Data Integration

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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

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

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

\[
\forall \text{Buyer, Seller, Price} \left[ \exists \text{Product} \left[ \text{person(Buyer, “Los Angeles”) \land purchase(Buyer, Seller, Product, Price) \land Price > 10000} \right] \rightarrow \text{big-LA-buyers(Buyer, Seller, Price)} \right]
\]
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

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

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

\[
\text{path}(X, Y) \leftarrow \text{arc}(X, Y)
\]

\[
\text{path}(X, Y) \leftarrow \text{path}(X, Z), \text{path}(Z, Y).
\]

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

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

\begin{center}
\begin{tikzpicture}[scale=0.8]
\node (a) at (0,0) {a};
\node (b) at (1,1) {b};
\node (c) at (1,-1) {c};
\node (d) at (2,0) {d};
\node (e) at (3,0) {e};
\draw (a) -- (b);
\draw (a) -- (c);
\draw (b) -- (d);
\draw (c) -- (d);
\draw (d) -- (e);
\end{tikzpicture}
\end{center}
Recursion in Datalog

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

**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

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

**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)
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 gets the new tuples: (a,d), (b,e), (c,e)

Iteration #2: path gets the new tuple: (a,e)
Recursion in Datalog

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

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

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

\[
\begin{align*}
\text{path} & : \{}
\end{align*}
\]

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:
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      • 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**: $q' = q \iff q' \subseteq q \wedge q \subseteq q'$

- **Complexity of Query Containment**
  - Conjunctive Queries (CQ), Union of CQs: NP-complete
  - CQ with comparisons (=, <, $\neq$): $\Pi^p_2$-complete
  - FOL, recursive queries: Undecidable
Query Containment for Conjunctive Queries and Datalog

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.
Query Containment Example

q1 is the CQ: \( \text{path}(X,Y) :\text{-} \text{arc}(X,Z) \land \text{arc}(Z,W) \land \text{arc}(W,Y) \)

q2 is the value of path in the following recursive Datalog program:
- \( \text{path}(X,Y) :\text{-} \text{arc}(X,Y) \)
- \( \text{path}(X,Y) :\text{-} \text{path}(X,Z) \land \text{path}(Z,Y) \)

Intuitively, \( q1 \) = paths of length 3; \( q2 \) = 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 \( \text{path}(0, 3) \).
2. Compute \( q2(D) \)  
   \( \text{Ext}(\text{path}) = \{ (0,1), (1,2), (2,3), (0,2), (1,3), (0,3) \} \)
3. Since frozen head of \( q1 \), \( \text{path}(0, 3) \), 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 (\(\land, \lor, \lnot\)), description logics, …

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

![Diagram of Materialized Architecture: Data Warehouse]

- User
  - Application
  - Data Extraction
    - Wrapper
      - Data Source
    - Wrapper
      - Data Source
    - Wrapper
      - Data Source
  - Data Warehouse
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)
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
Answering queries using views

Given query $q$ and view definitions $V=\{V_1…V_n\}$

- $q'$ 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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Global-as-View (GAV)

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

MovieActor(title, actor) ← DB1(id, title, actor, year)
MovieActor(title, actor) ← DB2(title, director, actor, year)
MovieReview(title, review) ← DB1(id, title, actor, year) ∩ DB3(id, review)
Query Reformulation in GAV

Query reformulation = rule unfolding+simplification

Query: Find reviews for ‘DeNiro’ movies

\[
q(\text{title,review}) \leftarrow \text{MovieActor(title,'DeNiro'),}
\]
\[
\quad \text{MovieReview(title,review)}
\]

1. \[
q'(\text{title,review}) \leftarrow \text{DB1(id,title,'DeNiro',year), DB1(id,title,actor,year'), DB3(id,review)}
\]

Redundant

2. \[
q'(\text{title,review}) \leftarrow \text{DB2(title,director,'DeNiro',year), DB1(id,title,actor, year'), DB3(id,review)}
\]

Redundant wrt 1
Local-as-View (LAV)

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

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

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

Query: Reviews for comedies produced after 1950
\[ q(title, review) :- \text{Movie}(title, year, director, 'Comedy'), year \geq 1950, \text{MovieReview}(title, review) \]

Reformulated query:
\[ q'(title, review) :- V1(title, year, director), V2(title, review) \]

\[ V1(title, year, director) \rightarrow \text{Movie}(title, year, director, genre) \land \text{American}(director) \land year \geq 1960 \land genre = 'Comedy' \]
\[ V2(title, review) \rightarrow \text{Movie}(title, year, director, genre) \land year \geq 1990 \land \text{MovieReview}(title, review) \]
GAV vs. LAV

- Not modular
  - Addition of new sources changes the mediated schema
- Can be awkward to write mediated schema without loss of information
- Query reformulation easy
  - reduces to view unfolding (polynomial)
  - Can build hierarchies of mediated schemas
- Best when
  - Few, stable, data sources
  - well-known to the mediator (e.g. corporate integration)
    - Garlic, TSIMMIS, HERMES

- Modular--adding new sources is easy
- Very flexible--power of the entire query language available to describe sources
- Reformulation is hard
  - Involves answering queries only using views (can be intractable)
- Best when
  - Many, relatively unknown data sources
  - possibility of addition/deletion of sources
    - Information Manifold, InfoMaster, Emerac
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Query Reformulation in LAV

The Bucket Algorithm

[Levy+1996]

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

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

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

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

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

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

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

User Query (using mediator relations):

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

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

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

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

V4\((\text{student, course, number}) \rightarrow \text{Registered(}\text{student, course, year}), \text{Course(}\text{course, number}), \text{Enrolled(}\text{student, dept}), \text{number} \leq 100\)

\[ q(S,D) :- \]

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

V2 \((S, D, C')\)

V4 \((S, C', N')\)
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

q(S,D) :-
Enrolled(S,D), Registered(S,C,Y), Course(C,N), N ≥ 300, Y ≥ 1995
V2(S,D,C') V1(S,N',Y)
V4(S,C',N') V2(S,D',C)
V4(S,C,N')
1. Filling the Buckets

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

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

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

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

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

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

\[ V_4(S,C',N') \quad V_2(S,D',C) \]

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

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

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

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

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

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

\[ V_2(S,D,C') \quad V_1(S,N',Y) \quad V_1(S',N,Y') \quad V_4(S,C',N') \quad V_2(S,D',C) \quad V_4(S,C,N') \]

\[ q'(S,D) :\ - \ V_2(S,D,C'), \ V_1(S,N',Y), \ V_1(S',N,Y'), \ N \geq 300, Y \geq 1995 \]
2. Checking Containment

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

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

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

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

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

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

V1(student, number, year) \rightarrow Registered(student, course, year), Course(course, number), number \geq 500, year \geq 1992

V2(student, dept, course) \rightarrow Registered(student, course, year), Enrolled(student, dept)

V3(student, course) \rightarrow Registered(student, course, year), year \leq 1990

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

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

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

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

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

\[ \text{Registered}(S,C',Y) \land \text{Enrolled}(S,D) \land \text{Registered}(S,C'',Y) \land \text{Course}(C'',N) \land N \geq 500 \land Y \geq 1992 \land V1(\text{student},\text{number},\text{year}) \rightarrow \text{Registered}(\text{student},\text{course},\text{year}), \text{Course}(\text{course},\text{number}), \text{number} \geq 500, \text{year} \geq 1992 \]

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

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

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

\begin{align*}
q(S,D) & : \text{-} \ Enrolled(S,D), \ Registered(S,C,Y), \ Course(C,N), \ N \geq 300, \ Y \geq 1995 \\
& \quad \text{V2}(S,D,C') \quad \text{V1}(S,N',Y) \quad \text{V1}(S',N',Y') \\
& \quad \text{V4}(S,C',N') \quad \text{V2}(S,D',C) \\
& \quad \text{V4}(S,C,N')
\end{align*}

\begin{align*}
q'(S,D) & : \text{-} \ V2(S,D,C'), \ V1(S,N',Y), \ V1(S',N,Y'), \ N \geq 300, Y \geq 1995 \\
q'(S,D) & : \text{-} \ V2(S,D,C'), \ V1(S,N,Y), \ N \geq 300, Y \geq 1995
\end{align*}

\begin{align*}
\text{Registered}(S,C',Y) & ^ \ \text{Enrolled}(S,D) ^ \\
\text{Registered}(S,C''',Y) & ^ \ \text{Course}(C''',N) ^ \ N \geq 500 ^ \ Y \geq 1992 ^ \\
N \geq 300 ^ \ Y \geq 1995 & \rightarrow
\end{align*}

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

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

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

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

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

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

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

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

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

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

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

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

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

Registered(S,C',Y) ^ Enrolled(S,D) ^
Registered(S,C'',Y) ^ Course(C'',N) ^ N \geq 500 ^ Y \geq 1992 ^
N \geq 300 ^ Y \geq 1995 \rightarrow

Enrolled(S,D) ^ Registered(S,C'',Y) ^ Course(C'',N) ^ N \geq 500 ^ Y \geq 1995

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

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

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

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

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

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

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

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\]

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

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

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

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

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

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

\[ \text{V4(}\text{student,course,number)} \rightarrow \text{Registered(}\text{student,course,year)}, \text{Course(}\text{course,number)}, \text{Enrolled(}\text{student,dept)}, \text{number} \leq 100 \]
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)
The Inverse-Rules Algorithm: Example

\[ V1(\text{dept, course}) \rightarrow \text{Enrolled(student, dept)} \land \text{Registered(student, course)} \]

\[ \forall D, C [v1(D, C) \rightarrow \exists S [ e(S, D) \land r(S, C)]] \]
\[ \equiv \neg v1(D, C) \lor [e(f(D, C), D) \land r(f(D, C), C)] \]
\[ \equiv [\neg v1(D, C) \lor e(f(D, C), D)] \land [\neg v1(D, C) \lor r(f(D, C), C)] \]
\[ \equiv [v1(D, C) \rightarrow e(f(D, C), D)] \land [v1(D, C) \rightarrow r(f(D, C), C)] \]
\[ \equiv e(f(D, C), D) \leftarrow v1(D, C) \]
\[ r(f(D, C), C) \leftarrow v1(D, C) \]
The Inverse-Rules Algorithm: Example

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

\[ v_1(D,C) \rightarrow \text{Enrolled}(S,D) \land \text{Registered}(S,C) \]

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

\[ \text{Enrolled}(f(D,C),D) \leftarrow v_1(D,C) \]

\[ \text{Registered}(f(D,C),C) \leftarrow v_1(D,C) \]

\[ q(D) \leftarrow v_1(D,\text{"DB"}) \]

\[ \text{Ext}(v_1) = \{ (\text{"CS"}, \text{"DB"}), (\text{"EE"}, \text{"DB"}), (\text{"CS"}, \text{"AI"}) \} \]

\[ \text{Ext}(q) = \{ (\text{"CS"}), (\text{"EE"}) \} \]
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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:

\[ \text{AAAIdb}^f (X) \rightarrow \text{AAAI Papers}(X) \]
\[ \text{CitationDB}^{bf}(X,Y) \rightarrow \text{Cites}(X,Y) \]
\[ \text{AwardDB}^b(X) \rightarrow \text{Award Paper}(X) \]

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

q(X) ← AwardPaper(X)

• Problem: *Unbounded* union of conjunctive queries

q1(X) ← AAAIdb(X), AwardDB(X)
q1(X) ← AAAIdb(X1), CitationDB(X1,X), AwardDB(X)
...
q1(X) ← AAAIdb(X1), CitationDB(X1,X2), …, CitationDB(Xn,X), AwardDB(X)

• Solution: Recursive Rewriting

papers(X) ← AAAIdb(X)
papers(X) ← papers(Y), CitationDB(Y,X)
q'(X) ← papers(X), AwardDB(X)

AAAIdbf(X) → AAAIPapers(X)
CitationDBbf(X,Y) → Cites(X,Y)
AwardDBbf(X) → AwardPaper(X)
Inverse-Rules Algorithm Binding Patterns

Sources:

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

Query: find all the award winning papers:

\[ q(X) \leftarrow \text{AwardPaper}(X) \]
Inverse-Rules Algorithm
Inverse + Domain Rules (1)

Inverted Rules:

\begin{align*}
\text{AAAIPapers}(X) & \leftarrow \text{AAAIdb}(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{AAAIdb}(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
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    • Local-as-View:
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      • Inverse-Rules Algorithm
  • Source Capabilities: Recursive Rewritings