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

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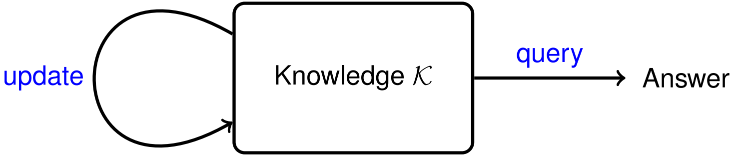
Joint work with Alexander Hudek and Grant Weddell

Knowledge Representation: a Big Picture



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

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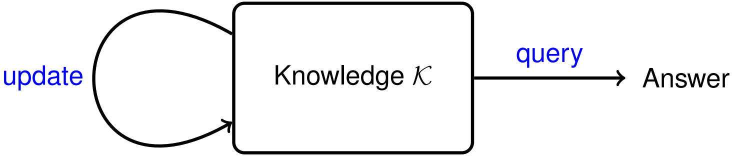

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Structured World:

- $\mathcal{K}$ 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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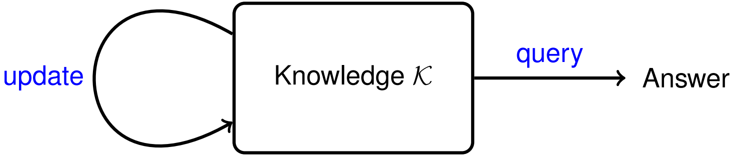

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Probabilistic World:

- $\mathcal{K}$ 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]

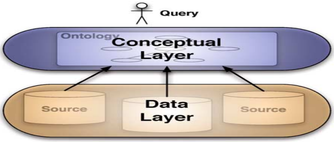
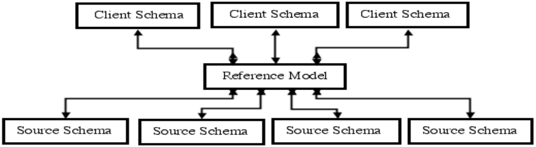


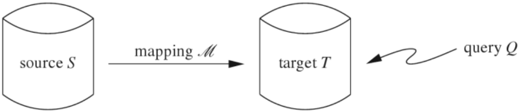
Fig. 1. Ontology-based data access.

Information Integration [Genesereth: Data Integration, 2010]

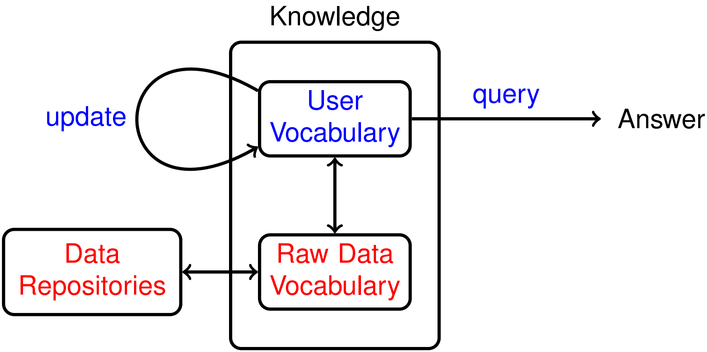


Data Exchange [Arenas et el.: Data Exchange, 2014]

The general setting of data exchange is this:



Data vs. Metadata



1. Metadata: constraints formulated in FOL (static)
2. Data: ground tuples (can be "modified")

   ⇒ user queries and updates only about data.

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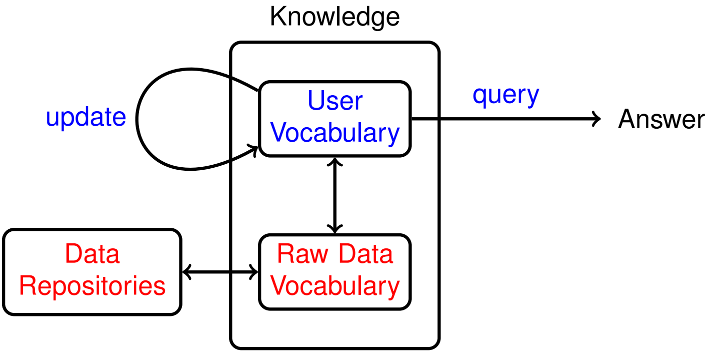

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(Physical) Data Independence

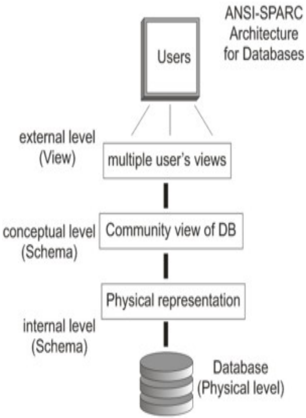
IDEA:

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

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

Physical Data Independence and ADTs

- data independence [Bachman, 1969, Date and Hopewell, 1971] and [Codd, 1970]
- ADTs [Liskov and Zilles, 1974]



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

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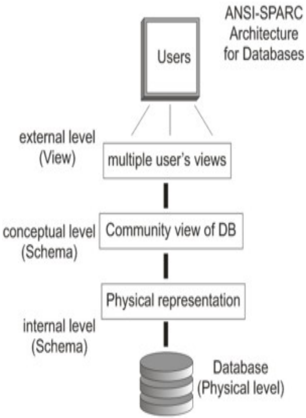

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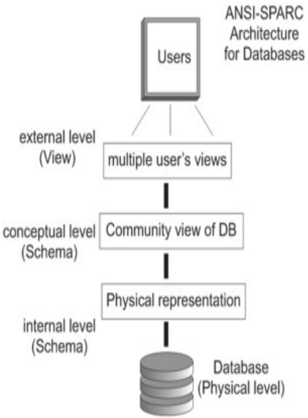

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Outline

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/$\mathcal{EL}_{\perp}$/$\mathcal{CFD}^{\forall}_{\mathrm{nc}}$/“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?*

Information System: *YES*

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User: 

What does a User Want? ...but is afraid to ask

1. what I know and what I don't is just a single model (CWA);
2. queries are model-checked against this model;
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YES, BUT:

- it better run fast!! (and preferably without having to code algorithms/data structures by hand)
- and performance/data storage-representation/. . . can all be improved/changed without changing the user queries/updates

User Queries and Updates – for TODAY

Queries: First-order (open) formulae over the user vocabulary

$\Rightarrow$ only *range-restricted* formulae

Updates: Instances of *Delta-relations* (tuples to be inserted/deleted) for ALL relations in the user vocabulary

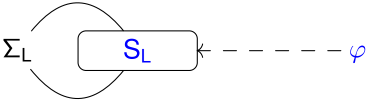
$\Rightarrow$ only *consistency-preserving transactions* allowed

. . . a.k.a. the Relational Model and Relational Calculus [Codd, 1972].

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)



Logical Schema
and User Queries

Rewritability and Definability

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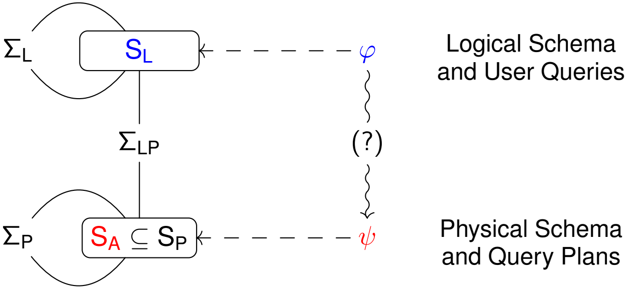

[Borgida, de Bruijn, Franconi, Seylan, Straccia, Toman, Weddell: On Finding Query Rewritings under Expressive Constraints. SEBD 2010: 426-437]

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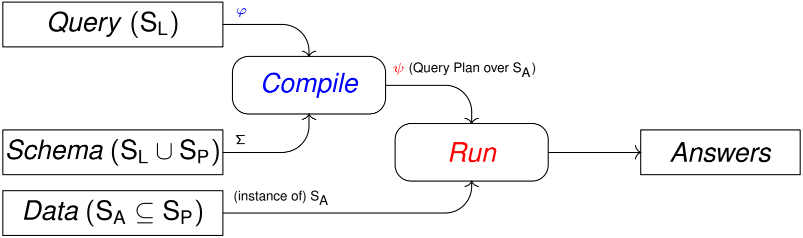
- implementation can pick from many models

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



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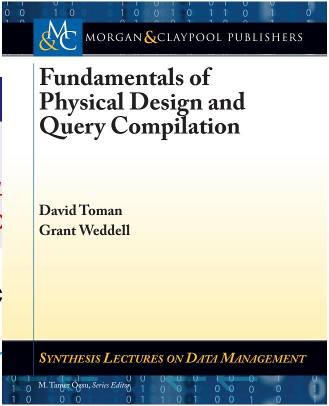

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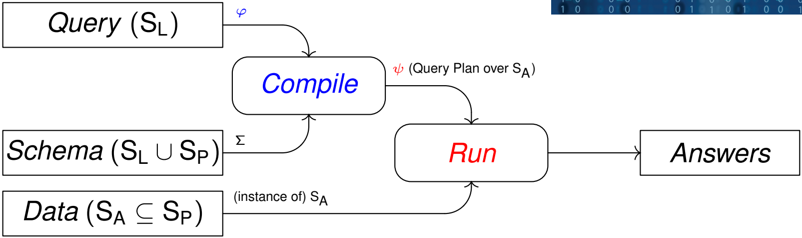

This is NOT OMQ/OBDA (by example)

$$\mathsf{S_L} = \{\texttt{emp}/1, \texttt{wkr}/1, \texttt{mgr}/1\} \text{ and } \Sigma_\mathsf{L} = \left\{ \begin{array}{l} \texttt{mgr}(x) \vee \texttt{wkr}(x) \leftrightarrow \texttt{emp}(x) \\ \texttt{mgr}(x) \wedge \texttt{wkr}(x) \rightarrow \bot \end{array} \right\}$$

$$\mathsf{S_A} = \{\texttt{emp}/1/0, \texttt{mgr}/1/0\}$$

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$\mathsf{S_A} = \{\mathtt{emp}/1/0, \mathtt{mgr}/1/0\}$

Query $\{x \mid \mathtt{wkr}(x)\}$ over $\mathtt{mgr} = \{\text{Fred}\}$, and $\mathtt{emp} = \{\text{Fred}, \text{Wilma}\}$

Certain Answer under OWA: $\{\ \}$

Answer under CWA: $\{\text{Wilma}\}$

(obtained by executing the plan $\{x \mid \mathtt{emp}(x) \wedge \neg\mathtt{mgr}(x)\}$).

What can we do with this?

Goal #2

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

1. standard RDBMS physical designs (and more),
   - access to search structures (index access and selection),
   - horizontal partitioning/sharding,
   - column store/index-only plans,
2. pointer-based data structures (including main mamory),
3. hash-based access to data (including hash-joins),
4. multi-level storage (aka disk/remote/distributed files), . . .
5. materialized views,
6. updates through logical schema
7. . . .

. . . 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

Pointers in Main Memory-Logical Schema

```
CREATE TABLE employee (
  num      INTEGER NOT NULL,
  name     CHAR(20),
  worksin  INTEGER  NOT NULL
  PRIMARY KEY (num),
  FOREIGN KEY (worksin)
        REFERENCES department
)
```

```
CREATE TABLE department (
  num      INTEGER NOT NULL,
  name     CHAR(50),
  manager  INTEGER NOT NULL,
  PRIMARY KEY (num),
  FOREIGN KEY (manager)
        REFERENCES employee
)
```

this corresponds to

- $S_L = \{\texttt{employee}/3, \texttt{department}/3\}$ and
- $\Sigma_L = \{\, \texttt{employee}(x, y_1, z_1) \wedge \texttt{employee}(x, y_2, z_2) \rightarrow y_1 = y_2 \wedge z_1 = z_2,$
  $\texttt{employee}(x, y, z) \rightarrow \exists u, v.\texttt{department}(z, u, v), \ \ldots \text{and many more} \,\}.$

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```
CREATE TABLE department (
  num     INTEGER NOT NULL,
  name    CHAR(50),
  manager INTEGER NOT NULL,
  PRIMARY KEY (num),
  FOREIGN KEY (manager)
        REFERENCES employee
)
```

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additional logical constraints (for example):

- managers are employees that manage a department (a view)
- managers work in their own departnemts (business rule)
- workers and managers partition employees (partition), etc.

Pointers in Main Memory-Physical Design

1. Records:

```
struct emp {                       struct dept {
    int       num;                     int       num;
    char[20]  name;                    char[50]  name;
    dept*     dept; };                 mgr*      emp;   };
```

2. a linked list of `emp` records.

that corresponds to

- Access paths (S_A):
  - `empfile`/1/0: set (list) of *addresses* of `emp` records;
  - `emp-num`/2/1: pairs `emp` record address-`emp` number (pointer navigation)
    same for `emp-name`/2/1 and `emp-dept`/2/1;
  - `dept-num`/2/1: pairs `dept` record address-`dept` number
    same for `dept-name`/2/1 and `dept-mgr`/2/1.
- Integrity constraints ($\Sigma_P \cup \Sigma_{LP}$):

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

Query Plans that Navigate Pointers

1. List employee numbers, names, and departments (`employee`(x, y, z)):

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

or, in C-like syntax:

```
for e in empfile do
    x := e->num;
    y := e->name;
    d := e->dept;
    z := d->num;
```

University of Waterloo

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

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

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

≫ Caveat: we do NOT have a (direct) way to “scan” `depatment`s! ≪

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

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

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…needs *duplicate elimination* during projection.

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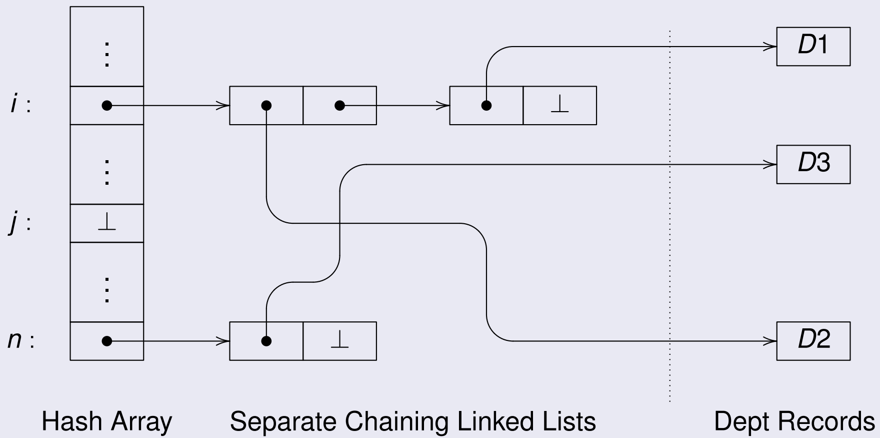
…NO *duplicate elimination* during projection.

. . . and we can actually 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:

$S_A \supseteq \{\texttt{hash}/2/1, \texttt{hasharraylookup}/2/1, \texttt{listscan}/2/1\}$.

Physical Constraints:

$$\Sigma_{LP} \supseteq \{\forall x, y.((\texttt{deptfile}(x) \wedge \texttt{dept-name}(x, y)) \rightarrow \exists z, w.(\texttt{hash}(y, z) \wedge \texttt{hasharraylookup}(z, w) \wedge \texttt{listscan}(w, x))),$$
$$\forall x, y.(\texttt{hash}(x, y) \rightarrow \exists z.\texttt{hasharraylookup}(y, z)),$$
$$\forall x, y.(\texttt{listscan}(x, y) \rightarrow \texttt{deptfile}(y)) \}$$

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

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

Access paths:

$S_A \supseteq \{\texttt{hash}/2/1, \texttt{hasharraylookup}/2/1, \texttt{listscan}/2/1\}$.

Physical Constraints:

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$$\forall x, y.(\texttt{listscan}(x, y) \to \texttt{deptfile}(y)) \}$$

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

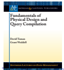
The access path `empfile` is refined by `emppages`/1/0 and `emprecords`/2/1:

- `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 $(\exists z.\mathtt{employee}(x_1, z) \wedge \mathtt{employee}(x_2, z))$:

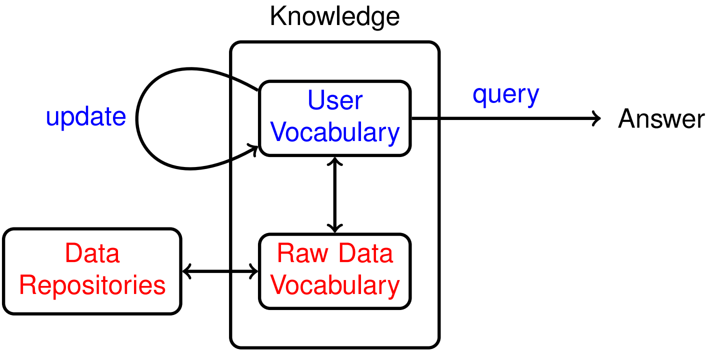
$$
\begin{aligned}
\exists y, z, w, v, p, q.&\mathtt{emppages}(p) \wedge \mathtt{emppages}(q) \\
&\wedge \mathtt{emprecords}(p, y) \wedge \mathtt{emp\text{-}num}(y, x_1) \wedge \mathtt{emp\text{-}name}(y, w) \\
&\wedge \mathtt{emprecords}(q, z) \wedge \mathtt{emp\text{-}num}(z, x_2) \wedge \mathtt{emp\text{-}name}(z, v) \\
&\qquad\qquad\qquad\qquad\qquad\qquad \wedge \mathtt{compare}(w, v).
\end{aligned}
$$

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

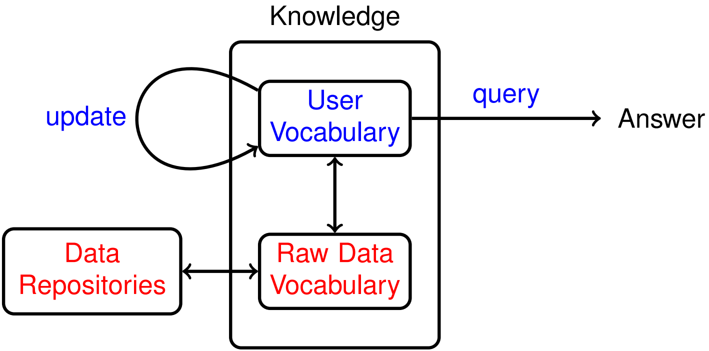
. . . more examples in .

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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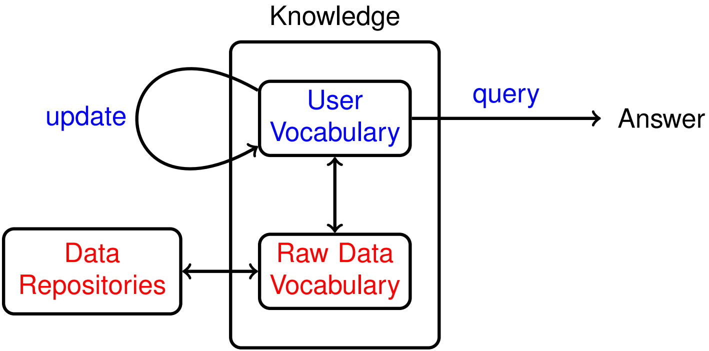
Updates



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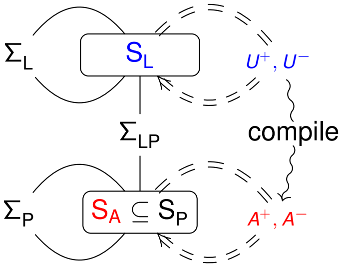
... we follow a *definable updates* approach here instead...

Updates and Definability

User updates *through logical schema ONLY*:
⇒ supplying "delta" relations (sets of tuples)

- Delta relations: R^+ (insertions) and R^- (deletions);



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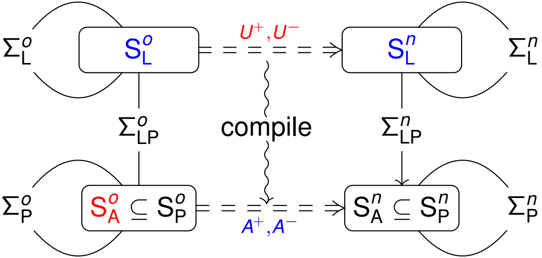

Update turned into *definability* question

Is A^n (or A^+, A^-) definable in terms of $A_i^o \in S_A^o$ (old access paths)
and U_j^+, U_j^- (user updates) for every access path $A \in S_A$?

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');
```

⇒ 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 

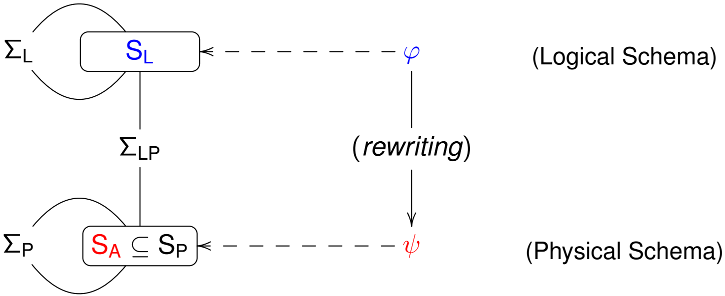
.

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)
disjunction	$\mapsto$	concatenation
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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 interpretation of the signature S_A (i.e., where the actual data is).

Beth Definability and Craig Interpolation

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How do we test for this?

φ is *Beth definable* [Beth'56] if

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

where Σ' (φ') is Σ (φ) in which symbols *NOT in* $\mathsf{S_A}$ are *primed*, respectively.

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How do we find ψ?

If $\Sigma \cup \Sigma' \models \varphi \rightarrow \varphi'$ then there is ψ s.t. $\Sigma \cup \Sigma' \models \varphi \rightarrow \psi \rightarrow \varphi'$ 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 $\Sigma \cup \Sigma' \models \varphi \rightarrow \varphi'$

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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):

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

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 through (a simple) Example

Example Schema

Rules: $q(x) \rightarrow a(x)$, $q(x) \rightarrow c(x)$, $a(x) \wedge c(x) \rightarrow q(x)$, $c(x) \rightarrow \exists y.b(x,y)$

Conditional Tableau through (a simple) Example

Example Schema

Rules: $q(x) \to a(x)$, $q(x) \to c(x)$, $a(x) \wedge c(x) \to q(x)$, $c(x) \to \exists y.b(x,y)$

Conditional Tableau

Σ^L		Σ^R
$q(0)[]\{\}$		
$a(0)[]\{\}$	$\to$	$a(0)[a(0)]\{\}$
$c(0)[]\{\}$	$\to$	$c(0)[c(0)]\{\}$
$b(0,1)[]\{\}$		$q(0)[a(0),c(0)]\{\}$
		$\bot[a(0),c(0)]\{\}$

Conditional Tableau through (a simple) Example

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$$a^L(\bar{x}) \to a(\bar{x}) \to a^R(\bar{x})$$

Conditional Tableau through (a simple) Example

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Closing Sets for Σ^L: $\{\neg a(0)\}$, $\{\neg c(0)\}$, $\{\neg b(0,1)\}$
Closing Sets for Σ^R: $\{a(0), c(0)\}$

Only atoms that are in closing sets appear in query plans!

University of Waterloo

Conditional Tableau through (a simple) Example

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Closing Sets for Σ^R: $\{a(0), c(0)\}$

Only atoms that are in closing sets appear in query plans!

Plans

Query plan 1: $a(x) \wedge c(x)$

Query plan 2: $a(x) \wedge (\exists y.b(x,y)) \wedge c(x)$

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. Conditional 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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Use the following rewrites to eliminate/minimize the use of $\{\cdot\}$:

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

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\end{aligned}
$$

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

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

Interpolation (in practice)

Difficulties with naive implementation/Obstacles

1. Structural properties of proofs (e.g., subformula property)
2. Alternative interpolants/plans (can we just *backtrack* the proof system?)

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Difficulties with naive implementation/Obstacles

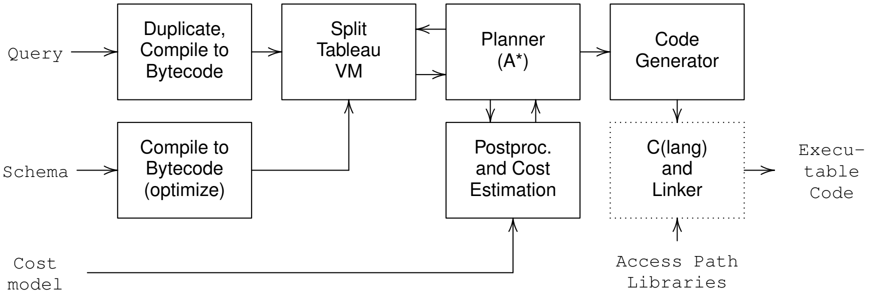
1. Structural properties of proofs (e.g., subformula property)
2. Alternative interpolants/plans (can we just *backtrack* the proof system?)

(A) solution: a *conditional tableau*:

1. reformulate the interpolation problem to
   $\Sigma^L \cup \Sigma^R \cup \Sigma^{LR} \models \varphi^L \to \varphi^R$ where $\Sigma^{LR} = \{\forall \bar{x}.P^L \leftrightarrow P \leftrightarrow P^R \mid P \in \mathrm{S_A}\}$
2. use conditional (ground) atoms and
   closing sets: sets of $\mathrm{S_A}$ literals that (fully) close a tableaau
3. separate general reasoning from interpolant enumeration
   VM-driven conditional tableau for $\Sigma^L \cup \{\varphi^L\}$ and for $\Sigma^R \cup \{\varphi^R \to \bot\}$
   A*-based interpolant generator w.r.t. closing sets and Σ^{LR}

Details: [Hudek et al., 2015, Toman and Weddell, 2017]

Compiler Architecture



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!

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