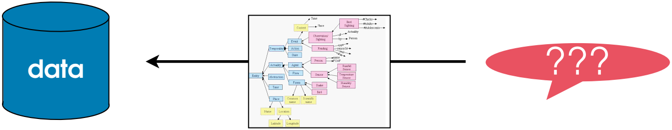
ONTOLOGY-MEDIATED QUERY ANSWERING

Meghyn Bienvenu (*CNRS & Université de Bordeaux*)

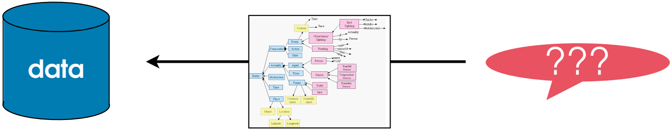


incomplete database
(ground facts)

ontology
(logical theory)

user query

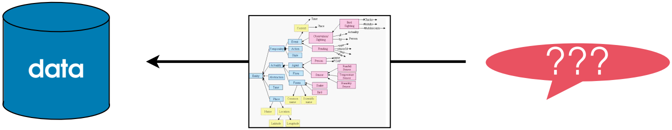
ONTOLOGY-MEDIATED QUERY ANSWERING (OMQA)



patient data	**medical knowledge**	**user query**
"Melanie has listeriosis" "Paul has Lyme disease"	"Listeriosis & Lyme disease are bacterial infections"	"Find all patients with bacterial infections"

The ontology (logical theory) specifies:

- terminology (or vocabulary) of the domain
- semantic relationships between terms
  - relations of specificity or generality, equivalence, disjointness, …



patient data
"Melanie has listeriosis"
"Paul has Lyme disease"

medical knowledge
"Listeriosis & Lyme disease are bacterial infections"

user query
"Find all patients with bacterial infections"

***expected answers*: Melanie, Paul**

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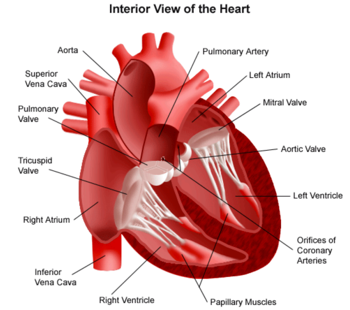
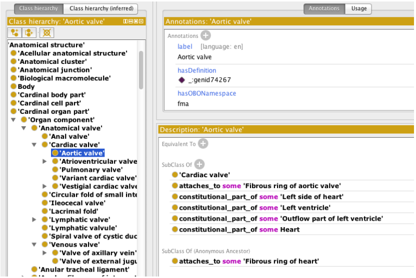
To support **automated reasoning**

- uncover implicit connections between terms, errors in modelling
- **exploit knowledge in the ontology during query answering**, to get back a **more complete set of answers** to queries

General medical ontologies: SNOMED CT ($\sim$ 400,000 terms!), GALEN

Specialized ontologies: FMA (anatomy), NCI (cancer), ...



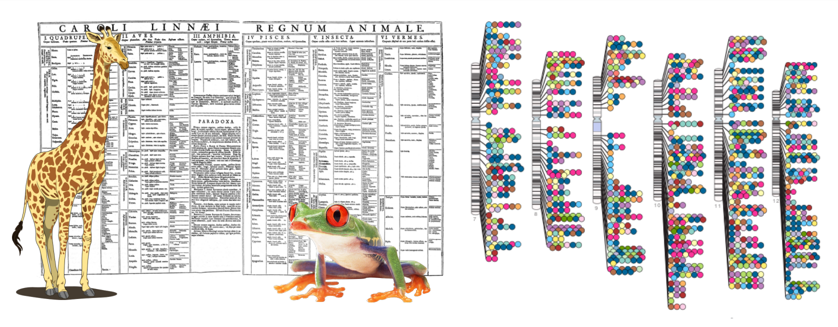


Querying & exchanging medical records (find patients for medical trials)

- myocardial infarction vs. MI vs. heart attack vs. 410.0

Supports tools for annotating and visualizing patient data (scans, x-rays)

Hundreds of ontologies at BioPortal (http://bioportal.bioontology.org/):
Gene Ontology (GO), Cell Ontology, Pathway Ontology, Plant Anatomy, ...



Help scientists share, query, & visualize experimental data

APPLICATIONS OF OMQA: ENTREPRISE INFORMATION SYSTEMS

Companies and organizations have lots of data

- need easy and flexible access to support decision-making

Example industrial projects:

- Public debt data: Sapienza Univ. & Italian Department of Treasury
- Energy sector: Optique EU project (several univ, StatOil, Siemens)

Ontologies typically described using logic-based formalisms

Description logics (DLs)

- family of decidable fragments of first-order logic (FO)
- concise variable-free syntax
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Existential rules (aka Datalog$^{+/-}$, tuple-generating dependencies)

- family of languages of rules of the form $\forall x(\exists \vec{y}\, \varphi(\vec{x}, \vec{y}) \rightarrow \exists \vec{z}\, \psi(\vec{x}, \vec{z}))$ where $\varphi(\vec{x}, \vec{y})$ and $\psi(\vec{x}, \vec{z})$ are conjunctions of atoms
- can have predicates of arbitrary arity

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Two approaches are incomparable and complementary

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- family of knowledge representation languages
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Computational properties well understood (decidability, complexity)

Many implemented reasoners and tools available for use

Sets of **existential rules** (aka tuple-generating dependencies):

$$\forall\vec{x}\ \varphi(\vec{x}) \rightarrow \exists\vec{y}\ \psi(\vec{x},\vec{y})$$

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- forward chaining (chase) halts
- backward chaining (rewriting) halts
- tree-like models

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Many complexity & decidability results, few implemented algorithms

Can consider extensions allowing equality, disjunction in rule heads

- such extensions less well understood

Introduction to DLs

Introduction to OMQA

Techniques for OMQA with Lightweight DLs

Research Questions in OMQA

INTRODUCTION TO DLS

Building blocks:

- concept names (unary predicates, classes) Prof Fellow Course
- role names (binary predicates, properties) teaches headOf
- individual names (constants) anna, cs101

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- individual names (constants) — anna, cs101

Constructors to build complex concepts and roles $\sqcup, \sqcap, \neg, \forall, \exists, \ldots$

$\mathsf{Faculty} \sqcap \neg\mathsf{Prof}$ $\exists\mathsf{teaches}.\mathsf{GradCourse}$ $\mathsf{teaches}^{-}$

Note: allowed constructors **depends on chosen DL**

DL knowledge base (KB) = ABox (data) + TBox (ontology)

ABox = finite set of **concept and role assertions (facts)**

Prof(anna) teaches(tom, cs101)

TBox (ontology) = finite set of **axioms**

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$\mathsf{Prof}(\mathsf{anna})$ $\mathsf{teaches}(\mathsf{tom}, \mathsf{cs101})$

TBox (ontology) = finite set of axioms

- concept inclusions $C \sqsubseteq D$ (C, D possibly complex concepts)

  $\mathsf{Prof} \sqsubseteq \mathsf{Faculty}$ $\exists\mathsf{teaches}.\mathsf{GradCourse} \sqsubseteq \mathsf{Prof}$

- role inclusions $R \sqsubseteq S$ (R, S possibly complex roles)

  $\mathsf{taughtBy} \sqsubseteq \mathsf{teaches}^-$ $\mathsf{headOf} \sqsubseteq \mathsf{memberOf}$

Note: allowed axioms **depends on chosen DL**

Professors and **lecturers** are **disjoint classes of faculty**

$$\mathsf{Prof} \sqsubseteq \mathsf{Faculty} \quad \mathsf{Lect} \sqsubseteq \mathsf{Faculty} \quad \mathsf{Prof} \sqsubseteq \neg\mathsf{Lect}$$

Every **course** is **either an undergrad or grad course**

$$\mathsf{Course} \sqsubseteq \mathsf{UCourse} \sqcup \mathsf{GCourse}$$

The relation takesCourse **connects students to courses**

$$\exists \mathsf{takesCourse}.\top \sqsubseteq \mathsf{Student} \quad \exists \mathsf{takesCourse}^{-}.\top \sqsubseteq \mathsf{Course}$$

Every student takes **at least 2** and **at most 5 courses**

$$\mathsf{Student} \sqsubseteq\ \geq 2\mathsf{takesCourse}.\top \sqcap \leq 5\mathsf{takesCourse}.\top$$

MORE EXAMPLES OF TBOX AXIOMS

Every grad student is supervised by some faculty member

$$\mathsf{GStudent} \sqsubseteq \exists \mathsf{supervisedBy}.\mathsf{Faculty}$$

The academic ancestor relation is transitive

$$\mathsf{supervisedBy} \sqsubseteq \mathsf{academicAnc} \qquad \mathit{trans}(\mathsf{academicAnc})$$

Students who only take grad-level courses are grad students

$$\mathsf{Student} \sqcap \forall \mathsf{takesCourse}.\mathsf{GCourse} \sqsubseteq \mathsf{GStudent}$$

FO translation:
$\forall x \; (\mathsf{Student}(x) \land (\forall y \; \mathsf{takesCourse}(x,y) \rightarrow \mathsf{GCourse}(y)) \rightarrow \mathsf{GStudent}(x)$

Interpretation $\mathcal{I}$ ("possible world") (like in first-order logic)

- domain of objects $\Delta^\mathcal{I}$ (possibly infinite set)
- interpretation function $\cdot^\mathcal{I}$ that maps
  - concept name $A \rightsquigarrow$ set of objects $A^\mathcal{I} \subseteq \Delta^\mathcal{I}$
  - role name $r \rightsquigarrow$ set of pairs of objects $r^\mathcal{I} \subseteq \Delta^\mathcal{I} \times \Delta^\mathcal{I}$
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Interpretation function $\cdot^{\mathcal{I}}$ extends to complex concepts and roles:

$\top$	$\Delta^{\mathcal{I}}$
$\bot$	$\emptyset$
$\neg C$	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
$C_1 \sqcap C_2$	$C_1{}^{\mathcal{I}} \cap C_2{}^{\mathcal{I}}$
$\exists R.C$	$\{d_1 \mid \text{there exists } (d_1, d_2) \in R^{\mathcal{I}} \text{ with } d_2 \in C^{\mathcal{I}}\}$
$\forall R.C$	$\{d_1 \mid d_2 \in C^{\mathcal{I}} \text{ for all } (d_1, d_2) \in R^{\mathcal{I}}\}$
r^-	$\{(d_2, d_1) \mid (d_1, d_2) \in r^{\mathcal{I}}\}$

Satisfaction in an interpretation

- $\mathcal{I}$ satisfies $C \sqsubseteq D \quad \Leftrightarrow \quad C^{\mathcal{I}} \subseteq D^{\mathcal{I}}$
- $\mathcal{I}$ satisfies $R \sqsubseteq S \quad \Leftrightarrow \quad R^{\mathcal{I}} \subseteq S^{\mathcal{I}}$
- $\mathcal{I}$ satisfies $A(a) \quad \Leftrightarrow \quad a^{\mathcal{I}} \in A^{\mathcal{I}}$
- $\mathcal{I}$ satisfies $r(a, b) \quad \Leftrightarrow \quad (a^{\mathcal{I}}, b^{\mathcal{I}}) \in r^{\mathcal{I}}$

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Model of a KB $\mathcal{K}$ = interpretation that satisfies all statements in $\mathcal{K}$

$\mathcal{K}$ **is satisfiable** = $\mathcal{K}$ has at least one model

$\mathcal{K}$ **entails** α (written $\mathcal{K} \models \alpha$) = every model $\mathcal{I}$ of $\mathcal{K}$ satisfies α

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Basic reasoning tasks:

- KB satisfiability: decide whether $\mathcal{K}$ is satisfiable
- Axiom entailment: decide whether $\mathcal{T} \models \alpha$ (with α an axiom)
  - Classification: decide $\mathcal{T} \models A \sqsubseteq B$ for every pair A, B of concept names

ABoxes are interpreted under the **open-world assumption**

- facts that are not in the ABox may still be true (e.g. can be inferred by exploiting information in the TBox)
- differs from the typical closed-world assumption from databases, where absent facts are interpreted as false

DIFFERENCES WITH DATABASE SETTING

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Semantics in terms of **arbitrary (possibly infinite) interpretations**

- differs from finite models considered in databases
- may consider an alternative semantics based upon finite models
  - for some DLs, two semantics behave the same
  - for others, often possible to reduce to arbitrary model reasoning

For today's talk, we'll focus on standard semantics (arbitrary models)

Prototypical expressive description logic $\mathcal{ALC}$:

- Concepts: $C := \top \mid \bot \mid A \mid \neg C \mid C \sqcap C \mid C \sqcup C \mid \exists r.C \mid \forall r.C$
- TBox axioms: only concept inclusions

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Highly expressive description logic $\mathcal{SHOIQ}$ ($\sim$ OWL 2)

- Extends $\mathcal{ALC}$ with:
  - number restrictions $\leq nR.C$ $\geq nR.C$ and nominals $\{a\}$
  - role inclusions $R_1 \sqsubseteq R_2$ and transitivity axioms $trans(R)$
  - inverse roles r^- (allowed in all types of axioms)

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“Lightweight” description logic $\mathcal{EL}$ (∼ OWL 2 EL)

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$\mathcal{ALCI}$ = extension of $\mathcal{ALC}$ with inverse roles ($\mathcal{I}$)

$\mathcal{ELH}$ = extension of $\mathcal{EL}$ with role inclusions ($\mathcal{H}$)

INTRODUCTION TO OMQA

Instance queries (IQs): find instances of a given concept or role

Faculty(x)   teaches(x, y)

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Conjunctive queries (CQs) $\sim$ SPJ queries in SQL, BGPs in SPARQL

conjunctions of atoms, some variables can be existentially quantified

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(find all faculty members that teach something)

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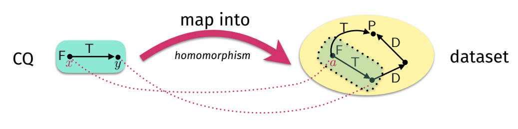
Ontology-mediated query (OMQ):

pair $(\mathcal{T}, q)$ with $\mathcal{T}$ a TBox and q a query (IQ / CQ)

Answering CQs in database setting



database D + query q $\rightsquigarrow$ set of answers $ans(q, D)$

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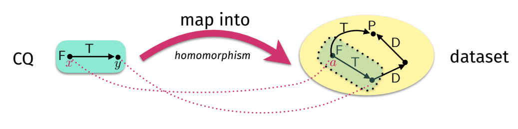

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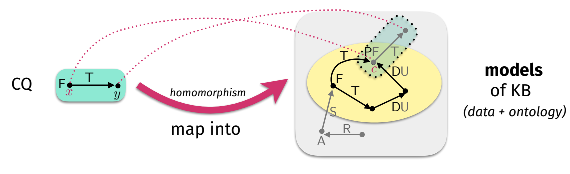
Answering CQs in the presence of a TBox (ontology)



model $\mathcal{I}$ of KB $(\mathcal{T}, \mathcal{A})$ + query q $\rightsquigarrow$ set of answers $ans(q, \mathcal{I})$

Question: how to combine the answers from different models?

Certain answers:

- tuples of inds $\vec{a}$ such that $\vec{a} \in ans(q, \mathcal{I})$ for **every model** $\mathcal{I}$ of $(\mathcal{T}, \mathcal{A})$
- corresponds to a form of **entailment**, we'll write $\mathcal{T}, \mathcal{A} \models q(\vec{a})$

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Ontology-mediated query answering =
problem of computing / verifying certain answers

OMQA EXAMPLE

TBox (ontology):

$$\mathsf{Prof} \sqsubseteq \mathsf{Faculty} \qquad \mathsf{Fellow} \sqsubseteq \mathsf{Faculty} \qquad \mathsf{Prof} \sqsubseteq \neg\mathsf{Fellow}$$
$$\mathsf{Prof} \sqsubseteq \exists \mathsf{teaches}.\top \qquad \exists \mathsf{teaches}^{-}.\top \sqsubseteq \mathsf{Course}$$

ABox (data):

$$\{\mathsf{Prof}(\mathsf{anna}), \mathsf{Fellow}(\mathsf{tom}), \mathsf{teaches}(\mathsf{tom}, \mathsf{cs101})\}$$

Query: $q(x) = \exists y.\mathsf{Faculty}(x) \wedge \mathsf{teaches}(x, y)$

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Query: $q(x) = \exists y.\mathsf{Faculty}(x) \wedge \mathsf{teaches}(x, y)$

Get the following certain answers:

- anna — $\mathsf{Prof}(\mathsf{anna})$ + $\mathsf{Prof} \sqsubseteq \mathsf{Faculty}$ + $\mathsf{Prof} \sqsubseteq \exists\mathsf{teaches}.\top$
- tom — $\mathsf{Fellow}(\mathsf{tom})$ + $\mathsf{Fellow} \sqsubseteq \mathsf{Faculty}$ + $\mathsf{teaches}(\mathsf{tom}, \mathsf{cs101})$

OMQA viewed as a **decision problem** (yes-or-no question):

PROBLEM:	**$\mathcal{Q}$ answering in $\mathcal{L}$** ($\mathcal{Q}$ a query language, $\mathcal{L}$ a DL)
INPUT:	An **n-ary query** $q \in \mathcal{Q}$, an **ABox** $\mathcal{A}$, an **$\mathcal{L}$-TBox** $\mathcal{T}$, and a **tuple** $\vec{a} \in \mathsf{Ind}(\mathcal{A})^n$
QUESTION:	**Does $\mathcal{T}, \mathcal{A} \models q(\vec{a})$?**

OMQA viewed as a **decision problem** (yes-or-no question):

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QUESTION: **Does** $\mathcal{T}, \mathcal{A} \models q(\vec{a})$**?**

Combined complexity: in terms of size of whole input

Data complexity: in terms of **size of $\mathcal{A}$ only**

- view rest of input as fixed (of constant size)
- motivation: ABox (data) typically much larger than rest of input

data complexity $\leq$ combined complexity

INTRACTABILITY FOR EXPRESSIVE DLS

Recall the DL $\mathcal{ALC}$: $C := \top \mid \bot \mid A \mid \neg C \mid C \sqcap C \mid C \sqcup C \mid \exists r.C \mid \forall r.C$

Satisfiability, IQ answering, and CQ answering in $\mathcal{ALC}$ are:

- EXPTIME-complete in combined complexity
- coNP-complete in data complexity

Even worse news for CQ answering in $\mathcal{ALCI}$ (= $\mathcal{ALC}$ + inverse roles):

- 2EXPTIME-complete in combined complexity
- coNP-complete in data complexity

OMQA WITH LIGHTWEIGHT DLS

Negative results led to proposal of **new DLs with lower complexity**

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DL-Lite family of DLs (basis for **OWL 2 QL**)

- designed with OMQA in mind
- capture main constructs from conceptual modelling
- key technique: query rewriting ($\sim$ backward chaining)

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- well suited for medical and life science applications
- key technique: saturation ($\sim$ forward chaining)

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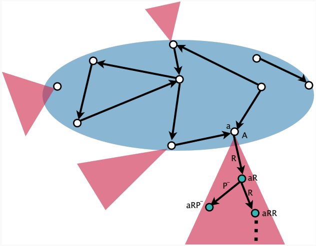
- key technique: saturation ($\sim$ forward chaining)

Commonality: cannot express disjunction (Horn logics), existence of a canonical / universal model

For Horn ontologies (no form of disjunction) like DL-Lite, $\mathcal{EL}$:
enough to consider a single canonical model

- idea: exhaustively apply ontology axioms to dataset (like the chase)
- possibly infinite ($A \sqsubseteq \exists r.A$)
- forest-shaped (dataset + new tree structures for $\exists$-axioms)
- give correct answer to all CQs



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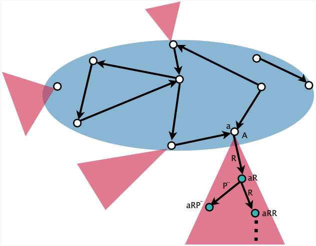

OMQA with Horn DLs =

finding ways to
map the query into
the canonical model

We present the **dialect DL-Lite$_R$** (which underlies **OWL2 QL profile**).

DL-Lite$_R$ TBoxes contain

- **concept inclusions** $B_1 \sqsubseteq B_2$, $B_1 \sqsubseteq \neg B_2$
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Example TBox inclusions:

- Every professor teaches something: $\mathsf{Prof} \sqsubseteq \exists \mathsf{teaches}$
- Everything that is taught is a course: $\exists \mathsf{teaches}^- \sqsubseteq \mathsf{Course}$
- Head of dept implies member of dept: $\mathsf{headOf} \sqsubseteq \mathsf{memberOf}$

Idea: reduce OMQA to database query evaluation

- rewriting step: TBox $\mathcal{T}$ + query $q \rightsquigarrow$ first-order (SQL) query q'
- evaluation step: evaluate query q' using relational DB system

Advantage: harness efficiency of relational database systems

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- FO query q' is an FO-rewriting of q w.r.t. TBox $\mathcal{T}$ iff for every ABox $\mathcal{A}$:

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Good news: every CQ and DL-Lite ontology has FO-rewriting

Reconsider the DL-Lite TBox $\mathcal{T}$:

$$\text{Prof} \sqsubseteq \text{Faculty} \qquad \text{Fellow} \sqsubseteq \text{Faculty} \qquad \text{Prof} \sqsubseteq \neg\text{Fellow}$$
$$\text{Prof} \sqsubseteq \exists\text{teaches} \qquad \exists\text{teaches}^{-} \sqsubseteq \text{Course}$$

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Evaluating the rewritten query over the earlier ABox

$$\{\mathsf{Prof}(\mathsf{anna}), \mathsf{Fellow}(\mathsf{tom}), \mathsf{teaches}(\mathsf{tom}, \mathsf{cs101})\}$$

produces the two certain answers: anna and tom

Can focus w.l.o.g. on rewritings over consistent ABoxes

"Classic" approach works roughly as follows on input $(q, \mathcal{T})$:

- Start with $S = \{q\}$
- Until S stabilizes, pick some $q' \in S$ and do one of the following:
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Alternative "semantic" approach (also producing a UCQ):

- Big $\bigvee$ over possible decompositions of q into ABox and "tree parts"
- For atoms mapped to ABox: check if find implying atom in data
- For subqueries mapped to tree parts:
  - ensure generating atom in data, merge "root" variables

Data complexity:

- rewriting takes constant time, yields FO query
- upper bound from FO query evaluation: AC_0 ($AC_0 \subseteq$ LogSpace $\subseteq$ P)
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Combined complexity:

- 'guess' a disjunct of UCQ-rewriting and how to map it into ABox
- CQ answering is NP-complete (same as for DBs)
- IQ answering is NLogSpace-complete ($\textsc{NLogSpace} \subseteq \mathrm{P}$)

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- Rewriting: $\bigvee_{(i_1,\ldots,i_n)\in\{0,1\}} A_1^{i_1}(x) \wedge A_1^{i_1}(x) \wedge \ldots \wedge A_1^{i_1}(x)$

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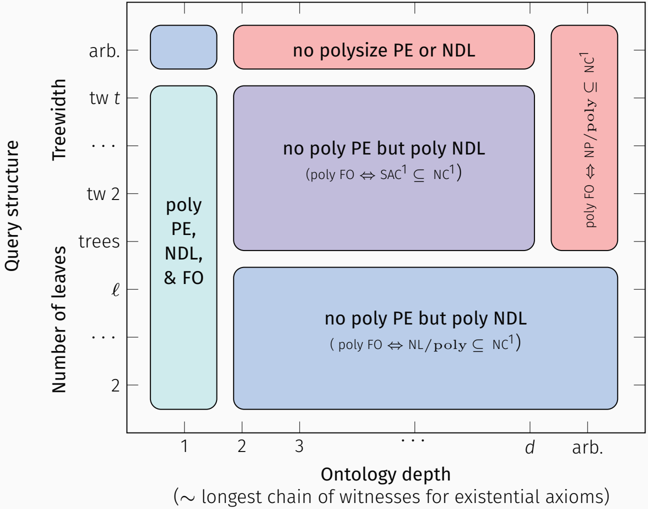
What happens if we adopt other representations?

- positive existential queries (PE), non-recursive Datalog (NDL), first-order queries (FO) (for DL-Lite$_{\mathcal{R}}$ ontologies, so-called ‘pure’ rewritings)



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We start with IQs and present a saturation-based approach.

Convenient to assume $\mathcal{EL}$ TBoxes given in normal form:

$$A_1 \sqcap \ldots \sqcap A_n \sqsubseteq B \quad A \sqsubseteq \exists r.B \quad \exists r.A \sqsubseteq B$$

(A, A_i, B concept names or $\top$)

TBox rules

$$\frac{A \sqsubseteq B_i \ (1 \leq i \leq n) \quad B_1 \sqcap \ldots \sqcap B_n \sqsubseteq D}{A \sqsubseteq D}\ \textsf{T1} \qquad \frac{A \sqsubseteq B \quad B \sqsubseteq \exists r.D}{A \sqsubseteq \exists r.D}\ \textsf{T2}$$

$$\frac{A \sqsubseteq \exists r.B \quad B \sqsubseteq D \quad \exists r.D \sqsubseteq E}{A \sqsubseteq E}\ \textsf{T3}$$

ABox rules

$$\frac{A_1 \sqcap \ldots \sqcap A_n \sqsubseteq B \quad A_i(a) \ (1 \leq i \leq n)}{B(a)}\ \textsf{A1} \qquad \frac{\exists r.B \sqsubseteq A \quad r(a,b) \quad B(b)}{A(a)}\ \textsf{A2}$$

Algorithm: apply rules exhaustively, check if $A(a)$ ($r(a,b)$) is present

EXAMPLE: SATURATION IN EL

$$\mathsf{PenneArrabiata} \sqsubseteq \exists \mathsf{hasIngred.ArrabiataSauce} \quad (1)$$
$$\mathsf{PenneArrabiata} \sqsubseteq \mathsf{PastaDish} \quad (2)$$
$$\mathsf{PastaDish} \sqsubseteq \mathsf{Dish} \quad (3)$$
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$$\mathsf{ArrabiataSauce} \sqsubseteq \exists \mathsf{hasIngred.Peperoncino} \quad (5)$$
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$\text{ArrabSauce} \sqsubseteq \text{Spicy}$	T3 : (5), (6), (7)	(10)
$\text{PenneArrab} \sqsubseteq \text{Spicy}$	T3 : (1), (10), (7)	(11)
$\text{PenneArrab} \sqsubseteq \text{Dish}$	T1 : (2), (3)	(12)
$\text{PenneArrab} \sqsubseteq \exists \text{hasIngred}.\text{Pasta}$	T2 : (2), (4)	(13)
$\text{PenneArrab} \sqsubseteq \text{SpicyDish}$	T1 : (11), (12), (8)	(14)
$\text{Spicy}(\mathbf{p})$	A1 : (11), (9)	(15)
$\text{Dish}(\mathbf{p})$	A1 : (12), (9)	(16)
$\text{SpicyDish}(\mathbf{p})$	A1 : (16), (15)	(17)

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Procedure runs in polynomial time in $|\mathcal{K}|$. This is optimal:

IQ answering in $\mathcal{EL}$ is P-complete for data & combined complexity

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- rules that generate all entailed facts over original individuals
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P data complexity extends to much richer Horn DLs

Way to use relational DBs to do CQ answering in $\mathcal{EL}$:

- saturate ABox using TBox axioms
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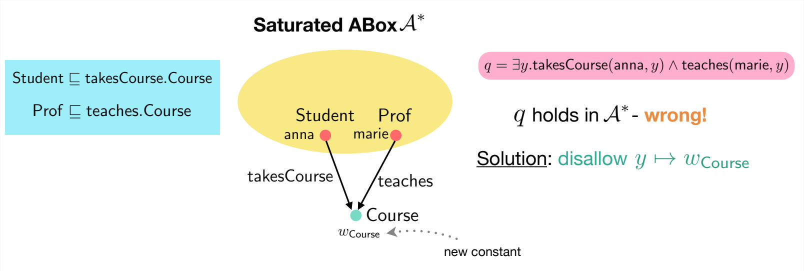
- evaluate query on saturated ABox $\Rightarrow$ superset of certain answers
- two strategies to block unsound answers:
  - add extra conditions to query
  - post-processing to identify and remove false answers



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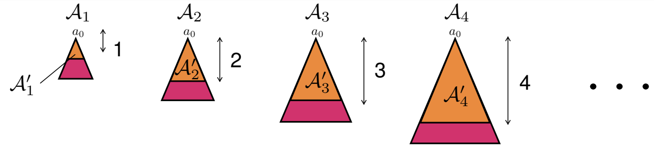
FO-rewritability is EXPTIME-complete in $(\mathcal{EL}, \mathrm{IQ})$ and $(\mathcal{EL}, \mathrm{CQ})$

Characterization of non-existence of FO-rewriting

OMQ $(\mathcal{T}, A(x))$ is **not FO-rewritable** iff there exist tree-shaped ABoxes



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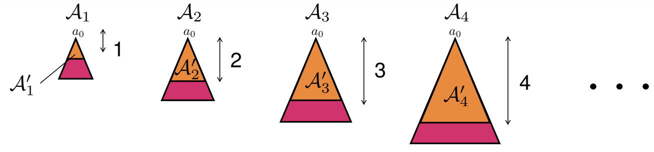

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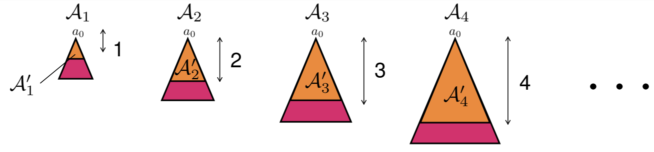

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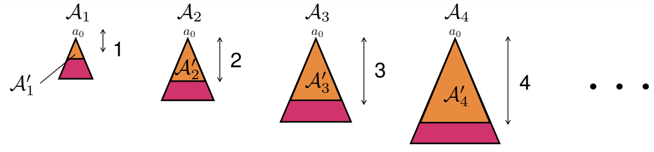

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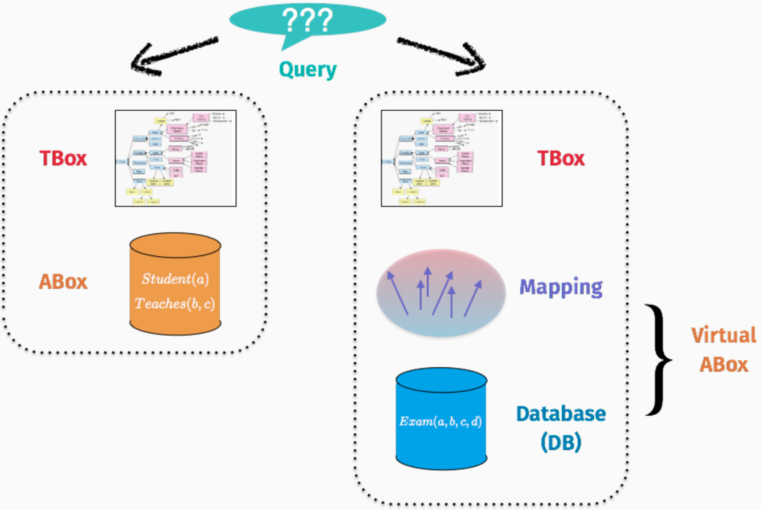
Can **generalize this technique to handle CQs and richer Horn DLs**

LINKING TO EXISTING DATA VIA MAPPINGS

TWO VARIANTS OF OMQA



So far: data given as ABox (unary + binary facts using TBox predicates)

Problem: how to apply the approach to existing relational data (arbitrary arity, different vocabulary)?

Solution: use mapping that specifies relationship between the database relations and the ontology predicates

Formally: mapping assertions of the form $\forall \vec{x}\, \varphi(\vec{x}) \rightarrow \psi(\vec{x})$ where:

- $\varphi(\vec{x})$ is an query formulated using DB relations
- $\psi(\vec{x})$ is a query in the ontology vocabulary

Global-as-view (GAV) mappings: ψ is an atom (without $\exists$-vars)

Database D + mapping $\mathcal{M}$ $\rightsquigarrow$ ABox $\mathcal{A}_{\mathcal{M},D}$

Models of $\langle \mathcal{T}, \mathcal{M}, D \rangle$ = models of the KB $\langle \mathcal{T}, \mathcal{A}_{\mathcal{M},D} \rangle$

Certain answers to q **w.r.t.** $\langle \mathcal{T}, \mathcal{M}, D \rangle$ =
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Handling mappings:

- apply mappings to generate ABox, proceed as usual
- virtual ABox: combine query rewriting with an extra unfolding step to get rewriting over DB relations

EXAMPLE: MAPPINGS

Suppose course data is stored in the two database tables:

$\texttt{UndergradCourses}$[CourseID, Year, Lecturer, Room, Timeslot]

$\texttt{GradCourses}$[CourseID, Lecturer, Room, Timeslot]

and employee data is stored in the table

$\texttt{Employee}$[EmpID,Name,Position,Dept]

The mapping could contain statements like: (initial $\forall$ omitted)

$$\exists y,r,t\, \texttt{UndergradCourses}(\mathsf{c}, y, \mathsf{l}, r, t) \rightarrow \mathsf{teaches}(\mathsf{l}, \mathsf{c})$$

$$\exists y,r,t\, \texttt{GradCourses}(\mathsf{c}, \mathsf{l}, r, t) \rightarrow \mathsf{teaches}(\mathsf{l}, \mathsf{c})$$

$$\exists n,d\, \texttt{Employee}(\mathsf{x}, n, Professor, d) \rightarrow \mathsf{Prof}(\mathsf{x})$$

to populate the ontology predicates teaches and Prof

EXAMPLE: MAPPING UNFOLDING

Unfolding of query q (over ontology vocabulary) w.r.t. mapping:

- find ways of unifying atoms in q with head atoms in mapping rules
- replace atoms in q by the bodies of (unified) matching rules

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For $q(x, y) = \mathrm{Prof}(x) \wedge \mathrm{teaches}(x, y)$, unfolding yields the following:

$$\exists n,d,z,r,t\ \mathtt{Employee}(\mathbf{x}, n, \mathit{Professor}, d) \wedge \mathtt{UndergradCourses}(\mathbf{y}, z, \mathbf{x}, r, t)$$
$$\vee\ \exists n,d,r,t\ \mathtt{Employee}(\mathbf{x}, n, \mathit{Professor}, d) \wedge \mathtt{GradCourses}(\mathbf{y}, \mathbf{x}, r, t)$$

Observe result uses only DB predicates, can be converted to SQL

Unfolding of query q (over ontology vocabulary) w.r.t. mapping:

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Observe **result uses only DB predicates**, can be converted to SQL

Opportunities for optimization: simplify rewriting by exploiting the fact that only needs to work for ABoxes induced by the mapping

OMQA RESEARCH

RESEARCH TOPICS IN OMQA

Ontology-mediated query answering:

- new paradigm for intelligent information systems
- offers many advantages, but also computational challenges
- active area with lots left to explore!

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Support for building and maintaining OMQA systems

- ontology + mapping bootstrapping, module extraction, debugging, ontology evolution and versioning
- inspired new reasoning tasks: query inseparability, query emptiness, justification finding, logical difference, ...

Improving the usability of OMQA systems

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Beyond classical OMQA:

- inconsistency-tolerant query answering
- probabilistic query answering
- privacy-aware query answering

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