Data Integration and Exchange

Traditional approach to databases

- A single large repository of data.
- Database administrator in charge of access to data.
- Users interact with the database through application programs.
- Programmers write those (embedded SQL, other ways of combining general purpose programming languages and DBMSs)
- Queries dominate; updates less common.
- DMBS takes care of lots of things for you such as

  query processing and optimisation

  concurrency control

  enforcing database integrity

Traditional approach to databases cont'd

- This model works very within a single organisation that either
  - does not interact much with the outside world, or
  - the interaction is heavily controlled by the DB administrators
- What do we expect from such a system?
  1. Data is relatively clean; little incompleteness
  2. Data is consistent (enforced by the DMBS)
  3. Data is there (resides on the disk)
  4. Well-defined semantics of query answering (if you ask a query, you know what you want to get)
  5. Access to data is controlled

The world is changing

- The traditional model still dominates, but the world is changing.
- Many huge repositories are publicly available
  - In fact many are well-organised databases, e.g., imdb.com, the CIA World Factbook, many genome databases, the DBLP server of CS publications, etc etc etc)
- Many queries cannot be answered using a single source.
- Often data from various sources needs to be combined, e.g.
  - company mergers
  - restructuring databases within a single organisation
  - combining data from several private and public sources

Background

- Requirement: Database Systems (3rd year)
- or fluency in relational databases:
  - relational model
  - relational algebra/calculus
  - SQL
- An understanding of the basic mathematical tools that serve as the foundation of computer science:
  - basic set theory,
  - graph theory,
  - theory of computation,
  - first-order logic.

Outline of the course

- Introduction to the problems of data integration and exchange. Key new components:
  - incomplete information
  - query rewriting
  - certain answers
- Data integration scenarios:
  - global-as-view, local-as-view, combined
  - virtual vs materialized
- How to distinguish easy queries from hard queries?
- Query answering in data integration scenarios:
  - view-based rewritings

Outline of the course cont'd

- Incomplete information in databases
  - theory, tables, complexity
  - practice (the ugly reality – SQL)
  - Open and closed worlds
- Data exchange: settings, source-to-target constraints, solutions
- Data exchange query answering:
  - conjunctive (select-project-join) queries
  - full relational algebra queries

    closed vs open worlds

Outline of the course cont'd

- Data exchange: XML data
  - tree patterns
  - consistency problems
  - query answering
- Schema management:
  - composition, other operations, schema evolution
- Inconsistent databases, repairs, query answering
- If time permits: ranking queries

Query answering from multiple sources

- Data resides in several different databases
- They may have different structures, different access policies etc
- Our view of the world may be very different from the view of the databases we need to use.
- Only portions of the data from some database could be available.
- That is, the sources do not conform to the schema of the database into which the data will be loaded.

What industry offers now: ETL tools

- ETL stands for **E**xtract–**T**ransform–**L**oad
  - Extract data from multiple sources
  - Transform it so it is compatible with the schema
  - Load it into a database
- Many self-built tools in the 80s and the 90s; through acquisition fewer products exist now
- The big players – IBM, Microsoft, Oracle – all have their ETL products; Microsoft and Oracle offer them with their database products.
- A few independent vendors, e.g. Informatica PowerCenter.
- Several open source products exist, e.g. Clover ETL.

ETL tools

- Focus:
  - Data profiling
  - Data cleaning
  - Simple transformations
  - Bulk loading
  - Latency requirements
- What they don't do yet:
  - **nontrivial transformations**
  - **query answering**
- But techniques now exist for interesting data integration and for query answering – and we shall learn them.
- They soon will be reflected in products (IBM and Microsoft are particularly active in this area)

Data profiling/cleaning

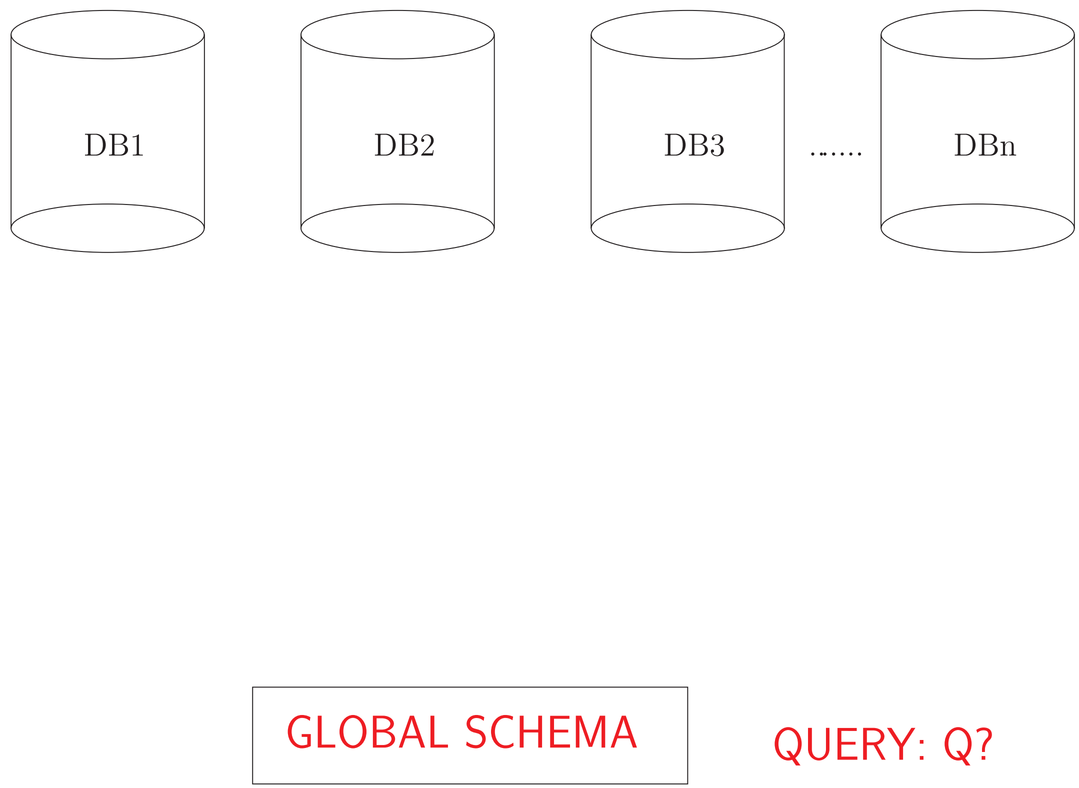
- Data profiling: gives the user a view of data:
  - Samples over large tables
  - statistics (how many different values etc)
  - Graphical tools for exploring the database
- Cleaning:
  - Same properties may have different names

    e.g. `Last_Name`, `L_Name`, `LastName`
  - Same data may have different representations
    - e.g. `(0131)555-1111` vs `01315551111`,
    - `George Str.` vs `George Street`
  - Some data may be just wrong

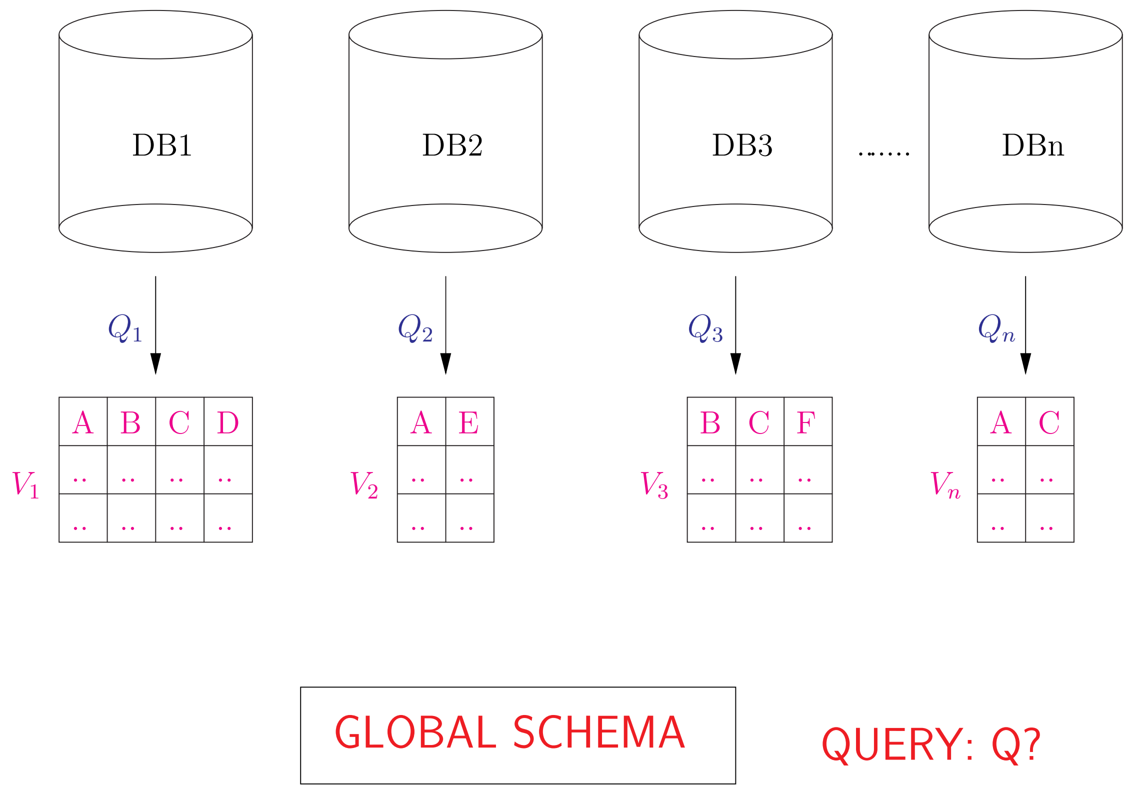
Data transformation

- Most transformation rules tend to be simple:
  - Copy attribute `LName` to `Last_Name`
  - Set age to be `current_year` – `DOB`
- Heavy emphasis on industry specific formats
- For example, Informatica B2B Data Exchange product offers versions for Healthcare and Financial services as well as specialised tools for formats including:
  - MS Word, Excel, PDF, UN/EDIFACT (Data Interchange For Administration, Commerce, and Transport), RosettaNet for B2B, and many specialised healthcare and financial form.
- These are format/industry specific and have little to do with the general tasks of data integration.

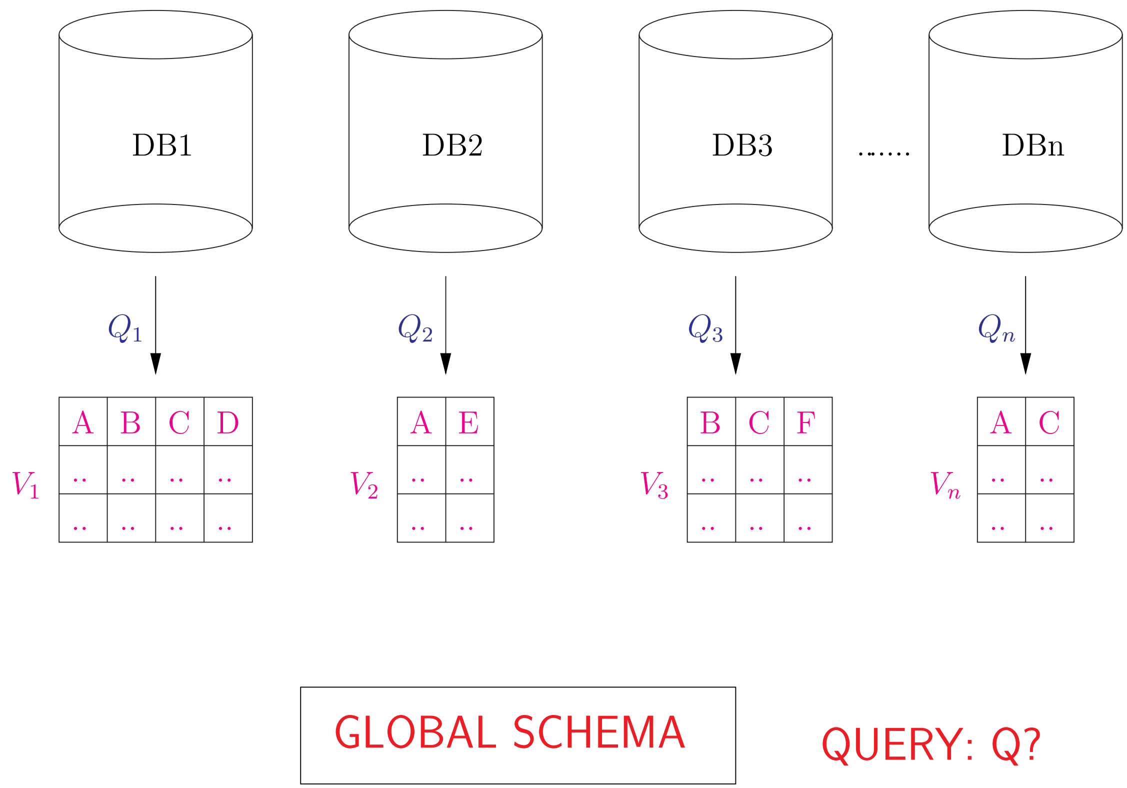
Data integration, scenario 1



Data integration



Data integration



Answer to Q is obtained by querying the views V_1 , ..., V_n

Data integration, query answering

- We have our view of the world (the Global Schema)
- We can access (parts of) databases $DB_1, \ldots, DB_n$ to get relevant data.
- It comes in the form of views, $V_1, \ldots, V_n$
- Our query against the global schema must be reformulated as a query against the views $V_1, \ldots, V_n$
- The approach is completely virtual: we never create a database the conforms to the global schema.

Data integration, query answering, a toy example

- List courses taught by permanent teaching staff during Winter 2007
- We have two databases:
  - D_1(name, age, salary) of permanent staff
  - D_2(teacher, course, semester, enrollment) of courses
- D_1 only publishes the value of the name attribute
- D_2 does not reveal enrollments
- The views:

$$\begin{aligned} V_1 &= \pi_{name}(D_1) \\ V_2 &= \pi_{teacher,course,semester}(D_2) \end{aligned}$$

- Next step: establish correspondence between attributes name of V_1 and teacher of V_2

Data integration, query answering, a toy example cont'd

- To answer query, we need to import the following data:

$$V_1$$

$$W_2 = \sigma_{semester='Winter\ 2007'}(V_2)$$

- Answering query:

$$\{course \mid \exists name, sem\ V_1(name) \wedge W_2(name, course, sem)\}$$

- Or, in relational algebra

$$\pi_{course}(V_1 \bowtie_{name=teacher} W_2)$$

Toy example, lessons learned

- We don't have access to all the data
- Some human intervention is essential (someone needs to tell us that teacher and name refer to the same entity)
- We don't run a query against a single database. Instead, we
  - run queries against different databases based on restrictions they impose
  - get results to use them locally
  - run another query against those results

Toy example, things getting more complicated

- Find informatics permanent staff who taught during the Winter 2007 semester, and their phone numbers
- We have additional personnel databases:
  - an informatics database $D_3(employee, phone, office)$, and
  - a university-wide database $D_4(employee, school, phone)$
  - for simplicity, assume all this information is public
- Now we have a choice:
  - use D_3 to get information about phones
  - use D_4 to get information about phones
  - use both D_3 and D_4 to get information about phones

Toy example cont'd

- First, we need some human involvement to see that employee, name, and teacher refer to the same category of objects
- If one uses D_3, then the query is

$$\begin{aligned}\{name,\ phone \mid\ & \exists sem, course, office\ V_1(name) \wedge \\ & W_2(name, course, sem) \wedge D_3(name, phone, office)\}\end{aligned}$$

- If one uses D_4, then the query is

$$\begin{aligned}\{name,\ phone \mid\ & \exists sem, course, school\ V_1(name) \wedge \\ & W_2(name, course, sem) \wedge D_4(name, school, phone)\}\end{aligned}$$

- But what if one uses both D_3 and D_4?

Toy example cont'd

- We could insist on the phone number being:
  - in either D_3 or D_4
  - in both D_3 and D_4, but not necessarily the same
  - in both D_3 and D_4, and the same in both databases
- One can write queries for all the cases, but which one should we use?
- New lessons:
  - databases that are being integrated are often inconsistent
  - query answering is by no means unique – there could be several ways to answer a query
  - different possibilities for answering queries are a result of inconsistencies and incomplete information

Toy example cont'd

- Suppose phone numbers in D_3 and D_4 are different.
- What is a sensible query answer then?
- A common approach is to use certain answers – these are guaranteed to be true.
- Another question: what if there is no record at all for the phone number in D_3 and D_4?
- Then we have an instance of incomplete information.

A different scenario

- So far we looked at virtual integration: no database of the global schema was created.
- Sometimes we need such a database to be created, for example, if many queries are expected to be asked against it.
- In general, this is a common problem with data integration: materialize vs federate.
- Materialize = create a new database based on integrating data from different sources.
- Federate = the virtual approach: obtain data from various sources and use them to answer queries.

Virtual vs Materialization

- A common situation for the materialization approach: merger of different organizations.
- A common situation for the federated approach: we don't have full access to the data, and the data changes often.

Common tasks in data integration

- How do we represent information?
  - Global schema, attributes, constraints
  - data formats of attributes
  - reconciling data from different sources
  - abbreviations, terminology, ontologies
- How do we deal with imperfect information?
  - resolve overlaps
  - handling missing data
  - handling inconsistencies

Common tasks in data integration cont'd

- How do we answer queries?
  - what information is available?
  - Can we get *the* answer?
  - if not, what is the semantics of query answering?
  - Is query answering feasible?
  - Is it possible to compute query answers at all?
  - If now, how do we approximate?
- Materialize or federate?

Common tasks in data integration cont'd

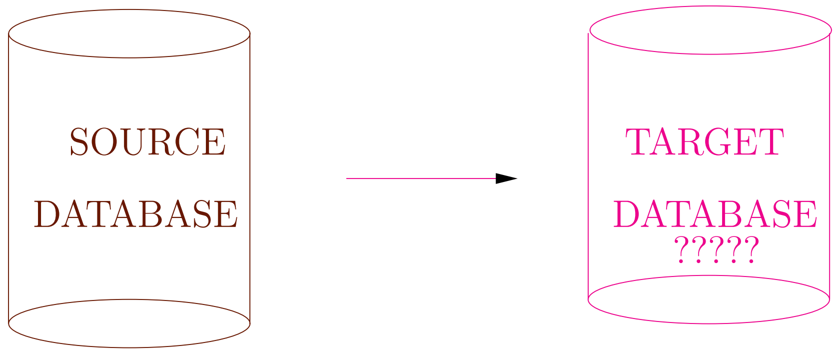
- Do it from scratch or use commercial tools?
  - many are available (just google for "data integration")
  - but do we fully understand them?
  - lots of them are very ad hoc, with poorly defined semantics
  - this is why it is so important to understand what really happens in data integration

Data Exchange

Source Schema S

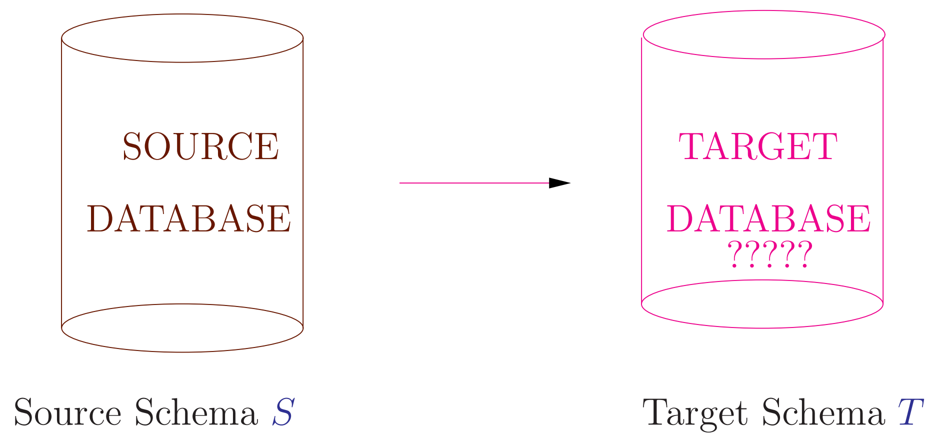
Target Schema T

Data Exchange



Source Schema S Target Schema T

Data Exchange



Query over the target schema: Q

How to answer Q so that the answer is consistent with the data in the source database?

Data exchange vs Data integration

Data exchange appears to be an easier problem:

- there is only one source database;
- and one has complete access to the source data.

But there could be many different target instances.

Problem: which one to use for query answering?

When do we have the need for data exchange

- A typical scenario:
  - Two organizations have their legacy databases, schemas cannot be changed.
  - Data from one organization 1 needs to be transfered to data from organization 2.
  - Queries need to be answered against the transferred data.

Data exchange – towards multiple instances

- A simple example: we want to create a target database with the schema

Flight(city1,city2,aircraft,departure,arrival)
Served(city,country,population,agency)

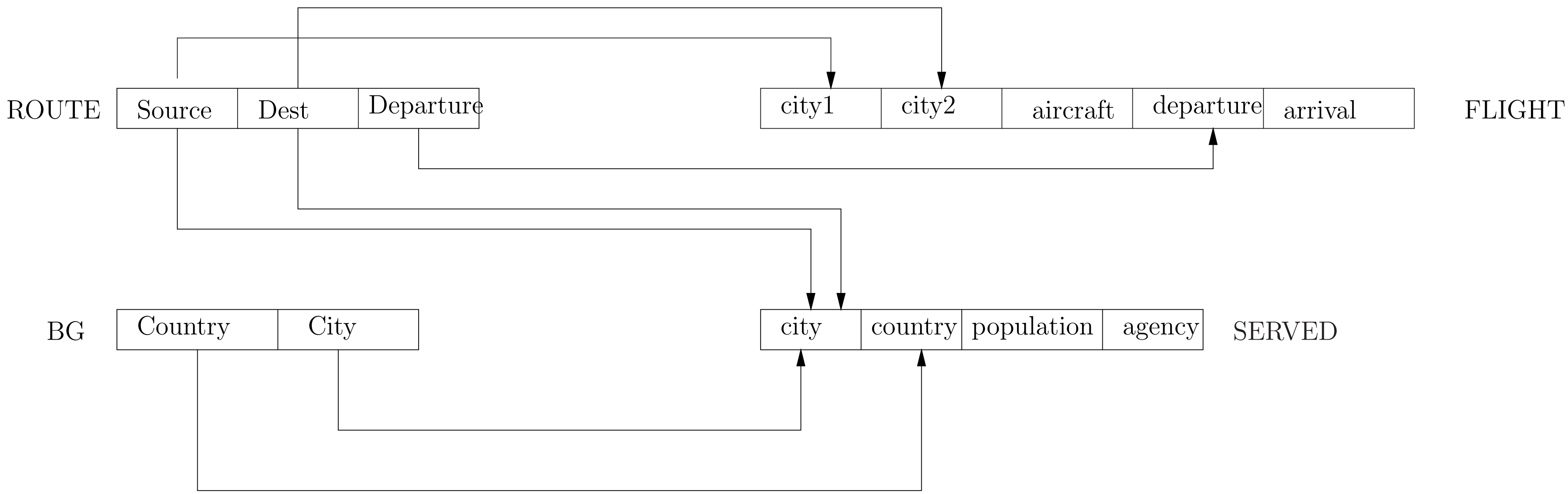
- We don't start from scratch: there is a source database containing relations

Route(source,destination,,departure)
BG(country,city)

- We want to transfer data from the source to the target.

Data exchange – relationships between the source and the target

How to specify the relationship?



Semantics??? For example, arrows from `city` – is the meaning *and* or *or*?

Data exchange – relationships between the source and the target

- Formal specification: we have a *relational calculus query* over both the source and the target schema.
- The query is of a restricted form, and can be thought of as a sequence of rules:

$$Flight(c1, c2, \_\_, dept, \_\_) \ :- \ Route(c1, c2, dept)$$

$$Served(city, country, \_\_, \_\_) \ :- \ Route(city, \_\_, \_\_), BG(country, city)$$

$$Served(city, country, \_\_, \_\_) \ :- \ Route(\_\_, city, \_\_), BG(country, city)$$

Data exchange – targets

- Target instances should satisfy the rules.
- What does it mean to satisfy a rule?
- Formally, if we take:

  Flight(c1, c2, __, dept, __) :– Route(c1, c2, dept)

  then it is satisfied by a source S and a target T if the constraint

$$\forall c_1, c_2, d \Big(\textit{Route}(c_1, c_2, d) \rightarrow \exists a_1, a_2 \ \big(\textit{Flight}(c_1, c_2, a_1, d, a_2) \big) \Big)$$

- This constraint is a relational calculus query that evaluates to *true* or *false*

Data exchange – targets

- What happens if there no values for some attributes, e.g. *aircraft*, *arrival*?
- We put in null values or some real values.
- But then we may have multiple solutions!

Data exchange – targets

Source Database:

ROUTE:

Source	Destination	Departure
Edinburgh	Amsterdam	0600
Edinburgh	London	0615
Edinburgh	Frankfurt	0700

BG:

Country	City
UK	London
UK	Edinburgh
NL	Amsterdam
GER	Frankfurt

Look at the rule

Flight(c1, c2, __, dept, __) :– *Route(c1, c2, dept)*

The right hand side is satisfied by

Route(Edinburgh, Amsterdam, 0600)

But what can we put in the target?

Data exchange – targets

Rule: *Flight(c1, c2, __, dept, __) :– Route(c1, c2, dept)*

Satisfied by: Route(Edinburgh, Amsterdam, 0600)

Possible targets:

- Flight(Edinburgh, Amsterdam, $\perp_1$, 0600, $\perp_2$)
- Flight(Edinburgh, Amsterdam, B737, 0600, $\perp$)
- Flight(Edinburgh, Amsterdam, $\perp$, 0600, 0845)
- Flight(Edinburgh, Amsterdam, B737, 0600, 0845)

They all satisfy the constraints!

Data exchange – queries

- Now consider two queries:
  - Q_1: Is there a flight from Edinburgh to Amsterdam that departs before 7am?
  - Q_2: Is there a flight from Edinburgh to Amsterdam that arrives before 9am?
- What is the difference?
  - Q_1 can be answered with certainty: in every solution we have a tuple Flight(Edinburgh, Amsterdam, __, 0600, __)
  - Q_2 cannot be answered with certainty: in some solutions we don't have a tuple Flight(Edinburgh, Amsterdam, a, t_1, t_2) with t_2 earlier than 9am.
- Our goal is to find certain answers.

Data exchange – queries

- But computing certain answers requires checking seemingly an infinite number of databases!
- How else can we do it?
- Create a good target instance T_{good} so that:
  - for a query Q we can define a query Q_r (its *rewriting*)
  - that satisfies the property:

$$\text{certain answers to } Q \;=\; Q_r(T_{good})$$

- Questions:
  - can we always find such a T_{good} and a rewriting algorithm $Q \mapsto Q_r$?
  - and if not, what restrictions do we impose on data exchange settings and/or queries?

Inconsistencies in databases

- If we integrate data, we shall always have inconsistencies:
  - One database says that we have John Smith with salary 20K in office 100
  - another says that we have John Smith with salary 30K in office 100
  - and the database must satisfy a key constraint: the name field is a key.
- Hence if we put

Name	Office	Salary
John Smith	100	20K
John Smith	100	30K
....	....	....

in our database, we have inconsistent data.

Inconsistencies in databases: query answering

- Q_1: Does John Smith sit in office 100?
- Q_2: Does John Smith make 20K?
- Difference:
  - Q_1 can be answered with certainty;
  - Q_2 cannot be.
- What does it mean to answer a query with certainty?
- If we repair a database so that it satisfies the constraints, the answer is true – no matter how we repair it.

Inconsistencies in databases: query answering

- In our example, two ways to repair:

R_1:

Name	Office	Salary
John Smith	100	20K
....	....	....

R_2:

Name	Office	Salary
John Smith	100	30K
....	....	....

- Q_1 is always true, Q_2 is not.
- But – the number of repairs could be very large (exponential – why?).
- Hence prohibitively expensive query answering algorithm.
- Question: when can query answering be made efficient?
- Perhaps it involves a rewriting of the original query.
- The key idea: query rewriting to obtain certain answers.

Schema mappings

- Last subject we deal with in this course.
- Still the least understood, but extremely important.
- Schema evolution: schema changes over time.
- Question – how to transfer data?
- Single step – data exchange.
- But what if we go through many steps? How do we transfer data, how do we answer queries?

Schema mappings

- Two data exchange scenarios:

Schema1	Schema2	Constraints12
Schema2	Schema3	Constraints23

- Suppose we know how to move data from Schema1 to Schema2, and then from Schema2 to Schema3?
- Can we describe this by a single set of schema constraints:

Schema1	Schema3	Constraints13

- This turns out to be a very nontrivial task, but it occurs very often in database schema management.
- And there are other operations – inverse, for example:

(Schema1 Schema2 Constraints12)

$\Downarrow$

(Schema2 Schema1 Constraints21)