Fundamentals of Database Systems
COMPSCI 351

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SQL
As a Query Language

What are Query Languages?

Query languages (QLs) give us

access and retrieval of data from a database

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- a declarative language with a strong formal foundation based on logic
- an industry standard language for specifying queries in real DBMSs

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Query Languages are not programming languages

- QLs not expected to be “Turing complete”
- QLs not intended to be used for complex calculations
- QLs support easy, efficient access to large data sets

Formal Relational Query Languages

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Both languages can essentially express the same queries

Query Languages Defined

Definition (Query Language (QL))

A **query language** is

- a formal language $\mathcal{L}$ such that
- each query $Q \in \mathcal{L}$ is associated with
  - an *input-schema* $in(Q)$,
  - an *output-schema* $out(Q)$, and
  - a *query mapping* $q(Q) : inst(in(Q)) \rightarrow inst(out(Q))$

    $\hookrightarrow$ i.e., taking databases over $in(Q)$ to databases over $out(Q)$

Comparison of Query Languages

Two queries Q_1 and Q_2 are **equivalent** (denoted $Q_1 \equiv Q_2$), if

- they have the same input-schema $in(Q_1) = in(Q_2)$,
- the same output-schema $out(Q_1) = out(Q_2)$, and
- the same query mapping $q(Q_1) = q(Q_2)$, i.e.,

  $\hookrightarrow$ for each database $db \in inst(in(Q_1))$ we have $q(Q_1)(db) = q(Q_2)(db)$

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Let $\mathcal{L}$ and $\mathcal{L}'$ be QLs

- $\mathcal{L}'$ **dominates** $\mathcal{L}$ (notation: $\mathcal{L} \sqsubseteq \mathcal{L}'$), if

  $\hookrightarrow$ for each query $Q \in \mathcal{L}$ there exists a query $Q' \in \mathcal{L}'$ with $Q' \equiv Q$
- $\mathcal{L}'$ and $\mathcal{L}$ are **equivalent** (notation: $\mathcal{L} \equiv \mathcal{L}'$), if

  $\hookrightarrow$ $\mathcal{L} \sqsubseteq \mathcal{L}'$ and $\mathcal{L}' \sqsubseteq \mathcal{L}$ both hold

Example: The Same Query in Different Languages

Consider our database schema from before

- MOVIE(title, year, country, run_time, genre), DIRECTOR(id, title, year)
- PERSON(id, first_name, last_name, year_born), ACTOR(id, title, year, role)

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What are the movies directed by 'Akira Kurosawa'?

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SQL

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FROM    MOVIE m, DIRECTOR d, PERSON p
                                        ;
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What are the movies directed by 'Akira Kurosawa'?

SQL

```
FROM    MOVIE m, DIRECTOR d, PERSON p
WHERE   m.title=d.title AND m.year=d.year AND
        d.id=p.id AND p.first_name='Akira' AND p.last_name='Kurosawa';
```

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Relational algebra

MOVIE DIRECTOR PERSON

Example: The Same Query in Different Languages

Consider our database schema from before

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- $\textsc{Person}$(id, first_name, last_name, year_born), $\textsc{Actor}$(id, title, year, role)

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$$\textsc{Movie} \bowtie \textsc{Director} \bowtie \textsc{Person}$$

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$$\sigma_{\text{first\_name='Akira'}}(\textsc{Movie} \bowtie \textsc{Director} \bowtie \textsc{Person})$$

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$$\sigma_{\text{last\_name}=\text{'Kurosawa'}}(\sigma_{\text{first\_name}=\text{'Akira'}}(\textsc{Movie} \bowtie \textsc{Director} \bowtie \textsc{Person}))$$

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$$\pi_{\text{title,year}}(\sigma_{\text{last\_name='Kurosawa'}}(\sigma_{\text{first\_name='Akira'}}(\textsc{Movie} \bowtie \textsc{Director} \bowtie \textsc{Person})))$$

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Relational calculus

$$\{ \quad | \quad \textsc{Movie}(x_{\text{title}}, x_{\text{year}}, x_{\text{country}}, x_{\text{run\_time}}, x_{\text{genre}}) \\ \textsc{Director}(x_{\text{id}}, x_{\text{title}}, x_{\text{year}}) \quad \textsc{Person}(x_{\text{id}}, \text{'Akira'}, \text{'Kurosawa'}, x_{\text{year\_born}}) \}$$

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$$\{ \qquad\qquad \mid \exists x_{\text{country}}, x_{\text{run\_time}}, x_{\text{genre}}, x_{\text{id}}, x_{\text{year\_born}} (\text{MOVIE}(x_{\text{title}}, x_{\text{year}}, x_{\text{country}}, x_{\text{run\_time}}, x_{\text{genre}}) \wedge \text{DIRECTOR}(x_{\text{id}}, x_{\text{title}}, x_{\text{year}}) \wedge \text{PERSON}(x_{\text{id}}, \text{'Akira'}, \text{'Kurosawa'}, x_{\text{year\_born}}))\}$$

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$$\{(x_{\text{title}}, x_{\text{year}}) \mid \exists x_{\text{country}}, x_{\text{run\_time}}, x_{\text{genre}}, x_{\text{id}}, x_{\text{year\_born}} (\textsc{Movie}(x_{\text{title}}, x_{\text{year}}, x_{\text{country}}, x_{\text{run\_time}}, x_{\text{genre}}) \wedge \textsc{Director}(x_{\text{id}}, x_{\text{title}}, x_{\text{year}}) \wedge \textsc{Person}(x_{\text{id}}, \text{'Akira'}, \text{'Kurosawa'}, x_{\text{year\_born}}))\}$$

SELECT... FROM... WHERE...

The basic form for all queries is given by the SELECT statement

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Comments

- $*$ in the attribute-list means all attributes
- Attribute names may be qualified with the table name
  - required, if attribute-names are not unique
- Attribute and table names can be renamed: ⟨name⟩ `AS` ⟨short name⟩
  - in this case the short name is required for qualification

Duplicates and Order

SQL is based on multisets (instead of sets)

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Add `ASC` or `DESC` for ascending or descending order

Example

English Language Query

- List all people with their id, first name, last name and the year they were born

Corresponding SQL Query

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Corresponding SQL Query

```
SELECT    *
FROM      PERSON
```

Example

English Language Query

- List all people with their id, first name, last name and the year they were born
- Provided their id is between 221 and 300 or greater than 999.

Corresponding SQL Query

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- List all people with their id, first name, last name and the year they were born
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Corresponding SQL Query

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SELECT  *
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WHERE   (id >= 221 AND id <= 300) OR id >= 1000
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- List all people with their id, first name, last name and the year they were born
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- Order the list first by last name, then by first name.

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```
SELECT    *
FROM      PERSON
WHERE     (id >= 221 AND id <= 300) OR id >= 1000
ORDER BY  last_name, first_name;
```

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List the first and last name of all movie directors of non-US movies together with the titles and production years of these movies.

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Corresponding SQL Query

```
SELECT  p.first_name, p.last_name, m.title, m.year
FROM    MOVIE m, PERSON p, DIRECTOR d
WHERE   d.title = m.title AND m.country <> 'USA' AND
        d.year = m.year AND d.id = p.id;
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Simple WHERE-Conditions

Condition in WHERE-clause (in queries, deletes, updates)

- Can be a simple comparison: $\langle$expression$\rangle$ $\langle$operator$\rangle$ $\langle$expression$\rangle$

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Simple `WHERE`-Conditions

Condition in `WHERE`-clause (in queries, deletes, updates)

- Can be a simple comparison: $\langle$expression$\rangle$ $\langle$operator$\rangle$ $\langle$expression$\rangle$
- The comparison operators can be $=$, $<>$, $<=$, $>=$, $>$ or $<$
- Expressions built from attributes, constant values and operators defined for the corresponding domains (see manuals for details)

More Complex `WHERE`-Conditions

Other conditions

- value lists:

  $\hookrightarrow$ ⟨attribute⟩ `BETWEEN` ⟨value⟩ `AND` ⟨value⟩, or

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- ⟨attribute⟩ `LIKE` ⟨string⟩ allows pattern matching
  - ↪ uses _ for a single symbol and % for any substring

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  - $\hookrightarrow$ uses _ for a single symbol and % for any substring

WHERE-clause may be **complex condition** using AND, OR and NOT

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List all movies together with their directors, provided the last name of the director begins with 'H' and ends with an 'o' followed by two more letters.

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Corresponding SQL Query

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SELECT   m.title, p.first_name, p.last_name
FROM     MOVIE m, PERSON p, DIRECTOR d
WHERE    m.title = d.title AND m.year = d.year AND
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Example

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List all movies produced between 1978 and 1995, ordered by year

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Corresponding SQL Query

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SELECT     title, year
FROM       MOVIE
WHERE      year BETWEEN 1978 and 1995
ORDER BY   year;
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Several functions can be used in a query, but not in combination with simple attributes

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Several functions can be used in a query, but not in combination with simple attributes

The result is significantly different, if `DISTINCT` is used

Example

English language query

How many actors are stored in the database?

Example

English language query

How many actors are stored in the database?

Corresponding SQL query

```
SELECT  COUNT (DISTINCT a.id) AS number_of_actors
FROM    ACTOR a
```

Example

English language query

List minimum, average and maximum run-time of all non-German movies

Example

English language query

List minimum, average and maximum run-time of all non-German movies

Corresponding SQL query

```
SELECT  MIN (run_time) AS min_run_time,
        AVG (run_time) AS avg_run_time,
        MAX (run_time) AS max_run_time
FROM    MOVIE
WHERE   country <> 'Germany';
```

Grouping

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`GROUP BY` ⟨attribute-list⟩

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The attributes in the attribute-list following the `GROUP BY` must be exactly the simple attributes in the list following the `SELECT` clause

Example

English language query

List each movie produced in 1999 together with its number of actors

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Corresponding SQL query

```
SELECT    m.title, m.year COUNT(DISTINCT a.id) AS number_of_actors
FROM      MOVIE m, ACTOR a
WHERE     a.title = m.title AND a.year = 1999 AND m.year = 1999
GROUP BY  m.title, m.year;
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The `HAVING` clause

The clause `HAVING` ⟨condition⟩ evaluates a condition on the groups

The `HAVING` clause

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The `HAVING` condition must apply to the group, not to individual tuples in the group

Example

List for all countries except Australia the number of movies, if there are at least two.

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```
SELECT      m.country, COUNT(m.title) AS number_of_movies
FROM        MOVIE m
WHERE       m.country <> 'Australia'
GROUP BY    m.country
HAVING      COUNT(*) >= 2;
```

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Sub-queries

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are just queries that are used within `WHERE`-conditions

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`EXISTS` ⟨sub-query⟩

tests whether sub-query results in non-empty relation

Sub-queries continued

`UNIQUE` ⟨sub-query⟩

tests if result of sub-query contains no duplicates

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before a sub-query makes sub-queries usable in comparison formulae

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ALL, SOME or ANY (SOME=ANY)

before a sub-query makes sub-queries usable in comparison formulae

Negation

In all these cases the condition involving the sub-query can be negated using a preceding NOT

Example

English Language Query

List for all countries except Spain the movies produced in that country, provided there are at least two of them. Order the result first ascending by country, then descending by the production year of the movie.

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List for all countries except Spain the movies produced in that country, provided there are at least two of them. Order the result first ascending by country, then descending by the production year of the movie.

Corresponding SQL Query

```
SELECT    m1.country, m1.year, m1.title
FROM      MOVIE m1
WHERE     m1.country <> 'Spain' AND m1.country IN (
                SELECT m2.country
                FROM MOVIE m2
                GROUP BY m2.country
                HAVING COUNT(*) >= 2)
ORDER BY  m1.country ASC, m1.year DESC;
```

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                 HAVING COUNT(*) >= 2)
ORDER BY  m1.country ASC, m1.year DESC;
```

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English Language Query

List the movies with exactly one actor, and return the first and last name of this actor.

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List the movies with exactly one actor, and return the first and last name of this actor.

Corresponding SQL Query

```
SELECT  m.title, m.year, p.first_name, p.last_name
FROM    MOVIE m, ACTOR a1, PERSON p
WHERE   m.title = a1.title AND m.year = a1.year AND a1.id = p.id AND NOT EXISTS(
            SELECT *
            FROM Actor a2
            WHERE a2.id <> a1.id AND a2.title = a1.title AND a2.year = a1.year);
```

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List the NZ movies together with their run time where the run time is longer than any Australian movie.

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List the NZ movies together with their run time where the run time is longer than any Australian movie.

Corresponding SQL Query

```
SELECT   m1.title, m1.year, m1.run_time
FROM     MOVIE m1
WHERE    m1.country = 'New Zealand' AND m1.run_time > ANY (
             SELECT m2.run_time
             FROM MOVIE m2
             WHERE m2.country='Australia');
```

Example

English Language Query

List the NZ movies together with their run time where the run time is longer than any Australian movie.

Corresponding SQL Query

```
SELECT  m1.title, m1.year, m1.run_time
FROM    Movie m1
WHERE   m1.country = 'New Zealand' AND m1.run_time > ANY (
            SELECT m2.run_time
            FROM Movie m2
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            WHERE m2.country='Australia');
```

Example

English Language Query

List the actors who played in most movies

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English Language Query

List the actors who played in most movies

Corresponding SQL Query

```
SELECT   p.first_name, p.last_name, p.id, a2.num_of_movies
FROM     PERSON p1, (
           SELECT a1.id, COUNT(DISTINCT a1.title, a1.year) AS num_of_movies
           FROM ACTOR a1
           GROUP BY a1.id ) a2
WHERE    p.id = a2.id AND a2.num_of_movies = (
           SELECT MAX(a4.num_of_movies)
           FROM (SELECT a3.id, COUNT(DISTINCT a3.title, a3.year) as num_of_movies
                 FROM ACTOR a3
                 GROUP BY a3.id ) a4);
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Limitations of SQL

FLIGHTS

Origin	Destination
Singapore	Tokyo
Singapore	Frankfurt
Singapore	Auckland
Tokyo	Joburg
⋮	

Reachability Query:
Find pairs of cities (O, D) such that one can fly from O to D with at most one stop

;

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```
  SELECT  F1.Origin, F2.Destination
  FROM    FLIGHTS F1, FLIGHTS F2
  WHERE   F1.Destination = F2.Origin
UNION
  SELECT  *
  FROM    FLIGHTS;
```

Another Reachability Query

Find pairs of cities (O, D) such that one can fly from O to D with at most two stops

;

Another Reachability Query

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```
UNION

UNION

                  ;
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UNION
    SELECT   *
    FROM     FLIGHTS;
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Another Reachability Query

Find pairs of cities (O, D) such that one can fly from O to D with at most two stops

```
    SELECT  F1.Origin, F3.Destination
    FROM    FLIGHTS F1, FLIGHTS F2, FLIGHTS F3
    WHERE   F1.Destination = F2.Origin AND F2.Destination = F3.Origin
UNION
    SELECT  F1.Origin, F2.Destination
    FROM    FLIGHTS F1, FLIGHTS F2
    WHERE   F1.Destination = F2.Origin
UNION
    SELECT  *
    FROM    FLIGHTS;
```

Reachability Queries in General

For any fixed k, we can write in SQL

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is not able to express this query

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New construct to express reachability

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SQL'99 solution

New construct to express reachability

SQL'92

is not able to express this query

This feature is not implemented in all products

A Different Point of View

Rewrite reachability queries as rules

$$\begin{aligned}\textsc{Reach}(x,y) &\ :-\textsc{Flights}(x,y)\\ \textsc{Reach}(x,y) &\ :-\textsc{Flights}(x,z),\textsc{Reach}(z,y)\end{aligned}$$

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Latter rule is *recursive*: $\textsc{Reach}$ refers to itself

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Evaluation

- Step 0: $\textsc{Reach}_0$ is initialised as the empty set

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Evaluation

- Step 0: $\textsc{Reach}_0$ is initialised as the empty set
- Step $i+1$:

$$\begin{aligned}\textsc{Reach}_{i+1}(x,y) &:- \textsc{Flights}(x,y)\\ \textsc{Reach}_{i+1}(x,y) &:- \textsc{Flights}(x,z), \textsc{Reach}_i(z,y)\end{aligned}$$

A Different Point of View

Rewrite reachability queries as rules

$$\textsc{Reach}(x, y) \quad : -\textsc{Flights}(x, y)$$
$$\textsc{Reach}(x, y) \quad : -\textsc{Flights}(x, z), \textsc{Reach}(z, y)$$

Latter rule is *recursive*: $\textsc{Reach}$ refers to itself

Evaluation

- Step 0: $\textsc{Reach}_0$ is initialised as the empty set
- Step $i + 1$:

$$\textsc{Reach}_{i+1}(x, y) \quad : -\textsc{Flights}(x, y)$$
$$\textsc{Reach}_{i+1}(x, y) \quad : -\textsc{Flights}(x, z), \textsc{Reach}_i(z, y)$$

- Stop condition:
  if $\textsc{Reach}_{i+1} = \textsc{Reach}_i$, then return it as answer of query

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

Step 0: $\text{REACH}_0 = \emptyset$

REACH_0

$\emptyset$

Example of Evaluation

$\textsc{Flights}$

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\textsc{Reach}_1(x, y) : -\textsc{Flights}(x, y)$
$\textsc{Reach}_1(x, y) : -\textsc{Flights}(x, z), \textsc{Reach}_0(z, y)$

$\textsc{Reach}_1$

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio)}

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$$\text{REACH}_2(x, y) :- \text{FLIGHTS}(x, y)$$
$$\text{REACH}_2(x, y) :- \text{FLIGHTS}(x, z), \text{REACH}_1(z, y)$$

REACH$_2$

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio)}

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\textsc{Reach}_2(x,y) :- \textsc{Flights}(x,y)$

$\textsc{Reach}_2(x,y) :- \textsc{Flights}(x,z), \textsc{Reach}_1(z,y)$

REACH$_2$

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio)}

Example of Evaluation

Flights

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

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$\textsc{Reach}_2(x,y) :- \textsc{Flights}(x,z), \textsc{Reach}_1(z,y)$

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{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio)}

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\text{REACH}_2(x, y) : -\text{FLIGHTS}(x, y)$

$\text{REACH}_2(x, y) : -\text{FLIGHTS}(x, z), \text{REACH}_1(z, y)$

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{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio)}

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
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Evaluation steps

$\textsc{Reach}_2(x, y) : -\textsc{Flights}(x, y)$

$\textsc{Reach}_2(x, y) : -\textsc{Flights}(x, z), \textsc{Reach}_1(z, y)$

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Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\text{REACH}_2(x, y) :- \text{FLIGHTS}(x, y)$

$\text{REACH}_2(x, y) :- \text{FLIGHTS}(x, z), \text{REACH}_1(z, y)$

REACH_2

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio)}

Example of Evaluation

Flights

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$$\textsc{Reach3}(x, y) :- \textsc{Flights}(x, y)$$
$$\textsc{Reach3}(x, y) :- \textsc{Flights}(x, z), \textsc{Reach2}(z, y)$$

Reach3

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio), (Singapore, Rio)}

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\text{REACH3}(x, y) : -\text{FLIGHTS}(x, y)$

$\text{REACH3}(x, y) : -\text{FLIGHTS}(x, z), \text{REACH2}(z, y)$

REACH3

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio), (Singapore, Rio)}

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\text{REACH}_3(x, y) :- \text{FLIGHTS}(x, y)$

$\text{REACH}_3(x, y) :- \text{FLIGHTS}(x, z), \text{REACH}_2(z, y)$

REACH3

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio), (Singapore, Rio)}

Example of Evaluation

Flights

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\textsc{Reach3}(x, y) : -\textsc{Flights}(x, y)$

$\textsc{Reach3}(x, y) : -\textsc{Flights}(x, z), \textsc{Reach2}(z, y)$

Reach3

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio), (Singapore, Rio)}

Example of Evaluation

Flights

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

$\textsc{Reach4}(x, y) : -\textsc{Flights}(x, y)$
$\textsc{Reach4}(x, y) : -\textsc{Flights}(x, z), \textsc{Reach3}(z, y)$

Reach4

$= \textsc{Reach3}$

Example of Evaluation

FLIGHTS

Origin	Destination
Singapore	Tokyo
Tokyo	Joburg
Joburg	Rio

Evaluation steps

Stop condition: $\textsc{Reach}_4 = \textsc{Reach}_3$

REACH

{(Singapore,Tokyo), (Tokyo,Joburg), (Joburg,Rio), (Singapore, Joburg), (Tokyo, Rio), (Singapore, Rio)}

Recursion with SQL'99

SQL'99 syntax mimics that of recursive rules

```
WITH RECURSIVE REACH(Origin,Destination) AS
(
   SELECT *
   FROM FLIGHTS
UNION
   SELECT F.Origin, R.Destination
   FROM FLIGHTS F, REACH R
   WHERE F.Destination = R.Origin
)
SELECT *
FROM REACH
```

Recursion in SQL'99: Syntactic restrictions

A different way to describe reachability as a recursive rule-based query:

$$\textsc{Reach}(x,y) :- \textsc{Flights}(x,y)$$
$$\textsc{Reach}(x,y) :- \textsc{Reach}(x,z), \textsc{Reach}(z,y)$$

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$$\textsc{Reach}(x, y) : -\textsc{Reach}(x, z), \textsc{Reach}(z, y)$$

This translates into an SQL'99 query

```
WITH RECURSIVE Reach(Origin,Destination) AS (
    SELECT * FROM Flights
UNION
    SELECT R1.Origin, R2.Destination
    FROM Reach R1, Reach R2
    WHERE R1.Destination = R2.Origin)
SELECT * FROM Reach
```

Recursion in SQL'99: Syntactic restrictions

A different way to describe reachability as a recursive rule-based query:

$$\textsc{Reach}(x,y) :- \textsc{Flights}(x,y)$$
$$\textsc{Reach}(x,y) :- \textsc{Reach}(x,z), \textsc{Reach}(z,y)$$

This translates into an SQL'99 query

```
WITH RECURSIVE REACH(Origin,Destination) AS (
    SELECT * FROM FLIGHTS
UNION
    SELECT R1.Origin, R2.Destination
    FROM REACH R1, REACH R2
    WHERE R1.Destination = R2.Origin)
SELECT * FROM REACH
```

Many implementations support *linear* recursion only

recursively defined relation mentioned just once in FROM line

Another Example of Recursion in SQL'99

Query: Find cities reachable from Singapore

Assume FLIGHTS contains the further attribute Aircraft

Another Example of Recursion in SQL'99

Query: Find cities reachable from Singapore

Assume FLIGHTS contains the further attribute Aircraft

```
WITH CITIES AS SELECT Origin, Destination FROM FLIGHTS
   RECURSIVE REACH(Origin,Destination) AS
(
   SELECT * FROM CITIES
UNION
   SELECT C.Origin, R.Destination
   FROM CITIES C, REACH R
   WHERE C.Destination = R.Origin
)
SELECT R.Destination
FROM REACH R
WHERE R.Origin = "Singapore"
```

Problems with Negation in Recursion

Consider rule such as $R(X) :- S(X), \neg R(X)$ in SQL

$$\begin{array}{l}
\texttt{WITH RECURSIVE } R(A) \texttt{ AS} \\
\quad (\texttt{SELECT } S.A \\
\quad\;\; \texttt{FROM } S \\
\quad\;\; \texttt{WHERE } S.A \texttt{ NOT IN } (\texttt{SELECT } R.A \texttt{ FROM } R)) \\
\texttt{SELECT} * \texttt{FROM } R
\end{array}$$

Problems with Negation in Recursion

Consider rule such as $R(X) : -S(X), \neg R(X)$ in SQL

```
WITH RECURSIVE R(A) AS
   (SELECT S.A
    FROM S
    WHERE S.A NOT IN (SELECT R.A FROM R))
SELECT * FROM R
```

For $S = \{1, 2\}$ evaluation leads to...

after step 0: $R_0 = \emptyset$;
after step 1: $R_1 = \{1, 2\}$;
...
after step $2n$: $R_{2n} = \emptyset$;
after step $2n + 1$: $R_{2n+1} = \{1, 2\}$;

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Problem: the evaluation does not terminate

negation (NOT IN) causes this problem

Summary for SQL

- SQL is the industry standard for defining and querying data
- DDL of SQL allows us to declare tables, views, and constraints
- DML of SQL allows us to specify and execute queries and updates
- SQL permits duplicate and partial information
  - $\hookrightarrow$ uses list semantics rather than set semantics of relational model
- SQL has several additional features, including
  - $\hookrightarrow$ Indices
  - $\hookrightarrow$ Access rights
  - $\hookrightarrow$ Aggregate functions
  - $\hookrightarrow$ Transitive closures
  - $\hookrightarrow$ Embedded SQL
  - $\hookrightarrow$ Dynamic SQL
  - $\hookrightarrow$ Transactions