Relational Model & Algebra

CompSci 316
Introduction to Database Systems

Announcements (Thur. Aug. 30)

- Homework #1 will be assigned Tuesday
  - Our VM is ready for download!
- Office hours: see course website
  - Different times on different days!
- Lecture notes
  - The “notes” version can be (printed out and) used for note-taking; the “complete” version will be posted after lecture, so be selective in what you copy down
- Duke Community Standard
- Still working on the room issue…

Relational data model

- A database is a collection of relations (or tables)
- Each relation has a list of attributes (or columns)
- Each attribute has a domain (or type)
  - Set-valued attributes not allowed
- Each relation contains a set of tuples (or rows)
  - Each tuple has a value for each attribute of the relation
  - Duplicate tuples are not allowed
    * Two tuples are identical if they agree on all attributes

* Simplicity is a virtue!
Example

<table>
<thead>
<tr>
<th>Student</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>SID</td>
<td>name</td>
</tr>
<tr>
<td>142</td>
<td>Bart</td>
</tr>
<tr>
<td>123</td>
<td>Milhouse</td>
</tr>
<tr>
<td>857</td>
<td>Lisa</td>
</tr>
<tr>
<td>456</td>
<td>Ralph</td>
</tr>
</tbody>
</table>

Ordering of rows doesn’t matter (even though the output is always in some order)

Schema versus instance

- Schema (metadata)
  - Specification of how data is to be structured logically
  - Defined at set-up
  - Rarely changes
- Instance
  - Content
  - Changes rapidly, but always conforms to the schema
  - Compare to type and objects of type in a programming language

Example

- Schema
  - Student (SID integer, name string, age integer, GPA float)
  - Course (CID string, title string)
  - Enroll (SID integer, CID integer)
- Instance
  - [{142, Bart, 10, 2.3}, {123, Milhouse, 10, 3.1}, ... ]
  - [{CPS316, Intro to Database Systems}, ... ]
  - [{(142, CPS316), (142, CPS310}, ... ]
Relational algebra
A language for querying relational databases based on operators:

- Core set of operators:
  - Selection, projection, cross product, union, difference, and renaming
- Additional, derived operators:
  - Join, natural join, intersection, etc.
- Compose operators to make complex queries

Selection
- Input: a table \( R \)
- Notation: \( \sigma_p R \)
  - \( p \) is called a selection condition/predicate
- Purpose: filter rows according to some criteria
- Output: same columns as \( R \), but only rows of \( R \) that satisfy \( p \)

Selection example
- Students with GPA higher than 3.0
  \( \sigma_{\text{GPA}>3.0} \text{Student} \)
More on selection

- Selection predicate in general can include any column of $R$, constants, comparisons ($\leq$, etc.), and Boolean connectives ($\land$: and, $\lor$: or, and $\neg$: not)
  - Example: straight A students under 18 or over 21
    \[ \sigma_{\text{GPA}=4.0 \land (\text{age}<18 \lor \text{age}>21)} \text{Student} \]
- But you must be able to evaluate the predicate over a single row of the input table
  - Example: student with the highest GPA
    \[ \sigma_{\text{GPA}=\text{max}} \text{Student} \]

Projection

- Input: a table $R$
- Notation: $\pi_L R$
  - $L$ is a list of columns in $R$
- Purpose: select columns to output
- Output: same rows, but only the columns in $L$

Projection example

- ID's and names of all students
  \[ \pi_{\text{SID, name}} \text{Student} \]
More on projection

- Duplicate output rows are removed (by definition)
  - Example: student ages

\[ \pi_{\text{age}} \text{Student} \]

<table>
<thead>
<tr>
<th>SID</th>
<th>name</th>
<th>age</th>
<th>GPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>Bart</td>
<td>10</td>
<td>2.3</td>
</tr>
<tr>
<td>123</td>
<td>Milhouse</td>
<td>10</td>
<td>3.1</td>
</tr>
<tr>
<td>857</td>
<td>Lisa</td>
<td>8</td>
<td>4.3</td>
</tr>
<tr>
<td>456</td>
<td>Ralph</td>
<td>8</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Cross product

- Input: two tables \( R \) and \( S \)
- Notation: \( R \times S \)
- Purpose: pairs rows from two tables
- Output: for each row \( r \) in \( R \) and each row \( s \) in \( S \), output a row \( rs \) (concatenation of \( r \) and \( s \))

Cross product example

- \( \text{Student} \times \text{Enroll} \)
A note on column ordering

- The ordering of columns in a table is considered unimportant (as is the ordering of rows).
- That means cross product is commutative, i.e., $R \times S = S \times R$ for any $R$ and $S$.

Derived operator: join

(A.k.a. “theta-join”)

- Input: two tables $R$ and $S$
- Notation: $R \bowtie p S$
  - $p$ is called a join condition/predicate
- Purpose: relate rows from two tables according to some criteria
- Output: for each row $r$ in $R$ and each row $s$ in $S$, output a row $rs$ if $r$ and $s$ satisfy $p$
- Shorthand for $\sigma_p (R \times S)$

Join example

- Info about students, plus CID’s of their courses
  
  \[
  \text{Student} \bowtie \sigma_{\text{Student} \_\text{SID} = \text{Enroll} \_\text{SID}} \text{ Enroll}
  \]
  
  Use `table_name.column_name` syntax to disambiguate identically named columns from different input tables.
Derived operator: natural join

- **Input:** two tables $R$ and $S$
- **Notation:** $R \bowtie S$
- **Purpose:** relate rows from two tables, and
  - Enforce equality on all common attributes
  - Eliminate one copy of common attributes
- **Shorthand for** $\pi_L(R \bowtie_p S)$, where
  - $p$ equates all attributes common to $R$ and $S$
  - $L$ is the union of all attributes from $R$ and $S$, with duplicate attributes removed

Natural join example

- **Student $\bowtie$ Enroll**
  - $\pi_{SID \bowtie \text{name}, \text{age}, \text{GPA}, \text{CID}}(\text{Student $\bowtie$ Enroll, SID} \bowtie \text{Enroll, SID})$

Union

- **Input:** two tables $R$ and $S$
- **Notation:** $R \cup S$
  - $R$ and $S$ must have identical schema
- **Output:**
  - Has the same schema as $R$ and $S$
  - Contains all rows in $R$ and all rows in $S$, with duplicate rows eliminated
Difference

- Input: two tables \( R \) and \( S \)
- Notation: \( R - S \)
  - \( R \) and \( S \) must have identical schema
- Output:
  - Has the same schema as \( R \) and \( S \)
  - Contains all rows in \( R \) that are not found in \( S \)

Derived operator: intersection

- Input: two tables \( R \) and \( S \)
- Notation: \( R \cap S \)
  - \( R \) and \( S \) must have identical schema
- Output:
  - Has the same schema as \( R \) and \( S \)
  - Contains all rows that are in both \( R \) and \( S \)
- Shorthand for

Renaming

- Input: a table \( R \)
- Notation: \( \rho_{S}^{R} \), \( \rho_{(A_{1}, A_{2}, \ldots)}^{R} \) or \( \rho_{S(A_{1}, A_{2}, \ldots)}^{R} \)
- Purpose: rename a table and/or its columns
- Output: a renamed table with the same rows as \( R \)
- Used to
  - Avoid confusion caused by identical column names
  - Create identical column names for natural joins
Renaming example

- SID’s of students who take at least two courses
  \(\text{Enroll} \bowtie_2 \text{Enroll}\)

Expression tree syntax:

Summary of core operators

- Selection: \(\sigma_p R\)
- Projection: \(\pi_k R\)
- Cross product: \(R \times S\)
- Union: \(R \cup S\)
- Difference: \(R - S\)
- Renaming: \(\rho_{S(A_1A_2...)}R\)
  - Does not really add “processing” power

Summary of derived operators

- Join: \(R \bowtie_p S\)
- Natural join: \(R \bowtie S\)
- Intersection: \(R \cap S\)

- Many more
  - Semijoin, anti-semijoin, quotient, …
An exercise

- Names of students in Lisa’s classes

Writing a query bottom-up:

\[ \text{Their names} \]

Students in Lisa’s classes

Lisa’s classes

Who’s Lisa?

\[ \sigma_{\text{name} = \text{Lisa}} \]

\[ \text{Student} \]

Another exercise

- CID’s of the courses that Lisa is NOT taking

Writing a query top-down:

\[ \pi_C ID \]

Course

\[ \sigma_{\text{name} = \text{Lisa}} \]

\[ \text{Student} \]

A trickier exercise

- Who has the highest GPA?

A deeper question:

When (and why) is “−” needed?
Monotone operators

- If some old output rows may need to be removed
  - Then the operator is non-monotone
- Otherwise the operator is monotone
  - That is, old output rows always remain "correct" when more rows are added to the input
- Formally, for a monotone operator \( op \):
  \[ R \subseteq R' \implies \text{op}(R) \subseteq \text{op}(R') \] for any \( R, R' \)

Classification of relational operators

- Selection: \( \sigma_R \)
- Projection: \( \pi_R \)
- Cross product: \( R \times S \)
- Join: \( R \bowtie_p S \)
- Natural join: \( R \bowtie S \)
- Union: \( R \cup S \)
- Difference: \( R - S \)
- Intersection: \( R \cap S \)

Why is “−” needed for highest GPA?

- Composition of monotone operators produces a monotone query
  - Old output rows remain "correct" when more rows are added to the input
- Is highest-GPA query monotone?
### Why do we need core operator $X$?

- Difference
  - The only non-monotone operator
- Cross product
- Union
- Selection? Projection?

### Extensions to relational algebra

- Duplicate handling (“bag algebra”)
- Grouping and aggregation
- Extension (or extended projection) to allow new attribute values to be computed

> All these will come up when we talk about SQL.
> But for now we will stick with standard relational algebra without these extensions

### Why is r.a. a good query language?

- Simple
  - A small set of core operators whose semantics are easy to grasp
- Declarative?
  - Yes, compared with older languages like CODASYL.
  - Though operators do look somewhat “procedural”
- Complete?
  - With respect to what?
Relational calculus

- \[ \{ s . S I D \mid s \in \text{Student} \wedge \neg (\exists s' \in \text{Student} : s . G P A < s' . G P A) \}, \text{or} \]
  \[ \{ s . S I D \mid s \in \text{Student} \wedge (\forall s' \in \text{Student} : s . G P A \geq s' . G P A) \} \]

- Relational algebra = “safe” relational calculus
  - Every query expressible as a safe relational calculus query is also expressible as a relational algebra query
  - And vice versa

- Example of an unsafe relational calculus query
  - \[ \{ s . \text{name} \mid \neg (s \in \text{Student}) \} \]
  - Cannot evaluate this query just by looking at the database

Turing machine?

- Relational algebra has no recursion
  - Example of something not expressible in relational algebra: Given relation \( \text{Parent(\text{parent}, \text{child})} \), who are Bart’s ancestors?

- Why not Turing machine?
  - Optimization becomes undecidable
  - You can always implement it at the application level

- Recursion is added to SQL nevertheless!