From Data Independence to Ontology Based Data Access (and back)

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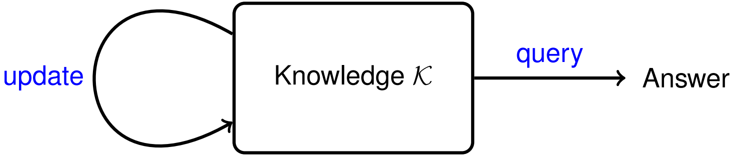
Joint work with Alexander Hudek and Grant Weddell

Knowledge Representation: a Big Picture



What is "Knowledge" (how is it represented, and does the user care?)

$\Rightarrow$ not really as long as the updates and queries "play nicely together"

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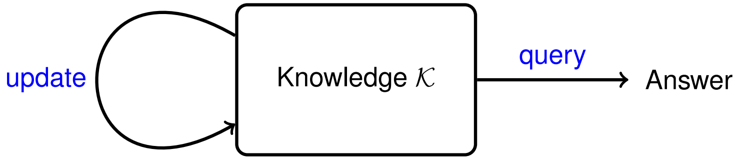

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$\Rightarrow$ not really as long as the updates and queries "play nicely together"

Structured World:

- $\mathcal{K}$ is a (first order) theory,
- queries are (FO) formulæ with answers defined by entailment, and
- updates are (variations on) belief revision.

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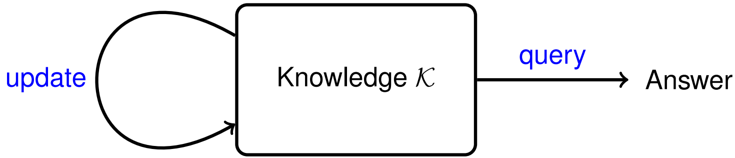

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Probabilistic World:

- $\mathcal{K}$ is a ML model (e.g., neural net),
- queries are inputs (e.g., photos) and answers are labels
- updates are pairs of, e.g., photos with their labels.

Ontology-based Data Access (OBDA) [Calvanese et al.: Mastro, 2011]

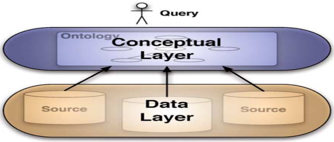
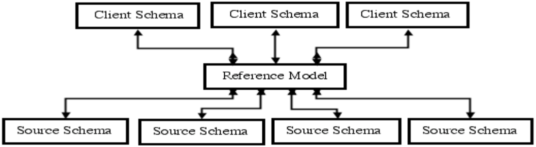


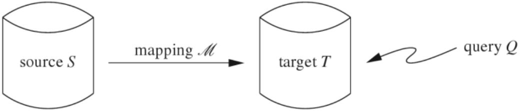
Fig. 1. Ontology-based data access.

Information Integration [Genesereth: Data Integration, 2010]

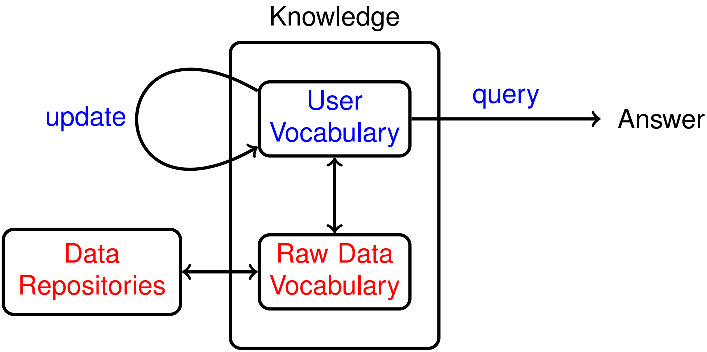


Data Exchange [Arenas et el.: Data Exchange, 2014]

The general setting of data exchange is this:



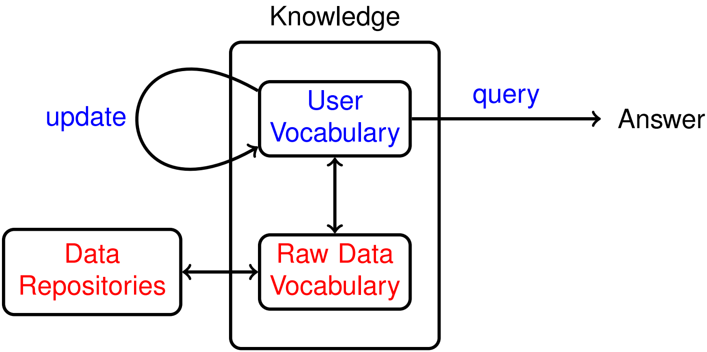
Data vs. Metadata



1. Metadata: constraints formulated in FOL (static) [called a TBox]
2. Data: ground tuples (can be "modified") [called an ABox]

$\Rightarrow$ user queries and updates only about data.

Data vs. Metadata



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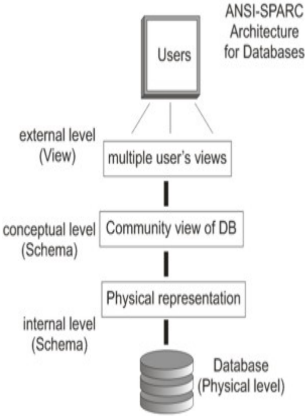
(Physical) Data Independence

IDEA:

Separate the users' view(s) of the data from the way it is physically represented.

- independent customized user views;
- changes to conceptual structure without affecting users;
- physical storage details hidden from users;
- changes to physical storage without affecting logical view;

Originally just two levels: physical and conceptual/logical [Codd1970].



[ANSI/X3/SPARC Standards Planning and Requirements Committee, Bachman, 1975]

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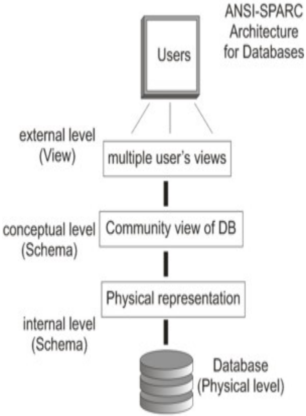

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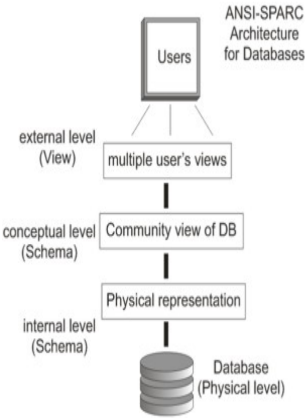

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Outline

1. Queries
2. Updates
3. How does it Work and (Performance) Bonus
4. Future Research/Open Issues

QUERIES AND QUERY COMPILATION

The Structured/Logical Way (via an OBDA example)

Queries and Ontologies

Queries are answered not only w.r.t. *explicit data* ($\mathcal{A}$)
but also w.r.t. *background knowledge* ($\mathcal{T}$)

$\Rightarrow$ Ontology-based Data Access (OBDA)

Example

- Socrates is a MAN (explicit data)
- Every MAN is MORTAL (ontology)

List all MORTALs $\Rightarrow$ {Socrates} (query)

How do we answer queries?

Using *logical implication* (to define *certain answers*):

$$\text{Ans}(\varphi, \mathcal{A}, \mathcal{T}) := \{\varphi(a_1, \ldots, a_k) \mid \mathcal{T} \cup \mathcal{A} \models \varphi(a_1, \ldots, a_k)\}$$

$\Rightarrow$ answers are *ground φ-atoms* logically implied by $\mathcal{A} \cup \mathcal{T}$.

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The Logical Way: Complexity

The Good News

LOGSPACE/PTIME (data complexity) for query answering:

- (U)CQ and
- DL-Lite/$\mathcal{EL}_\bot$/$\mathcal{CFD}_{\mathrm{nc}}^{\forall}$/“rules”-lite (Horn), s-t dependencies,. . .

The Bad News

- no negative queries/sub-queries
- no negations in ABox
- no closed-world assumption
- counter-intuitive query answers

$\Rightarrow$ the same goes for *information integration, data exchange, etc.*

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Difficulties: Unintuitive Answers

Example

- $EMP(Sue)$
- $EMP \sqsubseteq \exists PHONENUM$ (or $\forall x.EMP(x) \rightarrow \exists y.PHONENUM(x, y)$)

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User: *Does Sue have a phone number?*

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User: 

Rewritability and Definability

User and System Expectations

Queries	range-restricted FOL (a.k.a. SQL)
Ontology/Schema	range-restricted FOL $\Sigma := \Sigma_L \cup \Sigma_{LP} \cup \Sigma_P$
Data	CWA (complete information)

Rewritability and Definability

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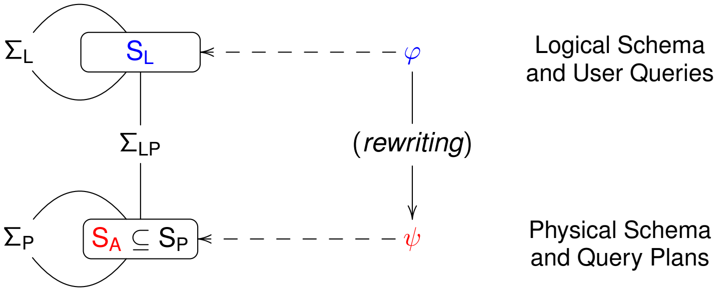

[Borgida, de Bruijn, Franconi, Seylan, Straccia, Toman, Weddell: On Finding Query Rewritings under Expressive Constraints. SEBD 2010: 426-437]

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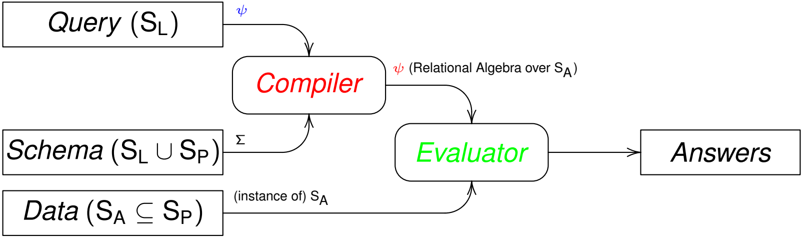
- to users it looks like a *single model* (of the logical schema)
- implementation can pick from many models

  but *definable* queries answer the same in each of them



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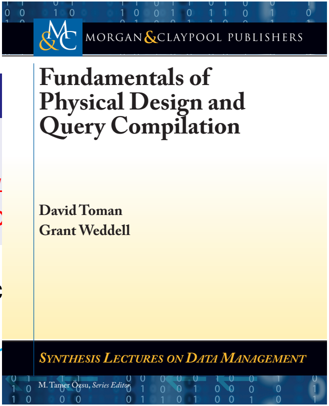

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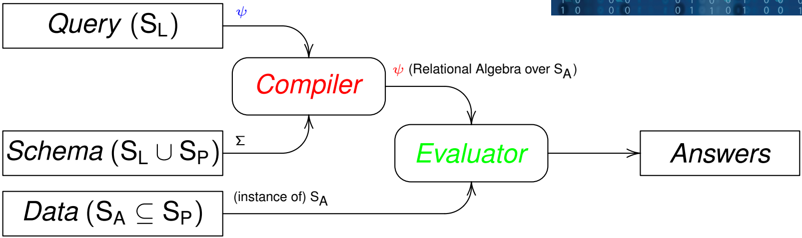

(First-order) Query Rewritability

Rewritability (Decision Problem)

Given

1. a TBox $\mathcal{T}$ and
2. a Query φ

decide whether there is a FO query ψ such that

$$\text{Ans}(\varphi, \mathcal{A}, \mathcal{T}) = \text{Ans}(\psi, \mathcal{A}, \emptyset)$$

for every ABox $\mathcal{A}$ (optionally where ψ is over a sub-vocabulary of $\mathcal{T}$).

[Bienvenu, Lutz, Wolter: First-Order Rewritability of Atomic Queries in Horn Description Logics. IJCAI 2013. (and many papers followed...)]

What can we do?

GOAL

Generate query plans *that compete with hand-written programs in C*

1. standard RDBMS physical designs
2. linked data structures, pointers, . . .
3. access to search structures (index access and selection),
4. hash-based access to data (including hash-joins),
5. multi-level storage (aka disk/remote/distributed files), . . .
6. materialized views (FO-definable),

. . . all without having to code (too much) in C/C++ !

Standard Physical Designs

1. scanning (flat) files
2. primary and secondary indices (via record ids/addresses)
3. horizontal partitioning/sharding
4. column store/index-only plans
5. (disjoint) generalizations

Example: disjoint subclasses

Query

```
undergrad(x,y) <-> ex(r,ustudent(r,x,y))
```

…with access paths `student` and `gstudent`

Example: disjoint subclasses

Query

```
undergrad(x,y) <-> ex(r,ustudent(r,x,y))
```

```
% coverage
student(r,x,y) -> (gstudent(r) or ustudent(r,x,y)),
ustudent(r,x,y) -> student(r,x,y),
gstudent(r) -> ex([x,y],student(r,x,y)),
% disjointness
gstudent(r) and ex([x,y],ustudent(r,x,y)) -> bot,
% key
student(r,x1,y1) and student(r,x2,y2) ->
                                  (x1=x2 and y1=y2)
```

...with access paths `student` and `gstudent`

Example: disjoint subclasses

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undergrad(x,y) <-> ex(r,ustudent(r,x,y))
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…with access paths `student` and `gstudent`

```
david$ compile tests/848ex/subclass2.fol
query(undergrad,2,0,[var(0,0,1,int),var(0,0,2,int)]) <->
  ex(var(0,19,4),
    and (
      student(var(0,19,4),var(0,0,1),var(0,0,2))
      not (
        gstudent(var(0,19,4))
      ) ) )
```

Example: disjoint subclasses

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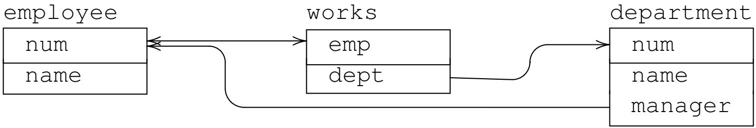
      not (
        gstudent(var(0,19,4))
      ) ) )
```

or, in C-like syntax:

for (r, x, y) in `student` do
        if r in `gstudent` skip else return (x, y);

Lists and Pointers

1. Logical Schema



2. Physical Design: a *linked list of `emp` records pointing to `dept` records*.

```
record emp of                      record dept of
       integer     num                    integer     num
       string      name                   string      name
       integer     salary                 reference   manager
       reference   dept
```

3. Access Paths: $\texttt{empfile}/1/0$, $\texttt{emp-num}/2/1$, … (but no `deptfile`)

4. Integrity Constraints (many), e.g.,

$$\forall x, y, z.\texttt{employee}(x, y, z) \rightarrow \exists w.\texttt{empfile}(w) \wedge \texttt{emp-num}(w, x),$$
$$\forall a, x.\texttt{empfile}(a) \wedge \texttt{emp-num}(a, x) \rightarrow \exists y, z.\texttt{employee}(x, y, z), \ldots$$

What can this do: navigating pointers

1. List all employee numbers and names (employee(x, y)):

$$\exists a.\texttt{empfile}(a) \wedge \texttt{emp-num}(a, x) \wedge \texttt{emp-name}(a, y)$$

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or, in C-like syntax:

```
for a in empfile do
        x := a->num;
        y := a->name;
```

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1. List all employee numbers and names $(\texttt{employee}(x, y))$:

   $$\exists a.\texttt{empfile}(a) \wedge \texttt{emp-num}(a, x) \wedge \texttt{emp-name}(a, y)$$

2. List all department numbers and their names $(\exists z.\texttt{department}(x, y, z))$:

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2. List all department numbers and their names $(\exists z.\texttt{department}(x, y, z))$:

$$\exists a, d, e.\texttt{empfile}(a) \land \texttt{emp-dept}(a, d) \land \texttt{dept-num}(d, x) \land \texttt{dept-name}(d, y)$$

$\Rightarrow$ needs "departments have at least one employee".

What can this do: navigating pointers

1. List all employee numbers and names (employee(x, y)):

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$$\exists a, b, d.\texttt{empfile}(a) \wedge \texttt{emp-dept}(a, d) \wedge \texttt{dept-num}(d, x) \wedge \texttt{dept-name}(d, y) \wedge \texttt{dept-mgr}(d, a)$$

$\Rightarrow$ needs "managers work in their own departments".

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$\Rightarrow$ needs "departments have at least one employee".

... needs *duplicate elimination* during projection.

$$\exists a, b, d.\texttt{empfile}(a) \land \texttt{emp-dept}(a, d) \land \texttt{dept-num}(d, x) \land \texttt{dept-name}(d, y) \land \texttt{dept-mgr}(d, a)$$

$\Rightarrow$ needs "managers work in their own departments".

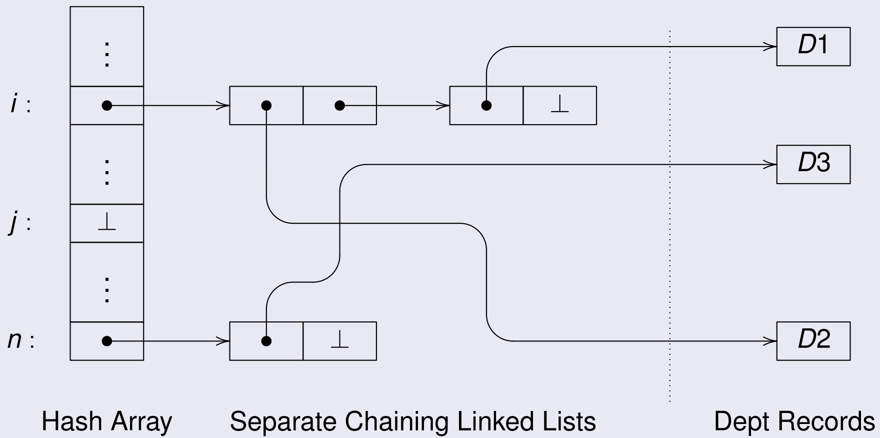
... NO *duplicate elimination* during projection.

. . . and we really can synthesize this!

```
david$ compile tests/new_fe/book-em-v4-new-query.fol
query(q0dept2,2,0,[var(0,0,1,int),var(0,0,2,int)]) <->
  ex(var(0,76,4),
    ex(var(0,81,5),
      and (
        and (
          empfile(var(0,76,4))
          emp_dept(var(0,76,4),var(0,81,5))
        )
        and (
          and (
            dept_num(var(0,81,5),var(0,0,1))
            dept_name(var(0,81,5),var(0,0,2))
          )
          dept_mgr(var(0,81,5),var(0,76,4))
        )
      )
    )
```

What can it do: Hashing, Lists, et al.

Hash Index with (list-based) Separate Chaining



What can it do: Hashing, Linked lists, et al.

Hash Index on `department`'s `name`:

Access paths:

$\mathsf{S}_\mathsf{A} \supseteq \{\mathtt{hash}/2/1, \mathtt{hasharraylookup}/2/1, \mathtt{listscan}/2/1\}$.

Physical Constraints:

$$\begin{aligned}\Sigma_{\mathsf{LP}} \supseteq \{ & \forall x,y.((\mathtt{deptfile}(x) \wedge \mathtt{dept\text{-}name}(x,y)) \to \exists z,w.(\mathtt{hash}(y,z) \\ & \qquad \wedge \mathtt{hasharraylookup}(z,w) \wedge \mathtt{listscan}(w,x))), \\ & \forall x,y.(\mathtt{hash}(x,y) \to \exists z.\mathtt{hasharraylookup}(y,z)), \\ & \forall x,y.(\mathtt{listscan}(x,y) \to \mathtt{deptfile}(y)) \qquad \}\end{aligned}$$

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$$\forall x, y.(\texttt{hash}(x, y) \to \exists z.\texttt{hasharraylookup}(y, z)),$$
$$\forall x, y.(\texttt{listscan}(x, y) \to \texttt{deptfile}(y)) \}$$

Query:

$\exists y.(\texttt{department}(x_1, p, y) \wedge \texttt{employee}(y, x_2))\{p\}$.

$$\exists h, l, d, e.\texttt{hash}(p, h) \wedge \texttt{hasharraylookup}(h, l) \wedge \texttt{listscan}(l, d) \wedge \texttt{dept-name}(d, p) \wedge \texttt{dept-num}(d, x_1) \wedge \texttt{dept-mgr}(d, e) \wedge \texttt{emp-name}(e, x_2)$$

What can this do: two-level store

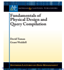
The access path empfile is refined by emppages/1/0 and emprecords/2/1:

emppages returns (sequentially) disk pages containing emp records, and
emprecords given a disc page, returns emp records in that page.

5. List all employees with the same name $(\exists z.\texttt{employee}(x_1, z) \wedge \texttt{employee}(x_2, z))$:

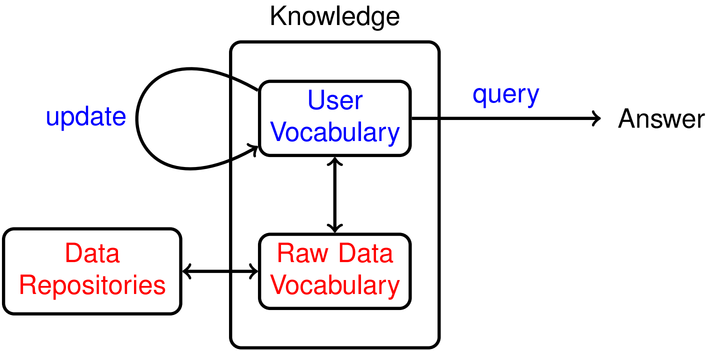
$$\exists y, z, w, v, p, q.\texttt{emppages}(p) \wedge \texttt{emppages}(q) \\ \wedge \texttt{emprecords}(p, y) \wedge \texttt{emp-num}(y, x_1) \wedge \texttt{emp-name}(y, w) \\ \wedge \texttt{emprecords}(q, z) \wedge \texttt{emp-num}(z, x_2) \wedge \texttt{emp-name}(z, v) \\ \wedge \texttt{compare}(w, v).$$

$\Rightarrow$ this plan implements the *block nested loops join* algorithm.

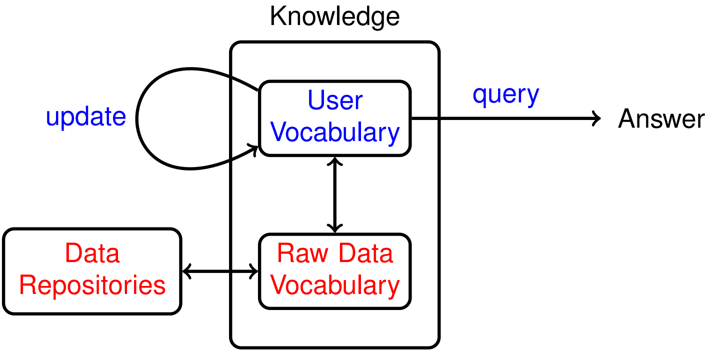
. . . more examples in .

UPDATES

Updates


Knowledge
update
User Vocabulary
query
Answer
Data Repositories
Raw Data Vocabulary

Updates



1. Katsuno, Mendelzon: On the Difference between Updating a Knowledge Base and Revising It. KR 1991.
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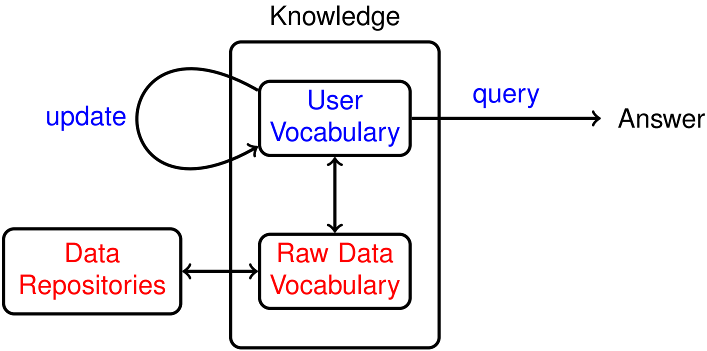

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. . . we follow a *definable updates* approach here instead. . .

Updates and Definability

User updates *only through logical schema*:

⇒ supplying "delta" relations (sets of tuples)

- Two copies of the schema: Σ^{old} and Σ^{new};
- Delta relations: R^+ (insertions) and R^- (deletions);
- Constraints: $\forall\bar{x}.(R^{old}(\bar{x}) \vee R^+(\bar{x})) \equiv (R^{new}(\bar{x}) \vee R^-(\bar{x}))$,
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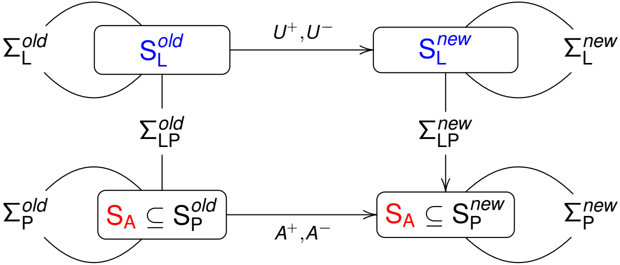

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Update turned into *definability* question

Is A^{new} (or A^{+}, A^{-}) definable in terms of $A_i^{old} \in \mathsf{S}_\mathsf{A}^{old}$ (old access paths) and U_j^{+}, U_j^{-} (user updates) for every access path $A \in \mathsf{S}_\mathsf{A}$?

Unknown/Anonymous Values?

Example (Add a new Undergraduate student)

```
INSERT into undergrad values (1234, 'Wilma');
```

⇒ the request then needs to be translated to

```
INSERT into student values (0xFE1234, 1234, 'Wilma');
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⇒ but where did `0xFE1234` came from? (definability issue!)

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Constant Complement: [Bancilhon, Spyratos: Update semantics of relational views. ACM Trans. Database Syst. 6(4), 1981.]

additional access paths that *provide* such values:

⇒ in our case `student-addr(id,adress)`
⇒ and where $\texttt{undergrad}^{+} = \{(1234, \mathit{Vilma})\}$

$$\texttt{student}^{+}(x_1, x_2, x_3) = \texttt{undergrad}^{+}(x_1, x_3) \wedge \texttt{student-addr}(x_2, x_1)$$

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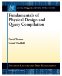
The additional access path(s) correspond to *space allocation*

. . . and cyclic dependencies are broken via *reification*.

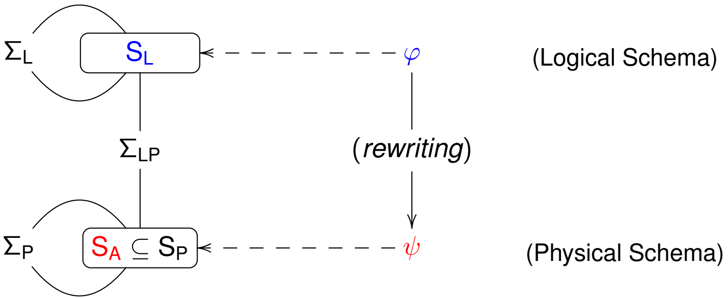
. . . more details and examples in .

HOW DOES IT ALL WORK?

The Plan

Definability and Rewriting

Queries	range-restricted FOL over S_L *definable* w.r.t. Σ and S_A
Ontology/Schema	range-restricted FOL
Data	CWA (complete information for S_A symbols)



Query Plans via Interpolation

IDEA #1: Plans as Formulas

Represent *query plans* as (annotated) range-restricted formulas ψ over S_A:

atomic formula	$\mapsto$	access path (`get-first`–`get-next` iterator)
conjunction	$\mapsto$	nested loops join
existential quantifier	$\mapsto$	projection (annotated w/duplicate info)
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Non-logical (but necessary) Add-ons

1. Non-logical properties/operators
   - binding patterns
   - duplication of data and duplicate-preserving/eliminating projections
   - sortedness of data (with respect to the *iterator semantics*) and sorting
2. Cost model

Beth Definability and Craig Interpolation

IDEA #2: What Queries do we allow?

We only allow queries that have *the same answer* in every model of Σ

. . . for a fixed signature S_A (i.e., where the actual data is).

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$$\Sigma \cup \Sigma' \models \varphi \rightarrow \varphi'$$

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How do we find ψ?

If $\Sigma \cup \Sigma' \models \varphi \to \varphi'$ then there is ψ s.t. $\Sigma \cup \Sigma' \models \varphi \to \psi \to \varphi'$ with $\mathcal{L}(\psi) \subseteq \mathcal{L}(S_A)$.

… ψ is called the *Craig Interpolant* [Craig'57].

…we extract an *interpolant* ψ from a (TABLEAU) proof of $\Sigma \cup \Sigma' \models \varphi \to \varphi'$

Issues with TABLEAU

Dealing with the *subformula property* of Tableau

$\Rightarrow$ analytic tableau *explores* formulas *structurally*

$\Rightarrow$ (to large degree) the structure of interpolant depends on where access paths are present in queries/constraints.

Factoring *logical reasoning* from *plan enumeration*

$\Rightarrow$ backtracking tableau to get alternative plans: too slow, too few plans

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IDEA #3:

Separate *general constraints* from *physical rules* in the formulation of the definability question (and the subsequent interpolant extraction):

$$\Sigma^L \cup \Sigma^R \cup \Sigma^{LR} \models \varphi^L \rightarrow \varphi^R \text{ where } \Sigma^{LR} = \{\forall \bar{x}.P^L \leftrightarrow P \leftrightarrow P^R \mid P \in \mathsf{S_A}\}$$

Factoring *logical reasoning* from *plan enumeration*

$\Rightarrow$ backtracking tableau to get alternative plans: too slow, too few plans

IDEA #4:

Define *conditional* tableau exploration (using general constraints) and separate it from plan generation (using physical rules)

Conditional Tableau and Closing Sets

1. Byte code generation for `q/2`

```
q(x,y) <-> ex(z,table(x,x,z) and table(z,y,y)
                              and not table(x,x,x))
```

2. Split Tableau Construction

```
L { -p0basetable(sl19:7,sl14:3,sl0:2,sl0:2) }
L { -p0basetable(sl19:5,sl0:1,sl0:1,sl14:3) }
L { +p0basetable(sr19:8,sl0:1,sl0:1,sl0:1) }
R { -p0basetable(sr19:8,sl0:1,sl0:1,sl0:1),
    +p0basetable(sl19:7,sl14:3,sl0:2,sl0:2),
    +p0basetable(sl19:5,sl0:1,sl0:1,sl14:3) }
```

3. Cost-based Optimization (A*)
4. C code Generation (+ compilation/linking w/runtime library)

[Hudek, Toman, Weddell: On Enumerating Query Plans Using Analytic Tableau. TABLEAUX 2015.]
[Toman, Weddell: An Interpolation-based Compiler and Optimizer for Relational Queries (System design Report). IWIL-LPAR 2017.]

Conditional Tableau: Result

```
query(q,2,0,[var(0,0,1,int),var(0,0,2,int)]) <->
  ex(var(0,14,3),
    ex(var(0,19,5),
      ex(var(0,19,7),
        and (
          and (
            p0basetable(var(0,19,7),var(0,14,3),
                        var(0,0,2),var(0,0,2))
            p0basetable(var(0,19,5),var(0,0,1),
                        var(0,0,1),var(0,14,3))
          )
          not (
            ex(var(1,19,8),
              p0basetable(var(1,19,8),var(0,0,1),
                          var(0,0,1),var(0,0,1))
            )
          ) ) ) ) )
```

Postprocessing: Duplicate Elimination Elimination

IDEA:

Separate the projection operation ($\exists \bar{x}.$) to

- a duplicate preserving projection ($\exists$) and
- an explicit (idempotent) duplicate elimination operator ($\{\cdot\}$).

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$$
\begin{aligned}
Q[\{R(x_1,\ldots,x_k)\}] &\leftrightarrow Q[R(x_1,\ldots,x_k)] \\
Q[\{Q_1 \wedge Q_2\}] &\leftrightarrow Q[\{Q_1\} \wedge \{Q_2\}] \\
Q[\{\neg Q_1\}] &\leftrightarrow Q[\neg Q_1] \\
Q[\neg\{Q_1\}] &\leftrightarrow Q[\neg Q_1] \\
Q[\{Q_1 \vee Q_2\}] &\leftrightarrow Q[\{Q_1\} \vee \{Q_2\}] \quad \text{if } \Sigma \cup \{Q[]\} \models Q_1 \wedge Q_2 \to \bot \\
Q[\{\exists x.Q_1\}] &\leftrightarrow Q[\exists x.\{Q_1\}] \quad \text{if} \\
& \Sigma \cup \{Q[] \wedge (Q_1)[y_1/x] \wedge (Q_1)[y_2/x] \models y_1 \approx y_2
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$$

… reasoning abstracted: a DL $\mathcal{CFD}^{\forall -}_{nc}$ (a PTIME fragment)

[Toman, Weddell: Using Feature-Based Description Logics to avoid Duplicate Elimination in Object-Relational Query Languages. Künstliche Intell. 34(3): 2020]

Summary

Take Home

While in theory *interpolation* essentially solves the *query rewriting over FO schemas/views* problem, the devil is (as usual) in the details.

[Borgida, de Bruijn, Franconi, Seylan, Straccia, Toman, Weddell: On Finding Query Rewritings under Expressive Constraints. SEBD 2010: 426-437

. . . but an (almost) working system only this year.

1. FO tableau based interpolation algorithm
   - ⇒ enumeration of plans factored from of tableau reasoning
   - ⇒ extra-logical binding patterns and cost model
2. Post processing (using $\mathcal{CFDI}_{\text{nc}}$ approximation)
   - ⇒ duplicate elimination elimination
   - ⇒ cut insertion
3. Run time
   - ⇒ library of common data/legacy structures+schema constraints
   - ⇒ finger data structures to simulate merge joins et al.

Research Directions and Open Issues

1. Dealing with ordered data? (merge-joins etc.: we have a partial solution)
2. Decidable schema languages (decidable interpolation problem)?
3. More powerful schema languages (inductive types, etc.)?
4. Beyond FO Queries/Views (e.g., count/sum aggregates)?
5. Coding extra-logical bits (e.g., binding patterns, postprocessing, etc.) in the schema itself?
6. Standard Designs (a plan can always be found as in SQL)?
7. Explanation(s) of non-definability?
8. Fine(r)-grained updates?
9. ...

. . . and, as always, performance, performance, performance!