\quad C := C[L \mapsto \top]$; $L :=$ next-leaf(C);
4. **done**
5. **return** C;

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$\Rightarrow$ computes a syntactically-minimal co-referring expression for C.
$\Rightarrow$ order of enumeration $\rightarrow$ variant minimal co-referring expressions.

Reasoning and QA with CBoxes [DL18]

Theorem (CBox Admissibility)

Let $\mathcal{T}$ be a $\mathcal{CFDI}_{nc}^{\forall}$ TBox and C a concept description. Then C is a singular referring expression w.r.t. $\mathcal{T}$ if and only if the knowledge base

$$(\mathcal{T} \cup \{A \sqsubseteq \neg B\}, \mathrm{Simp}(a : C) \cup \mathrm{Simp}(b : C) \cup \{a : A, b : B\})$$

is inconsistent, where a and b are distinct constant symbols, and A and B are primitive concepts not occurring in $\mathcal{T}$ and C.

Theorem (Satisfiability of KBs with CBoxes)

Let $\mathcal{K} = (\mathcal{T}, \mathcal{C})$ be a knowledge base with an admissible CBox $\mathcal{C}$. Then $\mathcal{K}$ is consistent iff $(\mathcal{T}, \mathrm{Simp}(\mathcal{C}))$ is consistent.

Theorem (Query Answering)

Let $\mathcal{K} = (\mathcal{T}, \mathcal{C})$ be a consistent knowledge base and $Q = \{(x_1, \ldots, x_k) : \varphi\}$ a conjunctive query over $\mathcal{K}$. Then $(C_1, \ldots, C_k)$ is a certain answer to Q in $\mathcal{K}$ if and only if $(a_{C_1}, \ldots, a_{C_k})$ is a certain answer to Q over $(\mathcal{T}, \mathrm{Simp}(\mathcal{C}))$.

Conceptual Modelling

(Decoupling *modelling* from *identification* issues)

Conceptual Modeling and Identification [ER16]

Thesis:

Modeling of *Entities* and their *Relationships* **should be decoupled** from issues of *managing the identity* of such entities.

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Weak Entities and dominant entity identification

Example (`ROOM` within `BUILDING`)

For the entity set `ROOM` with attributes `room-number` and `capacity`

$\Rightarrow$ natural attributes are insufficient to identify `ROOM`s

$\Rightarrow$ need for a *key* of dominant set, such as `BUILDING`

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Weak Entities and dominant entity identification

Preferred Identification in sub/super-classes

Example (`PERSON` and `FAMOUS-PERSON`)

For the entity set `FAMOUS-PERSON` a sub-entity of `PERSON`

⇒ choice of key (`ssn`) for `PERSON` forces *the same* key for `FAMOUS-PERSON`

⇒ we may *prefer* to use `name` in this case (e.g., *Eric Clapton* or *The Edge*)

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Generalizations and heterogeneity

Example (`LEGAL-ENTITY`: `PERSON` or `COMPANY`)

For the entity set `LEGAL-ENTITY` a generalization of `PERSON` and `COMPANY`

$\Rightarrow$ commonly *required* to create an *artificial* attribute `le-num`
$\Rightarrow$ despite the fact that all entities are already identified
by the (more) natural `ssn` and (`name,city`) identifiers.

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Generalizations and heterogeneity

Contributions

1. Methodology that allows decoupling identification from modeling;
2. Referring Expressions that subsequently resolve identity issues; and
3. Compilation-based technology that makes further translation to a *pure relational model* seamless.

Abstract (Relational) Model ARM

A simple conceptual model $\mathcal{C}$

Common features of so-called “attribute-based” semantic models

$\Rightarrow$ class hierarchies, disjointness, coverage, attributes and typing, functional dependencies, ...

Example (DMV)

```
class PERSON (ssn: INT, name: STRING,
  isa LEGAL-ENTITY, disjoint with VEHICLE)
class COMPANY (name: STRING, city: STRING,
  isa LEGAL-ENTITY)
class LEGAL-ENTITY (covered by PERSON, COMPANY)
class VEHICLE (vin: INT, make: STRING,
  owned-by: LEGAL-ENTITY)
class CAN-DRIVE (driver: PERSON, driven: VEHICLE)
```

Abstract (Relational) Model ARM

A simple conceptual model ARM

Common features of so-called “attribute-based” semantic models

$\Rightarrow$ class hierarchies, disjointness, coverage, attributes and typing, functional dependencies, . . .

Example (DMV and Relational Understanding)

```
table PERSON (self: OID, ssn: INT, name: STRING,
  isa LEGAL-ENTITY, disjoint with VEHICLE)
table COMPANY (self: OID, name: STRING, city: STRING,
  isa LEGAL-ENTITY)
table LEGAL-ENTITY (covered by PERSON, COMPANY)
table VEHICLE (self: OID, vin: INT, make: STRING,
  owned-by: LEGAL-ENTITY)
table CAN-DRIVE (self: OID, driver: PERSON, driven: VEHICLE)
```

Abstract Relational Queries

SQLP

(pretty) standard `select-from-where-union-except` SQL syntax

. . . with extensions to ARM: abstract attributes (`OID`) and attribute paths

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- *The name of anyone who can drive a vehicle made by Honda*:

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select d.driver.name from CAN-DRIVE d
where d.driven.make = 'Honda'
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  attribute paths in the `select` and `where` clauses

- *The owners of Mitsubishi vehicles*:

```
select v.owned-by from VEHICLE v
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 heterogeneous results (`PERSON`s and `COMPAN`ies)

Note that queries **do NOT** rely on *(external) identification* of entities/objects.

How to Make this Technology Succeed?

1. ARM/SQLP Helps Users (User Study) [EKAW18]
2. ARM/SQLP Can be Efficiently Implemented [ER16]
   - Mapping to *standard relational model* with the help of *referring expressions*
   - Reverse-Engineering ARM from Legacy Relational Schemata

Experimental Design (HCI experiments)

Hypotheses

H_t: no difference between RM/SQL and ARM/SQLP in the mean time taken

H_c: no difference between RM/SQL and ARM/SQLP in the mean correctness

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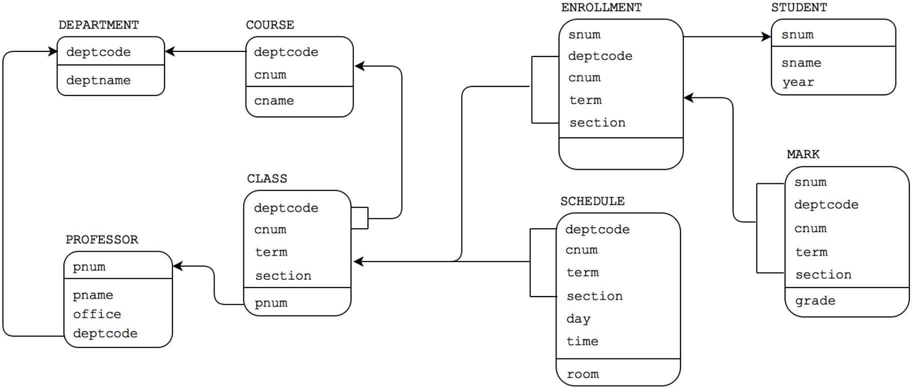
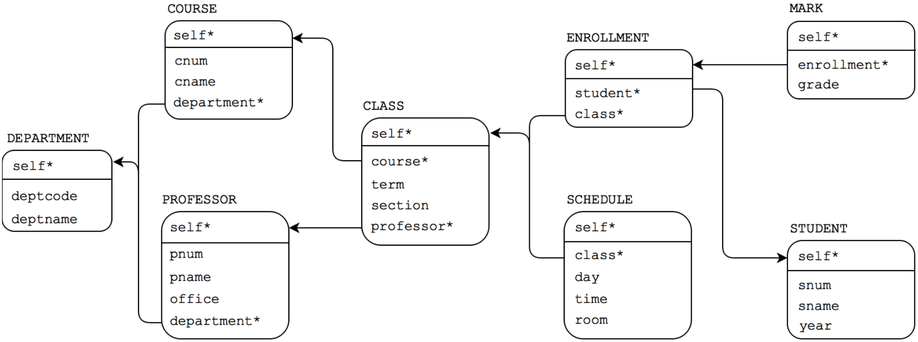
Methods

- Undergraduate (9) and Graduate (15) UW students
- Protocol
  1. Instructions (5”) and Examples of SQL/SQLP (10”)
  2. Six Questions (Q1–Q6), no time limit
  3. Subjects recorded start/end times for each Question
- Performance Assessment
  1. 3 assessors
  2. agreed upon grading scale

Course Enrollment as an RM Schema



Course Enrolment as an ARM Schema



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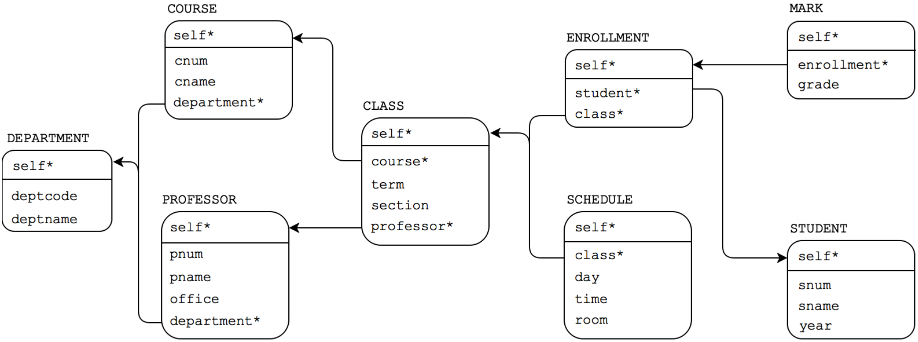

ARM *completely frees* domain experts/users from the need to understand how entities are *identified* in an information system.

Example Queries

Query: *Names of students who have been taught by ‘Prof. Alan John’*

RM/SQL:

```
select distinct s.sname as name
from STUDENT s, ENROLLMENT e, CLASS c, PROFESSOR p
where e.snum = s.snum
and e.deptcode = c.deptcode and e.cnum = c.cnum
and e.term = c.term and e.section = c.section
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ARM/SQLP:

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select distinct e.student.sname as name
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```

ARM Schema and Path Navigation

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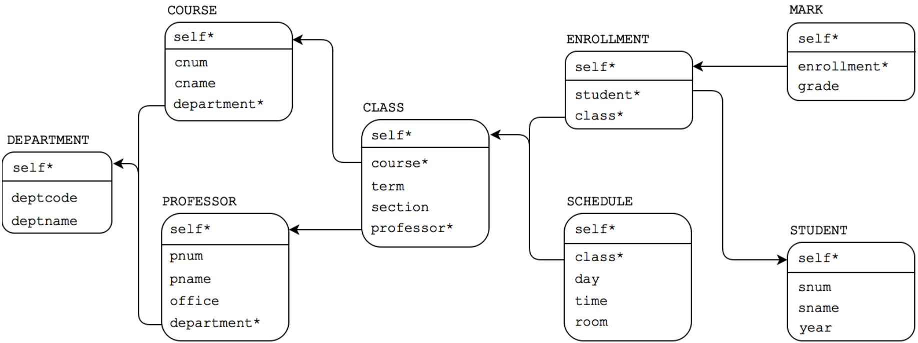
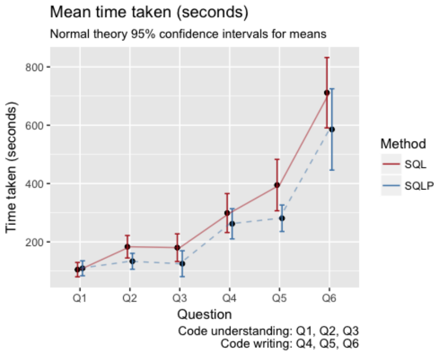
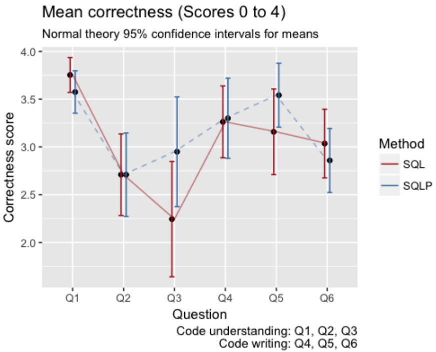


Experiments: Results

Mean performance for all subjects: SQL solid; SQLP dashed.





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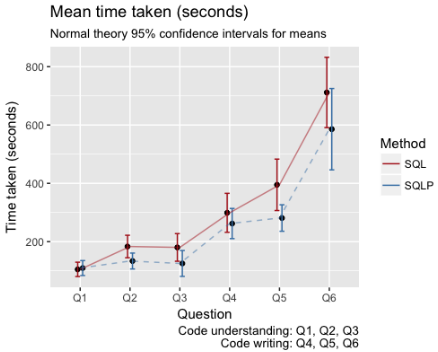

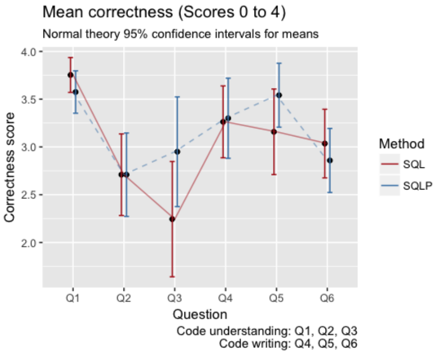

- SQLP outperforms SQL in time taken
- No significant difference in correctness (Q3, Q5 almost significant)

How to make the Technology Succeed?

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2. ARM/SQLP Can be Efficiently Implemented [ER16]
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Referring to Abstract Entities

Example (How to refer to `LEGAL-ENTITY`)

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Goal(s)

1. Flexible assignment of *Referring Expression Types* to classes,
2. Automatic check(s) for *sanity* of such an assignment, and
3. Compilation of queries (updates) over ARM to ones over concrete tables.

Referring Type Assignment (RTA)

IDEA

Assign a referring expression type RTA(T) to each table T in Σ.

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Example

Is every RTA(.) assignment "good"? Consider the SQLP query

$$\texttt{select}\ x.\texttt{self}\ \ \texttt{from}\ \texttt{PERSON}\ x, \texttt{COMPANY}\ y\ \ \texttt{where}\ x.\texttt{self} = y.\texttt{self}$$

1. assignment: RTA($\texttt{PERSON}$) $= (\texttt{ssn} = ?)$,
   RTA($\texttt{COMPANY}$) $= (\texttt{name} = ?, \texttt{city} = ?)$

   $\Rightarrow$ the ability to compare the $\texttt{OID}$ values is lost $\Rightarrow$ BAD RTA!;

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   $\Rightarrow$ the ability to compare the OID values is lost $\Rightarrow$ BAD RTA!;

2. (modified) assignment:

   $\text{RTA}(\texttt{COMPANY}) = (\texttt{PERSON} \to \texttt{ssn} = ?); (\texttt{name} = ?, \texttt{city} = ?)$

   $\Rightarrow$ the ability to compare the OID values is preserved as COMPANY objects are *identified* by ssn values when *also residing* in PERSON.

Referring Type Assignment (RTA)

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Assign a referring expression type RTA(T) to each table T in Σ.

Definition (Identity-resolving RTA(.))

Let Σ be a ARM schema and RTA a referring type assignment for Σ. Given a linear order $\mathcal{O} = (T_{i_1}, \ldots, T_{i_n})$ on the set Tables(Σ), define $\mathcal{O}$(RTA) as the referring expression type RTA(T_{i_1}); ... ; RTA(T_{i_k}).

We say that RTA is *identity resolving* if there is some linear order $\mathcal{O}$ such that the following conditions hold for each $T \in$ Tables(Σ):

1. RTA(T) $=$ Prune($\mathcal{O}$(RTA), T),
2. $\Sigma \models (\texttt{covered by } \{T_1, ..., T_n\}) \in T$, and
3. for each component $T_j \rightarrow (\text{Pf}_{j,1} = ?, \ldots, \text{Pf}_{j,k_j} = ?)$ of RTA(T), the following also holds:
   (i) $\text{Pf}_{j,i}$ is well defined for T_j, for $1 \leq i \leq k_j$, and
   (ii) $\Sigma \models (\texttt{pathfd } \text{Pf}_{j,1}, \ldots, \text{Pf}_{j,k_j} \rightarrow id) \in T_j$.

Referring Type Assignment (RTA)

IDEA

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Definition (Identity-resolving RTA(.))

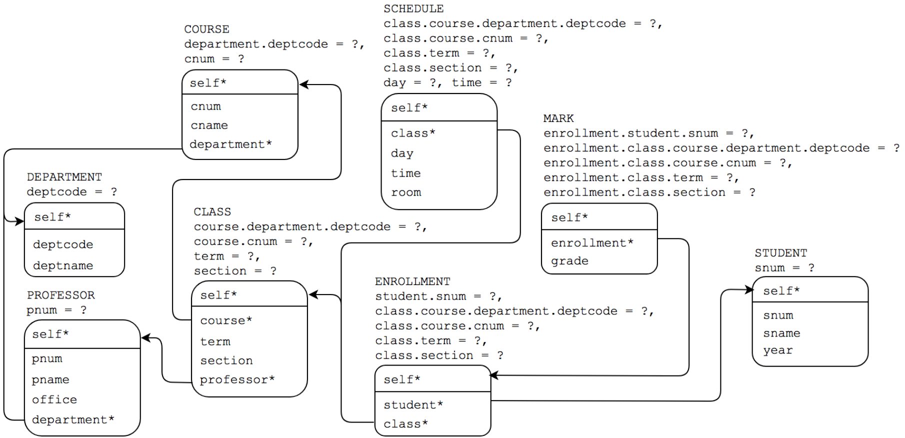
The definition achieves the following:

1. Referring expression types assigned to classes (tables) that can share objects must guarantee that a particular object is *uniquely* identified;
2. Referring expression types for disjoint classes/tables can be assigned *independently*;

Consequences:

- Referring expressions serve as a sound&complete proxy for entity/object (`OID`) equality;
- Referring expression can be *coerced* to a least common supertype.

Course Enrollment as an ARM Schema



Concrete Relational Back-end

1. Every *abstract attribute* and its referring expression type

   ⇒ a *concrete relational representation* (denoted by Rep(.)):

   essentially a discriminated variant record;

2. (distinct) Representations can be *coerced* to a common supertype

   ⇒ the ability to *compare the representations*

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Theorem

Let Σ *be a ARM schema and let* RTA *an identity resolving type assignment for* Σ*. For any SQLP query Q over* Σ

$$\mathrm{Rep}(Q(I), \Sigma) = (\mathrm{C}^{\Sigma,\mathrm{RTA}}(Q))(\mathrm{Rep}(I, \Sigma))$$

for every database instance I of Σ*.* □

Obtaining an Initial ARM Schema (legacy setting)

RM2ARM Algorithm (highlights; see [EKAW18])

For every table in RM:

1. add "`self OID`" (as a new primary key)
2. replace *foreign keys* with *unary* ones and discard original FK attributes
   - ⇒ what if original FK overlaps with primary key attributes?
   - ⇒ how about *cycles* between (overlapping) PKs and FKs?
3. add *ISA* constraints (and remove corresponding FKs)
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4. add *disjointness* constraints
   - ⇒ for tables with different PKs
5. generate *referring expressions* (so the ARM2RM mapping works)

Summary

Contributions

Referring expressions allow one to get more/better (certain) answers . . .

1. General approach to OBDA-style query answering;
2. Methodology that allows decoupling identification from modeling;
3. Referring Expressions that subsequently resolve identity issues; and
4. Compilation-based technology translation to *pure relational model*.

Future work&Extensions

1. Strong Identification (distinct referring expr's refer to distinct objects);
2. More complex referring expression types;
3. Replacing types by other *preferred way* to chose among referring expressions (e.g., *length*/*formula complexity*/...measure);
4. Alternatives to concrete representations;
5. More general/axiomatic definition of identity resolving RTA(.)s;

Message from our Sponsors

Data Systems Group at the University of Waterloo

Data Systems Group

- $\sim$10 professors, affiliated faculty, postdocs, $\sim$45 grads, . . .
- Wide range of research interests
  - Advanced query processing/Knowledge representation
  - System aspects of database systems and Distributed data management
  - Data quality/Managing uncertain data/Data mining
  - Information Retrieval and “big data”
  - New(-ish) domains (text, streaming, graph data/RDF, OLAP)
- Research sponsored by governments, and local/global companies

  NSERC/CFI/OIT and Google, IBM, SAP, OpenText, . . .
- Part of a School of CS with 85+ professors, 350+ grad students, etc.

  AI&ML, Algorithms&Data Structures, PL, Theory, Systems, . . .

Cheriton School of Computer Science has been ranked #18 in CS by the world by *US News and World Report* (#1 in Canada).

. . . and we are always looking for good graduate students (MMath/PhD)