Valued Dictionary Abstract Data Types: Databases - SQL

CS240: Data Structures and Data Management
Slide Set 14

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Outline

SQL

Implementation

Outline

- We will spend about two lectures on databases
    1. Overview of databases
    2. Terminology
    3. SQL
    4. Relational Algebra
    5. Implementation

Overview

- A large amount of structured data stored for a long time
  - Gigabytes and Terabytes of information
  - Generally outlasts the original technology
- Updates are frequent
- Most of the data exists indefinitely
- Nature of searches change over time
- Utilize a DBMS – Database Management System
- Only consider relational databases

Peanuts Database

- Students Relation:

StudentID	Name	Address	Phone
12345	C. Brown	12 Apple St.	555-1234
67890	L. Van Pelt	34 Pear Ave.	555-5678
22222	P. Patty	56 Grape Blvd.	555-9999

- Grades Relation:

Course	StudentId	Grade
CS101	12345	85
CS101	67890	70
EE200	12345	65
EE200	22222	75
CS101	33333	83
PH100	67890	69

Peanuts Database

- Courses Relation:

Course	Prerequisite
CS101	CS100
EE200	EE005
EE200	CS100
CS120	CS101
CS121	CS120
CS205	CS101
CS206	CS121
CS206	CS205

- Times Relation:

Course	Day	Hour
CS101	M	9AM
CS101	W	9AM
CS101	F	9AM
EE200	T	10AM
EE200	W	1PM
EE200	R	10AM

- Rooms Relation:

Course	Room
CS101	Turing Aud.
EE200	25 Ohm Hall
PH100	Newton Lab

Terminology

- Attribute – Name of a set
  - Column name
- Tuple – Ordered set; maps attributes to values
  - One row of a table
- Relation – Finite set of tuples
  - The table
  - This is the actual information
- Relation Scheme – Set of attribute names in a relation
  - Set of column names for a table
- Database – Set of relations
  - Set of tables
- Database Scheme – Set of relation schemes in a database
  - All the attributes and their various relationships

Assumptions

- No duplicate rows
- Exactly one entry in any row i and column j of a relation
- Rows are not ordered
- Columns are ordered

Queries

- We will focus on lookups/queries primarily
- More powerful requests than standard `Find( key )`
  - Random Access – find tuple with key K
  - Sequential Access – a list of all the tuples
  - Value – find tuple with attribute $A = v$
  - Range – find all tuples with attributes in given range
  - Function – compute function f for an attribute over a relation
  - Boolean – find all tuples satisfying a boolean expression
  - Quantified – give a yes or no answer
  - Similarity – tuples matching a regular expression

SQL

- General form of the SQL `SELECT` statement:

  `SELECT`
  (`DISTINCT` — ε)
  (*columns* — * — ¡*aggregate function*¿ ¡*column*¿)
  `FROM` *relations*
  (`WHERE` *conditions* — ε)
  (`GROUP BY` *columns* — ε)
  (`ORDER BY` *columns* — ε)

- *conditions* consists of attribute names connected by logical and arithmetic operators
- *aggregate function* can be:
  - `AVG()`
  - `MIN()`
  - `MAX()`
  - `COUNT()`
  - `SUM()`

Queries

- Note: The result of a query is a new (unnamed) relation
- List the personal information for all of the students sorted by student number:

Solution

```
SELECT Name, Address, Phone FROM Students
ORDER BY StudentID;
```

- List all student numbers for which a grade has been recorded:

Solution

```
SELECT StudentID FROM Grades;
```

- List all unique student numbers for which a grade has been recorded:

Solution

```
SELECT DISTINCT Student ID FROM Grades;
```

Queries

- What is the highest student number?

Solution

```
SELECT MAX(StudentID) FROM Students;
```

- Provide a nicer column name for the above query.

Solution

- What is Charlie Brown's phone number?

Solution

```
SELECT Phone FROM Students WHERE Name ='C.Brown';
```

- What is the average grade in each course?

Solution

```
SELECT Course, AVG(Grade) FROM Grades GROUP BY
Course;
```

Cartesian Product

- We saw the set operators union, intersection and difference
- We can also take the Cartesian product
- Every tuple in first set is combined with every tuple in the second set

$$R = \begin{array}{c|c} \textbf{A} & \textbf{B} \\ \hline 0 & 1 \\ 2 & 3 \end{array} \qquad S = \begin{array}{c|c} \textbf{A} & \textbf{B} \\ \hline 0 & 1 \\ 4 & 5 \end{array} \qquad T = \begin{array}{c|c|c} \textbf{C} & \textbf{D} & \textbf{E} \\ \hline 6 & 7 & 8 \end{array}$$

- $R \times T$: $\qquad R \times S$:

Queries

- What grade did each student receive (using their name, not their student number)?

Solution

```
SELECT R.Name, S.Course, S.Grade FROM Students R,
Grades S
WHERE R.StudentId=S.StudentId;
```

- What prerequisites must Charlie Brown have taken?

Solution

```
SELECT DISTINCT C.Prerequisite
FROM Students S, Grades G, Courses C
WHERE S.name = 'C. Brown'
AND S.StudentID = G.StudentID
AND G.course=C.course;
```

Queries

- Suppose we had the following CS240Grades Relation:

StudentId	Grade
98765	85
⋮	⋮

- What student numbers got above average in the course?

Solution

```
SELECT StudentId
FROM CS240Grades C1,
(SELECT AVG(Grade) AS A
FROM CS240Grades) C2
WHERE C1.Grade > C2.A
```

Summary

- Databases are one of the main motivation for efficient Data Structures.
- Sorted data is helping, but not always available (or is sorted in another order).

Outline

Relational Algebra

- Allows us to build mathematical expressions for relational queries
- Express query without giving details of how to implement
- Allows for optimizations
  - One SQL statement may correspond to numerous expressions
  - Use algebraic laws to convert expressions
  - Apply rules to (hopefully) minimize total work

Select

- $\sigma_C(R)$
- Select tuples from relation R satisfying condition C
- C can be connected by arithmetic and boolean operators
- Horizontal subset
- Like the `WHERE` clause in SQL
- **Example**: List all the tuples for grades reported in course CS101

Solution

$\sigma_{Course=``CS101''}(Grades)$

Project

- $\pi_A(R)$
- Delete from relation R all attributes not in A
- Implicitly removes duplicate rows
- Vertical subset
- Like the `SELECT DISTINCT` clause in SQL
- **Example**: List all the students and their phone numbers

Solution

$\pi_{Name,Phone}(Students)$

- We can perform composition between various operators
- **Example**: List all student numbers having taken CS101

Solution

$\pi_{StudentID}(\sigma_{Course=''CS101''}(Grades))$

Join

- $R \bowtie_a S$
- Concatenate all tuples from R and S where $R.a = S.a$
- Removes duplicate columns
- Natural Join – $R \bowtie S$
  - R and S have only one column in common
- Combines `FROM` and `WHERE` clause in SQL
- **Example**: List the time and room for each class

Solution

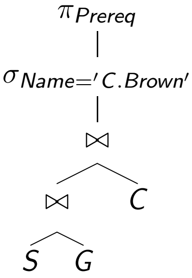
$Rooms \bowtie Times$

Representation

- What prerequisites must Charlie Brown have taken?
- Directly translate the SQL from last lecture:

$$\pi_{Prereq}\Big(\sigma_{Name='C.Brown'}\big((S \bowtie G) \bowtie C\big)\Big)$$

- We can draw an expression tree:

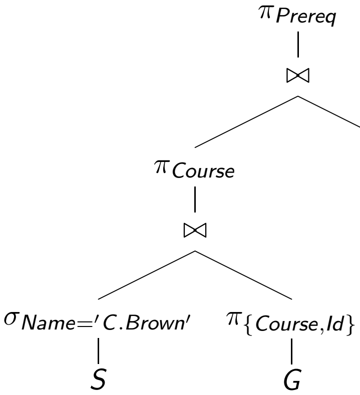


An Optimization

- An equivalent representation:

$$\pi_{Prereq}\Big(\pi_{Course}\big(\sigma_{Name='C.Brown'}(S) \bowtie \pi_{\{Course,Id\}}(G)\big) \bowtie C\Big)$$

- Corresponding expression tree:



How to Optimize

1. Optimize the expression tree
   - Usually, $\textsc{Cost}(\bowtie) \geq \textsc{Cost}(\pi) \geq \textsc{Cost}(\sigma)$
   - We want to push selection and projection as far down the tree as possible
   - Apply laws such as:
     - $\sigma_c(R \bowtie S) \equiv \sigma_c(R) \bowtie S \quad \text{if } c \notin S$
     - $\pi_A(R \bowtie S) \equiv \pi_A\big(\pi_{A'}(R) \bowtie \pi_{A''}(S)\big)$
   - Duplicate detection should be left until the end
   - Use heuristics to decide when to apply rules
2. Optimize the implementation of each operator
   - Our focus

Database Implementation

- Still treat a database as a dictionary ADT
- Primary Key – One or more fields whose value(s) uniquely identify each tuple in a relation
- Primary Index – Main data structure organized by primary keys
  - B^+-Tree
  - Extendible Hashing
  - What is 12345's phone number?
- Secondary Index – An index based on another attribute
  - What is Charlie Brown's phone number?
- Updates are more expensive, but certain queries are much faster

Indices

- The secondary index does not store data
- Points to where the data is in the primary index
- Example:
  - `Id` is the primary key with the index stored in a hash table
  - `Name` is the secondary index stored in a B-Tree

Implementing Operators

- Generally either sorting based or hashing based
- Choice depends on size of relation and existing indices
- Union
  - Sort both relations
  - Merge removing duplicates
  - What if you know there are no duplicates?
- Difference
  - Identical

Simple Operators

- Intersection
  - Still much the same
  - Usually implemented as special case of the join operator
- Projection
  - Scan each tuple
  - Removing duplicates is primary problem
  - Sort as you perform the scan
  - Could also utilize a hash table

Selection

- Duplicate detection not an issue
- Equality Selection
  - $\sigma_{A=v}$
  - Use (extendible) hashing
  - Consider Students with `Id` as primary index

    Good: $Id = 12345$

    Bad: $Id > 12345$

    Bad: Name = 'C.Brown'

Selection

- Range Selection
  - $\sigma_{v \leq A \leq w}$
  - Use B^{+}-Tree
  - Consider Grades with `(Course,Id)` as primary index

    Good: Course = CS101 & Id = 12345

    Good: Course = CS101

    Bad: Id = 12345
- Chose the appropriate index based on particular request
- Create indices based on the queries users tend to ask

Join

- Suppose we have the following relations (with sample data):
- **R**:

A	**B**
0	6
2	1
4	3

- **S**:

B	**C**
6	4
3	8
9	12
6	15

- Perform $R \bowtie S$

A	**B**	**C**
0	6	4
0	6	15
4	3	8

- Let $r = |R|$ and $s = |S|$

Join

There are several ways to implement Joins:

- Nested Loop
- Sorted Join
- Index Join

What are the advantages of each implementation?

Join

nested loop: very costly (Cost $= rs$)

```
for each tuple a in R
   for each tuple b in S
     if a.B = b.B then output a, b
```

Join

sort join: merge, mark as R or S and sort on B

```
merge R and S
sort on B attribute
go through linearly, joining on grouped elements (since
they will be sorted together)
```

(Cost $= (r+s)\log(r+s)$)

Join

index join: if index on join element B (Cost $= r + s$ if index is $O(1)$ time to find tuples (hash table). Cost$=r + s \log s$ if B-tree used on index)

```
for each tuple a in R
   use index of S to find tuples b where b.B=a.B
   for each tuple b in S
     output a, b
```

Summary

- Database is a whole field of research, we barely scratched the surface here.
- Database is one of the main motivations for efficient data-structures: how to manage very large amount of data.
- How to compute things is not the whole story, but also in which order to compute it.