Knowledge Representation and Semantic Technologies

OWL 2

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Weak sides of OWL 1

- OWL 1 = first release of OWL (2004)
- Three versions of OWL 1:
  - OWL Full: undecidable
  - OWL-DL: reasoning is exponential
  - OWL-Lite: almost same complexity as OWL-DL
- Main criticism: processing OWL is computationally too expensive (exponential)
- especially in Semantic Web applications, scalability (or at least tractability) of processing/reasoning is a crucial property

Limits of OWL-DL reasoners

- performance of OWL-DL reasoners:
- "practically good" for the intensional level
  - the size of a TBox is not likely to scale up too much
- not good for the extensional level
  - unable to handle instances (ABoxes) of large size (or even medium size)...
  - ...even for the basic extensional service (instance checking)

Limits of OWL-DL reasoners

- why are these tools so bad with (large) ABoxes?
- two main reasons:
- current algorithms are mainly derived by algorithms defined for purely intensional tasks
    - no real optimization for ABox services
- these algorithms work in main memory

  => bottleneck for very large instances

OWL-DL technology vs. large instances

- the limits of OWL-DL reasoners make it impossible to use these tools for real data integration on the web
- web sources are likely to be data intensive sources
- e.g., relational databases accessed through a web interface
- on the other hand, data integration is **the** prominent (future) application for Semantic Web technology! [Berners-Lee et al., IEEE Intelligent Systems, May 2006]

A solution: OWL profiles

- how to overcome these limitations if we want to build data-intensive Semantic Web applications?
- solution 1 : do not reason over ontologies
- solution 2: limit the expressive power of the ontology language

  => tractable fragments of OWL (**OWL profiles**)
- solution 3: wait for more efficient OWL-DL reasoners
- to arrive at solution 2, we may benefit from the new technology developed for OWL tractable fragments

Tractable OWL fragments

- idea: sacrifice part of the expressiveness of the ontology language to have more efficient ontology tools
- OWL Lite is a standardized fragment of OWL-DL
- is OWL Lite OK?
- NO! it is still too expressive for ABox reasoning (OWL Lite is not really “lite”!)

Tractable OWL fragments

- The second version of OWL (called OWL2) became a W3C recommendation on October 2009
- Besides the OWL2 Full language and the OWL2 DL language, this recommendation contains three fragments of OWL2 DL called **OWL 2 PROFILES:**
  - **OWL 2 QL** based on the DL **DL-Lite**
  - **OWL 2 EL** based on the DL **EL**
  - **OWL 2 RL** based on the DL **RL**

DL-Lite

- DL-Lite is a tractable OWL-DL fragment
- defined by the DIS-Sapienza DASI research group
- main objectives:
  - allow for very efficient treatment of large ABoxes...
  - ...even for very expressive queries (conjunctive queries)

The DL-Lite family

- DL-Lite is a family of Description Logics
- **DL-Lite$_{core}$** = basic DL-Lite language
- main DL-Lite dialects:
  - **DL-Lite$_F$** (DL-Lite$_{core}$ + role functionality)
  - **DL-Lite$_R$** (DL-Lite$_{core}$ + role hierarchies)
  - **DL-Lite$_A$** (DL-Lite$_F$ + DL-Lite$_R$ + attributes + domains)
- the current OWL 2 QL proposal is based on DL-Lite$_R$

DL-Lite$_F$ syntax

concept expressions:
- atomic concept A
- role domain $\exists R$
- role range $\exists R^-$

role expressions:
- atomic role R
- inverse atomic role R^-

- DL-Lite$_F$ **TBox** = set of
  - concept inclusions
  - concept disjointness assertions
  - functional assertions (stating that a role is functional)
- DL-Lite$_F$ **ABox** = set of ground atoms, i.e., assertions
  - A(a) with A concept name
  - R(a,b) with R role name

Example

TBox:

MALE $\sqsubseteq$ PERSON	concept inclusion
FEMALE $\sqsubseteq$ PERSON	concept inclusion
PERSON $\sqsubseteq$ $\exists$hasFather	concept inclusion
$\exists$hasFather$^-$ $\sqsubseteq$ MALE	concept inclusion
PERSON $\sqsubseteq$ $\exists$hasMother	concept inclusion
$\exists$hasMother$^-$ $\sqsubseteq$ FEMALE	concept inclusion
MALE $\sqsubseteq\neg$FEMALE	concept disjointness
funct(hasMother)	role functionality

ABox:

MALE(Bob), MALE(Paul), FEMALE(Ann),
hasFather(Paul,Ann), hasMother(Mary,Paul)

Expressiveness of DL-Lite vs. OWL-DL

main expressive limitations of DL-Lite w.r.t. OWL-DL:

1. **restricted disjunction:**
   - no explicit disjunction
   - binary Horn implications (concept and role inclusions)
2. **restricted negation:**
   - no explicit negation
   - concept (and role) disjointness
3. **restricted existential quantification:**
   - e.g., no qualified existential concepts
4. **limited role cardinality restrictions:**
   - only role functionality allowed
   - not a “real” problem

Expressiveness of DL-Lite vs. RDF/RDFS

DL-Lite captures RDFS...

- RDFS classes = concepts
- RDFS properties = roles
- rdfs:subClassOf = concept inclusion
- rdfs:subPropertyOf = role inclusion
- rdfs:domain = role domain
- rdfs:range = role range

but: DL-Lite does not allow for meta-predicates

DL-Lite extends RDFS:

- "exact" role domain and range
- concept and role disjointness
- inverse roles
- functional roles

DL-Lite vs. conceptual data models

- DL-Lite captures a very large subset of the constructs of conceptual data modeling languages (UML class diagrams, E-R)
- e.g., DL-Lite$_A$ captures almost all the E-R model:
  - entities = concepts
  - binary relationships = roles
  - entity attributes = concept attributes
  - relationship attributes = role attributes
  - cardinality constraints (0,1) = concept inclusions and role functionalities
  - ...

⇒ DL-Lite = a simple yet powerful ontology language

DL-Lite abilities

tractability of TBox reasoning:

- all TBox reasoning tasks in DL-Lite are tractable, i.e., solvable in polynomial time

tractability of ABox+TBox reasoning:

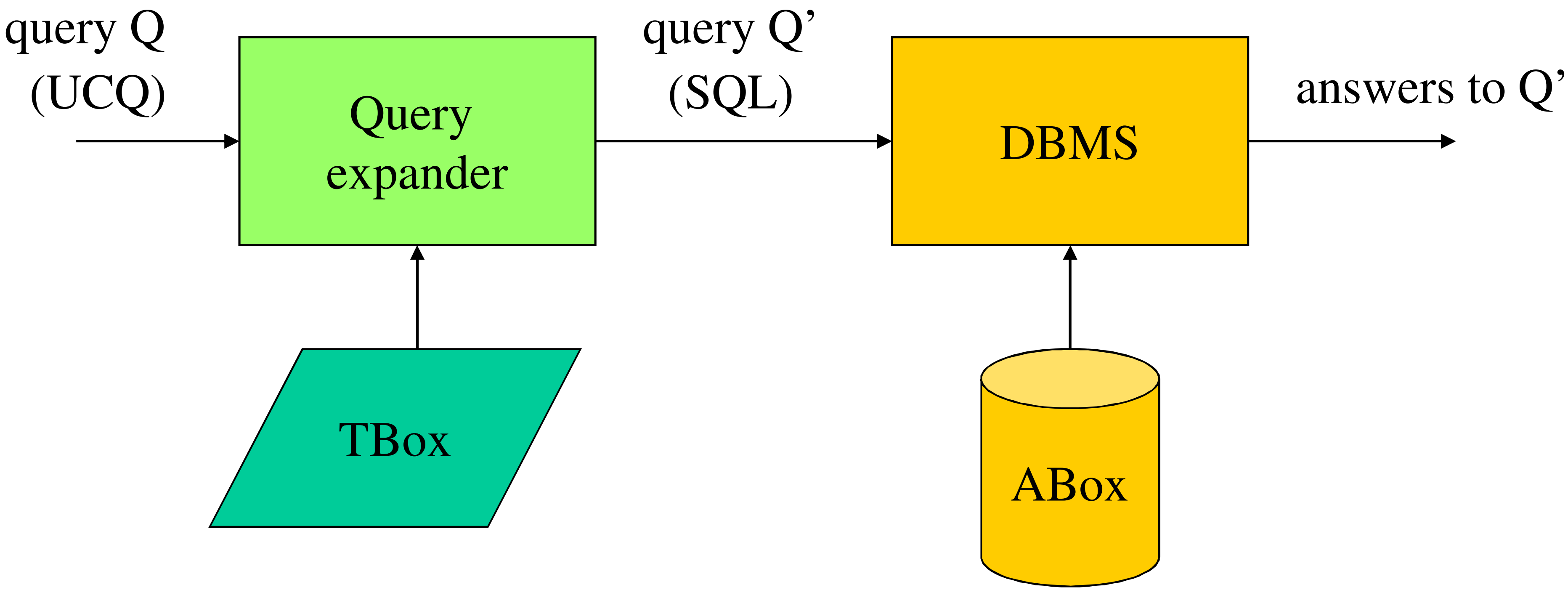
- instance checking and instance retrieval in DL-Lite are solvable in polynomial time
- conjunctive queries over DL-Lite ontologies can be answered in polynomial time (actually in LogSpace) with respect to *data complexity* (i.e., the size of the ABox)

Query answering in DL-Lite

a glimpse on the query answering algorithm:

- **query answering in DL-Lite can be reduced to evaluation of an SQL query over a relational database** (this is the **first-order rewritability** property)
- query answering by query rewriting + relational database evaluation:
  1. the ABox is stored in a relational database (set of unary and binary tables)
  2. the conjunctive query Q is rewritten with respect to the TBox, obtaining an SQL query Q'
  3. query Q' is passed to the DBMS which returns the answers

Query answering in DL-Lite



Example

TBox:

$MALE \sqsubseteq PERSON$

$MALE \sqsubseteq \neg FEMALE$

$\exists hasFather^{-} \sqsubseteq MALE$

$\exists hasMother^{-} \sqsubseteq FEMALE$

$FEMALE \sqsubseteq PERSON$

$PERSON \sqsubseteq \exists hasFather$

$PERSON \sqsubseteq \exists hasMother$

input query:

q(x) :- PERSON(x)

rewritten query:

q'(x) :- PERSON(x) $\vee$
FEMALE(x) $\vee$
MALE(x) $\vee$
hasFather(y,x) $\vee$
hasMother(y,x)

Example

rewritten query:

q'(x) :- PERSON(x) ∨
FEMALE(x) ∨
MALE(x) ∨
hasFather(y,x) ∨
hasMother(y,x)

ABox:

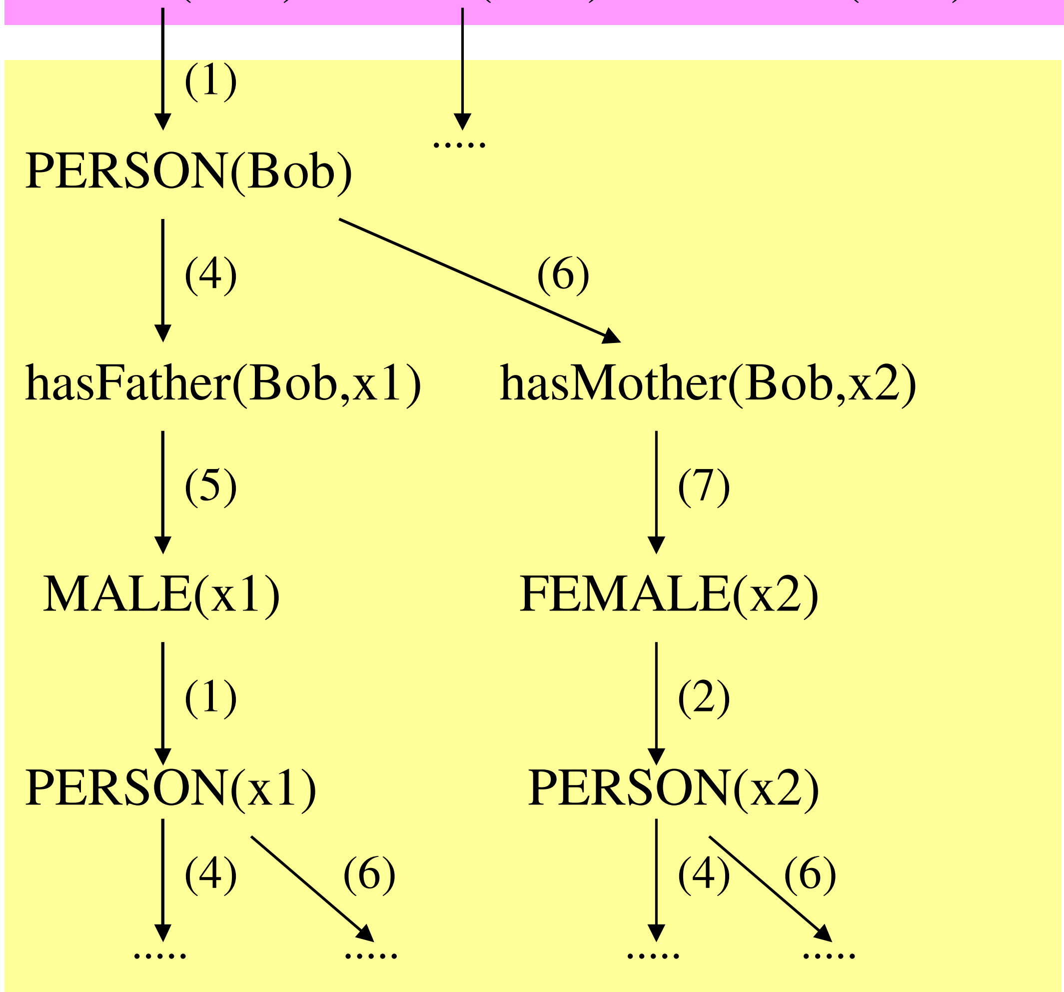
MALE(Bob)
MALE(Paul)
FEMALE(Ann)
hasFather(Ann,Paul)
hasMother(Paul,Mary)

answers to query:

{ Bob, Paul, Ann, Mary }

Answering queries: chasing the ABox

MALE(Bob) MALE(Paul) FEMALE(Ann) hasFather(Paul,Ann) hasMother(Mary,Paul)



CHASE of the ABox with respect to the TBox = adding to the ABox all instance assertions that are logical consequences of the TBox

the chase represents the **canonical model** of the whole KB

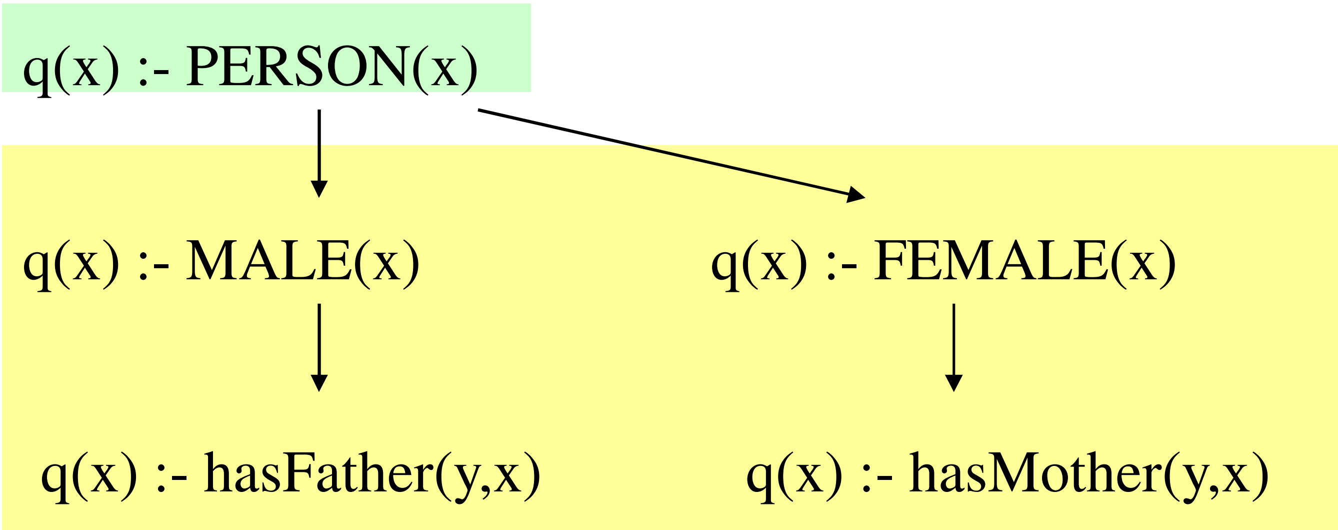
problem: the chase of the ABox is in general infinite

Query rewriting algorithm for DL-Lite

how to avoid the infinite chase of the ABox?

CHASE of the query:

- inclusions are applied “from right to left”
- this chase always terminates
- this chase is computed independently of the ABox



Query rewriting algorithm for DL-Lite

the rewriting algorithm iteratively applies two rewriting rules:

- **atom-rewrite**
- **reduce**

Atom-rewrite

atom-rewrite takes an atom of the conjunctive query and rewrites it applying a TBox inclusion

The inclusion is used as a rewriting rule (right-to-left)

Example:

- T = { D $\sqsubseteq$ C }
- q :- C(x), R(x,y), D(y)
- atom-rewrite(q, C(x), D $\sqsubseteq$ C) = q :- D(x), R(x,y), D(y)

Reduce

reduce takes two unifiable atoms of the conjunctive query and merges (unifies) them

Example:

- q :- C(x), R(x,y), R(y,z), D(z)
- reduce(q, R(x,y), R(y,z)) = q:- C(x), R(x,x), D(x)
  (the unification of R(x,y) and R(y,z) implies x=y=z)

Query rewriting algorithm for DL-Lite

Algorithm PerfectRef (q, $\mathcal{T}$)
Input: conjunctive query q, DL-Lite TBox $\mathcal{T}$
Output: union of conjunctive queries PR

```
PR := {q};
repeat
    PR0 := PR;
    for each q ∈PR0 do
    (a) for each g in q do
            for each positive inclusion I  in 𝒯 do
              if I is applicable to g
              then PR := PR ∪{atom-rewrite(q,g,I)};
    (b) for each g1, g2 in q  do
          if g1 and g2 unify then PR := PR ∪{reduce(q,g1,g2)}
until PR0 = PR;
return PR
```

Reasoning in DL-Lite

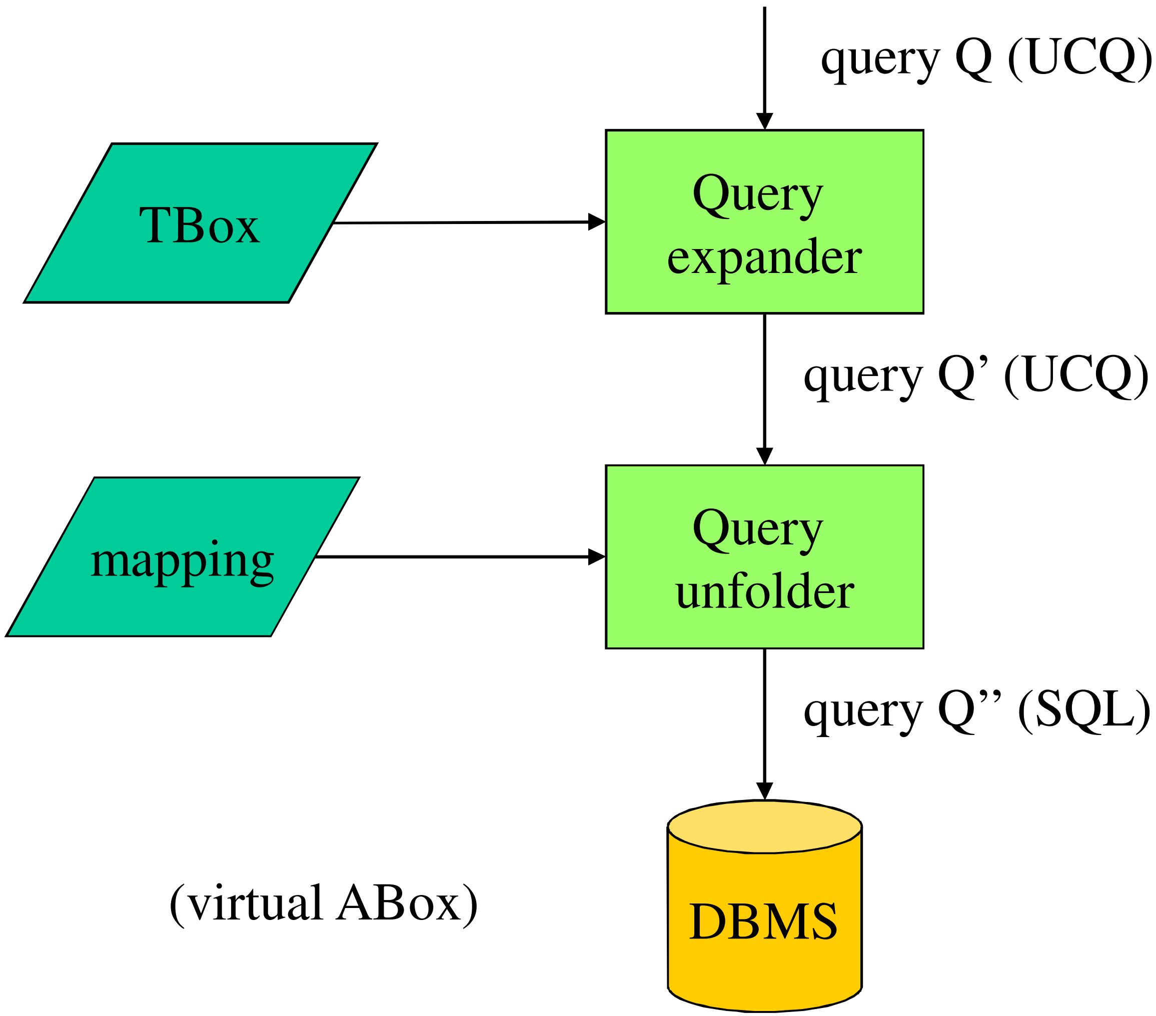
- this query answering technique is in LOGSPACE with respect to data (ABox) complexity
- polynomial technique for deciding KB consistency in DL-Lite
- all main reasoning tasks in DL-Lite can be reduced to either KB consistency or query answering

  => all main reasoning tasks in DL-Lite are tractable

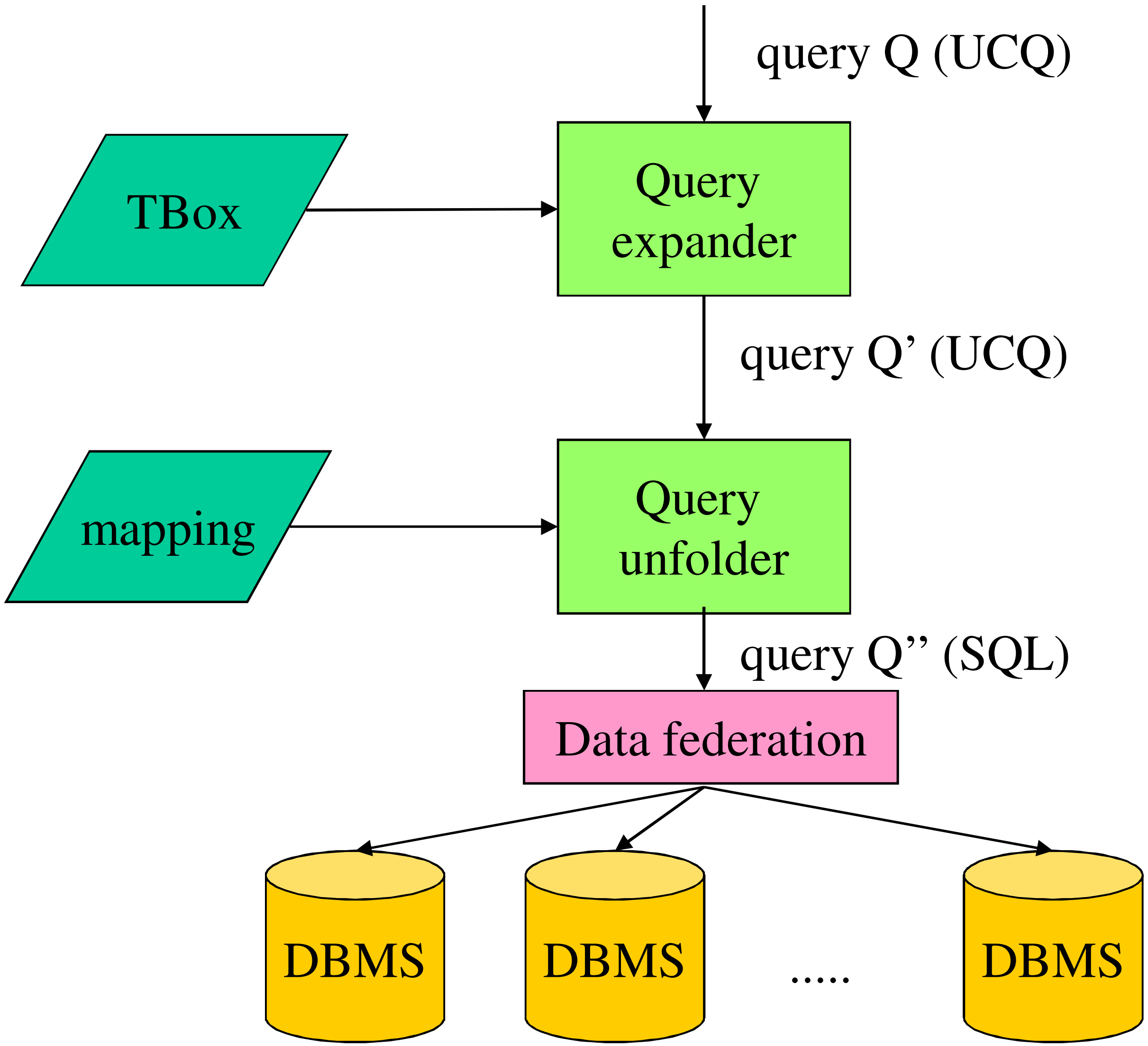
QuOnto

- QuOnto is a reasoner for DL-Lite
- developed by DASI lab at DIS-Sapienza
- implements the above answering technique for conjunctive queries
- able to deal with very large instances (comparable to standard relational databases!)
- currently used in MASTRO, a system for ontology-based data integration

MASTRO (single database)



MASTRO-I (data integration)



The EL family of DLs

- The EL family of description logics underlies the OWL 2 EL profile
- Several members:
  - EL (core language)
  - $EL_{\bot}$
  - ELH
  - EL++
  - …

Syntax of EL

concept expressions:
- atomic concept A
- concept conjunction $C_1 \sqcap C_2$
- qualified existential $\exists R.C$

role expressions:
- atomic role R

- EL **TBox** = set of concept inclusions
- EL **ABox** = set of ground atoms, i.e., assertions
  - A(a) with A concept name
  - R(a,b) with R role name

EL ontology: Example

TBox:

MALE $\sqsubseteq$ PERSON

FEMALE $\sqsubseteq$ PERSON

PERSON $\sqsubseteq$ $\exists$hasFather.MALE

PERSON $\sqsubseteq$ $\exists$hasMother.FEMALE

STUDENT $\sqcap$ EMPLOYEE $\sqsubseteq$ WORKING-STUDENT

ABox:

MALE(Bob), MALE(Paul), FEMALE(Ann),

hasFather(Paul,Ann), hasMother(Mary,Paul),

HAPPY(Ann), EMPLOYEE(Paul), STUDENT(Paul)

Computational properties of EL

Complexity of reasoning in EL (and in other languages of this family):

- Intensional (TBox) reasoning is PTIME-complete (i.e., tractable)
- Instance checking is PTIME-complete
- Conjunctive query answering is PTIME-complete with respect to data complexity
  - This implies that first-order rewritability does NOT hold for EL
- Conjunctive query answering is NP-complete with respect to combined complexity

The Description Logic RL: Syntax

concept expressions:

- atomic concept A
- concept conjunction $C_1 \sqcap C_2$
- qualified existential $\exists R.C$
- qualified existential $\exists R.\bot$

role expressions:

- atomic role R
- inverse role R^-

- RL **TBox** =
  - set of concept inclusions of the form $C \sqsubseteq A$ or $C \sqsubseteq \bot$
  - set of role inclusions $R_1 \sqsubseteq R_2$
- RL **ABox** = set of ground atoms, i.e., assertions
  - $A(a)$ with A concept name
  - $R(a,b)$ with R role name

RL ontology: Example

TBox:

$MALE \sqsubseteq PERSON$

$FEMALE \sqsubseteq PERSON$

$hasMother \sqsubseteq hasParent$

$hasFather \sqsubseteq hasParent$

$MALE \sqcap FEMALE \sqsubseteq \bot$

$STUDENT \sqcap EMPLOYEE \sqsubseteq WORKING\text{-}STUDENT$

$\exists hasParent.HAPPY \sqsubseteq HAPPY$

ABox:

MALE(Bob), MALE(Paul), FEMALE(Ann),

hasFather(Paul,Ann), hasMother(Mary,Paul),

HAPPY(Ann), EMPLOYEE(Paul), STUDENT(Paul)

Computational properties of RL

Complexity of reasoning in RL:

- Intensional (TBox) reasoning is PTIME-complete (i.e., tractable)
- Instance checking is PTIME-complete
- Conjunctive query answering is PTIME-complete with respect to data complexity
  - This implies that first-order rewritability does NOT hold for RL
- Conjunctive query answering is NP-complete with respect to combined complexity
- Reasoning in RL can be reduced to reasoning in positive Datalog

Reasoning in RL (and RDFS)

ABox reasoning and query answering in RL (and RDFS) can be done through **forward chaining** (a.k.a. **materialization**), which corresponds to the **chase** procedure mentioned above.

- Chase of the ABox with respect to the TBox = adding to the ABox all instance assertions that are logical consequences of the TBox
- In the case of RL (and RDFS) no new individual is introduced by the chase, so this procedure always terminates (and requires polynomial time)
- After this materialization step, the TBox can be discarded and conjunctive queries can be answered by evaluating them on the materialized ABox

Reasoning in RL: Example

TBox:

$MALE \sqsubseteq PERSON$
$FEMALE \sqsubseteq PERSON$
$hasMother \sqsubseteq hasParent$
$hasFather \sqsubseteq hasParent$
$MALE \sqcap FEMALE \sqsubseteq \bot$
$STUDENT \sqcap EMPLOYEE \sqsubseteq WORKING\text{-}STUDENT$
$\exists hasParent.HAPPY \sqsubseteq HAPPY$

ABox:

MALE(Bob), MALE(Paul),
FEMALE(Ann),
hasFather(Paul,Ann),
hasMother(Mary,Paul),
HAPPY(Ann), EMPLOYEE(Paul),
STUDENT(Paul)

Materialization

TBox:

MALE $\sqsubseteq$ PERSON
FEMALE $\sqsubseteq$ PERSON
hasMother $\sqsubseteq$ hasParent
hasFather $\sqsubseteq$ hasParent
MALE $\sqcap$ FEMALE $\sqsubseteq$ $\bot$
STUDENT $\sqcap$ EMPLOYEE $\sqsubseteq$ WORKING-STUDENT
$\exists$hasParent.HAPPY $\sqsubseteq$ HAPPY

Materialized ABox (chase):

MALE(Bob), MALE(Paul),
FEMALE(Ann),
hasFather(Paul,Ann),
hasMother(Mary,Paul),
HAPPY(Ann), EMPLOYEE(Paul),
STUDENT(Paul),

PERSON(Bob), PERSON(Paul),
PERSON(Ann),
hasParent(Paul,Ann),
hasParent(Mary,Paul),
HAPPY(Paul), HAPPY(Mary),
WORKING-STUDENT(Paul)

Query answering

TBox:

MALE $\sqsubseteq$ PERSON
FEMALE $\sqsubseteq$ PERSON
hasMother $\sqsubseteq$ hasParent
hasFather $\sqsubseteq$ hasParent
MALE $\sqcap$ FEMALE $\sqsubseteq \bot$
STUDENT $\sqcap$ EMPLOYEE $\sqsubseteq$
WORKING-STUDENT
$\exists$hasParent.HAPPY $\sqsubseteq$ HAPPY

Query: (happy grandchildren)

q(x) :- HAPPY(x), hasParent(x,y),
hasParent(y,z).

Answer = { Mary }

Materialized ABox:

MALE(Bob), MALE(Paul),
FEMALE(Ann),
hasFather(Paul,Ann),
hasMother(Mary,Paul),
HAPPY(Ann), EMPLOYEE(Paul),
STUDENT(Paul),

PERSON(Bob), PERSON(Paul),
PERSON(Ann),
hasParent(Paul,Ann),
hasParent(Mary,Paul),
HAPPY(Paul), HAPPY(Mary),
WORKING-STUDENT(Paul)

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