Logical Approach to Physical Data Independence
and Query Compilation
Introduction, Background, and Goals

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Organization
Lectures/Exercises

- web page:
  
  http://cs.uwaterloo.ca/~david/cs848s14/

- schedule:

  Thursday 9:30-12:19
Introduction and Goals

**Textbook (aka Shameless plug)**

Preferred projects will be related to applying (some) of the ideas presented in this class to your own area of research: this can further your own research and may help you to consider alternative views/approaches to what you have been thinking about already.

1. project proposal: one page due Lecture 6;
2. project presentation: 10-20 minutes (depending on the number of projects) in Lecture 10;
3. report (in pdf, up to 10 pages), source code (if applicable) within a week of last Lecture.
Assessment

1. class participation, including assignments (15%)
2. in class presentation either of your project or of a paper from the reading list (25%)
3. project (60%)
USE SCENARIOS AND GOALS
Physical Data Independence

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

[ANSI/X3/SPARC Standards Planning and Requirements Committee, Bachman, 1975]
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- independent customized user views,
- changes to conceptual structure without affecting users.

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- physical storage details hidden from users,
- changes to physical storage without affecting conceptual view,

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

- physical storage details hidden from users,
- changes to physical storage without affecting conceptual view,

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

[ANSI/X3/SPARC Standards Planning and Requirements Committee, Bachman, 1975]
A Conceptual (user) view of PAYROLL data:

Example of PAYROLL data:

1. Mary is an employee.
2. Mary's employee number is 3412.
3. Mary's salary is 72000.

Example of PAYROLL:

4. There is a kind of entity called an employee.
5. There are attributes called enumber, name and salary.
6. Each employee entity has attributes enumber, name and salary.
7. Employees are identified by their enumber.
Example: PAYROLL

A physical design for PAYROLL:

8. There is a file of records called emp-file.
9. There are record fields emp-num, emp-name and emp-salary.
10. Each emp-file record has the fields emp-num, emp-name and emp-salary.
11. File emp-file is organized as a B-tree data structure that supports an emp-lookup operation, given a value for attribute enumber.

12. Records in file emp-file correspond one-to-one to employee entities.
13. Record fields in file emp-file encode the corresponding attribute values for employee entities, for example, emp-num encodes an enumber.
Ontology-based Data Access

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Queries are answered not only w.r.t. explicit data
but also w.r.t. background knowledge

⇒ Ontology-based Data Access (OBDA)
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**Example**
- Socrates is a MAN *(explicit data)*
- Every MAN is MORTAL *(background)*

*List all MORTALs* ⇒ {Socrates} *(query)*
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Fig. 1. Ontology-based data access.

[Calvanese et al.: Mastro]
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Question:
Is Aristoteles a MORTAL?
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List all MORTALs ⇒ {Socrates} (query)

Question:
Is Aristoteles a MORTAL? … can we really say “NO”?
PROBLEM:
How to transfer (reformat) data conforming to a source schema to data conforming to a target schema?
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The general setting of data exchange is this:

source $S$ \xrightarrow{\text{mapping } M} \text{target } T \xrightarrow{\text{query } Q}

[Arenas et al: Foundations of Data Exchange]
PROBLEM:
How to transfer (reformat) data conforming to a source schema to data conforming to a target schema?

Issues:
- what should happen when the target is more complex than the source?
- how do we answer queries over the target?
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Data integration provides a uniform access to a set of data sources, through a unified representation called global schema. A mapping specifies the relationship between the global schema and the sources.

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Variants “which way do the arrows point” [Lenzerini]
GAV (global as a view), LAV (local as a view), and GLAV (“both ways”).
Common Threads and Issues

- In general two *schemas*: Conceptual/Logical and Physical
  - both endowed with *metadata* (vocabulary, ...)
  - mappings connect the schemas
  - (source) data only "in" the *physical* schema
  - queries only over the *conceptual/logical* schema

**Issues to be formalized/fixed:**
1. Formal description of the two schemas (same formalism for both?)
2. Language(s) for metadata and mappings
3. *(user level)* Data representation
4. *(user level)* Query language (semantics–aka when is an answer an answer?)
5. Algorithms/Execution model for queries: e.g., does *materialization* matter?
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Phyical Data Independence: My Motivation

Goal: Application of the Ideas to Embedded Systems

1. High-level conceptual view of the system
2. High level query (and, eventually, update) language
3. Fine-grained physical schema description
4. Flexible conceptual-physical mappings
5. Queries (updates) *compiled* to operations on physical level
### Physical Data Independence: My Motivation

#### Goal: Application of the Ideas to Embedded Systems

1. High-level conceptual view of the system [relational]
2. High level query (and, eventually, update) language [SQL]
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   [pointer navigation, field extraction, conditionals, ...]

Challenge: The code generated from queries must be competitive with hand-written code.
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Example of LINUX-INFO data:

1. process (called) `gcc` is running;
2. `gcc`’s process number is 1234;
3. the user (id) running `gcc` is 145;
4. `gcc` uses files “foo.c” and “foo.o”.

Example of LINUX-INFO data:
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2. gcc’s process number is 1234;
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Example of LINUX-INFO metadata:
5. There entities called process and file.
6. There are attributes called pno, pname, uname, and fname.
7. Each process entity has attributes pno, pname and uname.
8. Each file entity has attribute fname.
9. Processes are identified by their pno.
10. Files are identified by their fname.
11. There is a relationship uses between processes and files.
A physical design for LINUX (selected by Linus Torvalds).

12 There are process records called `task-struct`.

13 Each `task-struct` record has record fields `pid`, `uid`, `comm`, and `fds`.

14 All `task-structs` is organized as a tree data structure.

15 The `task-struct` records correspond one-to-one to process entities.

16 Record fields in `task-struct` encode the corresponding attribute values for process entities, for example, `pid` encodes an `pno`, etc.

17 Similarly, `fs`s correspond appropriately to (open) file entities.

18 `fds` field of `task-struct` is an array of `fds`; a non-null entry in this array indicates that the process corresponding to this `task-struct` is using the file identified by the `name` field of the `fd` record in the array.
User Query:

find all files used by processes invoked by user 145.
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Query Plan:

for each task-struct \( t \) in tree of task-structs

check if \( t \)'s uid field is 145 and, if so

scan the fds array in \( t \) and

if the file descriptor (fd) is non-NULL

print out the name of file field in fd.
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Is the plan correct?

... and how do/can we answer this question?
UNIFYING LOGIC-BASED APPROACH
Vocabularies: Relational Model for both Conceptual and Physical Schemata.

Conceptual/Logical ($S_L$):

- predicate symbols $R_1/a_1, \ldots, R_k/a_k$ ($a_i$ is the arity of $R_i$)
- (possibly) constants $c_1, \ldots, c_n$
Metadata and Signatures

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**Physical (S\textsubscript{P}):**

- predicate symbols $S_1/b_1, \ldots, S_k/b_k$
- a distinguished subset $S_A \subseteq S_P$ of *access paths*
  - denote *capabilities to retrieve tuples* (i.e., data structures)
  - (optionally) binding patterns (restrictions on tuple retrieval)
  - associated with set of *tuples* (closed-world semantics)
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... a standard way of defining interpretations
Metadata and Constraints

Metadata: First-order sentences $\Sigma$ over $S_L \cup S_P$.

Conceptual/Logical ($\Sigma_L$):

$\Rightarrow$ keys, inclusion dependencies, hierarchies, . . .
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$\Rightarrow$ formulae that link to symbols in $S_L$ (mapping constraints).
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$\Rightarrow$ formulae that link to symbols in $S_L$ (mapping constraints).

. . . we resort to fragments of FOL to gain better computational properties
Example: LINUX-INFO

Conceptual/Logical:

\[ S_L = \{ \text{process/3, file/1, uses/2} \} \]
\[ \Sigma_L = \{ \text{process}(x, y_1, z_1) \land \text{process}(x, y_2, z_2) \rightarrow y_1 = y_2 \land z_1 = z_2, \]
\[ \text{uses}(x, y) \rightarrow \exists z, w. \text{process}(x, z, w) \land \text{file}(y), \quad ... \} \]

Physical:

\[ S_A = \{ \text{task_struct/1/0, pid/2/1, uid/2/1, fds/2/1, fname/2/1} \} \]
\[ \Sigma_P = \{ \text{task_struct}(x) \rightarrow \exists y, z, w. \text{pid}(x, y) \land \text{uid}(z) \land \text{fds}(x, w) \]
\[ \text{pid}(x_1, y) \land \text{pid}(x_2, y) \rightarrow x_1 = x_1 \]
\[ \text{process}(x, y, z) \rightarrow \exists t. \text{task_struct}(t) \land \text{pid}(t, x), \quad ... \} \]
Queries and Answers

Queries: First-order formulae ($\varphi$) over $S_L$.

$$\Rightarrow \exists p, n, u.\text{process}(p, n, u) \land u = 145 \land \text{uses}(p, f) \land \text{file}(f)$$
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Data $D$:
Sets of (ground) tuples that fix meaning of every access path.
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answers *in common* when evaluating $\varphi$ over *every* interpretation (database) that is a model of $\Sigma$ and that extend $D$. 
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Definition (Certain Answers)

$$\text{cert}_{\Sigma, D}(\varphi) = \{ \bar{a} \mid \Sigma \cup D \models \varphi(\bar{a}) \}$$

logical implication

$$= \bigcap_{I \models \Sigma \cup D} \{ \bar{a} \mid I \models \varphi(\bar{a}) \}$$

answer in every model
The BAD News (and what can be done)

Theorem

“$\vec{a} \in \text{cert}_{\Sigma,D}(\varphi)$?” is undecidable.

$\Rightarrow$ sources of undecidability: both $\Sigma$ and $\varphi$!
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Standard solution:

1. restrict \( \Sigma \) to decidable fragments of FOL (e.g., DLs)
2. restrict \( \varphi \) to a decidable fragment of FOL (e.g., UCQ)
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<table>
<thead>
<tr>
<th></th>
<th>$S_L, \Sigma_L$</th>
<th>$S_P, \Sigma_P$</th>
<th>queries</th>
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<td>Information Integration</td>
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</table>
What do Relational Systems do??

IDEA: “make it look like a single model”

(severely) restrict what logical schema may look like:

every logical predicate $P(\bar{x})$ must correspond 1-1 to some access path.

... conceptual/logical symbols in queries are (mere aliases of) access paths.

... completely against the idea of physical data independence.
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Is this enough? $\neg P(x)$? $\forall x. P(x)$? ... depend on the *domain* of the model
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**IDEA-2: “only queries that think there is a single model”**

A formula $\varphi$ is *domain independent* if for all pairs of models $I_1, I_2$ of $D$ and valuation $\theta$ we have

$$I_1, \theta \models \varphi \text{ if and only if } I_2, \theta \models \varphi.$$

... $I_1$ and $I_2$ can only differ in their *domains* (hence the name).
A LOGSPACE Algorithm

IDEA

Domain independent formulae can be evaluated in a model based on the *active domain of* $D$ (set of individuals that appear in the access paths).
A LOGSPACE Algorithm

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A Turing machine $T_\varphi$

- read only input tape storing (an encoding of) $\vec{a}$ and $D$;
- read/write work tape storing a counter for each variable in $\varphi$ (log $|D|$ bits) and fixed number of auxiliary counters;
- a finite control that implements top-down satisfaction check w.r.t. a valuation defined by the current state of the counters
  $\Rightarrow$ used as pointers to individuals on the work tape.
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Theorem

$$\text{cert}_{\Sigma,D}(\varphi) = \{ \vec{a} | \langle \vec{a}, D \rangle \in \mathcal{L}(T_\varphi) \}.$$
Range-restricted Formulas and Relational Algebra

Nobody uses that algorithm!
Range-restricted Formulas and Relational Algebra

Nobody uses that algorithm! Instead:

Range-restricted Formulae (queries):

\[ \varphi ::= R(\bar{x}) \mid \varphi \land x = y \mid \varphi \land \varphi \mid \exists s. \varphi \mid \varphi \lor \varphi \mid \varphi \land \neg \varphi \]

Bottom-up “Algebraic” Query Evaluation:

every production above maps (at least naively) to an algebraic operation on finite relations:

- scan (with renaming),
- selection,
- join,
- projection,
- union, and
- difference.
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Datalog (limited iteration)

- additional predicates defined as a fixpoint positive query allows PTIME-complete problems.
comprehensive framework based on certain answers that unifies many database/KR approaches to handling information in presence of background information/theory/ontology;

too expressive and in turn computationally in-feasible;

practical (relational) systems: (almost) trivial instance of the framework.
Summary

- comprehensive framework based on certain answers that unifies many database/KR approaches to handling information in presence of background information/theory/ontology;
- too expressive and in turn computationally in-feasible;
- practical (relational) systems: (almost) trivial instance of the framework.

Plan of Lectures:

1. Classical OBDA: another way of gaining tractability (and its limits)
2. Database Approach Extension and Interpolation
3. Modeling Complex Physical Designs
4. Updates of Data and Future Directions