A BRIEF INTRODUCTION TO ONTOLOGY-MEDIATED QUERY ANSWERING

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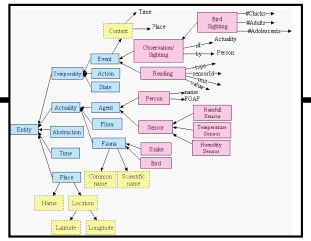
ONTOLOGY-MEDIATED QUERY ANSWERING (OMQA)

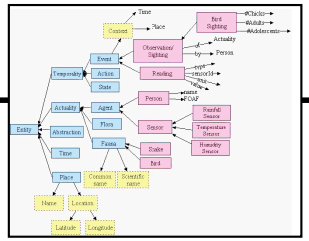
incomplete database
(ground facts)



ontology
(logical theory)

user query

ONTOLOGY-MEDIATED QUERY ANSWERING (OMQA)



patient data

"Melanie has listeriosis"
"Paul has Lyme disease"

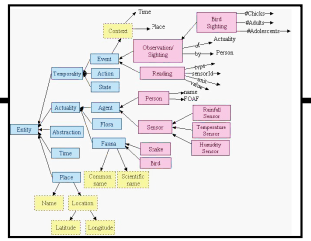
medical knowledge

"Listeriosis & Lyme disease are bacterial infections"

user query

"Find all patients with bacterial infections"

ONTOLOGY-MEDIATED QUERY ANSWERING (OMQA)



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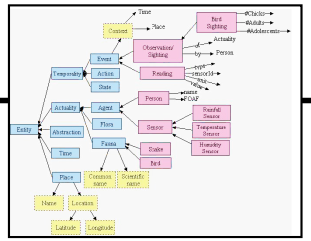

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The ontology (logical theory) specifies:

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

WHAT ARE ONTOLOGIES GOOD FOR?

To **standardize the terminology** of an application domain

- meaning of terms is constrained, so less misunderstandings
- by adopting a common vocabulary, easy to share information

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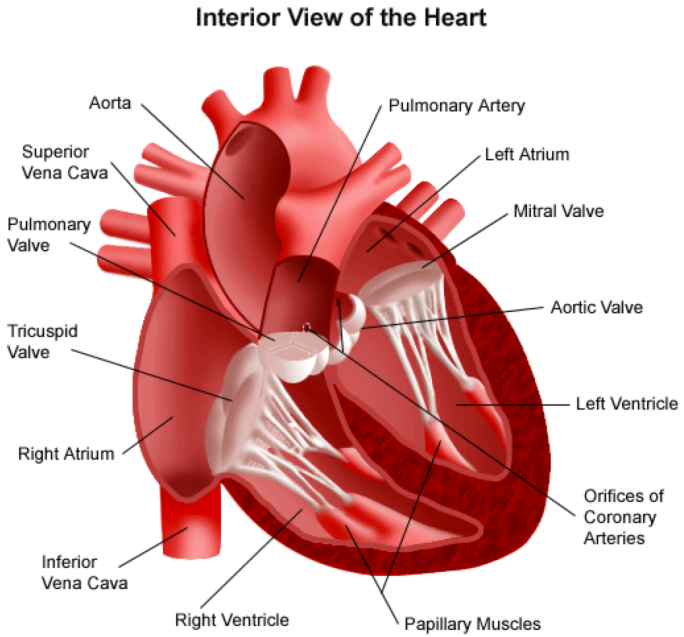
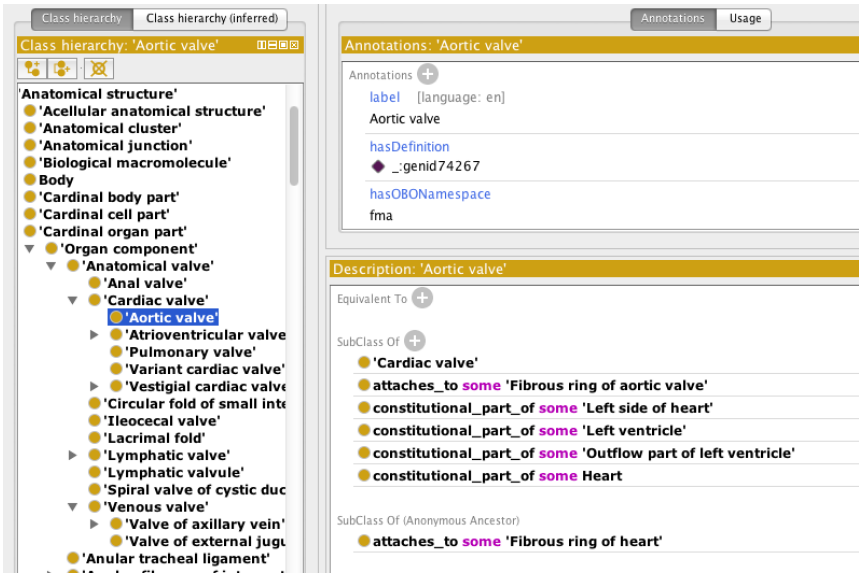
To support **automated reasoning**

- 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

APPLICATIONS OF OMQA: MEDICINE

General medical ontologies: SNOMED CT, GALEN
Specialized ontologies: FMA (anatomy), NCI (cancer), ...



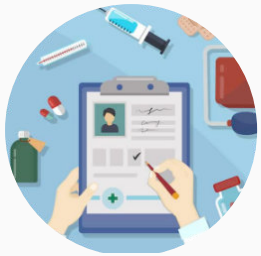


Querying & exchanging medical records (find patients for medical trials)

Supports analysis of health data for medical research

Large-scale comprehensive medical ontology

- more than 350,000 concepts on all aspects of clinical healthcare:
  - symptoms, diagnosis, medical procedures, body structures, organisms, substances, pharmaceutical products, etc.



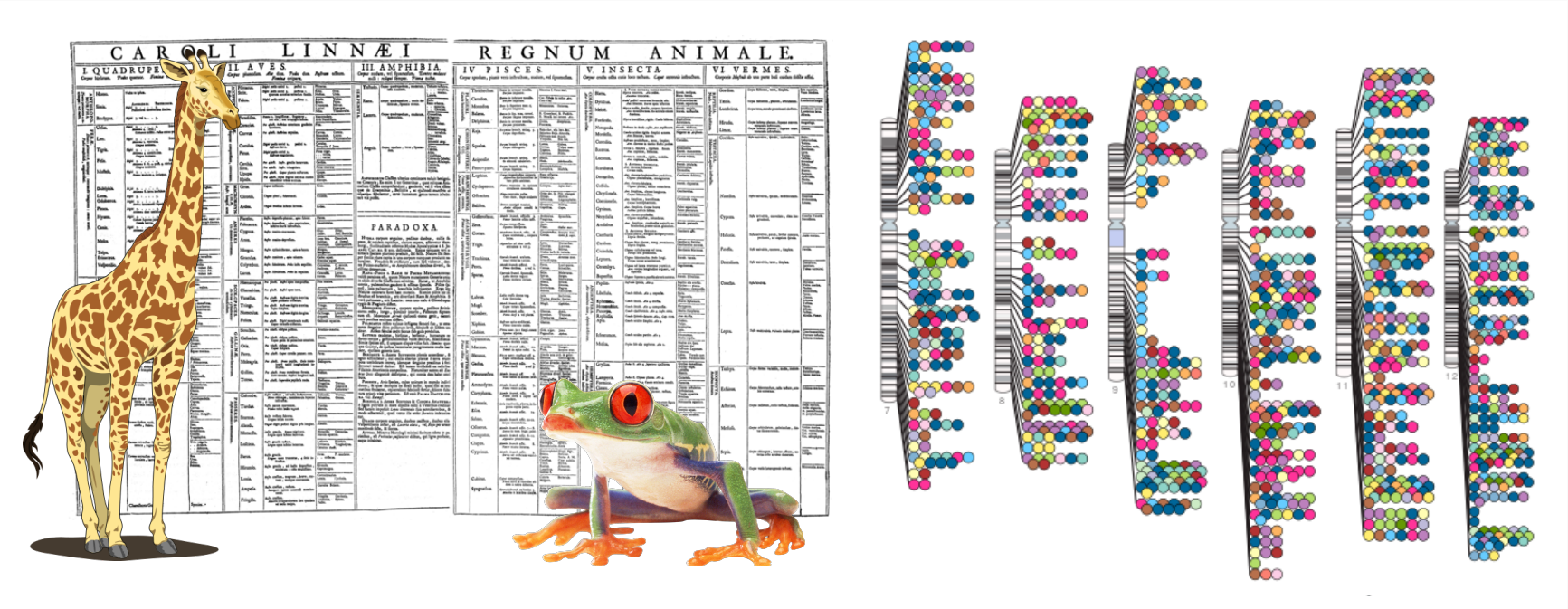


Widely adopted standard for healthcare terminology

- in use in $>$ 80 countries (including U.S., Canada, UK)
- utilized in health IT (e.g. IBM Watson Health, Babylon Health)

APPLICATIONS OF OMQA: LIFE SCIENCES

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

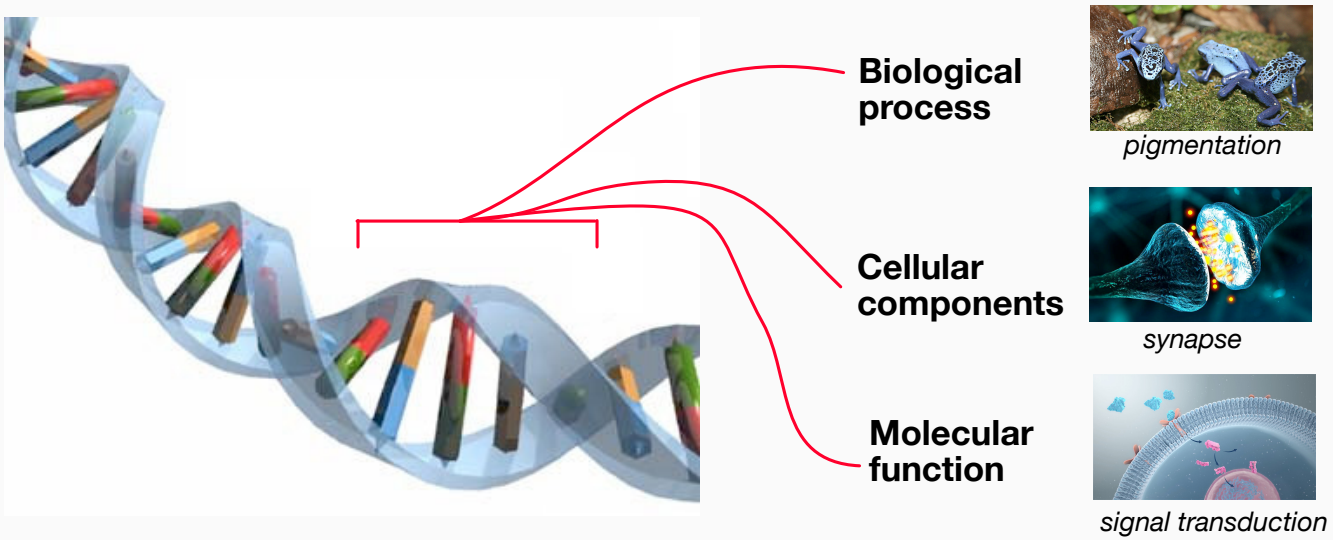


Help scientists share, query, & visualize experimental data

ZOOM ON: GENE ONTOLOGY

Aim: rigorous shared vocabulary to describe the roles of genes across different organisms

Annotations: evidence-based statements relating specific gene product to specific ontology terms



Very successful endeavour:

- > 100K published scientific articles with keyword “Gene Ontology”
- > 700K experimentally-supported annotations

APPLICATIONS OF OMQA: ENTREPRISE INFORMATION SYSTEMS

Companies and organizations have lots of data

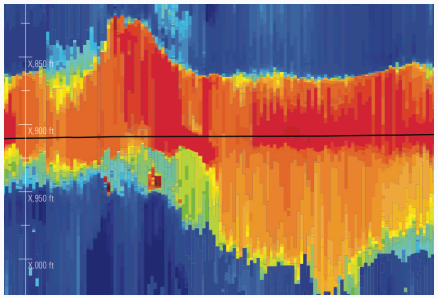
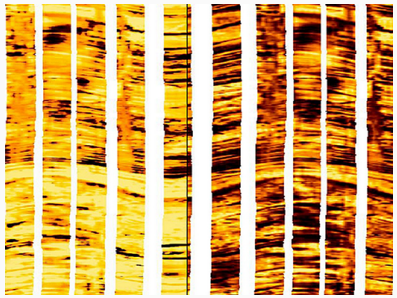
- need easy and flexible access to support decision-making

Example industrial projects:

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

ZOOM ON: STATOIL USECASE

Goal: aid geologists in gathering information for analysis


Difficulties:

- relevant data stored across $>$ 3000 database tables
  - geologist question = complex query (thousands of terms, 50-200 joins)
- must ask IT staff, may take several days to get answer

Solution:

- ontology provides familiar vocabulary for query formulation
- mappings link database tables to ontology terms
- use reasoning to automatically transform ontology query into executable database query

OUR FOCUS: DESCRIPTION LOGIC ONTOLOGIES

Ontologies typically described using logic-based formalisms

Description logics (DLs) are:

- family of knowledge representation languages
- popular means for specifying ontologies
- range from fairly simple to highly expressive
- basis of the web ontology language OWL (W3C standard)

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Formally: correspond to **decidable fragments of first-order logic**

- inherit well-defined semantics
- succinct, variable-free syntax

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Many implemented reasoners and tools available for use

Introduction to DLs and OMQA

OMQA with Data-Tractable DLs

- DL-Lite ($\sim$ OWL 2 QL)
- $\mathcal{EL}$ ($\sim$ OWL 2 EL)

Research Questions in OMQA

INTRODUCTION TO DLS AND OMQA

Building blocks:

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

Constructors to build complex descriptions $\sqcup, \sqcap, \neg, \forall, \exists, \ldots$

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

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Ontology (aka TBox) = set of axioms

- concept inclusions

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

- role inclusions

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

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

Expressive $\mathcal{ALC}$ $\rightsquigarrow$ OWL (2)

- only concept inclusions, with concepts formed as follows:

$$\top \mid \bot \mid A \mid \neg C \mid C \sqcap D \mid C \sqcup D \mid \exists R.C \mid \forall R.C$$

- reasoning provably intractable (EXPTIME)

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Lightweight DL-Lite ⇝ OWL 2 QL

- concept inclusions $B_1 \sqsubseteq (\neg) B_2$ with $B_i = A \mid \exists R \mid \exists R^-$
- role inclusions $S_1 \sqsubseteq (\neg) S_2$ with $S_i := R \mid R^-$
- designed for data-intensive applications

EXAMPLES OF ONTOLOGY AXIOMS

Professors and lecturers are disjoint classes of faculty

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

Every Master's student is supervised by some faculty member

$$\text{MStudent} \sqsubseteq \exists \text{supervisedBy}.\text{Faculty}$$

Master's students are students who only take Master-level courses

$$\text{MStudent} \sqsubseteq \text{Student} \sqcap \forall \text{takesCourse}.\text{MCourse}$$

FO translation:

$\forall x\ (\text{MStudent}(x) \rightarrow (\text{Student}(x) \wedge \forall y\ \text{takesCourse}(x, y) \rightarrow \text{MCourse}(y))$

Focus on two common types of queries for DL ontologies:

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

$$\mathrm{Faculty}(x) \qquad \mathrm{teaches}(x, y)$$

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

conjunctions of atoms, some variables can be existentially quantified

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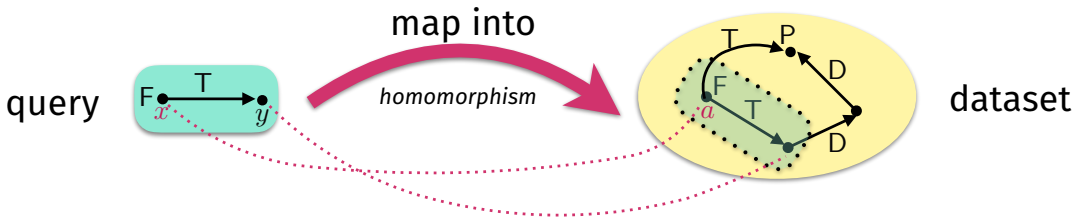
Assume data is set of unary and binary facts in ontology vocabulary

- different format / vocabulary $\Rightarrow$ use mappings

Answering CQs in database setting



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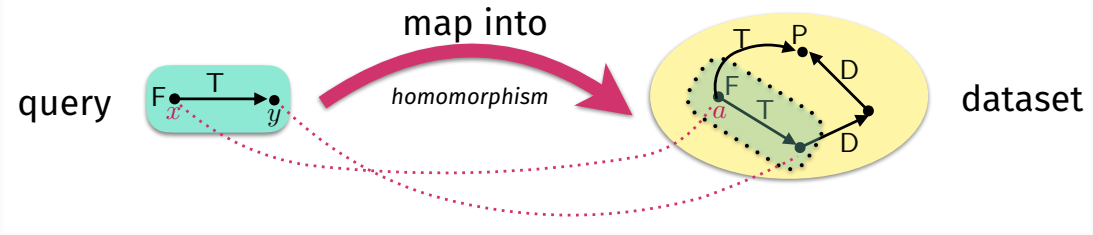
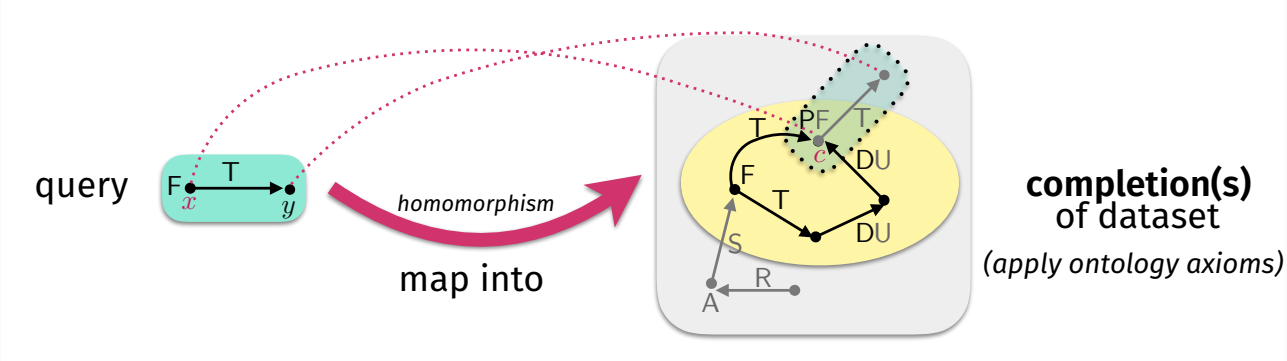


Answering CQs in the presence of an ontology



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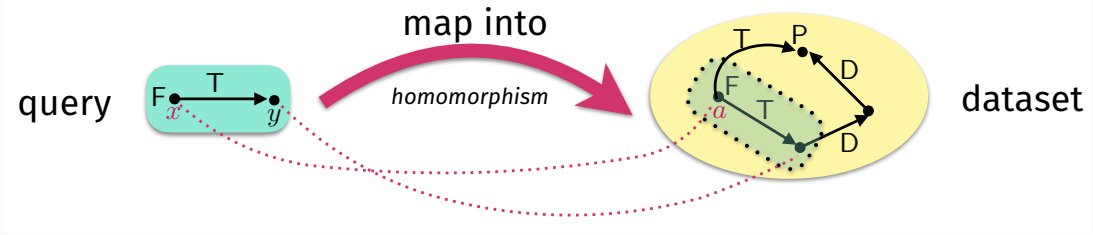

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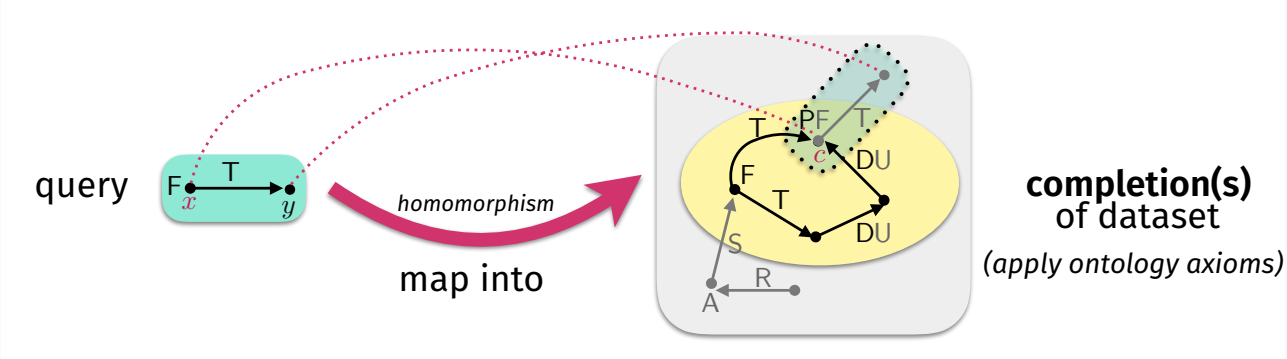

Certain answers: tuples $\vec{a}$ of individuals such that $\mathcal{O}, \mathcal{D} \models q(\vec{a})$

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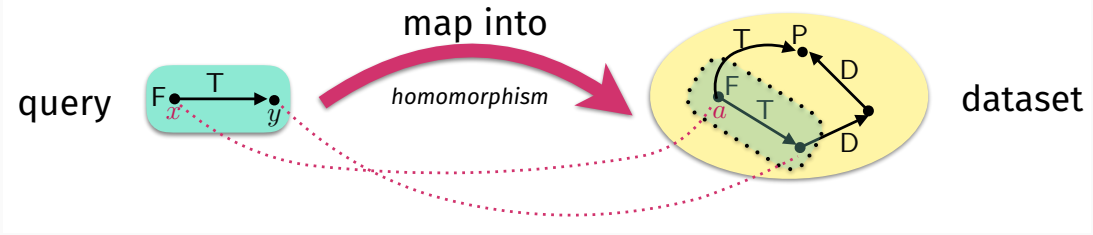

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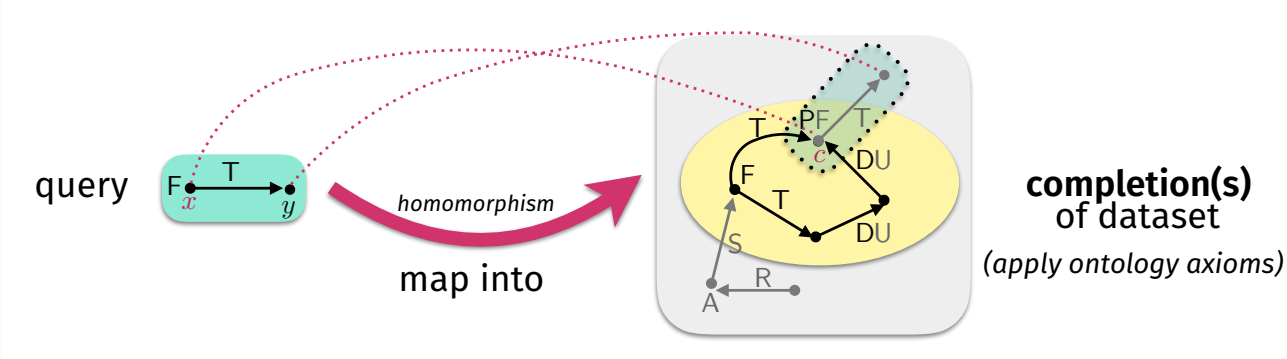

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Ontology-mediated query answering =
problem of computing / verifying **certain answers**

EXAMPLE: OMQA WITH DL-LITE ONTOLOGIES

Ontology, expressed in **DL-Lite**: (lightweight DL designed for OMQA)

$$\begin{array}{lll} \mathsf{Prof} \sqsubseteq \mathsf{Faculty} & \mathsf{Fellow} \sqsubseteq \mathsf{Faculty} & \mathsf{Prof} \sqsubseteq \neg \mathsf{Fellow} \\ \mathsf{Prof} \sqsubseteq \exists \mathsf{teaches} & \exists \mathsf{teaches} \sqsubseteq \mathsf{Faculty} & \exists \mathsf{teaches}^{-} \sqsubseteq \mathsf{Course} \end{array}$$

Dataset:

$$\mathcal{D}_1 = \{\mathsf{Prof}(\mathsf{anna}), \mathsf{Fellow}(\mathsf{tom}), \mathsf{teaches}(\mathsf{tom}, \mathsf{cs101})\}$$

Query: $q_1(x) = \exists y.\mathsf{Faculty}(x) \wedge \mathsf{teaches}(x, y)$

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Get the following answers:

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

COMPLEXITY OF OMQA

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** $q \in \mathcal{Q}$, a **data instance** $\mathcal{D}$, an $\mathcal{L}$**-ontology** $\mathcal{O}$, and a **tuple** $\vec{a} \in \mathsf{Ind}(\mathcal{A})^n$

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Combined complexity: in terms of **size of whole input**

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

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

$$\textbf{data complexity} \leq \textbf{combined complexity}$$

INTRACTABILITY OF OMQA IN ALC AND ALCI

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

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

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

The situation is even worse for $\mathcal{ALCI}$ (= $\mathcal{ALC}$ + inverse roles):

- 2EXPTIME-complete(!) in combined complexity
- coNP-complete in data complexity

OMQA WITH DATA-TRACTABLE DLS

DATA-TRACTABLE 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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Commonality: cannot express disjunction (Horn logics),
existence of a canonical / universal model (like chase in DBs)

We present the dialect DL-Lite$_R$ (which underlies OWL 2 QL profile).

DL-Lite$_R$ axioms:

- concept inclusions $B_1 \sqsubseteq B_2$, $B_1 \sqsubseteq \neg B_2$
- role inclusions $S_1 \sqsubseteq S_2$, $S_1 \sqsubseteq \neg S_2$

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Example axioms:

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

QUERY REWRITING

Idea: reduce OMQA to database query evaluation

- rewriting step: ontology $\mathcal{O}$ + 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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Key notion: first-order (FO) rewriting

- FO query q' is an FO-rewriting of q w.r.t. $\mathcal{O}$ iff for every dataset $\mathcal{D}$:

$$\mathcal{O}, \mathcal{D} \models q(\vec{a}) \quad \Leftrightarrow \quad DB(\mathcal{D}) \models q'(\vec{a})$$

Informally, evaluating q' over $\mathcal{D}$ (viewed as DB) gives correct result

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Advantage: harness efficiency of relational database systems

Key notion: first-order (FO) rewriting

- FO query q' is an FO-rewriting of q w.r.t. $\mathcal{O}$ iff for every dataset $\mathcal{D}$:

$$\mathcal{O}, \mathcal{D} \models q(\vec{a}) \quad \Leftrightarrow \quad DB(\mathcal{D}) \models q'(\vec{a})$$

Informally, evaluating q' over $\mathcal{D}$ (viewed as DB) gives correct result

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

EXAMPLE: QUERY REWRITING IN DL-LITE

Reconsider the DL-Lite ontology $\mathcal{O}$:

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

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The following query is a rewriting of $q(x)$ w.r.t. $\mathcal{O}$:

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$$q(x) \quad \vee \quad \mathsf{Prof}(x) \quad \vee \quad \exists y.\mathsf{Fellow}(x) \wedge \mathsf{teaches}(x, y)$$

Evaluating the rewritten query over the earlier dataset

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

produces the two certain answers: anna and tom

COMPLEXITY OF OMQA IN DL-LITE

Data complexity:

- rewriting takes constant time, yields FO query
- upper bound from FO query evaluation: AC_0 ($AC_0 \subseteq$ LogSpace $\subseteq$ P)
- CQ answering is in AC_0 for data complexity

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Combined complexity:

- 'guess' a disjunct of the rewriting and how to map it into data
- CQ answering is NP-complete (same as for DBs)
- IQ answering is NLogSpace-complete (NLogSpace $\subseteq$ P)

Next consider the logic $\mathcal{EL}$:

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We present a saturation-based approach.

Convenient to assume $\mathcal{EL}$ ontologies 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 $\top$)

Deriving new ontology axioms

$$\frac{A \sqsubseteq B_i \ (1 \leq i \leq n) \quad B_1 \sqcap \ldots \sqcap B_n \sqsubseteq D}{A \sqsubseteq D} \ \text{O1} \qquad \frac{A \sqsubseteq B \quad B \sqsubseteq \exists r.D}{A \sqsubseteq \exists r.D} \ \text{O2}$$

$$\frac{A \sqsubseteq \exists r.B \quad B \sqsubseteq D \quad \exists r.D \sqsubseteq E}{A \sqsubseteq E} \ \text{O3}$$

Deriving new facts

$$\frac{A_1 \sqcap \ldots \sqcap A_n \sqsubseteq B \quad A_i(a) \ (1 \leq i \leq n)}{B(a)} \ \text{D1} \qquad \frac{\exists r.B \sqsubseteq A \quad r(a,b) \quad B(b)}{A(a)} \ \text{D2}$$

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

EXAMPLE: SATURATION IN EL

$$\mathsf{PenneArrabiata} \sqsubseteq \exists \mathsf{hasIngred}.\mathsf{ArrabiataSauce} \quad (1)$$

$$\mathsf{PenneArrabiata} \sqsubseteq \mathsf{PastaDish} \quad (2)$$

$$\mathsf{PastaDish} \sqsubseteq \mathsf{Dish} \quad (3)$$

$$\mathsf{PastaDish} \sqsubseteq \exists \mathsf{hasIngred}.\mathsf{Pasta} \quad (4)$$

$$\mathsf{ArrabiataSauce} \sqsubseteq \exists \mathsf{hasIngred}.\mathsf{Peperoncino} \quad (5)$$

$$\mathsf{Peperoncino} \sqsubseteq \mathsf{Spicy} \quad (6)$$

$$\exists \mathsf{hasIngred}.\mathsf{Spicy} \sqsubseteq \mathsf{Spicy} \quad (7)$$

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$$\text{ArrabSauce} \sqsubseteq \text{Spicy} \quad \text{O3} : (5), (6), (7) \quad (10)$$

$$\text{PenneArrab} \sqsubseteq \text{Spicy} \quad \text{O3} : (1), (10), (7) \quad (11)$$

$$\text{PenneArrab} \sqsubseteq \text{Dish} \quad \text{O1} : (2), (3) \quad (12)$$

$$\text{PenneArrab} \sqsubseteq \exists \text{hasIngred}.\text{Pasta} \quad \text{O2} : (2), (4) \quad (13)$$

$$\text{PenneArrab} \sqsubseteq \text{SpicyDish} \quad \text{O1} : (11), (12), (8) \quad (14)$$

$$\text{Spicy}(\mathbf{p}) \quad \text{D1} : (11), (9) \quad (15)$$

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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

Different techniques required to handle conjunctive queries

Combined approach (another way to exploit DBs):

- saturate ABox using the TBox axioms
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- evaluate query on saturated ABox $\Rightarrow$ superset of certain answers
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Complexity of CQ answering in $\mathcal{EL}$:

- P-complete in data complexity (scale polynomially in $|\mathcal{A}|$)
- NP-complete in combined complexity

OMQA RESEARCH

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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, ...

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Beyond classical OMQA:

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

Questions ?