ANALYSIS OF BIG DATA ARCHITECTURES

Dimensions of Big Data architectures

- **Data model(s)**:
  - Relations, trees (XML, JSON), graphs (RDF, others…), nested relations
  - Query language
- **Heterogeneity** (DM, QL): none, some, a lot
- **Scale**: small (~10-20 sites) or large (~10.000 sites)
- **ACID** properties
- **Control**:
  - Single master w/complete control over N slaves (Hadoop/HDFS)
  - Sites publish independently and process queries as directed by single master/*mediator*
  - Many-mediator systems, or peer-to-peer (P2P) with *super-peers*
  - Sites completely independent (P2P)

Architectures we will cover

- Distributed databases
- Mediator (data integration) systems
- Dataspaces, data lakes

- Peer-to-peer data management systems
- Structured data management on top of MapReduce

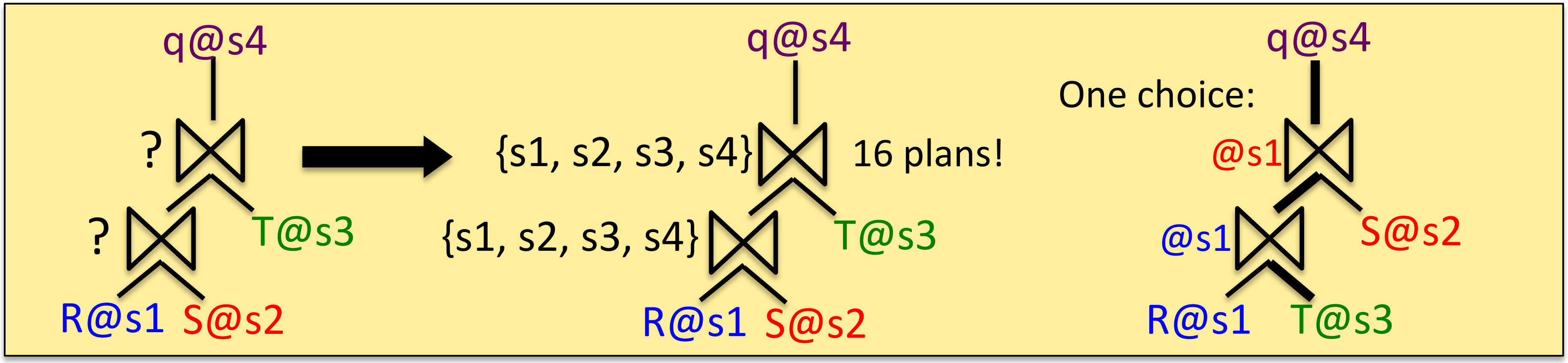
DISTRIBUTED RELATIONAL DATABASES

Distributed relational databases

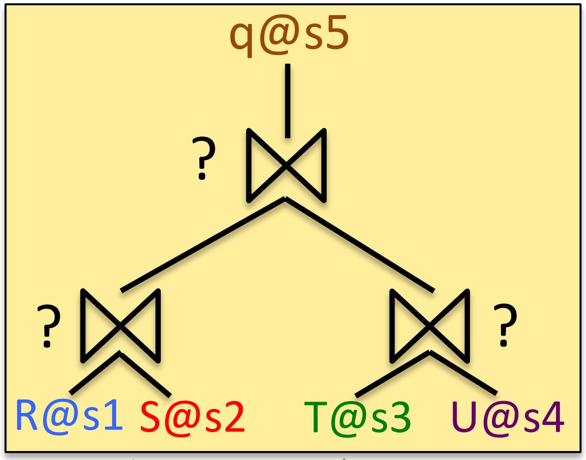
- Oldest distributed architecture ('70s): IBM System R*
- Illustrate/introduce the main priciples
- Data is distributed among many *nodes* (*sites*, *peers*...)
  - **Data catalog**: information on which data is stored where
    - Explicit : « All Paris sales are stored in Paris ». Horizontal/vertical table fragmentation Catalog stored at a master/central server.
    - Implicit: « Data is distributed by the value of the city » (« somewhere »)
- Queries are distributed (may come from any site)
- Query processing is distributed
  - Operators may run on different sites → network transfer
  - Another layer of complexity to the optimization process

Distributed query optimization

Example 1: R@s1, S@s2, T@s3, q@s4



Example 2: R@s1, S@s2, T@s3, U@s4, q@s5

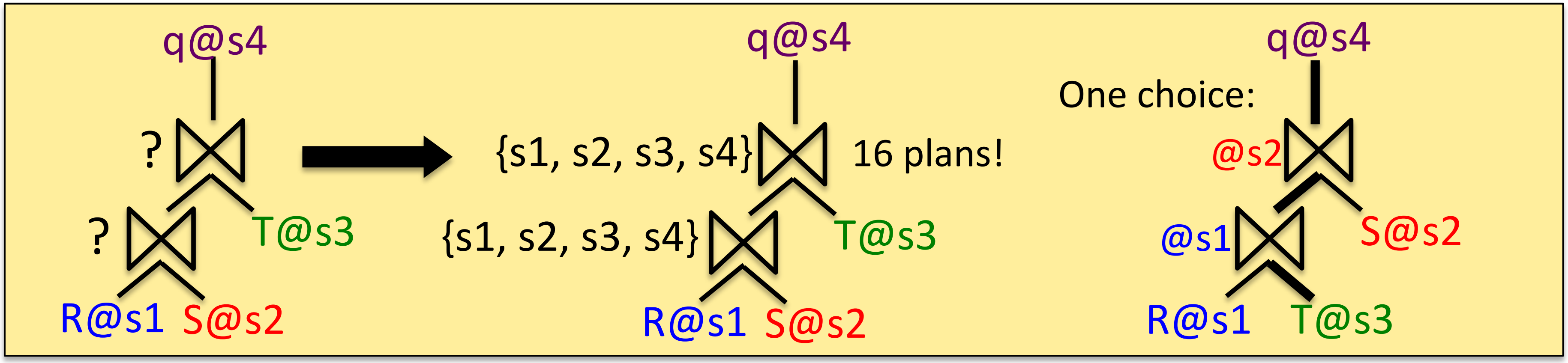


Plan pruning criteria if all the sites and network connections have equal performance:

- *Ship the smaller collection*

Distributed query optimization

Example 1: R@s1, S@s2, T@s3, q@s4



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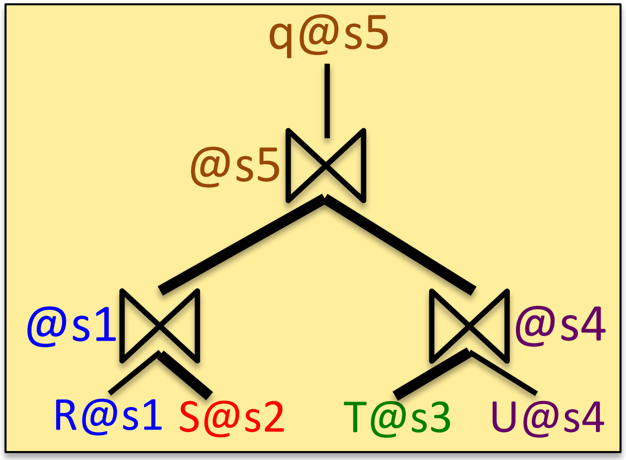

Plan pruning criteria if all the sites and network connections have equal performance:

- *Ship the* *<u>smaller</u>* *collection*
- *Transfer to join partner or the query site*

Distributed query optimization

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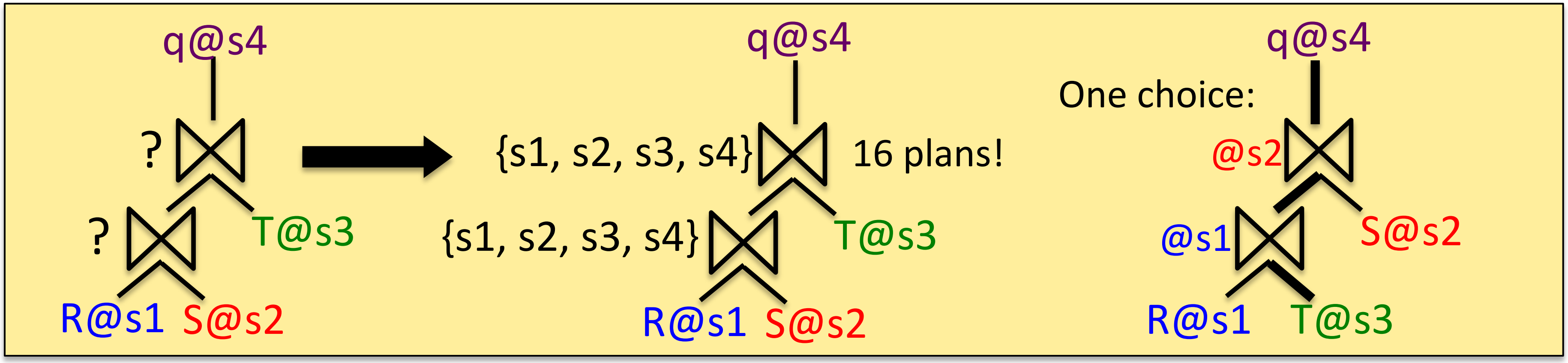

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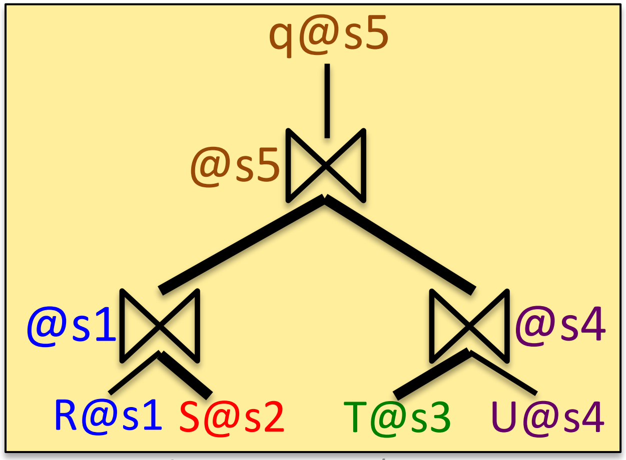


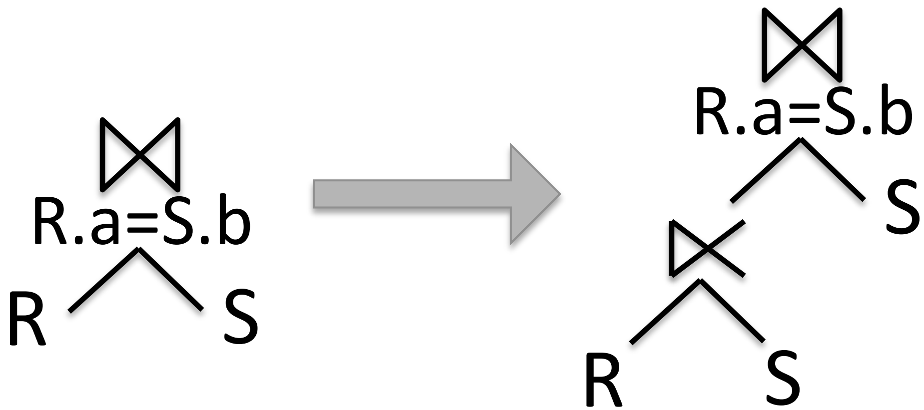
Plan pruning criteria if all the sites and network connections have equal performance:

- *Ship the smaller collection.*
- *Transfer to join partner or the query site*

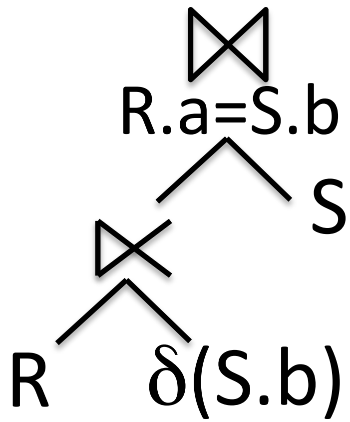
This plan illustrates total effort != response time

Distributed query optimization technique: semijoin reducers

- R join S = (R semijoin S) join S



Or, more exactly:



  - Useful in distributed settings to reduce transfers: *if the distinct S.b values* are smaller than *the non-matching R tuples*
  - Symetrical alternative: R join S = R join (S semijoin R)
  - This gives one more alternative in every join → search space explosion
  - Heuristics [Stocker, Kossmann et al., ICDE 2001]

Distribution of control in distributed relational DBs (1970s)

Servers DB1@site1: R1(a,b), S1(a,c)

Server DB2@site2: R2(a,b), S2(a,c),

Server DB3@site3: R3(a,b),
S3(a,c) defined as:

```
select * from DB1.S1 union all
select * from DB2.S2 union all
select R1.a as a, R2.b as c from DB1.R1 r1, DB2.R2 r2
where r1.a=r2.a
```

DB3@site3 decides what to import from site1, site2 (« hard links »)

Site1, site2 are independent servers

Also: replication policies, distribution etc. (usually with one or a few masters)

Modern distributed databases: H-Store (subsequently VoltDB), 2016

- From the team of Michael Stonebraker (Turing Award, author of the Postgres system)
  – H-Store: research prototype
  – VoltDB: commercial product issued from H-Store
- Main goal: quick OLTP (**o**nline **t**ransaction **p**rocessing), e.g., sales, likes, posts...
- Built to run on **cluster** for horizontal scalability

- **Share-nothing architectur**e: each node stores tables **shards** (+ k replication for durability)

Frequent concept in Big Data architectures: shards

- **Shard** = small fragment of a data collection (e.g., a table)
- The assignment of data items (e.g. tuples) into shards is often done by **hashing** on tuple key
  - The table must have at least one key
  - Hashing ensures (with high probability) uniform distribution

- Key-based hashing is used as a mechanism for implementing distributed data catalogs. We will encounter it often.

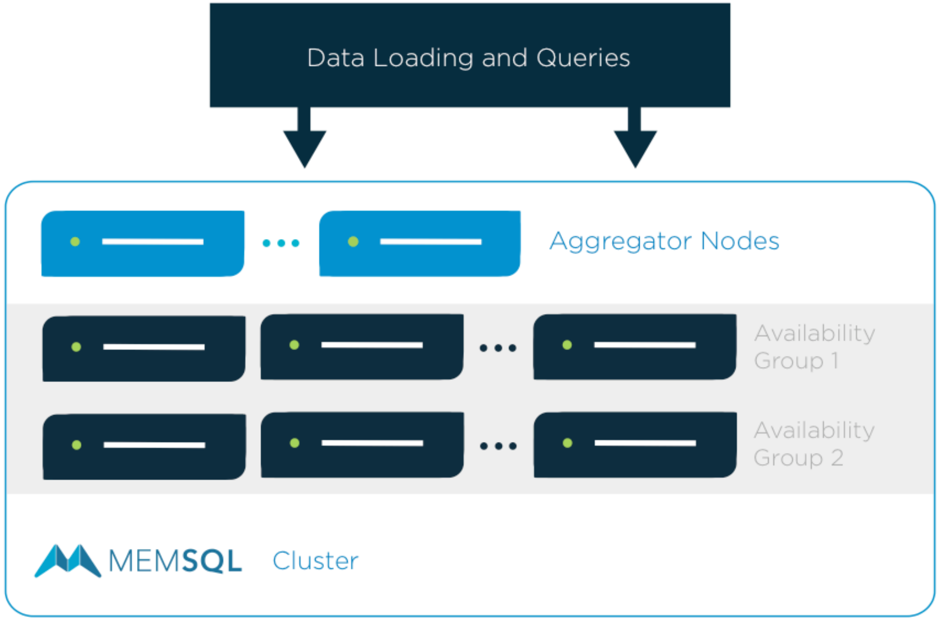
H-Store transactions

- Applications call **stored procedures** = code which also contains SQL queries
  – Each contained SQL query is partially unknown (depends on parameters specified at runtime); H-Store "pre-optimizes" it
- 1 **transaction** = 1 call of a stored procedure
- Can be submitted to any node, together with parameters
- The node can run the procedure up to the query(ies) → updated, completely known plan → transaction manager

Modern distributed RDB: MemSQL (2013)

MemSQL runs with

- a **master aggregator**, responsible of the metadata (catalog)
- possibly more aggregators
- at least one **leaf**, each of which stores part(s) of some table(s)
- In each leaf, there are **partitions** (by default: 1 per CPU core)



Availability group: a set of machines + a set of replica machines (one-to-one)

Query processing in MemSQL

- **Indexes** managed within each partition
- In general, every query is run with a level of parallelism equal to the number of partitions

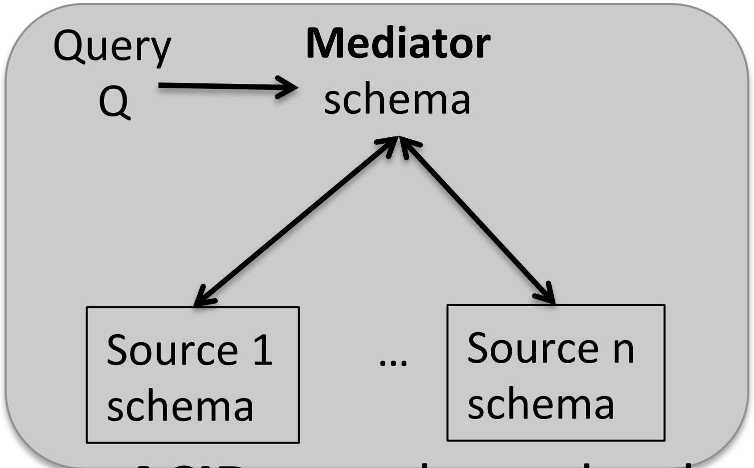
- **Select** queries are executed by the leaves which hold some partition(s) with data matching the query
- **Aggregation** queries run at the leaves involved and at the aggregator(s)
- **Join** queries
  - Easy if one input is a *reference* (small) table: one that is replicated fully to every machine in the cluster
  - Otherwise, they recommend **sharing the shard key across tables to be joined**
    - Also called **co-partitioning**, we will be seeing this again
  - Otherwise, joins will incur data transfer within the cluster.

MEDIATOR SYSTEMS

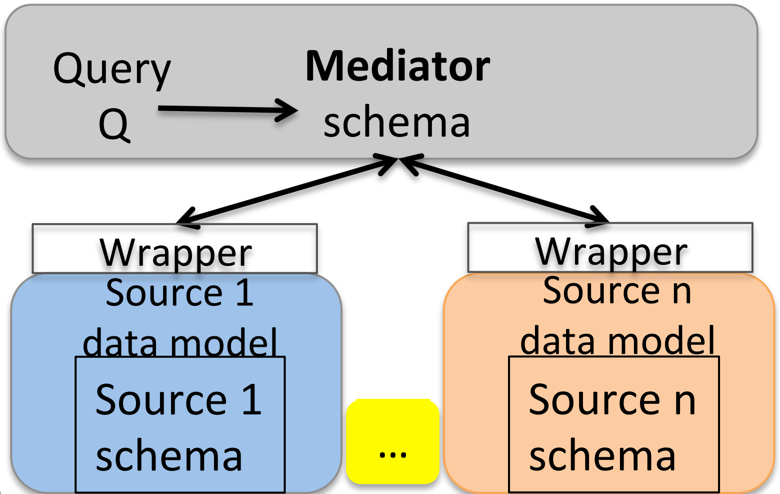
Mediator systems

- A set of **data sources**, each with: data model, query language, and schema (also called source schemas).
  - DM and QL may differ across sources
- A **mediator** with its own DM, QL and mediator schema
- Queries are asked against the mediator schema

Common data model (sources+mediator)



Mediator data model



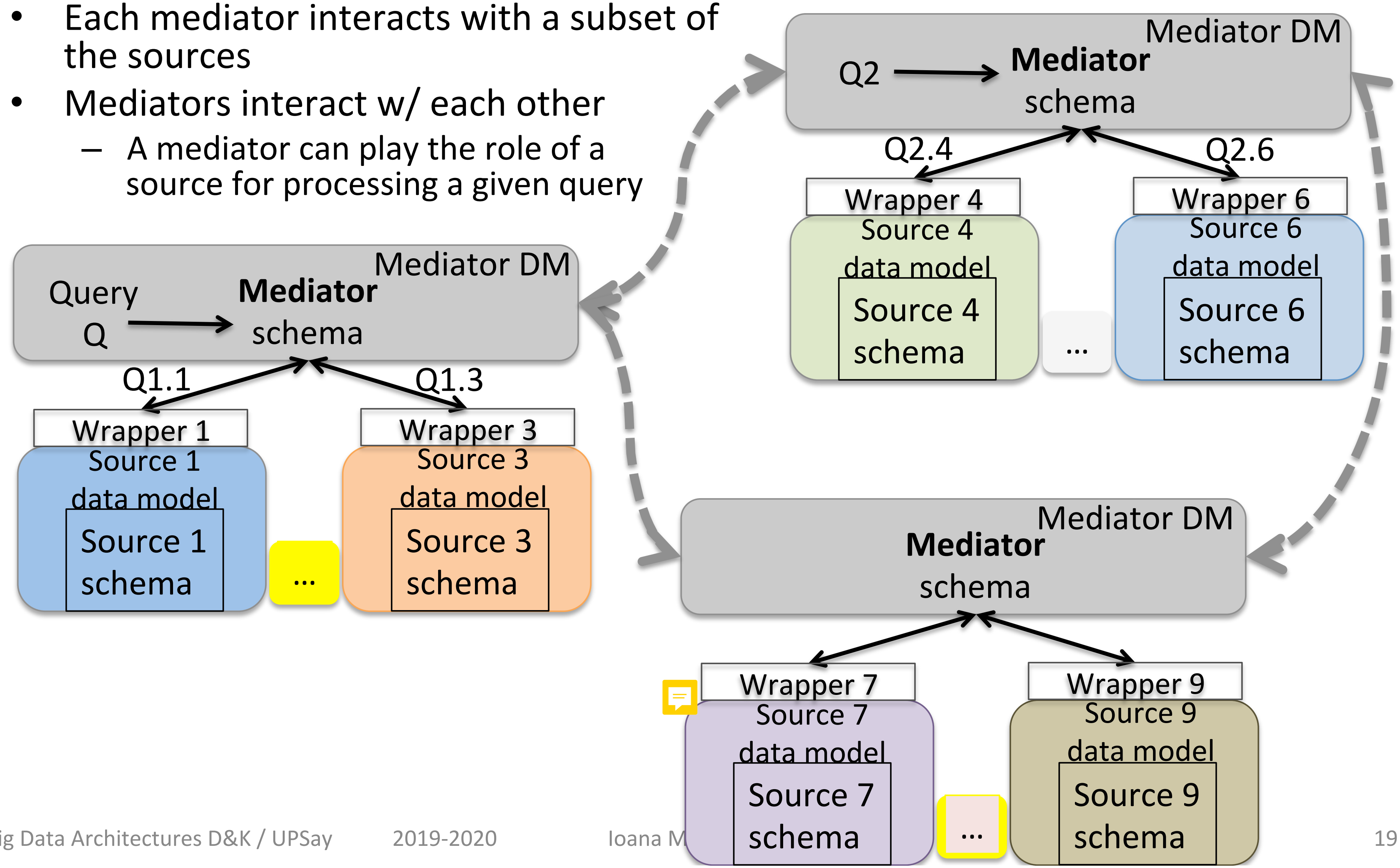
- **ACID**: mostly read-only; **size**: small
- **Control**: Independent publishing; mediator-driven integration

EXAMPLE: TATOOINE DEMO

[VLDB 2016, [HTTPS://TEAM.INRIA.FR/CEDAR/TATOOINE/](https://team.inria.fr/cedar/tatooine/)]

Many-mediator systems

- Each mediator interacts with a subset of the sources
- Mediators interact w/ each other
  - A mediator can play the role of a source for processing a given query



Many-mediator systems

- Each mediator interacts with a subset of the sources
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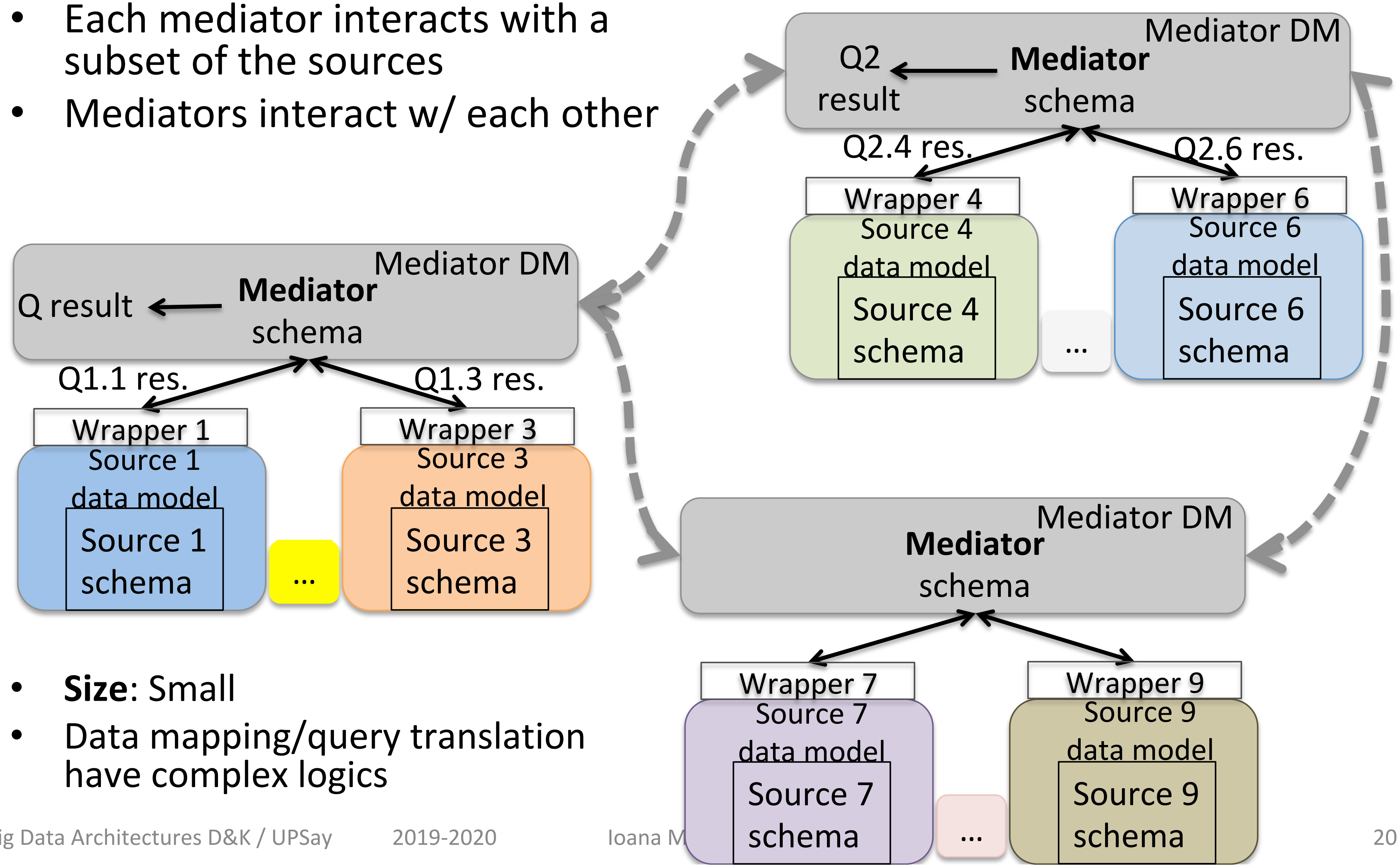
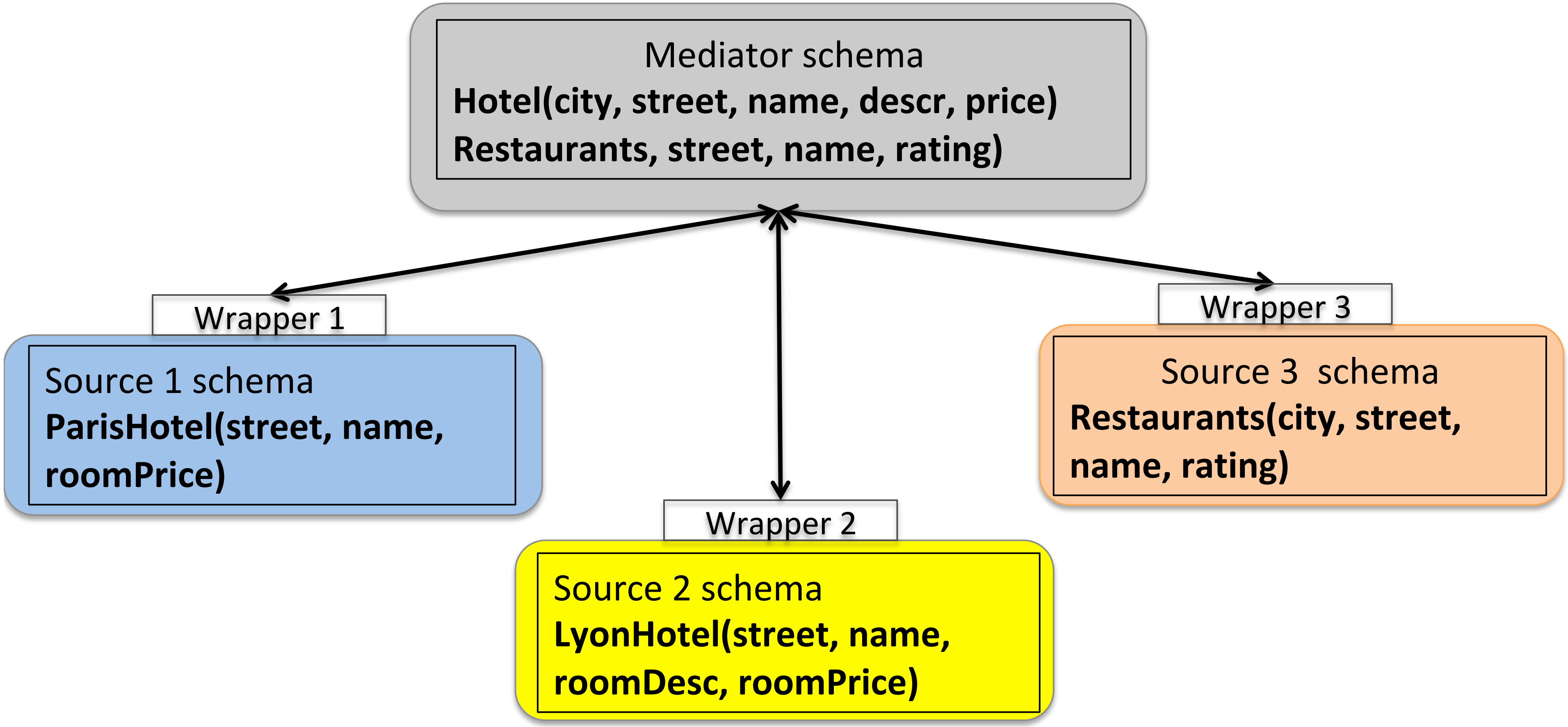


- **Size**: Small
- Data mapping/query translation have complex logics

Connecting the source schemas to the global schema

- Sample scenario:



Connecting the source schemas to the global schema

- Data only exists in the sources.
- Applications only have access to, and only query, the mediator schema.

- How to express the **relation** between
  - the **mediator schema** acccessible to applications, and
  - the **source schemas** reflecting the real data
  - so that a query over the mediator schema can be **automatically translated** into a query over the source schemas?
- Three approaches exist (see next)

Connecting the source schemas to the global schema: Global-as-view (GAV)

s1:ParisHotels(street, name, roomPrice)
s2:LyonHotel(street, name, roomDesc, roomPrice)
s3:Restaurant(city, street, name, rating)
Global: Hotel(city, street, name, descr, price),
Restaurant(city, street, name, rating)

<u>Defining **Hotel** as a view over the source schemas:</u>

define view Hotel as
select 'Paris' as city, street, name, null as roomDesc, roomPrice as price
from s1:ParisHotels

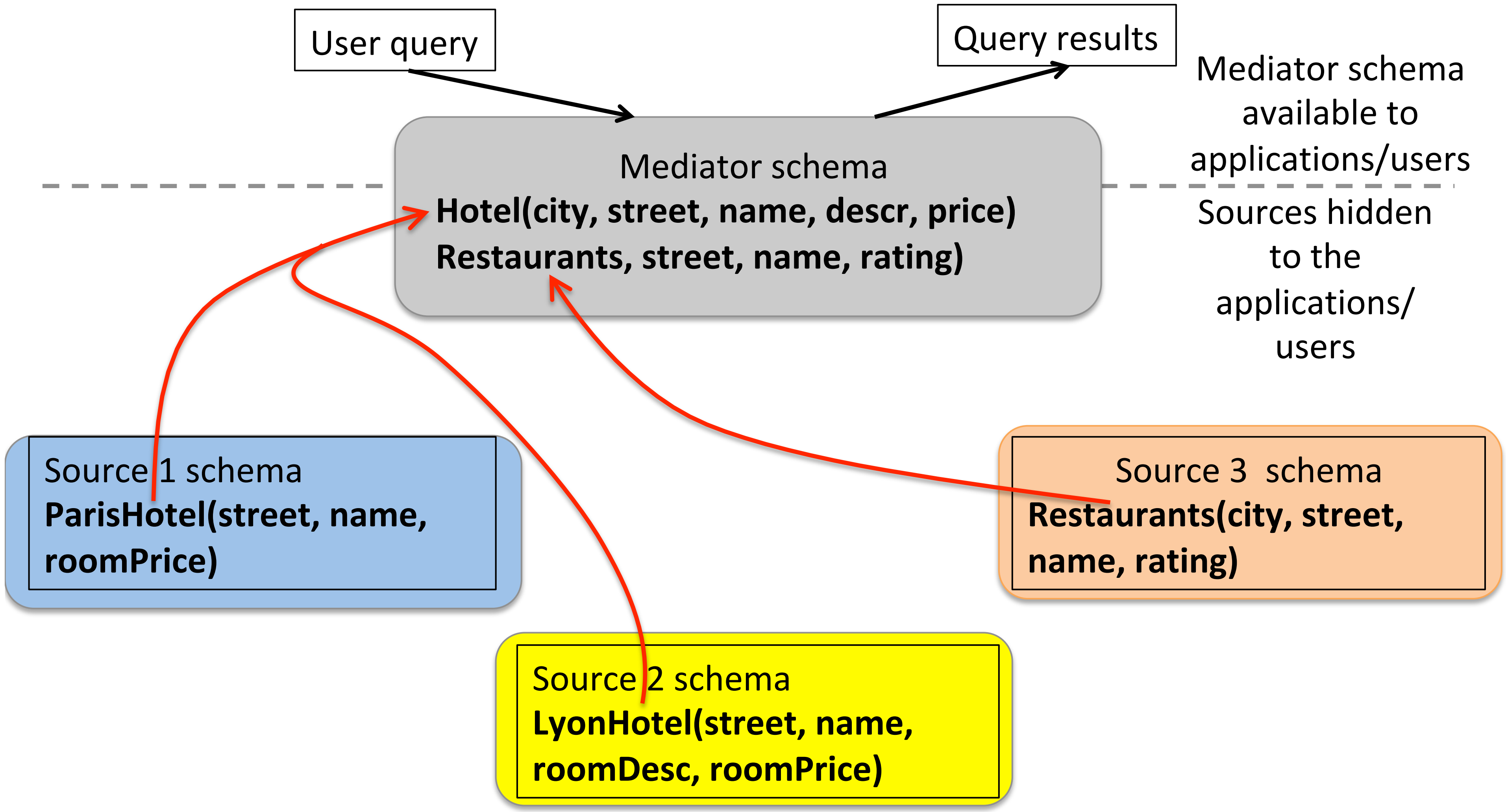
union all

select 'Lyon' as city, street, name, descr as roomDesc, price
from s2:LyonHotel

<u>Defining **Restaurant** as a view over the source schemas:</u>

define view Restaurant as select * from s3:Restaurant

Connecting the source schemas to the global schema: Global-as-View



Query processing in global-as-view (GAV)

define view **Hotel** as
select 'Paris' as city, street, name, null as roomDesc, roomPrice as price
from s1:ParisHotels

union all

select 'Lyon' as city, street, name, descr as roomDesc, price
from s2:LyonHotel

Query:

select * from Hotel where city='Paris' and price<200 *becomes*:

select * from (select 'Paris' as city... union... select 'Lyon' as city...)
where city='Paris' and price < 200 *which becomes:*
select * from (select 'Paris' as city...)
where city='Paris' and price < 200 *which becomes:*
select * from s1:ParisHotels where price < 200

Query processing in global-as-view (GAV)

define view **Hotel** as
select 'Paris' as city, street, name, null as roomDesc, roomPrice as price
from s1:ParisHotels

union all

select 'Lyon' as city, street, name, descr as roomDesc, price from s2:LyonHotel

define view **Restaurant** as select * from s3:Restaurant

Query:

select h.street, r.rating from Hotel h, Restaurant r where h.city=r.city and r.city='Lyon' and and h.street=r.street and h.price<200 *becomes:*

select h.street, r.rating from (select 'Paris' as city... from s1:ParisHotels

union all select 'Lyon' as city... from s2:LyonHotel) h, (select * from s3:Restaurant) r where h.city=r.city and r.city='Lyon' and h.street=r.street and h.price<200

which becomes:

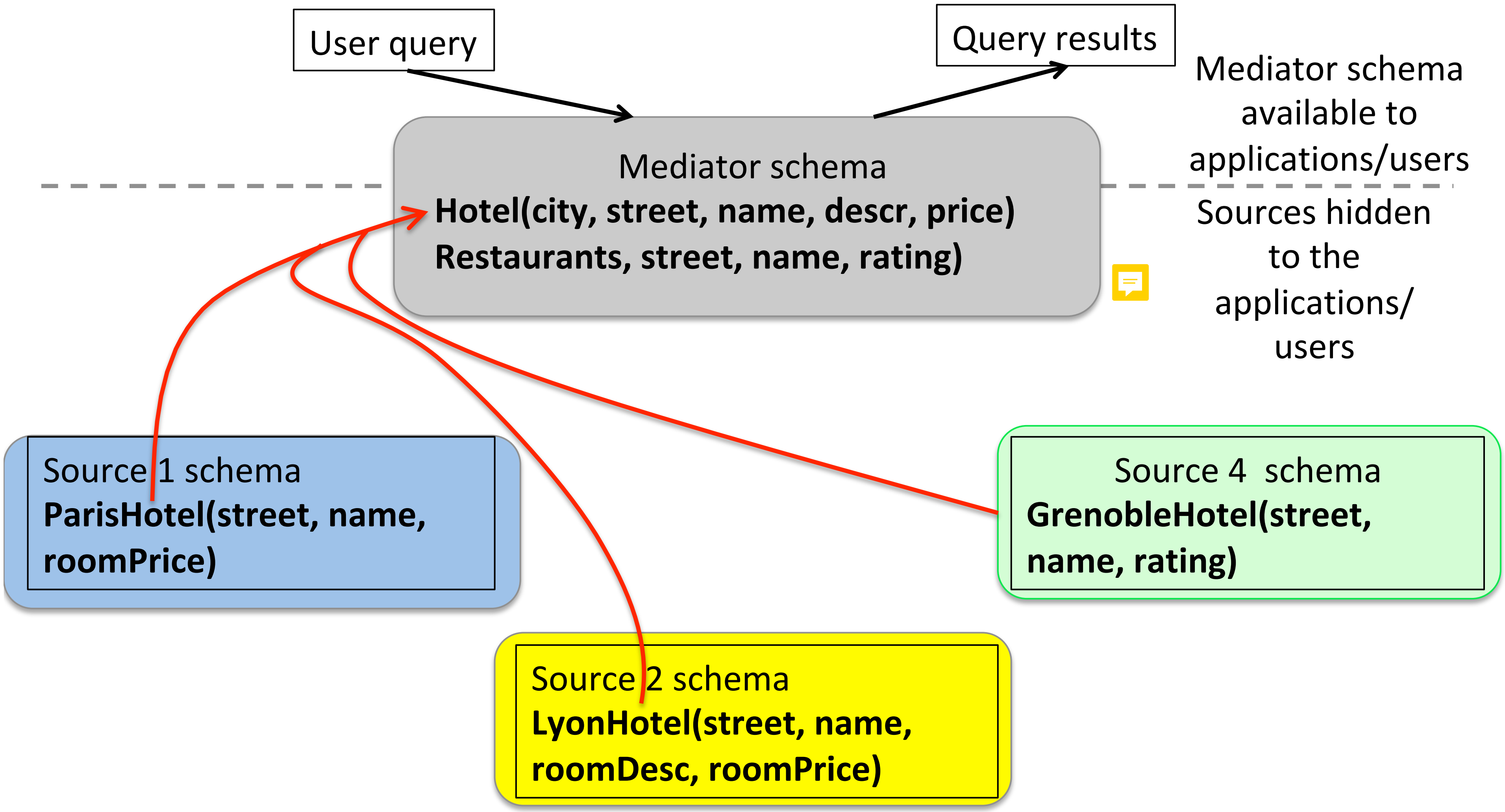
select h.street,r.rating from (select ... from s2:LyonHotel) h, s3:Restaurant r where r.city='Lyon' and h.street=r.street and h.price<200 *which becomes:*

select h.street, r.rating from s2:LyonHotel h, s3.Restaurant r where r.city='Lyon' and h.price<200 and h.street=r.street

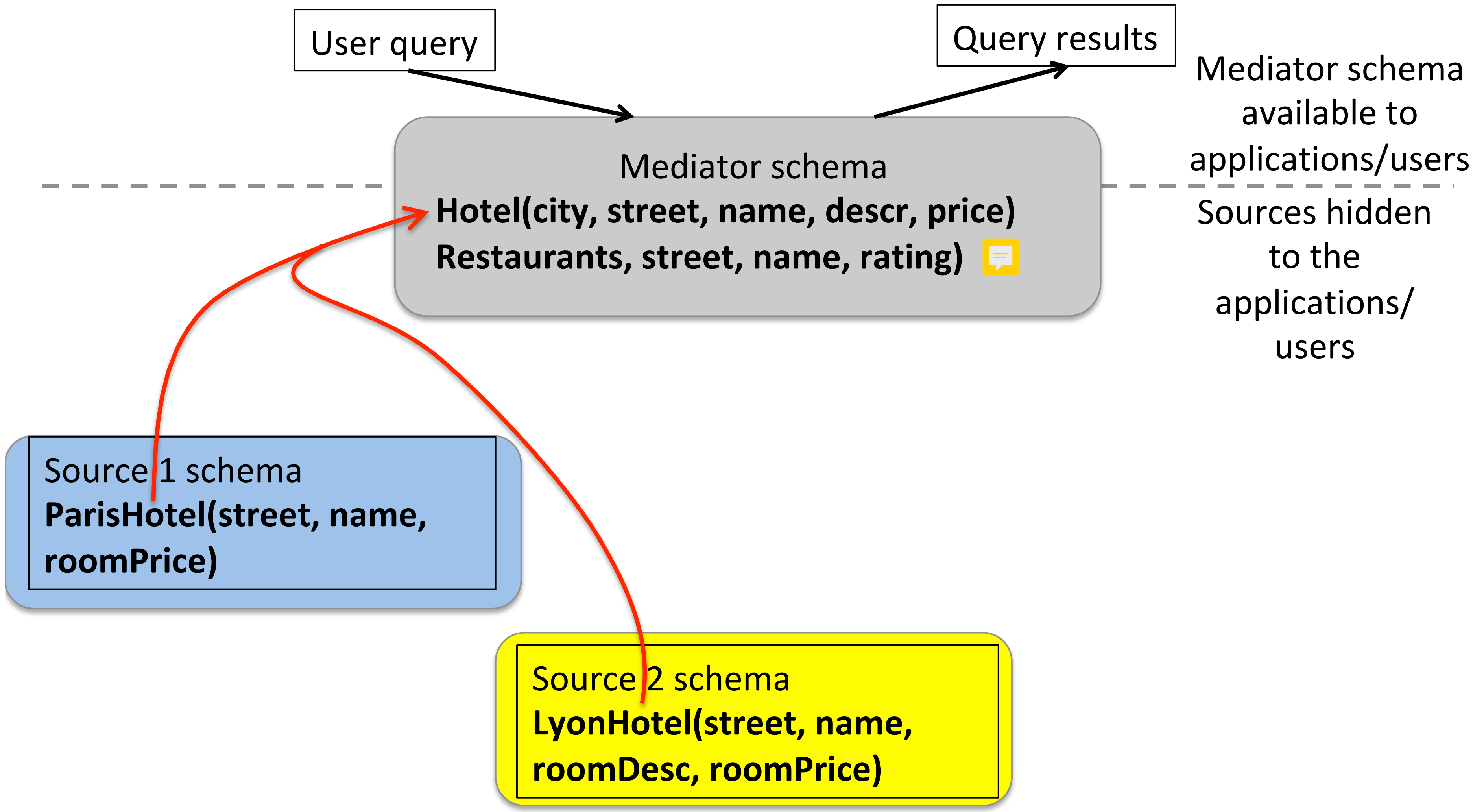
Concluding remarks on global-as-view (GAV)

- Query processing = **view unfolding**: replacing the view name with its definition and working out simple equivalences from there
  - Allows to push to each data source as much as it can do (trusted heuristic)
- **Weakness**: changes in the data sources require changes of the global schema
  - In the worst case, all applications written based on this global schema need to be updated
  - Hard to maintain

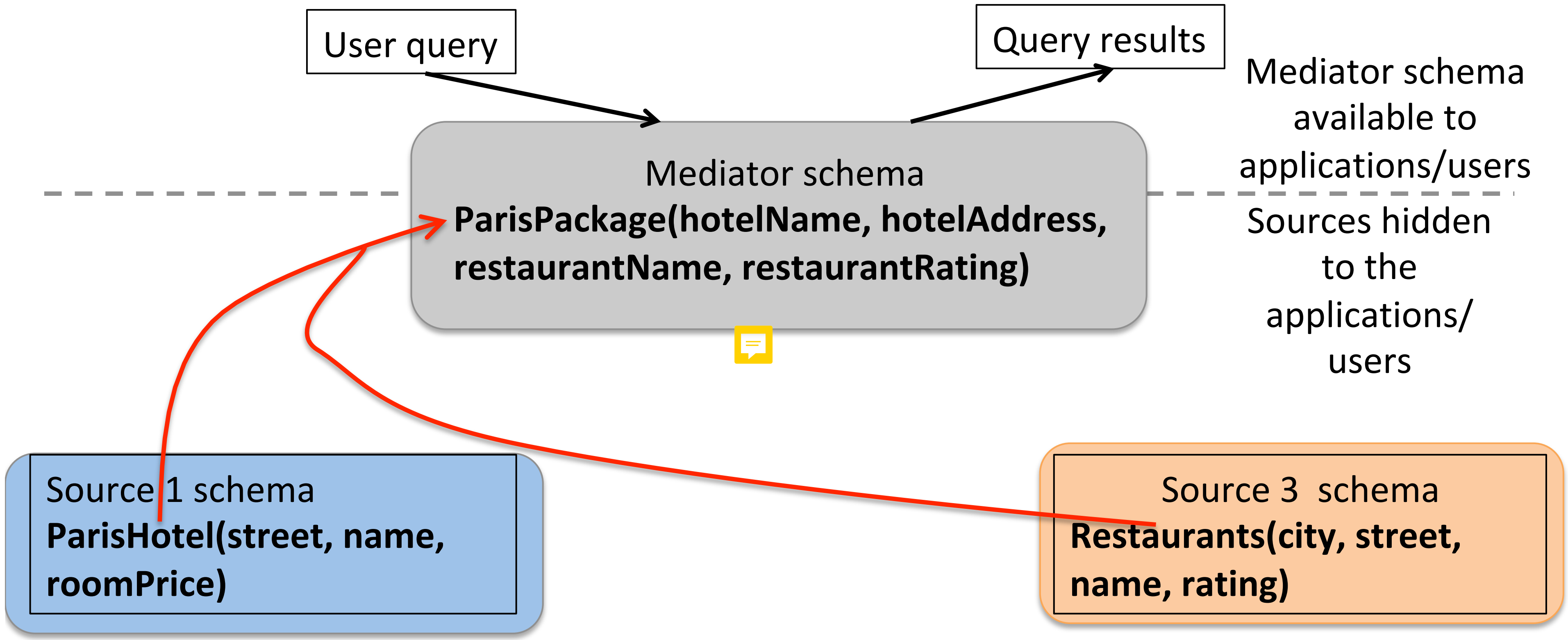
Global-as-View: Adding a new source



Global-as-View: Removing a source (1)



Global-as-View: removing a source (2)



If **Source3.Restaurant** withdraws, the **ParisPackage** relation in the global schema becomes empty; applications cannot even access **Source1.ParisHotels**, even though they are still available.

Connecting the source schemas to the global schema: Local-as-view (LAV)

s1:ParisHotel(street, name, roomPrice)

s2:LyonHotel(street, name, roomDesc, roomPrice)

s3:Restaurant(city, street, name, rating)

Global: Hotel(city, street, name, descr, price), **Restaurant**(city, street, name, rating)

<u>Defining **s1:ParisHotels** as a view over the global schema:</u>

```
define view s1:ParisHotels as
select street, name, price as roomPrice
from Hotel where city='Paris'
```

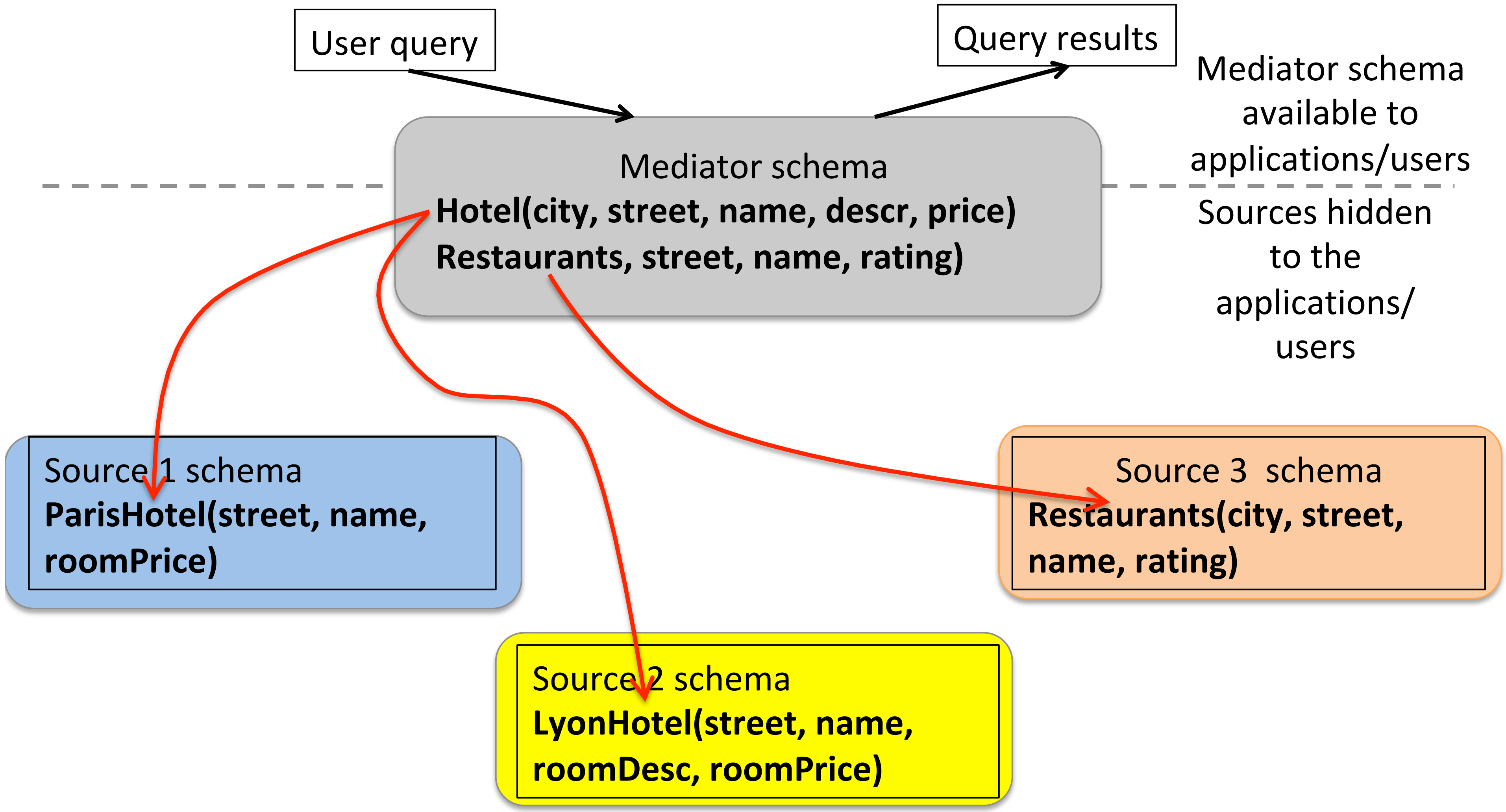
<u>Defining **s2:LyonHotel** as a view over the global schema:</u>

```
define view s2:LyonHotel as
select street, name, descr as roomDesc, price as roomPrice
from Hotel where city='Lyon'
```

<u>Defining **s3:Restaurant** as a view over the global schema:</u>

```
define view s3:Restaurant as
select * from Restaurant
```

Connecting the source schemas to the global schema: Local-as-View



GAV and LAV have different expressive power

- **Some GAV scenarios cannot be expressed in LAV**
- Example:
  create view **ParisPackage** as
  select ph.name as hotelName, ph.street as hotelAddress,
  r.name as restaurantName, r.rating as restaurantRating
  from s1:ParisHotel ph, s3:Restaurants r
  where r.city='Paris' and r.street=ph.street
- The view only contains (hotel, restaurant) pairs that are on the same street
- It is not possible to express this with LAV mappings
  - LAV describes each source *individually* w.r.t. the global schema
  - Not in correlation with data available in *other sources*

GAV and LAV have different expressive power

- There exist **LAV scenarios that cannot be expressed in GAV**
- Example:
  - Not possible to express in GAV that s1:ParisHotels only has data about Paris, while s2:LyonHotel only has data from Lyon
  - A query about hotels in Paris will also be sent to s2, although it will bring no results
  - LAV query processing avoids this (see next)

GAV and LAV have different expressive power

- There exist **GAV scenarios that cannot be expressed in LAV**
- Example:

  create view **ParisPackage** as
  select ph.name as hotelName, ph.street as hotelAddress, r.name as restaurantName, r.rating as restaurantRating
  from s1:ParisHotel ph, s3:Restaurants r
  where r.city='Paris' and r.street=ph.street

- The closest we can do is define s1.ParisHotel and s3.Restaurants *each* as a projection over ParisPackage
- But this changes the semantics of ParisPackage:
  - It does not express that *only Paris restaurants* are in ParisPackage
  - Not possible to express that only (hotel, restaurants) *on the same street* are available through the integration system
  - ParisPackage becomes the cartesian product of ParisHotel with all restaurants...

Query processing in Local-as-View (LAV)

define view **s1:ParisHotels** as
select street, name, price as roomPrice
from Hotel where city='Paris'
define view **s2:LyonHotel** as
select street, name, descr as roomDesc, price as roomPrice
from Hotel where city='Lyon'
define view **s3:Restaurant** as
select * from Restaurant

Query:
select h.street, h.price, r.rating
from Hotel h, Restaurant r
where r.city=h.city and h.street=r.street

Query processing in Local-as-View (LAV)

define view **s1:ParisHotels** as
select street, name, price as roomPrice
from Hotel where city='Paris'
define view **s2:LyonHotel** as
select street, name, descr as roomDesc, price as roomPrice from Hotel where city='Lyon'
define view **s3:Restaurant** as
select * from Restaurant

Step 1: identify potentially useful views

Query:
select h.street, h.price, r.rating from Hotel h, Restaurant r where r.city=h.city and h.street=r.street

Query processing in Local-as-View (LAV)

Query:
select h.street, h.price, r.rating from Hotel h, Restaurant r
where r.city=h.city and h.street=r.street

Step 2: generate **view combinations** that may be used to answer the query (one view for each table in the query):

- **s1:ParisHotels and s3:Restaurant**
- s2:LyonHotels and s3:Restaurant

Step 3: for each view combination and each view, check:

- If the view returns the attributes we need:
  - Those returned by the query, *and*
  - Those on which possible query joins are based
- If the view selections (if any) are compatible with those of the query
- If one condition is not met, discard the view combination.

define view s**1:ParisHotels** as
select street, name, price as roomPrice
from Hotel where city='Paris'

The query needs:

- street, price, rating (returned): the view provides them
- city and street for the join: street is provided, city is not (but it is a constant, thus known)

The view has a selection on the city which the query did not have → The view provides part of the query result, but does not contradict the query.

The view s1:ParisHotels is OK.

define view s3:Restaurant as select * from Restaurant

The view s3:Restaurants is OK.

The view combination s1:ParisHotels, s3:Restaurants is OK provided that Restaurant.city is set to Paris.

Query processing in Local-as-View (LAV)

Query:
select h.street, h.price, r.rating from Hotel h, Restaurant r
where r.city=h.city and h.street=r.street

Step 2: generate **view combinations** that may be used to answer the query (one view for each table in the query):

s1:ParisHotels and s3:Restaurant

s2:LyonHotels and s3:Restaurant

Step 3: for each view combination and each view, check:

[...]

If one condition is not met, discard the view combination.

Step 4: for each view combination, add the necessary joins among the views, possibly selections and projections → rewriting

Query rewriting using s1:ParisHotels and s3:Restaurant:

select h.street, h.price, r.rating

from s1:ParisHotels h and s3:Restaurant r

where r.city='Paris' and h.street=r.street

This is a partial rewriting, and so is:

Query rewriting using s2:LyonHotel and s3:Restaurant:

select h.street, h.price, r.rating

from s2:LyonHotels h and s3:Restaurant r

where r.city='Lyon' and h.street=r.street

Query processing in Local-as-View (LAV)

Query:
select h.street, h.price, r.rating from Hotel h, Restaurant r
where r.city=h.city and h.street=r.street

Step 2: generate **view combinations** that may be used to answer the query (one view for each table in the query):

s1:ParisHotels and s3:Restaurant

s2:LyonHotels and s3:Restaurant

Step 3: for each view combination and each view, check:

[...]

If one condition is not met, discard the view combination.

Step 4: for each view combination, add the necessary joins among the views, possibly selections and projections → rewriting

Step 5: return the union of the rewritings thus obtained

Full query rewriting:

select h.street, h.price, r.rating
from **s1:ParisHotels** h and **s3:Restaurant** r
where r.city='Paris' and h.street=r.street
union all
select h.street, h.price, r.rating
from **s2:LyonHotel** h and **s3:Restaurant** r
where r.city='Lyon' and h.street=r.street

Query processing in Local-as-View (LAV)

define view s1:ParisHotels as... from Hotel where city='Paris'
define view s2:LyonHotel as... from Hotel where city='Lyon'
define view s3:Restaurant as select * from Restaurant

Query:
select h.street, h.price, r.rating
from Hotel h, Restaurant r
where r.city=h.city and h.street=r.street

Rewriting of the query using the views:

select h1.street, h1.price, r3.rating
from s1:ParisHotels h1, s3:Restaurant r3
where h1.city=r3.city and h1.street=r3.street

union all

select h2.street, h2.price, r3.rating
from s2:LyonHotels h2, s3:Restaurant r3
where h2.city=r3.city and h2.street=r3.street

Concluding remarks on Local-as-View (LAV)

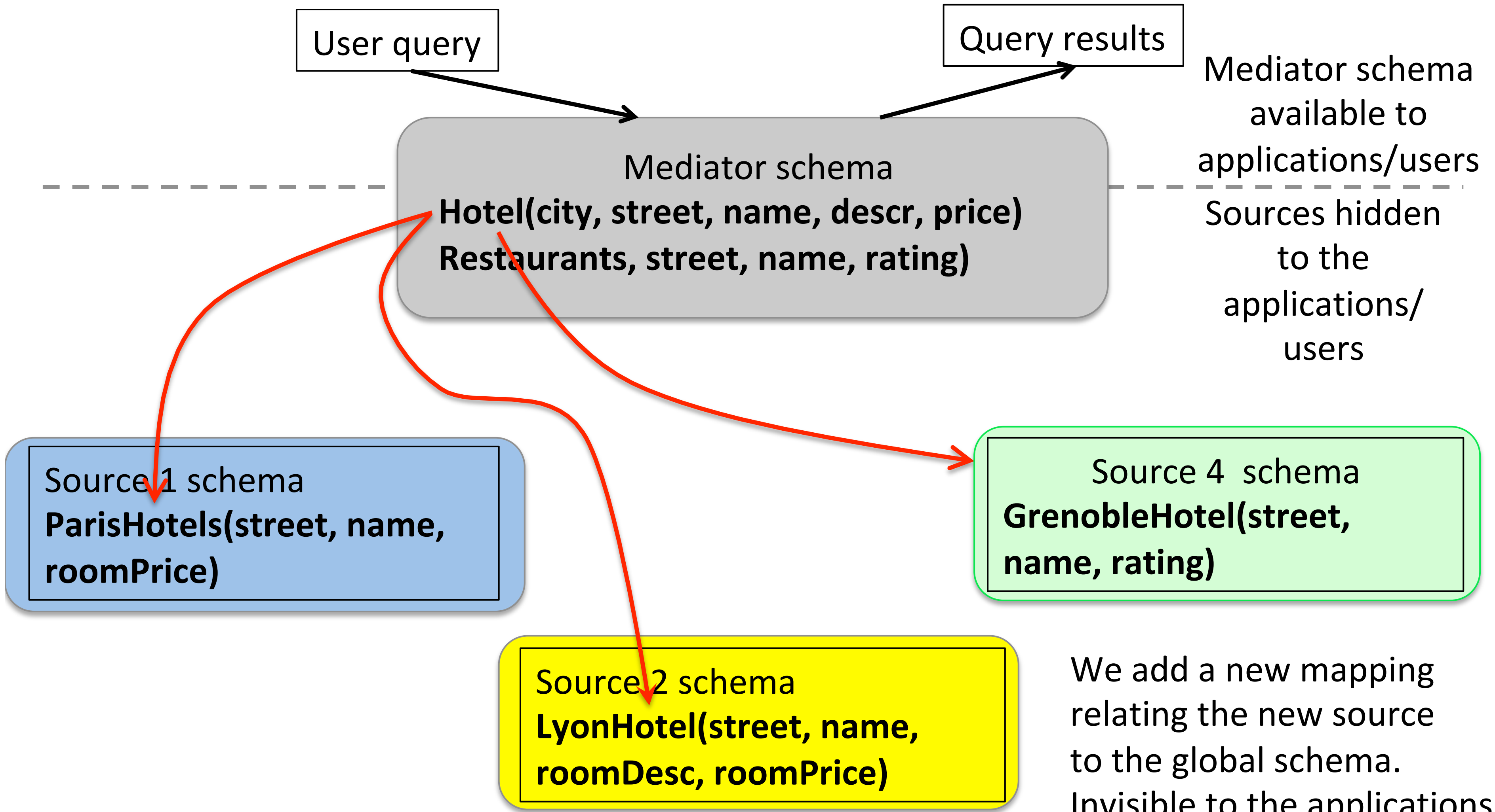
Query processing

- The problem of finding all rewritings given the source and global schemas and the view definitions = **view-based query rewriting**, NP-hard in the size of the (schema+view definitions).
  - These are often much smaller than the data

The schema definition is **more robust**:

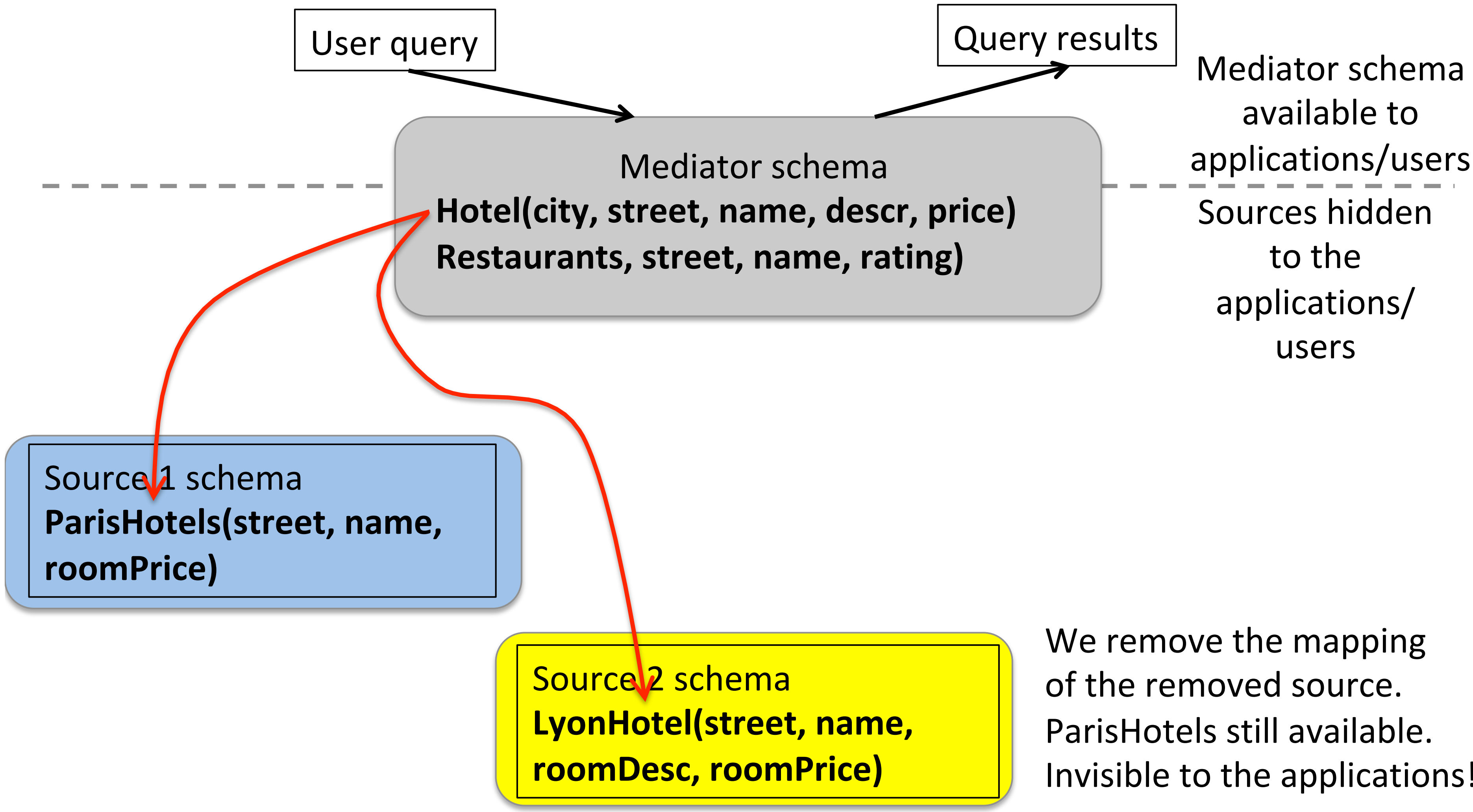
- One can independently add/remove sources from the system without the global schema being affected at all (see next)
- Thus, no application needs to be aware of the changes in the schema

Local-as-View: adding a new source



We add a new mapping relating the new source to the global schema. Invisible to the applications!

Local-as-View: Removing a source



We remove the mapping of the removed source.
ParisHotels still available.
Invisible to the applications!

Connecting the source schemas to the global schema: Global-Local-as-View (GLAV)

Generalizes both GAV and LAV

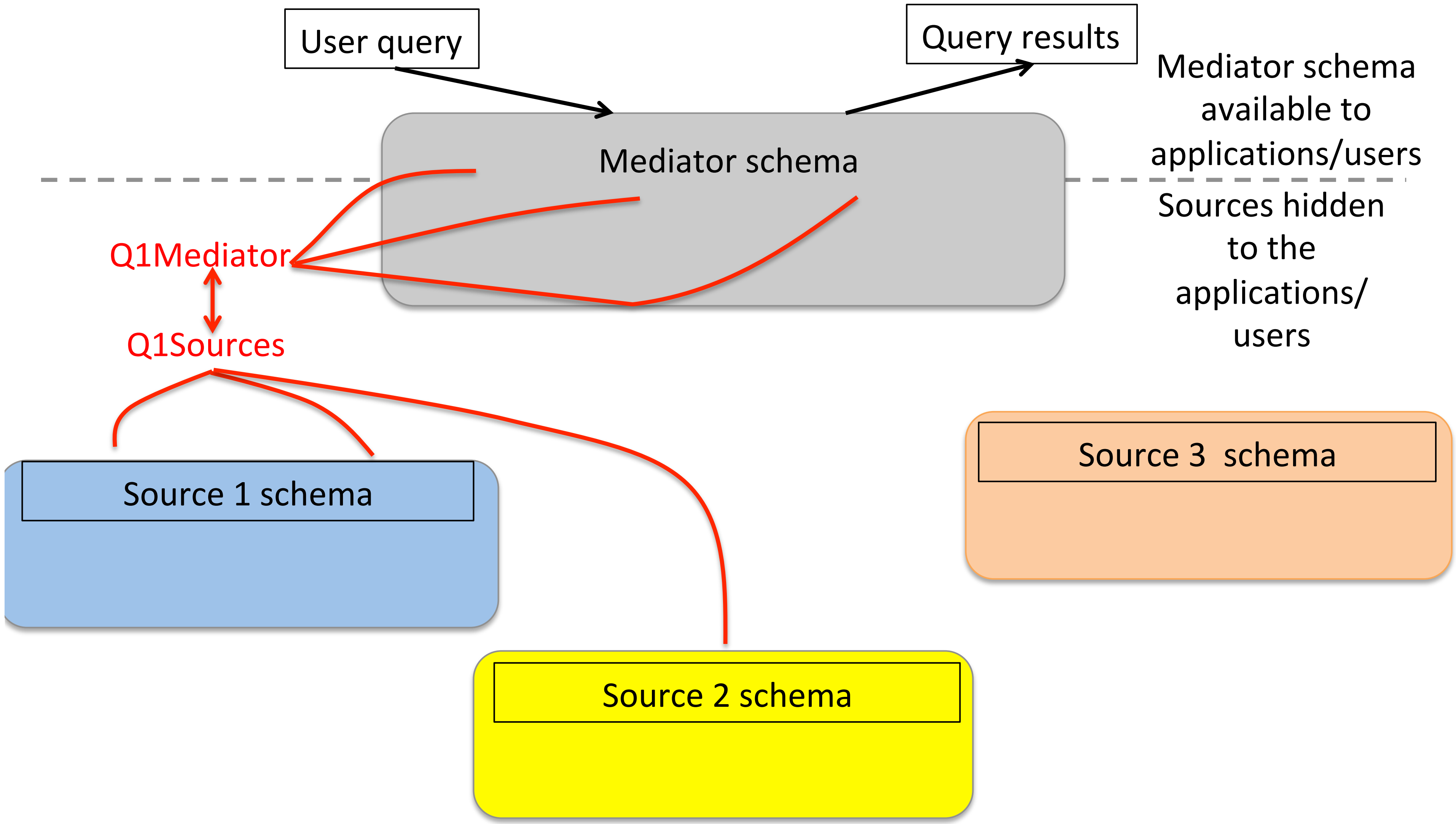
1 mapping = 1 pair (query over 1 or several sources schemas,
query over the mediator schema)

Q1Mediator(m:r1, m:r2, m:r3, ...) ←→ Q1Sources(s1:t1, s2:t1, ...) Q2Mediator(m:r1, m:r2, m:r3, ...) ←→ Q2Sources(s1:t1, s2:t1, ...) Q2Mediator(m:r1, m:r2, m:r3, ...) ←→ Q3Sources(s1:t1, s2:t1, ...)

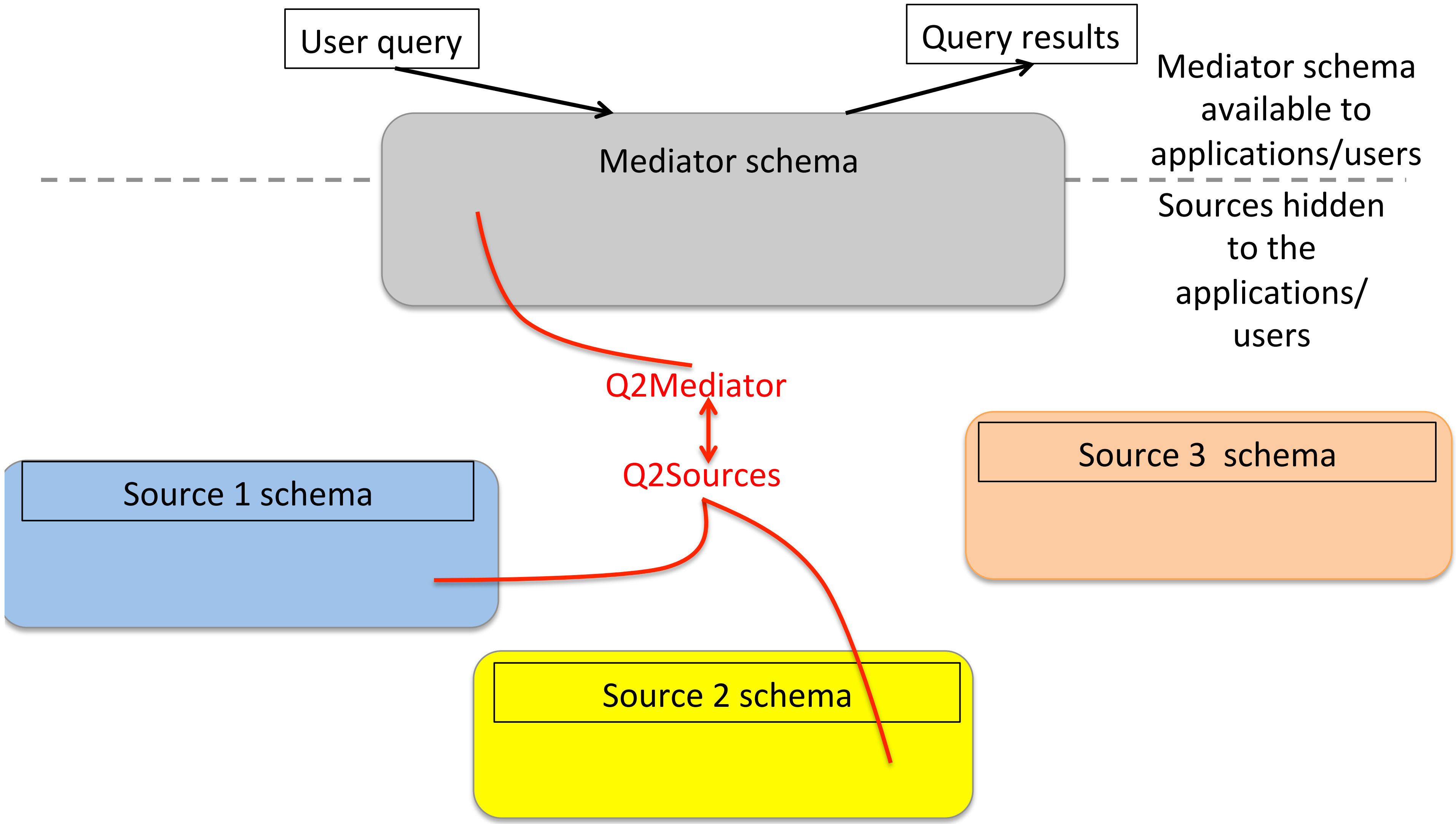
Semantics: there is a tuple in QiMediator(...) for each result of QiSources(...)

- A GAV mapping is a particular case of GLAV mapping where QMediator is exactly one mediator relation
- A LAV mapping is a particular case of GLAV mapping where QSources is exactly one source relation

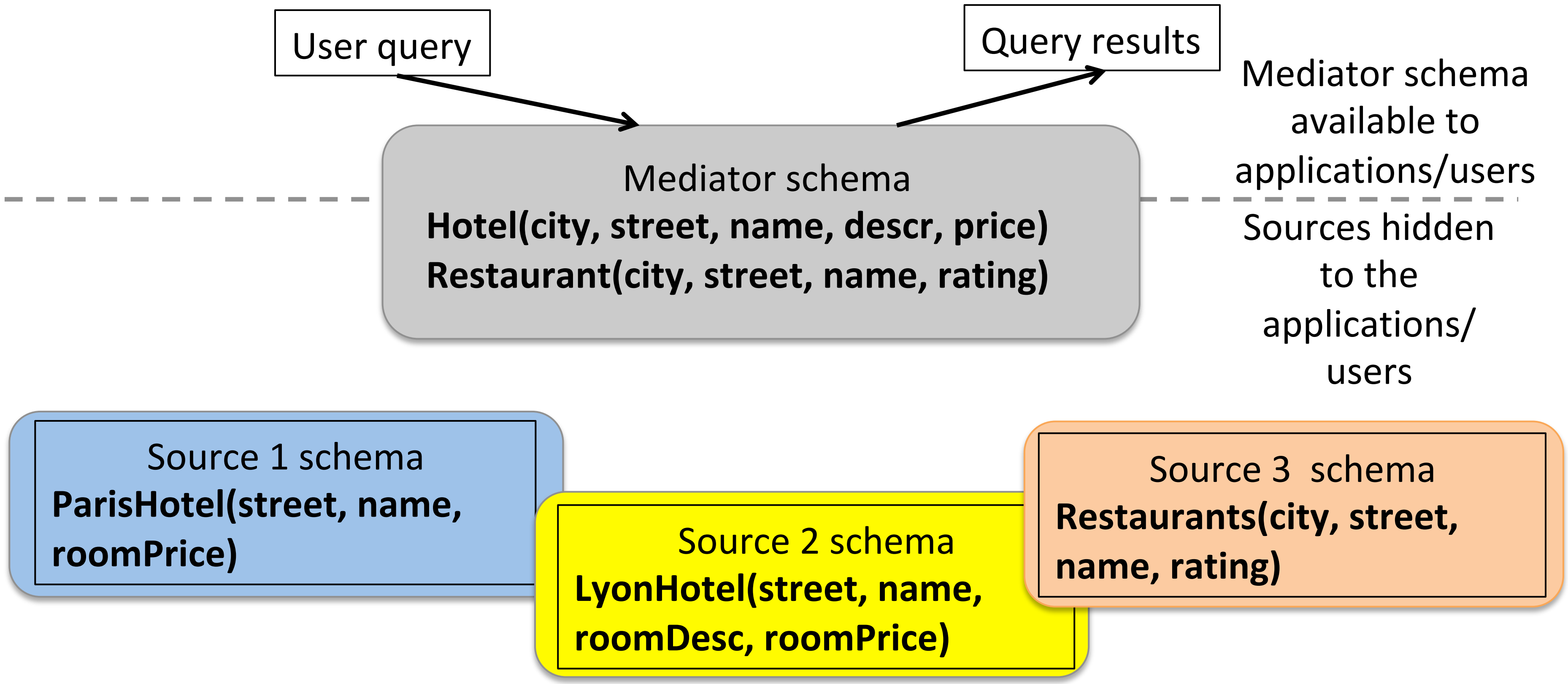
Connecting the source schemas to the global schema: Global-Local-as-View (GLAV)



Connecting the source schemas to the global schema: Global-Local-as-View (GLAV)

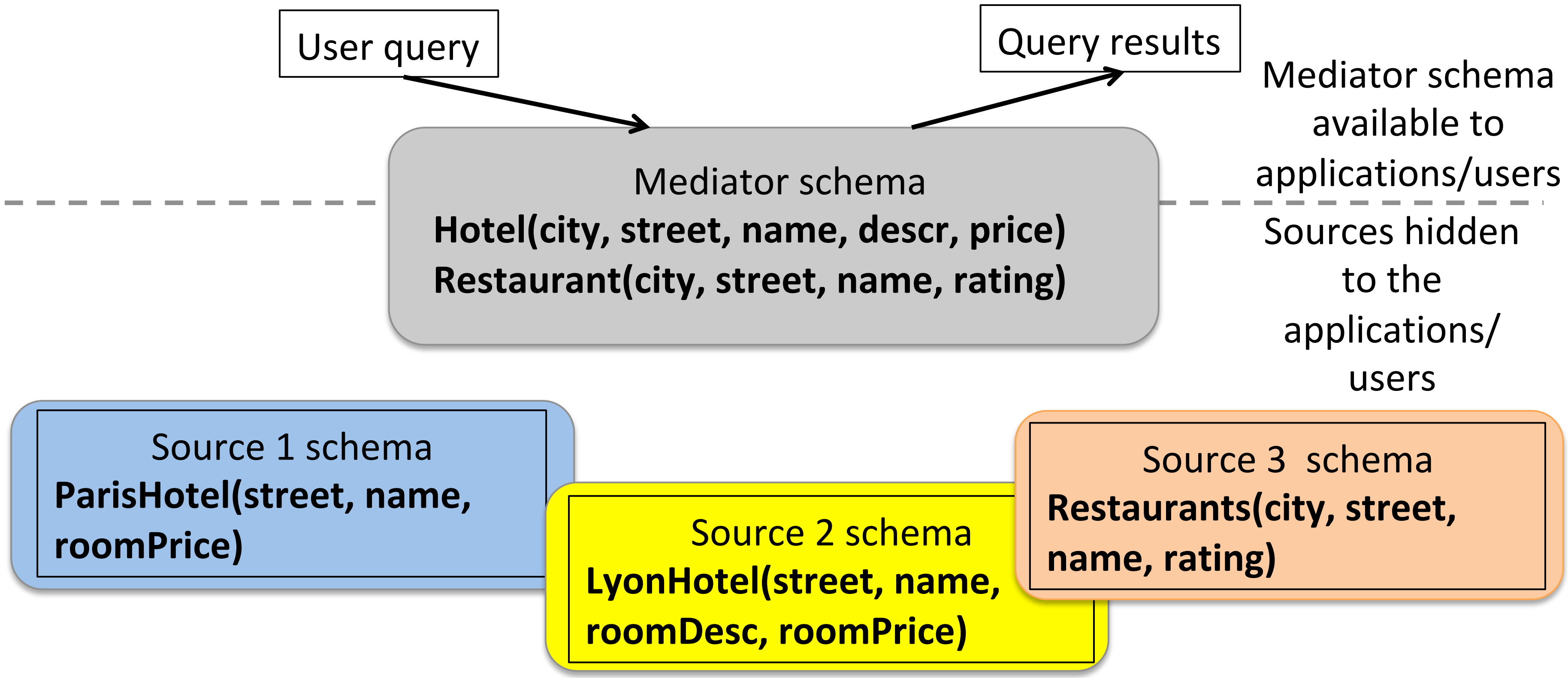


Global-Local-as-View: example



Previous LAV mapping of Source 1:
Q1Mediator: select street, name, price as roomPrice from Hotel where city='Paris'
Q1Sources: select * from ParisHotel

Global-Local-as-View: example

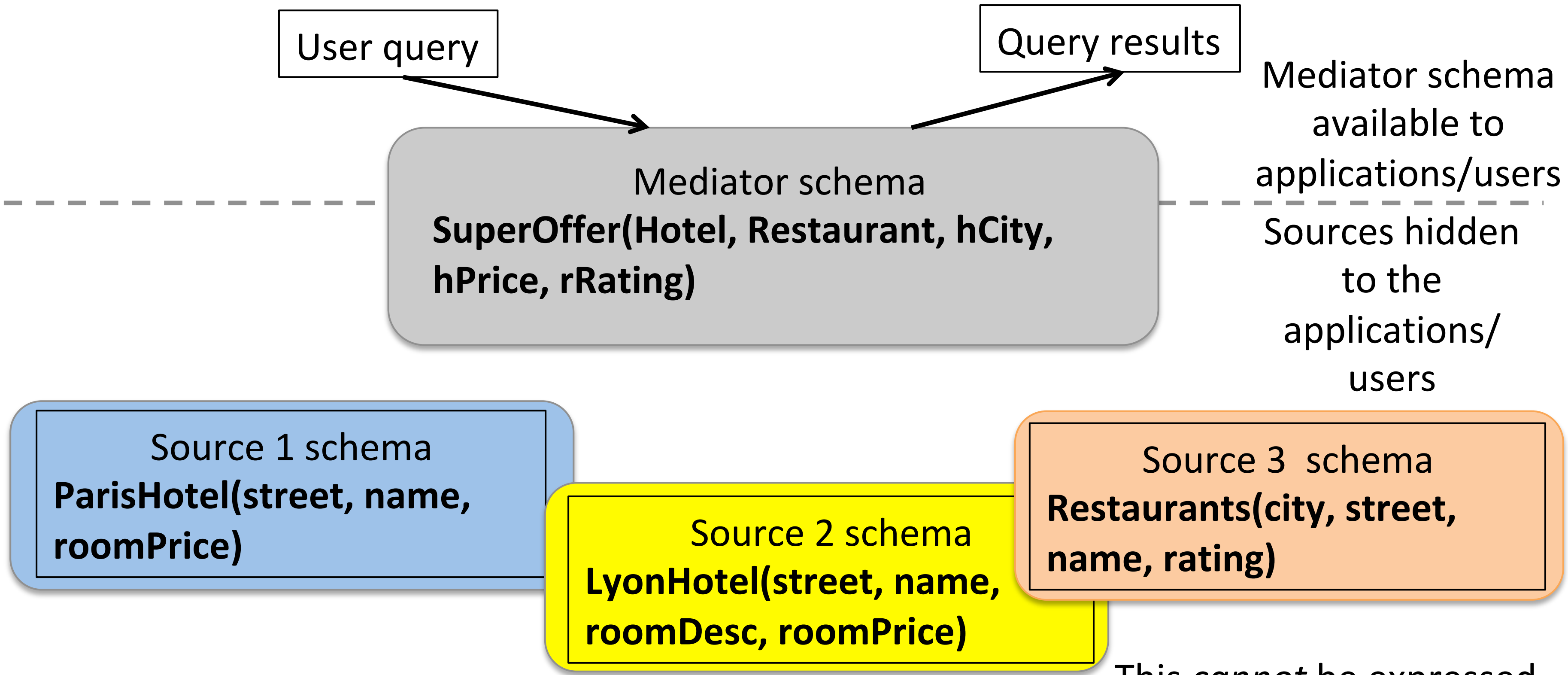


Previous GAV mapping of Hotel:

Q2Mediator: select * from Hotel

Q2Sources: select 'Paris' as city, street, name, null as descr, roomPrice as price from ParisHotel
union
select 'Lyon' as city, street, name, roomDesc as descr, roomPrice as price from LyonHotel

Global-Local-as-View: example

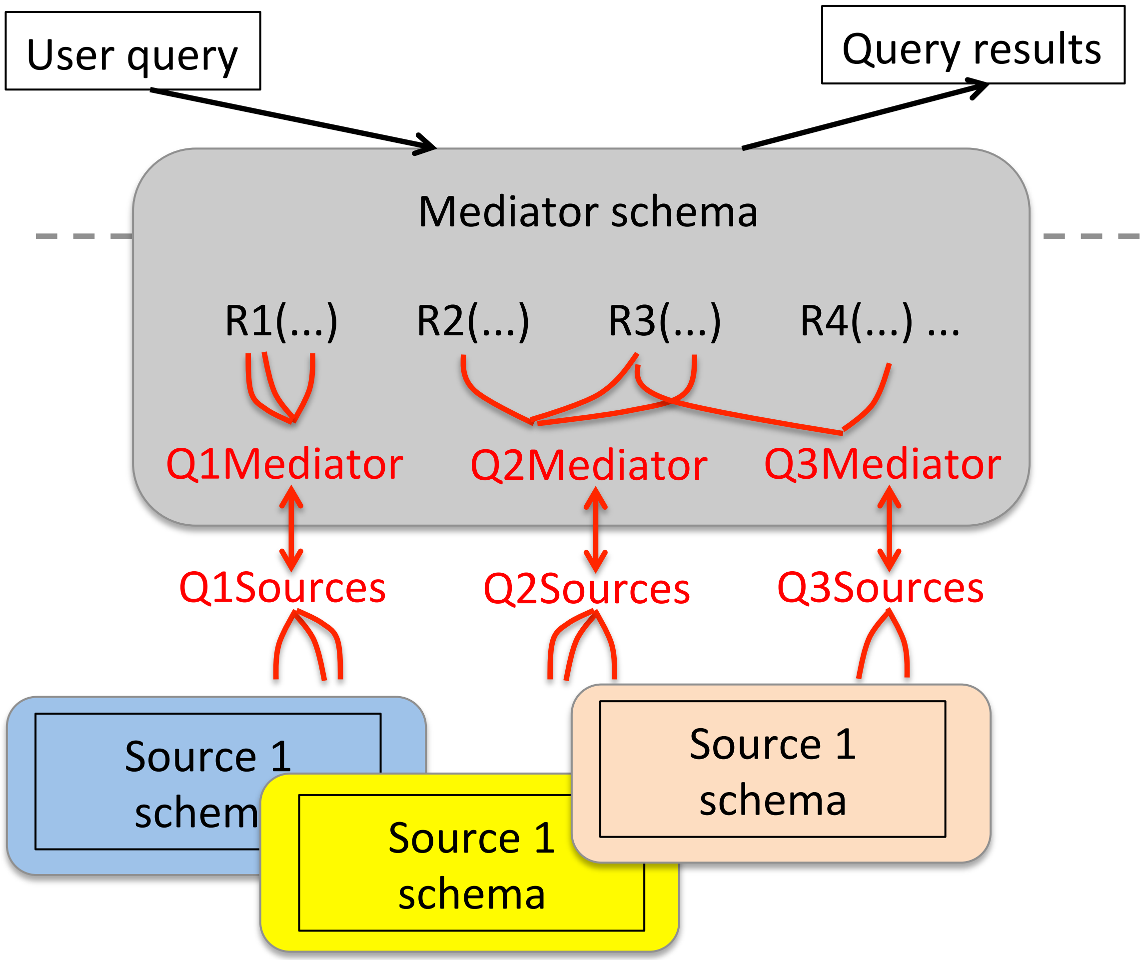


This *cannot* be expressed either in LAV or GAV.

New GLAV mapping:
Q3Mediator: select * from SuperOffer where hCity='Lyon'
Q3Sources: select lh.name, r.name, h.roomPrice * 0.5 as hPrice, r.rating as rRating
from LyonHotel lh, Restaurants r
where r.city='Lyon' and name='Lion d'Or' and r.street=lh.street

This mapping says: "each result of Q3Sources leads to a SuperOffer in Lyon".
Other mappings could define more SuperOffers in Lyon, or in other cities, or with rRating=3...

Query Processing in GLAV



User queries asked on the mediator schema.

Q1Mediator, Q2Mediator, ... are queries over this schema

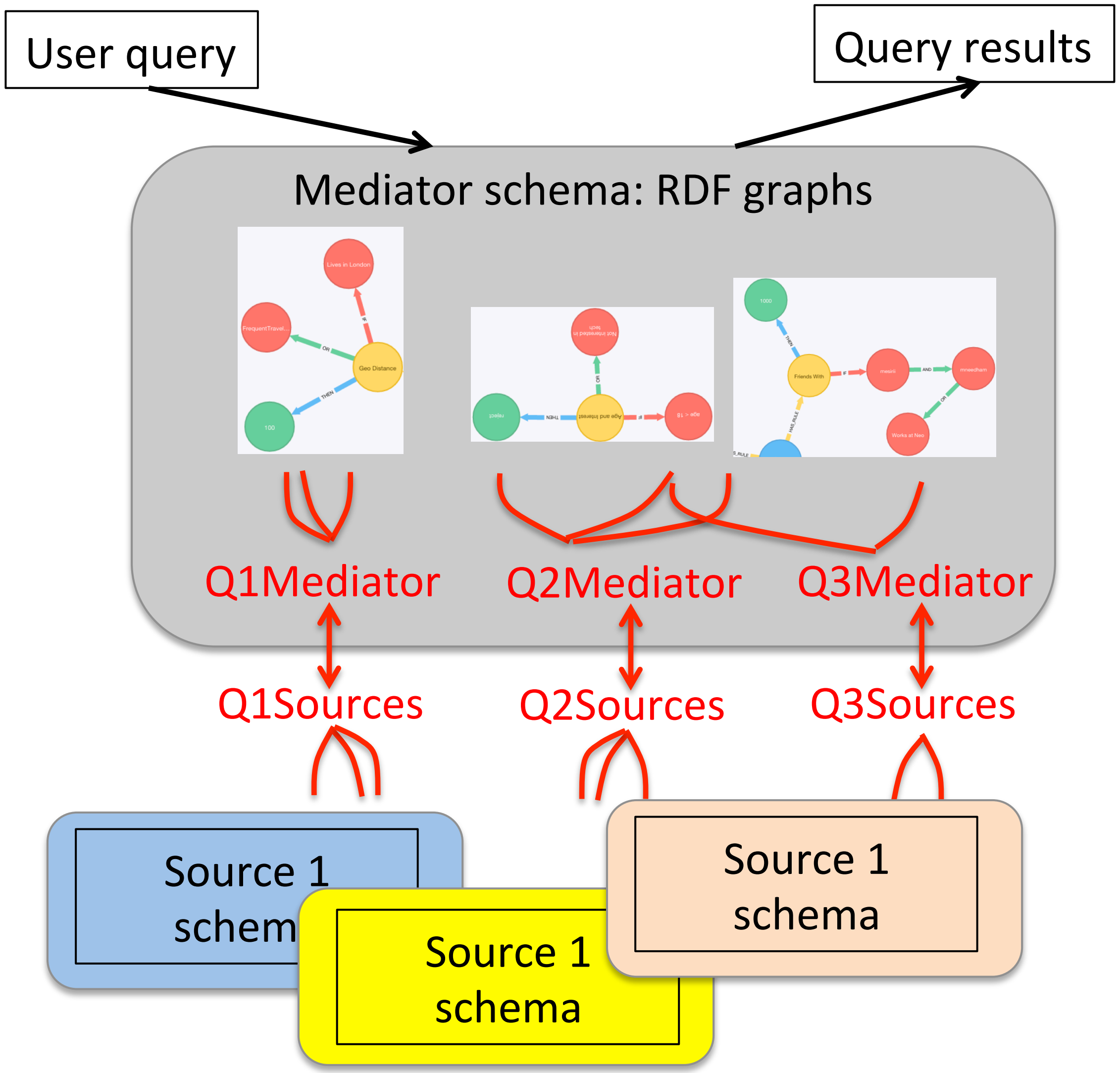
1. Apply **LAV**-style rewriting considering each QiMediator as a view over the mediator schema.
   – This leads to rewritings of Q over QiMediator relations (Q1Mediator, Q2Mediator, ...)
2. For each such rewriting, in **GAV** style, replace the symbol QiMediator by the query QiSources.
   – This leads to a rewriting of the query over the sources.

Examples: find all super offers in Paris? in Lyon?

Concluding remarks on GLAV

- The most flexible approach
  - Can express LAV, GAV, and more
- If a source changes or sources are added, as long as Q1Sources can be rewritten, applications will not be impacted
  - Only the "invisible" part of the system needs maintenance
- Query rewriting remains expensive because it includes view-based query rewriting (NP-hard) as well as query unfolding (very simple)

Modern mediators: GLAV with RDF global schema



Idea 1: RDF global schema
Advantages:
We do not have to fix a set of relations in advance
We can use ontologies to add semantics to the global schema
Idea 2: write GLAV mappings, e.g.:

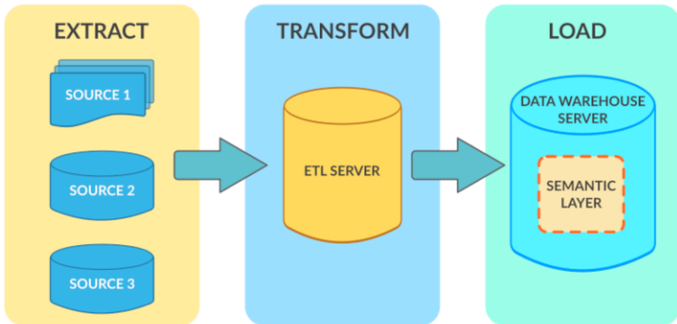
1. **Q1Sources**: an SQL query returning (x, y, z) tuples
   Q1Mediator: (x, 'friend', y), (y, 'worksfor' z)
   Q1Mediator "*creates RDF out of relational data*"
2. **Q2Sources**: an XPath query returning (z) nodes
   Q2Mediator:
   (z, 'type', Company)

If common z value, the graphs built by Q1,2Mediator **connect**!

Concluding remarks on mediators

- **Data integration**: treat several data sources as a single one
  - Old problem that is not going away (quite the contrary)!
- **Needs:**

1. *Understand* the sources and *how they relate to the global schema* we want
2. Then, either:
   1. *Extract* the data from the sources, *transform* it into the global schema, and *load* it into a **data warehouse (ETL)**, or



   2. Devise a **mediator** which interacts with the sources and provides the illusion of a single database.
      We have seen GAV, LAV and GLAV mediation.

DATA SPACES, DATA LAKES

Data spaces

- "Data spaces" (Franklin, Halevy, Maier, 2005):
  - Many heterogeneous data sources...
  - On a single or on multiple machines
  - But, unlike data integration systems, the sources
    - May not be **structured**: text, email, Web pages, directories...
      - Therefore, different data models, or unstructured (no data model) = text
    - May not reside in **databases**
      - Therefore, no source query language

Data spaces

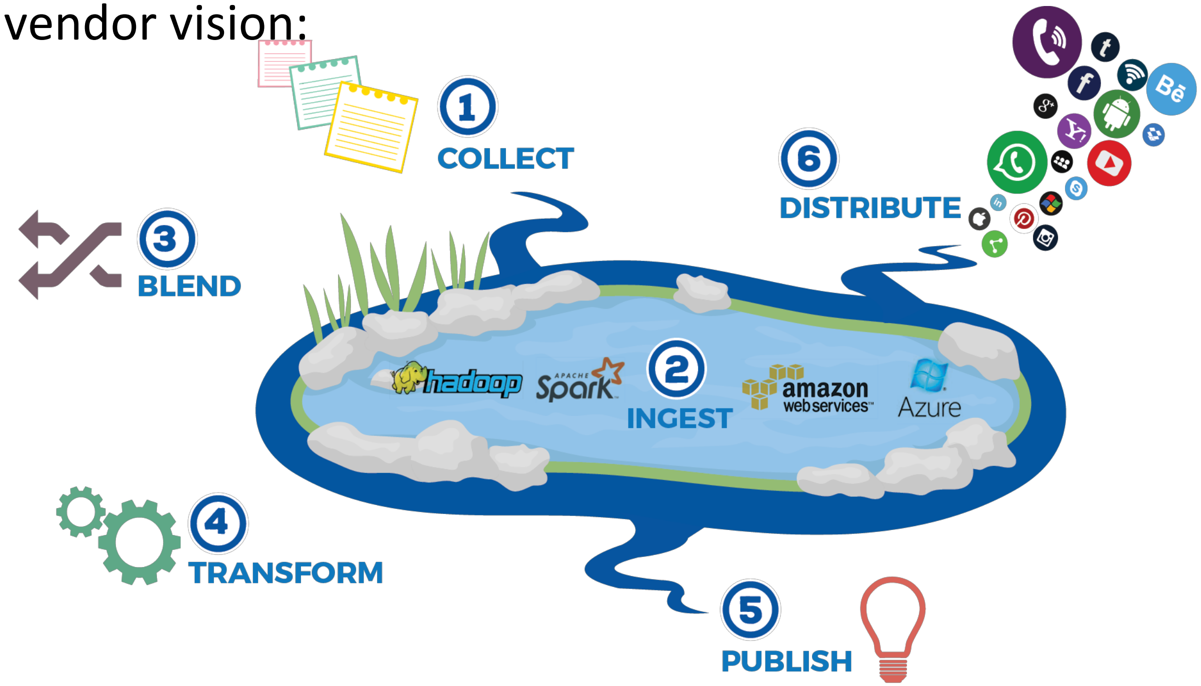
- How to query the data space?
- Keyword query: kw1, kw2, ..., kwn
  - E.g., "rent flat Chamonix"
- Answers:
  - From a text file: **minimal text fragments** that contain all kwds
  - From a database:
    - **One tuple** it if contains all the kwds, or
    - **A few tuples** if they join and they contain all the kwds, or
    - A **minimal JSON tree** that contains all the kwds etc.
  - *Score* to decide which answers to return first
- **No schema, no integration effort**: too many sources, too heterogeneous
- Keyword query paradigm

Data lakes

- Popular term, started around 2010 (cca)
- Mostly in **companies**
- Many data sources: Tens, hundreds, thousands
  - Most of the time relational. Also: text, JSON
  - Developed more or less independently of each other, with no knowledge of each other
    - Different schemas; different names for same things; slightly different semantics (e.g., "customer" vs. "customer who bought something in the last year")
  - Some relationships probably exist between the schemas of the different databases
  - ... but finding and expressing them has become beyond current human capacity

Data lake: usage

- Positive vendor vision:



- The hard part is BLEND because this requires understanding data which...
  - Has been designed 10 years ago by someone who has since left the company...
  - Was meant for (or was gathered by) an application the company no longer uses..
  - Lacks documentation (or the documentation obsolete)...
  - Overlaps partially with a few other sources and (it is feared) with many others...
- No point in learning from data we don't understand!

Data lakes: problems and products

- Problems:
  - Automatically **summarizing** a data source: *data profiling*
  - **Identifying relationships** between different data sources: *data matching*, *data profiling*, *data cleaning*
    - So that the data lake is not a "data swamp"
    - Build an understanding/relationships between the data sources over time
  - Query processing over data sources whose relationships are well understood follow the mediator or the warehouse (ETL) path

Data lake products:

- https://www.ibm.com/analytics/data-management/data-lake
- https://blogs.oracle.com/emeapartnerbiepm/oracle-analytics-cloud-data-lake-edition-available