Ontology Based Data Access and Data Independence

(an alternative look)

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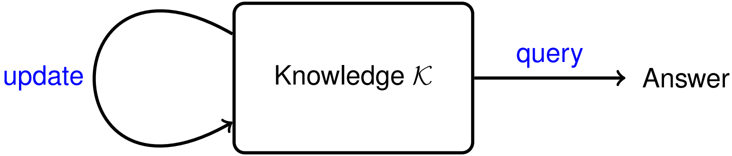
Joint work with Alexander Hudek and Grant Weddell

Knowledge Representation: a Big Picture



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

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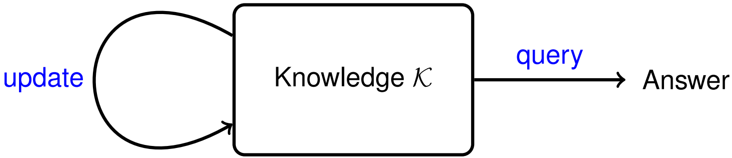

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Structured World:

- $\mathcal{K}$ 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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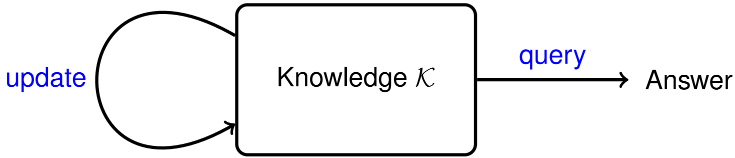

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Probabilistic World:

- $\mathcal{K}$ 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]

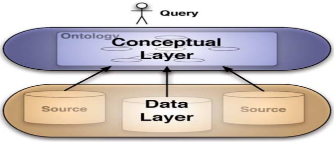
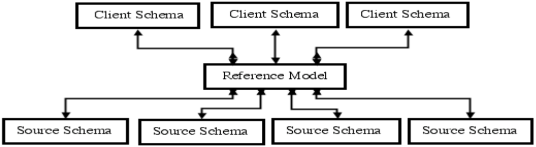


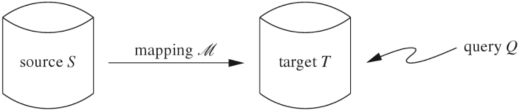
Fig. 1. Ontology-based data access.

Information Integration [Genesereth: Data Integration, 2010]

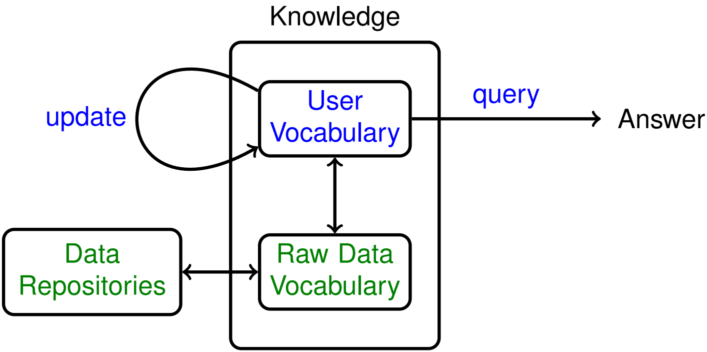


Data Exchange [Arenas et el.: Data Exchange, 2014]

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")

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

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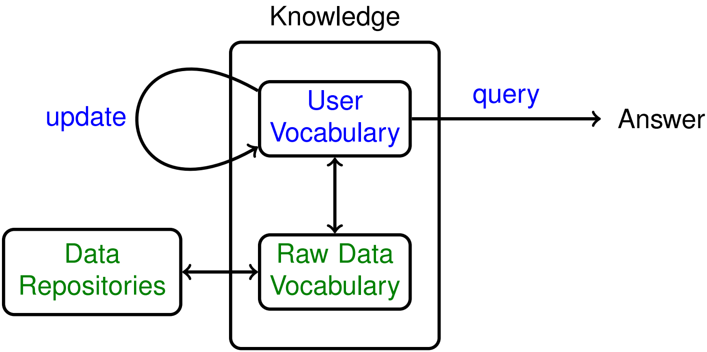

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(Physical) Data Independence

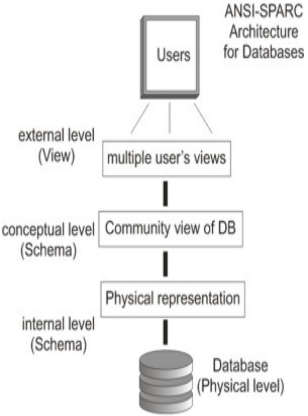
IDEA:

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

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

Physical Data Independence and ADTs

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



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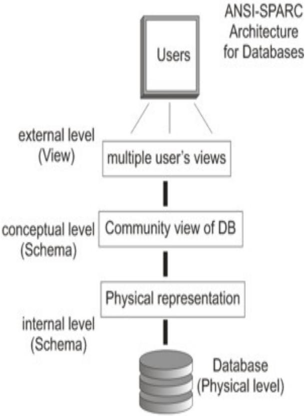

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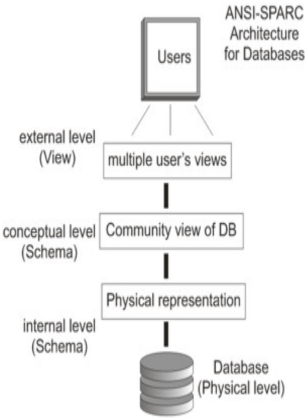

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Common Threads and Issues

- In general two *schemas*: Conceptual/Logical and Physical

  ⇒ both endowed with *metadata* (vocabulary, constraints, . . .)

  ⇒ mappings that connect the two schemas

- Rules: (1) queries (updates) over the *conceptual/logical* schema only,
  (2) raw data as instance of the *physical* schema only,
  (3) *conceptual/logical* and *physical* schemata are *disjoint*.

- Issues to be formalized/fixed:
  1. Formal description of the two schemas (same formalism for both?)
  2. Language(s) for metadata, mappings, etc.
  3. User Interface:
     - Data Model
     - Query (and Update) Language (e.g., when is an answer really an answer?)

- Algorithms/Execution model for user queries and updates

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Outline

Queries and Query Answering

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*):

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

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

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The Bad News

- undecidable in general
- coNP-complete (data complexity) from $\mathcal{ELI}$ up to $\mathcal{SROIQ}$ and (U)CQs

The Good News

LOGSPACE/PTIME (data complexity) for query answering:

- DL-Lite/$\mathcal{EL}_\perp$/$\mathcal{CFD}^{\forall}_{nc}$/"rules"-lite (Horn), s-t dependencies, ...
- and (still only) (U)CQ

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Approaches to Ontology-based Data Access

Main Task

INPUT: $\underbrace{\text{Ontology } (\mathcal{T}), \text{ Data } (\mathcal{A})}_{\text{Knowledge Base}(\mathcal{K})}$, and a Query ($Q$)

OUTPUT: $\{a \mid \mathcal{K} \models Q[a]\}$

1. Reduction to *standard reasoning* (e.g., satisfiability)
2. Reduction to *querying a relational database*

   $\Rightarrow$ *very* good at $\{a \mid \mathcal{A} \models Q[a]\}$ for range restricted Q

   $\Rightarrow$ what to do with $\mathcal{T}$??

   1. incorporate into Q (perfect rewriting for DL-Lite et al. (AC^0 logics)); or
   2. incorporate into $\mathcal{A}$ (combined approach for $\mathcal{EL}$ (PTIME-complete logics));

      or sometimes both ($\mathcal{CFDI}$ or Horn-$\mathcal{ALC}*$ logics).

Combined Combined Approach to OMQ

Theorem (Combined Combined Approach [Eiter et al., 2012] [Toman and Weddell, 2013])

Let $\mathcal{K} = (\mathcal{T}, \mathcal{A})$ be a Horn-$\mathcal{SHIQ}$ (or Horn-$\mathcal{DLFD}$) knowledge base and φ a conjunctive query. Then there is

1. *a FO (typically UCQ) query $\varphi_{\mathcal{T}}$, called a query rewriting, and*
2. *a Datalog program $\Pi_{\mathcal{T}}$, called an ABox completion program,*

such that

$$\mathcal{K} \models \varphi[\vec{x} \mapsto \vec{a}] \iff \Pi_{\mathcal{T}}(\mathcal{A}) \models \varphi_{\mathcal{T}}[\vec{x} \mapsto \vec{a}]$$

where $\Pi_{\mathcal{T}}(\mathcal{A})$ is the minimal model of $\Pi_{\mathcal{T}}$ over $\mathcal{A}$, the completion of $\mathcal{A}$ w.r.t. $\mathcal{T}$.

Perfect Reformulation [Calvanese et al., 2007]:

$\Pi_{\mathcal{T}}$ is an identity on $\mathcal{A}$;

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- no negative queries/sub-queries (SQL??)
- no negations in ABox
- **no closed-world assumption**
- **counter-intuitive query answers**

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Difficulties: (Data) Complexity

Example (Why can't we have CWA?)

- relations: "$ColNode(x, y)$" and "$Edge(x, y)$";
- the data: graph $(Node^{\mathcal{I}}, Edge^{\mathcal{I}})$, and $Colour^{\mathcal{I}} = \{r, g, b\}$.
- ontology: $\forall x.Node(x) \to \exists y.ColNode(x, y)$;
  $\forall x, y.ColNode(x, y) \to Colour(y)$;
- query: $\exists x, y, z.Edge(x, y) \land ColNode(x, z) \land ColNode(y, z)$

PROBLEM: having *exactly* 3 colours is not in DL-Lite (or even HORN).

$\Rightarrow$ same examples for other non-Horn features, e.g., disjunction

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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...)]

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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Information System: *YES*

User: *OK, tell me Sue's phone number!*

Information System: *(no answer)*

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Information System: *(no answer)*

User: 

The problem: Users (essentially) EXPECT CWA

What does $\mathcal{A} = \{EMP(Bob), EMP(Sue)\}$ mean?

OWA: $Bob^{\mathcal{I}} \in EMP^{\mathcal{I}}, Sue^{\mathcal{I}} \in EMP^{\mathcal{I}}$ (KR folks)

CWA: $\{Bob^{\mathcal{I}}, Sue^{\mathcal{I}}\} = EMP^{\mathcal{I}}$ (DB folks and users)

. . . at least for *their* relations (i.e., in the conceptual schema).

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Simulations:

CWA in OWA: *closure axioms*: $\forall x.EMP(x) \rightarrow (x = Bob) \vee (x = Sue)$;

OWA in CWA: *auxiliary symbols*: $ExpEMP(Bob), ExpEMP(Sue)$
and *constraints*: $\forall x.ExpEMP(x) \rightarrow EMP(x)$

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!!
  $\Rightarrow$ preferably without having to code algorithms/data structures by hand
- algorithms/performance/data storage-representation/. . .
  can be changed *without changes to user queries/updates*

User Queries and Updates – for TODAY

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

$\Rightarrow$ only *range-restricted* formulae

(i.e., with appropriate *binding pattern restrictions*)

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

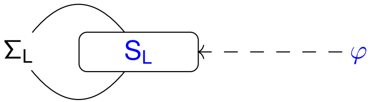
$\Rightarrow$ only *consistency-preserving transactions* allowed

. . . 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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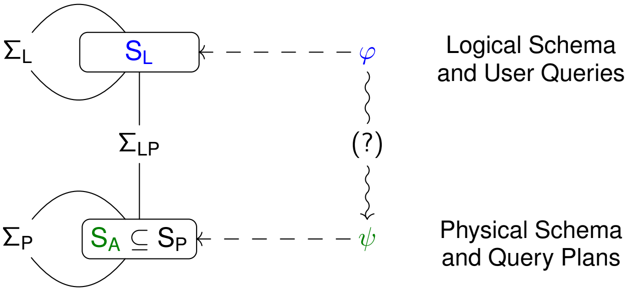

[Borgida, de Bruijn, Franconi, Seylan, Straccia, Toman, Weddell: On Finding Query Rewritings under Expressive Constraints. SEBD 2010: 426-437]

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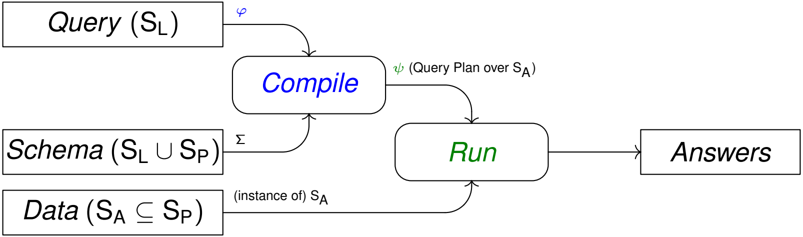
- implementation can pick from many models

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



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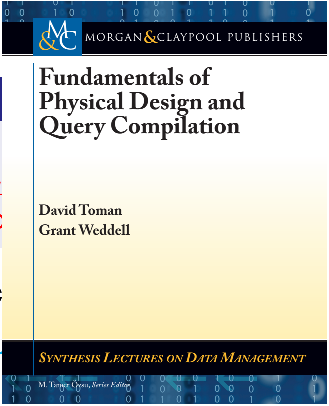

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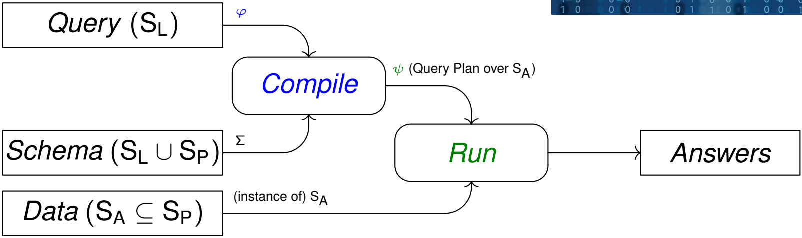

This is NOT OMQ/OBDA (by example)

Example (Horizontal Partition)

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

This is NOT OMQ/OBDA (by example)

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$\mathsf{S_A} = \{\mathtt{emp}/1,\ \mathtt{mgr}/1\}$, note that $\mathtt{wkr}/1$ is NOT in $\mathsf{S_A}$;

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

This is NOT OMQ/OBDA (by example)

Example (Horizontal Partition)

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

$\mathsf{S_A} = \{\mathtt{emp}/1,\ \mathtt{mgr}/1\}$, note that $\mathtt{wkr}/1$ is NOT in $\mathsf{S_A}$;

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

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

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

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

Pointers in Main Memory-Logical Schema

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CREATE TABLE 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 ($\Sigma_P \cup \Sigma_{LP}$):

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

Query Plans that Navigate Pointers

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

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

or, in C-like syntax:

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

Query Plans that Navigate Pointers

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

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

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

$\gg$ Caveat: we do NOT have a (direct) way to "scan" `depatment`s! $\ll$

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

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

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

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

…needs *duplicate elimination* during projection.

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

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

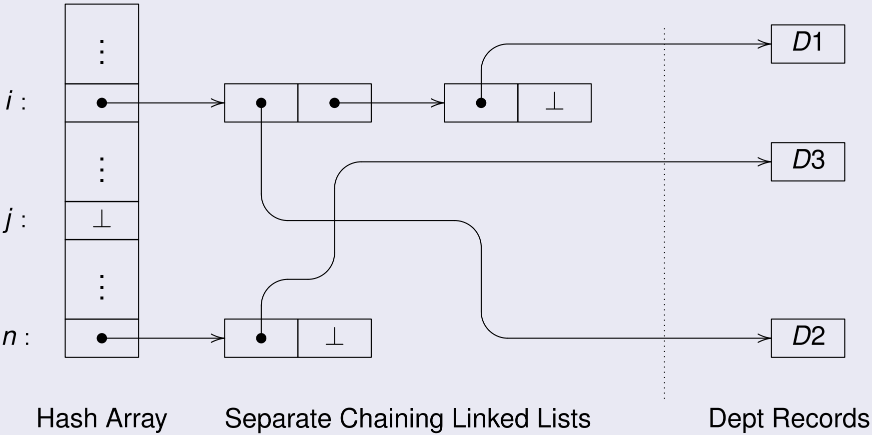
…NO *duplicate elimination* during projection.

. . . and we can actually synthesize this!

```
david$ compile tests/new_fe/book-em-v4-new-query.fol
query(dept2,2,0,[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:

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

Physical Constraints:

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

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

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4. List departments and their managers given dept name p $(\exists y.\texttt{department}(x_1, p, y) \wedge \texttt{employee}(y, x_2)\{p\})$:

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

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
$(\exists z.\mathtt{employee}(x_1, z) \land \mathtt{employee}(x_2, z))$:

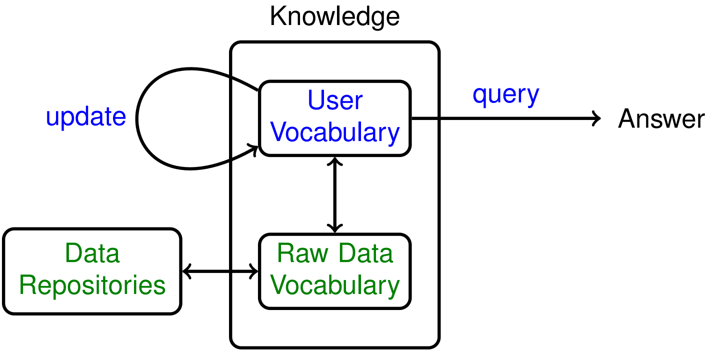
$$\begin{aligned}&\exists y, z, w, v, p, q.\mathtt{emppages}(p) \land \mathtt{emppages}(q)\\ &\quad \land \mathtt{emprecords}(p, y) \land \mathtt{emp\text{-}num}(y, x_1) \land \mathtt{emp\text{-}name}(y, w)\\ &\quad \land \mathtt{emprecords}(q, z) \land \mathtt{emp\text{-}num}(z, x_2) \land \mathtt{emp\text{-}name}(z,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

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

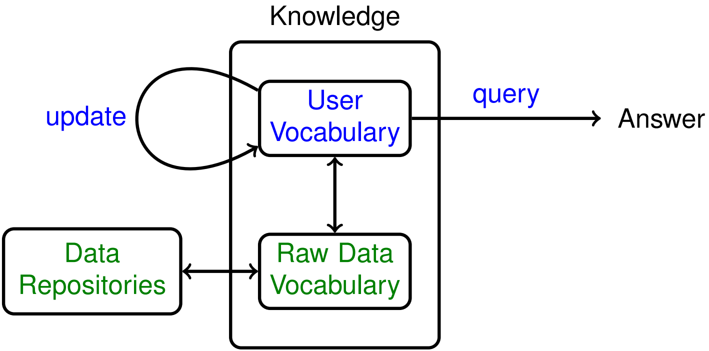
. . . more examples in .

UPDATES

Updates

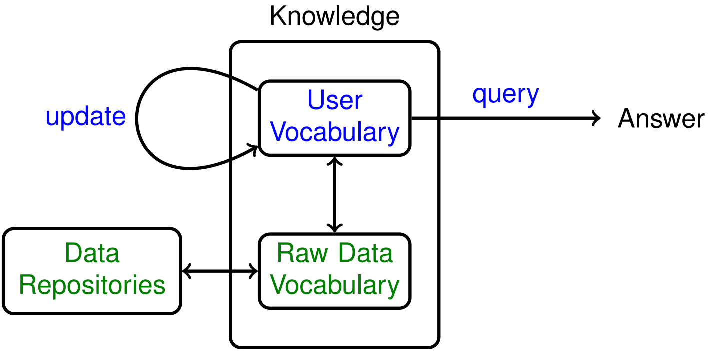

Knowledge
update
User Vocabulary
query
Answer
Data Repositories
Raw Data Vocabulary

Updates



1. Katsuno, Mendelzon: On the Difference between Updating a Knowledge Base and Revising It. KR 1991.
2. De Giacomo, Lenzerini, Poggi, Rosati: On Instance-level Update and Erasure in Description Logic Ontologies. J. Log. Comput. 19(5) 2009.

Updates



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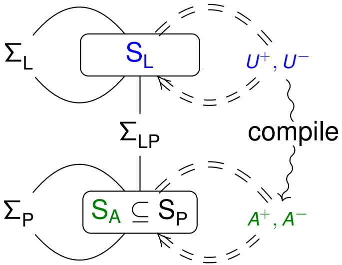
. . . we use *definable updates* approach instead. . .

Updates and Definability

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

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



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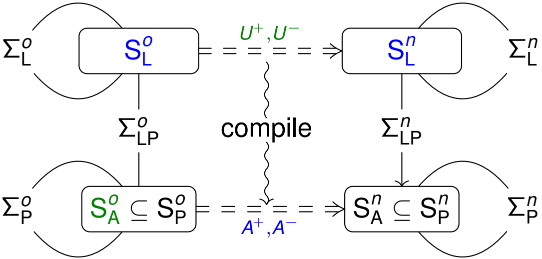

Update turned into *definability* question

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 $A \in S_A$?

Update Example

Example (Update Schema)

$$S_L = \{\texttt{emp}^o/1, \texttt{wkr}^o/1, \texttt{mgr}^o/1\} \cup \{\texttt{emp}^n/1, \texttt{wkr}^n/1, \texttt{mgr}^n/1\} \cup$$

$$\Sigma = \left\{ \begin{array}{l} \texttt{mgr}^o(x) \vee \texttt{wkr}^o(x) \leftrightarrow \texttt{emp}^o(x) \\ \texttt{mgr}^o(x) \wedge \texttt{wkr}^o(x) \to \bot \end{array} \right\} \cup \left\{ \begin{array}{l} \texttt{mgr}^n(x) \vee \texttt{wkr}^n(x) \leftrightarrow \texttt{emp}^n(x) \\ \texttt{mgr}^n(x) \wedge \texttt{wkr}^n(x) \to \bot \end{array} \right\} \cup$$

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$$\Sigma = \left\{\begin{array}{l} \mathtt{mgr}^o(x) \vee \mathtt{wkr}^o(x) \leftrightarrow \mathtt{emp}^o(x) \\ \mathtt{mgr}^o(x) \wedge \mathtt{wkr}^o(x) \rightarrow \bot \end{array}\right\} \cup \left\{\begin{array}{l} \mathtt{mgr}^n(x) \vee \mathtt{wkr}^n(x) \leftrightarrow \mathtt{emp}^n(x) \\ \mathtt{mgr}^n(x) \wedge \mathtt{wkr}^n(x) \rightarrow \bot \end{array}\right\} \cup$$
$$\left\{\begin{array}{l} \mathtt{emp}^o(x) \vee \mathtt{emp}^+(x) \leftrightarrow \mathtt{emp}^n(x) \vee \mathtt{emp}^-(x), \mathtt{emp}^o(x) \wedge \mathtt{emp}^+(x) \rightarrow \bot, \ldots \\ \mathtt{mgr}^o(x) \vee \mathtt{mgr}^+(x) \leftrightarrow \mathtt{mgr}^n(x) \vee \mathtt{mgr}^-(x), \mathtt{mgr}^o(x) \wedge \mathtt{mgr}^+(x) \rightarrow \bot, \ldots \\ \mathtt{wkr}^o(x) \vee \mathtt{wkr}^+(x) \leftrightarrow \mathtt{wkr}^n(x) \vee \mathtt{wkr}^-(x), \mathtt{wkr}^o(x) \wedge \mathtt{wkr}^+(x) \rightarrow \bot, \ldots \end{array}\right\}$$

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$$\Sigma = \left\{\begin{array}{l} \mathtt{mgr}^o(x) \vee \mathtt{wkr}^o(x) \leftrightarrow \mathtt{emp}^o(x) \\ \mathtt{mgr}^o(x) \wedge \mathtt{wkr}^o(x) \to \bot \end{array}\right\} \cup \left\{\begin{array}{l} \mathtt{mgr}^n(x) \vee \mathtt{wkr}^n(x) \leftrightarrow \mathtt{emp}^n(x) \\ \mathtt{mgr}^n(x) \wedge \mathtt{wkr}^n(x) \to \bot \end{array}\right\} \cup$$
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Result(s)

$$\mathtt{emp}^+(x) := (\mathtt{wkr}^+(x) \vee \mathtt{mgr}^+(x)) \wedge \neg\mathtt{emp}^o(x)$$
$$\mathtt{emp}^-(x) := (\mathtt{wkr}^-(x) \vee \mathtt{mgr}^-(x)) \wedge \neg(\mathtt{wkr}^+(x) \vee \mathtt{mgr}^+(x))$$

. . . and we can again synthesize that

```
david$ compile tests/new_fe/mgrwkr-upd.fol
query(empi,1,0,[var(0,0,1,int)]) <->
  and ( or (
      wkri(var(0,0,1))
      mgri(var(0,0,1))
    ) not (
      empo(var(0,0,1))
  ) )

query(empd,1,0,[var(0,0,1,int)]) <->
  and ( or (
      wkrd(var(0,0,1))
      mgrd(var(0,0,1))
    ) not ( or (
        mgri(var(0,0,1))
        wkri(var(0,0,1))
) ) )
```

Unknown/Anonymous Values?

Example (Add a new Worker record (needs an address))

```
INSERT into worker values (1234);
```

⇒ the request then needs to be translated to

```
INSERT into worker-physical values (0xFE1234, 1234);
```

⇒ 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 `worker-addr(id,adress)`
⇒ and where $\texttt{worker}^{+} = \{(1234)\}$

$$\texttt{worker-physical}^{+}(x_2, x_1) = \texttt{worker}^{+}(x_1) \wedge \texttt{worker-addr}(x_1, x_2)$$

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additional access paths that *provide* such values:

⇒ in our case `worker-addr(id,adress)`

⇒ and where $\texttt{worker}^+ = \{(1234)\}$

$$\texttt{worker-physical}^+(x_2, x_1) = \texttt{worker}^+(x_1) \land \texttt{worker-addr}(x_1, x_2)$$

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

…and cyclic dependencies are broken via *reification*.

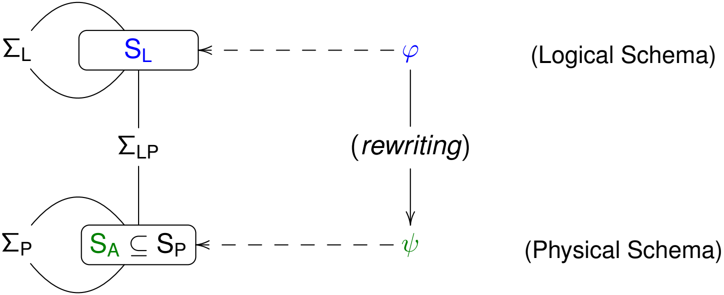
…more details and examples in .

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 $\mathsf{S_A}$:

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
negation	$\mapsto$	simple complement

Query Plans via Interpolation

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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).

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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 $\mathcal{L}(\psi) \subseteq \mathcal{L}(\mathsf{S_A})$.

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

...and we can extract ψ from a (TABLEAU) proof of $\Sigma \cup \Sigma' \models \varphi \rightarrow \varphi'$

TABLEAU Proofs

1. Make entailment into formula to be proven:

$$\begin{array}{rll} \Sigma \cup \Sigma' \models \varphi \to \varphi' & \text{iff} & \models ((\bigwedge \Sigma) \wedge (\bigwedge \Sigma')) \to (\varphi \to \varphi') \quad \text{iff} \\ & & \models (\bigwedge \Sigma) \to ((\bigwedge \Sigma') \to (\varphi \to \varphi')) \quad \text{iff} \\ & & \models (\bigwedge \Sigma) \to (\varphi \to ((\bigwedge \Sigma') \to \varphi')) \quad \text{iff} \\ & & \models ((\bigwedge \Sigma) \wedge (\varphi) \to ((\bigwedge \Sigma') \to \varphi') \end{array}$$

or, equivalently, $(\bigwedge \Sigma) \ \wedge (\bigwedge \Sigma') \ \wedge \alpha \ \wedge \neg\alpha'$ is inconsistent;

2. Apply TABLEAU expansion rules to $(*)$ until all branches are closed;

$$\frac{S \cup \{\alpha, \beta\}}{S}\ \alpha \wedge \beta \in S\,, \qquad \frac{S \cup \{\alpha\} \qquad S \cup \{\beta\}}{S}\ \alpha \vee \beta \in S\,, \quad \ldots$$

where a branch S is *closed* if $\{\alpha, \neg\alpha\} \subseteq S$ (or $\perp \in S$).

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$$\Sigma \cup \Sigma' \models \varphi \to \varphi' \quad \text{iff} \quad \begin{array}{ll} \models ((\bigwedge \Sigma) \wedge (\bigwedge \Sigma')) \to (\varphi \to \varphi') & \text{iff} \\ \models (\bigwedge \Sigma) \to ((\bigwedge \Sigma') \to (\varphi \to \varphi')) & \text{iff} \\ \models (\bigwedge \Sigma) \to (\varphi \to ((\bigwedge \Sigma') \to \varphi')) & \text{iff} \\ \models ((\bigwedge \Sigma) \wedge (\varphi) \to ((\bigwedge \Sigma') \to \varphi') & \end{array}$$

   or, equivalently, $(\bigwedge \Sigma)^L \wedge (\bigwedge \Sigma')^R \wedge \alpha^L \wedge \neg \alpha'^R$ is inconsistent;

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   where a branch S is *closed* if $\{\alpha, \neg\alpha\} \subseteq S$ (or $\perp \in S$).

3. Extract an interpolant from (2); this needs extra $.^L$ and $.^R$ annotations.

TABLEAU and Interpolant Extraction (sketch)

- an interpolant $S \xrightarrow{int} \psi$; invariant $(\bigwedge S^L) \to \psi$ and $\psi \to (\neg \bigwedge S^R)$
  where S^L and S^R are the $.^L$ and $.^R$-tagged subsets of S;

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  where S^L and S^R are the $.^L$ and $.^R$-tagged subsets of S;
- tableau rules (sample):
  - LR clash $\boxed{S \cup \{R^L, \neg R^R\} \xrightarrow{int} R}$, where $R \in \mathsf{S}_\mathsf{A}$
    as $(\bigwedge S^L \wedge R^L) \to R$ and $R \to (R^R \vee \neg \bigwedge S^R)$;

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    as $(\bigwedge S^L \wedge R^L) \to R$ and $R \to (R^R \vee \neg \bigwedge S^R)$;
  - L-conjunction $\boxed{\dfrac{S \cup \{\alpha^L, \beta^L\} \xrightarrow{int} \delta}{S \cup \{(\alpha \wedge \beta)^L\} \xrightarrow{int} \delta}}$
    as $(\bigwedge S^L \wedge \alpha^L \wedge \beta^L) \to \delta$ implies $(\bigwedge S^L \wedge (\alpha \wedge \beta)^L) \to \delta$;

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  - L-conjunction $\boxed{\dfrac{S \cup \{\alpha^L, \beta^L\} \xrightarrow{int} \delta}{S \cup \{(\alpha \wedge \beta)^L\} \xrightarrow{int} \delta}}$
    as $(\bigwedge S^L \wedge \alpha^L \wedge \beta^L) \to \delta$ implies $(\bigwedge S^L \wedge (\alpha \wedge \beta)^L) \to \delta$;
  - R-Disjunction $\boxed{\dfrac{S \cup \{\alpha^R\} \xrightarrow{int} \delta_\alpha \qquad S \cup \{\beta^R\} \xrightarrow{int} \delta_\beta}{S \cup \{(\alpha \vee \beta)^R\} \xrightarrow{int} \delta_\alpha \wedge \delta_\beta}}$
    as $\bigwedge S^L \to \delta_\alpha, \delta_\alpha \to \neg(\alpha^R \wedge \bigwedge S^R)$ and $\bigwedge S^L \to \delta_\beta, \delta_\beta \to \neg(\beta^R \wedge \bigwedge S^R)$
    implies $(\bigwedge S^L) \to \delta_\alpha \wedge \delta_\beta, \delta_\alpha \wedge \delta_\beta \to \neg((\alpha \vee \beta)^R \wedge \bigwedge S^R)$.
  - etc. (see [Fitting] for details)

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

Issues with Tableau

Dealing with the *subformula property* of Tableau

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IDEA #3:

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

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

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 Formulæ and Tableau

Conditional Formulæ

$\varphi[C]\{B\}$ where C is a set of (ground) atoms over S_A and B branch descriptors
$\Rightarrow$ φ only exists in T if all atoms in C are "used" in a plan tableau

Absorbed Range-restricted Formulæ: ANF

$$Q \;::=\; R(\bar{x}) \mid \bot \mid Q \wedge Q \mid Q \vee Q \mid \forall \bar{x}.R(\bar{x}) \to Q,$$

. . . and all $\exists$'s are Skolemized.

Conditional Tableau Rules for ANF

$$\frac{S \cup \{\varphi[C], \psi[C]\}}{(\varphi \wedge \psi)[C] \in S} \text{ (conj)} \qquad \frac{S \cup \{\varphi[C]\} \qquad S \cup \{\psi[C]\}}{(\varphi \vee \psi)[C] \in S} \text{ (disj)}$$

$$\frac{S \cup \{(\varphi[\bar{t}/\bar{x}])[C \cup D]\}}{\{R(\bar{t})[C], (\forall \bar{x}.R(\bar{x}) \to \varphi)[D]\} \subseteq S} \text{ (abs)} \qquad \frac{S \cup \{R(\bar{t})[R(\bar{t})]\}}{S} \; R(\bar{x}) \in \mathsf{S}_\mathsf{A} \text{ (phys)}$$

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Conditional Tableau and Interpolation

Conditional Tableau for $(Q, \Sigma, \mathsf{S_A})$

Proof trees (T^L, T^R): T^L for $\Sigma^L \cup \{Q^L(\bar{a})\}$ over $\{P^L \mid P \in \mathsf{S_A}\}$
T^R for $\Sigma^R \cup \{Q^R(\bar{a}) \to \perp\}$ over $\{P^R \mid P \in \mathsf{S_A}\}$

Closing Set(s)

We call a set C of literals over $\mathsf{S_A}$ a *closing set* for T if, for every branch

1. there is an atom $R(\bar{t})[D]$ such that $D \cup \{\neg R(\bar{t})\} \subseteq C$.
2. there is $\perp[D]$ such that $D \subseteq C$.

$\Rightarrow$ there are many different *minimal* closing sets for T.

Observation

For an arbitrary closing set C, the interpolant for $T^L(T^R)$ is $\perp(\top)$.

Conditional Tableau through an Example

Example (Horizontal Partition)

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

$\mathsf{S_A} = \{\mathtt{emp}/1,\ \mathtt{mgr}/1\}$, note that $\mathtt{wkr}/1$ is NOT in $\mathsf{S_A}$;

Conditional Tableau through an Example

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$S_A = \{\mathtt{emp}/1,\ \mathtt{mgr}/1\}$, note that $\mathtt{wkr}/1$ is NOT in S_A;

ANF of Σ

$$\left\{ \begin{array}{ll} \mathtt{emp}(x) \rightarrow \mathtt{wkr}(x) \vee \mathtt{mgr}(x), & \mathtt{mgr}(x) \rightarrow \mathtt{emp}(x), \\ \mathtt{mgr}(x) \wedge \mathtt{wkr}(x) \rightarrow \bot, & \mathtt{wkr}(x) \rightarrow \mathtt{emp}(x) \end{array} \right\}$$

Conditional Tableau through an Example

ANF of Σ

$$\left\{ \begin{array}{ll} \mathtt{emp}(x) \to \mathtt{wkr}(x) \vee \mathtt{mgr}(x), & \mathtt{mgr}(x) \to \mathtt{emp}(x), \\ \mathtt{mgr}(x) \wedge \mathtt{wkr}(x) \to \bot, & \mathtt{wkr}(x) \to \mathtt{emp}(x) \end{array} \right\}$$

ANF of the Query

$$\begin{array}{l} \mathtt{query}(x) \to \mathtt{wkr}(x), \quad \mathtt{wrk}(x) \to \mathtt{query}(x) \quad \text{and} \\ \mathtt{query}^{L}(0), \quad \mathtt{query}^{R}(0) \to \bot \end{array}$$

Conditional Tableau through an Example

ANF of Σ

$$\left\{ \begin{array}{ll} \mathtt{emp}(x) \rightarrow \mathtt{wkr}(x) \vee \mathtt{mgr}(x), & \mathtt{mgr}(x) \rightarrow \mathtt{emp}(x), \\ \mathtt{mgr}(x) \wedge \mathtt{wkr}(x) \rightarrow \bot, & \mathtt{wkr}(x) \rightarrow \mathtt{emp}(x) \end{array} \right\}$$

ANF of the Query

$$\begin{array}{l} \mathtt{query}(x) \rightarrow \mathtt{wkr}(x), \quad \mathtt{wrk}(x) \rightarrow \mathtt{query}(x) \quad \text{and} \\ \mathtt{query}^{L}(0), \quad \mathtt{query}^{R}(0) \rightarrow \bot \end{array}$$

$$\begin{array}{lcl} T^{L} & & T^{R} \\ \hline \mathtt{query}(0)[]\{\} & & \\ \mathtt{wkr}(0)[]\{\} & & \\ \mathtt{emp}(0)[]\{\} & \rightarrow & \mathtt{emp}(0)[\mathtt{emp}(0)]\{\} \\ & & \mathtt{wkr}(0)[\mathtt{emp}(0)]\{1.0\} \\ & & \mathtt{query}(0)[\mathtt{emp}(0)]\{1.0\} \\ & & \bot[\mathtt{emp}(0)]\{1.0\} \\ \mathtt{mgr}(0)[\mathtt{mgr}(0)]\{\} & \leftarrow & \mathtt{mgr}(0)[\mathtt{emp}(0)]\{1.1\} \\ \bot[\mathtt{mgr}(0)]\{\} & & \end{array}$$

Conditional Tableau through an Example

T^L		T^R
$\mathtt{query}(0)[]\{\}$		
$\mathtt{wkr}(0)[]\{\}$		
$\mathtt{emp}(0)[]\{\}$	$\to$	$\mathtt{emp}(0)[\mathtt{emp}(0)]\{\}$
		$\mathtt{wkr}(0)[\mathtt{emp}(0)]\{1.0\}$
		$\mathtt{query}(0)[\mathtt{emp}(0)]\{1.0\}$
		$\bot[\mathtt{emp}(0)]\{1.0\}$
$\mathtt{mgr}(0)[\mathtt{mgr}(0)]\{\}$	$\leftarrow$	$\mathtt{mgr}(0)[\mathtt{emp}(0)]\{1.1\}$
$\bot[\mathtt{mgr}(0)]\{\}$		

Closing sets:

$\{\neg\mathtt{emp}(0)\}, \{\mathtt{mgr}(0)\}$ $\qquad$ $\{\neg\mathtt{mgr}(0), \mathtt{emp}(0)\}$

Conditional Tableau through an Example

T^L		T^R
$\mathtt{query}(0)[]\{\}$		
$\mathtt{wkr}(0)[]\{\}$		
$\mathtt{emp}(0)[]\{\}$	$\rightarrow$	$\mathtt{emp}(0)[\mathtt{emp}(0)]\{\}$
		$\mathtt{wkr}(0)[\mathtt{emp}(0)]\{1.0\}$
		$\mathtt{query}(0)[\mathtt{emp}(0)]\{1.0\}$
		$\bot[\mathtt{emp}(0)]\{1.0\}$
$\mathtt{mgr}(0)[\mathtt{mgr}(0)]\{\}$	$\leftarrow$	$\mathtt{mgr}(0)[\mathtt{emp}(0)]\{1.1\}$
$\bot[\mathtt{mgr}(0)]\{\}$		

Closing sets:

$\{\neg\mathtt{emp}(0)\}, \{\mathtt{mgr}(0)\}$ $\qquad$ $\{\neg\mathtt{mgr}(0), \mathtt{emp}(0)\}$

Query Plan:

$$\mathtt{query}(x) \leftrightarrow \mathtt{emp}(x) \wedge \neg\mathtt{mgr}(x)$$

Plan Enumeration

Physical Tableau T^P for a Plan P

P	:	L_P	R_P
$R(\bar{t})$	:	$\{\{\neg R^L(\bar{t})\}\}$	$\{\{R^R(\bar{t})\}\}$
$P_1 \wedge P_2$	:	$L_{P_1} \cup L_{P_2}$	$\{S_1 \cup S_2 \mid S_1 \in R_{P_1}, S_2 \in R_{P_2}\}$
$P_1 \vee P_2$	:	$\{S_1 \cup S_2 \mid S_1 \in L_{P_1}, S_2 \in L_{P_2}\}$	$R_{P_1} \cup R_{P_2}$
$\neg P_1$	:	$\{\{L^L(\bar{t}) \mid L^R(\bar{t}) \in S\} \mid S \in R_{P_1}\}$	$\{\{L^R(\bar{t}) \mid L^L(\bar{t}) \in S\} \mid S \in L_{P_1}\}$
$\exists x.P_1$	:	$L_{P_1[t/x]}$	$R_{P_1[t/x]}$

Observation

For a range-restricted formula P over S_A there is an analytic tableau tree T^P that uses only formulæ in $\Sigma^{LR} \cup \{\forall x.\text{true}^R(x)\}$ such that:

1. Open branches of T^P correspond to *sets of literals* $C \in L_P$ (left branch) or $C \in R_P$ (right branch); and
2. The interpolant extracted from the closed tableau $T^P[T^L, T^R]$, the *closure of* (T^L, T^R) by (the *branches* of) T^P, is logically equivalent to P.

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Logical&Physical Combined, Controlling the Search

Basic Strategy

1. build (T^L, T^R) for $(Q, \Sigma, \mathsf{S_A})$ to a *certain depth*,
2. build T^P and test if each element in $L_P(R_P)$ closes $T^L(T^R)$.

   if so, $T^P[T^L, T^R]$ is closed tableau yielding an interpolant equivalent to P;

   (...otherwise extend depth in step 1 and repeat.)

NOTE: in step 2 we can "test" many Ps (plan enumeration), but
how do we know which ones to try? while building these bottom-up?

Controlling the Search

- only use the (phys) rule in $T^L(T^R)$ for $R(\bar{t})$ that appears in $T^R(T^L)$,
- only consider *fragments* that help closing (T^L, T^R)

  $\Rightarrow$ this is determined using the minimal closing sets for (T^L, T^R).

... combine with A^* search (among Ps) with respect to a *cost model*.

Closing Sets (more complex example)

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 $\{\cdot\}$:

$$
\begin{array}{rcll}
\psi[\{R(x_1,\ldots,x_k)\}] & \leftrightarrow & \psi[R(x_1,\ldots,x_k)] & \\
\psi[\{\psi_1 \wedge \psi_2\}] & \leftrightarrow & \psi[\{\psi_1\} \wedge \{\psi_2\}] & \\
\psi[\{\neg\psi_1\}] & \leftrightarrow & \psi[\neg\psi_1] & \\
\psi[\neg\{\psi_1\}] & \leftrightarrow & \psi[\neg\psi_1] & \\
\psi[\{\psi_1 \vee \psi_2\}] & \leftrightarrow & \psi[\{\psi_1\} \vee \{\psi_2\}] & \text{if } \Sigma \cup \{\psi[]\} \models \psi_1 \wedge \psi_2 \rightarrow \bot \\
\psi[\{\exists x.\psi_1\}] & \leftrightarrow & \psi[\exists x.\{\psi_1\}] & \text{if} \\
 & & \multicolumn{2}{r}{\Sigma \cup \{\psi[] \wedge \psi_1[y_1/x] \wedge \psi_1[y_2/x] \models y_1 \approx y_2}
\end{array}
$$

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$$
\begin{aligned}
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\psi[\{\neg\psi_1\}] &\leftrightarrow \psi[\neg\psi_1] \\
\psi[\neg\{\psi_1\}] &\leftrightarrow \psi[\neg\psi_1] \\
\psi[\{\psi_1 \vee \psi_2\}] &\leftrightarrow \psi[\{\psi_1\} \vee \{\psi_2\}] \qquad \text{if } \Sigma \cup \{\psi[]\} \models \psi_1 \wedge \psi_2 \to \bot \\
\psi[\{\exists x.\psi_1\}] &\leftrightarrow \psi[\exists x.\{\psi_1\}] \qquad \text{if} \\
&\qquad \Sigma \cup \{\psi[] \wedge \psi_1[y_1/x] \wedge \psi_1[y_2/x] \models y_1 \approx y_2
\end{aligned}
$$

... reasoning abstracted in FunDL-Lite (a PTIME fragment)

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

Postprocessing: Duplicate Elimination Elimination

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

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

$\Rightarrow$ dept number (x) and name (y) do NOT functionally determine employee (e).

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

$\Rightarrow$ dept number (x) and name (y) do functionally determine employee (e) and dept (d).

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$\Rightarrow$ dept number (x) and name (y) do NOT functionally determine employee (e).

. . . needs *duplicate elimination* during projection.

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

$\Rightarrow$ dept number (x) and name (y) do functionally determine employee (e) and dept (d).

. . . does NOT need *duplicate elimination* during projection.

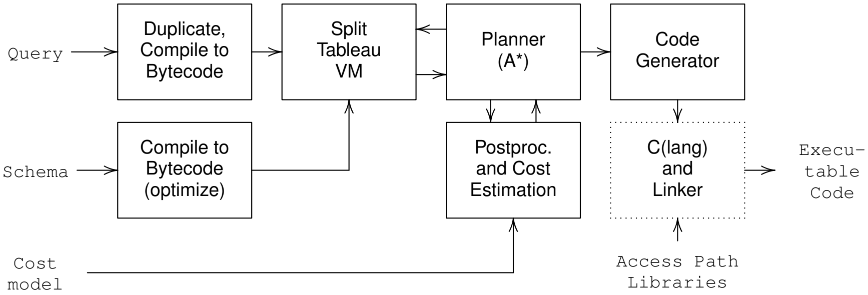
Interpolation (summary)

(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 to generate
   closing sets: sets of $\mathrm{S_A}$ literals that (fully) close the tableau
3. separate general reasoning from interpolant enumeration
   1) VM-driven conditional tableau for $\Sigma^L \cup \{\varphi^L\}$ and for $\Sigma^R \cup \{\varphi^R \to \bot\}$
   2) A*-based interpolant generator w.r.t. closing sets and Σ^{LR}
4. FunDL-Lite *postprocessing* to deal w/duplicates *et al.*

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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