Announcements

- Homework info:
  - HW #7: Due this coming Friday (6 PM).
  - Then just one more HW remains (on “NoSQL”!)
- This week’s plan:
  - Today: Physical DB design (e.g., use of indexes).
  - Indexing-related quiz in discussions this week.
  - Next up: NoSQL & Big Data (a la AsterixDB)
    - Not in book, so...
    - See (and DO) materials linked to wiki syllabus!
Overview

- After ER design, schema refinement, and the definition of views, we have the *conceptual* and *external* schemas for our database.
- The next step is to choose indexes, make clustering decisions, and to refine the conceptual and external schemas (if necessary) to meet performance goals.
- We should start by understanding the *workload*:
  - Most important queries and how often they arise.
  - Most important updates and how often they arise.
  - Desired performance goals for those queries/updates?

Decisions to Be Made Include...

- What indexes should we create?
  - Which relations should have indexes? What field(s) should be their search keys? Should we build several indexes?
- For each index, what kind of an index should it be?
  - B+ tree? Hashed? Clustered? Unclustered?
- Should we make changes to the conceptual schema?
  - Consider alternative normalized schemas? (There are multiple choices when decomposing into BCNF, etc.)
  - Should we ``undo'' some decomposition steps and settle for a lower normal form? ("Denormalization.")
  - Horizontal partitioning, materialized views, replication, ...
Understanding the Workload

- For each query in the workload:
  - Which relations does it access?
  - Which attributes are retrieved?
  - Which attributes are involved in selection/join conditions? (And how selective are these conditions expected to be?)

- For each update in the workload:
  - Which attributes are involved in selection/join conditions? (And how selective are these conditions likely to be?)
  - The type of update (INSERT/DELETE/UPDATE), and the attributes that are affected.

Index Classification (Review)

- **Primary vs. secondary**: If search key contains the primary key, then called the primary index.
  - *Unique* index: Search key contains a *candidate* key.
- **Clustered vs. unclustered**: If order of data records is the same as, or `close to`, the order of stored data records, then called a clustered index.
  - A table can be clustered on at most one search key.
  - Cost of retrieving data records via an index varies *greatly* based on whether index is clustered or not!
Clustered vs. Unclustered Indexes (Review)

Clustered Indexes:
- Index entries refer to the index file.
- Data entries are directly accessible.

Unclustered Indexes:
- Index entries refer to the data file.
- Data entries are accessed through the index file.

Choice of Indexes (Cont’d.)

- **One approach:** Consider the most important queries in turn. Consider the best query plan using the current indexes, and see if a better plan is possible with an additional index. If so, create it.
  - This implies that we must understand and see how a DBMS evaluates its queries. *(Query evaluation plans.)*
  - Let’s start by discussing simple 1-table queries!
- **Before creating an index,** must also consider its impact on updates in the workload.
  - **Trade-off:** Indexes can make queries go faster, but updates will become slower. *(Indexes require disk space, too.)*
Index Selection Guidelines

- Attributes in WHERE clause are candidates for index keys.
  - Exact match condition → hashed index (or B+ tree if not available).
  - Range query → B+ tree index.
    - Clustering especially useful for range queries, but also helps with equality queries with duplicate values (non-key field index).
- Multi-attribute search keys should be considered when a WHERE clause contains several conditions.
  - Order of attributes matters for range queries.
  - Such indexes can sometimes enable index-only strategies for important queries (e.g., aggregates / grouped aggregates).
    - For index-only strategies, clustering isn’t important!
- Choose indexes that benefit as many queries as possible.
  - Only one index can be clustered per relation, so choose it based on important queries that can benefit the most from clustering.

Examples of Clustered Indexes

**SELECT** E.dno 
**FROM** Emp E 
**WHERE** E.age > 40

**SELECT** E.dno, 
**COUNT** (*)&
**FROM** Emp E 
**WHERE** E.age > 10 
**GROUP** **BY** E.dno

- B+ tree index on E.age can be used to get qualifying tuples.
  - How selective is the condition?
  - Should the index be clustered?

**SELECT** E.dno 
**FROM** Emp E 
**WHERE** E.hobby = 'Stamps'

- Consider the GROUP BY query.
  - If most tuples have E.age > 10, using E.age index and sorting the retrieved tuples may be costly.
  - Clustered E.dno index may win!

- Equality queries & duplicates:
  - Clustering on E.hobby helps!
Indexes with Composite Search Keys

- **Composite Search Keys**: Search on a combination of fields.
  - **Equality query**: Every field value is equal to a constant value. E.g. wrt <sal,age> index:
    - (age=20 AND sal=75)
  - **Range query**: Some field value is a range, not a constant. E.g. again wrt <sal,age> index:
    - age=20; or (age=20 AND sal > 10)
- Data entries in index sorted by search key to support such range queries.
  - **Lexicographic order**

Various composite key indexes using lexicographic (ASC) order.

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>Salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bob</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Sue</td>
<td>13</td>
<td>75</td>
</tr>
<tr>
<td>Joe</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>Cal</td>
<td>11</td>
<td>80</td>
</tr>
<tr>
<td>Bob</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Sue</td>
<td>75</td>
<td>13</td>
</tr>
<tr>
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<td>10</td>
</tr>
<tr>
<td>Joe</td>
<td>12</td>
<td>20</td>
</tr>
</tbody>
</table>

Data records (sorted by name)

Data entries in index sorted by <sal,age>

Data entries sorted by <sal>

Composite Search Keys

- To retrieve Emp records with age=30 AND sal=4000, an index on <age, sal> would be better than an index only on age or an index only on sal.
  - Note: Choice of index key orthogonal to clustering.
- If condition is: 20<age<30 AND 3000<sal<5000:
  - Clustered B+ tree index on <age, sal> or <sal, age> is best.
- If condition is: age=30 AND 3000<sal<5000:
  - Clustered <age, sal> index much better than <sal, age> index! *(Think about why!)*
- Composite indexes are larger; updated more often.
### Index-Only Query Plans

- Some queries can be answered without retrieving any tuples from one or more of the relations involved if a suitable index is available. (Sometimes called a "covering index" for the given query.)

  - `SELECT E.dno, COUNT(*) 
    FROM Emp E 
    GROUP BY E.dno`

  - `SELECT E.dno, MIN(E.sal) 
    FROM Emp E 
    GROUP BY E.dno`

  - `SELECT AVG(E.sal) 
    FROM Emp E 
    WHERE E.age=25 AND E.sal BETWEEN 3000 AND 5000`

### Some Illustrated Index-Only Plans

Data records (Emp table, clustered by `name`)

- `SELECT sal, age 
  FROM Emp 
  WHERE age > 11 
  AND age <= 13;`

- `SELECT * FROM Emp;`

- `SELECT AVG(sal) 
  FROM Emp 
  GROUP BY sal;`

- `SELECT MIN(sal) 
  FROM Emp 
  GROUP BY sal;`

- `SELECT COUNT(*) 
  FROM Emp 
  GROUP BY age;`

- `SELECT age, COUNT(*) 
  FROM Emp 
  GROUP BY age;`

- `SELECT DISTINCT sal 
  FROM Emp;`

**Note:** The index files are each much smaller than the main file!
Index Selection for Joins

- When considering a join condition:
  - Index Nested Loop join (INLJ) method:
    - For each outer table tuple, use its join attribute value to probe the inner table for tuples to join (match) it with.
    - Indexing the inner table’s join column will help!
    - Good for this index to be clustered if the join column is not the inner’s key and inner tuples need to be retrieved.
  - Sort-Merge join (SMJ) method:
    - Sort outer and inner tables on join attribute value and then scan them concurrently to match tuples.
    - Clustered B+ trees on both join column(s) good for this!
  - Hash join (HJ) method:
    - Indexing not needed (not for the join, anyway).

Example 1

SELECT E.ename, D.mgr
FROM Emp E, Dept D
WHERE D.dname = 'Toy' AND E.dno = D.dno

- Hash index on D.dname supports ‘Toy’ selection.
  - Given this, an index on D.dno is not needed.
- Hash index on E.dno allows us to get matching (inner) Emp tuples for each selected (outer) Dept tuple.
- What if WHERE included: ‘` ... AND E.age=25’’?
  - Could retrieve Emp tuples using index on E.age, then join with Dept tuples satisfying dname selection. (Comparable to strategy that uses the E.dno index.)
  - So, if E.age index is already created, this query provides less motivation for adding an E.dno index.
Example 2

- Clearly, Emp (E) should be the outer relation.
  - Suggests that we build an index (hashed) on D.dno.
- What index should we build on Emp?
  - B+ tree on E.sal could be used, OR an index on E.hobby could be used. Only one of these is needed, and which is better depends upon the selectivity of the conditions.
  - As a rough rule of thumb, equality selections tend to be more selective than range selections.
- As both examples indicate, our choice of indexes is guided by the plan(s) that we expect an optimizer to consider for a query. \( \rightarrow \) Understand query optimizer!

Clustering and Joins

- Clustering is especially important when accessing inner tuples in INLJ (index nested loops join).
  - Should make index on E.dno clustered. (Q: See why?)
- Suppose that the WHERE clause were instead:
  - WHERE E.hobby = 'Stamps' AND E.dno = D.dno
  - If most employees collect stamps, Sort-Merge join may be worth considering. A clustered index on D.dno would help.
- Summary: Clustering is useful whenever many tuples are to be retrieved for a value or range of values.
Tuning the Conceptual Schema

- The choice of conceptual schema should be guided by the workload, in addition to redundancy issues:
  - We may settle for a 3NF schema rather than BCNF.
  - Workload may influence the choice we make in decomposing a relation into 3NF or BCNF.
  - We might denormalize (i.e., undo a decomposition step), or we might add fields to a relation.
  - We might consider vertical decompositions.

- If such changes come after a database is in use, it’s called schema evolution; might want to mask some of the changes from applications by defining views.

Some Example Schemas (& Tradeoffs)

- Contracts (Cid, Sid, Jid, Did, Pid, Qty, Val)
- Depts (Did, Budget, Report)
- Suppliers (Sid, Address)
- Parts (Pid, Cost)
- Projects (Jid, Mgr)

- We will concentrate on Contracts, denoted as CSJDPQV. The following ICs were given to hold: JP \( \rightarrow \) C, SD \( \rightarrow \) P, C \( \rightarrow \) CSJDPQV.
  - Currently this relation is in 3NF....
Settling for 3NF vs BCNF

- CSJDPQV can be decomposed into SDP and CSJDQV, and both relations would then be in BCNF
  - Lossless decomposition, not dependency-preserving.
  - Adding CJP could make it dependency-preserving too.
- But suppose that the query below is very important:
  - Find the # of copies (Q) of part P ordered in contract C.
  - Requires a join on the decomposed schema, but can be answered by a scan of the original relation CSJDPQV.
  - Could lead us to settle for the 3NF schema CSJDPQV!

Further Denormalization

- Suppose that the following query is important:
  - Is the value of a contract less than the budget of the department?
- To speed up this query, we might add a (redundant) field budget B to Contracts.
  - This would add a transitive FD D \(\rightarrow\) B w.r.t. Contracts.
  - Thus, Contracts would no longer even be in 3NF...!
- Might choose to modify Contracts this way if this query is sufficiently important and we can’t obtain adequate performance otherwise (e.g., by adding indexes or by finding an alternative 3NF schema.)
Decomposition of a BCNF Relation

- Suppose that we choose \{ SDP, CSJDQV \}. This is in BCNF, so there is no “reason” to decompose further.
- However, suppose that two queries are very frequent:
  - Find the contracts C held by suppliers S.
  - Find the contracts C that departments D are involved in.
- Decomposing CSJDQV into CS, CD and CJQV could speed up these queries (note why!). (“Vertical partitioning.”)
- On the other hand, the query below would now be slower (as it would need to do a join: CS $\bowtie$ CJQV):
  - Find the total value V of all contracts C held by supplier S.

A Vertical Partitioning Example

<table>
<thead>
<tr>
<th>eno</th>
<th>email</th>
<th>name</th>
<th>addr</th>
<th>salary</th>
<th>age</th>
<th>dno</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><a href="mailto:joe@aol.com">joe@aol.com</a></td>
<td>Joe</td>
<td>1 Main St.</td>
<td>100000</td>
<td>25</td>
<td>10</td>
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(VERTICAL PARTITIONING: $\ltimes$)
Horizontal Decompositions

- Prior def’n. of decomposition: Relation replaced by a set of joinable relations that are *projections*. (That’s the most important and most common case.)
- Occasionally, we may want to instead replace a relation by a set of relations that are *selections*.
  - Each new relation has same schema as the original, but only a subset of the rows.
  - Collectively, the new relations contain all rows of the original. (Typically, the new relations are *disjoint*.)
  - Original relation is the UNION (ALL) of the new ones (i.e., rather than the JOIN of the new ones).

Horizontal Decompositions (Cont’d.)

- Suppose contracts with values over 10000 are subject to different rules. (This means queries on Contracts will frequently contain the condition \( \text{val} > 10000 \).)
- One approach to deal with this would be a clustered B+ tree index on the \( \text{val} \) field of Contracts.
- Another approach is to replace Contracts by two new relations, LargeContracts & SmallContracts, with the same attributes (CSJDPQV).
  - Performs like index on such queries, but no index overhead.
  - Can build clustered indexes on other attributes, in addition!
Masking Schema Changes

CREATE VIEW Contracts(cid, sid, jid, did, pid, qty, val) AS
SELECT *
FROM LargeContracts
UNION ALL
SELECT *
FROM SmallContracts

- The replacement of Contracts by LargeContracts and SmallContracts can be masked by this view.
- However, queries with \(\text{val} > 10000\) must be run on LargeContracts* for fast execution; users concerned with performance must be aware of this change.

(*The DBMS isn’t aware of the two tables’ value constraints.)

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(Horizontal partitioning: ∪)

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Tuning Your Queries (and Views)

- If a query runs slower than expected, see if an index needs to be re-built, or if **table statistics** are too old.
- Sometimes, the DBMS may not be executing the plan you had in mind. Common areas of weakness:
  - Selections involving **null values**.
  - Selections involving **arithmetic or string expressions**.
  - Selections involving **OR conditions**.
  - **Lack of more advanced evaluation features** like index-only strategies or certain join methods, or poor size estimation.
- Check the query plan! Then adjust the choice of indexes or maybe **rewrite the query/view**.

Miscellany for Query Tuning

- Minimize the use of **DISTINCT**: don't need/say it if duplicates are acceptable or answer contains a key.
- Consider the DBMS’s use of indexes when writing arithmetic expressions: **E.age = 2*D.age** will benefit from an index on **E.age**, but it might not benefit from an index on **D.age**!
Physical DB Design Summary

- DB design consists of several tasks: requirements analysis, conceptual design, schema refinement, physical design and finally tuning.
  - In general, will go back and forth between tasks to refine a DB design; decisions in one task can influence choices in another task.

- Understanding the workload for the application, and the performance goals, is essential to a good design.
  - What are the important queries and updates? What attributes/relations are involved?

Summary (Cont’d.)

- The conceptual schema should perhaps be refined by considering performance criteria and workload:
  - May choose 3NF or a lower normal form over BCNF.
  - May choose among several alternative decompositions based on the expected workload.
  - May actually denormalize, or undo, some decompositions.
  - May consider further vertical or horizontal decompositions.
  - Importance of dependency-preservation depends on the dependency to be preserved and the cost of the IC check.
    - Can add a relation for dep-preservation (e.g., the CJP example); or else, can check dependency using a join (e.g., using a trigger).
Summary (Cont’d.)

- Over time, the indexes may have to be fine-tuned (dropped, created, re-built, ...) for performance.
  - Should examine the query plan(s) used by the system and adjust the choice of indexes appropriately.
- Sometimes the system may still not find a good plan:
  - Null values, arithmetic conditions, string expressions, the use of ORs, etc., can “confuse” some query optimizers.
- So, may have to rewrite a particular query or view:
  - Might need to re-examine your complex nested queries, complex conditions, or operations like DISTINCT.
- Any lingering questions...?