



Data Integration

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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

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

head

body

Datalog

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

big-LA-buyers(Buyer, Seller, Price) :-

head

person(Buyer, "Los Angeles"),
purchase(Buyer, Seller, Product, Price),
Price > 10000.

body

Datalog

\forall Buyer, Seller, Price

antecedent

[\exists Product [person(Buyer, "Los Angeles") \wedge
purchase(Buyer, Seller, Product, Price) \wedge
Price > 10000)]

First-Order Logic

\rightarrow big-LA-buyers(Buyer, Seller, Price)]

consequent

Conjunctive Queries and Views

```
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
```

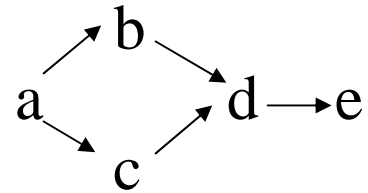
big-LA-buyers(Buyer, Seller, Price) :-
 person(Buyer, "Los Angeles"),
 purchase(Buyer, Seller, Product, Price),
 Price > 10000.

Datalog rule ~ view definition

Rule body ~ select-from-where construct of SQL

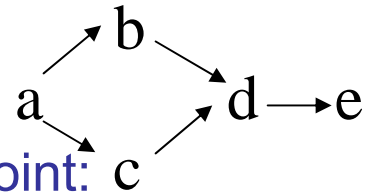
Recursion in Datalog

```
path(X, Y) :- arc(X, Y)
path(X, Y) :- path(X, Z), path(Z, Y).
```



Recursion in Datalog

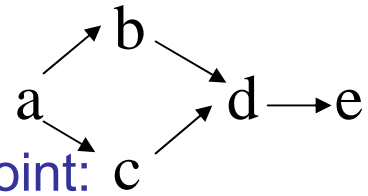
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Semantics: evaluate the rules bottom-up until a fixpoint:

Recursion in Datalog

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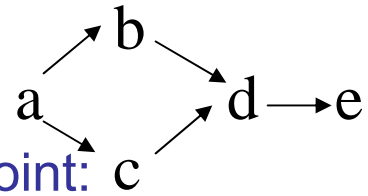


Semantics: evaluate the rules bottom-up until a fixpoint:

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

Recursion in Datalog

```
path(X, Y) :- arc(X, Y)
path(X, Y) :- path(X, Z), path(Z, Y).
```



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

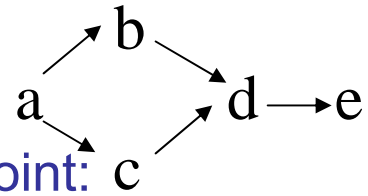
Iteration #0: arc: {(a,b), (a,c), (b,d), (c,d), (d,e)}

path: {}

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

Recursion in Datalog

```
path(X, Y) :- arc(X, Y)
path(X, Y) :- path(X, Z), 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)}

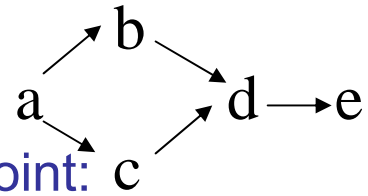
path: {}

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

```
path(X, Y) :- arc(X, Y)
path(X, Y) :- path(X, Z), path(Z, Y).
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Semantics: evaluate the rules bottom-up until a fixpoint:

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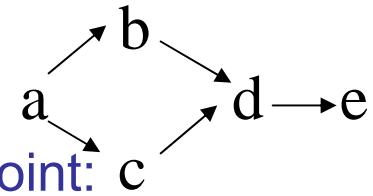
Iteration #1: path: {(a,b), (a,c), (b,d), (c,d), (d,e)}

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

```
path(X, Y) :- arc(X, Y)
path(X, Y) :- path(X, Z), 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)

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

Iteration #4: Nothing changes => stop.



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 - Local Completeness Information



Query Containment

- *Query Containment:* $q' \subseteq q$
 - $\forall D \ q'(D) \subseteq q(D)$
 - $q' \models q$
- *Query Equivalence:* $q' = q \leftrightarrow q' \subseteq q \wedge q \subseteq q'$
- **Complexity of Query Containment**
 - Conjunctive Queries (CQ), Union of CQs: NP-complete
 - CQ with comparisons ($=, <, \neq$): Π_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: $\text{path}(X,Y) \text{ :- arc}(X,Z) \ \& \ \text{arc}(Z,W) \ \& \ \text{arc}(W,Y)$

q2 is the value of path in the following recursive Datalog program:

$\text{path}(X,Y) \text{ :- arc}(X,Y)$

$\text{path}(X,Y) \text{ :- path}(X,Z) \ \& \ \text{path}(Z,Y)$

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 $q1 \subseteq q2$



Outline

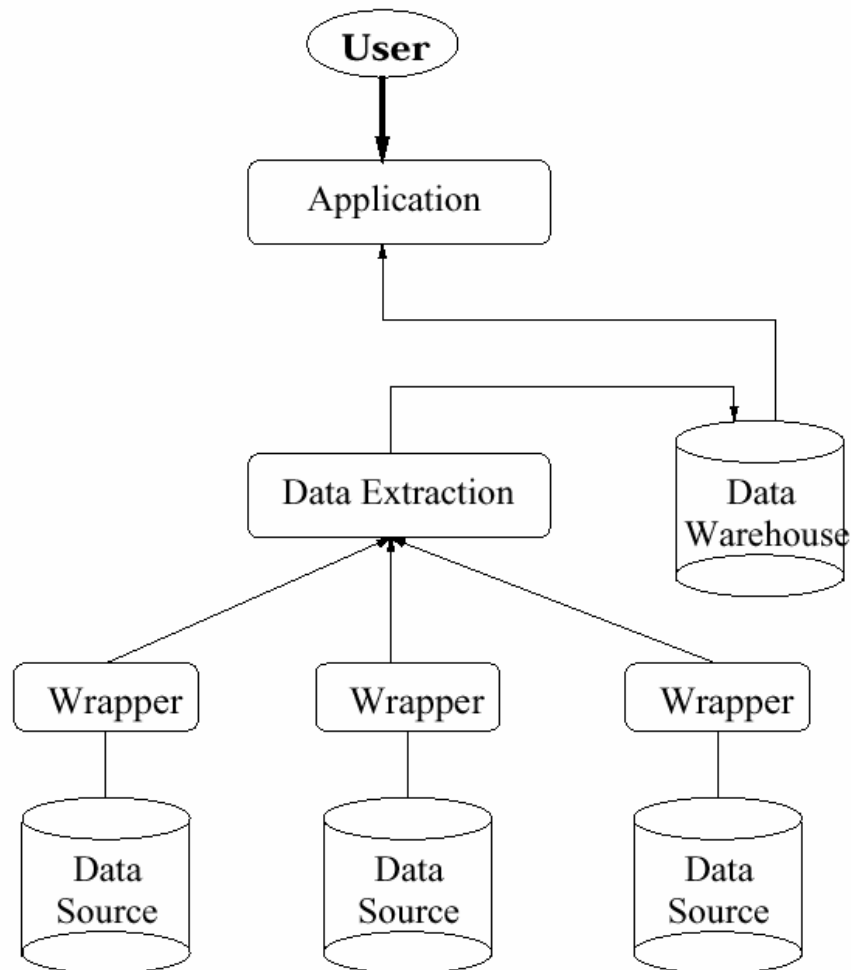
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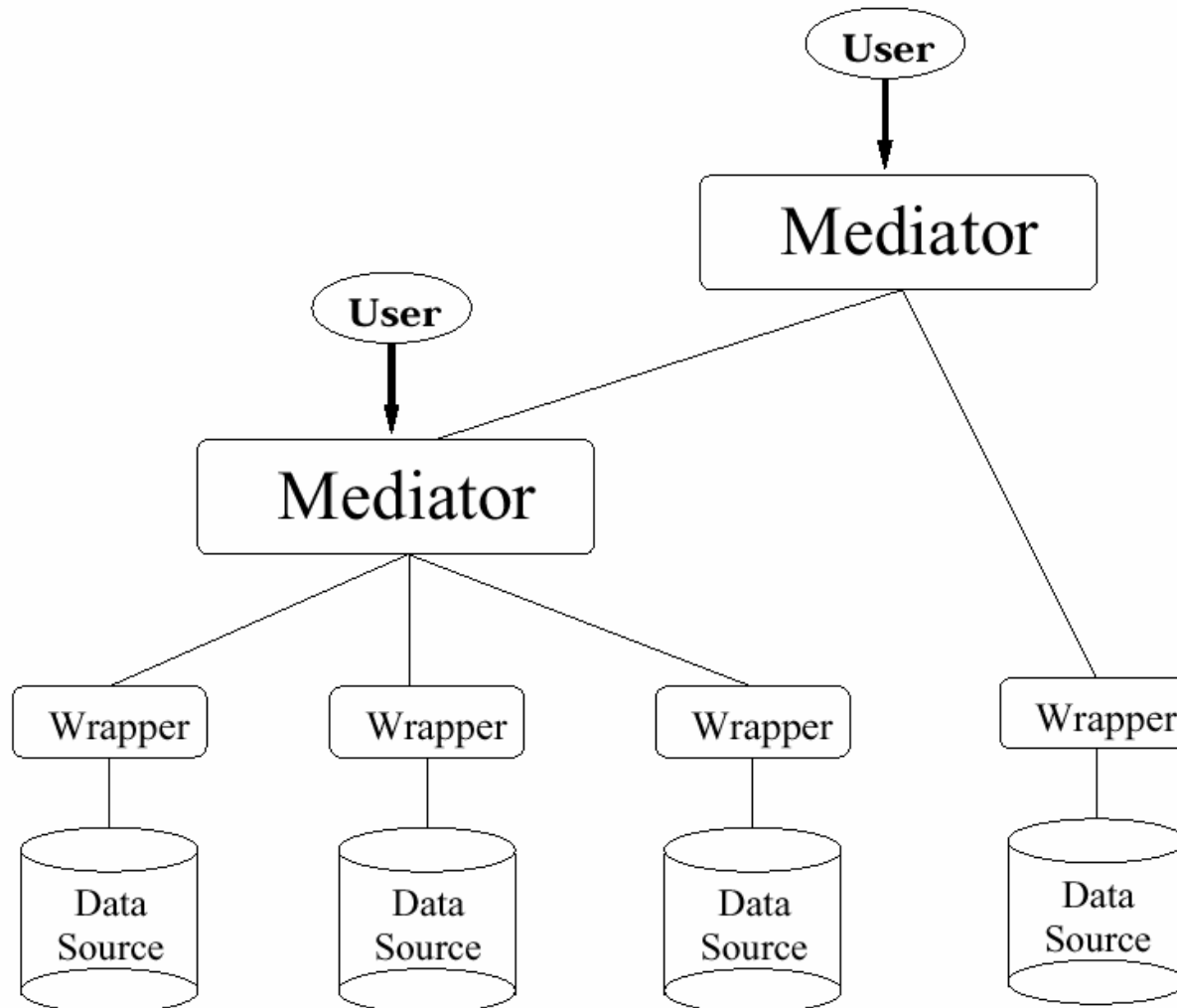
Principal Dimensions of Data Integration

- 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 (\wedge, \vee, \neg), description logics, ...
- Types of Sources
 - Structured (DB's) vs. semi-structured (Web)
 - Source capabilities: positive and negative

Materialized Architecture: Data Warehouse

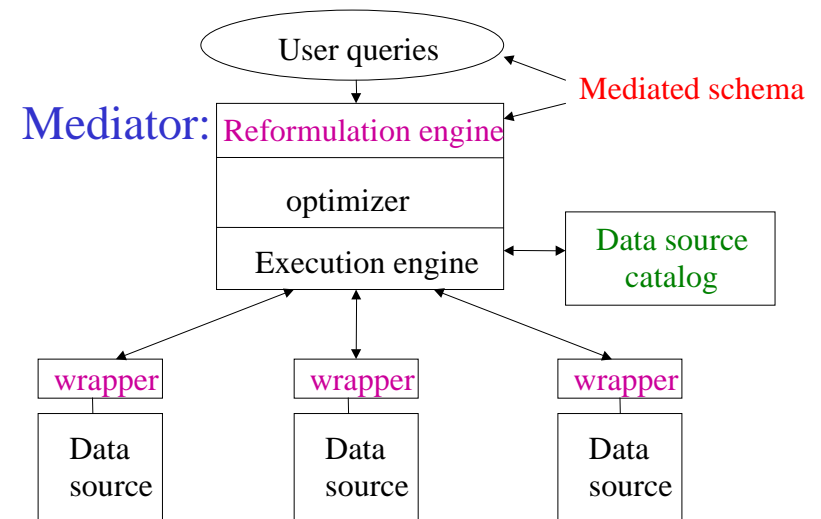


Virtual Architecture: Mediator



Virtual Integration Architecture

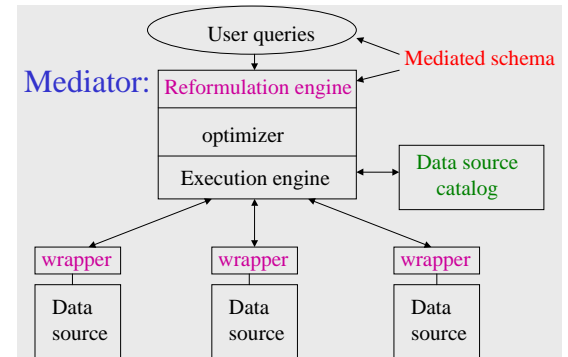
- Leave the data in the sources
- When a query comes in:
 - Determine the relevant sources to the query
 - Break down the query into sub-queries for the sources
 - Get the answers from the sources, and combine them appropriately
- Data is fresh. Approach scalable
- Issues:
 - Relating Sources & Mediator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



Answering queries using views

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

- 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) \leftarrow
DB1(id,title,actor,year)

MovieActor(title,actor) \leftarrow
DB2(title,director,actor,year)

MovieReview(title, review) \leftarrow
DB1(id,title,actor,year) \wedge DB3(id,review)



Query Reformulation in GAV

Query reformulation = rule unfolding+simplification

Query: *Find reviews for 'DeNiro' movies*

$q(\text{title}, \text{review}) :- \text{MovieActor}(\text{title}, \text{'DeNiro'}),$
 $\text{MovieReview}(\text{title}, \text{review})$

1. $q'(\text{title}, \text{review}) :- \text{DB1}(\text{id}, \text{title}, \text{'DeNiro'}, \text{year}),$
 ~~$\text{DB1}(\text{id}, \text{title}, \text{actor}, \text{year}')$~~ , $\text{DB3}(\text{id}, \text{review})$

Redundant

~~2. $q'(\text{title}, \text{review}) :-$
 $\text{DB2}(\text{title}, \text{director}, \text{'DeNiro'}, \text{year}),$
 $\text{DB1}(\text{id}, \text{title}, \text{actor}, \text{year}')$, $\text{DB3}(\text{id}, \text{review})$~~

Redundant
wrt 1



Local-as-View (LAV)

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

$V1(\text{title, year, director}) \stackrel{\subseteq}{\rightarrow} \text{Movie}(\text{title, year, director, genre})$
 $\wedge \text{American}(\text{director}) \wedge \text{year} \geq 1960 \wedge \text{genre} = \text{'Comedy'}$

$V2(\text{title, review}) \stackrel{\subseteq}{\rightarrow} \text{Movie}(\text{title, year, director, genre}) \wedge$
 $\text{year} \geq 1990 \wedge \text{MovieReview}(\text{title, review})$



Query Reformulation in LAV

Query: *Reviews for comedies produced after 1950*

$q(\text{title}, \text{review}) :- \text{Movie}(\text{title}, \text{year}, \text{director}, \text{'Comedy'}), \text{year} \geq 1950, \text{MovieReview}(\text{title}, \text{review})$

Reformulated query:

$q'(\text{title}, \text{review}) :- V1(\text{title}, \text{year}, \text{director}),$
 $V2(\text{title}, \text{review})$

$q' \subseteq q$

$V1(\text{title}, \text{year}, \text{director}) \rightarrow \text{Movie}(\text{title}, \text{year}, \text{director}, \text{genre}) \wedge$
 $\text{American}(\text{director}) \wedge \text{year} \geq 1960 \wedge \text{genre} = \text{'Comedy'}$

$V2(\text{title}, \text{review}) \rightarrow \text{Movie}(\text{title}, \text{year}, \text{director}, \text{genre}) \wedge \text{year} \geq 1990 \wedge$
 $\text{MovieReview}(\text{title}, \text{review})$



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 $\{V_i\}$

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

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

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

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

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

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

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

$V2(\text{student, dept, course}) \rightarrow \text{Registered}(\text{student, course, year}),$
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 $\text{Course}(\text{course, number}), \text{Enrolled}(\text{student, dept}), \text{ number} \leq 100$

$q(S, D) :-$

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

$V2(S, D, C')$

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

1. Filling the Buckets

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

$V2(\text{student}, \text{dept}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}),$
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$V3(\text{student}, \text{course}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}), \text{year} \leq 1990$

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

$q(S, D) :-$

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

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

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

$V4(S, C, N')$

1. Filling the Buckets

$V1(\text{student}, \text{number}, \text{year}) \rightarrow \text{Registered}(\text{student}, \text{course}, \text{year}),$
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 $\text{Enrolled}(\text{student}, \text{dept})$

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

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 $\text{Course}(\text{course}, \text{number}), \text{Enrolled}(\text{student}, \text{dept}), \text{number} \leq 100$

$q(S, D) :-$

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

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

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

$V4(S, C, N')$

2. Checking Containment

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

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

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

$V4(S,C,N')$

2. Checking Containment

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

$v_2(S,D,C')$ $v_1(S,N',Y)$ $v_1(S',N,Y')$

$v_4(S,C',N')$ $v_2(S,D',C)$

$v_4(S,C,N')$

2. Checking Containment

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

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

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

$V4(S,C,N')$

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

2. Checking Containment

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

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

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

$V4(S,C,N')$

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

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

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

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

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

$V4(S,C,N')$

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

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

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

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

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

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

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

2. Checking Containment

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

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

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

$V4(S,C,N')$

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

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

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

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

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

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

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

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

2. Checking Containment

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

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

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

$V4(S,C,N')$

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

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

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

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

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

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

2. Checking Containment

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

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

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

$V4(S,C,N')$

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

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

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

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

$N \geq 300 \wedge Y \geq 1995 \rightarrow$

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

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

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

$V4(S,C,N')$

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

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

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

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

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

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

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 $V4(S,C,N')$

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

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

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

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

$N \geq 300 \wedge Y \geq 1995 \rightarrow$

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

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

$\Rightarrow q' \subseteq q$ (and q' is a maximally-contained rewriting of q)

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

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



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

[Duschka+1997]

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

$\forall 1(\text{dept}, \text{course}) \rightarrow \text{Enrolled}(\text{student}, \text{dept}) \wedge \text{Registered}(\text{student}, \text{course})$

$$a \rightarrow b \equiv \neg a \vee b$$

$\forall D, C [\forall 1(D, C) \rightarrow \exists S [e(S, D) \wedge r(S, C)]]$

$\equiv \neg \forall 1(D, C) \vee [e(f(D, C), D) \wedge r(f(D, C), C)]$

$\equiv [\neg \forall 1(D, C) \vee e(f(D, C), D)] \wedge [\neg \forall 1(D, C) \vee r(f(D, C), C)]$

$\equiv [\forall 1(D, C) \rightarrow e(f(D, C), D)] \wedge [\forall 1(D, C) \rightarrow r(f(D, C), C)]$

\equiv

$e(f(D, C), D) \leftarrow \forall 1(D, C)$

$r(f(D, C), C) \leftarrow \forall 1(D, C)$

The Inverse-Rules Algorithm: Example

$q(D) \leftarrow \text{Enrolled}(S,D) \wedge \text{Registered}(S, \text{"DB"})$

$v1(D,C) \rightarrow \text{Enrolled}(S,D) \wedge \text{Registered}(S,C)$

$q(D) \leftarrow \text{Enrolled}(S,D) \wedge \text{Registered}(S, \text{"DB"})$

$\text{Enrolled}(f(D,C),D) \leftarrow v1(D,C)$

$\text{Registered}(f(D,C),C) \leftarrow v1(D,C)$

$q(D) \leftarrow v1(D, \text{"DB"})$

$\text{Ext}(v1) = \{(\text{"CS"}, \text{"DB"}), (\text{"EE"}, \text{"DB"}), (\text{"CS"}, \text{"AI"})\}$

$\text{Ext}(q) = \{(\text{"CS"}), (\text{"EE"})\}$



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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:

$AAAIdb^f(X) \rightarrow AAAIPapers(X)$

$CitationDB^{bf}(X, Y) \rightarrow Cites(X, Y)$

$AwardDB^b(X) \rightarrow AwardPaper(X)$

Query: find all the award winning papers:

$q(X) \leftarrow AwardPaper(X)$



Recursive Rewritings

$q(X) \leftarrow \text{AwardPaper}(X)$

- Problem: *Unbounded* union of conjunctive queries

$q_1(X) \leftarrow \text{AAAIdb}(X), \text{AwardDB}(X)$

$q_1(X) \leftarrow \text{AAAIdb}(X_1), \text{CitationDB}(X_1, X), \text{AwardDB}(X)$

...

$q_1(X) \leftarrow \text{AAAIdb}(X_1), \text{CitationDB}(X_1, X_2), \dots, \text{CitationDB}(X_n, X),$
 $\text{AwardDB}(X)$

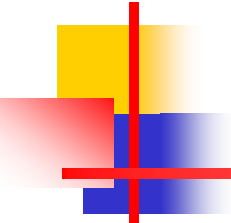
- Solution: Recursive Rewriting

$\text{papers}(X) \leftarrow \text{AAAIdb}(X)$

$\text{papers}(X) \leftarrow \text{papers}(Y), \text{CitationDB}(Y, X)$

$q'(X) \leftarrow \text{papers}(X), \text{AwardDB}(X)$

| |
|---|
| $\text{AAAIdb}^f(X) \rightarrow \text{AAAI}P\text{apers}(X)$ |
| $\text{CitationDB}^{bf}(X, Y) \rightarrow \text{Cites}(X, Y)$ |
| $\text{AwardDB}^b(X) \rightarrow \text{AwardPaper}(X)$ |



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

Inverse + Domain Rules (1)

Inverted Rules:

$AAAI\text{Papers}(X) \leftarrow AAAI\text{db}(X)$

$\text{Cites}(X, Y) \leftarrow \text{dom}(X) \wedge \text{CitationDB}(X, Y)$

$\text{AwardPaper}(X) \leftarrow \text{dom}(X) \wedge \text{AwardDB}(X)$

Domain Rules:

$\text{dom}(Y) \leftarrow \text{dom}(X) \wedge \text{CitationDB}(X, Y)$

$\text{dom}(X) \leftarrow AAAI\text{db}(X)$

Query:

$q(X) \leftarrow \text{AwardPaper}(X)$



Inverse-Rules Algorithm

Inverse + Domain Rules (2)

Simplifying the program:

$$q(X) \leftarrow \text{dom}(X) \wedge \text{AwardDB}(X)$$
$$\text{dom}(Y) \leftarrow \text{dom}(X) \wedge \text{CitationDB}(X, Y)$$
$$\text{dom}(X) \leftarrow \text{AAAIdb}(X)$$



Summary

- Dimensions of Data Integration
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 - Inverse-Rules Algorithm
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