# 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`<br>
  ( `DISTINCT` — $\varepsilon$ )<br>
  ( *columns* — $*$ — *¡aggregate function¿ ¡column¿* )<br>
  `FROM` *relations*<br>
  ( `WHERE` *conditions* — $\varepsilon$ )<br>
  ( `GROUP BY` *columns* — $\varepsilon$ )<br>
  ( `ORDER BY` *columns* — $\varepsilon$ )
- *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

SQL

Implementation

## 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

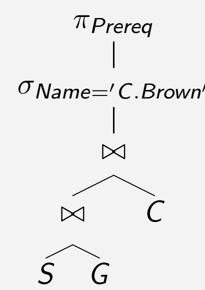
Solution
$Rooms \bowtie Times$

## 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:

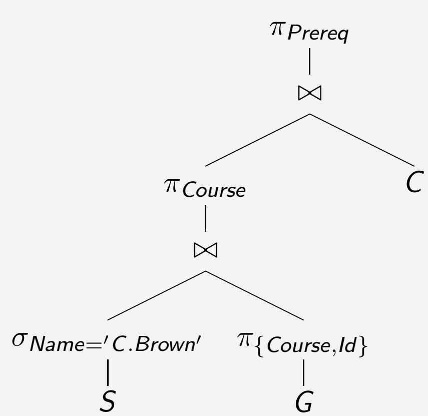



## An Optimization

- 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:
     - $\sigma_c(R \bowtie S) \equiv \sigma_c(R) \bowtie S \quad \text{if } c \notin S$
     - $\pi_A(R \bowtie S) \equiv \pi_A(\pi_{A'}(R) \bowtie \pi_{A''}(S))$
   - 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
  - $\mathrm{B}^{+}$-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 $\mathrm{B}^{+}$-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.