Part 15: Basics of Physical DB Design

References:

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- Silberschatz/Korth/Sudarshan: Database System Concepts, 3rd Edition. Chap. 11: "Indexing and Hashing" (only parts of Sections 11.1–3, 11.8)
- Kemper/Eickler: Datenbanksysteme (in German), 4th Ed., Ch. 7, Oldenbourg, 2001.
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- Corey/Abbey/Dechichio/Abramson: Oracle8 Tuning. ORACLE Press, 1998.
- Oracle 8i Concepts, Release 2 (8.1.6), Oracle Corporation, 1999, Part No. A76965-01. Page 10-23 ff: "Indexes"
- Oracle 8i Administrator's Guide, Release 2 (8.1.6), Oracle Corporation, 1999, Part No. A76956-01. Chapter 14: "Managing Indexes".
- Oracle 8i Designing and Tuning for Performance, Release 2 (8.1.6), Oracle Corporation, 1999, Part No. A76992-01. Chapter 12: "Data Access Methods".
- Oracle 8i SQL Reference, Release 2 (8.1.6), Oracle Corp., 1999, Part No. A76989-01. CREATE INDEX, page 7-291 ff.
- Gray/Reuter: Transaction Processing, Morgan Kaufmann, 1993, Chapter 15.
- Lipeck: Skript zur Vorlesung Datenbanksysteme (in German), Univ. Hannover, 1996.

Objectives

After completing this chapter, you should be able to:

- enumerate necessary input data for physical design.
- explain the effects of buffering disk blocks in main memory.
- explain the basic structure of a B^+-tree.
- explain which queries can be evaluated faster using an index.
- explain why indexes have not only advantages.
- formulate the basic `CREATE INDEX` command in SQL.

Overview

1. General Remarks
2. B^+-Tree Indexes
3. Advantages and Disadvantages of Indexes
4. Other Physical Design Issues

Motivation (1)

- Consider a table with information about customers:

CUSTOMERS			
CUSTNO	FIRST_NAME	LAST_NAME	...
1000001	John	Smith	...
1000002	Ann	Miller	...
1000003	David	Meyer	...
⋮	⋮	⋮	⋮

- Assume further that this table is relatively big.

  E.g. there are 2 Million customers (rows). If the table has columns `FIRST_NAME`, `LAST_NAME`, `STREET`, `CITY`, `STATE`, `ZIP`, `PHONE`, `EMAIL`, the average disk space per row might be about 100 byte, and (including certain overheads), the table will be about 230 MB large.

Motivation (2)

- Suppose that a specific customer record is queried:

```
SELECT *
FROM   CUSTOMERS
WHERE  CUSTNO = 1000002
```

- Without special data structures, the DBMS simply checks `CUSTNO = 1000002` for each row of the table.

  This is called a "Full Table Scan". All rows are read from the disk.

- The query will run about 12 seconds.

  Currently (2001), 20 MB/s in a sequential scan are quite typical. 12 seconds are significantly too long for interactive work. If 100 clerks use the DB, each can pose a query only every 20 minutes.

Physical Database Design (1)

- The purpose of physical DB design is to ensure that the DBS meets the performance requirements.
- Requires knowledge of / estimates for:
  - ◇ Size of the tables, distribution of data.
  - ◇ How often each application program is executed.
  - ◇ Which queries and updates are contained in each application program.
  - ◇ Performance requirements.

    Interactive programs usually need fast answers (below 1–2 seconds), some seldomly executed programs could run a little longer, and reports may be generated over night.

Physical Database Design (2)

- Since these parameters are difficult to estimate and change over time, be prepared to repeat the physical design step from time to time.

  Creating a new index is simple in relational systems. However, having to buy entirely new hardware because performance criteria are not met, is a problem. It is necessary to think about realistic system loads during the design. There are tools for simulating given loads. Don't start using the system before ascertaining that it will work.

- Physical design depends on the chosen DBMS.

  The DBMS, how it works, and its performance tuning parameters must be understood very well.

Disks

- Usually, the time spent for disk accesses is much longer than all the computation in main memory.
- Thus, one often counts only how many blocks are read/written.

  A block is a unit of e.g. 2KB which the DBMS always transfers as a whole between main memory and the disk. Disks do not allow to access every single byte. Only entire blocks can be read or written.

- Reading blocks sequentially from the disk is faster than jumping to far away blocks.

  The disk head must move to another cylinder/track and wait there until the needed sector comes in sight.

Buffering

- A copy of the most recently read blocks is kept in main memory (buffer, cache).

  Reading blocks from the disk is much slower than memory accesses. Goal: Many block requests (90%) can be answered from the cache.

- Not all blocks can be kept in memory, since the DB is normally much bigger than the main memory.

  E.g. the DB is several GB, the main memory 256MB.

- The first execution of a query takes much longer than executing the same query a second time.

  For small DBs, soon the entire DB will be in main memory, and disk accesses are only needed to make updates durable (not for queries).

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B^+-Trees (1)

- DBMS offer a variety of special access structures to find the requested record without reading the entire file. The most common one is the B^+-tree.

  Every modern DBMS contains some variant of B-trees. In addition it may support other specialized index structures.

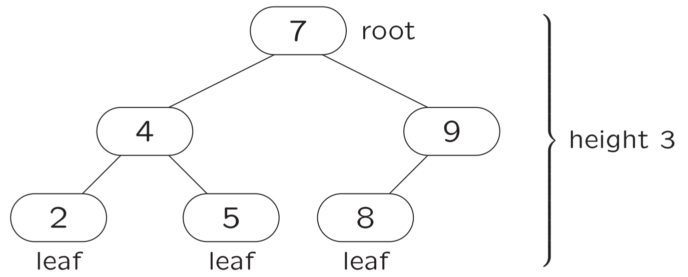
- B-trees are named after Rudolf Bayer.

  Bayer/McCreight: Organization and Maintenance of Large Ordered Indices. Acta Informatica 1(3), 173–189, 1972.

- B^*-trees and B^+-trees are (normally) synonyms.

B^+-Trees (2)

- In general, B-trees work like standard binary search trees:



The search starts in the root node. If the searched value is less than the value in the root node, the search continues in the left subtree, if it is larger, the search continues in the right subtree.

B$^+$-Trees (3)

- In a B-tree, the branching factor (fan out) is much higher than 2.

  Anyway a whole block must be read from the disk.

- Normal binary trees can degenerate to a linear list. B-trees are balanced, so this cannot happen.

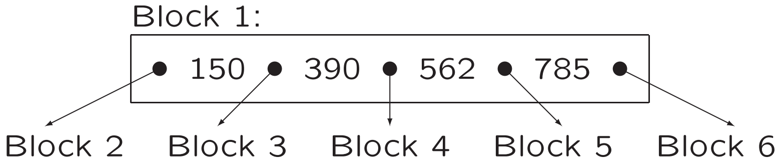
  E.g. if values are inserted in ordered sequence, they are always inserted to the right in a normal binary tree.

- In a B$^+$-tree (not in a B-tree) the values in inner nodes (non-leaves) are repeated in the leaf nodes.

  The tree height might decrease, since the pointer to the row is needed only in the leaf nodes. Also one can easily get a sorted sequence.

B$^+$-Trees (4)

- A B$^+$-tree consists of branch blocks and leaf blocks. The branch blocks guide the search for a row:

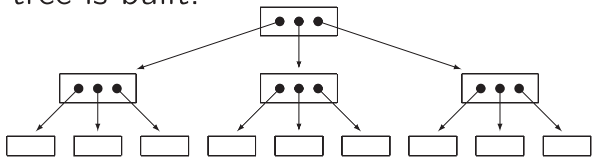


- If the requested CUSTNO is $\leq$150, continue in Block 2. For CUSTNO $>$ 150 and CUSTNO $\leq$ 390, go to Block 3. ...
  If CUSTNO $>$ 785, continue in Block 6.

  Because of the limited space, 3-digit customer numbers are used.

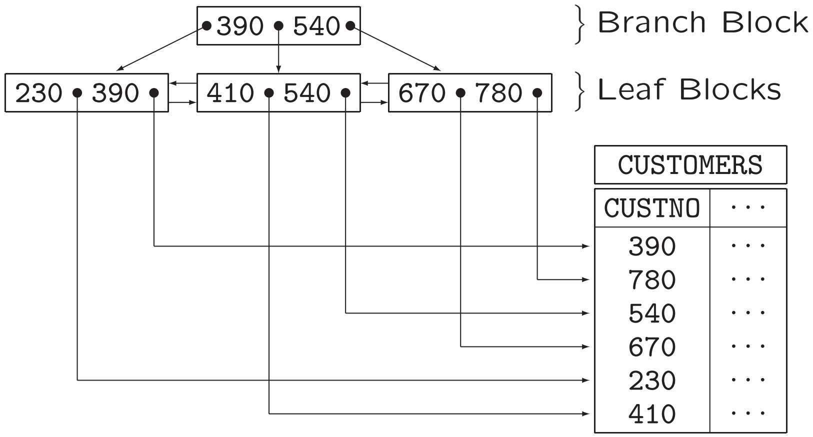
B$^+$-Trees (5)

- The referenced blocks have the same structure, so that a tree is built:



- The blocks in the lowest level ("leaf blocks") contain all occurring customer numbers (in ordered sequence) together with the address ("ROWID") of the corresponding CUSTOMERS row.

B$^+$-Trees (6)



B$^+$-Trees (7)

- In a B-tree, all leaf blocks must have the same distance (number of edges) from the root. Thus B-trees are balanced.

  This ensures that the chain of links which must be followed in order to access a leaf node is never long. For B-trees, the complexity of searching (tree height) is $O(\log(n))$, where n is the number of entries.

- Nodes in the same tree can contain differently many values, but each node must be at least half full.

  (Except the root, which might contain only a single customer number.) If the blocks had to be completely full, an insertion of one tuple could require a change of every block in the tree. With the relaxed requirement, insertion/deletion are possible in $O(\log(n))$.

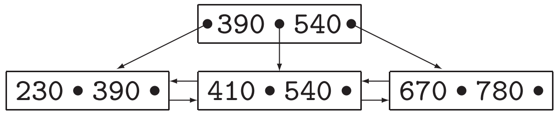
B$^+$-Trees (8)

- Insertion Algorithm:
  - ◇ Search the leaf node into which the new value must be inserted.
  - ◇ If that node has still empty space: insert. Done.
  - ◇ Otherwise, split the leaf node in the middle (one full node → two half full ones), do the insertion.
  - ◇ Now the branch block above must contain one additional value (middle value in splitted node).
  - ◇ If there is still space, ok. Otherwise split the branch block. And so on up to the root.

B$^+$-Trees (9)

Exercise:

- Consider again the B$^+$-tree from Slide 15-16:



- Assume that each node can contain at most two values (and must contain at least one value).
- Insert the value 123.
- Give an example for a value that can now be inserted without splitting any further nodes.

B$^+$-Trees (10)

- Real branching factors are much higher than shown above.
- A block of 2KB can probably contain about 100 customer numbers and the corresponding ROWIDs.

Height	Min. Num. Rows	Max. Num. Rows
1	1	100
2	$2 * 50 = 100$	$100^2 = 10000$
3	$2 * 50^2 = 5000$	$100^3 = 1000000$
4	$2 * 50^3 = 250000$	$100^4 = 100000000$

Height 1: Only root, which is at the same time leaf.
Height 2: Root as branch node, plus leaf blocks, as on Slide 15-16.

B^+-Trees (11)

- For the CUSTOMERS table with 2000000 entries, the B-tree will have height 4.

  Height 5 would require at least $2 * 50^4 = 12.5$ mio rows.

- A tree of height 4 requires 5 block accesses to get the row for a given customer number.

  Four for the index and one for fetching the row from the table with the ROWID obtained from the index. In rare circumstances ("migrated row"), 6 block accesses would be required in total.

- The query can be executed in 50ms.

  Fast modern disks need about 10ms per random block access.
  One disk can support about 14 such queries per second (70% load).

B^+-Trees (12)

- Table accesses via an index profit from caching of disk blocks:
  E.g. it is very likely that the root node of the index and some part of the next level will be in the buffer.

- Since the height of the B-tree grows only logarithmically in the number of rows, B-trees never become very high.

  Heights greater than 4 or 5 are rare in practice.

B^+-Trees (13)

- The index on CUSTNO was a unique index — there is only one row for every value (CUSTNO is a key).

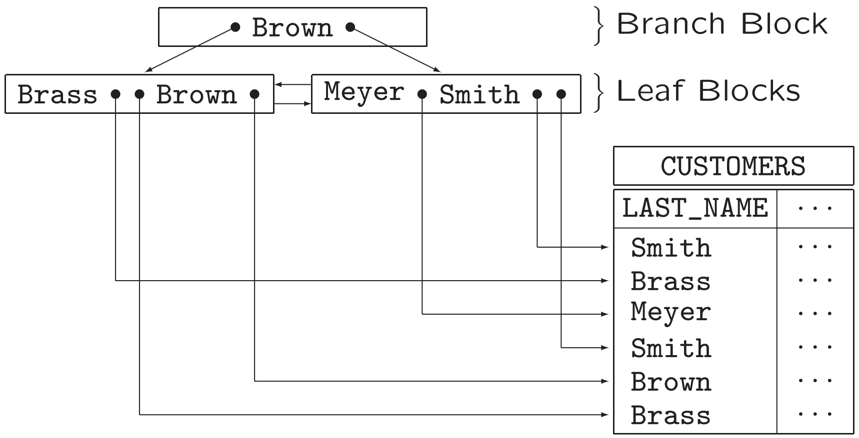
- B-trees also support non-unique indexes, e.g. on LAST_NAME. Then the leaf blocks can contain more than one row address for the same column value.

  Although LAST_NAME is not a key of the table, it is sometimes called the "search key" of the B-tree.

- It is also possible to create B-trees over the combination of two or more columns.

  Then the indexed values are basically the concatenation of column values (with e.g. a separator character).

B^+-Trees (14)



B+-Trees (15)

- A high branching factor (and thus a small tree height) is possible only if the data in the indexed column is not too long.

  E.g. an index over a column that contains strings of length 500 will need a higher tree (which still grows logarithmically). In Oracle, the indexed values may not be larger than about half of the block size.

- It suffices to store a prefix of the actual data in the branch blocks if this prefix already allows discrimination between the blocks on the next level.

  The full version of column data is anyway stored in the leaf blocks. In the above example, it suffices to store `'B'` in the root node.

Overview

Applications of Indexes (1)

- An index on the column A of the relation R is especially useful for equality conditions $A = c$ on tuple variables over the relation R.

  In relational algebra, this corresponds to the selection $\sigma_{A=c}(R)$.

- A B+-tree index can also be used for <, <=, >, >= conditions (range queries, `LIKE` with known prefix).
- However, indexes are only useful when only a small percentage of the rows are retrieved via the index.

  If many rows satisfy the condition, a full table scan is faster: Sequential reading of blocks is faster than random accesses, and all rows in a block are together processed (in an index lookup only single rows).

Applications of Indexes (2)

- An index can be used even if there are other conditions besides the one supported by the index:

```
SELECT *
FROM   CUSTOMERS
WHERE  LAST_NAME = 'Smith'
AND    CITY = 'Pittsburgh'
```

- If there is an index on the attribute `LAST_NAME`, the DBMS can use it to retrieve all rows that satisfy the first condition, and then simply check the second condition for each such row.

Applications of Indexes (3)

- A join can be evaluated using an index on one of the joined columns, e.g.:

```
SELECT C.LAST_NAME
FROM   INVOICES I, CUSTOMERS C
WHERE  I.AMOUNT > 20000
AND    C.CUSTNO = I.CUSTNO
```

- E.g. the DBMS can first find large invoices `I` and then use an index on `CUSTOMERS(CUSTNO)` to retrieve the customer data for each such invoice.

  Each single row `I` contains a specific customer number, for which one can use the index to find the matching row `C`.

Applications of Indexes (4)

- Some queries can even be answered entirely out of the index, without accessing the table itself: E.g. is there a customer with a given number?

  This is important for enforcing key/foreign key constraints.

- Sorting might sometimes profit from an index.

  This may speed up `ORDER BY`, `GROUP BY`, `DISTINCT`. The leaves of the B^+-tree contain all values in sorted sequence. However, this is really effective only in combination with a range query or if the query can be answered entirely out of the index. Otherwise accessing all rows of the table in random order might be slower than using e.g. the Mergesort algorithm (which does several *sequential* passes over the data).

Applications of Indexes (5)

- Indexes on combinations of two or more columns of a table will especially speed up queries that provide values for all these columns:

```
SELECT *
FROM   CUSTOMERS
WHERE  FIRST_NAME='John' AND LAST_NAME='Smith'
```

- If the index is a B-tree, it can also be used as an index for the first column (or in general a prefix).

  The first column of the combination is the main sorting criterion for the index. Here an index on `LAST_NAME, FIRST_NAME` would probably be more useful than the other way round. It could be used also as an index on `LAST_NAME` (it is slightly less efficient than a pure index).

Applications of Indexes (6)

Exercise:

- Consider the following query:

```
SELECT C.FIRST_NAME, C.LAST_NAME, C.PHONE
FROM   CUSTOMERS C, ORDERS O, ORDER_DETAILS D
WHERE  D.PRODNO = 123
AND    C.CITY = 'Pittsburgh'
AND    O.ORD_DATE >= '01-JAN-02'
AND    C.CUSTNO = O.CUSTNO AND O.ORDNO = D.ORDNO
```

- Which indexes could be useful for evaluating the query? Sketch two different evaluation possibilities.

  What information would the DBMS need for deciding which evaluation method is better?

Disadvantages of Indexes

- Indexes use disk space.

  The example index needs 30-50% of the space of the table.

- Queries become faster, but updates become slower because the indexes must be updated, too.
- Query optimization becomes slower: More alternatives for evaluating the query must be considered.

  But it might be possible to amortize the cost of query optimization over many executions of the same query.

- A full table scan can be much faster if nearly all blocks must be accessed anyway.

Hints for Selecting Indexes

- Check whether the query optimizer really uses the indexes.

  DBMS usually offer the possibility to see the result of query optimization (query evaluation plans, internal query programs).

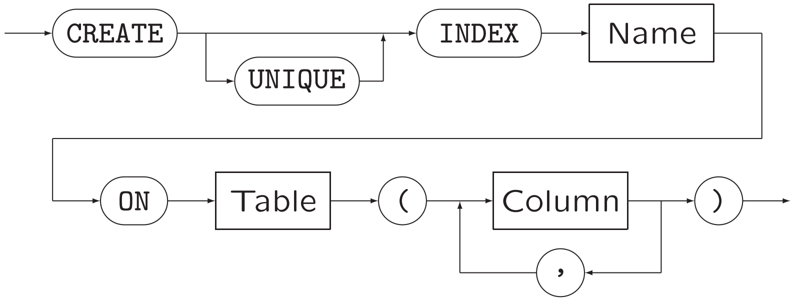
- It makes no sense to declare indexes on small tables.

  Except the indexes needed to enforce keys, see below.

- Do not declare too many indexes on tables that are often updated.
- Normally, an index is useful only if the condition is satisfied only by a small percentage of the rows.

Indexes in SQL (1)

- SQL command for creating an index (not SQL-92):



- E.g.: `CREATE INDEX CUSTIND1 ON CUSTOMERS(CITY)`

Indexes in SQL (2)

- The `CREATE INDEX` command is not contained in the SQL standards, but it is supported by most DBMS.

  The SQL standards do not treat physical storage concepts.

- `UNIQUE` means that for every value for the index column there is only one tuple.

  I.e. the index column is a key. Older SQL versions had no key declarations, so a unique indexes were used.

- Most DBMS automatically create a unique index for key constraints (`PRIMARY KEY` and `UNIQUE`).

  Thus the keys are enforced as before by means of unique indexes.
  It would be wrong to explicitly create another index for a key.

Indexes in SQL (3)

- Creating an index on a large table can take quite some time, need a lot of temporary disk space, and lock the entire table.

  One should not experiment with indexes during the main production hours. On some systems (e.g. DB2, but not Oracle), it might be necessary to rebind (re-optimize) application programs after relevant indexes were changed.

- Command for deleting indexes:

- E.g.: `DROP INDEX CUSTIND1`

Overview

Physical Design Issues (1)

- The index selection, i.e. deciding which indexes to create, is the classical physical design issue. But there is much more to do.
- Normally the table itself is stored as a "heap file" (without any specific order), but even for that there are various storage parameters.

  E.g. how much space in a block should be kept free for updates that make a row longer (because of physical pointers from indexes, it is not good to "migrate" a row to a different block). One should also ensure that the table is stored sequentially in one chunk of disk space (or only a few big pieces), not scattered over the entire disk (in many small pieces). Thus, one must define a storage size.

Physical Design Issues (2)

- Database management systems offer other access structures besides B-trees, e.g. hash methods.

  Oracle allows clustering tables together (good for joins). Instead of having separate indexes and table, it might also be possible to store the table data directly in the index (index-organized table).

- The distribution of tables etc. among different disks is also important for performance.

  Tables can be split into several parts (horizontal/vertical partitioning).

- In exceptional cases, tables could be denormalized.

  One pays for the performance gain with programmer time and less flexibility for changes.