Index

“Appear weak when you are strong, and strong when you are weak.”
- Sun Tzu

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Outline

1. Index Introduction
2. Classification
    - Data Structure
    - Physical Storage Index
    - Characteristics
    - Composite Index
3. Practices
    - Index Failures
    - Best Practices

1. Introduction

1.1. Index

- An index is a **data structure** that **improves the speed** of data retrieval operations.
- Indexes are **typically stored on disk**.

2. Classification

2.0. Classification

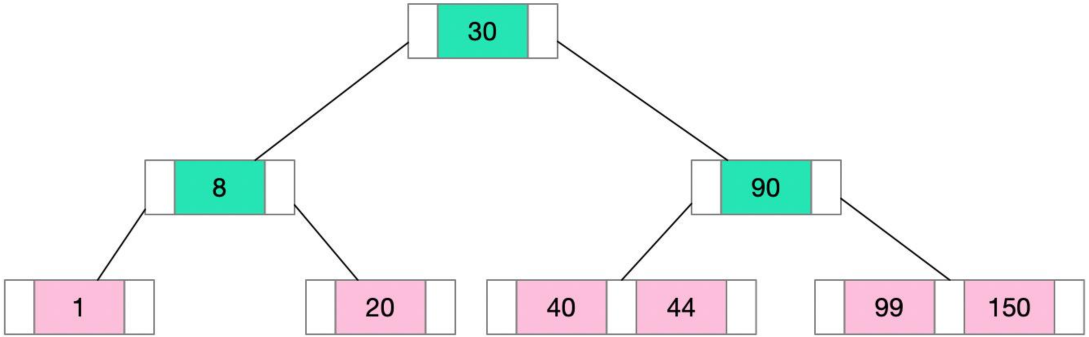
- By data structure: B+ tree index, Hash index, Fulltext (inverted) index, LSM Tree, …
- By physical storage: Clustered Index, Non-clustered Index (Secondary Index)
- By number of columns: Single-column Index, Composite index
- By characteristics: Primary Key Index, Unique Index, Prefix Index

2.1. Data Structure

2.1. Data Structure

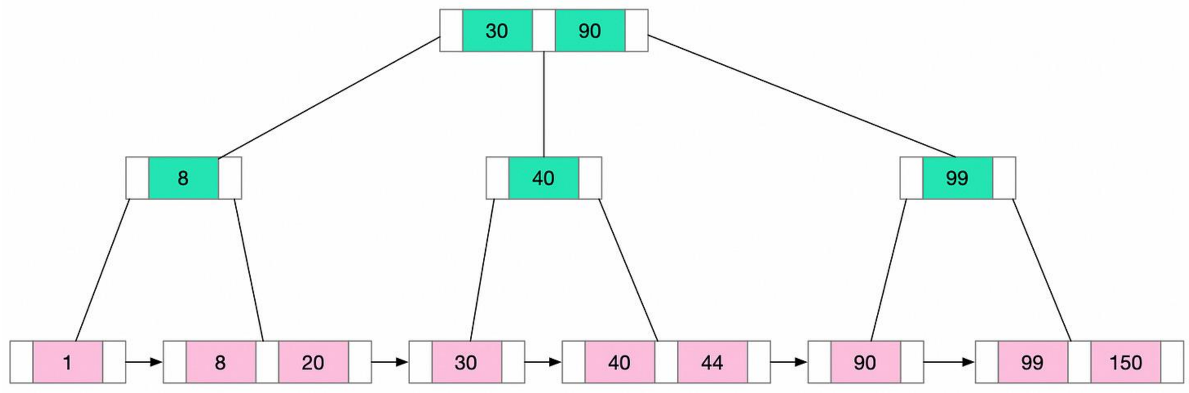
- What factors should be considered when mentioning data structure and algorithm?
- Use case
- **Time Complexity**
- **Space Complexity**
- Complexity of Implementation
- …

2.1.1. B-Tree (Balanced Tree)



- **All leaves are at the same level**. Each node contains a **sorted list of keys**.
- A non-leaf node with k children contains k-1 keys. This means if a node has three children (k=3), it will hold two keys (k-1)
- Insertion, deletion, and search operations can be performed in **O(Log N)** time

2.1.2. B+Tree

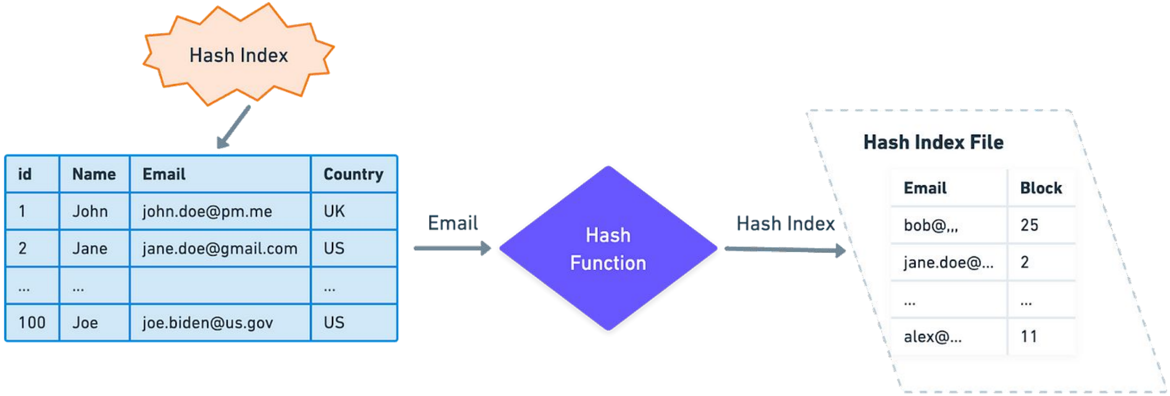


- The B+ Tree is a variant of the B-Tree
- The pointers to the actual records are stored only at the leaf nodes.
- The internal nodes only contain keys and pointers to other nodes. **Many keys can be stored in internal nodes**
  → **Reducing the overall height of the tree**.
  → Decreases the number of disk accesses
- **All leaf nodes are linked together in a linked list → efficient for range queries**

2.1.3. B-Tree vs B+Tree

Attribute	B-tree	B+ tree
Structure	Both leaf and internal nodes store keys and data.	Only leaf nodes store data (or pointers to data), while internal nodes only store keys.
Data Accessibility	Data can be accessed directly from both leaf and internal nodes.	Data can only be accessed by traversing to leaf nodes.
Efficiency	May be slightly less efficient for range queries as data is scattered throughout all nodes.	More efficient for range queries as all data is located in leaf nodes, which are linked for easy traversal.
Insertion and Deletion	Can be slightly more complex due to data being scattered across all nodes.	Slightly more efficient, as data resides only at leaf nodes, reducing the need for frequent reorganization.
Space Utilization	Might be less efficient, as all nodes store data.	More space-efficient, as data is stored only at leaf nodes.
Use Cases	Useful for database systems where data retrieval is usually targeted (i.e., specific keys).	More commonly used in database and file systems where range queries are more common.

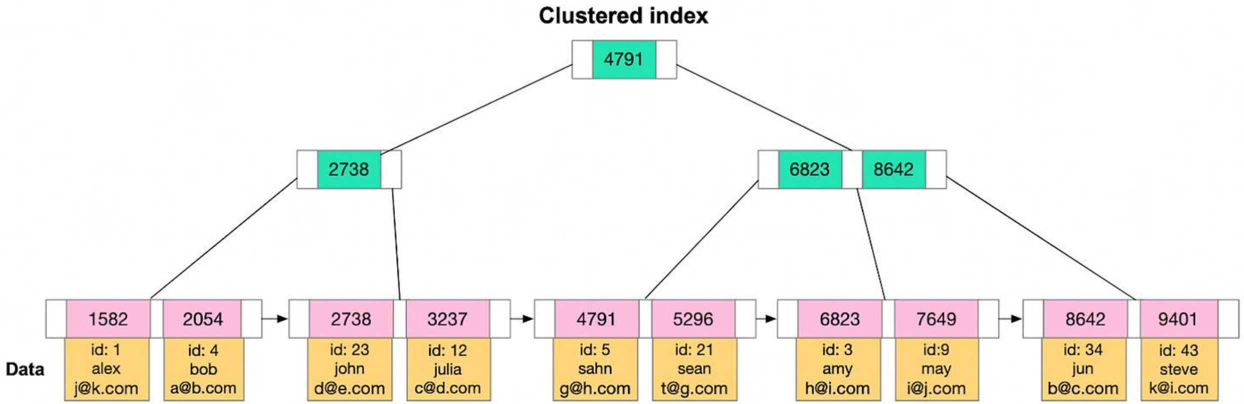
2.1.4. Hash Index



- Hash Index uses a hash function to map keys to specific locations
- Hash Index well-suited for **equality comparisons**, such as "=".
- **Limitations:**
  - **Range-based queries, sorting**
  - Collision

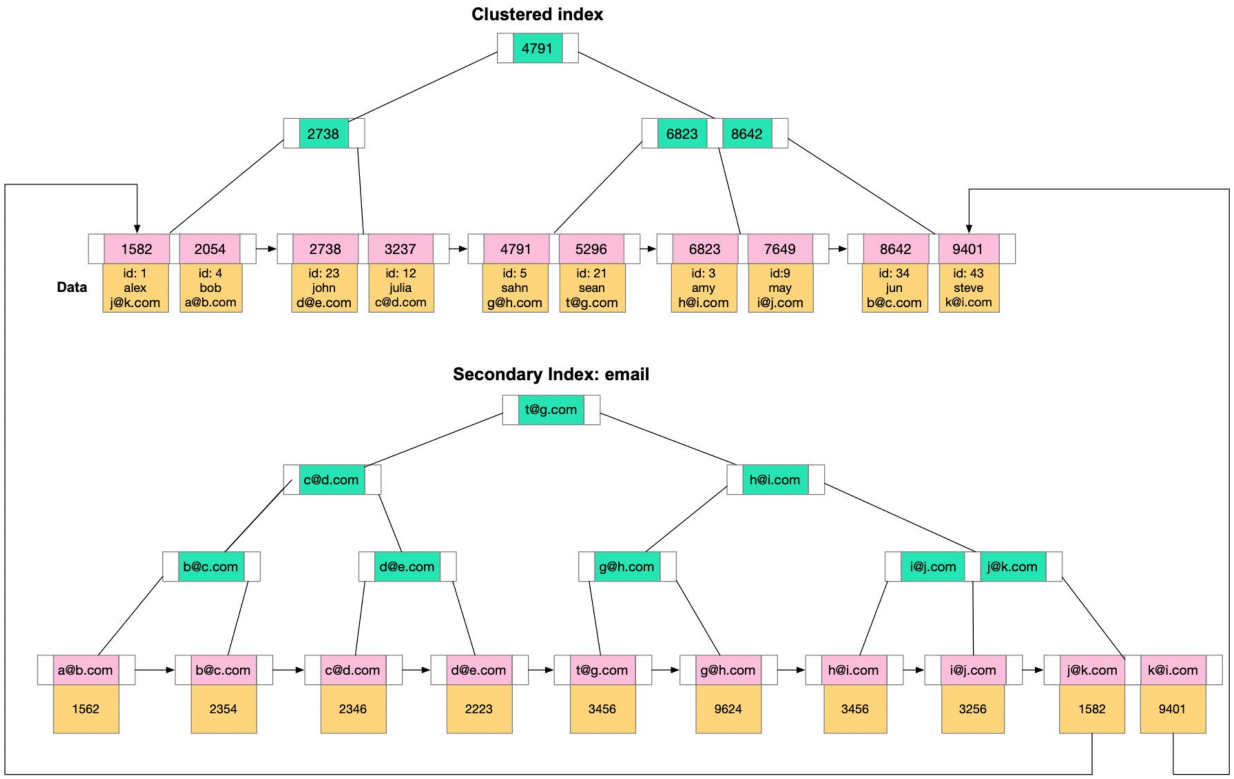
2.2. Physical Storage Index

2.2.1. Clustered Index



- Clustered Index is a type of index that determines the **physical order of the data in a table**.
- A table can have only one clustered index.
- The **leaf nodes** of the B+Tree of the clustered index store **actual data**
- **By default, primary key is used for clustered index**. But we can choose different column(s) for the clustered index, separate from the primary key.
- In InnoDB, cluster index use B+Tree structure, can not use Hash.

2.2.2. Non-clustered Index



2.2.2. Non-clustered Index

- Indexes are not clustered index, then non-clustered (secondary) indexes.
- **The value** (the leaf node of B+ Tree) of secondary index is **the primary key value**
- A table can have multiple secondary indexes
- Accessing data using a secondary index involves at least **two disk reads**. One to access the secondary index and another to access the clustered index to get actual data.

2.2.2. Non-clustered Index

What are disadvantages of indexes?

- **Slowing down write operations**
- **Occupying physical space**
- It takes time to create and maintain indexes

Why leaf node of secondary index point to the primary key value, not the disk address?

→ The **disk address of records might be change** during table operating, defragment, …

2.3. Characteristics

2.3.1. Characteristics

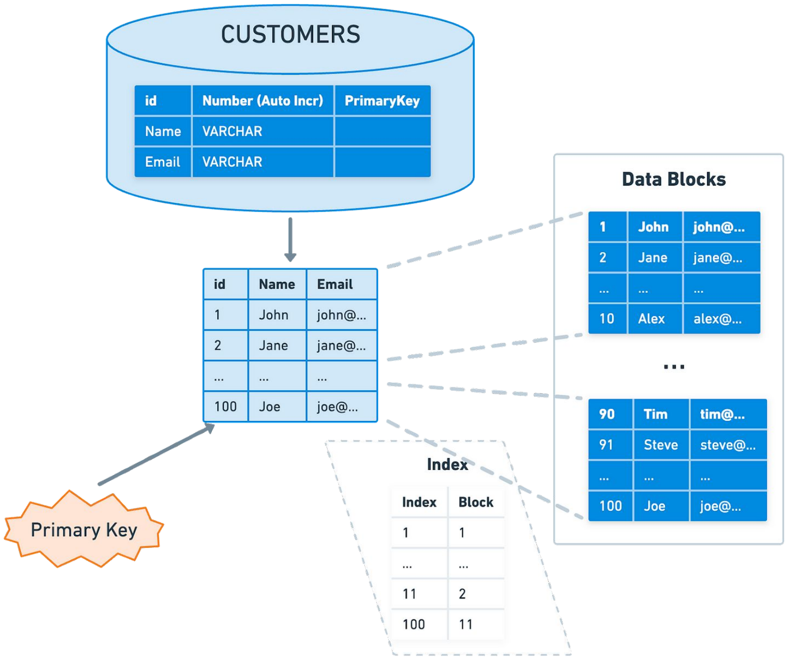
What is the difference between key & index?

- **Key means a constraint** imposed on the behaviour of the column.

  Example: primary key is non nullable field which uniquely identifies each row.
- **Index** is a special data structure that **facilitates data search** across the table.

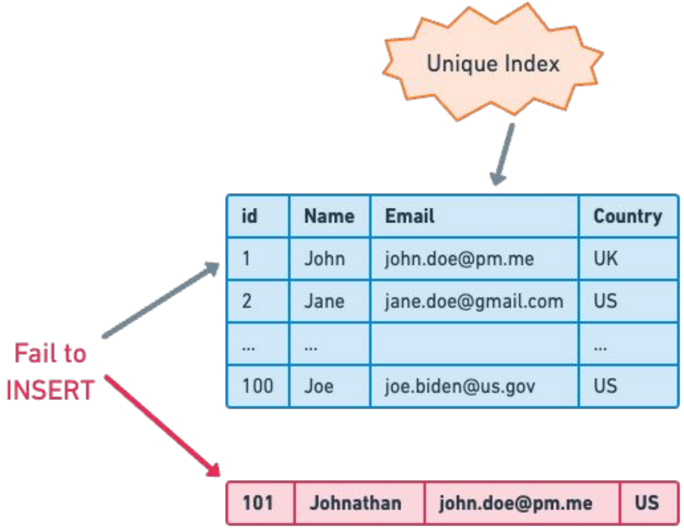
2.3.2. Primary Index

- Primary Index is a specific type of index that serves as a **unique identifier for each row in a table**.
- If the key is **sequential**, writing to the table is generally **efficient**.



2.3.3. Unique Index

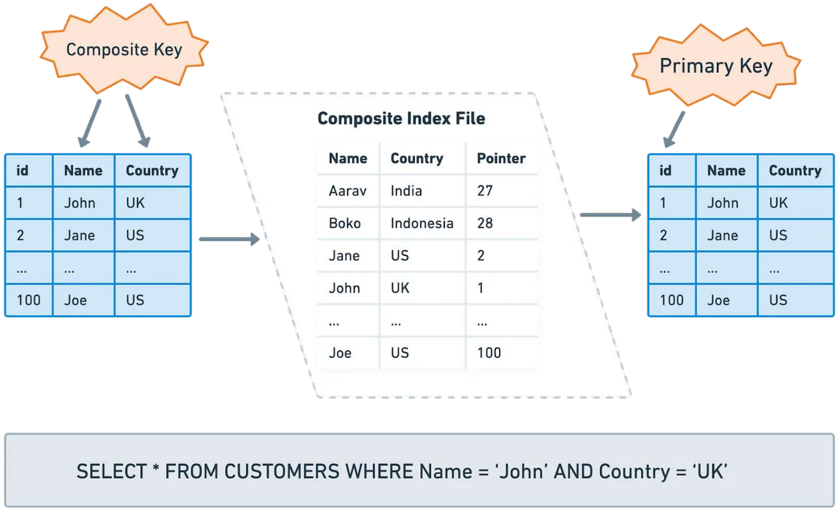
- The value of the index column must be unique, but **null values are allowed**.
- Command:
  CREATE UNIQUE INDEX index_name ON table_name(index_column_1,index_column_2, ...);



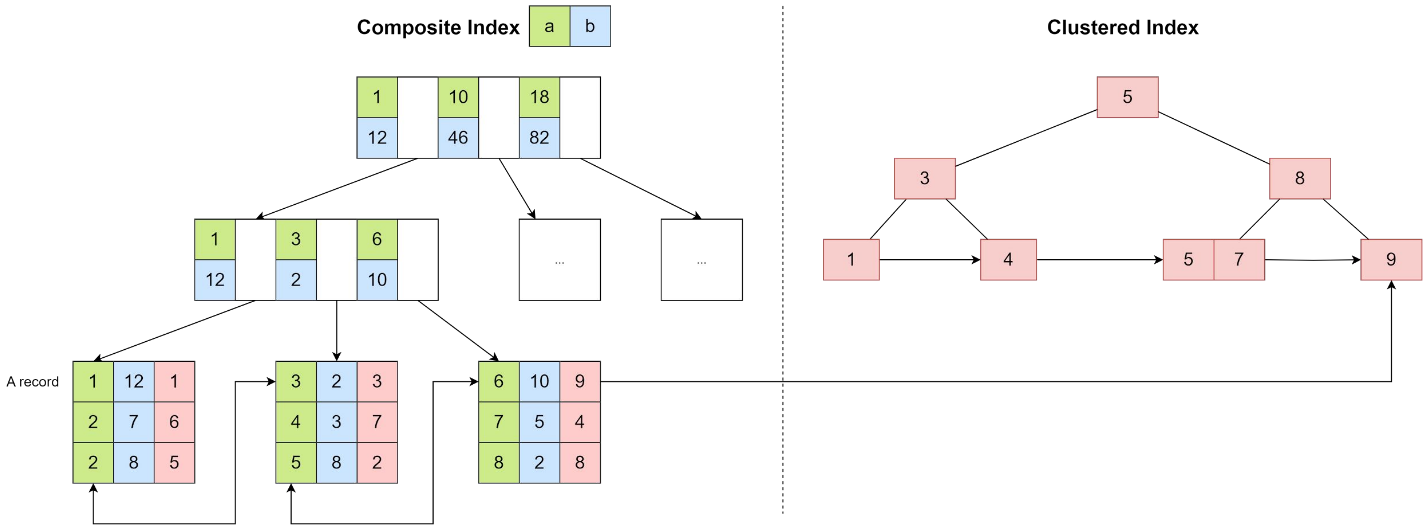
2.4. Number of Columns

2.4.1. Composite Index

- Composite Index is a multi-column index.
- **The more columns in a composite index, The more storage space in used**



2.4.1. Composite Index



2.4.1. Composite Index

Composite index: (country, provine, name). Which one uses index?

1. SELECT * FROM customers WHERE provine = 'Texas' AND country = 'US'; ✅
2. SELECT * FROM customers WHERE provine = 'Texas';
3. SELECT * FROM customers WHERE name = 'JANE' AND provine = 'Texas';
4. SELECT * FROM customers WHERE country = 'US'; ✅

→ **The filter conditions must include the first column in the composite index. The order of the filter conditions does not matter.**

2.4.1. Composite Index

Is composite index (country, provine, name) effective?

How do we determine the order in a composite index?

Approach: **Columns with high cardinality (the high number of distinct values) first.**

→ The B+Tree has more branches → Node has less keys

→ Time complexity decreases

Example: Composite index: (name, provine, country)

2.4.1. Composite Index

Composite Index (a, b)

Q1: SELECT * FROM table WHERE a > 1 AND b = 2

Q2: SELECT * FROM table WHERE a >= 1 AND b = 2

Q3: SELECT * FROM table WHERE a BETWEEN 2 AND 8 AND b = 2

Question:

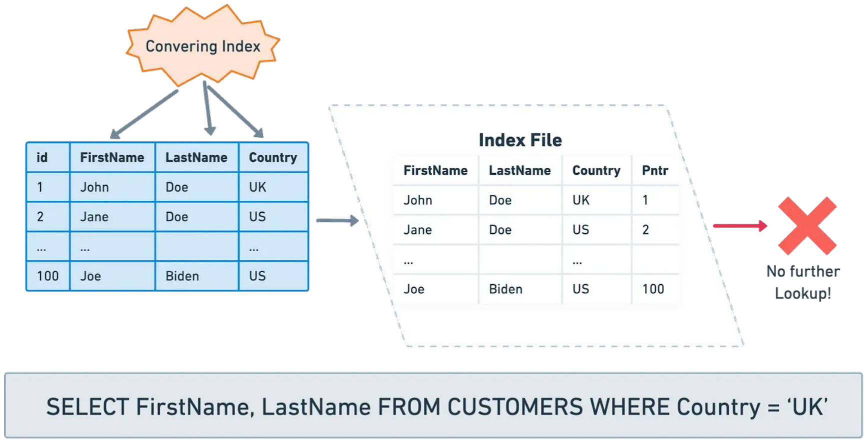
- Does each query use the index?
- How many columns are used?

Answer:

- Q1: yes, use (a)
- Q2: yes, use (a, b)
- Q3: yes, use (a, b)

2.4.2. Covering Index

- A covering index is an index that **contains all the columns in the SELECT**
- Answering the query by using the index alone, reducing disk I/O operations
  → improve the performance significantly
- Recommended: =< 5 columns



2.5. Other Indexes

Classified by data structure:

- Fulltext Index (Inverted index)
- Spatial Index: R-Tree (GIST - Postgres)
- Bitmap Index:
  - Use case: Read heavy on counting low-cardinality column.
  - Example: Count the number of orders in PROCESSING status.

3. Practices

3.1. Indexes in Use

When to use indexes?

- Read heavy: Frequent queries with WHERE, JOIN, GROUP BY, ORDER BY
- **Find small set of records**
- Fields with unique restrictions, such as product_id

When to not use indexes?

- Table has too little data
- Very low cardinality. For example: gender
- Only write heavy, no read much

3.2.1. Index Failures 01

Index on ‘name’ column

1. SELECT * FROM users WHERE name LIKE ‘%ronin’;
2. SELECT * FROM users WHERE name LIKE ‘%ronin%’;
3. SELECT * FROM users WHERE name LIKE ‘ronin%’;

3.2.2. Index Failures 02

Index on ‘id’ column

SELECT * FROM users WHERE id = 1 OR age = 18;

3.2.3. Index Failures 03

1. Column ‘id’: int
SELECT * FROM users WHERE id = ‘10’;

2. Column ‘id’: varchar
SELECT * FROM users WHERE id = 10

Because automatically convert the string to a number, and then compare it

3.2.4. Index Failures 04

Index on column ‘name’
SELECT * FROM users WHERE length(name) = 6;

→ Because the index saves the original value of the index field,
not the value calculated by the function.

Oracle, Postgres, MySQL 8.0+ support function index, but be careful with it!

3.2.5. Index Failures 05

Index on ‘id’ column:
SELECT * FROM users WHERE id + 1 = 10;
SELECT * FROM users WHERE id + 0 = 10 - 1;

→ Because the index saves the original value of the index field,
not the value calculated by expressions

3.3. Best Practices

- Limit the Number of Indexes
- The primary key index is preferably self-incrementing
  - No need to move the existing data
  - Reduce page split, fragmentation
- The index is best set to NOT NULL
  - Value comparison more complicated
  - NULL value is a meaningless value, but it will occupy physical space
- Covering Index
  - Reduce a lot of I/O operations
- Prefix index
  - Reduce the size of the index storage
- Regularly Monitor and Optimize the Indexes
  - B+ Tree might become imbalance overtime → rebuild index
- Prevent index failures

3.4. Note

- Index helps to reduce the number of search operations
- Index helps to reduce the number of disk I/O
- MySQL != Postgresql
    - Architecture
    - In postgres, columns in a row might be included in internal nodes and leaf nodes.

Recap

- All leaf nodes are linked together in a linked list → efficient for range queries
- Accessing data using a secondary index involves at least two disk reads. One to access the secondary index and another to access the clustered index to get actual data.
- Leverage composite index, covering index. And high cardinality first.

Appendix

- https://www.freecodecamp.org/news/database-indexing-at-a-glance-bb50809d48bd/
- Best practices:
  - Indexing Very Large Tables. A short guide to the best practices… | by Kovid Rathee | Towards Data Science
- Index Guideline:
  - MySQL: Building the best INDEX for a given SELECT
  - What every developer should know about SQL performance

Homework

- Dataset Setup Instructions
- Verify (3) theories in this lecture
    - Theory statement
    - SQL(s)
    - Result, explain

Thank you 🙏

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