Query Optimization in the Deep Web

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Rome, 10 June 2010

Outline

The deep Web

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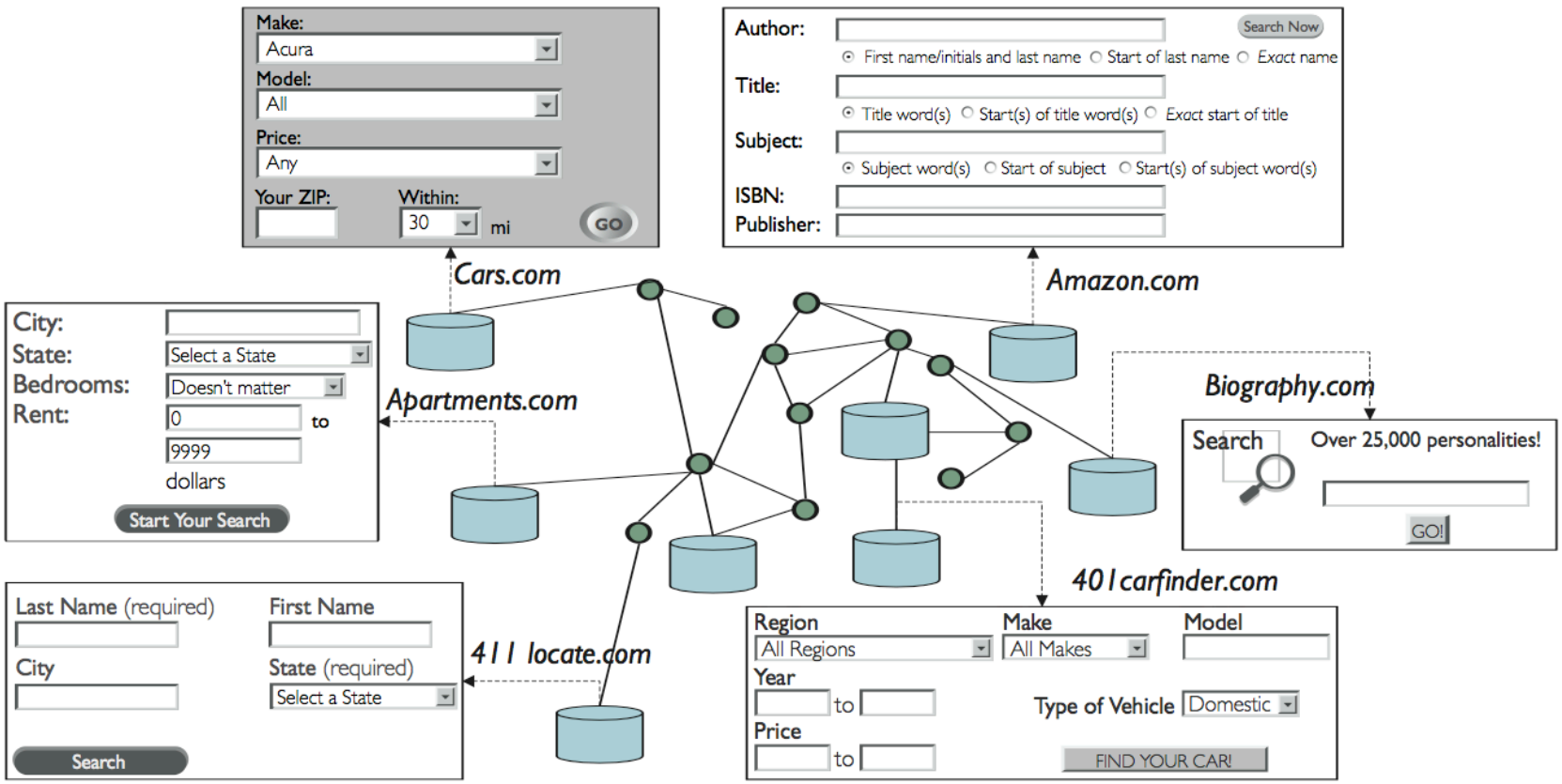
What is the Deep Web?

- Web pages (HTML mostly) have been indexed and searched for many years
- Such pages constitute the so-called Surface Web
  - huge, invaluable amount of information

What is the Deep Web?

- Web pages (HTML mostly) have been indexed and searched for many years
- Such pages constitute the so-called Surface Web
  - huge, invaluable amount of information
- The web has also continuously "deepened"
  - searchable databases, accessible usually through HTML forms
- The Deep Web (aka Hidden Web or Invisible Web) is not effectively crawlable nor indexeable
  - it is largely unexplored, apart from manual queries issued by users

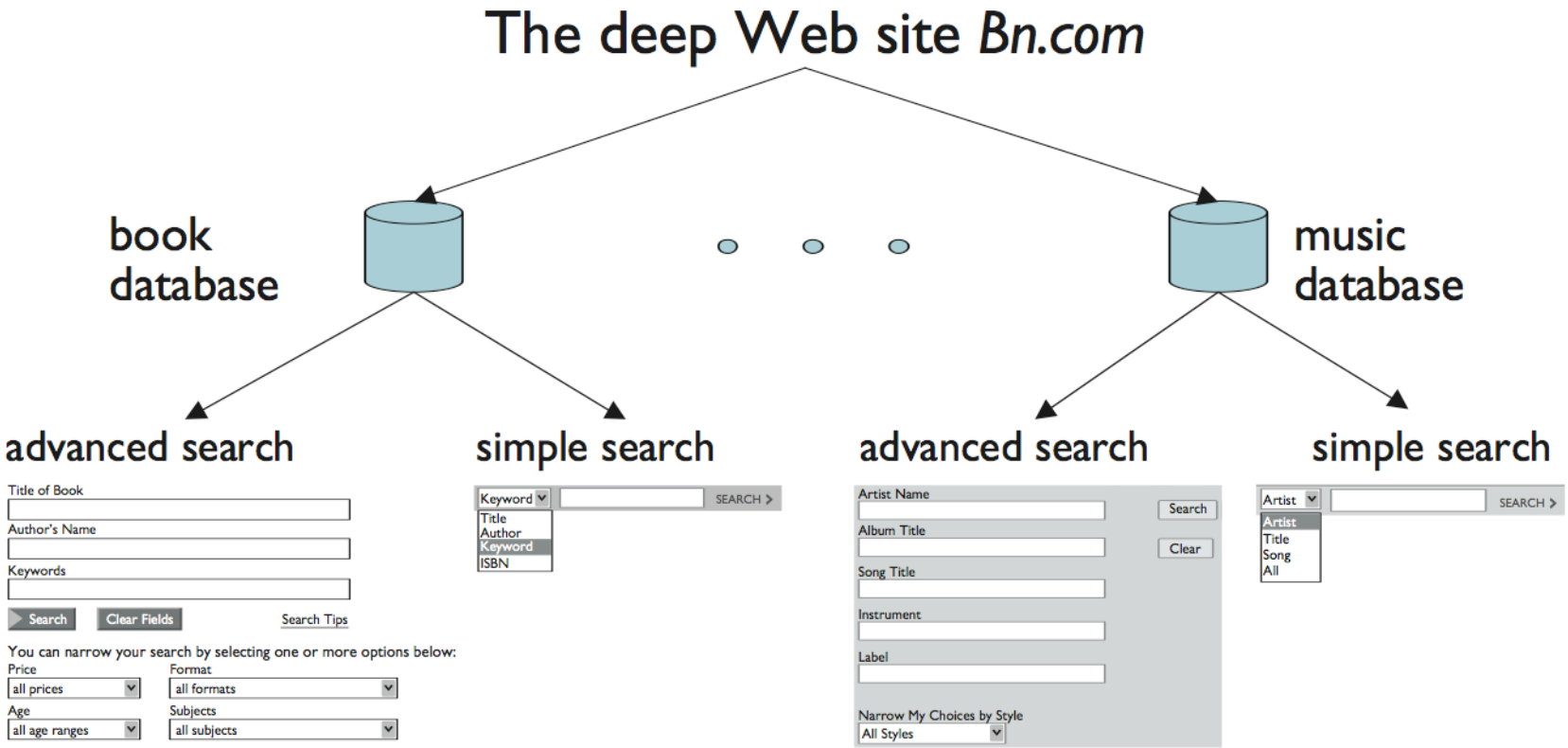
The conceptual view of the Deep Web [He et al. 2007]



A study of the existing Deep Web [He at al. 2007]

- Random sampling of 1M IP addresses
  - reserved and unused IPs removed
- HTML forms as query interfaces
  - non-query forms removed: site-search, login, subscription etc.
- duplicate query interfaces are removed

Duplicate query interfaces: example



Deep Web databases and sites

- Often, different query interfaces access the same database
- Two interfaces access the same data iff the objects retrieved from one can be found by accessing the other, and vice-versa
- Test: take five objects from one and check if they are found in the other
- Not always feasible!

Where to find query interfaces

- 100k IPs sampled
- 281 web servers found, crawled up to depth 10
  - 24 Deep Web sites
  - 129 query interfaces
  - 34 web databases
- 72% of interfaces within depth 3
- 94% of web databases appearing within depth 2
- 91.6% of Deep Web sites had their database within depth 3
- Deep Web not too deep

The scale of the Deep Web

- 1M IPs crawled up to depth 3
- Extrapolating from the 1M IPs to the entire IP space we get the following

	Sampling Results	*Total Estimate*	*99% Confidence Interval*
Deep Web sites	126	307,000	236,000 - 377,000
Web databases	190	450,000	366,000 - 535,000
–unstructured	*43*	*102,000*	62,000 - 142,000
–structured	*147*	*348,000*	275,000 - 423,000
Query interfaces	406	1,258,000	1,097,000 - 1,419,000

How structured is the Deep Web?

- Unstructured databases: objects as unstructured media (video, text, audio etc.)
- Structured databases: attribute-value pairs (i.e., relational tables)
- Analysis by manual inspection

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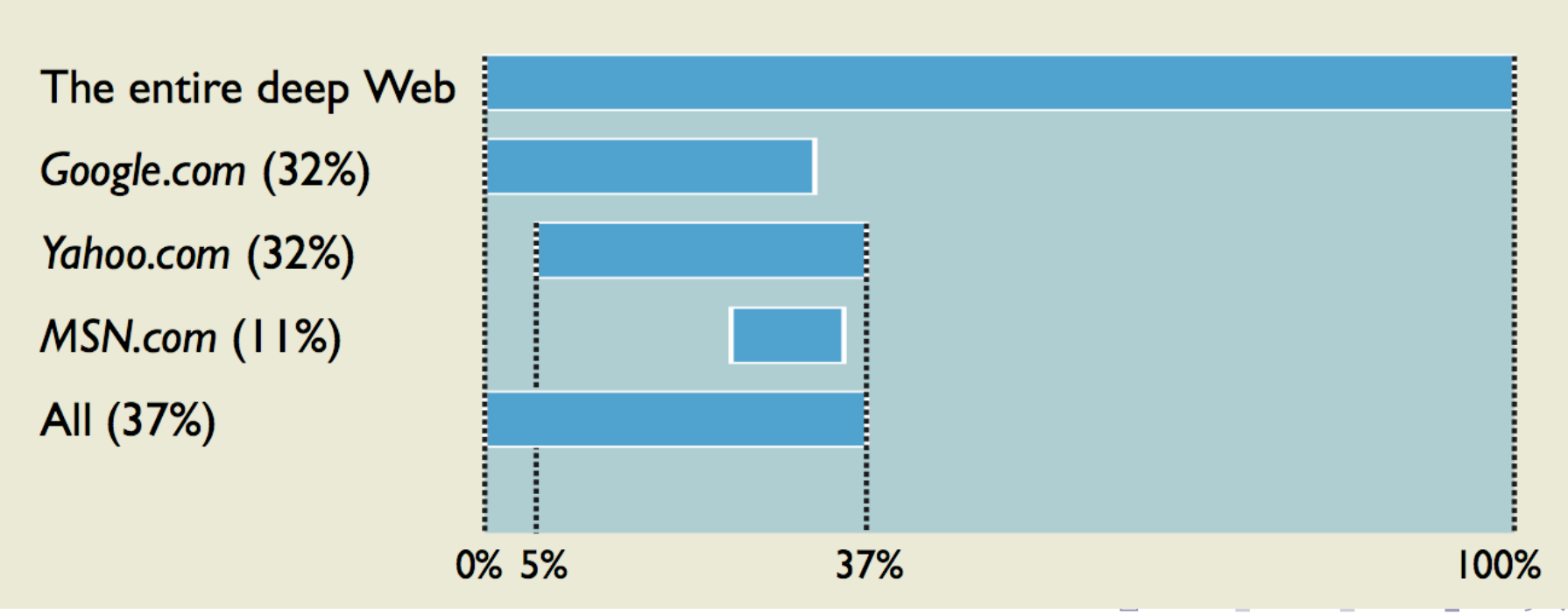
Subject distribution of the Deep Web

- Manual inspection
- Great diversity
- E-commerce sites only 49%
- Deep Web sources emerging outside e-commerce

Coverage of the Deep Web by search engines

- Some Deep Web result pages can be indexed (reachable via URL)
- Test: on a sample subset of Deep Web sites:
  - manually access with five random inputs
  - checking if the result pages are indexed by executing suitable searches



Coverage of the Deep Web by search engines

- Quite large coverage (Google and Yahoo! 32%) but with significant overlap
- The Deep Web is not completely invisible
  - however, a large part of it is!
- Different situation on the Shallow Web
  - little coverage overlap
  - possibility of effectively combining different search engines

Coverage of Deep Web directories

- Web portals exist that classify Deep Web databases in taxonomies
- Small coverage (15.6% max; 0.2% in one case)
- Manual (at least apparently) classification does not scale to the large size of the Deep Web

Access limitations

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Sources with access limitations

- Data sources in general may not always be queried freely:
  - Deep Web data accessible via forms
  - Legacy data wrapped in relational tables
  - Web services
  - ...
- Such sources are said to have access limitations
  - Some arguments may require to be bound to a constant
  - input vs output arguments
  - sometimes called bound vs free arguments

Access limitations - synonyms

- Access limitations are also commonly referred to as:
  - binding patterns
  - access patterns
  - access constraints
  - access hindrances

Access limitations - synonyms

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  - binding patterns
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    used only, but not always, by us

Example of data with access limitations

Data behind forms

- Data accessible through Web forms
  - phone directories
  - auctions
  - stores
  - ...

Modeling access limitations

Example: white pages

- Impossible to ask for all entries (filling in no fields)
- At least one field must be filled in
- The result is a table

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Modeling

- We model each source as a relational table with access limitations
- Filling in a field in the form corresponds to querying with a selection only

Example: whitepages.com – query

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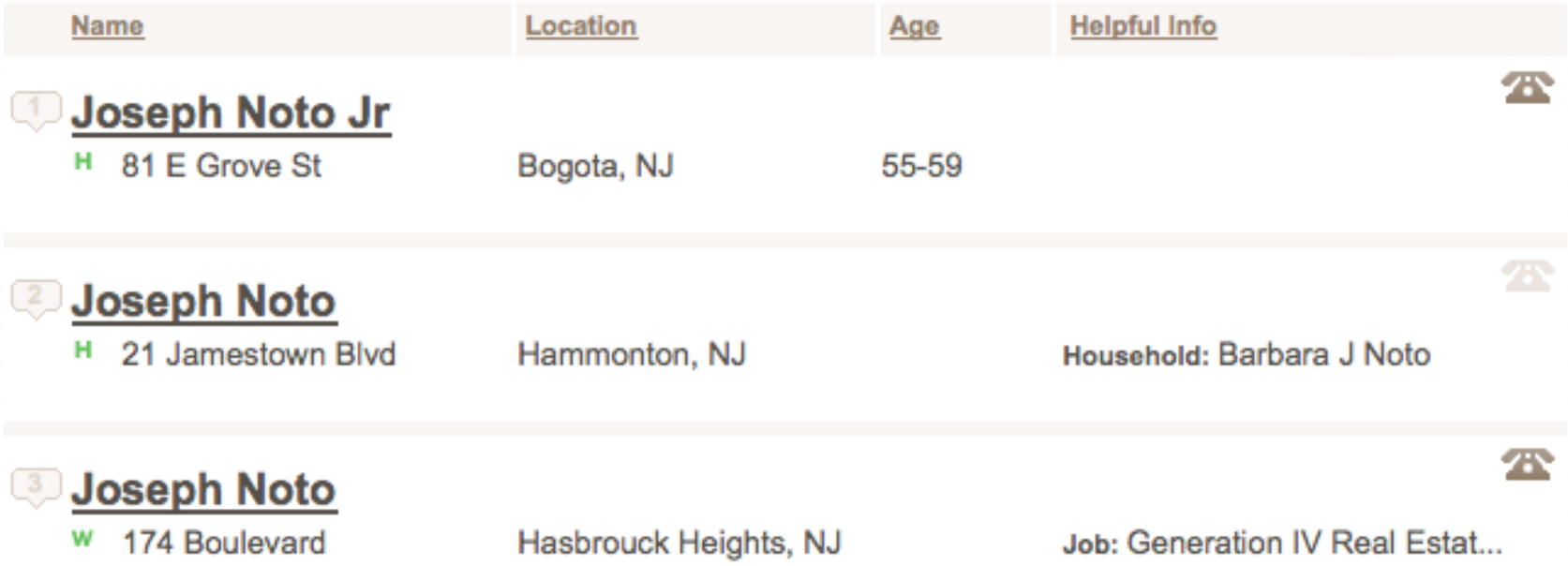
```
SELECT *
FROM whitepages
WHERE firstname='Joseph'
 AND lastname='Noto'
 AND stateprov='NJ'
```

Example: whitepages.com – results

	Name	Location	Age	Helpful Info
1	**Joseph Noto Jr** H 81 E Grove St	Bogota, NJ	55-59	
2	**Joseph Noto** H 21 Jamestown Blvd	Hammonton, NJ		**Household:** Barbara J Noto
3	**Joseph Noto** W 174 Boulevard	Hasbrouck Heights, NJ		**Job:** Generation IV Real Estat...

Example: whitepages.com – results



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First	Last	House no.	···
Joseph Jr	*Noto*	*81*	···
Joseph	*Noto*	*21*	···
Joseph	*Noto*	*174*	···

Relevant scenarios in the deep Web

- Surfacing
  - Indexing of deep Web result pages for search engines
- Centralized data integration
  - Sources are registered and wrapped in advance
  - Semantic mappings between sources and mediated schema are manually built
- Large-scale on-the-fly integration
  - Sources are chosen at query processing time

Surfacing

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Surfacing the Deep Web

- Surfacing precomputes relevant form submissions for all available HTML forms

  no specialization on a single domain
- The resulting URLs are indexed as any other web page
- The goal is a seamless inclusion of Deep Web pages into the web
- When a user clicks on a result, she is presented with fresh data contents by being redirected to the Deep Web source
- This allows for the inclusion of Deep Web pages into search engines

Scalability and main challenges

- The estimated number [Madhavan et al. 2007] of high-quality HTML forms is 10M approximately
- We need full automation

  Any human effort would be useless
- Main challenges of surfacing:
  1. deciding which forms to fill
  2. finding appropriate inputs for the forms

Considerations

- There are different kinds of inputs:
  1. selection inputs (e.g., pull-down)
  2. text inputs
  3. presentation inputs (e.g., sort-by)
- The fundamental problem is finding a good set of for submissions

Correlation among inputs

- Some inputs might be correlated (e.g., CITY and STATE, MINSALARY and MAXSALARY)
- Therefore, the set of values for an input to be instantiated should in principle different depending on the query template (binding pattern)
- However, this complicates things significantly
  - never considered in the literature

More considerations

- In surfacing, we aim at maximizing the coverage on the underlying data, while limiting the number of form submissions
- We want to cover as many Deep Web sites as possible
- Better to cover relevant information from many sites than deeply covering a few ones
- We do not want to cover the full contents of a Deep Web site: it is instead important to provide the search engine with seeds to diverse information on the site.

Selecting query templates: a tradeoff

- Selecting query templates with many input attributes retrieves in general more data, but it increases crawling traffic (generates all possible queries, or a large fraction of them)
- On the other hand, choosing too few input attributes retrieves too many tuples, often split into pages.
- Tradeoff!

Informative query templates

- A query template is informative if it generates several distinct pages from its form submissions
- Generated pages are assigned a signature; the higher the ratio signatures/submissions, the more informative the query template

Looking for informative templates

- Bottom-up method: if a candidate template of dimension (no. of input attributes) k is informative, we look for another of dimension $k+1$ that has as input attributes a superset of those of the former.
- This prunes the search significantly

Query Answering under Access Limitations

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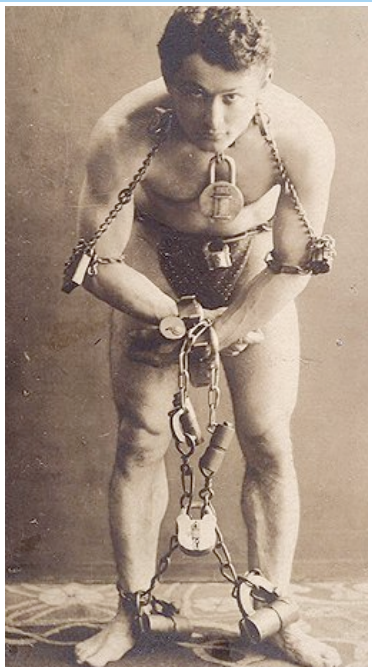
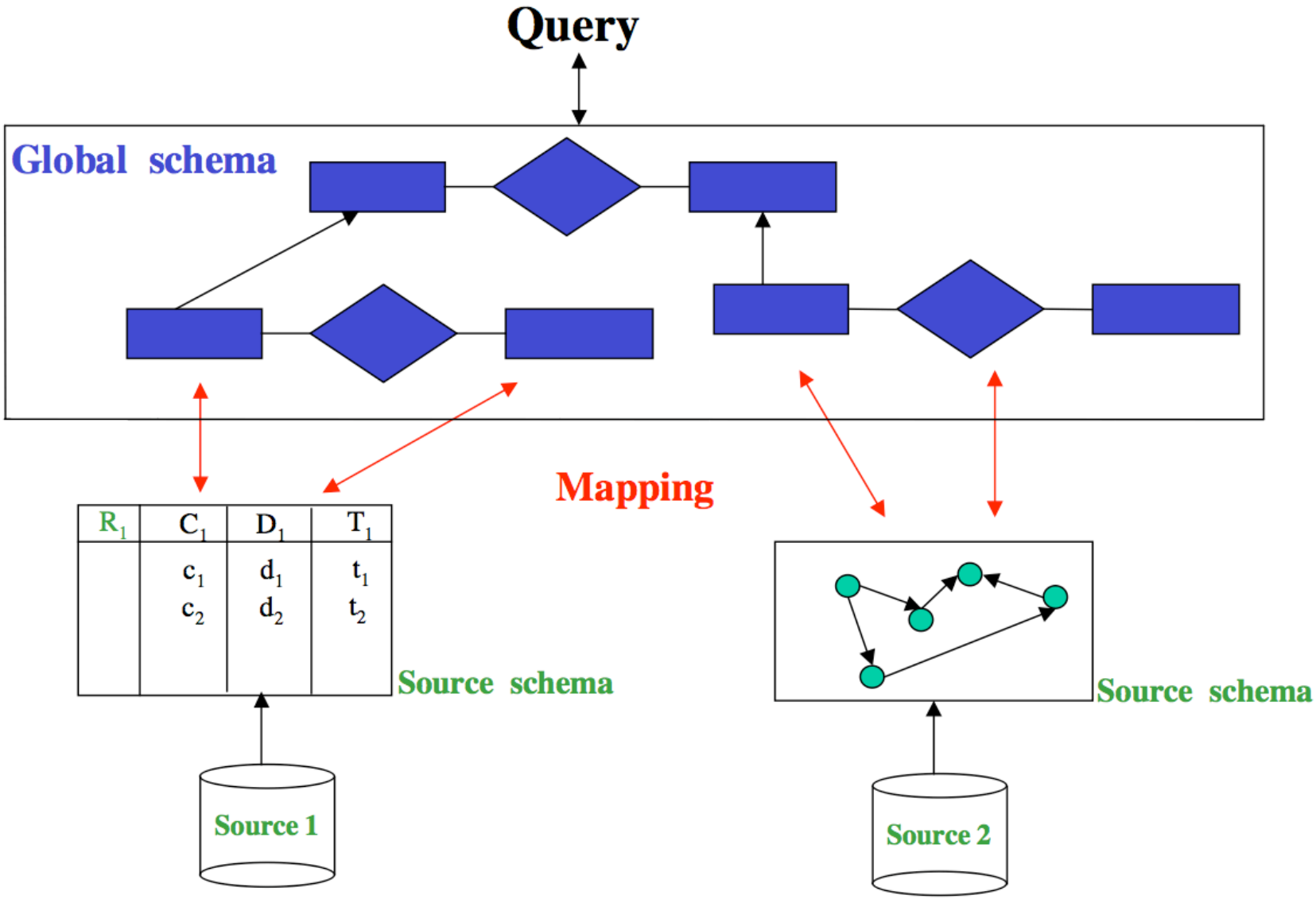


Traditional data integration setting

- Sources are wrapped as relational tables
  - with access limitations
- They are registered to a central system (mediator) with a reconciled schema
- Mappings between the wrapped sources and the mediator are manually (or semi-automatically) built
- Queries are posed over the reconciled schema
- We will focus on the problems posed by access limitations

Traditional data integration setting [Lenzerini IJCAI'03]



Example

Superscripts denote input and output attributes

Schema: concerts and artists

$r_1^{oio}(Title, City, Artist)$
$r_2^{ioo}(Artist, Nation, City)$

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Query

$q(A) \leftarrow r_2(A, italy, C), r_1(T, ny, A)$

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Query

$$q(A) \leftarrow r_2(A, italy, C), r_1(T, ny, A)$$

Answering strategy: q cannot be executed from left to right

- the body atoms of q can be reordered:

$$q'(A) \leftarrow r_1(T, ny, A), r_2(A, italy, C)$$

- q and q' are equivalent (q' is executable and q is orderable)
- its answer can be obtained as with no access limitations

Query answering under access limitations

Finding the exact answer

Can a CQ always be answered with all the tuples that would be found without access limitations?

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- It CQ q orderable into an executable query?

Query answering under access limitations

Finding the exact answer

Can a CQ always be answered with all the tuples that would be found without access limitations?

- Is CQ q executable *as is* from left to right?
- It CQ q orderable into an executable query?
  - Orderability sometimes called *feasibility* (ambiguous) and *executability* (ambiguous)
  - Can be considered as a syntactic version of executability
  - Reordering efficiently done in [Yang et al. PODS'06]
- Is CQ q stable, i.e., equivalent to an executable query
  - Stability sometimes called *feasibility* (ambiguous)
  - Can be considered as a semantic version of executability

Query answering under access limitations

Examples

Schema: $r_1^{oio}(Title, City, Artist)$,
$r_2^{ioo}(Artist, Nation, City)$

Query (executable): $q_e(A) \leftarrow r_1(T, ny, A), r_2(A, italy, C)$
Query (orderable): $q_f(A) \leftarrow r_2(A, italy, C), r_1(T, ny, A)$
Query (stable): $q_s(A) \leftarrow r_2(A, italy, C), r_1(T, ny, A), r_1(T, C', A)$

Query answering under access limitations

Results on stability

Theorem ([Li & Chang ICDT'01])

A CQ is stable iff its minimal equivalent is orderable.

Theorem ([Nash & Ludäscher PODS'04])

Stability is exactly as hard as query containment

Corollary ([Li & Chang ICDT'01])

Stability of conjunctive queries is NP-complete
Stability of Datalog queries in undecidable

Query answering under access limitations

Results on orderability

Theorem ([Yang et al. PODS'06])

Orderability is in P for conjunctive queries

Theorem ([Nash & Ludäscher PODS'04])

Orderability is NP-complete for FO queries

Theorem ([Yang et al. PODS'06])

Orderability is PSPACE-complete for non-recursive Datalog queries

Query answering under access limitations

Observations

- Limitations generally restrict the answers we can retrieve
  - Queries are not always stable
- We are interested in the best approximation of the query answers
- This might even require accessing off-query relations

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$q(A) \leftarrow r_2(A, italy, modena)$

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Best effort answering: no executable reordering of q exists

- Starting from the constant *modena*, we can access r_1
- then we can obtain tuples with new *Artist* constants
- with such values we can access r_2 and start over

Example

Superscripts denote input and output attributes

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Best effort answering: no executable reordering of q exists

- Starting from the constant *modena*, we can access r_1
- then we can obtain tuples with new *Artist* constants
- with such values we can access r_2 and start over
- We consider abstract domains (*Year*, *Artist* etc.)

⋆ We assume never to enumerate domain values

Example (cont'd)

Relation r_1

Title	City	Artist
azzurro	*modena*	*conte*

Relation r_2

Artist	Nation	City

Answer tuples

Example (cont'd)

Relation r_1

Title	City	Artist
azzurro	*modena*	*conte*

Relation r_2

Artist	Nation	City
conte	*italy*	*genoa*

Answer tuples

Example (cont'd)

Relation r_1

Title	City	Artist
azzurro	*modena*	*conte*
volare	*genoa*	*modugno*
K551	*genoa*	*kissin*

Relation r_2

Artist	Nation	City
conte	*italy*	*genoa*

Answer tuples

Example (cont'd)

Relation r_1

Title	City	Artist
azzurro	*modena*	*conte*
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K551	*genoa*	*kissin*

Relation r_2

Artist	Nation	City
conte	*italy*	*genoa*
kissin	*russia*	*moscow*
modugno	*italy*	*bari*

Answer tuples

Example (cont'd)

Relation r_1

Title	City	Artist
azzurro	*modena*	*conte*
volare	*genoa*	*modugno*
K551	*genoa*	*kissin*
sole_mio	*moscow*	*pavarotti*

Relation r_2

Artist	Nation	City
conte	*italy*	*genoa*
kissin	*russia*	*moscow*
modugno	*italy*	*bari*

Answer tuples

Example (cont'd)

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Relation r_2

Artist	Nation	City
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pavarotti	*italy*	*modena*

Answer tuples

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Relation r_1

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Relation r_2

Artist	Nation	City
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kissin	*russia*	*moscow*
modugno	*italy*	*bari*
pavarotti	*italy*	*modena*

Answer tuples

$\langle pavarotti \rangle$

Query answering under access limitations

Possible approximations

- Maximal answer a.k.a. maximally contained answer or reachable certain answer or obtainable answer
  - largest sound set of answer tuples that can be obtained by a query plan that respects the access limitations
- Minimally containing answer
  - smallest complete set of answer tuples that can be obtained by a query plan that respects the access limitations

Query answering under access limitations

- Schema $\mathcal{S}$ with access limitations
- Database instance D over $\mathcal{S}$
- Query q over D
- Set of initially known constants I
- Maximal answer denoted $\text{ans}(q, \mathcal{S}, D, I)$

Finding the maximal answer

- Basic technique in [Millstein et al. 2000]
- Answering is inherently recursive
- Need for a set of initial constants (usually those in the query)
- Notion of abstract domain associated to an attribute
- Encoding in positive Datalog

Query answering under access limitations

Finding the maximal answer: execution strategy

- To get all obtainable tuples, we need all possible constants for input attributes
- Enumerating all values of a domain: generally unfeasible
- Use all constants in the query and all constants from tuples retrieved from other relations
  - even those that are not mentioned in the query

Query answering under access limitations

Naive algorithm to compute the maximal answer

1. B = set of constants initially in the query
2. C = set of caches (one per relation)
3. while new valid accesses are possible
   - Make all accesses you can with constants in B
   - Put the obtained tuples in the corresponding cache in C
   - Put the obtained constants in B
4. Evaluate the query over the cache

Query answering under access limitations

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Answerability

A query q is answerable if there exists at least an instance D such that the maximal answer to q in D is non-empty (unanswerable otherwise)

Properties of queries under access limitations

Examples

Schema: $r_1^{oio}(Title, City, Artist), r_2^{ioo}(Artist, Nation, City)$

executable: $q_e(A) \leftarrow r_1(T, ny, A), r_2(A, italy, C)$

orderable: $q_f(A) \leftarrow r_2(A, italy, C), r_1(T, ny, A)$

stable: $q_s(A) \leftarrow r_2(A, italy, C), r_1(T, ny, A), r_2(T, C', A)$

answerable: $q_a(A) \leftarrow r_2(A, italy, modena)$

unanswerable: $q_u(A) \leftarrow r_2(A, italy, C)$

query	executable	orderable	stable	answerable
q_e	yes	yes	yes	yes
q_f		yes	yes	yes
q_s			yes	yes
q_a				yes
q_u	no	no	no	no

Naive program for previous example

$$
\begin{array}{lrcl}
\rho_1: & q(A) & \leftarrow & \hat{r}_2(A, italy, modena) \\
\rho_2: & \hat{r}_1(T, C, A) & \leftarrow & dom_C(C), r_1(T, C, A) \\
\rho_3: & \hat{r}_2(A, N, C) & \leftarrow & dom_A(A), r_2(A, N, C) \\
\rho_4: & dom_T(T) & \leftarrow & \hat{r}_1(T, C, A) \\
\rho_5: & dom_C(C) & \leftarrow & \hat{r}_1(T, C, A) \\
\rho_6: & dom_A(A) & \leftarrow & \hat{r}_1(T, C, A) \\
\rho_7: & dom_A(A) & \leftarrow & \hat{r}_2(A, N, C) \\
\rho_8: & dom_N(N) & \leftarrow & \hat{r}_2(A, N, C) \\
\rho_9: & dom_C(C) & \leftarrow & \hat{r}_2(A, N, C) \\
\rho_{10}: & dom_N(italy) & & \\
\rho_{11}: & dom_C(modena) & &
\end{array}
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rewritten query : ρ_1

cache rules: ρ_2, ρ_3

domain rules: $\rho_4 - \rho_{11}$

initial constants: *italy*, *modena*

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\rho_4: & dom_T(T) & \leftarrow & \hat{r}_1(T, C, A) \\
\cancel{\rho_5:} & \cancel{dom_C(C)} & \cancel{\leftarrow} & \cancel{\hat{r}_1(T, C, A)} \\
\rho_6: & dom_A(A) & \leftarrow & \hat{r}_1(T, C, A) \\
\cancel{\rho_7:} & \cancel{dom_A(A)} & \cancel{\leftarrow} & \cancel{\hat{r}_2(A, N, C)} \\
\rho_8: & dom_N(N) & \leftarrow & \hat{r}_2(A, N, C) \\
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\rho_{10}: & dom_N(italy) & & \\
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\end{array}
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Finding the relevant relations

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Optimizing the execution strategy

The naive algorithm

- Inefficient bottom-up approach:
  - All relations in the schema are always accessed in all possible ways
  - Accesses are costly (sources on the Web)

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- Inefficient bottom-up approach:
  - All relations in the schema are always accessed in all possible ways
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Idea: avoiding irrelevant accesses

- Some of the relations may be irrelevant to the query, i.e., they cannot help discovering tuples in the maximal answer
  - This depends on the query and the schema
  - Not only the relations mentioned in the query, but also the joins between them
- Accesses to such relations should be avoided

Relevance

Definition: relevance

A relation r is relevant for a query q if there are two instances D_1, D_2 that differ only on the tuples of R, and such that $\text{ans}(q, \mathcal{S}, D_1, I) \neq \text{ans}(q, \mathcal{S}, D_2, I)$.

$\text{ans}(q, \mathcal{S}, D, I)$: maximal answer to q over schema $\mathcal{S}$ (with limitations Λ), evaluated over database D using initial constants I (superset of those in q), as with the naive algorithm

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Determining relevance

- solved for connection queries in [Li & Chang TODS'01]
- solved for CQs with no projections in [C&M ICDE'08]

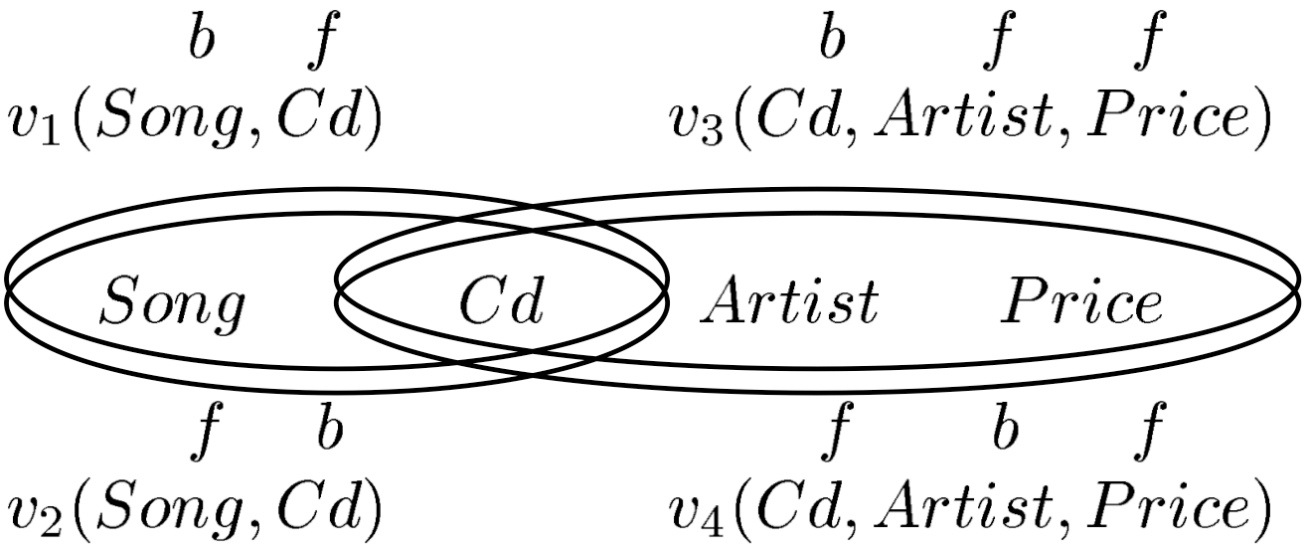
Connection queries [Li &Chang TODS'01]

Definition

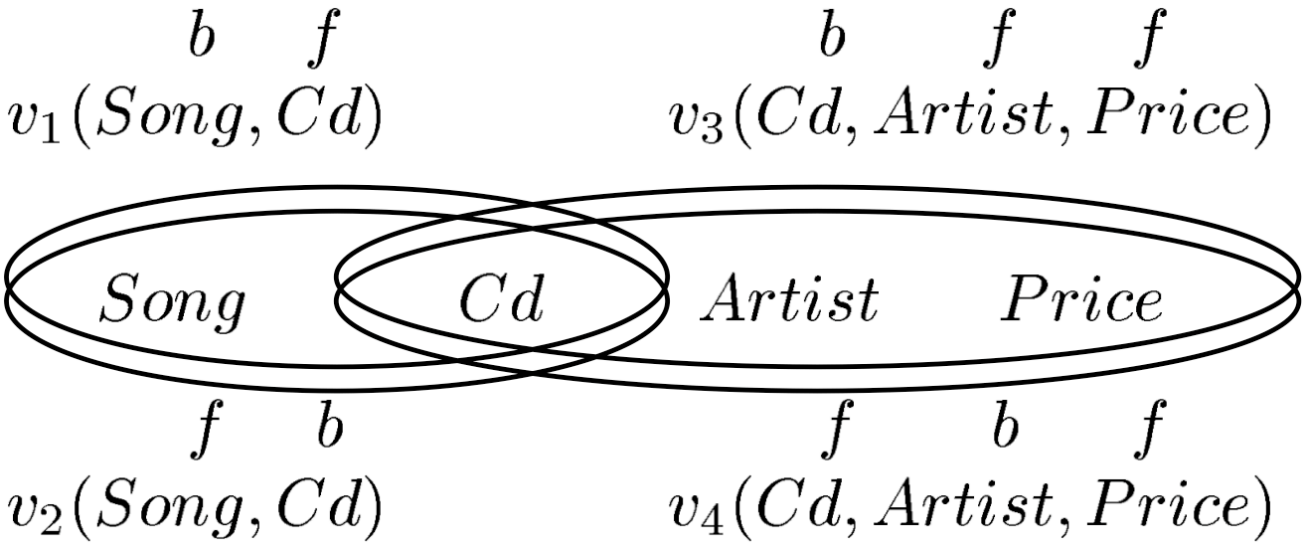
A connection query is a UCQ such that

- in each CQ, all attributes with the same domain are in a join

- Connection queries are useful for relations with disparate domains



Connection queries [Li &Chang TODS'01]



- Queries specified as $\langle I, O, C \rangle$
  - I is a list of input assignments *attribute=constant*
  - O is a list of output attributes the user is interested in
  - C is a list of connections, i.e., natural joins between relations, each join defining a CQ
  - example: $Q = \langle \{Song = t_1\}, \{Price\}, \{C_1, C_2, C_3, C_4\} \rangle$, where
  - $C_1 = \{v_1, v_3\}$, $C_2 = \{v_1, v_4\}$, $C_3 = \{v_2, v_3\}$, $C_4 = \{v_2, v_4\}$

Connection queries [Li &Chang TODS'01]

- A rewriting as a Datalog query can be provided that does not use any non-relevant relation
- ⋆ Connection queries do not cover CQs

Example: not a connection query

Schema: $supervisor^{oi}(Person, Person)$

- Can only ask who is supervisor of him/herself
- $q(X) \leftarrow supervisor(X, X)$ is a connection query
- $q(X, Y) \leftarrow supervisor(X, Y)$ is not a connection query

Relevance for CQs with no projections

- Relevance defined w.r.t. the body of a CQ in [C&M ICDE'08]
- This is equivalent to considering CQs with no projections
- Albeit incomplete, this notion of relevance allows pruning (some, perhaps not all) irrelevant relations from a query plan

Relevance for CQs with no projections

- Given a query and the schema, we represent dependencies among relations with a dependency graph (d-graph):
  - nodes are attributes
  - arcs tell which attributes provide values to feed attributes
- Sketchily represents how to extracts answers with the naive approach
- We prune non-relevant relations and accesses by deleting edges

Dependency graph

Nodes in the d-graph of query q:

- One black node for each argument of each atom occurring in q
- One white node for each argument of each relation not occurring in q
- Also marked with the access mode and the abstract domain

Arcs $u \longrightarrow v$ (v can receive values from u) if

- u and v have the same domain
- u is an output argument
- v is an input argument

Example

Schema

$showing^{io}(Location, Movie)$ $actor^{io}(Movie, Person)$
$married^{io}(Person, Person)$ $moviestar^{o}(Person)$
$production^{io}(Studio, Movie)$

Example

Schema

$showing^{io}(Location, Movie)$ $\quad$ $actor^{io}(Movie, Person)$
$married^{io}(Person, Person)$ $\quad$ $moviestar^{o}(Person)$
$production^{io}(Studio, Movie)$

Query

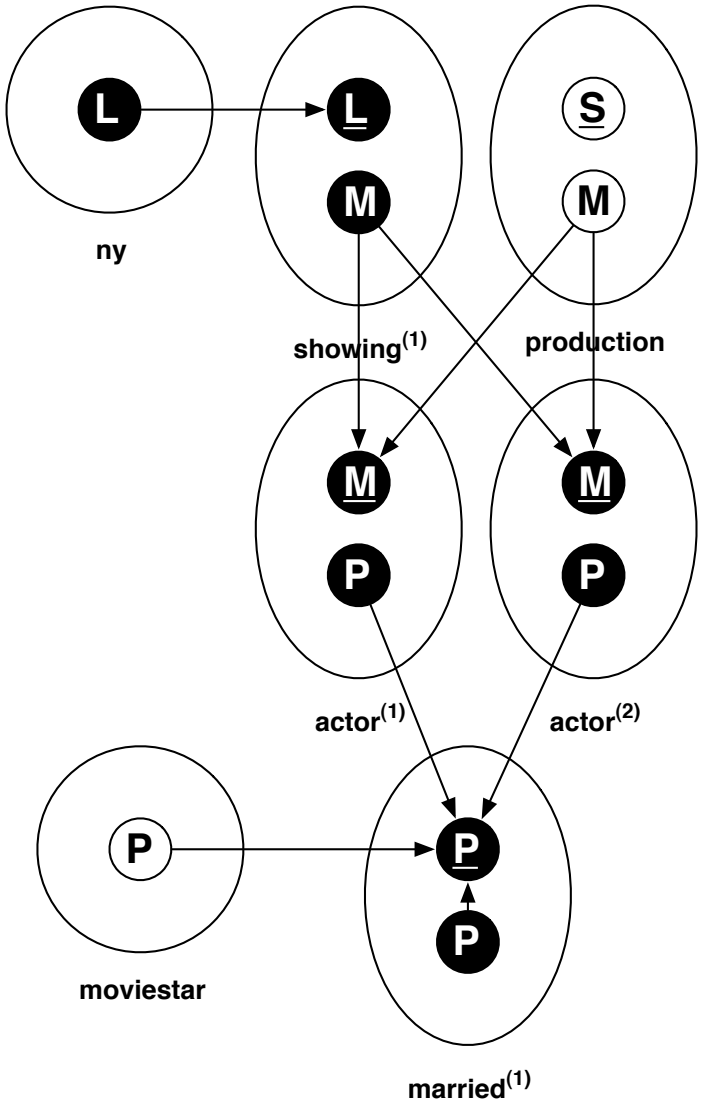
"actors in movies showing in New-York whose spouse has also played in some movie"

$$q(A) \leftarrow showing(ny, M), actor(M, A), married(A, A'), actor(M', A')$$

rewritten as

$$q(A) \leftarrow ny(L), showing(L, M), actor(M, A), married(A, A'), actor(M', A')$$

Example: d-graph



Marking the d-graph

Strong and weak arcs: intuition

- A strong arc $u \longrightarrow v$ denotes that v is "fed" through a join with values from u
- A weak arc $u \longrightarrow v$ denotes that v is "fed" with values from u but there is no join
- In the presence of a strong arc incoming on v, all weak arcs arcs incoming on v are unnecessary
  - unless they are needed to provide values to other nodes
- Strong arcs represent conditions that must hold all at the same time (intersection)
- Weak arcs represent conditions that are in a union

Pruning the d-graph

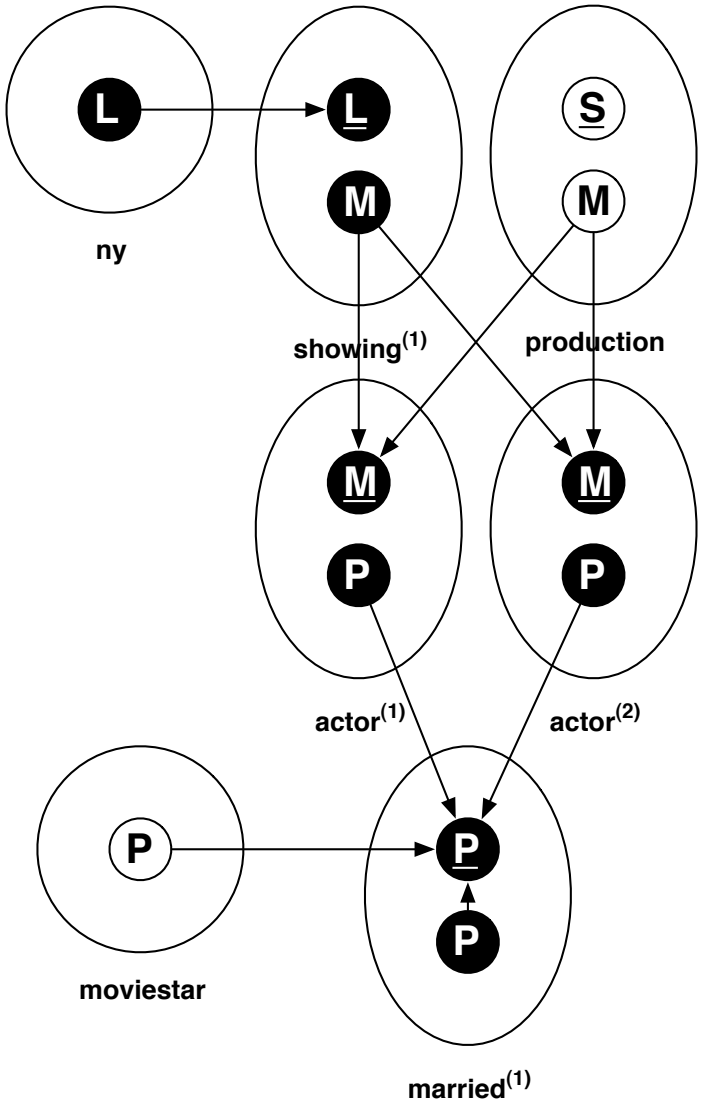
More terminology

- Candidate: arc whose corresponding nodes are in a join
- Cyclic: candidate that is in a cyclic path of candidates
  - Acyclicity enforced on strong arcs to preserve the maximal answer

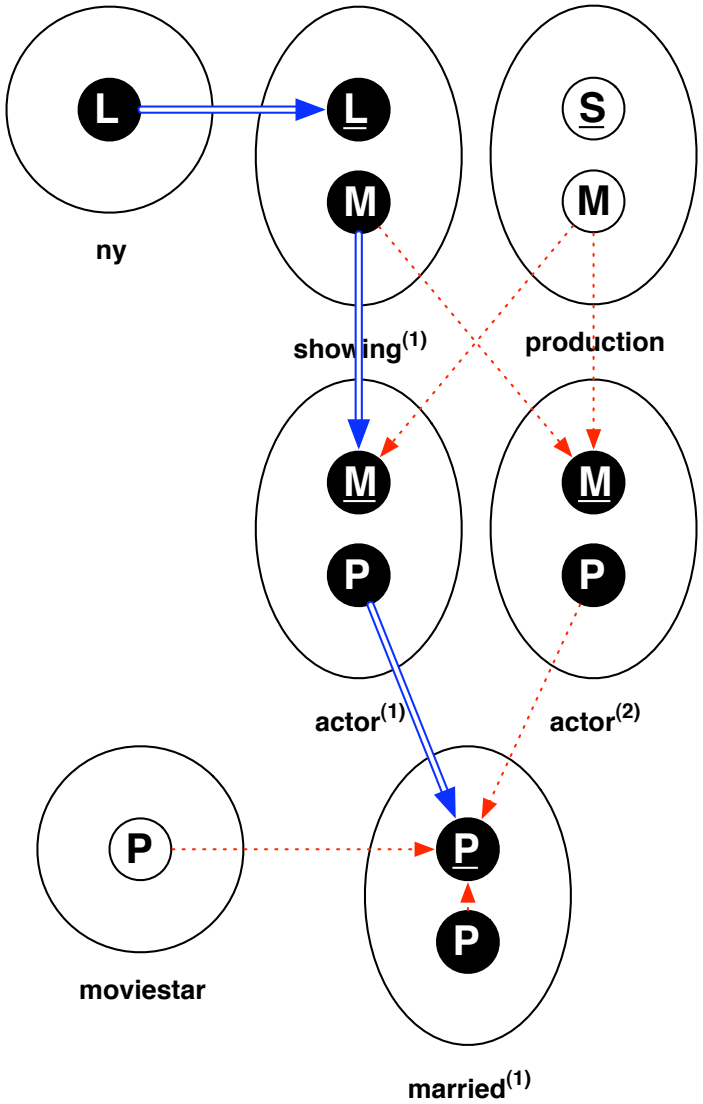
Determining strong and weak arcs

- Initial markings (as big as possible):
  - Strong arcs S_0 = all acyclic candidates
  - Deleted arcs D_0 = all arcs that are not candidates
  - A fixpoint algorithm unmarks the arcs until a consistent configuration is found

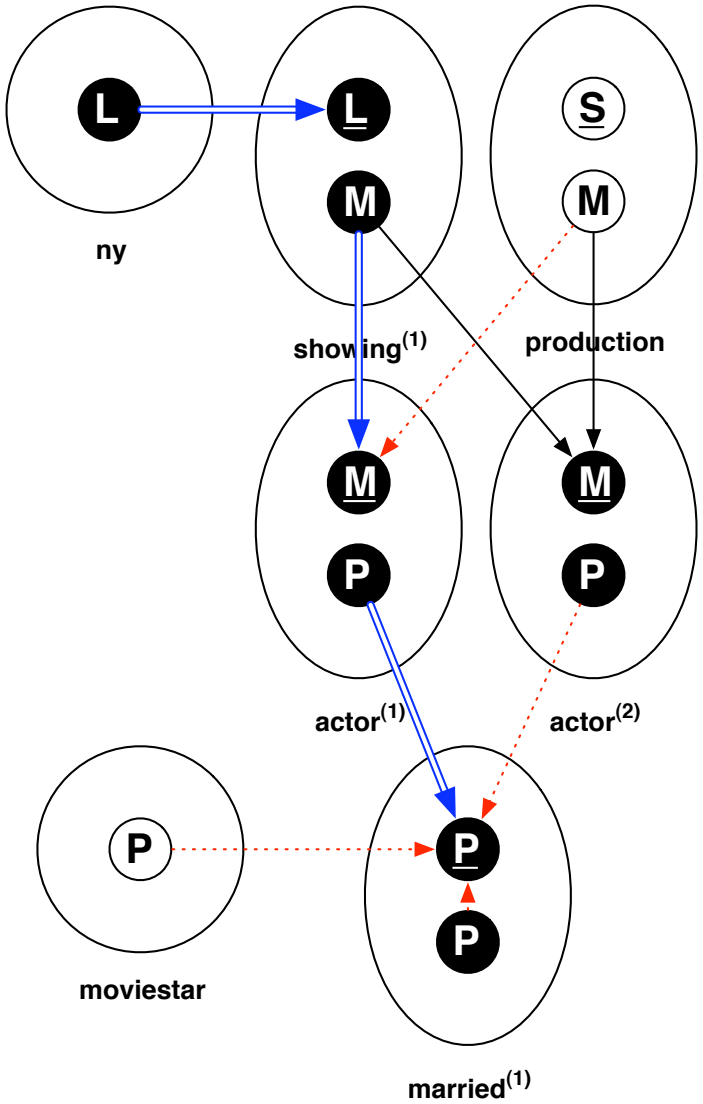
Example: d-graph (not marked)



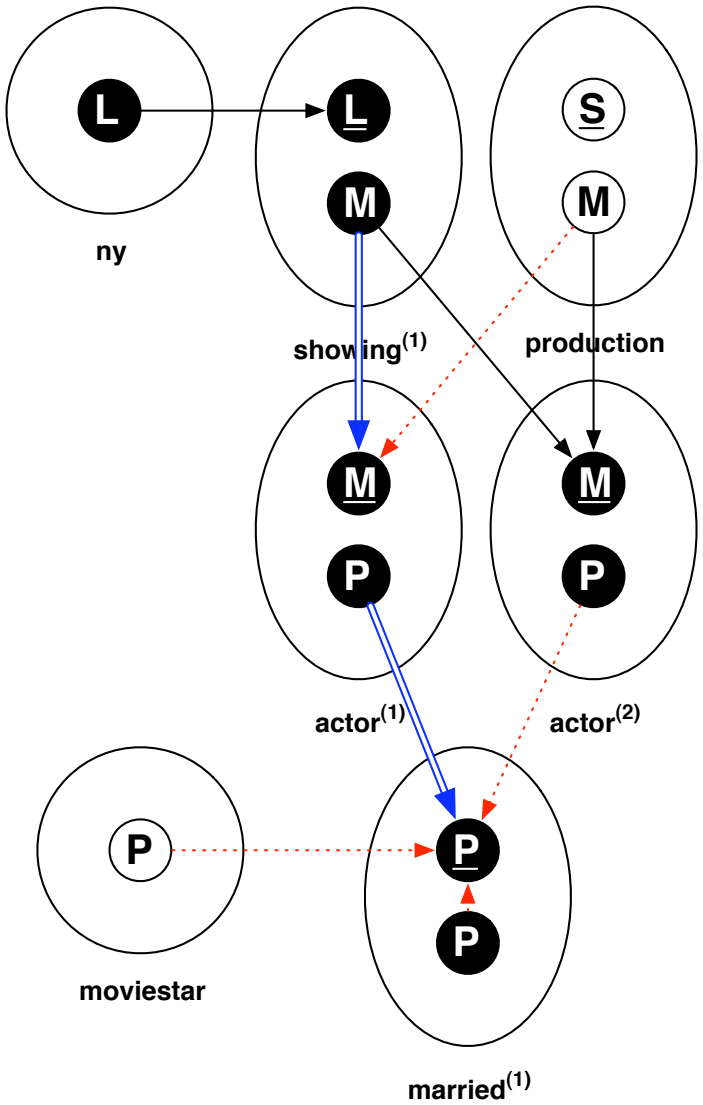
Example (cont'd): initial markings



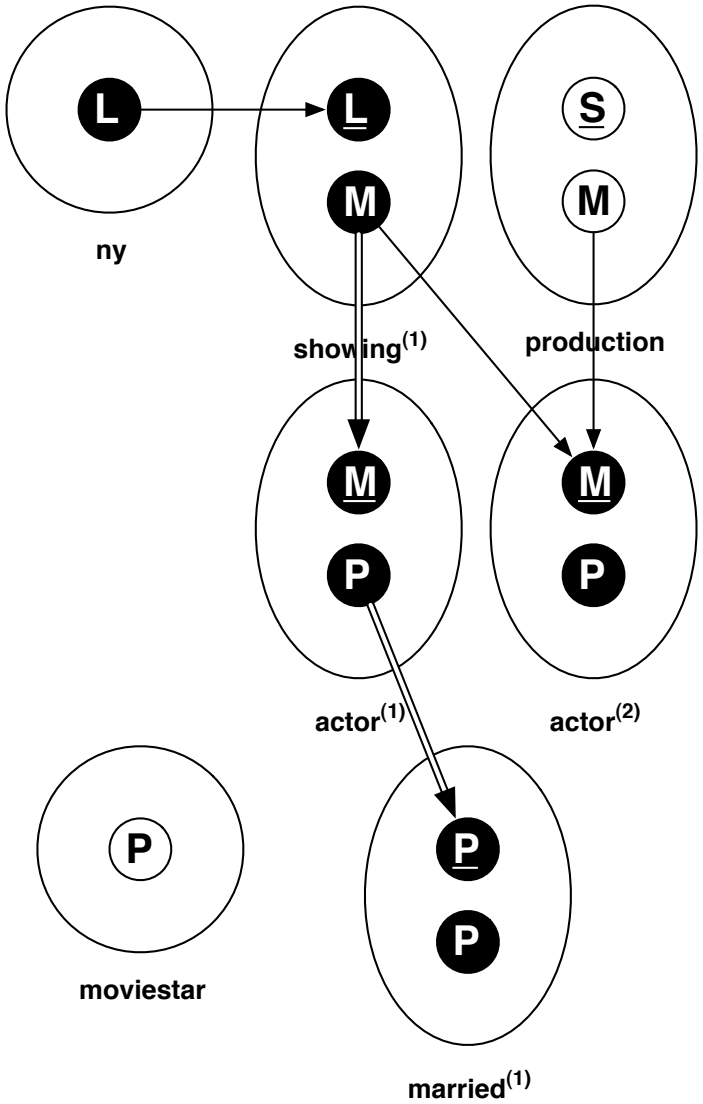
Unmarking deleted arcs not dominated by a strong arc



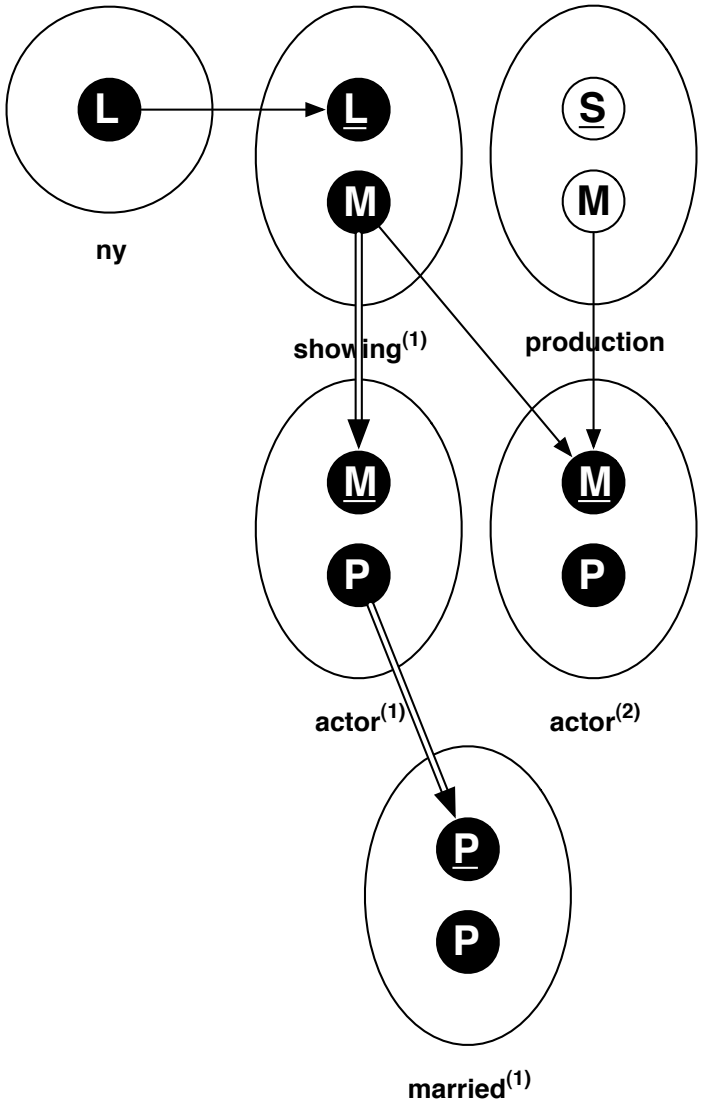
Unmarking strong arc followed by a weak arc



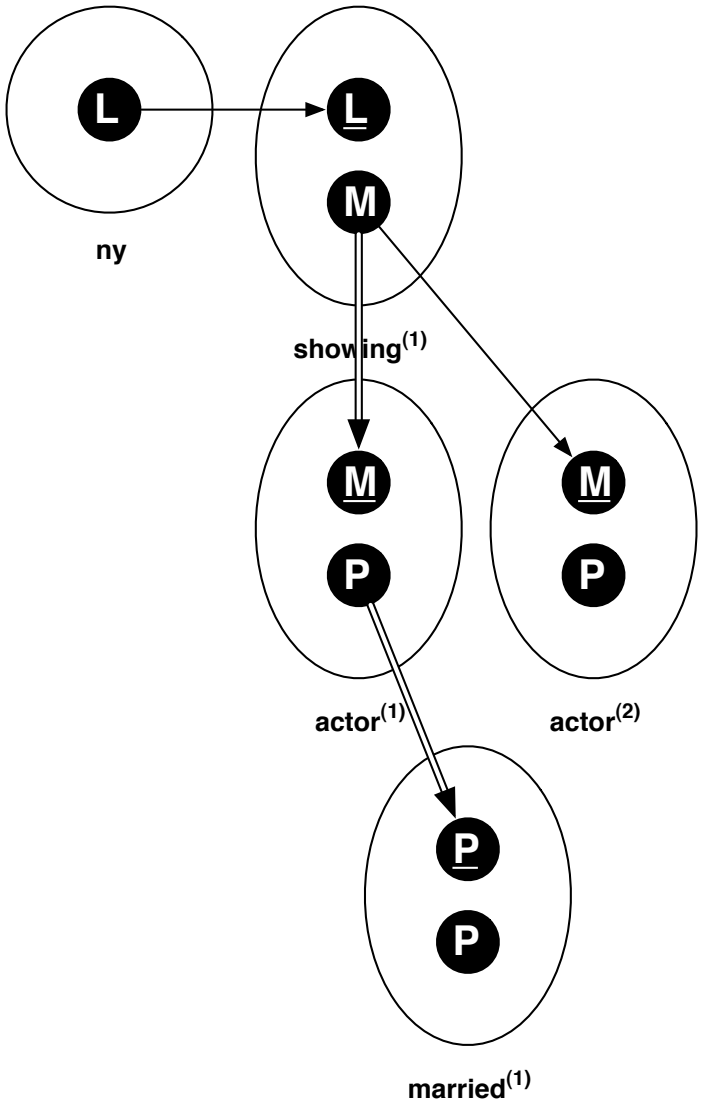
Fixpoint reached



Removing isolated white relations



Removing unaccessible white relations



Optimized query plan from the pruned d-graph

$$
\begin{aligned}
\rho_1 &: \quad q(A) \leftarrow \hat{showing}(ny, M), \hat{actor}_1(M, A), \\
&\qquad\qquad \hat{married}(A, A'), \hat{actor}_2(M', A') \\
\rho_2 &: \quad \hat{actor}_1(M, P) \leftarrow actor(M, P), dom_{Movie_1}(M) \\
\rho_3 &: \quad \hat{actor}_2(M, P) \leftarrow actor(M, P), dom_{Movie_2}(M) \\
\rho_4 &: \quad \hat{married}(P_1, P_2) \leftarrow married(P_1, P_2), dom_{Person}(P_1) \\
\rho_5 &: \quad \hat{showing}(L, M) \leftarrow showing(L, M), dom_{Location}(L) \\
\rho_6 &: \quad dom_{Movie_1}(M) \leftarrow \hat{showing}(\_, M) \\
\rho_7 &: \quad dom_{Movie_2}(M) \leftarrow \hat{showing}(\_, M) \\
\rho_8 &: \quad dom_{Person}(P) \leftarrow \hat{actor}(\_, P) \\
\rho_9 &: \quad dom_{Location}(ny)
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$$

rewritten query : ρ_1

cache rules: ρ_2, ρ_5

domain rules: $\rho_6 - \rho_9$

initial constants: ny

Optimized query plan in a more compact form

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rewritten query : ρ_1

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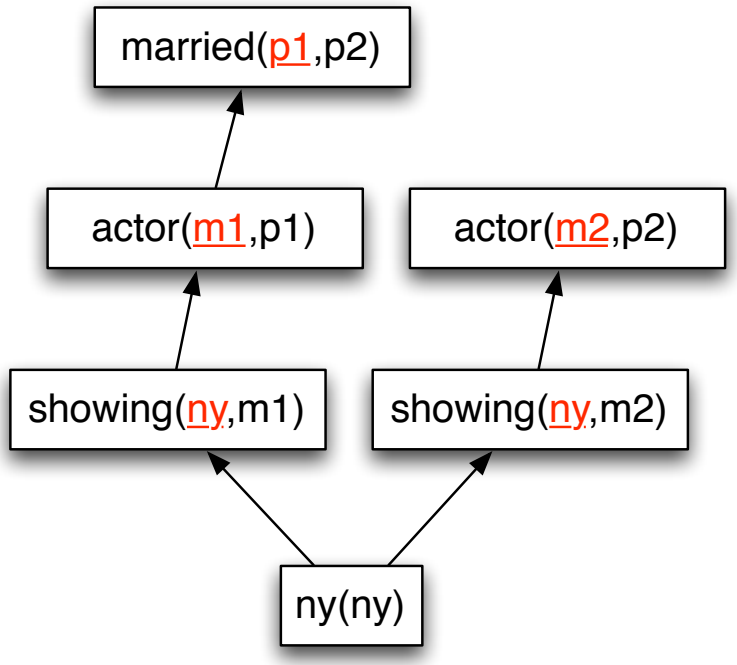
Properties of the pruned d-graph

Extraction forest

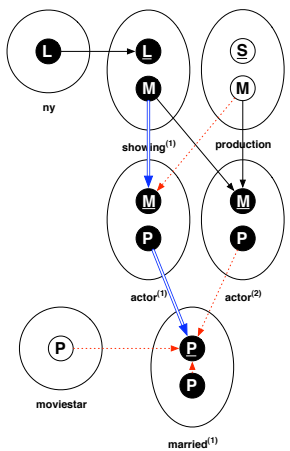
Roots: tuples in the input-free relations
Nodes: tuples in the DB
Arcs $u \curvearrowright v$: if output attribute in u is used in input attribute in v

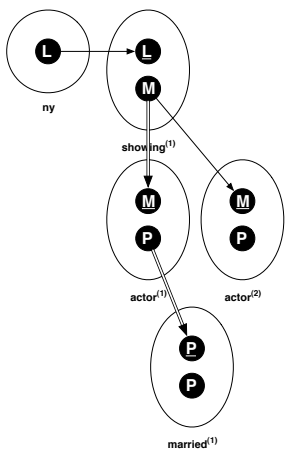


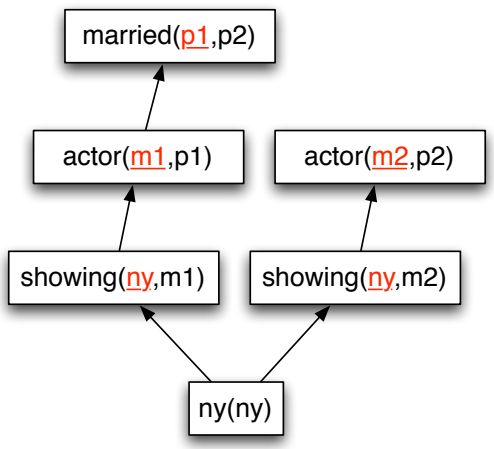
Properties of the pruned d-graph

Properties of deleted arcs in the pruned d-graph

- If $u \curvearrowright v$ is deleted, then each tuple in the answer has an extraction forest not containing $u \curvearrowright v$
- If $u \curvearrowright v$ is not deleted, then there is a database such that the answer contains a tuple whose extraction forests all contain $u \curvearrowright v$







Main results

Theorem: relevant sources

Relevant sources are exactly those appearing in the pruned d-graph

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Tractability result

- The algorithm performs a visit of the d-graph, visiting all edges plus some "neighbours" for every node
- ⋆ polynomial time complexity in the size of the d-graph

Extensions

General CQs

- The same technique cannot be extended to boolean CQs with cycles in the dependency graph
  - A relation r might be relevant to obtain all possible values (interesting for non-boolean queries) for some attributes
  - but maybe a value can be obtained without r
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- A fortiori, this technique does not extend to general CQs

- Stability can be reduced to non-relevance
  - Testing relevance for CQs is coNP-hard

Extensions

"Natural" CQs

- The d-graph technique can be extended to CQs obtained as the Cartesian product of non-boolean connected queries
  - Connected: every atom has a join with at least another atom in the query
  - Non-boolean: there is at least one variable in the head
  - Very natural sub-class of CQs
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Adding safe negation

- Safe negation can be added with no trouble
  - Negated atoms are immaterial to access limitations

Extensions

Datalog

- Determining relevance for Datalog queries is undecidable
  - Query containment in Datalog is undecidable
  - Query containment in Datalog can be reduced to relevance

Minimality of query plans

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Query plan

A deterministic program respecting the access limitations

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A deterministic program respecting the access limitations

$\forall$-minimality (strong)

A query plan Π is $\forall$-*minimal* iff, for every database D for $\mathcal{S}$, $Acc(D, \Pi) \subseteq Acc(D, \Pi')$ for every query plan Π' of Q.

$Acc(D, \Pi)$ is the set of accesses to relations done by Π over D.

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Proposition

$\forall$-minimality does not always exist.

Example: $q(X) \leftarrow r_1(X), r_2(Y)$ on schema $\{r_1^o, r_2^o\}$

Weaker minimality of plans

Preliminary criterion

$\Pi' \prec \Pi$ whenever, for every database D, $Acc(D, \Pi') \subseteq Acc(D, \Pi)$ and there is a database D' such that $Acc(D', \Pi') \subset Acc(D', \Pi)$.

$\prec$-minimality

Π is $\prec$-*minimal* iff for no query plan Π'' for Q it holds $\Pi'' \prec \Pi$.

Observations

- A $\prec$-minimal plan always exists for every query
- It is unique iff a $\forall$-minimal plan exists
  - in this case they coincide

Results on $\prec$-minimality

- A $\prec$-minimal plan is always derivable from the pruned d-graph
  - For "natural" CQs
- Plans can be expressed in Datalog
  - with left-to-right execution of body atoms
  - $\star$ plus some ad-hoc strategies required for evaluation

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  - For "natural" CQs
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  - ⋆ plus some ad-hoc strategies required for evaluation

Fast-failing strategy

Stop evaluation as soon as the result is certainly empty:

- Some of the caches are known to be empty, or
- Some of the joins in the query are known to fail

Query rewriting with views and constraints

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- Very general setting given in [Deutsch et al. TCS'07]:
  - UCQ$^{\neg}$ query q
  - Set of views V
  - Set of access limitations Λ
  - Set of integrity constraints Σ
- Problem $\{q, V, \Lambda, \Sigma\}$: rewriting queries using views in the presence of access patterns and integrity constraints

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- Problem $\{q, V, \Lambda, \Sigma\}$: rewriting queries using views in the presence of access patterns and integrity constraints
- Interest in finding rewritings providing
  - the maximally contained answer
  - the minimally containing answer

Query rewriting with views and constraints

- Possible reductions:
  - Encoding the views into the constraints: $\{q, V, \Lambda, \Sigma\} \rightsquigarrow \{q, \Lambda, \Sigma'\}$

Query rewriting with views and constraints

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  - Encoding the views into the constraints:
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  - Encoding the access limitations into the constraints:
    $\{q, V, \Lambda, \Sigma\} \rightsquigarrow \{q, V, \Sigma''\}$

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Query rewriting with views and constraints

Theorem ([Deutsch et al. TCS'07])

Stability is NP-complete in the size of the query for fixed views and inclusion constraints over UCQs and Π_2^P-complete for UCQ$^\neg$s

- The above result uses a chasing technique and holds only for those cases in which the chase exists
- Checking whether the chase exists is undecidable
- Fairly general sufficient conditions exist, though

Query containment under access limitations

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The containment problem

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- Relational schema $\mathcal{S}$
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Containment

Containment $q_1 \subseteq q_2$ holds if for every database D for $\mathcal{S}$ we have

$$q_1(D) \subseteq q_2(D)$$

The containment problem (cont'd)

Containment is useful for:

- query minimization
  - used to decide stability of a query
- optimization of query execution
- in general, optimization of formulas
  - e.g., containment can be used to simplify the evaluation of integrity constraints during integrity checking
- ...

Conjunctive query containment: algorithm

1. freeze body(q_1) and head(q_1) by turning each variable into a distinct (fresh) constant
2. evaluate q_2 over the frozen body of q_1
3. $q_1 \subseteq q_2$ iff the evaluation returns the frozen head of q_1

Testing containment amounts to checking the existence of a query homomorphism from q_2 to q_1 [Chandra & Merlin 1977].

Example

From [Ullman 1997]

$$
\begin{aligned}
q_1 : \quad & p(X, Z) \quad \leftarrow \quad a(X, Y), a(Y, Z) \\
q_2 : \quad & p(X, Z) \quad \leftarrow \quad a(X, U), a(V, Z)
\end{aligned}
$$

Example

From [Ullman 1997]

$$\begin{aligned} q_1 : \quad & p(X, Z) \quad \leftarrow \quad a(X, Y), a(Y, Z) \\ q_2 : \quad & p(X, Z) \quad \leftarrow \quad a(X, U), a(V, Z) \end{aligned}$$

Frozen body(q_1):

$$\begin{aligned} a(0, 1) \leftarrow \\ a(1, 2) \leftarrow \end{aligned}$$

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Frozen body(q_1):

$$\begin{array}{l} a(0,1) \leftarrow \\ a(1,2) \leftarrow \end{array}$$

Frozen head(q_1): $p(0,2) \leftarrow$

Example (contd.)

Applying q_2 to the frozen body(q_1), we find an answer substitution:

$$X \to 0,\ U \to 1,\ V \to 1,\ Z \to 2$$

that yields $p(0, 2)$ which is the frozen head of q_1.

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Therefore $q_1 \subseteq q_2$.

Note

The frozen body of q_1 is a representative of (a piece of) all databases that provide an answer to q_1

The containment problem with access limitations

Notation

- Conjunctive queries q_1, q_2
- Relational schema $\mathcal{S}$ with limitations Λ
- Initial constants $I \supseteq \text{const}(q_1) \cup \text{const}(q_2)$
- $\text{ans}(q, \mathcal{S}, D, I)$: maximal answer to q evaluated on a schema $\mathcal{S}$ under limitations Λ using initial constants I on database D.

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- $\text{ans}(q, \mathcal{S}, D, I)$: maximal answer to q evaluated on a schema $\mathcal{S}$ under limitations Λ using initial constants I on database D.

Containment

Containment $q_1 \subseteq_{\Lambda,I} q_2$ under limitations holds if for every database D for $\mathcal{S}$ we have

$$\text{ans}(q_1, \mathcal{S}, D, I) \subseteq \text{ans}(q_2, \mathcal{S}, D, I)$$

Comparing the two containments

$q_1 \subseteq q_2 \models q_1 \subseteq_{\Lambda,I} q_2$

Can be seen by applying homomorphisms:

- If there are extractible instances of the atoms in body(q_1)
- then there are extractible instances of the atoms in body(q_2)
  - that produce the same head

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$q_1 \subseteq_{\Lambda,I} q_2 \not\models q_1 \subseteq q_2$

Example:

- Schema: $r_1^{io}(A, X), r_2^{oo}(B, X)$
- q_1: $q_1(X) \leftarrow r_1(A, X)$ $\quad$ q_2: $q_2(X) \leftarrow r_2(B, X)$
- We have $q_1 \subseteq_{\Lambda,I} q_2$, e.g., for $I = \emptyset$
- but clearly $q_1 \not\subseteq q_2$

The containment problem with access limitations (cont'd)

- A conjunctive query q under access limitations can be rewritten as an executable (recursive) Datalog program that retrieves the maximal answer to q
- Therefore, checking containment amounts to checking containment between two Datalog programs
- Not a good idea: Datalog query containment is undecidable
  - however, programs have a special form

Decidability of the problem

- Query containment is actually decidable under access limitations even for more expressive classes than CQs

Theorem (Millstein et al. JCSS'03)

Given

- *a (potentially recursive) datalog program* Q_1
- *a nonrecursive datalog program* Q_2
- *a set* Λ *of one access pattern adornment for each relation*

determining whether $Q_1 \subseteq_{\Lambda,I} Q_2$ *is decidable.*

Reducing containment to monadic datalog

- Conjunctive query containment under access limitation can be reduced to containment between monadic datalog programs
- A datalog program is monadic if its recursive predicates are monadic

Theorem (Li & Chang TODS'01)

Containment of connection queries under access limitations is decidable

- This easily extends to general conjunctive queries

Theorem (Li & Chang TODS'01)

Containment of CQs under access limitations is decidable

- Same complexity (2EXPTIME) as containment between monadic datalog programs

Direct approach to containment checking

- A direct approach to query containment under access limitations can be given
- This gives also a slightly improved complexity bound

The chase

How can we find a representative of (a piece of) all databases that provide an answer to q_1 in the case with access limitations?

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The chase

Used for:

- query containment under relational dependencies [Johnson & Klug 1984]
- implication of relational dependencies
- querying incomplete data
- data integration and data exchange
- ...

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We have a different version...

The crayfish-chase

The crayfish-chase

The crayfish-chase

Idea

- We construct an extraction tree producing exactly the frozen body of q_1
- We proceed backwards (moving as a crayfish)
  - We start from the frozen body of q_1
  - We add tuples that provide values used in the input fields of the tuples in the frozen body of q_1
  - Then we add tuples that provide values for the input fields of the previous tuples
  - and so on
  - we continue until we "close off" with tuples for relations that have no input field

The crayfish-chase: example

Schema

$r_1^{iio}(A, B, A)$
$r_2^{io}(A, B)$
$r_3^{o}(A)$

Query

$q(X_2) \leftarrow r_1(a, X_1, X_2)$

answerable but non-executable

- W.l.o.g., we use constant-free queries
- First the query is frozen, then "expanded" by chasing
  - ⋆ Special constants ζ_i denote unknown values (labelled nulls)

The crayfish-chase: example (cont'd)

Query with constants eliminated

$$q(X_2) \leftarrow r_1(X_a, X_1, X_2), \ell_a(X_a)$$

- ℓ_a is an aux. predicate with extension $\{\langle a \rangle\}$
- the chase starts from the frozen body

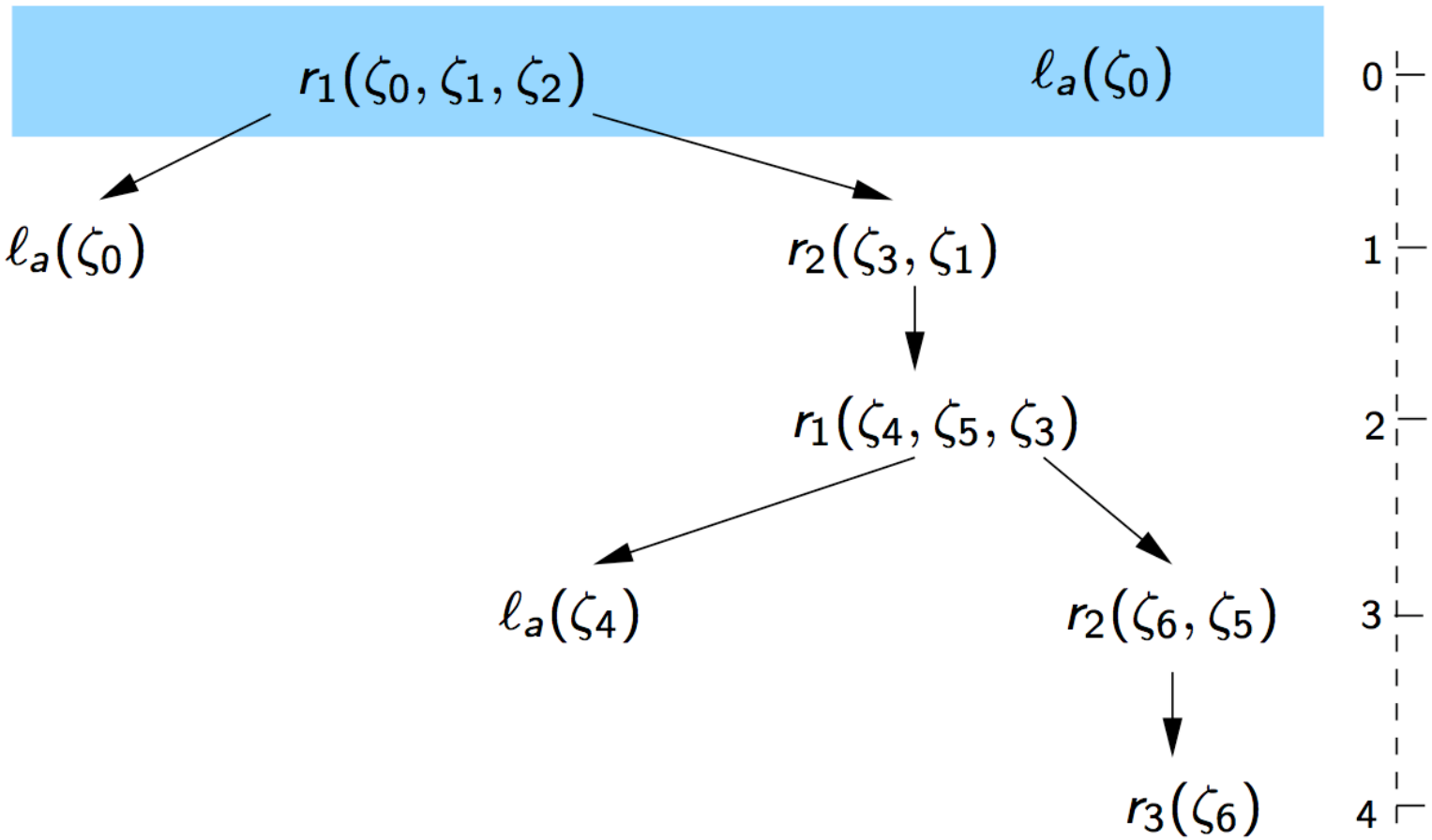
Frozen head

$$q(\zeta_2)$$

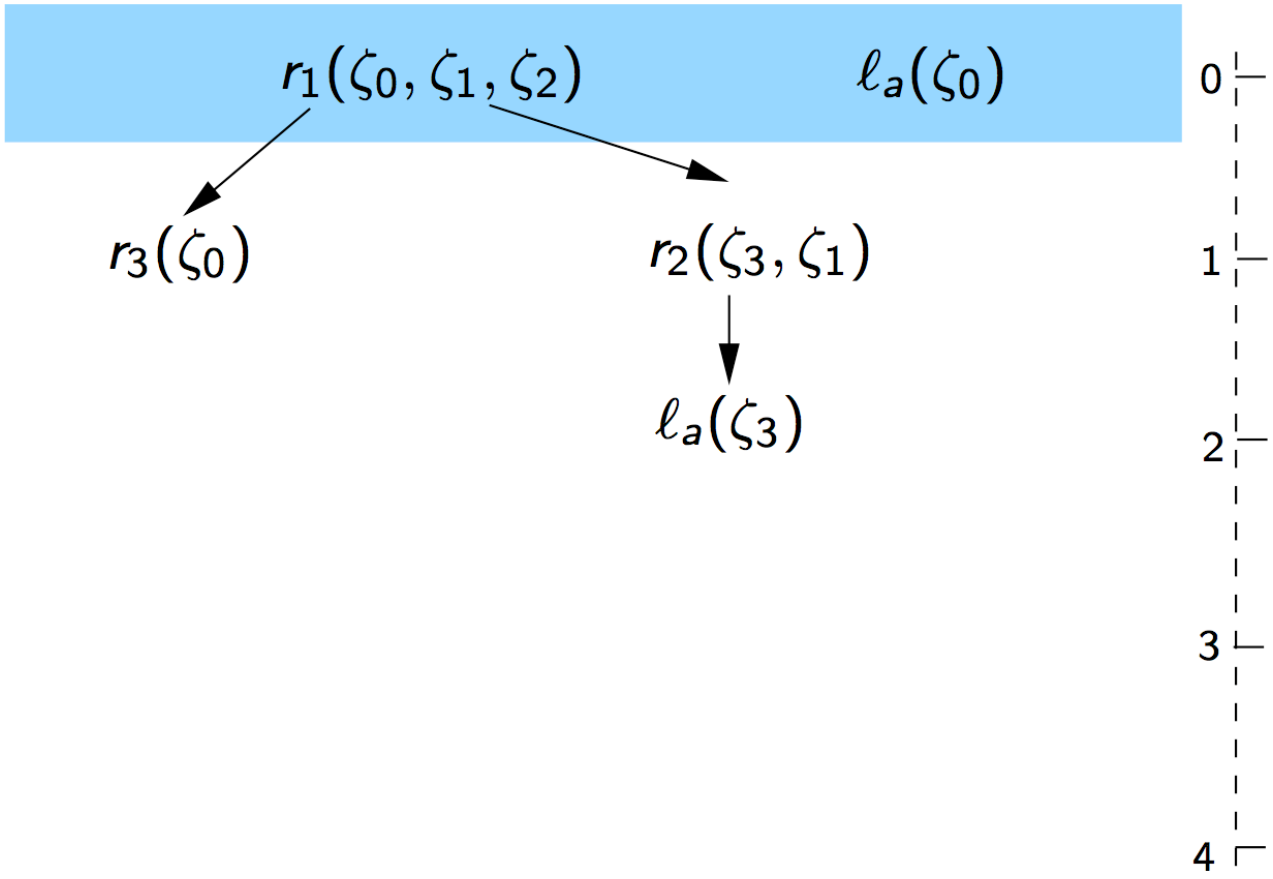
Frozen body

$$r_1(\zeta_0, \zeta_1, \zeta_2), \ell_a(\zeta_0)$$

Example of instance in the crayfish-chase



Example: another instance in the crayfish-chase



The crayfish-chase

Features

- Each constructible extraction tree producing the frozen body of q is a database of the crayfish chase
- The crayfish chase is
  - a set of databases, denoted cchase$(q, \mathcal{S}, I)$
  - a forest of extraction trees, layered in levels
- Every database represents one way of "extracting" an answer tuple
- Thus, the chase may serve as a tool for containment

Main property of the crayfish-chase

Theorem

$q_1 \subseteq_{\Lambda,I} q_2$ if and only if for every database $C \in \text{cchase}(q_1, \mathcal{S}, I)$

$$\text{frozen\_head}(q_1) \in q_2(C)$$

(frozen_head(q_1) is the same in every DB in the chase)

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Warning

Not yet a strategy for deciding containment!

- there may be an infinite number of databases in a chase
- there is no bound on the size of databases in the chase

Decidability

Theorem

IF there exists a finite database $C \in \text{cchase}(q_1, \mathcal{S}, I)$ such that $q_1(C) \not\subseteq q_2(C)$,

THEN there exists another finite database $C' \in \text{cchase}(q_1, \mathcal{S}, I)$ such that

1. $q_1(C') \not\subseteq q_2(C')$, and
2. C' has maximum level $\delta = 2 \cdot |\mathcal{S}| + |q_2| - 3$

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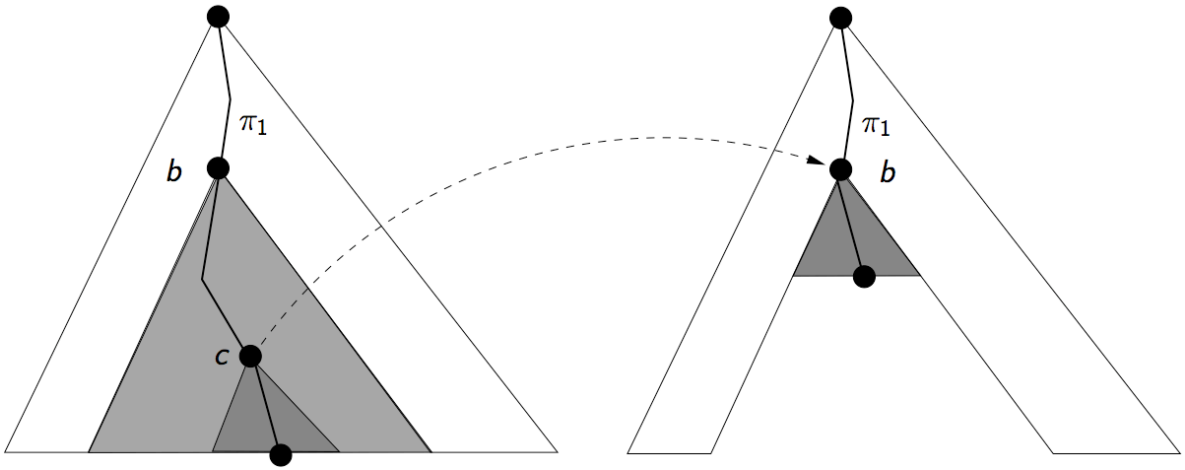
Consequence

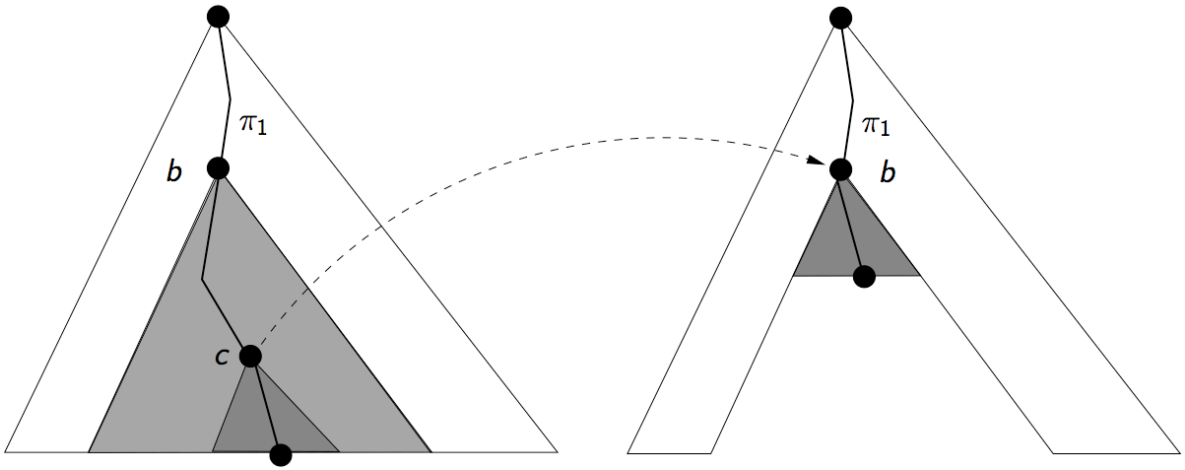
It is sufficient to check all databases in the chase up to a certain number of levels

Idea of the proof: iterative subtree replacement



- Take a counterexample C in cchase$(q_1, \mathcal{S}, I)$

Idea of the proof: iterative subtree replacement



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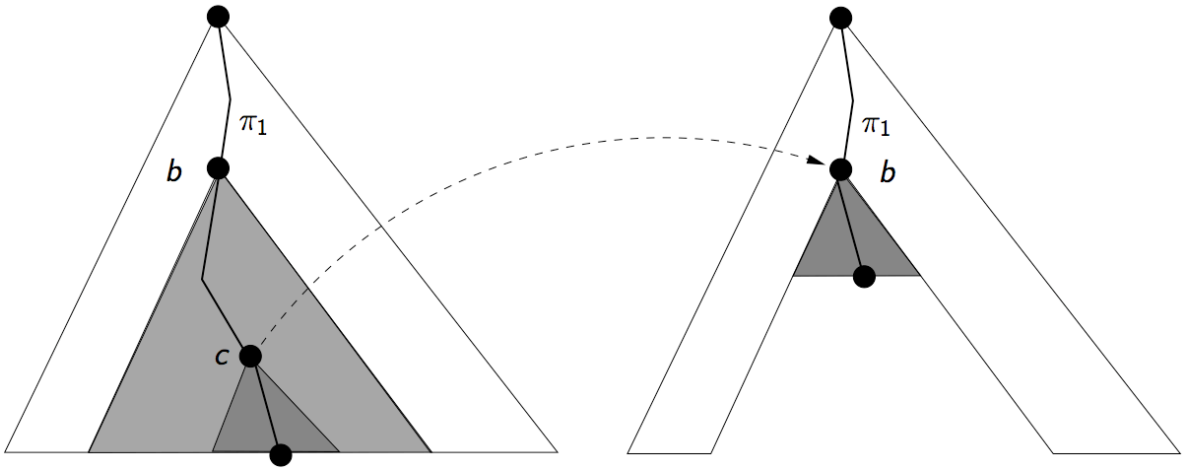

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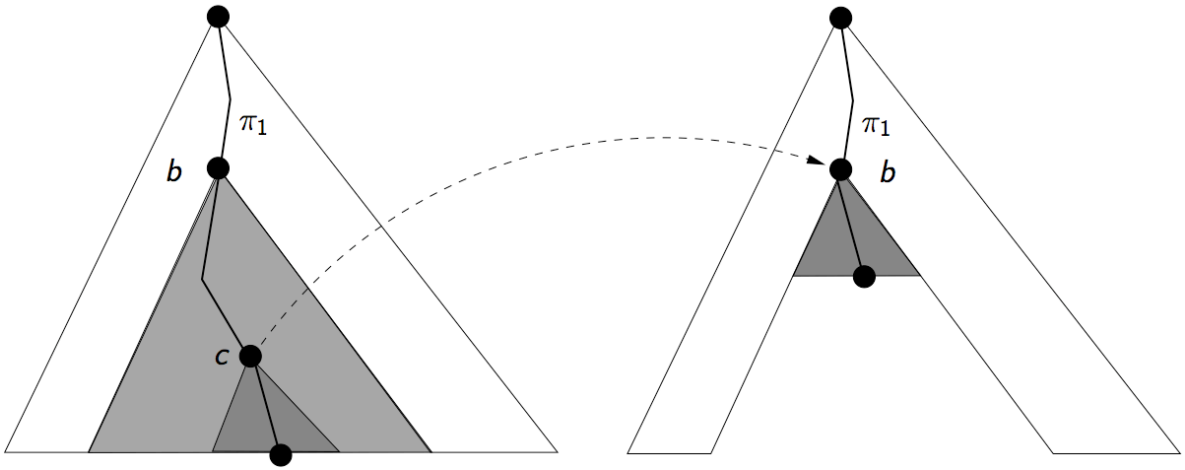

- Take a counterexample C in cchase$(q_1, \mathcal{S}, I)$
- if C exceeds the level δ, "shorten" it
- C is "shortened" by subtree replacement
- at each replacement, we get another counterexample

Complexity

Theorem

The complexity of checking containment of conjunctive queries under access limitations is in co-NEXPTIME.

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Proof sketch

1. guess $C \in \text{cchase}(q_1, \mathcal{S}, I)$ of depth less than the sufficient one; size $O(W^\delta)$ (W: max. arity)
2. evaluate q_2 over C: feasible in polynomial time in C and det. exp. time in q_2
3. if no counterexample to containment is found, then containment holds (otherwise containment does not hold)

Dynamic optimization

Dynamic optimization

Using constraints for dynamic optimization

Constraints considered in [C., Calvanese, M. JUCS'09]

- Functional dependencies (FD): $s : A \rightarrow B$
  - satisfied in D if, $\forall t_1, t_2 \in s^D$, $t_1[A] = t_2[A] \Rightarrow t_1[B] = t_2[B]$
- Simple full-width inclusion dependencies (SFWID): $s_1 \subseteq s_2$
  - Satisfied in D if $s_1^D \subseteq s_2^D$
  - Special case of inclusion dependencies
  - Relevant to model sources with several access patterns

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Notation

$\mathcal{A}(s)$: set of all attributes of source s
$\mathcal{I}(s)$: set of input attributes of source s

Using constraints for dynamic optimization

Idea for dynamic optimization

- Store accesses and answer tuples in caches
- Avoid accesses recognized as irrelevant thanks to the constraints
  - The access may already conflict with the extracted tuples on some FD that holds in the database
  - Or it may coincide with an access already made
- Requires deciding implication of FDs in the presence of FDs and SFWIDs
  - Implication is undecidable for FDs and general inclusion dependencies [Chandra & Vardi, SIAM J.Comp.'85]

Implication of FDs and SFWIDs

Let Γ be a set of FDs and SFWIDs

Results

- Implication of SFWIDs from Γ only depends on SFWIDs
  - FDs have no impact on the implication of SFWIDs
  - The reflexivity and transitivity rules are sound and complete

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Results

- Implication of SFWIDs from Γ only depends on SFWIDs
  - FDs have no impact on the implication of SFWIDs
  - The reflexivity and transitivity rules are sound and complete
- Implication of a FD on a source s from Γ:
  - consider only sources s_i for which $s \subseteq s_i$ is implied
  - assert on s all FDs holding on those sources s_i
  - decide implication of FDs using only the FDs on s (plus the asserted ones) with Armstrong's rules

Inference rules for SFWIDs and FDs

1. For every source s and all sets of attributes $\mathbf{A}, \mathbf{B} \subseteq \mathcal{A}(s)$,
   if $\mathbf{A} \subseteq \mathbf{B}$, then $s : \mathbf{B} \rightarrow \mathbf{A}$.
2. For every source s and all sets of attributes $\mathbf{A}, \mathbf{B}, \mathbf{C} \subseteq \mathcal{A}(s)$,
   if $s : \mathbf{A} \rightarrow \mathbf{B}$, then $s : \mathbf{AC} \rightarrow \mathbf{BC}$.
3. For every source s and all sets of attributes $\mathbf{A}, \mathbf{B}, \mathbf{C} \subseteq \mathcal{A}(s)$,
   if $s : \mathbf{A} \rightarrow \mathbf{B}$ and $s : \mathbf{B} \rightarrow \mathbf{C}$, then $s : \mathbf{A} \rightarrow \mathbf{C}$.
4. For every source s,
   $s \subseteq s$.
5. For all sources s_1, s_2, s_3,
   if $s_1 \subseteq s_2$ and $s_2 \subseteq s_3$, then $s_1 \subseteq s_3$.
6. For all sources s_1, s_2 and sets of attr. $\mathbf{A}, \mathbf{B} \subseteq \mathcal{A}(s_1) = \mathcal{A}(s_2)$,
   if $s_1 \subseteq s_2$ and $s_2 : \mathbf{A} \rightarrow \mathbf{B}$, then $s_1 : \mathbf{A} \rightarrow \mathbf{B}$.

Results on implication

Theorem

The inference rules $1-6$ *are sound and complete for implication of FDs and SFWIDs.*

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Theorem

Finite and unrestricted implication are equivalent for SFWIDs and FDs. (If there is a counterexample, then there is a finite one)

Example of dynamic optimization

Static info

Schema: $s^{iio}(A, B, C)$
FD: $s : A \rightarrow B, C$

Example of dynamic optimization

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Dynamic context

D is the database state
t is a tuple that has been extracted from s^D such that $t[A] = a$
Suppose we have some value b for attribute B

- Accessing s^D with $A = a, B = b$ is useless:
  - it can either provide t alone, if $b = t[B]$
  - or no tuple, if $b \neq t[B]$
- because of the FD!

Dynamic relevance

Access

An access (to a source s) is a selection query on s
A binding (for s) is a tuple of constants used for the input attributes in an access to s

Dynamic relevance

Let $\mathcal{T}$ be a set of tuples for sources $s_1, \ldots, s_n$.
Let Γ be a set of FDs and SFWIDs. An access is dynamically relevant wrt. Γ and $\mathcal{T}$ if there is a database $D \models \Gamma$ such that:

- $\mathcal{T}$ is the set of tuples extracted from D with some accesses
- the access extracts from D at least
  - one tuple not in $\mathcal{T}$ (tuple relevance), or
  - one constant not in $\mathcal{T}$ (binding relevance)

$\mathcal{T}$ represents the set of already extracted tuples

Dynamic relevance and keys

Result

If a subset of the input attributes is a key, an access α is dynamically tuple-relevant iff no already extracted tuple coincides with α's binding on the key attributes.

- Let γ be the FD

$$s : \mathbf{K} \rightarrow \mathcal{A}(s)$$

  with $\mathbf{K} \subseteq \mathcal{I}(s)$.
- Let b be a binding for s and $\mathbf{T}_s$ a set of tuples that satisfies γ.

Accessing s using b is dynamically relevant wrt. γ and $\mathbf{T}_s$ iff there exists no tuple $t \in \mathbf{T}_s$ such that $b[\mathbf{K}] = t[\mathbf{K}]$.

Dynamic relevance and FDs

Result

An access is not dynamically tuple-relevant if:

- it has the same binding as some extracted tuple
- it violates a FD together with some extracted tuple

Let γ be the FD

$$s : \mathbf{A} \rightarrow \mathbf{B}$$

with $\mathbf{A} \subseteq \mathcal{I}(s)$. Let b be a binding for s and $\mathbf{T}_s$ a set of tuples. Then accessing s using b is dynamically relevant wrt γ and $\mathbf{T}_s$ iff

1. no tuple $t \in \mathbf{T}_s$ is such that $t[\mathcal{I}(s)] = b[\mathcal{I}(s)]$, and
2. no tuple $t \in \mathbf{T}_s$ is such that $t[\mathbf{A}] = b[\mathbf{A}]$ and $t[\mathbf{B} \cap \mathcal{I}(s)] \neq b[\mathbf{B} \cap \mathcal{I}(s)]$.

Example of dynamic optimization using SFWIDs

Static info

$s_1^{iio}(Code, Surname, City)$
$s_2^{ooi}(Code, Surname, City)$

SFWID: $s_1 \subseteq s_2$
FD: $s_2 : Code \rightarrow Surname, City$
Constants: *Rome* and *Kyoto*

Dynamic context

$s_1^D = s_2^D =$

Code	*Surname*	*City*
2	*brown*	*sidney*
5	*williams*	*london*
7	*yamakawa*	*kyoto*
1	*wakita*	*kyoto*
9	*marietti*	*rome*

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Any access to s_1^D with the new extracted constants is useless to discover new constants

Dynamic relevance and SFWIDs

Interaction of FDs and SFWIDs

Let Γ be the following set of dependencies:

$$s_1 \subseteq s_2$$
$$s_2 : \mathbf{C} \rightarrow \mathbf{D}$$

with $\mathbf{C} \subseteq \mathcal{I}(s_1)$ and $\mathbf{D} \supseteq \mathcal{I}(s_2)$.
Let b be a binding for s_1 and $\mathbf{T_{s_2}}$ a set of tuples.
Accessing s_1 with b is dynamically binding-relevant with respect to Γ and $\mathbf{T_{s_2}}$ iff there exists no tuple $t \in \mathbf{T_{s_2}}$ such that $t[\mathbf{C}] = b[\mathbf{C}]$.

Main result

Theorem

Let $\mathcal{S}$ be a schema of sources with fixed maximum arity. Let Γ be a set of FDs and SFWIDs on sources in $\mathcal{S}$.
Dynamic relevance of an access with respect to Γ can be checked in polynomial time in the number of

- *dependencies in Γ*
- *attributes in $\mathcal{S}$*
- *tuples already extracted from sources in $\mathcal{S}$*

Conclusion

Conclusion

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Conclusions

- Different approaches to the deep Web
  - Surfacing
  - Vertical integration
  - Large-scale on-the-fly data integration
- Different techniques for query answering under access limitations
  - finding the exact answer
  - finding best-effort approximations of the answer (maximally contained or minimally containing)
- Static optimization
  - exclusion of irrelevant sources
  - minimization of the accesses

Conclusions

- Conjunctive query containment under access limitations
  - reduction to decidable (limitation-free) cases of containment
  - direct analysis with the crayfish-chase
- Query rewriting with views under access limitations and integrity constraints
  - reduction to query answering under integrity constraints
- Dynamic optimization
  - excluding accesses deemed irrelevant during query answering
    - by dependencies on the schema (FDs and SFWIDs), and
    - knowledge of the already extracted tuples

Research directions

Taming the Web

- Improving on-the-fly data extraction
  - HTML parsing
  - Linguistic aspects
- Schema inference

Static optimization

- More expressive queries than "natural" CQs and connection queries
- Sources with multiple access patterns
- Query containment
  - Tight bounds, expressive query classes, constraints

Acknowledgments

Thanks to:

- Diego Calvanese
- Bertram Ludäscher
- The Search Computing (SeCo) project
- EPSRC "Schema mappings..." project

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