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IT3090E - Databases

Chapter 8: Indexing

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Outline

- Overview of database storage structures
- Physical database files
- Database index

Objectives

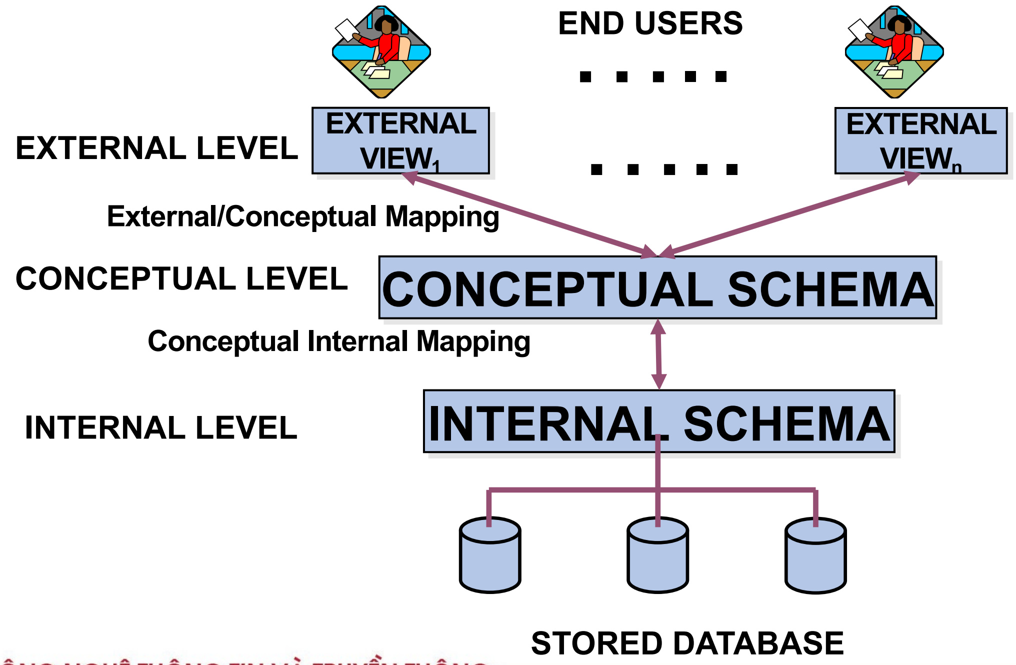
- Upon completion of this lesson, students will be able to:
  - Understand the physical database files
  - Understand the role of database indexes

Keywords

Heap file	Files of Unordered Records
Ordered file	Physically order the records of a file on disk based on the values of one of their fields (key field)
Index	A data structure that improves the speed of data retrieval operations
B-tree	A self-balancing tree data structure that enables efficient search

1. Overview of database storage structures

- ***3-tier Schema Model (ANSI-SPARC Architecture)***



1. Overview of database storage structures

- ***How does Mariadb store data***

```
MariaDB [(none)]> SHOW VARIABLES LIKE 'datadir';
+---------------+-----------------+
| Variable_name | Value           |
+---------------+-----------------+
| datadir       | /var/lib/mysql/ |
+---------------+-----------------+
```

```
MariaDB [student_management]> show tables;
+------------------------------+
| Tables_in_student_management |
+------------------------------+
| class                        |
| enrolled                     |
| faculty                      |
| student                      |
+------------------------------+
```

```
:/var/lib/mysql/student_management# ls -la

ql mysql   4096 Mar 12 02:05 .
ql mysql   4096 May  5 06:06 ..
ql mysql   1547 Mar 12 02:05 class.frm
ql mysql 114688 Mar 12 02:21 class.ibd
ql mysql     65 Mar 12 01:59 db.opt
ql mysql   1466 Mar 12 02:03 enrolled.frm
ql mysql 114688 Mar 12 02:18 enrolled.ibd
ql mysql   1005 Mar 12 02:04 faculty.frm
ql mysql  98304 Mar 12 02:16 faculty.ibd
ql mysql   1101 Mar 12 02:00 student.frm
ql mysql  98304 Mar 12 02:23 student.ibd
```

the .frm table file stores the table's format

the .ibd file stores the table's data

1. Overview of database storage structures

- ***How does Mariadb store data***
  - the .frm file stores the table's format

```
MariaDB [student_management]> describe student;
+-------+-------------+------+-----+---------+-------+
| Field | Type        | Null | Key | Default | Extra |
+-------+-------------+------+-----+---------+-------+
| snum  | int(11)     | NO   | PRI | NULL    |       |
| sname | varchar(40) | YES  |     | NULL    |       |
| major | varchar(30) | YES  |     | NULL    |       |
| level | varchar(10) | YES  |     | NULL    |       |
| age   | int(11)     | YES  |     | NULL    |       |
+-------+-------------+------+-----+---------+-------+
```

```
root@285e07e9458f:/var/lib/mysql/student_management# cat student.frm
?

VM?\!   ?s?$??%?牮B??
??PRIMARY??InnoDB??f\P
                      (/?
N?
 ?snum?sname?major?level?age?root@285e07e9458f:/var/lib/mysql/student
```

1. Overview of database storage structures

- ***How does Mariadb store data***
  - the .ibd file stores the table's data

```
MariaDB [student_management]> select * from student;
+------+------------------+---------+-------+-----+
| snum | sname            | major   | level | age |
+------+------------------+---------+-------+-----+
|    1 | Nguyen Van A     | CS      | JR    |  18 |
|    2 | Nguyen Viet Cuong| History | JR    |  19 |
|    3 | Nguyen Hong Ngoc | CS      | JR    |  19 |
|    4 | Mark Juke        | History | JR    |  20 |
|    5 | Elon Mulk        | CS      | JR    |  20 |
|    6 | Donal Trump      | CS      | JR    |  20 |
|    7 | Obama            | CS      | JR    |  20 |
|    8 | Tan Dung         | History | SR    |  30 |
+------+------------------+---------+-------+-----+
```

```
root@285e07e9458f:/var/lib/mysql/student_management# cat student.ibd
???]&!??????????????????????????&&???????????????????????????]&??Y?&??Y?&???j?&???
?????????????????????????????i??????????????????????????????????????????????????????
????????????????????????????????????????????????????????????????????????????????????
????????????i???????????????????????????????????????????????????????????????????????
?????????????????????????????????????????????????????????????j?&??Q?????????'??E?
9infimum
        supremum
                .?8?WNguyen Van ACSJR?8?:?cNguyen Viet CuongHistoryJR?  2?@??Nguyen H
ong NgocCSJR?    (0?1?iMark JukeHistoryJR?       0+?0??Elon MulkCSJR?
                                                                    8-?Q?kDonal Trum
pCSJR?@'?W??ObamaCSJRH?????Tan DungHistorySR?pc??Q?'??root@285e07e9458f:/var/lib/mys
```

VIỆN CÔNG

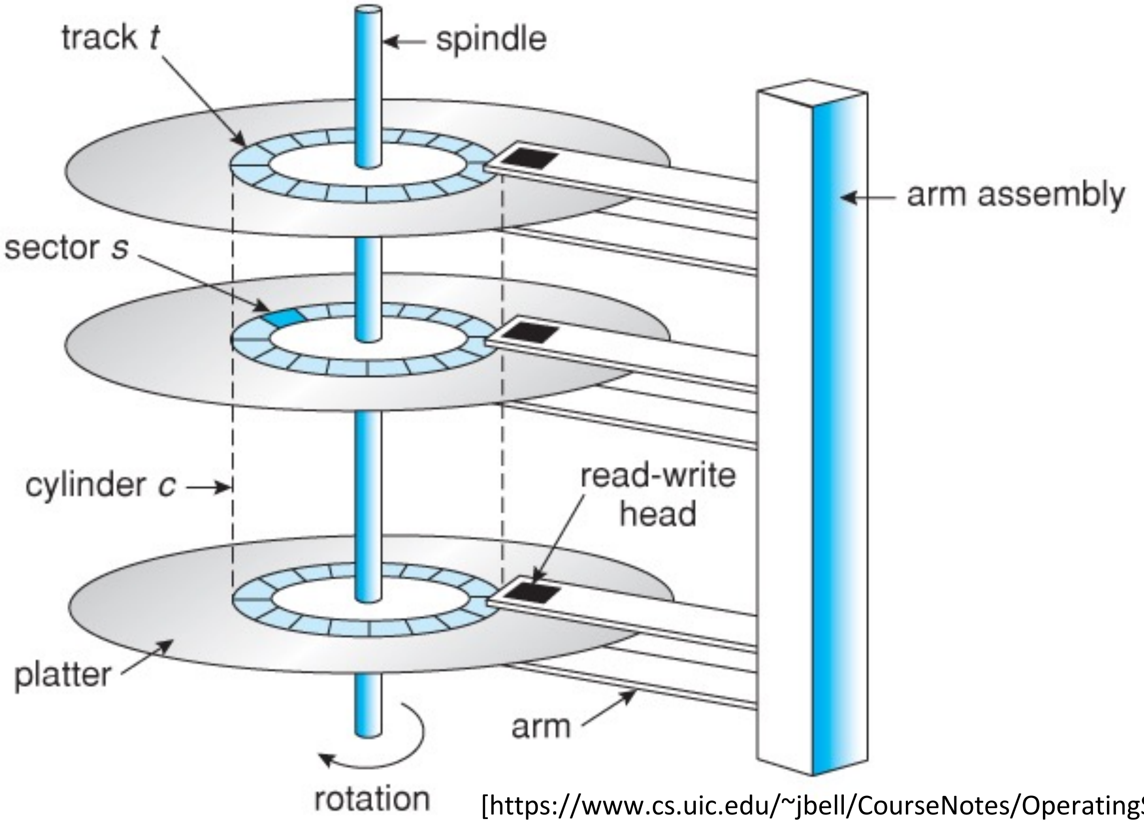
2. Physical database files

- Motivation
- Magnetic disks as data storage
- Primary file organizations

2.1. Motivation

- Databases typically store large amounts of data persistently on disks, because:
  - Databases are too large to fit entirely in main memory (RAM), but they can fit entirely on the disk
  - Disk storage is non-volatile, whereas main memory is volatile
- But:
  - Disk access is extremely slow, compared to CPU (processing) speed
  - So, the performance of the DBMS largely depends on the number of disk I/O operations that must be performed

2.2. Magnetic disks as data storage



[https://www.cs.uic.edu/~jbell/CourseNotes/OperatingSystems/10_MassStorage.html]

2.2. Magnetic disks as data storage

- A disk is a random access addressable device.
- Data is transferred between disk and main memory in units called **blocks**.
  - A block is a contiguous sequence of bytes from a single **track** of one platter.
  - Typical disk block sizes: 4KB – 8KB.
- Disk I/O (read/write from disk to main memory) **overhead** is the key factor of database performance optimization.
  - Disk overhead: the disk space required for information that is not data, but is used for location and timing

2.2. Magnetic disks as data storage

- Data files are decomposed into **pages**
  - Fixed size piece of contiguous information in the file
  - Unit of exchange between disk and main memory

- The disk is divided into blocks which have same size as pages
  - So that a page can be stored in any block

- Application's request for **read** item satisfied by:
  - Read page containing item to buffer in DBMS
  - Transfer item from buffer to application

- Application's request to **update** item satisfied by:
  - Read page containing item to buffer in DBMS (if it is not already there)
  - Update item in DBMS (main memory) buffer
  - Copy buffer page to page on disk

2.2. Magnetic disks as data storage

- I/O access to a page – **time** needed
  - Seek latency: time to position heads over cylinder containing page (some ms)
  - Rotational latency: additional time for platters to rotate so that start of block containing page is under head (some ms)
  - Transfer time: time for platter to rotate over block containing page (depends on block size)
  - Latency = seek latency + rotational latency

- Our goal is to minimize the average latency, and reduce the number of page transfers
  - Therefore, try to store pages containing related information close together on disk

  => Data file **organization**

2.2.1. Physical database design

- The process of physical database design involves choosing the particular data organization techniques that best suits the given application requirements
  - on SELECT, INSERT, UPDATE, DELETE

- The data stored on disk is organized as files of records:
  - Primary file organizations: determine how the file records are physically placed on the disk, and hence how the records can be accessed.
  - Secondary organization or auxiliary access structure allows efficient access to file records based on alternate fields.

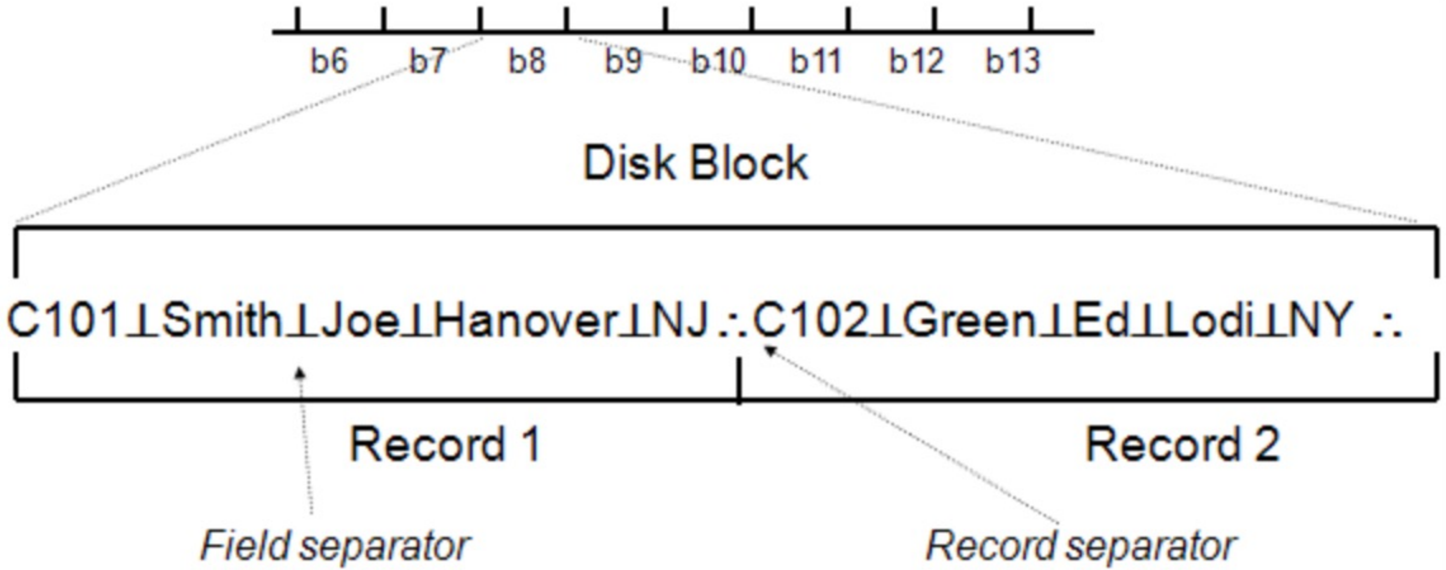
2.2.1. Physical database design

- **Primary file organizations** determine how the records of a file are physically placed on the disk, and hence how the records can be accessed.
  - A **heap file** (or **unordered file**) places the records on disk in no particular order by appending new records at the end of the file.
  - A **sorted file** (or **sequential file**) keeps the records ordered by the value of a particular field (called the sort key).
  - A **hashed file** uses a hash function applied to a particular field (called the hash key) to determine a record's placement on disk.
  - **N.B.:** The terminology may carry different meaning in different context. Sequential files in COBOL , for example, are unordered files.

2.2.1. Physical database design

- A **secondary organization** or **auxiliary access structure** allows efficient access to the records of a file based on alternate fields than those that have been used for the primary file organization.
  - Most of these exist as **indexes.**

2.2.2. Placing File Records on Disk



[http://holowczak.com/database-record-storage-index-structures/?doing_wp_cron=1622020116.6039350032806396484375]

2.2.2. Placing File Records on Disk

- Some definitions:
  - **Fixed length** records: Each record is of fixed length. Pad with spaces in each field
  - **Variable Length** records: Each record is as long as the data it contains.
  - **Unspanned** Records: A record is found in one and only one block. i.e., records do not span across block boundaries.
  - **Spanned** Records: Records are allowed to span across block boundaries.

- Often, to avoid too many disk I/O access, we try to avoid spanned records
  - **Blocking Factor:** number of tuples (records) that can fit into a single block.
    - Easier to set when there is no variable length attributes (*e.g.* type text (varchar with no upper limit))
    - Example: EMPLOYEE takes 100 bytes to store one tuple (record).
      - If the Block Size is 2,000 bytes, then we can store 20 EMPLOYEE tuples (records) in one block. Thus the *Blocking factor* is 2000/100 = 20

2.3. Primary file organizations

- More details about:
  - Files of Unordered Records (Heap Files)
  - Files of Ordered Records (Sorted Files)
  - Hashing Techniques

2.3. Primary file organizations

- **Files of Unordered Records (Heap Files)**
  - Records are placed in the file in the order in which they are inserted
  - INSERT: Inserting a new record is very efficient
    - New records are inserted at the end of the file
    - Insert takes constant time.
  - DELETE: not efficient
    - Delete takes o(n/2) time to locate the record to delete, then constant time to actually delete it
    - Leaves unused space in the disk block
      - require periodic reorganization
  - SELECT / UPDATE: not efficient
    - Select takes o(n/2) time (*n* is the number of records)
    - Update take o(n/2) time to locate the record to be updated + constant time (similar to Delete followed by Insert).

2.3. Primary file organizations

- **Files of Ordered Records (Sorted Files)**

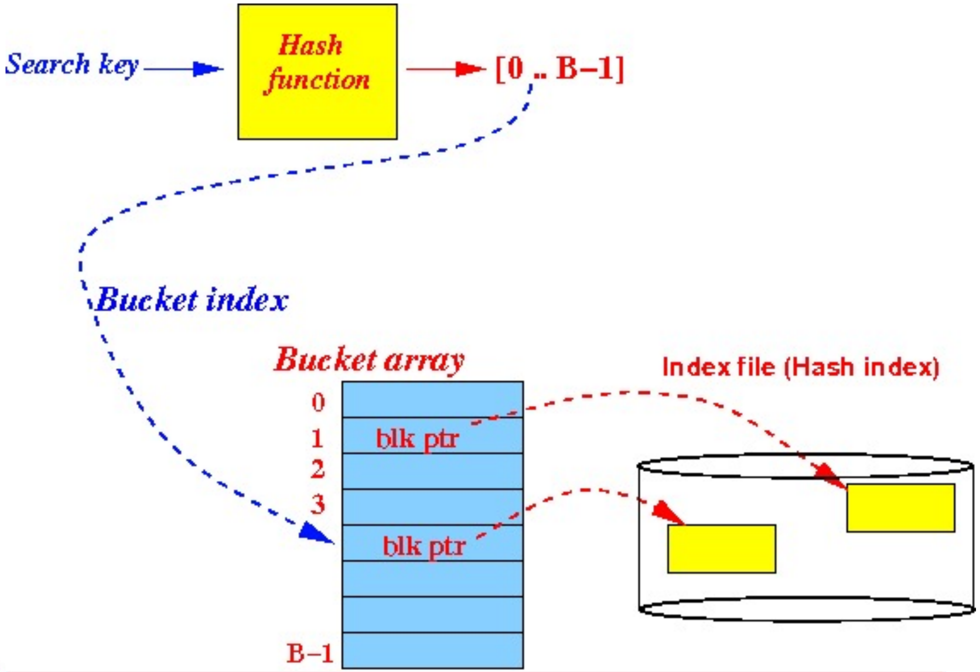
  - Physically order the records of a file on disk based on the values of one of their fields (key field)

  - SELECT: binary search (very fast)
    - Select takes $o(\log_2 n)$

  - INSERT/DELETE/UPDATE: more expensive
    - Insert (resp. delete) takes $o(\log_2 n)$ time to find the location for the new (resp. old) record plus o(n/2) to re-organize records
    - Update takes $o(\log_2 n)$ to locate the record to be updated, then another $o(\log_2 n)$ to locate the new location plus another o(n/2) to re-organize the rest of the data.

2.3. Primary file organizations

- **Hash files**
  - The address of the disk block in which the record is stored is the result of applying a hash function to the value of a particular field (hash field) of the record.
  - Very fast access to records for search on equality condition on the hash field.



[Emory Computer Science]

2.3. Primary file organizations

- **Hash files**
  - **Advantages**
    - If the hash field value is exactly known, then SELECT, INSERT, UPDATE, DELETE are very quick
    - Multiple records can be accessed at the same time (the storage location is independent between different records)
    - Suitable for online transaction systems like online banking, ticket booking system etc.

2.3. Primary file organizations

- **Hash files**
  - **Disadvantages**
    - If hash field is not unique, can lead to loss of data (older record overwritten by newer record with same hash field value)
    - All the records are randomly scattered in the memory => not efficient memory use
    - If the SELECT/UPDATE/DELETE is not based on the exact hash field(s), then this method is **very inefficient** (exhaustive search)
      - If there is multiple hash columns (*e.g.* name and phone number), and if we are searching any record using phone or name alone, it will not give correct results
    - If we are searching for a range of data, then this method is **very inefficient**
    - Range addresses are independent of the hash field range
      - Example: searching for the students born before 1995 will not be efficient
    - If these hash column(s) are frequently updated, then the data block address is also changed accordingly. Each update will generate new address. This is not acceptable

2.3. Primary file organizations

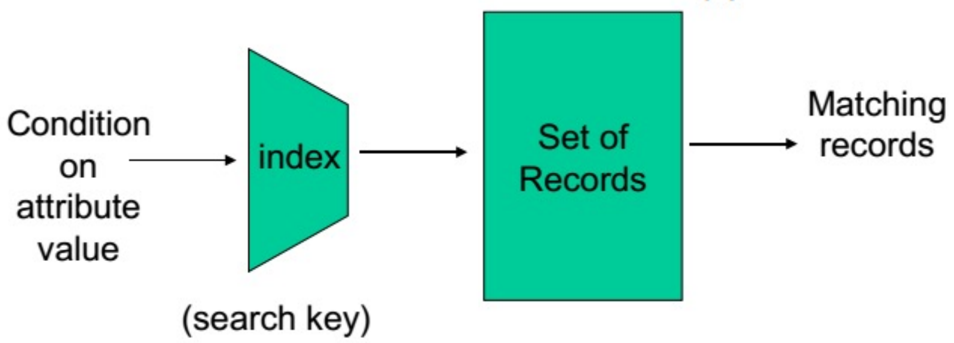
- **Hash files**
  - **Conclusion**
    - **Only** adapted for very specific applications where the data is only accessed by querying a given field (*e.g.* booking number)
    - For other cases, we'll use **secondary file organization** (mostly **indexes**)

3. Database indexes

- What is database index?
- Index data structures
- B+tree
- Sparse vs. Dense index
- Clustered vs. Non-clustered index
- Index creation in SQL
- Using indexes

3.1. What is database index?

- Secondary organization or auxiliary access structure (commonly index) allows efficient access to file records based on alternate fields

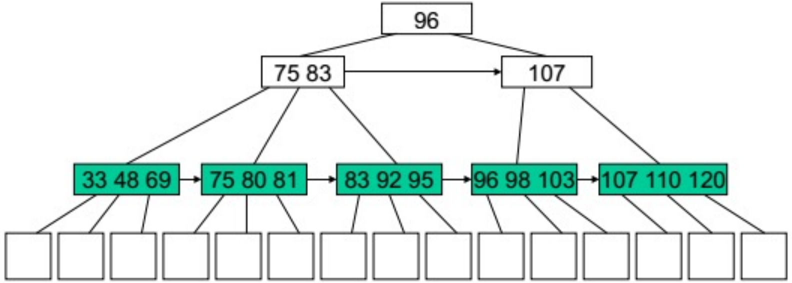


3.2. Index data structures

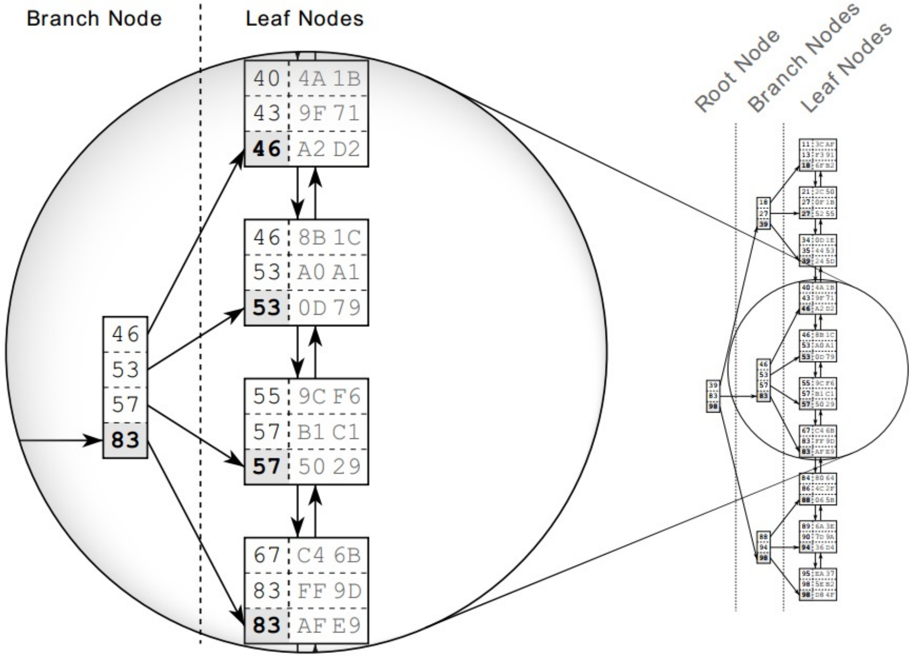
- Indexes can be implemented using different data structures.
  - B+-tree index
  - Traditional hash index
  - Dynamic hash index: number of buckets modified dynamically
  - Bitmap index (more often used in data warehouses than in tradiational relational databases)
  - R-tree: index for specific data types (points, lines, shapes)
  - quadtree: recursively partition a 2D plane into four quadrants
  - octree: quadtree version for three dimensional data
  - main memory indexes: T-tree, binary search tree

3.3. B+Tree

- Balanced tree of key-pointer pairs
- Keys are sorted by value
- Nodes are at least half full
- Access records for key: traverse tree from root to leaf



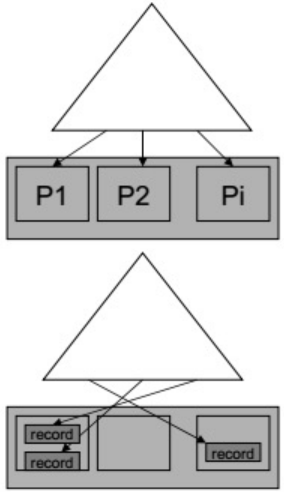
3.3.1. Example: B+ tree



© Gulutzan, Peter, and Trudy Pelzer. *SQL Performance Tuning*. Addison-Wesley Professional, 2003.

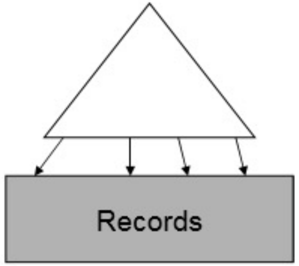
3.4. Sparse vs. Dense index

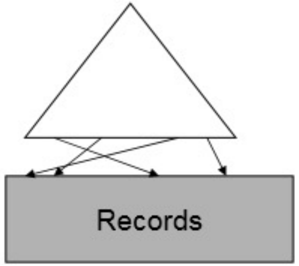
- Sparse index
  - pointers to disk **pages**
  - at most one pointer per disk page
  - usually much less pointers than records
- Dense index
  - pointers to individual **records**
  - one key per record
  - usually more keys than sparse index optimization: store repeating keys only once, followed by pointers



3.5. Clustered vs. Non-Clustered

- Clustered index on attribute X
  - This index controls the placement of records on disk
  - Only one clustered index per table
  - Can be dense or sparse (often sparse)
- Non-clustered index on attribute X
  - No constraint on table organization
  - Can have more than one index per table
  - Always dense

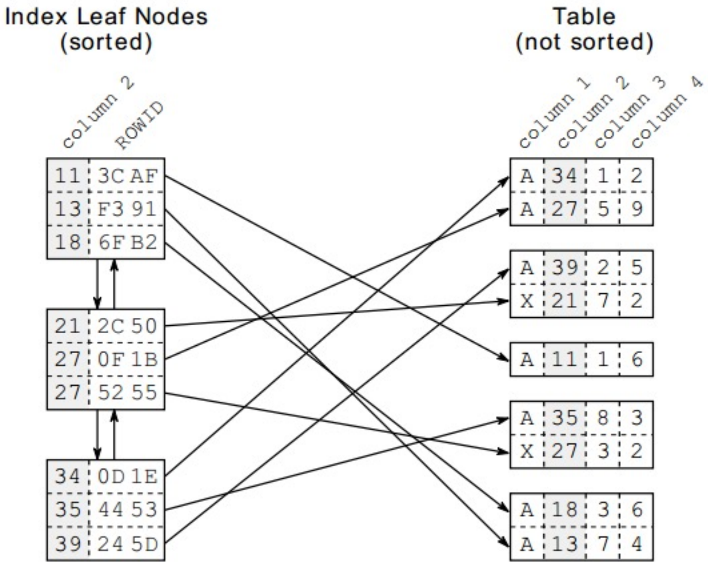




3.5. Clustered vs. Non-Clustered

- More details on clustered *vs.* non-clustered indexes:
  - https://www.geeksforgeeks.org/difference-between-clustered-and-non-clustered-index/
  - **Recall from Chapter 7**: by default, the index for a PK attribute is clustered, wheread the index for a unique attribute is unclustered.

3.5.1. Example: Non-clustered index



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3.6. Creating Index

- Important remark:
  - All relational DBMS **automatically** index the primary key of each table with a clustered index (B-tree in general)
  - So, if you declare an attribute as PK for a given table, you **DO NOT NEED** to create the corresponding index
  - When you make a search / join based on the Primary Key, you **DO NOT NEED** to specify that the index should be used
    - Because in clustered index, the index **is** the main data

3.6. Creating Index

- Syntax for creating the indexes together with the tables (example with MariaDB) – for non PK attributes

```
CREATE TABLE table_name(
    column_list,
    ...,
    FULLTEXT (column1,column2,..)
);
```

3.6. Creating Index

- Syntax for creating the indexes separately from the tables (with MariaDB) – for non PK attributes

```
CREATE [UNIQUE|FULLTEXT|SPATIAL] INDEX index_name [index_type]
ON tbl_name (index_col_name,...) [index_option]
[algorithm_option | lock_option] ...
```

- index_type: USING {BTREE | HASH}
- index_col_name: col_name [(length)] [ASC | DESC]
- index_option: [KEY_BLOCK_SIZE [=] value
{{{|}}} index_type
{{{|}}} WITH PARSER parser_name
{{{|}}} COMMENT 'string’
{{{|}}} CLUSTERING={YES| NO}] [IGNORED | NOT IGNORED]
- algorithm_option: ALGORITHM [=] {DEFAULT|INPLACE|COPY|NOCOPY|INSTANT}
- lock_option: LOCK [=] {DEFAULT|NONE|SHARED|EXCLUSIVE}

More details on [https://mariadb.com/kb/en/create-index/]

3.6. Creating Index

- Syntax for dropping indexes
  - The keyword is DROP
  - The syntax differ on the DBMS (some mention the source table, some others don't) => see the documentation for your DBMS

3.7. Using Indexes

- Example: FULLTEXT indexes, using mySQL

```
CREATE TABLE tutorial ( id INT UNSIGNED
AUTO_INCREMENT NOT NULL PRIMARY KEY, title
VARCHAR(200), description TEXT,
FULLTEXT(title,description) ) ENGINE=InnoDB;
```

```
SELECT * FROM tutorial WHERE
MATCH(title,description) AGAINST ('left right' IN
NATURAL LANGUAGE MODE);
```

id	title	description
5	SQL Full Outer Join	In SQL the FULL OUTER JOIN combines the results of both left and right outer joins and
3	SQL Left Join	The SQL LEFT JOIN, joins two tables and fetches rows based on a condition, which are m

[https://www.w3resource.com/mysql/mysql-full-text-search-functions.php]

Summary

- Overview of database storage structures
  - 3-tier Schema Model (ANSI-SPARC Architecture)
  - How MariaDB stores data
- Physical database file structures
  - Motivation
  - Magnetic disks as data storage
  - Primary file organizations
- Database index
  - What is database indexes?
  - Index data structures
  - B+tree
  - Spare vs. Dense index
  - Clustered vs. Non-clustered index
  - Index creation in SQL
  - Using indexes

Exercise 1

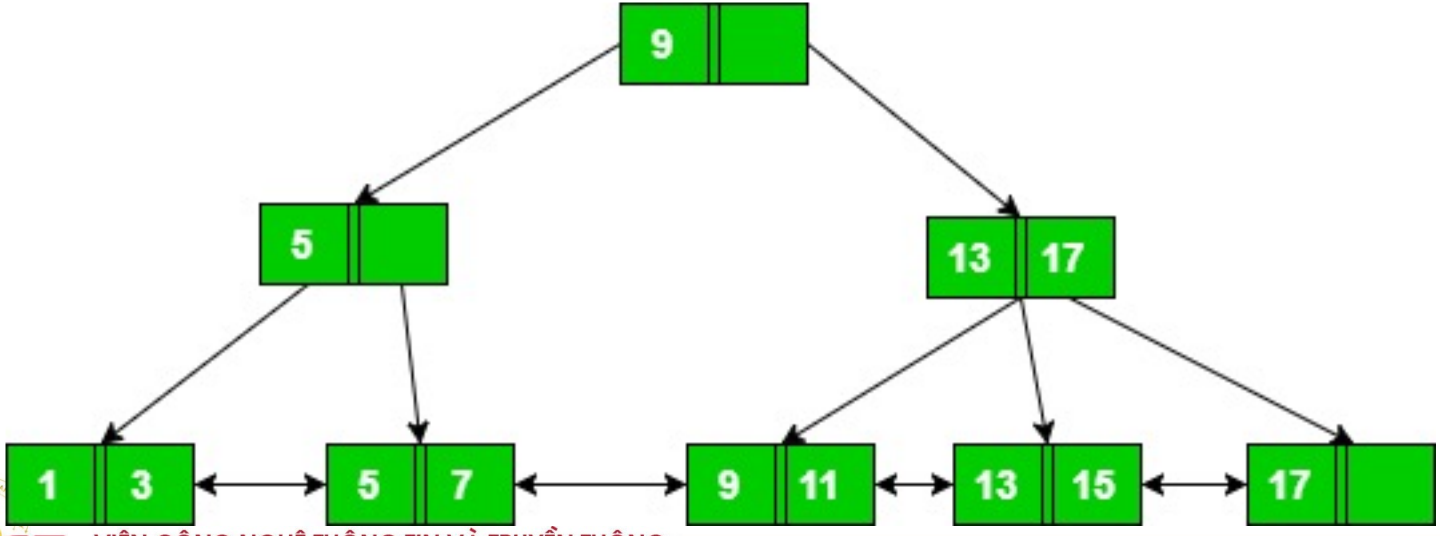
- Read the following definition of B+ tree: https://en.wikipedia.org/wiki/B%2B_tree
  - Extract (with branching factor B):

Node Type	Children Type	Min Number of Children	Max Number of Children	Example $b = 7$	Example $b = 100$
Root Node (when it is the only node in the tree)	Records	0	$b - 1$	0–6	1–99
Root Node	Internal Nodes or Leaf Nodes	2	b	2–7	2–100
Internal Node	Internal Nodes or Leaf Nodes	$\lceil b/2 \rceil$	b	4–7	50–100
Leaf Node	Records	$\lceil b/2 \rceil$	b	4–7	50–100

- Make the following exercise (with b=4):
  - https://opendsa-server.cs.vt.edu/embed/bPlusTreeInsertPRO#:~:text=In%20this%20exercise%20your%20job,the%20values%20in%20the%20stack.
  - There is a small bug in this API. You might need to run it multiple times to find it. Will you??

Exercise 2

- With the B+ tree (b=2) shown below, how much is the minimum number of nodes (including the root node) that must be fetched in order to satisfy the following query: “Get all records with a search key greater than or equal to 7 and less than 15”



Exercise 2

- Solution:
- Conclusion: B+ trees are very efficient for range searches.

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