Referring Expressions in Articial Intelligence and Knowledge Representation Systems

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(joint work with Alexander Borgida[†] and Grant Weddell[‡])

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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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How do we bridge the GAP?

Typical solutions:

1. OIDs (proxying entity *identity* by a number uniformly in the whole system)
   $\Rightarrow$ typically managed by *The System* (OO languages), or
2. Keys (proxying entity *identity* by a unique combination of values (local))
   $\Rightarrow$ typically declared/managed by user (Relational DBMS).

Object IDs: the Horror Stories

a.k.a. proxying identities by values in a data type (say `int`)

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Performance: The PROTEL2 Case

every object WILL have an OID (say 64 bits)

$\Rightarrow$ 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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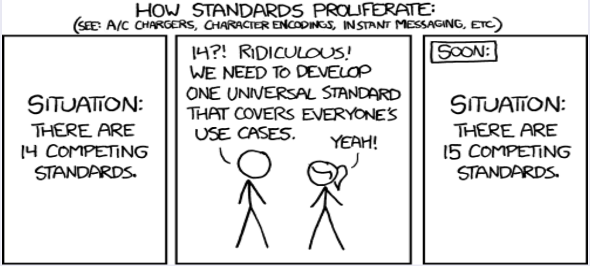
… and before someone mentions URL/URI/IRIs:



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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

⇒ 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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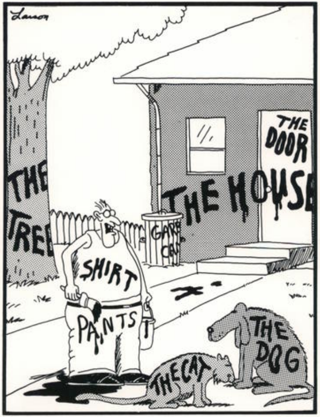
Alternative Preferred Answers

Internal (computer) addresses vs. physical locations of equipment

$\Rightarrow$ programs need electronic address (to route the electric signals)

$\Rightarrow$ technicians need physical location (to find the equipmant)

Relational Keys



"Now! . . . *That* should clear up a few things around here!"

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 recording 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

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

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.:

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

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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.,

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

   for all models $\mathcal{I}$ of $\mathcal{K}$.

$\Rightarrow$ this intuition may be refined w.r.t. queries (e.g., singular *among answers*)

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Why not *terms*?

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

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

Denoting/Non-denoting Referring Expressions

Singularity Revisited

$$|\{o \mid \mathcal{I}, [x \mapsto o] \models \phi\}| = 1 \quad \text{a denoting refering expression}$$
$$|\{o \mid \mathcal{I}, [x \mapsto o] \models \phi\}| = 0 \quad \text{a non-denoting refering expression}$$

for all $\mathcal{I} \models \mathcal{K}$; these ought to be the only two possibilities!

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Terms vs. Formulas Revisited [Artale et al., 2021]

Free (description) logics allow terms to be partial functions

$\Rightarrow$ $\iota\phi$ coerces a unary formula ϕ to a (partial) term

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How do we Guarantee Singularity?

1. (fresh) nominals [Artale et al., 2021]
2. functionality [Borgida et al., 2016]

Single Interpretations/Models

Generating Referring Expressions (GRE)

Task: given an *interpretation*, find formulæ (referring expressions) that denote (selected) single objects.

Carlos Areces, Santiago Figueira, Daniel Gorín: Using Logic in the Generation of Referring Expressions. Logical Aspects of Computational Linguistics 2011.

Carlos Areces, Alexander Koller, Kristina Striegnitz: Referring Expressions as Formulas of Description Logic. International Natural Language Generation Conference 2008.

Logical Theories and Knowledge Bases

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

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

- constant symbols (similar for function/predicate symbols)
  . . . can be interpreted by *different individuals* in different models

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- constant symbols (similar for function/predicate symbols)
  . . . can be interpreted by *different individuals* in different models

$\Rightarrow$ (standard) constants don't quite satisfy Russell's/Kripke's requirements
$\Rightarrow$ *rigid designators* (symbols interpreted identically in all models)?

Rigidity and Genericity: DB Theory Way

Database (theory) Approach

- Database Instances (aka models) *expect constants* to be rigid
  $\Rightarrow$ but constraints/queries do not *know*
- Database Queries are required to be *generic*
  $\Rightarrow$ 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*!

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.

DL22 Alexander Borgida, Enrico Franconi, David Toman, and Grant E. Weddell: Accessing Document Data Sources using Referring Expression Types. Proc. *Description Logics* DL 2022, 2022 (next week).

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 ($\mathcal{CFDI}$ or Horn-$\mathcal{ALC}*$ 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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Answer: $\{\,\}$

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 (??)

Referring Expressions (revisited)

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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 $\mathcal{K}$.

Controlling the number of Answers

Example KB

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

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

Controlling the number of Answers

Example KB

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

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

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

Answers: $x = \text{fred}$

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$$\mathrm{Person}(x) \rightarrow \exists y.\mathrm{fatherof}(y,x)$$
$$\}$$

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

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

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

Controlling the number of Answers

Example KB

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

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

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

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

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

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

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

Controlling the number of Answers II

Example KB

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

$$\mathcal{A} = \{\ \mathrm{spouse}(\mathrm{mary}, \mathrm{fred})\ \}$$

Controlling the number of Answers II

Example KB

$$\mathcal{T} = \{ \text{spouse}(x, y) \to \text{spouse}(y, x),$$
$$\text{spouse}(x, z) \wedge \text{spouse}(y, z) \to x = y$$
$$\text{spouse}(x, y) \to x \neq y \}$$
$$\mathcal{A} = \{ \text{spouse}(\text{mary}, \text{fred}) \}$$

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

Answers: $x = \text{fred}$

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

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

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

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

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

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

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$\text{mary} \neq \text{fred}$ (last constraint!) $\Rightarrow$ exactly 2 distinct objects

Controlling the number of Answers: Finite Representation

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

- potentially too many implied answers (infinitely many!)
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Yes (for logics with *recursively enumerable* logical consequence):

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

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$\Rightarrow$ is there a *finite representation* of all answers (and what is "all")?

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-$\mathcal{ALC}$)

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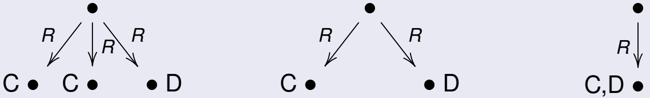

spurious R-successor C | just right (canonical) | spurious equality between R-successors

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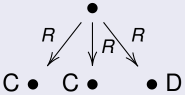

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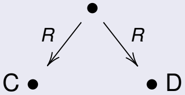

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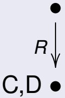

spurious equality
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$\Rightarrow$ *singular **certain** answers*: singular in a canonical model

$\Rightarrow$ coincide with singular answers in DLs with functional roles (FunDL).

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)

Controlling the number of Answers: Typing Restrictions

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

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.

Referring Expression Types

Desiderata: only Referring Expressions that are Singular

Given
1. a KB $\mathcal{K}$ (the "background knowledge"),
2. a query $\psi\{x_1, \ldots, x_k\}$, and
3. types $Rt_1, \ldots, Rt_k$ for 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 $\mathcal{K}$.

Examples of Typed Queries

Reference via a Single-Attribute Key

"The ssn# of any person with phone 1234567"

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

Examples of Typed Queries

Reference via a Single-Attribute Key

Reference by a Multi-Attribute Key

"The title and publisher of any journals"

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

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"

$$\begin{array}{l} \textbf{select } x : \mathit{Person} \rightarrow \mathit{ssn\#} = \{?\}\ ; \\ \qquad\qquad \mathit{Company} \rightarrow \mathit{tickerSymbol} = \{?\} \\ \textbf{where } \mathit{LegalEntity}(x) \end{array}$$

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

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."

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

answers:

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

REQA (Referring Expression-based QA)

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

REQA (outline, unary queries only)

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

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
$$T_i \to Pd_{i,1} = \{?\} \wedge \ldots \wedge Pd_{i,k_i} = \{?\};$$
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

Lite Description Logics

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

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

- Weak identification $\longrightarrow$ sequence of logical implications
- Query answering $\longrightarrow$ REQA
  + Combined Combined Approach

Logics with Tree Models (outside of 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:

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

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

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

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Issues:

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

Heterogeneous Data Integration (example)

Example

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

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...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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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;

$\Rightarrow$ 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 $(\mathcal{T}, \mathrm{Simp}(\mathcal{C}))$.

Documents and Ontologies

Ontologies for Documents: Goals

1. to capture *class mambership* of entities captured in a document, and
2. to establish *how entities are identified* in a document.

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2. to establish *how entities are identified* in a document.

IDEA: Documents as Concepts, Semantics as Ontology

1. Syntactical document structure captured as a concept in FunDL

   $\Rightarrow$ similar to the IBM IMS hierarchical data model

2. Ontology adds meaning to this concept and its subconcepts
   - identifies class membership of entities described by subdocuments,
   - discovers subdocuments pertaining to the same entity, and
   - drives document normalization.

Example: JSON Document


```
{ "collection": "person",
  "data" : [
    { "fname": "John", "lname": "Smith", "age": 25,
      "wife": { "fname" : "Mary" },
      "phone": [
         {"colour": "red", "dnum": "212 555-1234"}
      ]
    },
    { "fname": "Mary", "lname": "Jones",
      "salary": "$150,000 (CAD)",
      "spouse": { "fname": "John" },
      "phone": [
         {"loc": "home", "dnum": "212 555-1234"},
         {"loc": "work", "dnum": "212 666-4567"}
      ]
    }
  ]
}
```

Example: JSON as a FunDL Concept

$$
\begin{array}{l}
\exists\,\texttt{collection}.\{\texttt{"person"}\} \sqcap \\
\exists\,\texttt{data}.\exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\\
\qquad\qquad \exists\,\texttt{fname}.\{\texttt{"John"}\} \sqcap \exists\,\texttt{lname}.\{\texttt{"Smith"}\} \sqcap \\
\qquad\qquad \exists\,\texttt{age}.\{\texttt{"25"}\} \sqcap \exists\,\texttt{wife}.\exists\,\texttt{fname}.\{\texttt{"Mary"}\} \sqcap \\
\qquad\qquad \exists\,\texttt{phone}(\exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\\
\qquad\qquad\qquad\qquad \exists\,\texttt{colour}.\{\texttt{"red"}\} \sqcap \exists\,\texttt{dnum}.\{\texttt{"212 555-1234"}\}))) \sqcap \\
\qquad\quad \exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\\
\qquad\qquad \exists\,\texttt{fname}.\{\texttt{"Mary"}\} \sqcap \exists\,\texttt{lname}.\{\texttt{"Jones"}\} \sqcap \\
\qquad\qquad \exists\,\texttt{salary}.\{\texttt{"\$150000CAD"}\} \sqcap \exists\,\texttt{spouse}.\exists\,\texttt{fname}.\{\texttt{"John"}\} \sqcap \\
\qquad\qquad \exists\,\texttt{phone}(\exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\\
\qquad\qquad\qquad\qquad \exists\,\texttt{loc}.\{\texttt{"home"}\} \sqcap \exists\,\texttt{dnum}.\{\texttt{"212 555-1234"}\}) \sqcap \\
\qquad\qquad\qquad \exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\\
\qquad\qquad\qquad\qquad \exists\,\texttt{loc}.\{\texttt{"work"}\} \sqcap \exists\,\texttt{dnum}.\{\texttt{"212 666-4567"}\})))
\end{array}
$$

Example: Ontology

1. The TBox:

$$
\begin{array}{rcl}
(\exists\,\texttt{collection}.\top) \sqcap (\exists\,\texttt{data}.\top) & \sqsubseteq & \mathit{DOCUMENT} \\
(\exists\,\texttt{fname}.\top) \sqcap (\exists\,\texttt{lname}.\top) & \sqsubseteq & \mathit{PERSON} \\
\exists\,\texttt{dnum}.\top & \sqsubseteq & \mathit{PHONE} \\
\mathit{DOCUMENT} & \sqsubseteq & \mathit{DOCUMENT} : \texttt{collection} \to \mathit{id} \\
\mathit{PERSON} & \sqsubseteq & \mathit{PERSON} : \texttt{fname}, \texttt{lname} \to \mathit{id} \\
\mathit{PHONE} & \sqsubseteq & \mathit{PHONE} : \texttt{dnum} \to \mathit{id} \\
\mathit{PERSON} & \sqsubseteq & \exists\,\texttt{wife}.\mathit{PERSON}
\end{array}
$$

2. The Referring Expression Type Assignment:

$$
\begin{array}{rcl}
\mathrm{RTA}(\mathit{DOCUMENT}) & = & \mathit{DOCUMENT} \sqcap \exists\,\texttt{collection}.\{?\} \\
\mathrm{RTA}(\mathit{PERSON}) & = & \mathit{PERSON} \sqcap \exists\,\texttt{lname}.\{?\} \sqcap \exists\,\texttt{fname}.\{?\} \\
\mathrm{RTA}(\mathit{PHONE}) & = & \mathit{PHONE} \sqcap \exists\,\texttt{dnum}.\{?\}
\end{array}
$$

Example: Normalized CBox/Document

$$\begin{array}{l}
\underline{\mathit{DOCUMENT} \sqcap \exists\,\texttt{collection}.\{\texttt{"person"}\}} \sqcap \exists\,\texttt{data}(\\
\quad \exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\mathit{PERSON} \sqcap \exists\,\texttt{fname}.\{\texttt{"John"}\} \sqcap \exists\,\texttt{lname}.\{\texttt{"Smith"}\}) \sqcap \\
\quad \exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\mathit{PERSON} \sqcap \exists\,\texttt{fname}.\{\texttt{"Mary"}\} \sqcap \exists\,\texttt{lname}.\{\texttt{"Jones"}\}))
\end{array}$$

$$\begin{array}{l}
\underline{\mathit{PERSON} \sqcap \exists\,\texttt{fname}.\{\texttt{"John"}\} \sqcap \exists\,\texttt{lname}.\{\texttt{"Smith"}\}} \sqcap \\
\qquad \exists\,\texttt{age}.\{\texttt{"25"}\} \sqcap \exists\,\texttt{wife}.\exists\,\texttt{fname}\{\texttt{"Mary"}\} \sqcap \\
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\qquad\qquad \exists\,\texttt{dom}^{-}.\exists\,\texttt{ran}(\mathit{PHONE} \sqcap \exists\,\texttt{dnum}\{\texttt{"212 666-4567"}\}))
\end{array}$$

$$\underline{\mathit{PHONE} \sqcap \exists\,\texttt{dnum}\{\texttt{"212 555-1234"}\}} \sqcap \exists\,\texttt{loc}.\{\texttt{"home"}\} \sqcap \exists\,\texttt{colour}.\{\texttt{"red"}\}$$

$$\underline{\mathit{PHONE} \sqcap \exists\,\texttt{dnum}\{\texttt{"212 555-4567"}\}} \sqcap \exists\,\texttt{loc}.\{\texttt{"work"}\}$$

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Borgida et al. Accessing Document Data Sources using Referring Expression Types
Aug 10 at 11:25 in DL 2022, Session 112C (Taub 9)

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`

Conceptual Modeling and Identification [ER16]

Thesis:

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

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`

$\Rightarrow$ choice of key (`ssn`) for `PERSON` forces *the same* key for `FAMOUS-PERSON`
$\Rightarrow$ we may *prefer* to use `name` in this case (e.g., *Eric Clapton* or *The Edge*)

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Weak Entities and dominant entity identification

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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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Weak Entities and dominant entity identification

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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*:

```
select d.driver.name from CAN-DRIVE d
where d.driven.make = 'Honda'
```

  attribute paths in the `select` and `where` clauses

- *The owners of Mitsubishi vehicles*:

```
select v.owned-by from VEHICLE v
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  retrieving *abstract attributes* may yield
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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* $\Rightarrow$ and WITHOUT introducing *explicit, material* OIDs
   - Reverse-Engineering ARM from Legacy Relational Schemata

Experimental Design (HCI experiments)

Hypotheses

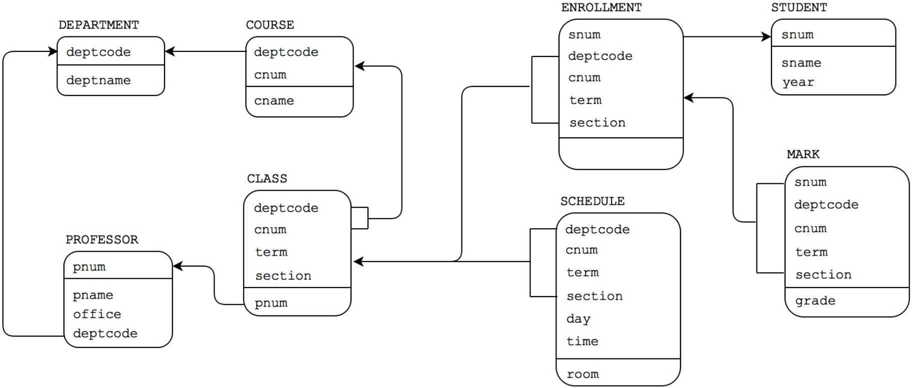
H_t: no difference between RM/SQL and ARM/SQLP in the mean time taken

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

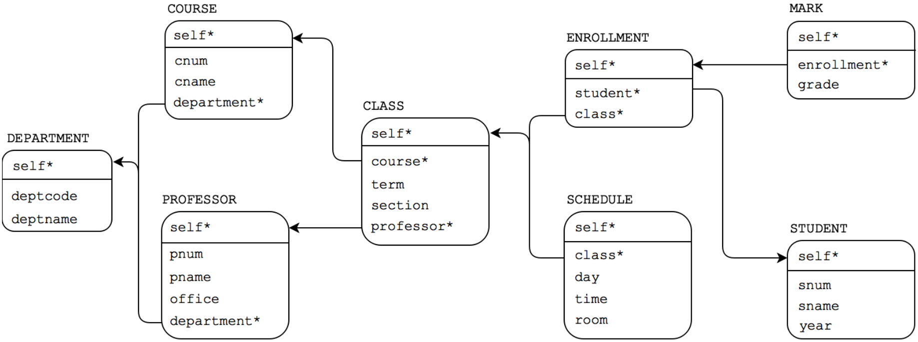
Methods

- 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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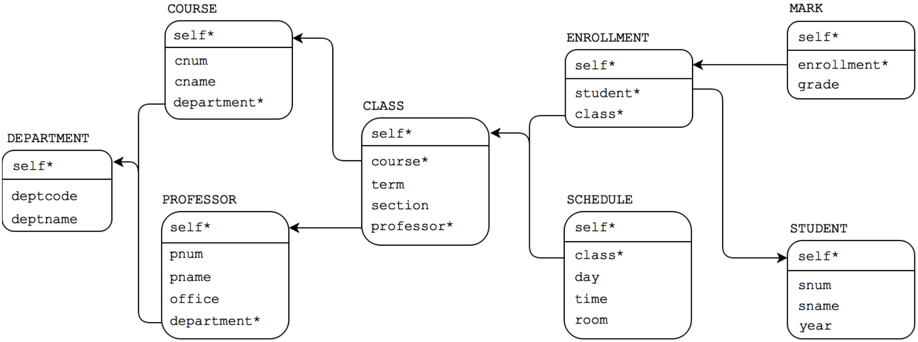

ARM *completely frees* domain experts/users from the need to understand how entities are *identified* in an information system.

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
and c.pnum = p.pnum and p.pname = 'Alan John'
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ARM/SQLP:

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

ARM Schema and Path Navigation

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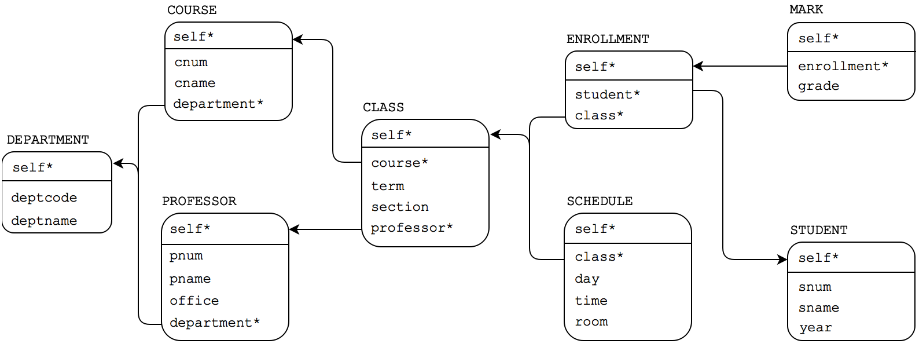
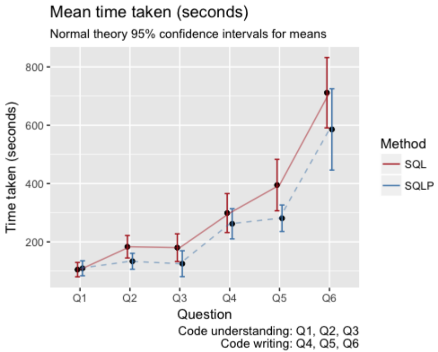
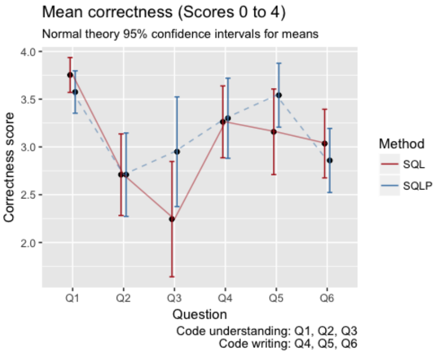



Experiments: Results

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





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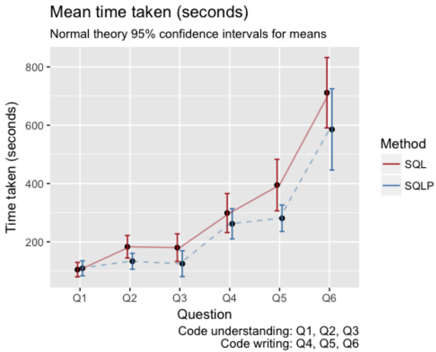

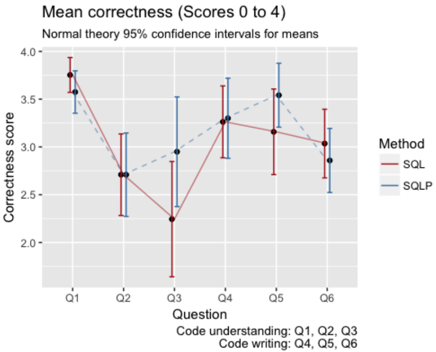

- SQLP outperforms SQL in time taken
- No significant difference in correctness (Q3, Q5 almost significant)

How to make the Technology Succeed?

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2. ARM/SQLP Can be Efficiently Implemented [ER16]
   - Mapping to *standard relational model* with the help of *referring expressions*
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Referring to Abstract Entities

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

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  `ssn` for `PERSON` and `(name, city)` for `COMPANY`.

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  `PERSON` → `ssn=?;` `COMPANY` → `(name=?, city=?).`

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

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

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2. (modified) assignment:

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

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

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 $T_j \rightarrow (\mathrm{Pf}_{j,1} = ?, \ldots, \mathrm{Pf}_{j,k_j} = ?)$ of RTA(T), the following also holds:
   (i) $\mathrm{Pf}_{j,i}$ is well defined for T_j, for $1 \leq i \leq k_j$, and
   (ii) $\Sigma \models (\texttt{pathfd}\ \mathrm{Pf}_{j,1}, \ldots, \mathrm{Pf}_{j,k_j} \rightarrow id) \in T_j$.

Referring Type Assignment (RTA)

IDEA

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

Definition (Identity-resolving RTA(.))

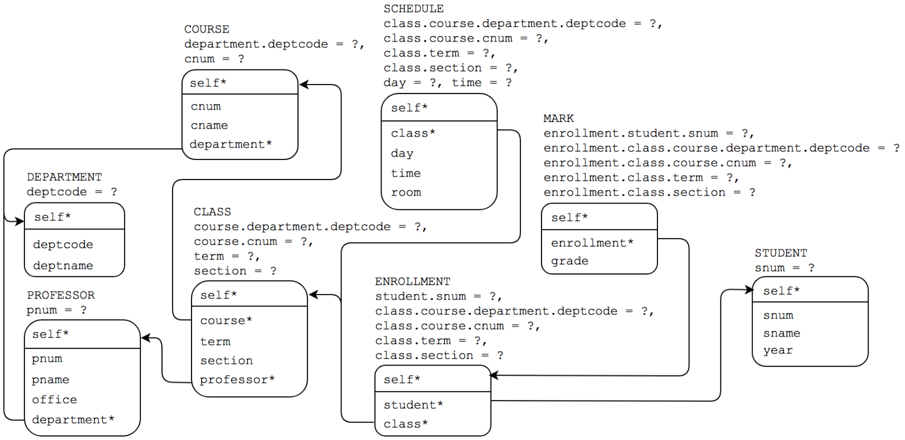
The definition achieves the following:

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
   $\Rightarrow$ a *concrete relational representation* (denoted by Rep(.)):
   essentially a discriminated variant record;
2. Representations can be *coerced* to a common supertype
   $\Rightarrow$ the ability to *compare the representations*
   a sound and complete proxy for comparing *object ids*;
3. A SQLP query is compiled to a standard SQL query over the concrete representation of an abstract instance in such a way that:

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. $\square$

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)
   - ⇒ from PK to PK foreign keys in RM
4. add *disjointness* constraints
   - ⇒ for tables with different PKs

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4. add *disjointness* constraints
   - ⇒ for tables with different PKs
5. generate *referring expressions* (so the ARM2RM mapping works)

SUMMARY

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Contributions

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

1. General approach to OBDA-style query answering

   $\Rightarrow$ Ability to refer to implicit individuals/entities

2. General approach to representing data

   $\Rightarrow$ without need for *object id invention*;

3. Methodology that allows decoupling identification from modeling

   $\Rightarrow$ Referring Expressions resolve identity issues and
   $\Rightarrow$ Compilation 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

- ∼15 professors, affiliated faculty, postdocs, ∼50 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 90+ professors, 450+ grad students, etc.

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

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