10. File Organizations and Indexes | Physical Schema

Summary

Tables are stored in data files. File can be thought of as a sequence of "Data Records"

There can be multiple tables in a file or there can be multiple files for a table.

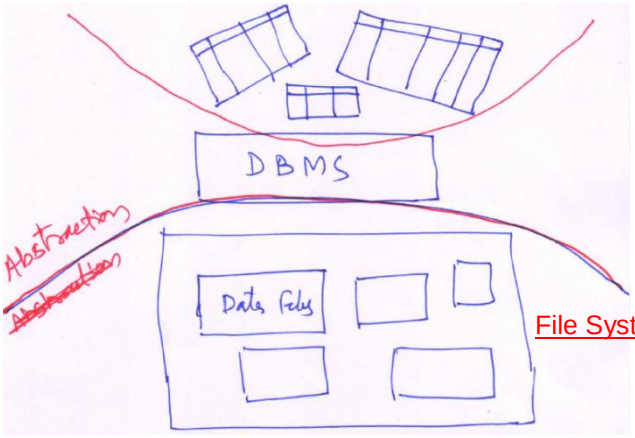
Data Files may not have any order. Data Files can be ordering data records on some field of a data record. Normally ordering of records is done on primary key. Unordered files are called "heap files" while other one if called ordered files.

Performing manipulation operations on "data files" may turn out to be expensive. For instance, performing insert operation is efficient in heap file but search operation is in efficient as it will be having complexity of order N. Search operation on ordered file will be better on ordered file (as we can perform binary search) than the heap file.

Indexes are used for improving the search operations on data files. Indexes should also try their best to have acceptable performance on INSERT, UPDATE, and DELETE as well.

A relation is a logical representation of databases.

DBMS lets us manipulate databases in logical manner like relations. Things like RDBMS implements relational abstraction over data in disk files.



File System

Data are stored in files on disks.

There are certain ways in which relations are stored in disk files –

1. One relation one disk files
2. All relation one file – SQLite, MS-access are such examples
3. One relation many files.

Structure of data on disks is referred as *physical schema*.

Physical schema typically defines the organization of *data records* in file(s), and access paths for finding data records.

In this chapter, we attempt understanding various *file organizations* and *indexes* for efficient access of data records.

Data Files:

Logically, a *data file* can be thought of collection of *data records*. For storing relations, a record typically represents a *tuple*.

While studying file organizations, we use a concept of *disk block*. It is a smallest storage unit for manipulating data in disk files. A disk block – can be of different sizes on different systems - 4KB, 8KB, 16KB or so. 8KB should a standard on a modern DBMS.

A data file can be chained (or indexed) collection of block clusters.

DBMS typically takes services of Operating system for manipulating disk files. Read/write operations are performed on disk blocks.

A block may store multiple records; though rare, but it is also possible to have records that do not fit in a block, and span to multiple blocks.

Records in a file can be of two types –

1. "fixed length record" and
2. "variable length records" –

These terms mean what they pronounce for.

If storage required for a record is fixed for all records in a data file, then it is fixed length record file; otherwise it is a variable length record file.

Length of a record in a file can be variable due to one and more of following reasons-

- If file stores tuples from more than one relations.
- Length of one or more fields is variable.
- A record having multi value fields.

Files with fixed length records are easier to implement and manage. However fix length variable records are less practical and variable length record files are common in practice.

For implementing variable length record files, there are different strategies, like

1. Having record header containing information of length for each field, or
2. We can have field separators, or so.

We do not get into more details here.

Operations on data files

- Insert a record
- Find a record,
- Find a set of records meeting some criteria
- Modify a record
- Delete a record, or a set of records meeting some criteria

There are various techniques for performing these operations on files; however the technique is dependent on "File Organization" used for recording data.

File Organizations

File Organizations is the way of organizing records in a file. That is how records are stored, how attribute values are separated within a record. How records are sequenced. How records are searched, etc.

Every file organization defines some methods to locate a record (or a set of records) in a file, referred as *Access Methods*. There can be multiple access methods on file organization but an access method may require a particular file organization.

File organization dictates procedure of performing said operations on files. Each file organization makes certain operations efficient while others expensive.

Many alternative file organizations exist, following are commonly used file organizations-

- Heap (random order) files
- Sorted Files (on some attribute).
- Indexes

Heap (random order) files:

- Records have no order
- Insertions are very efficient; in this case, often, as new records are added at the end of file.
- New records can also be placed at empty spaces anywhere in between of the file.
- Finding a record is expensive, as we can only perform sequential scan – in the order of N?

Sorted Files

- Records of file are sorted on some field(s), called as ordering field(s). Ordered field(s) is also called as search key. For example, you can store employee relation records sorted on ENO, or Department?

- Searching on ordering field is efficient as we can perform things like binary search – locate middle block, see if search key <value in ordering field of middle block, and so on.
  ==> Number of disk blocks needs to be processed is in the order of log2(N).
- Insertion in sorted file is expensive; can be performed as
  - Find appropriate location (block) in file where the record can be inserted (order needs to be maintained)
  - Once neighborhood is found, it may encounter various situations
    - One, the block containing neighborhood has room where the new record can be inserted –if so, new record is placed in that block
    - The block does not have room for new record – then see if next block has the room (and that still maintains order),
    - If still not possible, then an overflow block is added, and the new record is inserted there.
- Deletion is also expensive; done as following
  - Find record, record content is removed from the block; actual action will depend on how records are organized in a block.
  - One of the common strategies for space created by deleting a record is, keep it as blank and we do not shift the remaining records; such empty spaces are recycled using some strategy like "*free list*" maintenance or so.
- In a record modification operation, if we need to change values of ordering fields; then location of the record will change, in such as modification is performed in two steps-
  - Remove from current location
  - Insert at appropriate new location

How do you compute cost of an operation?

Disk I/O is considered as most significant component in performing database operations. Total number of disk blocks read and write measures the cost of performing an operation. A technique that processes (reads and writes) larger number of disk block is considered more expensive than the one that processes lesser number of blocks.

Suppose a file has 100000 records; let us say a record uses 350bytes, and store approximately 10 records in a 4KB block. The file will be using 10000 blocks. If file is "Heap File", in worst case, we need to read all the blocks, i.e. 10000; whereas if file is ordered then we can perform binary search log2(10000) , that is only 14 blocks; therefore, for searching in an "ordered file" is much efficient in comparison to a heap file.

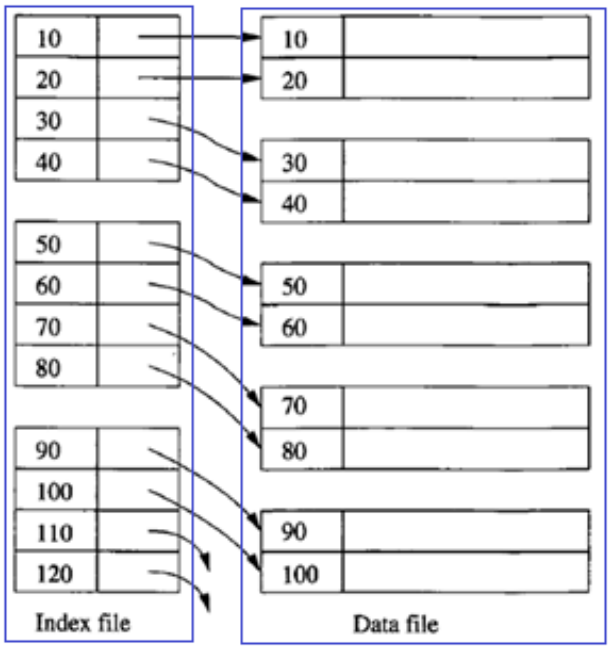
Indexes

Though sorted files improves the search performance in logarithmic order, it has following issues-

1. A file can be ordered only on one attribute (or attribute set)
2. Complexity of insert/delete/update is higher

Indexes help addressing these issues. Indexes are basically maps data records from a "key-values". Figure below from book[1] depicts some sample maps.

Index is basically a file that maps a "search-key value" to data record address (typically address of block containing corresponding data record).



Below are some types of index records-

- Index on ENO for employee relation
  <101, adr-1>,
  <103, adr-2>, ….
- Index on DNO for employee relation
  <1, <adr-1, adr-3, adr-7>>,
  <3, <adr-2, adr-5, adr-6>>, ….
- Index on (DNO, Salary)
  <<1, 30000>, <adr-1, adr-7>>,
  <<3, 45000>, <adr-6>>, ….

Indexes speed up searches for a subset of "records", based on values in certain fields; termed as "search key".

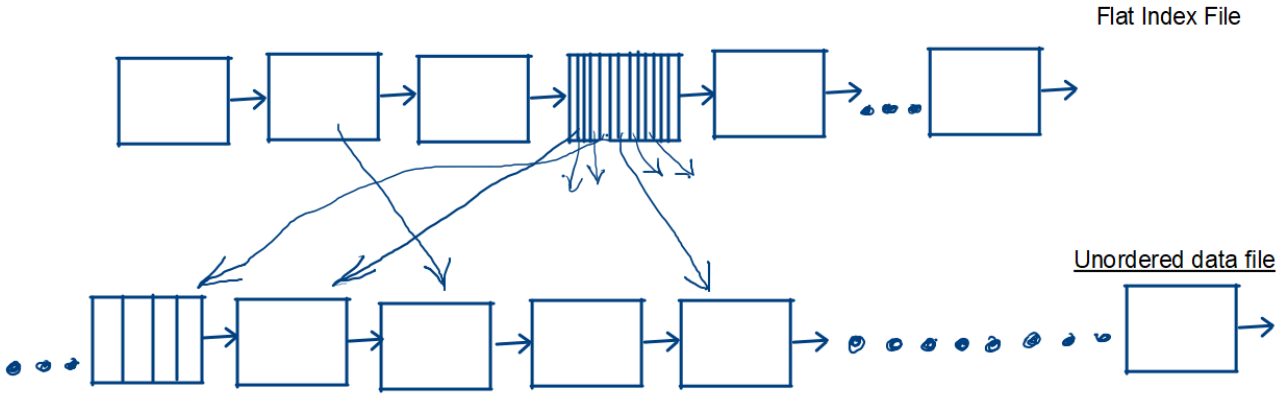
A "Search keys" for index is -

- Any subset of the attributes of a relation can be the search key for an index on the relation
- Search key may not be same as key of a relation.
- Typically, index has entries as following-
  <search-key, block/record-address>, or <search-key, block/record-address list>

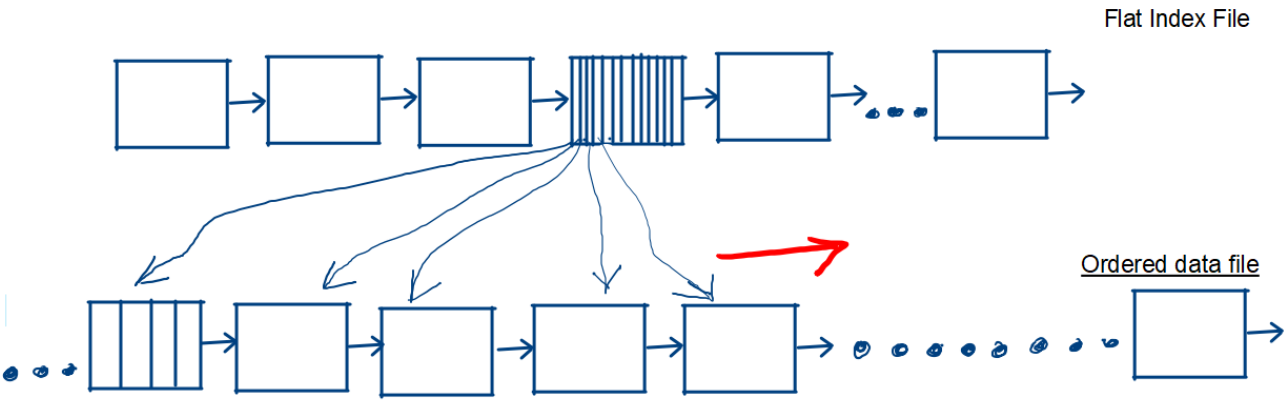
Note that Index helps in reducing number of blocks to be processed for file operations; they are even at advantage over the ordered files.

[1] Garcia-Molina, Hector. *Database systems: the complete book*. Pearson Education India, 2008.

Again consider the example of a file with 1lac records above. Size of index record will be much smaller than actual data record; let us say we can store 100 index records in a block; for 1lac index entries, we need 1000 blocks. Indexes are always sorted, therefore we can always perform binary search. In this case number of blocks to be read are $\log_2(1000)$=10blocks. Not much gain, though!



Index can be sparse when data file is also ordered on index search-key



However, in practice indexes are not that flat, they are *multi-level*.

Multi-level index

Helps in reducing disk I/O in locating records on disk; figure 14.4 below from book[2] depicts concepts of multiple level indexes.

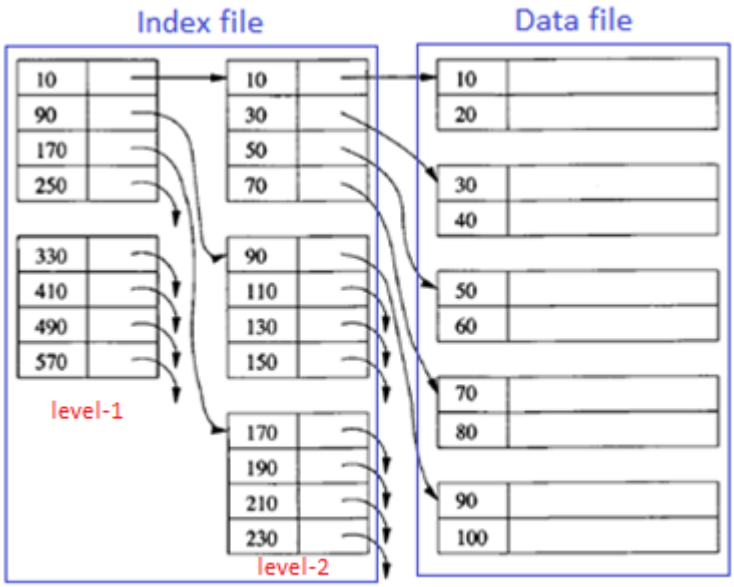
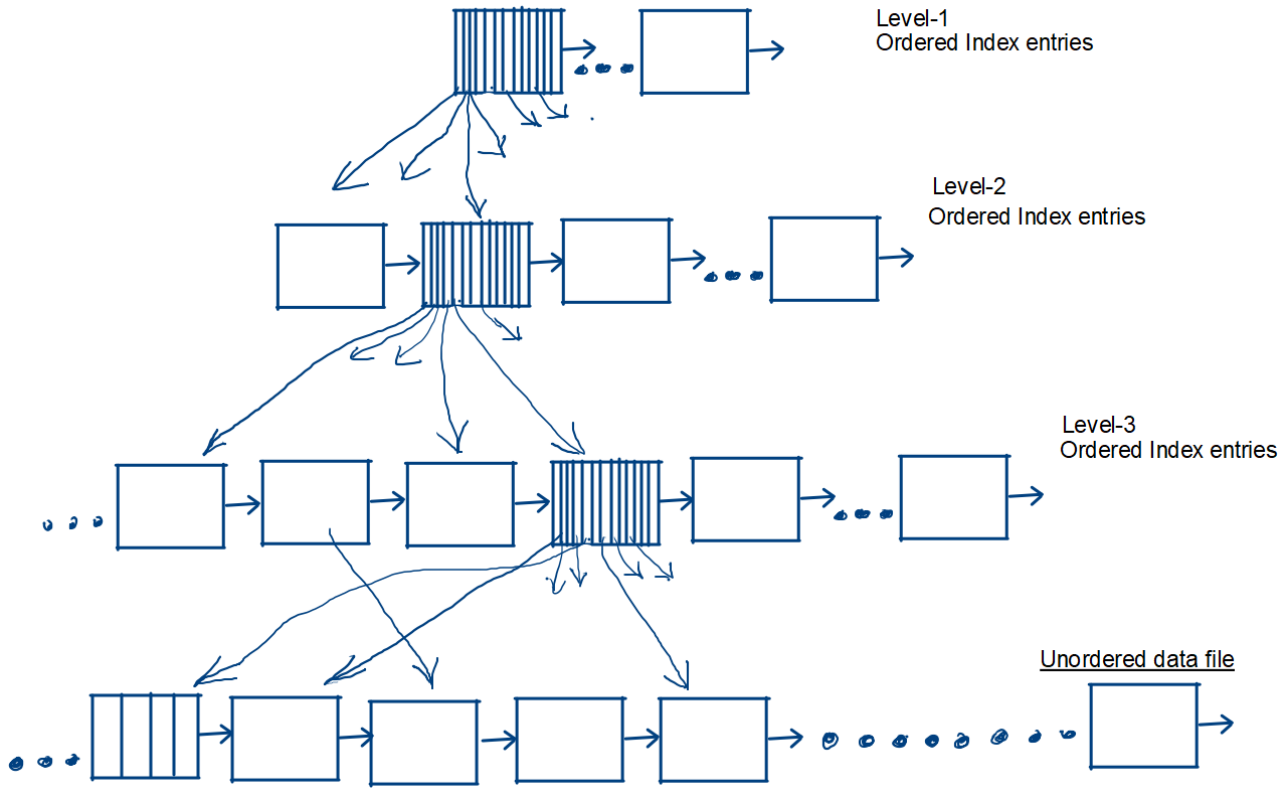


Figure 14.4: Adding a second level of sparse index

Following figure should give more insight into the index.



[2] Garcia-Molina, Hector. *Database systems: the complete book*. Pearson Education India, 2008.

To explain motivation of multi-level indexes, let us look at an example-

Suppose we build a dense index on a relation with 1 million tuples. Index entries are smaller than data records. Let us assume that 200 index entries fit on an 8 kilobyte block. Thus, our index occupies 5,000 blocks using approximately 40MB.

Let us say that index entries are maintained in ordered file organization.

Searching in such a file using binary search will require reading $\log_2(5000) = 13$ (approx.) blocks on average case.

Now suppose we create one higher level sparse index that holds one entry for each index block. Let us call this new index as level-1 index while original index as level-2 index, as shown in figure 14.4 above. At index level-1, for storing pointers to 5000 blocks (of level-2), we require 5000/200 = 25 blocks.

Therefore, size of index at Level-1 is 25 blocks, while it is of size 5000 blocks at level-2. Data record addresses are stored only at lowest level, which is two here.

Now, let us say, searching is performed as following-

1. Perform binary search at level-1, and locate block that contains address of block at level-2 that possibly contains address of data record. Number of blocks read at level-1 are log2(25) =5.
2. Read the corresponding block at level 2, and find out address of the data record. Number of blocks processed at level-2 is one.
3. Total numbers of blocks read in this approach are six.

==> The gain: 13 blocks (in case of ordered file) vs 6 blocks read (in two level index)!

This way, number of levels in an index can be more than two, and hence called as multi-level index.

Now suppose we create index at one more level. Now referring them level-1, level-2, level-3. At level-3, there are 5000 blocks. At level-2, there are 25 blocks to stored addresses of 5000 blocks. At level-1, there would be only one block storing address of 25 blocks.

Total Cost here shall be "1+1+1+1" = 4

Number of levels are typically determined such that index at top level (or root level) is small enough to be accommodated in single block. As a result, we just need to read one disk block at each level.

Thus, in general cost for locating a data record = number of levels + 1

Number of Records: 10 Lacs
Record Size: 350 B
Block Size: 8KB
Number of Records/Blocks: 20
Number of Blocks used by File: 50,000

1-Level Index:

Number of Index Records per block, say 200 entries/8KB block

Heap File (Un-Ordered)	Ordered File
File Search Cost: 50,000 blocks	Log2(50000) = 16 blocks
Index Search: Number of blocks used by "**10 lac index entries**" =10 lac/200= 5000 blocks Cost = log2(5000) = 13 blocks	Index Search: "Spars Index is possible" Only 50,000 index entries are required blocks used by index =50,000/200= 250 blocks Cost = log2(250) = 8 blocks
Total Cost=13 for Index Records + 1 Data Block=14	Total Cost=8 for Index Records + 1 Data Block=9

2-Level Index:

Heap File (Un-Ordered)	Ordered File
Level-2 Index Search: Number of blocks used by "**5000 index entries**" =5000/200=25 blocks Cost = log2(25) = 8 blocks	Level-2 Index search: Only 250 index entries are required blocks used by index =250/200= 2 blocks Cost = log2(2) = 1 block
Level-1 Index Search: 1 block	Level-1 Index Search: 1 block
Total Cost=8 (L2) + 1 (L1) + 1 = 10 blocks	Total Cost=1 (L2) + 1 (L1) + 1 =3 blocks

B+-tree Index

B+-tree is a multi-level index based on balanced binary search tree. It is a kind of balanced search tree adapted for database indexing and is a popular database indexing technique.

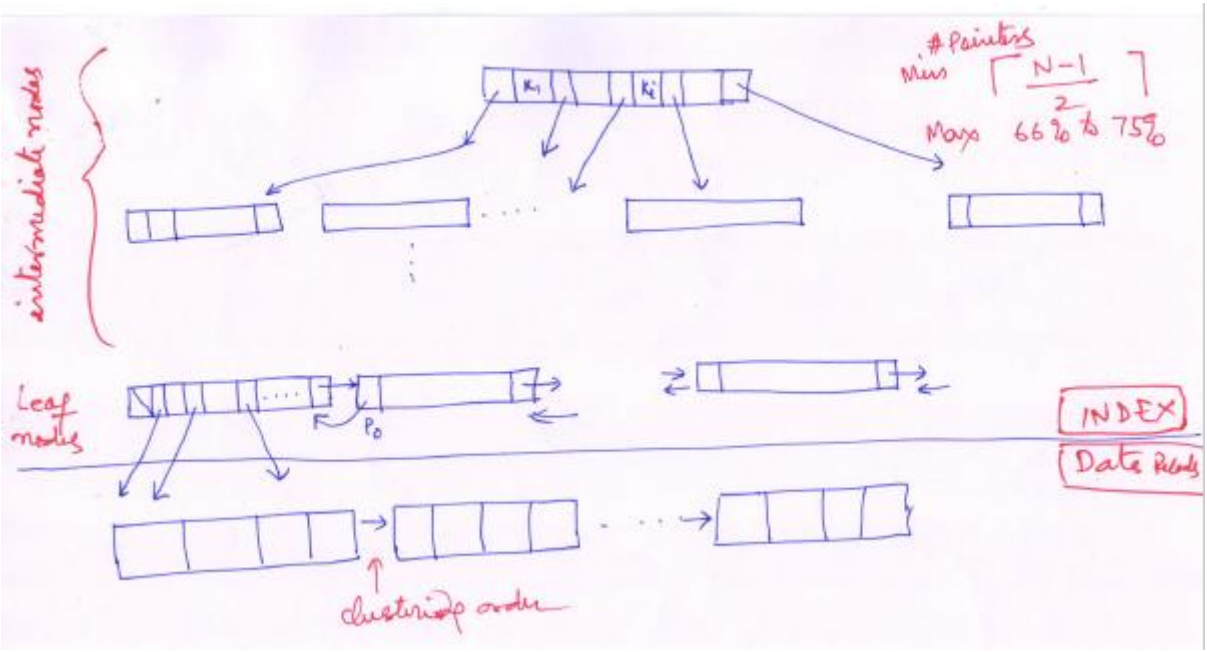
Characteristics of B^+-trees indexes:

- Only leaf nodes store address for data records. This enables increasing the number of pointers that can be stored in a node. And ultimately reducing the size of tree.
- A node is typically disk block; below is a general B+-tree node with n index entries-

P_1	K_1	P_2	…	P_{n-1}	K_{n-1}	P_n

  where P_1 through P_n are pointers, and K_1 through K_{n-1} are key values.
- Key values in a node are ordered.
- Size of all nodes is same.
- Nodes may not be used for full capacity; some empty space is kept to accommodate efficient inserts. [Min number of pointers = $\lceil (N-1)/2 \rceil$ and max is about 66% to 75%].
- Leaf nodes
  - Leaf nodes only contain pointers to data records.
  - The pointer P_n (that is last pointer) of a leaf node point to next leaf node, and thus forming the linked list of leaf nodes.
  - A pointer P_i in a leaf node points to record with search key <= K_i and > K_{i-1}
  - All leaf nodes combined will be in the order of search key.
  - Leaf node may also be linked doubly; may have a pointer like P_0 that refers to previous node.
  - Leaf node will contain pointer to all data records in data file, if it is dense index, which is usually the case is.
- Non-leaf node
  - Non leaf nodes contain pointers to its children nodes
  - A pointer P_i in a node points to record with search key < K_i and >= K_{i-1}
  - A search value appearing parent node will also appear in child node.

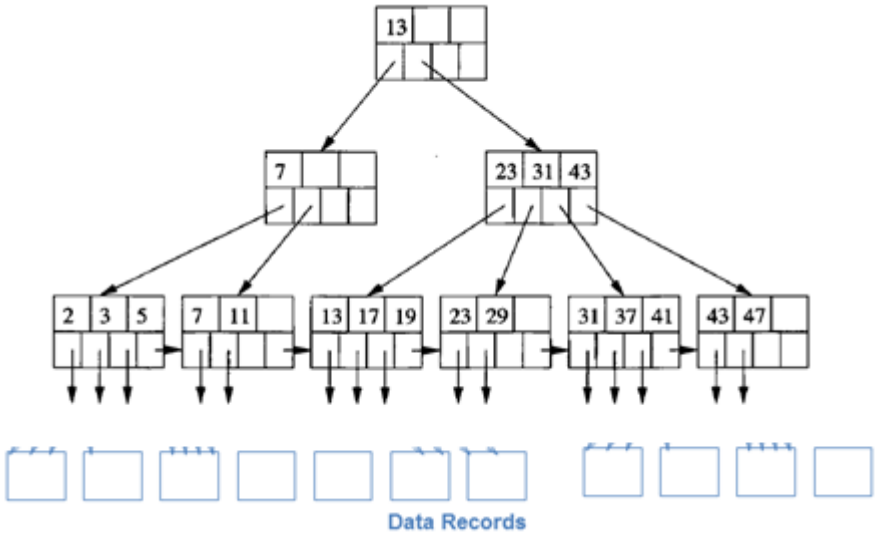
Figure below should be capturing the conceptual layout of a B^+-tree index. Note that leaf nodes are referring *data records*.



Hopefully you understand how we perform following operations on b-tree; almost same algorithms can be applied on a disk based B^+-tree of disk blocks containing index entries-

- Search: equality search, range search
- insert
- delete

We can use tree in figure below to explain.



Update on data file requires updating indexes as well

Below are some observations related to updating B+-tree based indexes-

- When we update data files (insert/update/delete), we need to updates all indexes (as said, there can be multiple indexes on a data file)
- To insert a record in data file, we also need to make appropriate index entry in B+-tree node; this new entry may require we splitting the node, and may further require balancing of tree, etc.
- While deleting a record from data file, we also need to remove corresponding index entry from B+-tree node; if the node becomes empty more than (let us say k/2), we require merging it with some other node,
- And so forth

Types of Indexes

- Primary and Secondary
- Dense and sparse
- Clustered and non-clustered

Structures of indexes

- Tree based
- Hash based

There can be multiple indexes on a data file.

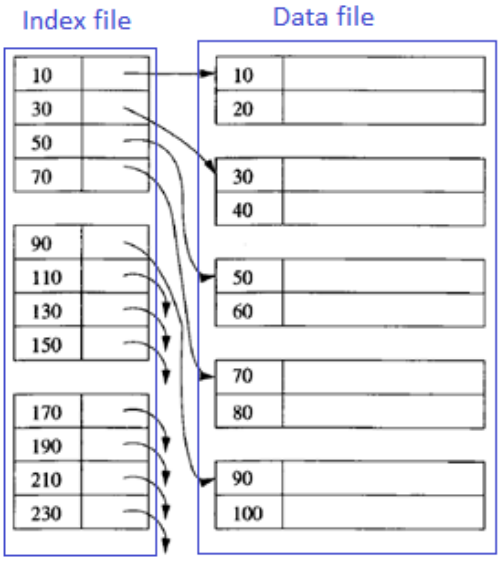


Figure 14.3: A sparse index on a sequential file

Clustered and non-clustered Index

- If records on disk file are sorted in index order then it is clustered index otherwise not.
- We can have data clustered only on one index.

Dense and Sparse Indexes

- If you have index entry for every search key-value in a file (relation), then it is dense index.
- "Clustered indexes" can only be sparse, where you do not store disk page address for each record. Advantage here is you have a smaller index and can load more portion of index in primary memory.
- In this case; search can be done by locating block for a key that is largest less than search-value; and then sequentially scanning sorted data file.

Figure 14.3 above from book[3] depicts concept of sparse index

Primary Index

- An index based on attributes on which data file is also physically sorted, is referred as *primary index.* In most cases primary index is based on primary key.
- Two data records are said to be duplicate if they have same value for search key field(s).
- If no duplicate exists then it is unique index, typically index on candidate key

Secondary Index

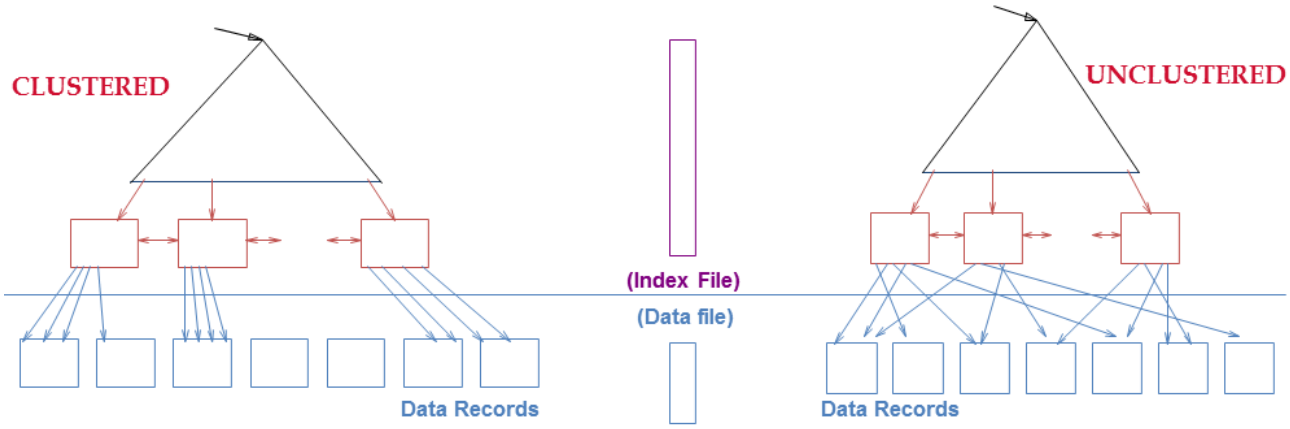
Indexes other than primary index are secondary indexes, and

- can be on any attributes
- need not to be unique
- However secondary index is always dense
- there can be multiple secondary indexes on a file of records to access records in multiple ways

Clustered vs. Un-clustered Indexes

- If order of data records is the same as, or "close to"; order of data entries in index, then index is called clustered index.
- A file can be clustered on at most one search key.
- To build clustered index, first sort the Heap file (with some free space on each block for future inserts).
  - Overflow blocks may be needed for inserts. (Thus, order of data recs is `close to', but not identical to, the sort order.)

Figure below depicts the logical layout of clustered and un-clustered indexes (from book[4])



[3] Garcia-Molina, Hector. *Database systems: the complete book*. Pearson Education India, 2008.
[4] Database Management Systems 3ed, Ramakrishnan and Gehrke

Also note how range search will get affected if data records are also in the order of index

Hash-Based Indexes

- Index is a collection of *buckets*. [also known as Hash Tables]
  - Bucket = *primary bucket* plus zero or more *overflow buckets*. (for collision handling)
  - Buckets contain index records.
- *Hashing function* **h**: **h**(*k*) = bucket in which index entry for key *k*.

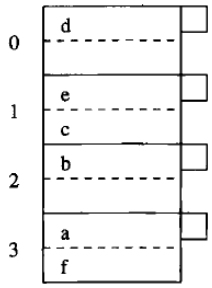


Figure 14.20: A hash table

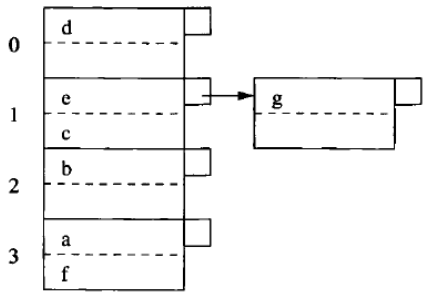


Figure 14.21: Adding an additional block to a hash-table bucket

==> Hash based indexes are only good for equality selections.

Static Hashing: Number of buckets and hash function remains same.

Dynamic Hashing: Number of buckets grow as data record grows. In that case hash function is also modified. It allows to accommodate the growth or shrinkage of the databases efficiently. Extendable hashing is one of the popular dynamic Hashing technique.

In **Extensible Hashing**, when a bucket is full, hash function is modified such that the bucket is split into two. As shown in the figure [from book[5]]

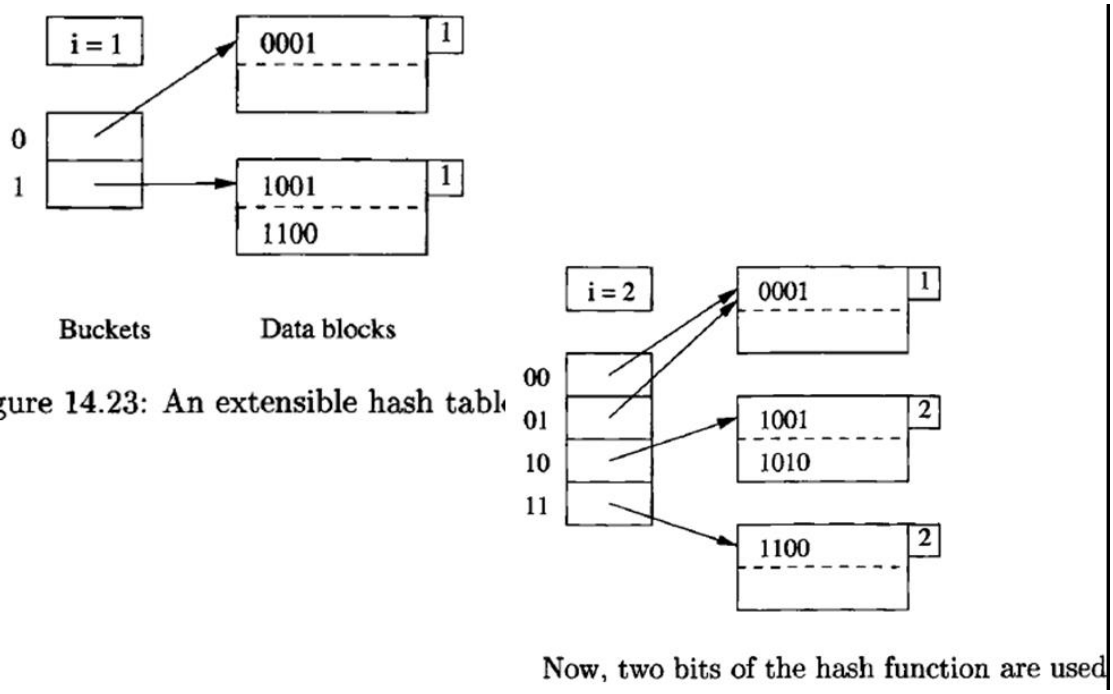


Figure 14.23: An extensible hash tabl

Now, two bits of the hash function are used

Maintenance of Indexes

- Since indexes are used as access path for data records on the disk, we need to update index too when
  - New record in the data file is added
  - "search-key" value of a record is getting modified
  - A record is getting deleted

Indexes – Benefit/Cost

- Indexes consume extra storage space – sometimes may be as large as database itself
- Still indexes are used, but a tradeoff is used for deciding number of indexes or so
- If selection queries are frequent, sorting the file or building an *index* is important.
- Index Maintenance: needs to be in sync with the data files and that slows down update (INSERT/Modify/Delete) operations.
- Reduces "concurrency"

[5] Garcia-Molina, Hector. Database systems: the complete book. Pearson Education India, 2008.

- If table size is small – you may not need index, and if table is huge and rarely updated we may have index on almost all attributes that are frequently used in retrieval queries

Indexing support in PostgreSQL

- Has CREATE INDEX command. Though not part of standard SQL!!
  Short form Syntax (postgre-SQL) -
  CREATE [UNIQUE] INDEX *index-name* ON *table* [USING method] (*col-name*)
- Method can be btree, hash, and some more. The default method is btree.
- Postgres's hash method hardly has any advantage over btree for equality check
- In most RDBMS, indexing on Primary Key is automatically created. For example, in relation, we get index named "employee_pkey" automatically created.

  CREATE INDEX EMP_DNO_IDX ON EMPLOYEE(DNO);

  CREATE INDEX EMP_DNO_IDX ON EMPLOYEE USING BTREE(DNO);
- We also ALTER INDEX and DROP INDEX commands

  DROP INDEX EMP_DNO_IDX;
- We can cluster the database based on some index

  CLUSTER employee USING emp_dno_idx;
  CLUSTER employee USING employee_pkey;

Rebuilding indexes

- Indexes may go "Corrupted" or "Bloated", and then we require rebuilding indexes. For the same we have re-index command
- Syntax: REINDEX { INDEX | TABLE | DATABASE | SYSTEM } name