Data Integration

Craig Knoblock
University of Southern California

These slides are based in part on slides from José Luis Ambite and Rao Kambhampati, which are in turn based in part on slides from Alon Halevy.
Outline

- Database Theory Background
  - Datalog
  - Query Containment
- Dimensions of Data Integration
  - Architecture
  - Content Descriptions
    - Global-as-View
    - Local-as-View:
      - Bucket Algorithm
      - Inverse-Rules Algorithm
- Source Capabilities: Recursive Rewritings
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Datalog

- Datalog Program = set of datalog rules
- Datalog rule = conjunctive query

\[ \text{big-LA-buyers}(\text{Buyer}, \text{Seller}, \text{Price}) :\]
\[
\text{head}
\]
\[
\text{person}(\text{Buyer}, \text{"Los Angeles"}),
\text{purchase}(\text{Buyer}, \text{Seller}, \text{Product}, \text{Price}),
\text{Price} > 10000.
\text{body} \]
Datalog

- Datalog Program = set of datalog rules
- Datalog rule = conjunctive query

\[
\text{big-LA-buyers}(\text{Buyer}, \text{Seller}, \text{Price}) :- \\
\text{person}(\text{Buyer}, \text{"Los Angeles"}), \\
\text{purchase}(\text{Buyer}, \text{Seller}, \text{Product}, \text{Price}), \\
\text{Price} > 10000. \\
\forall \text{Buyer}, \text{Seller}, \text{Price} \\
[ \exists \text{Product} [ \\
\text{person}(\text{Buyer}, \text{"Los Angeles"}) \land \\
\text{purchase}(\text{Buyer}, \text{Seller}, \text{Product}, \text{Price}) \land \\
\text{Price} > 10000 ) ] \\
\rightarrow \text{big-LA-buyers}(\text{Buyer}, \text{Seller}, \text{Price}) \\
\]
CREATE VIEW Big-LA-buyers AS
SELECT buyer, seller, price
FROM Person, Purchase
WHERE Person.city = "Los Angeles" AND
      Person.buyer = Purchase.buyer AND
      Purchase.price > 10000

big-LA-buyers(Buyer, Seller, Price) :-
person(Buyer, "Los Angeles"),
purchase(Buyer, Seller, Product, Price),
Price > 10000.

Datalog rule ~ view definition
Rule body ~ select-from-where construct of SQL
Recursion in Datalog

\[
\begin{align*}
\text{path}(X, Y) & \,:=\, \text{arc}(X, Y) \\
\text{path}(X, Y) & \,:=\, \text{path}(X, Z), \, \text{path}(Z, Y).
\end{align*}
\]
Recursion in Datalog

\[
\text{path}(X, Y) \quad ::= \quad \text{arc}(X, Y)
\]
\[
\text{path}(X, Y) \quad ::= \quad \text{path}(X, Z), \quad \text{path}(Z, Y).
\]

Semantics: evaluate the rules bottom-up until a fixpoint:
Recursion in Datalog

\[
\text{path}(X, Y) \quad :\quad \text{arc}(X, Y) \\
\text{path}(X, Y) \quad :\quad \text{path}(X, Z), \quad \text{path}(Z, Y). \\
\]

Semantics: evaluate the rules bottom-up until a fixpoint:
Iteration #0: arc: \{ (a,b), (a,c), (b,d), (c,d), (d,e) \}
\text{path: } \{ \}

\[
\begin{array}{c}
a \\
b \\
c \\
d \\
e
\end{array}
\]
Recursion in Datalog

\[
\text{path}(X, Y) \quad :- \quad \text{arc}(X, Y)
\]
\[
\text{path}(X, Y) \quad :- \quad \text{path}(X, Z), \; \text{path}(Z, Y).
\]

**Semantics:** evaluate the rules bottom-up until a fixpoint:

Iteration #0: arc: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}

path: \{
\}

Iteration #1: path: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}
Recursion in Datalog

\[
\text{path}(X, Y) \ :- \ \text{arc}(X, Y) \\
\text{path}(X, Y) \ :- \ \text{path}(X, Z), \ \text{path}(Z, Y).
\]

**Semantics:** evaluate the rules bottom-up until a fixpoint:

Iteration #0: arc: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}
path: \{

Iteration #1: path: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}

Iteration #2: path gets the new tuples: (a,d), (b,e), (c,e)
Recursion in Datalog

\begin{align*}
\text{path}(X, Y) & \rightarrow \text{arc}(X, Y) \\
\text{path}(X, Y) & \rightarrow \text{path}(X, Z), \text{path}(Z, Y).
\end{align*}

**Semantics:** evaluate the rules bottom-up until a fixpoint:

Iteration #0: arc: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}
path: \{\}

Iteration #1: path: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}

Iteration #2: path gets the new tuples: (a,d), (b,e), (c,e)

Iteration #3: path gets the new tuple: (a,e)
Recursion in Datalog

\[
\begin{align*}
\text{path}(X, Y) & : \quad \text{arc}(X, Y) \\
\text{path}(X, Y) & : \quad \text{path}(X, Z), \ \text{path}(Z, Y).
\end{align*}
\]

Semantics: evaluate the rules bottom-up until a fixpoint:

Iteration #0: arc: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}

path: \{\}

Iteration #1: path: \{(a,b), (a,c), (b,d), (c,d), (d,e)\}

Iteration #2: path gets the new tuples: (a,d), (b,e), (c,e)

Iteration #3: path gets the new tuple: (a,e)

Iteration #4: Nothing changes => stop.
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    - Local-as-View:
      - Bucket Algorithm
      - Inverse-Rules Algorithm
  - Source Capabilities: Recursive Rewritings
  - Local Completeness Information
Query Containment

- **Query Containment**: $q' \subseteq q$
  - $\forall D \; q'(D) \subseteq q(D)$
  - $q' \models q$
- **Query Equivalence**: $q' = q \iff q' \subseteq q \land q \subseteq q'$
- **Complexity of Query Containment**
  - Conjunctive Queries (CQ), Union of CQs: NP-complete
  - CQ with comparisons ($=, <, \neq$): $\Pi_p^2$-complete
  - FOL, recursive queries: Undecidable
Method of Canonical Databases

1. Create a canonical database $D$ that is the “frozen” body of $q_1$
2. Compute $q_2(D)$
3. If $q_2(D)$ contains the “frozen” head of $q_1$, then $q_1 \subseteq q_2$, otherwise not.
q1 is the CQ: \( \text{path}(X,Y) :\) arc(X,Z) & arc(Z,W) & arc(W,Y) 
q2 is the value of path in the following recursive Datalog program:

\[
\begin{align*}
\text{path}(X,Y) & : \text{arc}(X,Y) \\
\text{path}(X,Y) & : \text{path}(X,Z) \& \text{path}(Z,Y)
\end{align*}
\]

Intuitively, \( q1 = \text{paths of length 3} \); \( q2 = \text{paths of length 1 or more} \), \( q1 \subseteq q2 \)

1. Freeze \( q1 \), say with 0, 1, 2, 3 as constants for \( X, Z, W, Y \), respectively.

   \[ D = \{ \text{arc}(0, 1), \text{arc}(1, 2), \text{arc}(2, 3) \} \]

   Frozen head of \( q1 \) is path(0, 3).

2. Compute \( q2(D) \)

   \[ \text{Ext(path)} = \{ (0,1), (1,2), (2,3), (0,2), (1,3), (0,3) \} \]

3. Since frozen head of \( q1 \), path(0, 3), is in \( q2(D) \) then \( q1 \subseteq q2 \)
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Principal Dimensions of Data Integration

• Virtual vs. materialized architecture
• Access: query only or query & update?
• Mediated schema and query reformulation
  • Content Descriptions
    • Global-as-view
    • Local-as-view
  • Language for descriptions and queries: conjunctive queries (CQs), union of CQs, Datalog (recursion), first-order logic (\(\land, \lor, \neg\)), description logics, …

• Types of Sources
  • Structured (DB’s) vs. semi-structured (Web)
  • Source capabilities: positive and negative
Materialized Architecture: Data Warehouse
Virtual Architecture: Mediator
Virtual Integration Architecture

- Leave the data in the sources
- When a query comes in:
  - Determine the relevant sources to the query
  - Break down the query into sub-queries for the sources
  - Get the answers from the sources, and combine them appropriately
- Data is fresh. Approach scalable
- Issues:
  - Relating Sources & Mediator
  - Reformulating the query
  - Efficient planning & execution

Garlic [IBM], Hermes[UMD]; Tsimmis, InfoMaster[Stanford]; DISCO[INRIA]; Information Manifold [AT&T]; SIMS/Ariadne[USC]; Emerac/Havasu[ASU]
Desiderata for Relating Source-Mediator Schemas

- **Expressive power**: distinguish between sources with closely related data. Hence, be able to prune access to irrelevant sources.
- **Easy addition**: make it easy to add new data sources.
- **Reformulation**: be able to reformulate a user query into a query on the sources efficiently and effectively.
- **Nonlossy**: be able to handle all queries that can be answered by directly accessing the sources.

Reformulation

- **Given**:
  - A query $Q$ posed over the mediated schema
  - Descriptions of the data sources
- **Find**:
  - A query $Q'$ over the data source relations, such that:
    - $Q'$ provides only *correct answers* to $Q$, and
    - $Q'$ provides all possible answers to $Q$ given the sources.
Source Descriptions

Elements of source descriptions:

• Contents: source contains movies, directors, cast.
• Constraints: only movies produced after 1965.
• Completeness: contains *all* American movies.
• Capabilities:
  • Negative: source requires movie title or director as input
  • Positive: source can perform selections, joins, …
Approaches to Specification of Source Descriptions

• **Global-as-View (GAV):**
  Mediator relation defined as a view over source relations
  Ex: TSIMMIS (Stanford), HERMES (Maryland)

• **Local-as-View (LAV):**
  Source relation defined as view over mediator relations
  Ex: Information Manifold (AT&T), Tukwila(UW), InfoMaster (Stanford), Ariadne (USC)

View ~ named query ~ logical formula
Query Reformulation

Problem: rewrite the user query expressed in the mediated schema into a query expressed in the source schemas

Given a query $Q$ in terms of the mediated-schema relations, and descriptions of the information sources,

Find a query $Q'$ that uses only the source relations, such that

- $Q' \models Q$ (i.e., answers are correct; i.e., $Q' \subseteq Q$) and
- $Q'$ provides all possible answers to $Q$ given the sources
Given query $q$ and view definitions $V=\{V_1\ldots V_n\}$

- $q'$ is an *Equivalent Rewriting* of $q$ using $V$ if:
  - $q'$ refers only to views in $V$, and
  - $q' = q$

- $q'$ is a *Maximally-Contained Rewriting* of $q$ using $V$ if:
  - $q'$ refers only to views in $V$, and
  - $q' \subseteq q$, and
  - there is no rewriting $q_1$, such that $q' \subseteq q_1 \subseteq q$ and $q_1 \neq q$
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• Source Capabilities: Recursive Rewritings
Global-as-View (GAV)

Each mediator relation is defined as a view over source relations.

\[
\text{MovieActor}(title, actor) \leftarrow \\
\text{DB1}(id, title, actor, year) \\
\text{MovieActor}(title, actor) \leftarrow \\
\text{DB2}(title, director, actor, year) \\
\text{MovieReview}(title, review) \leftarrow \\
\text{DB1}(id, title, actor, year) \land \text{DB3}(id, review)
\]
Query Reformulation in GAV

Query reformulation = rule unfolding + simplification

Query: Find reviews for ‘DeNiro’ movies
q(title,review) :- MovieActor(title,‘DeNiro’),
                MovieReview(title,review)

1. q'(title,review) :- DB1(id,title,’DeNiro’,year),
                 DB1(id,title,actor,year’), DB3(id,review)  Redundant

2. q'(title,review) :-
                  DB2(title,director,’DeNiro’,year),
                  DB1(id,title,actor, year’), DB3(id,review)  Redundant wrt 1
Local-as-View (LAV)

- Each source relation is defined as a view over mediator relations

\[ V_1(\text{title, year, director}) \subseteq \text{Movie(title,year,director,genre)} \]
\[ \wedge \text{American(director)} \wedge \text{year } \geq 1960 \wedge \text{genre} = \text{‘Comedy’} \]

\[ V_2(\text{title, review}) \subseteq \text{Movie(title,year,director,genre)} \]
\[ \quad \wedge \text{year } \geq 1990 \wedge \text{MovieReview(title, review)} \]
Query Reformulation in LAV

Query: \textit{Reviews for comedies produced after 1950}

\[ q(\text{title,review}) :\neg \text{Movie(}\text{title,year,director,‘Comedy’)}, \text{year} \geq 1950, \text{MovieReview(}\text{title,review}) \]

Reformulated query:

\[ q'(\text{title,review}) :\neg \text{V1(}\text{title,year,director}), \text{V2(}\text{title,review}) \]

\[ \text{V1(}\text{title, year, director}) \rightarrow \text{Movie(}\text{title,year,director,genre}) ^ \text{American(}\text{director}) ^ \text{year} \geq 1960 ^ \text{genre} = \text{‘Comedy’} \]

\[ \text{V2(}\text{title, review}) \rightarrow \text{Movie(}\text{title,year,director,genre}) ^ \text{year} \geq 1990 ^ \text{MovieReview(}\text{title, review}) \]
<table>
<thead>
<tr>
<th>GAV</th>
<th>vs.</th>
<th>LAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not modular</td>
<td>Modular--adding new sources is easy</td>
<td></td>
</tr>
<tr>
<td>Addition of new sources changes the mediated schema</td>
<td>Very flexible--power of the entire query language available to describe sources</td>
<td></td>
</tr>
<tr>
<td>Can be awkward to write mediated schema without loss of information</td>
<td>Reformulation is hard</td>
<td></td>
</tr>
<tr>
<td>Query reformulation easy</td>
<td>• Involves answering queries only using views (can be intractable)</td>
<td></td>
</tr>
<tr>
<td>• reduces to view unfolding (polynomial)</td>
<td>Best when</td>
<td></td>
</tr>
<tr>
<td>• Can build hierarchies of mediated schemas</td>
<td>• Many, relatively unknown data sources</td>
<td></td>
</tr>
<tr>
<td>• Best when</td>
<td>• possibility of addition/deletion of sources</td>
<td></td>
</tr>
<tr>
<td>• Few, stable, data sources</td>
<td>• Information Manifold, InfoMaster, Emerac</td>
<td></td>
</tr>
<tr>
<td>• well-known to the mediator (e.g. corporate integration)</td>
<td></td>
<td>• Garlic, TSIMMIS, HERMES</td>
</tr>
</tbody>
</table>
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Query Reformulation in LAV
The Bucket Algorithm

Given: user query q, source descriptions \{V_i\}

1. Find relevant sources (fill buckets)
   For each relation \(g\) in query \(q\)
   - Find \(V_j\) that contains relation \(g\)
   - Check that constraints in \(V_j\) are compatible with \(q\)

2. Combine source relations \{V_j\} from each bucket into a conjunctive query \(q'\) and check for containment (\(q' \subseteq q\))
The Bucket Algorithm: Example

V1(student,number,year) → Registered(student,course,year), Course(course,number), number ≥ 500, year ≥ 1992
V2(student,dept,course) → Registered(student,course,year), Enrolled(student,dept)
V3(student,course) → Registered(student,course,year), year≤1990
V4(student,course,number) → Registered(student,course,year), Course(course,number), Enrolled(student,dept), number ≤ 100

User Query (using mediator relations):
q(S,D) :- Enrolled(S,D), Registered(S,C,Y), Course(C,N), N ≥300, Y≥1995.
1. Filling the Buckets

\[ V_1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \]
\[ \text{Course}(\text{course}, \text{number}), \text{number} \geq 500, \text{year} \geq 1992 \]

\[ V_2(\text{student}, \text{dept}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \]
\[ \text{Enrolled}(\text{student}, \text{dept}) \]

\[ V_3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \text{year} \leq 1990 \]

\[ V_4(\text{student}, \text{course}, \text{number}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \]
\[ \text{Course}(\text{course}, \text{number}), \text{Enrolled}(\text{student}, \text{dept}), \text{number} \leq 100 \]

\[ q(S, D) :- \]
\[ \text{Enrolled}(S, D), \text{Registered}(S, C, Y), \text{Course}(C, N), N \geq 300, Y \geq 1995 \]

\[ V_2(S, D, C') \]

\[ V_4(S, C', N') \]
1. Filling the Buckets

\[ V_1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \]
\[ \text{Course}(\text{course}, \text{number}), \text{number} \geq 500, \text{year} \geq 1992 \]

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\[ \text{Enrolled}(\text{student}, \text{dept}) \]

\[ V_3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \text{year} \leq 1990 \]

\[ V_4(\text{student}, \text{course}, \text{number}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \]
\[ \text{Course}(\text{course}, \text{number}), \text{Enrolled}(\text{student}, \text{dept}), \text{number} \leq 100 \]

\[ q(S,D) :- Enrolled(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995 \]

\[ V_2(S,D,C'), V_1(S,N',Y) \]
\[ V_4(S,C',N') V_2(S,D',C) \]
\[ V_4(S,C,N') \]
1. Filling the Buckets

\[
V_1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \\
\text{Course}(\text{course}, \text{number}), \text{number} \geq 500, \text{year} \geq 1992
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V_2(\text{student}, \text{dept}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \\
\text{Enrolled}(\text{student}, \text{dept})
\]

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V_3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \text{year} \leq 1990
\]

\[
V_4(\text{student}, \text{course}, \text{number}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \\
\text{Course}(\text{course}, \text{number}), \text{Enrolled}(\text{student}, \text{dept}), \text{number} \leq 100
\]

\[
q(S,D) :- \\
\text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995
\]

\[
V_2(S,D,C') \quad V_1(S,N',Y) \quad V_1(S',N,Y')
\]

\[
V_4(S,C',N') \quad V_2(S,D',C) \quad V_4(S,C,N')
\]
2. Checking Containment

\[ q(S,D) :\text{ Enrolled}(S,D), \text{ Registered}(S,C,Y), \text{ Course}(C,N), N \geq 300, Y \geq 1995 \]

\[
\begin{align*}
V_2(S, D, C') & \quad V_1(S, N', Y) & \quad V_1(S', N, Y') \\
V_4(S, C', N') & \quad V_2(S, D', C) & \quad V_4(S, C, N')
\end{align*}
\]
2. Checking Containment

$q(S,D) :- \text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995$

$V2(S,D,C') \quad V1(S,N',Y) \quad V1(S',N,Y')$

$V4(S,C',N') \quad V2(S,D',C)$

$V4(S,C,N')$
2. Checking Containment

\[ q(S,D) :- \text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995 \]

\[ V2(S,D,C') \quad V1(S,N',Y) \quad V1(S',N,Y') \]

\[ V4(S,C',N') \quad V2(S,D',C) \quad V4(S,C,N') \]

\[ q'(S,D) :- V2(S,D,C'), V1(S,N',Y), V1(S',N,Y'), N \geq 300, Y \geq 1995 \]
2. Checking Containment

\[ q(S,D) :- \text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995 \]

\[ \begin{align*}
V2(S,D,C') & \quad V1(S,N',Y) \quad V1(S',N,Y') \\
V4(S,C',N') & \quad V2(S,D',C) \\
& \quad V4(S,C,N')
\end{align*} \]

\[ q'(S,D) :- V2(S,D,C'), V1(S,N',Y), V1(S',N,Y'), N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :- V2(S,D,C'), V1(S,N,Y), N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :- V2(S,D,C'), V1(S,N,Y), N \geq 300, Y \geq 1995 \]
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\[ V2(S,D,C') \ V1(S,N',Y) \ V1(S',N,Y') \]

\[ V4(S,C',N') \ V2(S,D',C) \ V4(S,C,N') \]

\[ q'(S,D) :\ V2(S,D,C'), \ V1(S,N',Y), \ V1(S',N,Y'), \ N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :\ V2(S,D,C'), \ V1(S,N,Y), \ N \geq 300, Y \geq 1995 \]

\[ \text{Registered}(S,C',Y) \land \text{Enrolled}(S,D) \land \]

\[ V1(\text{student},\text{number},\text{year}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ Course(\text{course},\text{number}), \]

\[ \text{number} \geq 500, \ \text{year} \geq 1992 \]

\[ V2(\text{student},\text{dept},\text{course}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ \text{Enrolled}(\text{student},\text{dept}) \]

\[ V3(\text{student},\text{course}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ \text{year} \leq 1990 \]

\[ V4(\text{student},\text{course},\text{number}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ Course(\text{course},\text{number}), \]

\[ \text{Enrolled}(\text{student},\text{dept}), \ \text{number} \leq 100 \]
2. Checking Containment

\[ q(S,D) :\quad \text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995 \]

\[ V2(S,D,C') \quad V1(S,N',Y) \quad V1(S',N,Y') \]

\[ V4(S,C',N') \quad V2(S,D',C) \quad V4(S,C,N') \]

\[ q'(S,D) :\quad V2(S,D,C'), \ V1(S,N',Y), \ V1(S',N,Y'), N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :\quad V2(S,D,C'), \ V1(S,N,Y), \ N \geq 300, Y \geq 1995 \]

\[ \text{Registered}(S,C',Y) \land \text{Enrolled}(S,D) \land \]

\[ \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1992 \land \]

\[ V1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{Course}(\text{course}, \text{number}), \ \text{number} \geq 500, \ \text{year} \geq 1992 \]

\[ V2(\text{student}, \text{dept}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{Enrolled}(\text{student}, \text{dept}) \]

\[ V3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{year} \leq 1990 \]

\[ V4(\text{student}, \text{course}, \text{number}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{Course}(\text{course}, \text{number}), \ \text{Enrolled}(\text{student}, \text{dept}), \ \text{number} \leq 100 \]
2. Checking Containment

\[ q(S,D) :\text{-} \quad \text{Enrolled}(S,D), \ \text{Registered}(S,C,Y), \ \text{Course}(C,N), \ N \geq 300, \ Y \geq 1995 \]

\[ V2(S,D,C') \quad V1(S,N',Y) \quad V1(S',N,Y') \]

\[ V4(S,C',N') \quad V2(S,D',C) \quad V4(S,C,N') \]

\[ q'(S,D) :\quad V2(S,D,C'), \ V1(S,N',Y), \ V1(S',N,Y'), \ N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :\quad V2(S,D,C'), \ V1(S,N,Y), \ N \geq 300, Y \geq 1995 \]

\[ \text{Registered}(S,C',Y) \land \text{Enrolled}(S,D) \land \]

\[ \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1992 \land \]

\[ N \geq 300 \land Y \geq 1995 \rightarrow \]

\[ V1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{Course}(\text{course}, \text{number}), \]

\[ \text{number} \geq 500, \ \text{year} \geq 1992 \]

\[ V2(\text{student}, \text{dept}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{Enrolled}(\text{student}, \text{dept}) \]

\[ V3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{year} \leq 1990 \]

\[ V4(\text{student}, \text{course}, \text{number}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \ \text{Course}(\text{course}, \text{number}), \]

\[ \text{Enrolled}(\text{student}, \text{dept}), \ \text{number} \leq 100 \]
2. Checking Containment

\[ q(S,D) :\text{-} \quad \text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), N \geq 300, Y \geq 1995 \]

\[
\begin{align*}
V2(S,D,C') & \quad V1(S,N',Y) & \quad V1(S',N,Y') \\
V4(S,C',N') & \quad V2(S,D',C) & \quad V4(S,C,N')
\end{align*}
\]

\[ q'(S,D) :\text{-} \quad V2(S,D,C'), \quad V1(S,N',Y), \quad V1(S',N,Y'), \quad N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :\text{-} \quad V2(S,D,C'), \quad V1(S,N,Y), \quad Y \geq 1995 \]

Registered(S,C',Y) \land \text{Enrolled}(S,D) \land

Registered(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1992 \land

N \geq 300 \land Y \geq 1995 \Rightarrow

\text{Enrolled}(S,D) \land \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1995 \Rightarrow

\]

\[ V1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}),\text{Course}(\text{course}, \text{number}), \text{number} \geq 500, \text{year} \geq 1992 \]

\[ V2(\text{student}, \text{dept}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}),\text{Enrolled}(\text{student}, \text{dept}) \]

\[ V3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}),\text{year} \leq 1990 \]

\[ V4(\text{student}, \text{course}, \text{number}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}),\text{Course}(\text{course}, \text{number}),\text{Enrolled}(\text{student}, \text{dept}),\text{number} \leq 100 \]
2. Checking Containment

\[ q(S,D) :\quad \text{Enrolled}(S,D),\ \text{Registered}(S,C,Y),\ \text{Course}(C,N),\ N \geq 300,\ Y \geq 1995 \]

\[ \text{V1}(S,N',Y), \quad \text{V1}(S',N,Y') \]
\[ \text{V2}(S,D',C), \quad \text{V4}(S,C',N') \]

\[ q'(S,D) :\quad \text{V2}(S,D,C'),\ \text{V1}(S,N',Y),\ \text{V1}(S',N,Y'),\ N \geq 300, Y \geq 1995 \]

\[ q'(S,D) :\quad \text{V2}(S,D,C'),\ \text{V1}(S,N,Y),\ Y \geq 1995 \]

\[ \text{Registered}(S,C',Y) \land \text{Enrolled}(S,D) \land \]
\[ \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1992 \land \]
\[ N \geq 300 \land Y \geq 1995 \rightarrow \]
\[ \text{Enrolled}(S,D) \land \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1995 \rightarrow \]
\[ \text{Enrolled}(S,D) \land \text{Registered}(S,C,Y) \land \text{Course}(C,N) \land N \geq 300 \land Y \geq 1995 \]

\[ \text{V1}(\text{student},\text{number},\text{year}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}),\ \text{Course}(\text{course},\text{number}),\ \text{number} \geq 500,\ \text{year} \geq 1992 \]
\[ \text{V2}(\text{student},\text{dept},\text{course}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}),\ \text{Enrolled}(\text{student},\text{dept}) \]
\[ \text{V3}(\text{student},\text{course}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}),\ \text{year} \leq 1990 \]
\[ \text{V4}(\text{student},\text{course},\text{number}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}),\ \text{Course}(\text{course},\text{number}),\ \text{Enrolled}(\text{student},\text{dept}),\ \text{number} \leq 100 \]
2. Checking Containment

\[ q(S,D) :\sim \text{Enrolled}(S,D), \text{Registered}(S,C,Y), \text{Course}(C,N), \ N \geq 300, \ Y \geq 1995 \]
\[ V2(S,D,C') \quad V1(S,N',Y) \quad V1(S',N,Y') \]
\[ V4(S,C',N') \quad V2(S,D',C) \quad V4(S,C,N') \]

\[ q'(S,D) :\sim V2(S,D,C'), \ V1(S,N,Y), \ V1(S',N,Y'), \ N \geq 300, \ Y \geq 1995 \]
\[ q'(S,D) :\sim V2(S,D,C'), \ V1(S,N,Y), \ Y \geq 1995 \]

\[ \text{Registered}(S,C',Y) \land \text{Enrolled}(S,D) \land \]
\[ \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1992 \land \]
\[ N \geq 300 \land Y \geq 1995 \rightarrow \]
\[ \text{Enrolled}(S,D) \land \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1995 \rightarrow \]
\[ \text{Enrolled}(S,D) \land \text{Registered}(S,C,Y) \land \text{Course}(C,N) \land N \geq 300 \land Y \geq 1995 \]

\[ \Rightarrow q' \subseteq q \quad \text{(and } q' \text{ is a maximally-contained rewriting of } q) \]

\[ V1(\text{student},\text{number},\text{year}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ \text{Course}(\text{course},\text{number}), \ \text{number} \geq 500, \ \text{year} \geq 1992 \]
\[ V2(\text{student},\text{dept},\text{course}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ \text{Enrolled}(\text{student},\text{dept}) \]
\[ V3(\text{student},\text{course}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ \text{year} \leq 1990 \]
\[ V4(\text{student},\text{course},\text{number}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \ \text{Course}(\text{course},\text{number}), \ \text{Enrolled}(\text{student},\text{dept}), \ \text{number} \leq 100 \]
Outline

• Database Theory Background
  • Datalog
  • Query Containment

• Dimensions of Data Integration
  • Architecture
  • Content Descriptions
    • Global-as-View
    • Local-as-View:
      • Bucket Algorithm
      • Inverse-Rules Algorithm
  • Source Capabilities: Recursive Rewritings
  • Local Completeness Information
Inverse-Rules Algorithm

Idea: Construct an equivalent logic program whose evaluation yields the answer to the query

- The antecedent of the query and views is in term of mediator predicates
- Would like to have source predicates in antecedent so that program can be evaluated

⇒ Invert the rules
(simply by using standard logical manipulations)

[Duschka+1997]
The Inverse-Rules Algorithm: Example

\( V_1(\text{dept}, \text{course}) \rightarrow \text{Enrolled}(\text{student}, \text{dept}) \wedge \text{Registered}(\text{student}, \text{course}) \)

\( \forall D, C \ [V_1(D, C) \rightarrow \exists S [ e(S, D) \wedge r(S, C)]] \)

\begin{align*}
\equiv & \neg V_1(D, C) \vee [e(f(D, C), D) \wedge r(f(D, C), C)] \\
\equiv & [\neg V_1(D, C) \vee e(f(D, C), D)] \wedge [\neg V_1(D, C) \vee r(f(D, C), C)] \\
\equiv & [V_1(D, C) \rightarrow e(f(D, C), D)] \wedge [V_1(D, C) \rightarrow r(f(D, C), C)] \\
\equiv & e(f(D, C), D) \leftarrow V_1(D, C) \\
r(f(D, C), C) \leftarrow V_1(D, C)
\end{align*}
The Inverse-Rules Algorithm: Example

\[ q(D) \leftarrow \text{Enrolled}(S,D) \land \text{Registered}(S,"DB") \]
\[ v1(D,C) \rightarrow \text{Enrolled}(S,D) \land \text{Registered}(S,C) \]

\[ q(D) \leftarrow \text{Enrolled}(S,D) \land \text{Registered}(S,"DB") \]
\[ \text{Enrolled}(f(D,C),D) \leftarrow v1(D,C) \]
\[ \text{Registered}(f(D,C),C) \leftarrow v1(D,C) \]
\[ q(D) \leftarrow v1(D,"DB") \]

\[ \text{Ext}(v1) = \{("CS", "DB"), ("EE", "DB"), ("CS", "AI")\} \]
\[ \text{Ext}(q) = \{("CS"), ("EE")\} \]
Outline

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- Source Capabilities: Recursive Rewritings
Modeling Source Capabilities

Negative capabilities:
• A web-site may require certain inputs (in an HTML form) to answer a query
• Need to consider only valid query execution plans

Positive capabilities:
• A source may be database (understands SQL)
• Need to decide the placement of operations according to capabilities

Problem: how to describe and exploit source capabilities
Negative Capabilities: Binding Patterns

Sources:

\[ \text{AAAI}	ext{db}^f (X) \rightarrow \text{AAAI}	ext{Papers}(X) \]
\[ \text{CitationDB}^b(X,Y) \rightarrow \text{Cites}(X,Y) \]
\[ \text{AwardDB}^b(X) \rightarrow \text{AwardPaper}(X) \]

Query: find all the award winning papers:
\[ q(X) \leftarrow \text{AwardPaper}(X) \]
Recursive Rewritings

\[ q(X) \leftarrow \text{AwardPaper}(X) \]

- Problem: *Unbounded* union of conjunctive queries

\[ q_1(X) \leftarrow \text{AAAIdb}(X), \text{AwardDB}(X) \]
\[ q_1(X) \leftarrow \text{AAAIdb}(X_1), \text{CitationDB}(X_1, X), \text{AwardDB}(X) \]
\[ \ldots \]
\[ q_1(X) \leftarrow \text{AAAIdb}(X_1), \text{CitationDB}(X_1, X_2), \ldots, \text{CitationDB}(X_n, X), \text{AwardDB}(X) \]

- Solution: Recursive Rewriting

\[ \text{papers}(X) \leftarrow \text{AAAIdb}(X) \]
\[ \text{papers}(X) \leftarrow \text{papers}(Y), \text{CitationDB}(Y, X) \]
\[ q'(X) \leftarrow \text{papers}(X), \text{AwardDB}(X) \]
Inverse-Rules Algorithm
Binding Patterns

Sources:

\[ AAAIdb^f(X) \rightarrow AAAIPapers(X) \]
\[ CitationDB^{bf}(X,Y) \rightarrow Cites(X,Y) \]
\[ AwardDB^b(X) \rightarrow AwardPaper(X) \]

Query: find all the award winning papers:
\[ q(X) \leftarrow AwardPaper(X) \]
Inverse-Rules Algorithm

Inverted Rules:

\begin{align*}
\text{AAAIpapers}(X) & \leftarrow \text{AAAldb}(X) \\
\text{Cites}(X,Y) & \leftarrow \text{dom}(X) \land \text{CitationDB}(X,Y) \\
\text{AwardPaper}(X) & \leftarrow \text{dom}(X) \land \text{AwardDB}(X)
\end{align*}

Domain Rules:

\begin{align*}
\text{dom}(Y) & \leftarrow \text{dom}(X) \land \text{CitationDB}(X,Y) \\
\text{dom}(X) & \leftarrow \text{AAAldb}(X)
\end{align*}

Query:

\begin{align*}
q(X) & \leftarrow \text{AwardPaper}(X)
\end{align*}
Inverse-Rules Algorithm
Inverse + Domain Rules (2)

Simplyfing the program:

\[ q(X) \leftarrow \text{dom}(X) \land \text{AwardDB}(X) \]
\[ \text{dom}(Y) \leftarrow \text{dom}(X) \land \text{CitationDB}(X,Y) \]
\[ \text{dom}(X) \leftarrow \text{AAAIdb}(X) \]
Summary

- Dimensions of Data Integration
  - Architecture
  - Content Descriptions
    - Global-as-View
    - Local-as-View:
      - Bucket Algorithm
      - Inverse-Rules Algorithm
  - Source Capabilities: Recursive Rewritings