Relational Model and Algebra

Introduction to Databases
CompSci 316 Fall 2019
Announcements (Wed. Aug. 28)

• Sign up for Piazza, NOW!
• Gradiance RA Exercise assigned; due in a week
  • See “Help/Getting Started with Gradiance” of the course website
• Homework 1 posted today; due in 2½ weeks
  • See “Help/Submitting Non-Gradiance Work” for instructions on Gradescope
• Set up VM (virtual machine)
  • See “Help/VM-related” for instructions
  • Google Cloud coupon email sent
• Check Sakai email archive for any missed announcements
• I don’t have office hours today—make a (private) post on Piazza if there’s something urgent
• TA/UTA office hours to be posted soon
Edgar F. Codd (1923-2003)

- Pilot in the Royal Air Force in WW2
- Inventor of the relational model and algebra while at IBM
- Turing Award, 1981

Relational data model

• A database is a collection of relations (or tables)
• Each relation has a set of attributes (or columns)
• Each attribute has a name and a domain (or type)
  • Set-valued attributes are 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 duplicates if they agree on all attributes

☞ Simplicity is a virtue!
Example

**User**

<table>
<thead>
<tr>
<th>uid</th>
<th>name</th>
<th>age</th>
<th>pop</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>Bart</td>
<td>10</td>
<td>0.9</td>
</tr>
<tr>
<td>123</td>
<td>Milhouse</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>857</td>
<td>Lisa</td>
<td>8</td>
<td>0.7</td>
</tr>
<tr>
<td>456</td>
<td>Ralph</td>
<td>8</td>
<td>0.3</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**Group**

<table>
<thead>
<tr>
<th>gid</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>abc</td>
<td>Book Club</td>
</tr>
<tr>
<td>gov</td>
<td>Student Government</td>
</tr>
<tr>
<td>dps</td>
<td>Dead Putting Society</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**Member**

<table>
<thead>
<tr>
<th>uid</th>
<th>gid</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>dps</td>
</tr>
<tr>
<td>123</td>
<td>gov</td>
</tr>
<tr>
<td>857</td>
<td>abc</td>
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<tr>
<td>456</td>
<td>abc</td>
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<tr>
<td>456</td>
<td>gov</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Ordering of rows doesn’t matter (even though output is always in some order)
Schema vs. instance

• Schema (metadata)
  • Specifies the logical structure of data
  • Is defined at setup time
  • Rarely changes

• Instance
  • Represents the data content
  • Changes rapidly, but always conforms to the schema

Compare to types vs. collections of objects of these types in a programming language
Example

- **Schema**
  - `User (uid int, name string, age int, pop float)`
  - `Group (gid string, name string)`
  - `Member (uid int, gid string)`

- **Instance**
  - `User: {〈142, Bart, 10, 0.9〉, 〈857, Milhouse, 10, 0.2〉, ... }`
  - `Group: {〈abc, Book Club〉, 〈gov, Student Government〉, ... }`
  - `Member: {〈142, dps〉, 〈123, gov〉, ... }`
Relational algebra

A language for querying relational data based on “operators”

- **Core 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 (or predicate)

• Purpose: filter rows according to some criteria

• Output: same columns as $R$, but only rows or $R$ that satisfy $p$
Selection example

• Users with popularity higher than 0.5

$$\sigma_{pop > 0.5} User$$

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</table>
More on selection

• Selection condition can include any column of $R$, constants, comparison ($=, \leq, \text{ etc.}$) and Boolean connectives ($\land$: and, $\lor$: or, $\neg$: not)
  • Example: users with popularity at least 0.9 and age under 10 or above 12

$$\sigma_{\text{pop} \geq 0.9 \land (\text{age} < 10 \lor \text{age} > 12)} \text{ User}$$

• You must be able to evaluate the condition over each single row of the input table!
  • Example: the most popular user

$$\sigma_{\text{pop} \geq \text{ every pop in User}} \text{ User}$$

WRONG!
Projection

• Input: a table $R$
• Notation: $\pi_L R$
  • $L$ is a list of columns in $R$
• Purpose: output chosen columns
• Output: same rows, but only the columns in $L$
Projection example

- IDs and names of all users

\[ \pi_{uid,name} \text{User} \]

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<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

\[ \pi_{uid,name} \]

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<tr>
<td>...</td>
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</tbody>
</table>
More on projection

• Duplicate output rows are removed (by definition)
• Example: user ages
  \( \pi_{age} User \)

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</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

\( \pi_{age} \)
Cross product

• Input: two tables $R$ and $S$
• Natation: $R \times S$
• Purpose: pairs rows from two tables
• Output: for each row $r$ in $R$ and each $s$ in $S$, output a row $rs$ (concatenation of $r$ and $s$)
Cross product example

User $\times$ Member

<table>
<thead>
<tr>
<th>uid</th>
<th>name</th>
<th>age</th>
<th>pop</th>
<th>uid</th>
<th>gid</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>Milhouse</td>
<td>10</td>
<td>0.2</td>
<td>123</td>
<td>gov</td>
</tr>
<tr>
<td>857</td>
<td>Lisa</td>
<td>8</td>
<td>0.7</td>
<td>857</td>
<td>abc</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
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<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>123</td>
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<tr>
<td>857</td>
<td>abc</td>
</tr>
<tr>
<td>857</td>
<td>gov</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A note on column ordering

- Ordering of columns is unimportant as far as contents are concerned

\[
\begin{array}{cccc}
\text{uid} & \text{name} & \text{age} & \text{pop} \\
123 & Milhouse & 10 & 0.2 \\
123 & Milhouse & 10 & 0.2 \\
123 & Milhouse & 10 & 0.2 \\
857 & Lisa & 8 & 0.7 \\
857 & Lisa & 8 & 0.7 \\
857 & Lisa & 8 & 0.7 \\
\ldots & \ldots & \ldots & \ldots \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{uid} & \text{gid} & \text{uid} & \text{name} \\
123 & gov & 123 & Milhouse \\
123 & gov & 123 & Milhouse \\
857 & abc & 857 & Lisa \\
857 & abc & 857 & Lisa \\
857 & abc & 857 & Lisa \\
\ldots & \ldots & \ldots & \ldots \\
\end{array}
\]

- So cross product is \textit{commutative}, i.e., for any \( R \) and \( S \), \( R \times S = S \times R \) (up to the ordering of columns)
Derived operator: join

(A.k.a. “theta-join”)

• Input: two tables $R$ and $S$

• Notation: $R \bowtie_{\varphi} S$
  • $\varphi$ is called a join condition (or 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 $\varphi$

• Shorthand for $\sigma_{\varphi}(R \times S)$
Join example

- Info about users, plus IDs of their groups

$$User \bowtie_{User.uid=Member.uid} Member$$

<table>
<thead>
<tr>
<th>uid</th>
<th>name</th>
<th>age</th>
<th>pop</th>
</tr>
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<tbody>
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<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Prefix a column reference with table name and “." to disambiguate identically named columns from different tables.

<table>
<thead>
<tr>
<th>uid</th>
<th>gid</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>gov</td>
</tr>
<tr>
<td>857</td>
<td>abc</td>
</tr>
<tr>
<td>857</td>
<td>gov</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Derived operator: natural join

• Input: two tables $R$ and $S$
• Notation: $R \bowtie S$
• Purpose: relate rows from two tables, and
  • Enforce equality between identically named columns
  • Eliminate one copy of identically named columns
• Shorthand for $\pi_L(R \bowtie \rho S)$, where
  • $\rho$ equates each pair of columns common to $R$ and $S$
  • $L$ is the union of column names from $R$ and $S$ (with duplicate columns removed)
Natural join example

\[ \text{User} \bowtie \text{Member} = \pi_? (\text{User} \bowtie_? \text{Member}) \\
= \pi_{uid, name, age, pop, gid} (\text{User} \bowtie \text{User}.uid = \text{Member}.uid) \]

<table>
<thead>
<tr>
<th>uid</th>
<th>name</th>
<th>age</th>
<th>pop</th>
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<td>...</td>
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</tr>
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</table>

<table>
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<tr>
<th>uid</th>
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</thead>
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<tr>
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<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
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 removed)
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 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 $R - (R - S)$

• Also equivalent to $S - (S - R)$

• And to $R \bowtie S$
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 table with the same rows as $R$, but called differently
• Used to
  • Avoid confusion caused by identical column names
  • Create identical column names for natural joins
• As with all other relational operators, it doesn’t modify the database
  • Think of the renamed table as a copy of the original
Renaming example

• IDs of users who belong to at least two groups

\[ \text{Member } \Join \text{ Member} \]

\[ \pi_{\text{uid}} \left( \text{Member } \Join \text{Member}.\text{uid=}\text{Member}.\text{uid} \land \text{Member}.\text{gid} \lor \text{Member}.\text{gid} \right) \]

\[ \pi_{\text{uid}_1} \left( \rho_{(\text{uid}_1,\text{gid}_1)} \text{Member} \right) \Join \rho_{(\text{uid}_2,\text{gid}_2)} \text{Member} \land \text{uid}_1=\text{uid}_2 \land \text{gid}_1 \neq \text{gid}_2 \]
Expression tree notation

\[
\pi_{\text{uid}_1} \bowtie \text{uid}_1 = \text{uid}_2 \land \text{gid}_1 \neq \text{gid}_2
\]

\[
\rho(\text{uid}_1, \text{gid}_1) \quad \rho(\text{uid}_2, \text{gid}_2)
\]

Member
Summary of core operators

• Selection: $\sigma_p R$
• Projection: $\pi_L R$
• Cross product: $R \times S$
• Union: $R \cup S$
• Difference: $R - S$
• Renaming: $\rho_{S(A_1,A_2,...)} R$
  • 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 users in Lisa’s groups

**Writing a query bottom-up:**

Their names

Users in
Lisa’s groups

Lisa’s groups

Who’s Lisa?
Another exercise

- IDs of groups that Lisa doesn’t belong to

**Writing a query top-down:**

```
\begin{center}
\begin{tikzpicture}
  \node {Group} child {node {\(\pi_{gid}\)}} child {node {Member \(\sigma_{\text{name}="Lisa"}\)}} child {node {User}};
\end{tikzpicture}
\end{center}
```

All group IDs \(\pi_{gid}\)

IDs of Lisa’s groups \(\pi_{gid}\)
A trickier exercise

• Who are the most popular?

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 $op$:
  $$ R \subseteq R' \text{ implies } op(R) \subseteq op(R') \text{ for any } R, R' $$

Add more rows to the input...

What happens to the output?
Classification of relational operators

• Selection: $\sigma_p R$  
  Monotone
• Projection: $\pi_L R$
• 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”?

• Composition of monotone operators produces a monotone query
  • Old output rows remain “correct” when more rows are added to the input

• Is the “highest” query monotone?
Why do we need core operator $X$?

• Difference
  • The only non-monotone operator

• Projection

• Cross product

• Union

• Selection?
  • Homework problem
Extensions to relational algebra

• Duplicate handling ("bag algebra")
• Grouping and aggregation
• "Extension" (or "extended projection") to allow new column values to be computed

收受 All these will come up when we talk about SQL
收受 But for now we will stick to standard relational algebra without these extensions
Why is r.a. a good query language?

• Simple
  • A small set of core operators
  • 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

• \{u.uid \mid u \in User \land 
\neg (\exists u' \in User: u.pop < u'.pop)\}, or

• \{u.uid \mid u \in User \land 
(\forall u' \in User: u.pop \geq u'.pop)\}

• 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
  • \{u.name \mid \neg (u \in User)\}
  • Cannot evaluate it just by looking at the database
Turing machine

• A conceptual device that can execute any computer algorithm
• Approximates what general-purpose programming languages can do
  • E.g., Python, Java, C++, ...

So how does relational algebra compare with a Turing machine?
Limits of relational algebra

• Relational algebra has no recursion
  • Example: given relation $Friend(uid1, uid2)$, who can Bart reach in his social network with any number of hops?
    • Writing this query in r.a. is impossible!
    • So r.a. is not as powerful as general-purpose languages

• But why not?
  • Optimization becomes undecidable
  ☐ Simplicity is empowering
  • Besides, you can always implement it at the application level, and recursion is added to SQL nevertheless!