# Speed Up Your Database Systems

## CS307 Lab12, Spring 2019

Ziqin Wang

Southern University of Science and Technology
*11712310@mail.sustech.edu.cn*

May 7, 2019

Southern University
of Science and
Technology

# Contents

# Contents

# What is index?

- How to search efficiently?
  - Strategy: Divide and Conquer, e.g. *Binary Search*
  - Assumption: Stored In Order
- What if one want to search for ...
  - "The movie named ***Titanic***"
    $\Longrightarrow$ `title`
  - "**Chinese** movies released in **1999**"
    $\Longrightarrow$ `country` & `year_released`

**But ...**

Data are not stored in multiple orders

# What is index?

Think about a Chinese Dictionary

- Words are listed in alphabetical order
- We still have
  - 音序检字法
  - 部首检字法
  - 笔顺检字法
- How is this achieved?

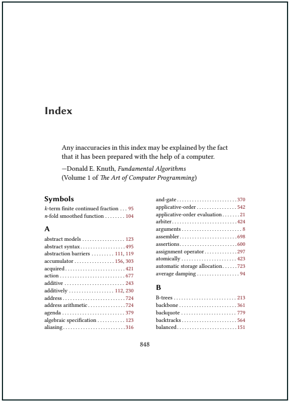
# What is index?

## Concept

An *index* is a data structure which improves the **efficiency** of **retrieving** data with specific values from a database.

## Remark

- Indexes in databases is similar to indexes in books
  - Data are stored in *pages* (blocks)
  - Indexes locate a row by (filename, block #, offset)
- Indexing is beyond the scope of Relational Theory



Index

Any inaccuracies in this index may be explained by the fact that it has been prepared with the help of a computer.

—Donald E. Knuth, *Fundamental Algorithms* (Volume 1 of *The Art of Computer Programming*)



848

Figure: Index page of *Structure and Interpretation of Computer Programs*, 2nd ed., by H. Abelson, G. J. Sussman and J. Sussman, licensed under CC BY-SA 4.0.

# How to get an index?

- You have already benefited from indexes off-the-shelf
  - `PRIMARY KEY` constraint
  - `UNIQUE` constraint
- Why does your DBMS create them automatically?

# How to get an index?

Or, you can `CREATE INDEX`[1] on your own:

## SQL Command Syntax

```
CREATE INDEX index_name
ON table_name (column_name [, ...]);
```

[1] https://www.postgresql.org/docs/current/sql-createindex.html

# Index Taxonomy

- In terms of storage structure, is the index completely separated with the data records?
  - No $\Longrightarrow$ **Integrated index**, e.g.
    - PK index in a MySQL InnoDB database
    - PK index in a SQL Server database
  - Yes $\Longrightarrow$ **External index**, e.g.
    - Indexes in a PostgreSQL database
    - Indexes in a MySQL MyISAM database
- Does the index specify the order in which records are stored in the data file?
  - Yes $\Longrightarrow$ **Clustered index** (a.k.a. primary index[2])
  - No $\Longrightarrow$ **Non-clustered index** (a.k.a. secondary index)

---

[2]Someone may consider *primary index* as the alias of *integrated index*, and consider *secondary index* as the alias of *external index*. It depends on who you are talking with.

# Index Taxonomy

- Does every search key in the data file correspond to an index entry?
  - Yes $\Longrightarrow$ **Dense Index**
  - No $\Longrightarrow$ **Sparse Index**

- Does the search key contain more than one attribute?
  - Yes $\Longrightarrow$ **Multi-key index** (Multi-column index)
  - No $\Longrightarrow$ **Single-key index** (Single-column index)

# Index implementation

Data Structures for Indexes

- Ordered
  - *B*-tree and its variants (e.g. $B^+$-tree)
  - Generalizations of *B*-tree, e.g. *R*-tree
  - ...
- Unordered
  - Hash tables
  - Bitmap
  - ...

**Question**

What is the common limitation of unordered indexes?

# Index implementation: *B*-tree definition[3]

**Definition**

A *B-tree of order m* satisfies that

1. For every node, # of children $=$ # of keys $+ 1$
2. **(Ordered)** For a node containing $n$ keys $(K_1 < K_2 < K_3 < \cdots < K_n)$ with $n+1$ children (pointed by $P_0, P_1, P_2, \ldots, P_n$), any key $k_{sub_i}$ in the sub-tree pointed by $P_i$ satisfies that $K_i < k_{sub_i} < K_{i+1}$
3. **(Multiway)** For an internal node, $\lceil m/2 \rceil \leq$ # of children $\leq m$, except that a root node may have less than $\lceil m/2 \rceil$ children
4. **(Always balanced)** All leaves appear on the same level

---

[3] Here we mainly follow D. E. Knuth's definition [2]. Note that the *B*-tree defined in *CLRS* [3] is slightly different. Read `https://stackoverflow.com/a/45826413` for further comparison.

# Index implementation: *B*-tree definition

## Terminology

- $\lceil m/2 \rceil$ is the called the *minimum branching factor* (a.k.a. *minimum degree*) of the tree
- A B-tree of order m is usually called a *$\lceil m/2 \rceil$-m tree*, like 2-3 tree, 2-4 tree, 3-5 tree, 3-6 tree, …

## Remark

In practice, the order *m* is much larger (typically on the order of 100)

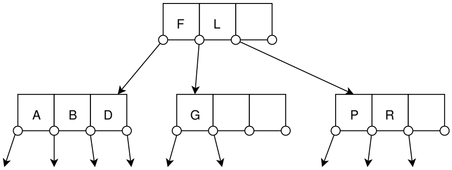



Figure: An example of B-tree (2-4 tree, a.k.a. 2-3-4 tree)

## Question

Note that a *B*-tree usually waste some space. Why do we prefer *B*-tree to balanced BST (e.g. AVL tree, red-black tree, etc.)?

# Index implementation: Why *B*-trees?

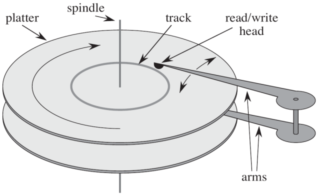



Figure: A typical disk drive (Retrieved from *CLRS* 3rd ed., pp. 485. [3])

Memory Hierarchy [4]

| Technology | Access time |
|---:|---|
| DRAM | 50-70 ns |
| Magnetic disk | 5-20 ms |

- Locality $\longrightarrow$ Paging
  - disk page $\leftrightarrow$ *B*-tree node
  - $m$ is chosen with consideration on the page size
  - # of disk I/O $\leftrightarrow$ height of *B*-tree
- Height of a *B*-tree

$$h \leq 1 + \log_{\lceil m/2 \rceil} \left( \frac{n+1}{2} \right)$$

(What's the height of a *B*-tree of order 200 with two million search keys?)

# Index implementation: *B*-tree operations

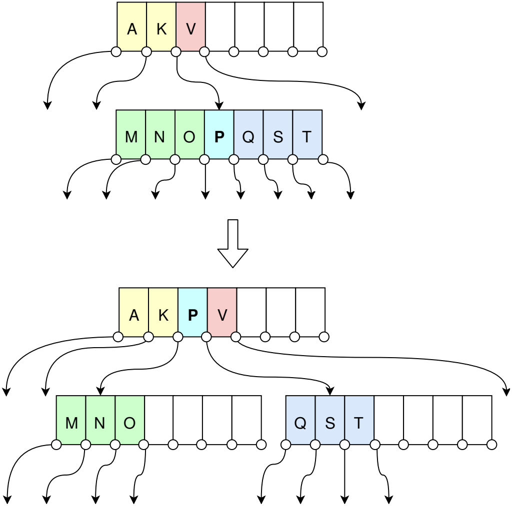
Tree operations:

- Search
- Insert
- Delete
- Update: Delete + Insert

What is special in *B*-tree?

- Split
- Merge

# Index implementation: Split a node in a *B*-tree



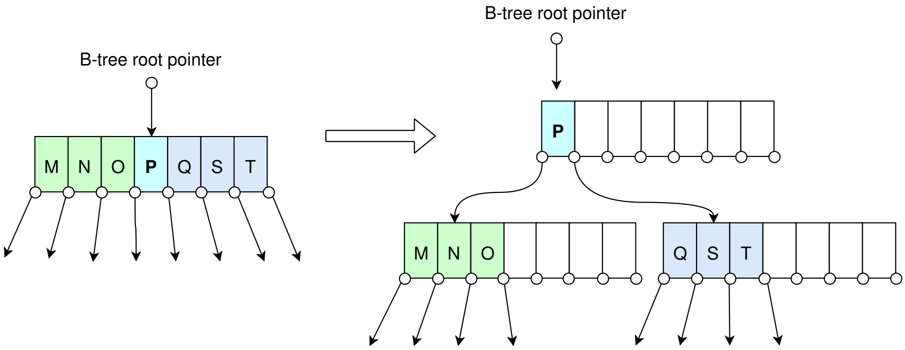

**Observation**

In this example, the height of the *B*-tree doesn't change after splitting.

**Question**

What if the parent node is also full?

# Index implementation: Split the root node of a *B*-tree




## Remark

Note that the height of the *B*-tree is increased by one. This is the only way that a *B*-tree increases its height.

# Index implementation: Delete a key in a *B*-tree

More complicated than insertion. May involve

- Rotation
- Merging

Suggestions:

- Watch the video [9].
- Read the related chapters [2, 3].

# Index implementation: $B^+$-tree vs. $B$-tree

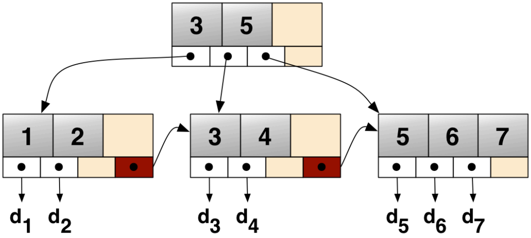



Figure: An example of $B^+$-tree (published by Grundprinzip under CC BY 3.0)

| $B$-tree | $B^+$-tree |
|---|---|
| Data stored in every node | Data stored only in leaves |
| No sequential links | Leaves linked sequentially |

# Index implementation: Benefits of $B^+$-trees

| | | |
|---|---|---|
| Data stored only in leaves | $\Longrightarrow$ | Larger $m$ and smaller height |
| Leaves linked sequentially | $\Longrightarrow$ | Better support for range query |

# Negative impacts of indexes: Storage overhead

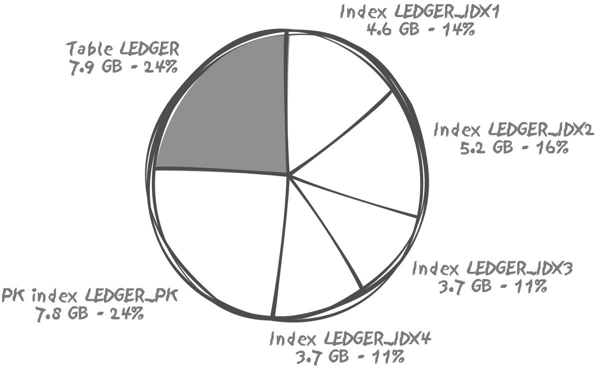



Figure: A real-life case: Data versus Index out of a 33 GB total (Retrieved from *The Art of SQL*, ch. 3, pp. 57. [5])

**Reminder**

The more indexes created, the more storage space consumed.

# Negative impacts of indexes: Processing overhead

**Reminder**

Indexing may speed up data retrieval, but will bring overhead to `INSERT`, `UPDATE`, and `DELETE` operations.

Indexes and **Backup**:

- Logical backup
- Physical backup

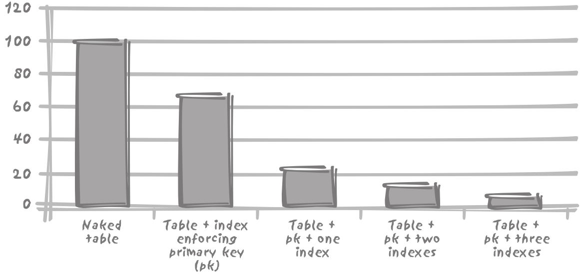



Figure: The impacts of indexes on insertion with Oracle (Retrieved from *The Art of SQL*, ch. 3, pp. 57. [5])

# Index it or not: Where indexing may help

- Check whether the PK / Unique index helps first
- Index those columns frequently appeared as search criteria
  - `=`
  - `<, <=, >, >=, BETWEEN`
  - `IN`
  - `EXISTS`
  - `LIKE` (prefix matching)
- Columns involved in foreign key constraints
  - Why indexing?
  - Think about two directions
  - Will you frequently update/delete those referenced records?

# Index it or not: Where indexing may not help

- Longest prefix matching of multi-key indexes
  - When specifying a composite primary key or creating a multi-key index, the order of columns matters.
  - If required, you may consider creating indexes for (col1, col2, col3), (col2), and (col3) respectively.
- Function applied

```
SELECT attr1, attr2
FROM table
WHERE function(column) = search_key;
```

  - Add one more column to store the function value? 2NF violated
  - Or, utilize *indexes on expressions* [4]

```
CREATE INDEX idx_name ON table1(function(col1));
```

---

[4] The expression should be deterministic. For detailed usage, please refer to https://www.postgresql.org/docs/11/indexes-expressional.html

# Index it or not: Where indexing may not help

- Low selectivity

```
SELECT
  1.0 * COUNT(DISTINCT country) / COUNT(country)
FROM movies;
```

- Small tables
  - Why?

**Reminder**

- Full scan $\neq$ Bad scheme
- Index retrieval $\neq$ Good scheme

# Contents

# How `JOIN` works

Some widely used `JOIN` algorithms:

- Nested-loop join
- Hash join
- Sort-merge join

# How JOIN works: Nested loop join

```
for each row in t1 match C1(t1)
    for each row in t2 match P(t1, t2)
        if C2(t2)
           add t1|t2 to the result
```

Improvement: Block nested-loop join

# How `JOIN` works: Hash join

1. Create a hash table for the smaller table `t1` in the memory
2. Scan the larger table `t2`. For each record `r`,
   1. compute the hash value of `r.join_attribute`
   2. map to corresponding rows in `t1` using the hash table

# How `JOIN` works: Sort-merge join (a.k.a. merge join)

1. Sort tables `t1` and `t2` respectively according to the join attributes
2. Perform an interleaved scan of `t1` and `t2`. When encountering a matched value, join the related rows together.

**Observation**

When there are indexes on the join attributes, step 1, the most expensive operation, can be skipped because `t1` and `t2` are already sorted in this scenario.

# Query optimizer

- Equivalence rules in Relational Algebra
  Example:

$$\sigma_{\theta_1 \wedge \theta_2}(R_1 \bowtie_\theta R_2) = (\sigma_{\theta_1}(R_1)) \bowtie_\theta (\sigma_{\theta_2}(R_2))$$

- Cost estimation
- Limitation

# EXPLAIN the execution plan

- So, has the DBMS used the index?
- Which algorithm did it use on earth?

```
EXPLAIN SELECT *
FROM movies m INNER JOIN countries c
    ON m.country = c.country_code;
```

```
Hash Join (cost=6.16..201.16 rows=9538 width=49)
  Hash Cond: (m.country = c.country_code)
  ->  Seq Scan on movies m (cost=0.00..169.38 rows=9538 width=31)
  ->  Hash  (cost=3.85..3.85 rows=185 width=18)
        ->  Seq Scan on countries c (cost=0.00..3.85 rows=185 width=18)
```

# EXPLAIN the execution plan

Some tools like *pgAdmin* can visualize the execution plan for you

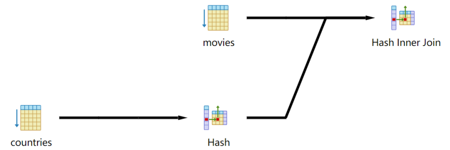



Figure: Execution plan visualized by pgAdmin 4

**Reminder**

- Full scan $\neq$ Bad scheme; Index retrieval $\neq$ Good scheme.
- When data stored are different, which implies different statistics, DBMS may have different execution plan for the same query.

# Contents

# Parameterized SQL

Parsing SQL costs time → DBMS cache parsed SQL in memory

Essentially the same statement, but caching doesn't help :(

```
String sql = "INSERT␣INTO␣students(name)␣VALUES␣("
        + stuName + ")";
```

Solution: variable binding

```
String sql = "INSERT␣INTO␣students(name)␣VALUES␣(?)";
PreparedStatement insert = con.prepareStatement(sql);
// ...
insert.setString(1, student.getName());
insert.executeUpdate();
con.commit();
```

# Parameterized SQL

Why SQL parameterization is so important? Avoid SQL injection!

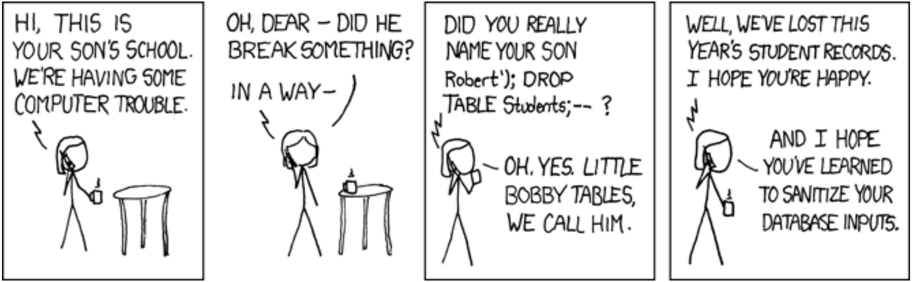



Figure: Exploits of a mom (Retrieved from `https://xkcd.com/327/`)

字符拼接一时爽，删库脱库火葬场!

# Caching fetched data

Some DBMS can even cache query result. (Or you can consider other solutions like Memcached.)

Useful if

1. High-read
2. Low-write

# Contents

# Performance consideration beyond a single query

- Overhead outside the DBMS
  - TCP/IP protocol stack overhead
  - Context switch
- Multiple small operations vs. Batch operation
- Hardware consideration

# Bibliography I


[1] A. Siberschatz, H. F. Korth, and S. Sudarshan, “Indexing and hashing,” in *Database System Concepts*, 6th ed. New York: McGraw-Hill, 2011, ch. 11, pp. 475-536.

[2] D. E. Knuth, “Multiway trees,” in *The Art of Computer Programming*, vol. 3, 2nd ed. Willard, Ohio: Addison-Wesley, 1998, ch. 6, sec. 6.2.4, pp. 481-489.

[3] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein, “B-tree,” in *Introduction to Algorithms*, 3rd ed. Cambridge, MA: MIT Press, 2009, ch. 18, pp. 277-289.

# Bibliography II


[4] D. A. Patterson and J. L. Hennessy, “Memory technologies,” in *Computer Organization and Design: the hardware/software interface*, 5th ed. Waltham, MA: Elsevier Inc., 2011, ch. 5, sec. 5.2, pp. 378-383.

[5] S. Faroult and P. Robson, “Tactical Dispositions: Indexing,” in *The Art of SQL*, Sebastopol, CA: O’Reilly Media, Inc., 2006, ch. 3, pp. 55-74.

[6] 张金鹏, 张成远, and 季锡强, “数据结构和算法,” in *MariaDB 原理与实现*, Beijing, China: Posts & Telecom Press, 2015, ch. 9, pp. 197-218.

[7] “Indexes,” in *PostgreSQL 11 Documentation*. Available at `https://www.postgresql.org/docs/11/indexes.html`.

# Bibliography III


[8] E. Demaine, “Lecture 5: Amortization: Amortized Analysis”, *MIT OpenCourseWare, 6.046 Design and Analysis of Algorithms, Spring 2015*. Available at `https://youtu.be/3MpzavN3Mco`.

[9] A. S. Biswas, “Recitation 2: 2-3 Trees and B-trees”, *MIT OpenCourseWare, 6.046 Design and Analysis of Algorithms, Spring 2015*. Available at `https://youtu.be/TOb1tuEZ2X4`.