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Introduction to Databases, Fall 2005  
IT University of Copenhagen

**Lecture 9: Database efficiency**

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# — Today's lecture —

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- Database efficiency
- Indexing
- A little about schema tuning
- Database tuning cases

## — What you should remember from previously —

In this lecture I will assume that you remember:

- That we characterized a DBMS as a system for providing **efficient**, **convenient**, and **safe** storage of and **multi-user** access to (possibly **massive**) amounts of **persistent** data.
- That each of the words in bold are important.

# — Database efficiency —

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This lecture is on **database efficiency**:

The property that the database uses a (mostly) small amount of computational and storage resources.

Here, “small” is relative to the best use of resources we could hope for:

- We don't want the database to use 100 times more storage or computation time than the best that the computer could be programmed to do.

# — RDBMS efficiency is largely automatic —

One of the reasons for the success of RDBMSs is that, to a large extent, they are efficient “automatically”.

*One of the great dividends of investing in an RDBMS is that you don't have to think too much about the computer's inner life. You're the programmer and say what kinds of data you want. The computer's job is to fetch it and you don't really care how.*

Philip Greenspun in “SQL for Web Nerds”

This lecture is about some of the things that you, as a database programmer, might have to do to help the RDBMS improve efficiency:

- Define suitable indexes.
- “Tune” the database schema.

## — Hard drives —

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Relations of large databases are usually stored on hard drives.

Hard drives can store large amounts of data, but work rather slowly compared to the memory of a modern computer:

- The time to access a specific piece of data is on the order of  $10^6$  times slower.
- The rate at which data can be read is on the order of 10 – 100 times slower.

For databases that do not fit in the computer's main memory, the time used for accessing disks is usually the *main performance bottleneck*.

## — Using several hard drives —

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Many database systems use several hard drives to:

- Enable several pieces of data to be fetched in parallel.
- Increase the total rate of data from disk.

Systems of several disks are often arranged in so-called RAID systems, which support various levels of performance improvement and error resilience.

Even in systems with many hard drives, the time used for accessing disks is usually the main performance bottleneck.

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**Next: Indexing**

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## — Full table scans —

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When a DBMS encounters a query of the form

```
SELECT *  
FROM R  
WHERE <condition>
```

the obvious thing to do is read through the tuples of R and report those tuples that satisfy the condition.

This is called a **full table scan**.

## Selective queries

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Consider the selection query from before:

```
SELECT *  
FROM R  
WHERE <condition>
```

- If we have to report 80% of the tuples in R, it makes sense to do a full table scan.
- On the other hand, if the query is very **selective**, and returns just a small percentage of the tuples we might hope to do better:
  - Is there a way of “skipping over” tuples that will not be selected?

## — Problem session (5 minutes) —

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What ways of “going directly to the desired information” do you know?

Consider for example:

- A phone book.
- A dictionary.
- A cookbook.

Can you give examples where the equivalent of a full table scan is needed?

## Point queries

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Consider a selection query with a single equality in the condition:

```
SELECT *  
FROM R  
WHERE grade = 11
```

This is a so-called **point query**: We report all grades at the “point” 11.

Point queries are often very selective.

Suppose the tuples of R were sorted by grade. Then the DBMS could:

1. Search for the first tuple with grade 11.
2. Report this and all the following tuples with grade 11.

## — Range queries —

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Consider a selection query with a single inequality in the condition:

```
SELECT *  
FROM R  
WHERE 6 < grade AND grade < 10
```

This is an example of a **range query**, since we report all grades in the range 7 to 9.

Suppose that the tuples of R were sorted according to grade. Then the DBMS could:

1. Search for the first tuple with grade  $> 6$ .
2. Report this and all the following tuples with grade  $< 10$ .

# Indexes

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To be able to quickly find the first tuple with a specific grade, the DBMS may build an **index** on the grade attribute.

A database index is similar to an index in the back of a book:

1. For every piece of data you might be interested in (e.g., the attribute value 9), the index says where to find it.
2. The index itself is organized such that one can quickly do the lookup.

Looking for information in a relation with the help of an index is called an **index scan**.

## — Primary indexes —

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If the tuples of a relation are stored sorted according to some attribute, an index on this attribute is called **primary**.

- Primary indexes make point and range queries on the key *very efficient*.
- Many DBMSs automatically build a primary index on the primary key of each relation. (In Oracle the programmer must explicitly specify that the table should be index organized.)
- A primary index is sometimes referred to as a **clustering** or **sparse** index.

## — Secondary indexes —

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It is possible to have more than one index on a relation. While not part of the SQL standard, additional indexes can usually be created by writing statements such as:

```
CREATE INDEX gradeIndex ON projects (grade);
```

The non-primary indexes are called **secondary indexes**.

- Secondary indexes make *most* point queries on the key more efficient.
- Secondary indexes make *some* range queries on the key more efficient.
- A secondary index is sometimes referred to as **non-clustering** or **dense** index.



## — Indexes on several attributes —

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An index can be defined on one or more attributes, e.g.

```
CREATE INDEX myIndex ON projects (grade,start,exam);
```

Such an index speeds up point queries such as:

```
SELECT * FROM projects  
WHERE grade = 13 AND start='2003-11-24' AND exam='2004-01-28';
```

Due to the way indexes are (usually) implemented, an index on several attributes automatically gives index for any **prefix** of these attributes.

### **Example:**

myIndex also gives an index for (grade,start) and for (grade).

## — Indexes on several attributes, intuition —

An index on the attributes (*grade*, *start*, *exam*) has a *similar effect* as storing the tuples sorted first according to *grade*, secondly according to *start*, and thirdly sorted according to *exam*.

<i>grade</i>	<i>start</i>	<i>exam</i>
...	...	...
11	2003-11-24	2004-01-28
11	2004-11-27	2005-01-07
13	2003-11-24	2004-01-28
13	2003-11-24	2004-01-28
13	2003-11-24	2005-01-07
13	2004-11-27	2005-01-07
13	2004-11-27	2005-01-07

## — Problem session (5 minutes) —

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What kinds of point and range queries are “easy” when the relation is stored as in the previous example:

- A range query on the first attribute?
- A range query on the second attribute?
- A point query on the second attribute?
- A point query on the first attribute combined with a range query on the second attribute?
- A point query on the second attribute combined with a range query on the first attribute?

## — Index scan versus full scan —

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Point and range queries on the attribute(s) of the primary index are almost always best performed using an index scan.

Secondary indexes should be used with high selectivity queries:

- As a rule of thumb, a secondary index scan is faster than a full table scan for queries returning less than 10-20% of a relation.

## — Choosing whether to use the index —

Even if an index scan is possible, a good DBMS sometimes chooses to do a full table scan.

The decision is usually based on *statistics* on the data in the relation, which allows the selectivity of the query to be estimated.

Often computation of the statistics is controlled manually. In Oracle, statistics can be computed as follows:

```
ANALYZE TABLE <relation> COMPUTE STATISTICS;
```

## — Time usage of indexes —

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Based on what you have seen until now, a natural question would be:

*Why not make indexes for all possible sets of attributes?*

The main reason is that indexes need to be updated when the relation changes, and index updates take time.

Thus we have the following trade-off for every index:

- It speeds up certain database queries, but
- slows down every update to the relation.

Whether an index is a good idea is thus a matter of weighing the time saved on queries against the additional time spent on updates.

## — Dropping and re-creating indexes —

Some types of updates to a large part of a relation can be done efficiently if there is no index:

- Adding a large number of new tuples.
- Deleting or updating a large fraction of existing tuples.

However, if such updates affect indexed attributes, it is likely that a number of disk accesses are needed *for every tuple* that is inserted or changed.

In such cases, it can be more efficient to temporarily disable the index, and rebuild it again once the updates have been done.

## — Problem session (5-10 minutes) —

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Suppose that you are the administrator of a database with two common queries,  $Q_1$  and  $Q_2$ .

- Both queries take 100 ms to execute without an index.
- For each query we may choose to build an index which lowers the query time to 40 ms.
- The time for inserting a new tuple is 20 ms, plus 20 ms for each index.

When is it advantageous to have indexes for  $Q_1$  and/or  $Q_2$ ?



## — Space usage of indexes —

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In addition to taking time to update, an index has a space cost.

- **Primary indexes** usually have modest space requirements, i.e., considerably less than the space for the relation itself.
- **Secondary indexes** use space similar to that required for the attributes indexed.

For space reasons, one should therefore be careful with creating secondary indexes on large amounts of data.

## — Other uses of indexes —

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Indexes are used by the DBMS to speed up other operations than point and range queries.

- **Join operations** are sometimes considerably faster when the join attributes are indexed.
- Indexes are used by DBMSs to efficiently check **referential integrity constraints** (such indexes are usually automatically created).

## — Other types of indexes —

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Indexing is a science of its own:

- There are special index types such as *bitmap indexes* and *hash indexes* that are more efficient than standard (“B-tree” indexes) for some types of data.
- There are *join indexes* that speed up join operations (but are expensive to update).
- There are indexes for geometric and multidimensional data.
- There are indexes for textual data.
- ...

The second part of GUW contains much more material on this, but a deeper understanding of indexes is beyond the scope of this course.

## — Join “Advanced database technology” —

For those of you who are fortunate enough to have taken an introductory course in algorithms (at ITU or elsewhere), there is the possibility to learn about the inner workings of indexes in the spring semester:

Advanced database technology Lectures and exercises on Thursdays Taught by Srinivasa Rao and Rasmus Pagh Based on the second part of GUW + supplementary material
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The course contains explanation of disk based algorithms, indexes, query optimization, and many other things to make you a database expert!

Understand performance rules of thumb and know when they apply!

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**Next: A little about schema tuning**

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## — Use the “smallest” possible data type —

DBMSs often offer many different data types<sup>a</sup>.

Among other things, this is to allow programmers to choose a data type with the smallest possible space usage.

Space may have an impact on time, e.g., if tuples are twice as long as needed, a full table scan takes twice as long as needed.

In Oracle, space can often be saved by replacing fixed length strings such as CHAR(20) with variable length strings such as VARCHAR(20).

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<sup>a</sup>**Warning:** Data types and their definition differ from one DBMS to another.

## — Use of a code table —

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For non-standard data types with few possible values (e.g. “types of wood”), space can be saved by introducing a relation with short integer codes for each possible value (encoded in a less space efficient data type).

The drawback of this approach is that a join operation is necessary to combine the information in the two relations – however, this is no big deal if the code table is small.

## — Normalization and efficiency —

**The good:** Normalization can be used to eliminate redundancy in a database design, and thus avoid all sorts of problems. Also, less redundancy means that e.g. full table scans are faster.

**The bad:** Normalization implies that more join operations must be performed when answering database queries. Performance may not be adequate.

Sometimes a database designer may choose to **denormalize** a database schema, i.e., join several relation schemas into one.

- This may make some queries run faster.
- However, updates must then be handled more carefully, and the space usage may rise.



# — Denormalization —

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Typical denormalization scenarios:

- **One-one relationship.** Joining the relations of the two entity sets will result in little (or no) redundancy, and will usually still be normalized.
- **Many-one relationship.** Joining in this case will not result in a much larger relation if an entity on the “one” side is typically related to few entities on the “many” side, or if the total size of the attributes on the “one” side is small.

Some dangers of denormalization:

- Destroys the advantages of a normalized design. Requires more programming and is more error-prone.
- May speed up some queries, but slow others down.

On-going research on join processing suggest that in future database systems the effect of denormalization may diminish.

## — Denormalization vs materialized views —

An alternative to denormalizing the database schema is to create a materialized view that maintains the join of some of the relations.

### **The good:**

- Accessing the materialized view is the same as accessing the corresponding relation in a denormalized design.
- Updates can be done in the normalized schema (no anomalies).

### **The bad:**

- Space usage is even larger than in denormalized design.
- The DBMS may not handle updates as efficiently as updates in a hand-coded denormalized design.

## — Vertical and horizontal partitioning —

Related to, but independent of, denormalization, the DB programmer can instruct the DBMS to use a particular physical layout of a relation.

- **Vertical partitioning.** If some (frequent) queries deal only with some attributes of a relation, it can speed up processing to physically split the relation into two parts – one with those attributes, and one with the rest.
- **Horizontal partitioning.** If some (frequent) queries deal with tuples having a particular value on some attribute, it can speed up processing to physically split the relation into parts depending on the value of that attribute. This is a “light” alternative to having a primary index.

The cost of horizontal partitioning is that it takes more time to retrieve an entire tuple. The cost of vertical partitioning is that insertions of new tuples take more time.

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**Next: Database tuning cases**

(following the SQL for Web Nerds web page on tuning)

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## — Most important points in this lecture —

As a minimum, you should after this week:

- Remember that disk accesses are the performance bottleneck of most large databases.
- Be able to estimate the value of a particular index based on:
  - The selectivity of typical queries.
  - The frequency of queries and updates.
- Know some basic schema tuning techniques.

In this lecture many details were given that you will not find in the course book or supplementary material:

You are expected to know this to the detail given by the slides.

## — Next lecture —

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Next time we will talk about *transactions*, which are collections of updates grouped together by the database programmer:

- ACID properties of transactions.
- Isolation levels in SQL.
- Deadlocks.

Also, we will have a guest lecturer, Solution Architect *Jakob Leander* from Accenture, who will talk about commercial DBMSs.