Part VII

Query Basics: Algebra & Calculus
Query Basics: Algebra & Calculus

1. Criteria for Queries
2. Query Algebras
3. Relational Algebra: Extensions
4. Query Calculus
5. Examples for the Domain Calculus
Learning goals for today . . .

- Understanding of formal basics of relational query languages
- Knowledge to formalize queries with relational algebra
- Knowledge to formalize calculus queries
Introduction

so far:

- Relation schemata with basic relations that are saved in databases

now:

- "derived" relation schemata with virtual relations that are calculated from basis relations (basis relations keep unchanged)
Terms

- **Query**: Sequence of operations that calculate a result relation from basis relations
  - Present result relations interactively on a monitor or further processing via program ("Embedding")

- **View**: Sequence of operations that is long-term saved under a view name and that can be called again with this name; results in a view relation

- **Snapshot**: Result relation of a query that is stored under a Snapshot-Name, but that is never calculated twice (with changed basis relations) (e.g., annual balance sheets)
Criterion for Query Languages

- **Ad-Hoc-Formalization**: User should be able to formalize a query without a need to write a complete program.

- **Descriptiveness**: User should formalize "What do I want?" instead of "How do I get what I want?"

- **Collection-based**: Each operation should operate on a collection of data at the same time, not navigating on single elements ("one-tuple-at-a-time")

- **Closure**: Result is again a relation that can be used as input for the next query.
Criterion for Query Languages /2

- **Adequacy**: All constructs of the underlying data model are supported.
- **Orthogonality**: Language constructs are in similar situations also similar applicable.
- **Optimizability**: Language consists of few operations for which optimization rules exist.
- **Efficiency**: Any operation is efficient executable (in the relation model each operation has a complexity $\leq O(n^2)$, $n$ number of tuples of the relation).
Criterion for Query Languages /3

- **Safety**: No query, that is syntactically correct, may result in an endless loop or give an infinite result.

- **Limitation**: (comes from Safety, Optimizability, Efficiency) Query language should not be a complete programming language.

- **Completeness**: The language must at least be able to express the queries of a standard language (such as the to be introduced relation algebra of this chapter or the safe relation calculus).
Query Algebra

- Math: Algebra defined with range of values and on this defined operators
- For database queries: Contents of the database are values, and operators define functions for the calculation of query results
  - Relational Algebra
  - Algebra Extensions
Relational Algebra

- **Hide Columns**: Projection $\pi$
- **Search Rows**: Selection $\sigma$
- **Connect Tables**: Join $\bowtie$
- **Unite Tables**: Union $\cup$
- **Subtract Tables from each other**: Difference $-$
- **Rename Columns**: Renaming $\beta$
  (important for $\bowtie$ and $\cup$, $-$)
Relational Algebra: Overview

Selection

Projection

Join

Selection

Projection

Join

Join
Projection

- **Syntax**
  
  \[ \pi_{\text{AttributeSet}} \left( \text{Relation} \right) \]

- **Semantics**
  
  \[ \pi_X(r) := \{ t(X) \mid t \in r \} \]

  For \( r(R) \) and \( X \subseteq R \) attribute set in \( R \)

- **Property** for \( Y \subseteq X \subseteq R \)
  
  \[ \pi_Y(\pi_X(r)) = \pi_Y(r) \]

- **Attention:** \( \pi \) removes duplicates (Set Semantics)
Projection: Example

\[ \pi_{\text{Region}}( \text{PRODUCER}) \]

<table>
<thead>
<tr>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Australia</td>
</tr>
<tr>
<td>Kalifornien</td>
</tr>
<tr>
<td>Bordeaux</td>
</tr>
<tr>
<td>Hessen</td>
</tr>
</tbody>
</table>
## Projection: Example 2

\[ \pi_{\text{District, Region}}(\text{PRODUCER}) \]

<table>
<thead>
<tr>
<th>District</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barossa Valley</td>
<td>South Australia</td>
</tr>
<tr>
<td>Napa Valley</td>
<td>Kalifornien</td>
</tr>
<tr>
<td>Saint-Emilion</td>
<td>Bordeaux</td>
</tr>
<tr>
<td>Pomerol</td>
<td>Bordeaux</td>
</tr>
<tr>
<td>Rheingau</td>
<td>Hessen</td>
</tr>
</tbody>
</table>
Selection

- Syntax

\[ \sigma_{\text{Condition}}(\text{Relation}) \]

- Semantics (for \( A \in R \))

\[ \sigma_{A=a}(r) := \{ t \in r \mid t(A) = a \} \]
Selection Conditions

- **Constant Selection**

  \[ \text{Attribute} \, \theta \, \text{Constant} \]

  boolean predicate \( \theta \) is = or \( \neq \), for linear ordered range of values also \( \leq, <, \geq \) or \( > \)

- **Attribute Selection**

  \[ \text{Attribute}_1 \, \theta \, \text{Attribute}_2 \]

  logic connection of multiple Constant- or Attribute-Selections with \( \land, \lor \) or \( \neg \)
Selection: Properties

- Commutativity

\[ \sigma_{A=a}(\sigma_{B=b}(r)) = \sigma_{B=b}(\sigma_{A=a}(r)) \]

- when \( A \in X, X \subseteq R \)

\[ \pi_X(\sigma_{A=a}(r)) = \sigma_{A=a}(\pi_X(r)) \]

- Distributivity respect. \( \cup, \cap, \neg \)

\[ \sigma_{A=a}(r \cup s) = \sigma_{A=a}(r) \cup \sigma_{A=a}(s) \]
Selection: Example

\[ \sigma_{\text{Vintage} > 2000}(\text{WINES}) \]

<table>
<thead>
<tr>
<th>WineID</th>
<th>Name</th>
<th>Color</th>
<th>Vintage</th>
<th>Vineyard</th>
</tr>
</thead>
<tbody>
<tr>
<td>2168</td>
<td>Creek Shiraz</td>
<td>Red</td>
<td>2003</td>
<td>Creek</td>
</tr>
<tr>
<td>3456</td>
<td>Zinfandel</td>
<td>Red</td>
<td>2004</td>
<td>Helena</td>
</tr>
<tr>
<td>2171</td>
<td>Pinot Noir</td>
<td>Red</td>
<td>2001</td>
<td>Creek</td>
</tr>
<tr>
<td>4961</td>
<td>Chardonnay</td>
<td>White</td>
<td>2002</td>
<td>Bighorn</td>
</tr>
</tbody>
</table>
Join

- Syntax of the natural join
  \[ Relation_1 \bowtie Relation_2 \]

- Semantics
  \[
  r_1 \bowtie r_2 := \{ t \mid t(R_1 \cup R_2) \land \\
  \forall i \in \{1, 2\} \exists t_i \in r_i : t_i = t(R_i) \}
  \]

- Join links tables over equally named columns at equal attribute values
Join: Properties

- Schema for $r(R) \bowtie r(S)$ is union of the attribute sets $RS = R \cup S$
- from $R_1 \cap R_2 = \emptyset$ follows $r_1 \bowtie r_2 = r_1 \times r_2$
- Commutativity: $r_1 \bowtie r_2 = r_2 \bowtie r_1$
- Associativity: $(r_1 \bowtie r_2) \bowtie r_3 = r_1 \bowtie (r_2 \bowtie r_3)$
- thus allowed:

$$\bowtie_{i=1}^p r_i$$
### Join: Example

**WINES $\bowtie$ PRODUCER**

<table>
<thead>
<tr>
<th>WineID</th>
<th>Name</th>
<th>...</th>
<th>Vineyard</th>
<th>District</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1042</td>
<td>La Rose Grand Cru</td>
<td></td>
<td>Ch. La Rose</td>
<td>Saint-Emilion</td>
<td>Bordeaux</td>
</tr>
<tr>
<td>2168</td>
<td>Creek Shiraz</td>
<td></td>
<td>Creek</td>
<td>Barossa Valley</td>
<td>South Australia</td>
</tr>
<tr>
<td>3456</td>
<td>Zinfandel</td>
<td></td>
<td>Helena</td>
<td>Napa Valley</td>
<td>Kalifornien</td>
</tr>
<tr>
<td>2171</td>
<td>Pinot Noir</td>
<td></td>
<td>Creek</td>
<td>Barossa Valley</td>
<td>South Australia</td>
</tr>
<tr>
<td>3478</td>
<td>Pinot Noir</td>
<td></td>
<td>Helena</td>
<td>Napa Valley</td>
<td>Kalifornien</td>
</tr>
<tr>
<td>4711</td>
<td>Riesling Reserve</td>
<td></td>
<td>Müller</td>
<td>Rheingau</td>
<td>Hessen</td>
</tr>
<tr>
<td>4961</td>
<td>Chardonnay</td>
<td></td>
<td>Bighorn</td>
<td>Napa Valley</td>
<td>Kalifornien</td>
</tr>
</tbody>
</table>
Renaming

- Syntax

\[ \beta_{\text{new} \leftarrow \text{old}}(\text{Relation}) \]

- Semantic

\[ \beta_{B \leftarrow A}(r) := \{ t' \mid \exists t \in r : t'(R - A) = t(R - A) \land t'(B) = t(A) \} \]

- changes attribute names from \textit{old} to \textit{new}

\[ \beta_{\text{Name} \leftarrow \text{LastName}} (\text{CRITIC}) \]

- with renaming now possible
  - Join, where Cartesian products were applied (different attributes get equal naming),
  - Cartesian products, where Joins were applied (equal attributes get different naming),
  - Set operations
Calculation of the Cross Product

- Natural Join **degenerates to a cross product**, when no shared attributes exist
- Enforce by renaming
  - Example: $R_1(A, B, C)$ and $R_2(C, D)$
    \[
    R_1 \times R_2 \equiv R_1 \bowtie \beta_{E \leftarrow C}(R_2)
    \]
- Cross product + selection simulates natural join
  \[
  R_1 \bowtie R_2 \equiv \sigma_{R_1.C = R_2.C}(R_1 \times R_2)
  \]
Set Operations: Semantics

- formal for $r_1(R)$ and $r_2(R)$
  - Union $r_1 \cup r_2 := \{ t \mid t \in r_1 \lor t \in r_2 \}$
  - Intersection $r_1 \cap r_2 := \{ t \mid t \in r_1 \land t \in r_2 \}$
  - Difference $r_1 - r_2 := \{ t \mid t \in r_1 \land t \not\in r_2 \}$

- Intersection $\cap$ is superfluous as $r_1 \cap r_2 = r_1 - (r_1 - r_2)$
Independence and Completeness

- Minimal relational algebra:
  \[ \Omega = \pi, \sigma, \bowtie, \beta, \cup \text{ and } \neg \]

- Independence: no operator can be left off without losing completeness

- Other independent set: \( \bowtie \) and \( \beta \) replaced by \( \times \)

- Relational Completeness: every other set of operators with same expressive power as \( \Omega \)

- Strict relational completeness: for any expression with operators out of \( \Omega \) there is an equivalent expression also with the other set of operations
Relational Algebra: Extensions

- further Join operations
- Division
- Grouping and nested grouping relations
- ...
Join Variants

- for \( L(AB), R(BC), S(DE) \)

- **Equi-Join**: Equality condition over explicit specified and possibly different attributes
  \[
  r(R) \bowtie_{C=D} r(S)
  \]

- **Theta-Join** (\( \theta \)-join): arbitrary join condition
  \[
  r(R) \bowtie_{C>D} r(S)
  \]

- **Semi-Join**: only attributes of the operands appear in the result
  \[
  r(L) \Join r(R) = \pi_L(r(L) \Join r(R))
  \]
Outer Join

- Adoption of "dangling tuples" into the result and fill up with null values
- **Full Outer Join** takes all tuples of both operands
  \[ r \bigtriangleup \bigcirc s \]
- **Left Outer Join** takes all tuples of the left operand
  \[ r \bigtriangledown \bigcirc s \]
- **Right Outer Join** takes all tuples of the right operand
  \[ r \bigtriangledown \bigcirc s \]
Outer Join /2

LEFT

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

RIGHT

<table>
<thead>
<tr>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

LEFT OUTER JOIN

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>\bot</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>\bot</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

RIGHT OUTER JOIN

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>\bot</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

FULL OUTER JOIN

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>\bot</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
Problem: Quantifiers

- Express universal quantification (allquantor) in relational algebra, even though quantification in the selection condition is not allowed.

- **Division** (can be derived from $\Omega$)
  - $r_1(R_1)$ and $r_2(R_2)$ given with $R_2 \subseteq R_1$, $R' = R_1 - R_2$. Then is
  \[
r'(R') = \{ t \mid \forall t_2 \exists t_1 \in r_1 : t_1(R') = t \land t_1(R_2) = t_2 \}\]
    \[= r_1 \div r_2\]

- Division of $r_1$ by $r_2$
  \[
r_1 \div r_2 = \pi_{R'}(r_1) - \pi_{R'}((\pi_{R'}(r_1) \Join r_2) - r_1)\]
## Division Example I

### Wine Recommendation

<table>
<thead>
<tr>
<th>Wine</th>
<th>Critic</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Rose Grand Cru</td>
<td>Parker</td>
</tr>
<tr>
<td>Pinot Noir</td>
<td>Parker</td>
</tr>
<tr>
<td>Riesling Reserve</td>
<td>Parker</td>
</tr>
<tr>
<td>La Rose Grand Cru</td>
<td>Clarke</td>
</tr>
<tr>
<td>Pinot Noir</td>
<td>Clarke</td>
</tr>
<tr>
<td>Riesling Reserve</td>
<td>Gault-Millau</td>
</tr>
</tbody>
</table>

### Guides 1

<table>
<thead>
<tr>
<th>Critic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parker</td>
</tr>
<tr>
<td>Clarke</td>
</tr>
</tbody>
</table>

### Guides 2

<table>
<thead>
<tr>
<th>Critic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parker</td>
</tr>
<tr>
<td>Gault-Millau</td>
</tr>
</tbody>
</table>
Division Example II

- Division with first table

\[ \text{WINE\_RECOMMENDATION} \div \text{GUIDES1} \]

gives

<table>
<thead>
<tr>
<th>Wine</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Rose Grand Cru</td>
</tr>
<tr>
<td>Pinot Noir</td>
</tr>
</tbody>
</table>

- Division with second critics table

\[ \text{WINE\_RECOMMENDATION} \div \text{GUIDES2} \]

gives

<table>
<thead>
<tr>
<th>Wine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riesling Reserve</td>
</tr>
</tbody>
</table>
Term Division

- Analogy to the arithmetic operation of integer division

The integer division is in this sense the inverse to the multiplication by giving the result of the biggest number for which the multiplication with the divisor is smaller than the dividend. Analogously holds: $r = r_1 \div r_2$ is the biggest relation for which $r \bowtie r_2 \subseteq r_1$ is.
Division in SQL

- Simulation of the Allquantor (Division)
- with double Negation:

```sql
select distinct Wine
from WINE_RECOMMENDATION w1
where not exists (  
    select * from GUIDES2 g  
    where not exists (  
        select * from WINE_RECOMMENDATION w2  
        where g.Critic = w2.Critic and w1.Wine = w2.Wine))
```

- "Gives all wines, thus no wine exists that is not recommended by all critics in the relation GUIDES2".
- (We use the relation GUIDES2, as the in the textbook stated result relation refers to this comparison relation.)
Grouping

- Grouping Operator $\gamma$:

$$\gamma f_1(x_1), f_2(x_2), \ldots, f_n(x_n); A(r(R))$$

- Extends the attribute scheme of $r(R)$ by new attributes that correspond with the function application $f_1(x_1), f_2(x_2), \ldots, f_n(x_n)$

- Application of the function $f_i(x_i)$ on the subset of the tuples of $r(R)$ which have the same attribute values for the attributes $A$

```
select f_1(x_1), f_2(x_2), \ldots, f_n(x_n); A
from R
group by A
```
Semantics of the Grouping Operator

- empty attribute set $A = \emptyset$:
  \[
  \gamma_{F(X) ; \emptyset} (r(R)) = r(R) \times r(R)^{F(X)}
  \]
  with $r(R)^{F(X)}$ is relation with attribute $F(X)$ and a tuple as value of $F(X)$ on $r(R)$

- without function:
  \[
  \gamma_{\emptyset ; \emptyset} (r(R)) = r(R)
  \]

- general case:
  \[
  \gamma_{F(X) ; A} (r(R)) = \bigcup_{t \in R} \gamma_{F(X) ; \emptyset} (\sigma_{A = t . A}(r(R)))
  \]
Query Calculus

- Calculus: A formal logic language to formalize statements
- Goal: The use of such a calculus to formalize database queries
- Logic-based approach:
  - Database contents match an assignment of a predicate logic
  - Query: derived predicates
A General Calculus

- Motivation: Mathematical Notation

\[ \{x^2 \mid x \in \mathbb{N} \land x^3 > 0 \land x^3 < 1000\} \]

- Query has the form

\[ \{f(\bar{x}) \mid p(\bar{x})\} \]

- $\bar{x}$ denotes set of free variables

\[ \bar{x} = \{x_1 : D_1, \ldots, x_n : D_n\} \]
A General Calculus \( /2 \)

- Function \( f \) denotes result function over \( \overline{x} \)
  - Important special cases: Declaration of a variable itself (\( f \) is here the identity function) and tuple construction (result of type \text{tuple of})

- \( p \) selection predicate over free variables \( \overline{x} \)
  - Terms of variables, constants, and function applications
  - Predicates of data types, such as \( \leq, <, >, \geq, \ldots \)
    - \( \rightarrow \) atomic formulas over terms
  - Relation to current database \( \rightarrow \) database predicates, e.g., relation name in the RM
  - predicate logical operators \( \land, \lor, \neg, \forall, \exists \)
    - \( \rightarrow \) formulas
Result Declaration of a Query

\[ \bar{x} = \{x_1 : D_1, \ldots, x_n : D_n\} \]

1. Declare all assignments of free variables in \( \bar{x} \), for which the predicate \( p \) gets true.
2. Apply function \( f \) on the values given by this assignment.

Under which circumstances do calculus queries give infinite results?

→ Safety of queries
Relational Calculus

- **Domain Calculus**: Variables take values of elementary data type (*domains*)
- **Tuple calculus**: Variables vary over tuple values (according to the lines of a relation)
Tuple Calculus

- Basics of SFW-Queries in SQL
- Variables are tuple valued
- Example:
  \[ \{ w \mid w \in \text{WINES} \land w.\text{Color} = 'Red' \} \]
Tuple Calculus: Example

- **constructed tuple**

  \[ \{ \langle w.\text{Name}, w.\text{Vineyard} \rangle \mid w \in \text{WINES} \land w.\text{Color} = 'Red' \} \]

- **Join**

  \[ \{ \langle e.\text{Vineyard} \rangle \mid e \in \text{PRODUCER} \land w \in \text{WINES} \land e.\text{Vineyard} = w.\text{Vineyard} \} \]

- **Nesting**

  \[ \{ \langle w.\text{Name}, w.\text{Vineyard} \rangle \mid w \in \text{WINES} \land \exists e \in \text{PRODUCER}(w.\text{Vineyard} = e.\text{Vineyard} \land e.\text{Region} = 'Bordeaux') \} \]
Motivation: The Language QBE

- "Query by Example"
- Queries in QBE: Entries in table frameworks
- Intuition: Example entries in tables
- Precursor of several table-based query interfaces of commercial systems
- Based on logical calculus with area variables
Queries in QBE: Selection and Projection

Query: "All rock-albums of the years before 2006"

\[
\{ t \mid \text{Album}(\_, t, j, \text{'Rock'}, \_, \_) \land j < 2006 \}\]

<table>
<thead>
<tr>
<th>Album</th>
<th>ANr</th>
<th>Title</th>
<th>Year</th>
<th>Genre</th>
<th>Price</th>
<th>MNr</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.</td>
<td></td>
<td></td>
<td>&lt;2006</td>
<td>Rock</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Queries in QBE: Join

- Query: "All Rock albums of German musicians"

<table>
<thead>
<tr>
<th>Album</th>
<th>ANr</th>
<th>Title</th>
<th>Year</th>
<th>Genre</th>
<th>Price</th>
<th>MNr</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.</td>
<td></td>
<td>Rock</td>
<td></td>
<td></td>
<td></td>
<td>_musician</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Musician</th>
<th>MNr</th>
<th>Name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>_musician</td>
<td></td>
<td></td>
<td>Germany</td>
</tr>
</tbody>
</table>

\{ t | Album(_,t,_,'Rock',_,m) \\
\quad \land \text{Musician}(m,_,'Germany') \}
Queries in QBE: Self-Join

- Query: "Countries with two or more musicians"

<table>
<thead>
<tr>
<th>Musician</th>
<th>MNr</th>
<th>Name</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>_one</td>
<td></td>
<td></td>
<td>P. _country</td>
</tr>
<tr>
<td>¬ _one</td>
<td></td>
<td></td>
<td>_country</td>
</tr>
</tbody>
</table>

\[
\{ l \mid \text{Musician}(x, _, l) \land \text{Musician}(y, _, l) \land x \neq y \}
\]
QBE in MS-Access

- MS-Access: Database program for Windows
  - Basis relations with keys
  - Foreign keys with graphical statement of relations
  - Graphical definition of queries (SQL-similar)
  - Interactive definition of forms and reports

- Support of QBE
Access: Projection and Selection

<table>
<thead>
<tr>
<th>Feld:</th>
<th>Name</th>
<th>Jahrgang</th>
<th>Farbe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabelle:</td>
<td>WEINE</td>
<td>WEINE</td>
<td>WEINE</td>
</tr>
<tr>
<td>Sortierung:</td>
<td></td>
<td>&gt;2005</td>
<td>&quot;Rot&quot;</td>
</tr>
<tr>
<td>Anzeigen:</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Kriterien:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>oder:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Access: Join
Domain Calculus

- **Terms:**
  - Constants, such as 42 or ’MZ-4’
  - Variables for data types, such as \( x \)
    Data type declaration usually takes place implicitly and is not declared explicitly!
  - Function application \( f(t_1, \ldots, t_n) \): Function \( f \), terms \( t_i \), such as \( \text{plus}(12, x) \) resp. in infix notation \( 12 + x \)

- **Atomic formulas:**
  - Predicate application \( \Theta(t_1, \ldots, t_n) \), \( \Theta \in \{<, >, \leq, \geq, \neq, =, \ldots \} \)
    data-type predicate, terms \( t_i \)
    Binary predicates are usually in infix-notation.
    Example: \( x = y \), \( 42 > x \) or \( 3 + 7 = 11 \).
Domain Calculus /2

- **Atomic formulas** (advanced):
  - Predicate application for database predicates noted as $R(t_1, \ldots, t_n)$ for a relation name $R$
  - Providing: $n$ must be the arity of the relation $R$ and all $t_i$ must be of the same type
  - Example: $\text{PRODUCER}(x, 'Hessen', z)$

- **Formula** as usual with $\land$, $\lor$, $\neg$, $\forall$ and $\exists$
Domain Calculus /3

**Query:** \( \{x_1, \ldots, x_n \mid \phi(x_1, \ldots, x_n)\} \)

- \( \phi \) is formula over the in the result list contained variables \( x_1 \) to \( x_n \)
- Result is set of tuples
- Tuple construction comes implicitly from the values of the variables in the result list

**Example**

\[ \{x \mid \text{PRODUCER}(x, y, z) \land z = 'Hessen'\} \]
Basic Domain Calculus

- Restriction of the domain calculus:
  - **Range of values**: Integer
  - **Data type predicates** are restricted to equivalence and elementary comparison operations as in relational algebra
  - **Function applications** are not allowed; besides domain variables only constants can be used as terms
Safety

- **Safe Queries** (also *semantic safe queries*):
  - Queries that give a finite result for each database state $\sigma(\mathcal{R})$

- Example for unsafe queries:
  \[{x, y \mid \neg R(x, y)}\]

- Example for safe queries:
  \[{x, y \mid R(x, y)}\]
Safe Queries /2

Further example for safe queries:

\[ \{ x, y \mid y = 10 \land x > 0 \land x < 10 \} \]

Safety comes directly from the rules of arithmetics.

Semantic safety is in general not decidable!
Syntactically Safe Queries

- **Syntactically Safe Queries**: Queries that are subject to syntactic restrictions to enforce semantic safety.

- **Basic idea**: Any free variable $x_i$ must be bound to a finite area anywhere in $\phi(x_1, \ldots)$ by a **positive occurrence** $x_i = t$ or $R(\ldots, x_i, \ldots)$.

- Binding to finite areas must hold for the whole condition, in particular for all branches of an disjunction.
Safe Queries Overview

queries

safe queries

syntactic safe queries
Examples Domain Calculus

- Query: "All vineyards of producers in Hessen."

\[ \{ x \mid \text{PRODUCER}(x, y, z) \land z = 'Hessen' \} \]

- Simplified notation: Each unbound variable (here \( y \) and \( z \)) in the condition part existentially bound with \( \exists \)

- Complete version:

\[ \{ x \mid \exists y \exists z \text{PRODUCER}(x, y, z) \land z = 'Hessen' \} \]

- Saving of domain variables, by using constants as parameters of the predicate:

\[ \{ x \mid \text{PRODUCER}(x, y, 'Hessen') \} \]
Examples Domain Calculus /2

- Abbreviation for arbitrary, different existentially bound variables is the \( \_ \) symbol:

\[
\{ x \mid \text{PRODUCER}(x, \_, z) \land z = \text{’Hessen’}\}
\]

- Different appearances of the symbol \( \_ \) stand for pairwise different variables
Examples Domain Calculus /3

- Query: "Regions with more than two vineyards."

\[
\{ z \mid \text{PRODUCER}(x, y, z) \land \text{PRODUCER}(x', y', z) \land x \neq x' \}
\]

- Query shows a join binding on the third attribute of the PRODUCER-relation

- Join binding can easily come from the use of the same domain variables as parameter in different relation predicates
Examples Domain Calculus /4

- Query: "From which region are which wines with the vintage before 1970 in the supply?"

\[
\{y, r \mid \text{WINES}(x, y, z, j, w) \land \text{PRODUCER}(w, a, r) \land j < 1970\}
\]

- Join over two relations
Examples Domain Calculus /5

- Query: "From which regions are red wines?"

\[
\{ z \mid \text{PRODUCER}(x, y, z) \land \exists a \exists b \exists c \exists d (\text{WINE}(a, b, c, d, x) \land c = 'Red') \}
\]

- Use of a existentially bound subquery

- Such subqueries could be dissolved due to the rules of predicate logic as follows:

\[
\{ z \mid \text{PRODUCER}(x, y, z) \land (\text{WINE}(a, b, c, d, x) \land c = 'Red') \}
\]
Example Domain Calculus /6

- Query: "Which vineyard has only wines of the vintage after 1995 in its supply?"

\[
\{ x \mid \text{PRODUCER}(x, y, z) \land \forall a \forall b \forall c \forall d (\text{WINE}(a, b, c, d, x) \implies d > 1995) \}\}

- Universally bound subformulas cannot be dissolved
Expressiveness of the Domain Calculus

Domain calculus is **strict relational complete**, i.e. to any term $\tau$ of the relational algebra there is an equivalent (safe) term $\eta$ of the area calculus.
Implementation of Relational Operations

Given: Relation schema $R(A_1, \ldots, A_n)$ and $S(B_1, \ldots, B_m)$

- Union (for $n = m$)

$$R \cup S \overset{\Delta}{=} \{x_1 \ldots x_n \mid R(x_1, \ldots, x_n) \lor S(x_1, \ldots, x_n)\}$$

- Difference (for $n = m$)

$$R - S \overset{\Delta}{=} \{x_1 \ldots x_n \mid R(x_1, \ldots, x_n) \land \neg S(x_1, \ldots, x_n)\}$$

- Natural Join

$$R \bowtie S \overset{\Delta}{=} \{x_1 \ldots x_n x_{n+1} \ldots x_{n+m-i} \mid R(x_1, \ldots, x_n) \land S(x_1, \ldots, x_i, x_{n+1}, \ldots, x_{n+m-i})\}$$

Assumption: the first $i$ attributes of $R$ and $S$ are the join attributes, thus $A_j = B_j$ for $j = 1 \ldots i$
Implementation of Relational Operations /2

- **Projection**

\[
\pi_{\overline{A}}(R) \triangleq \{ y_1 \ldots y_k \mid \exists x_1 \ldots \exists x_n (R(x_1, \ldots, x_n) \land y_1 = x_{i_1} \\
\phantom{\pi_{\overline{A}}(R) \triangleq \{ y_1 \ldots y_k \mid} \land \cdots \land y_k = x_{i_k}) \}
\]

Attribute list of the projection: \( \overline{A} = (A_{i_1}, \ldots, A_{i_k}) \)

- **Selection**

\[
\sigma_{\phi}(R) \triangleq \{ x_1 \ldots x_n \mid R(x_1, \ldots, x_n) \land \phi' \}
\]

\( \phi' \) comes from \( \phi \), by insertion of the variable \( x_i \) at the place of the attribute names \( A_i \)
Summary

- Formal models for queries in database systems
- Relational algebra
  - Operational approach
  - Queries as nesting of operations on relations
- Query calculus
  - Logic-based approach
  - Queries as derived predicates
  - *see Book: sections 4.2.3, 4.2.4 and 9.3*
Control Questions

- Which meaning do equivalence, independence and completeness have in the relational algebra?
- How can the semantic of the extended SQL-operations be expressed in relational algebra?
- What is the difference between relational algebra and relational query calculus?
- What is the role of safety in queries?