# DATABASE PERFORMANCE AND INDEXES

CS121: Introduction to Relational Database Systems

Fall 2014 – Lecture 11

# Database Performance



- Many situations where query performance needs to be improved
  - e.g. as data size grows, query performance degrades and tuning needs to be performed
  - Extreme cases: data warehouses with millions or billions of rows to aggregate and summarize
- To optimize queries effectively, we must understand what the database is doing under the hood
  - e.g. "Why are correlated subqueries slow to evaluate?"
    - Because an inner query must be evaluated *for each row* considered by the outer query. Thus, a good idea to avoid!

# Database Performance (2)



- Next two lectures will explore how most databases evaluate queries
  - Specifically, how are relational algebra operations implemented, and what optimizations do they employ?
  - As usual, there are always exceptions!  (e.g. MySQL)
    - Important to be aware of, so you understand each DBMS' limitations
- Today, will concentrate more on data storage and access methodologies
- Next time, explore relational algebra implementations
  - These are built on top of topics covered today

# Disk Access!



- First rule of database performance:
  **Disk access is <u>the</u> most expensive thing databases do!**
- Accessing data in memory can be 10-100ns
- Accessing data on disk can be up to 10s of ms
  - *That's 5-6 orders of magnitude difference!*
  - Even solid-state drives are 10s-100s of μs (1000x slower)
- Unfortunately, disk IO is usually unavoidable
  - Usually the data simply doesn't fit into memory…
  - Plus, the data needs to be persistent for when the DB is shut down, or when the server crashes, etc.
- DBs work very hard to minimize the amount of disk IO

# Planning and Optimization



- When the query planner/optimizer gets your query:
  - It explores many equivalent plans, estimating their cost (primarily IO cost), and chooses the least expensive one
  - Considers many options in evaluating your query:
    - What access paths does it have to the data you want?
    - What algorithms can it use for selects, joins, sorting, etc?
    - What is the nature of the data itself?
      - i.e. statistics generated by the database, directly from your data
- The planner will do the best it can… ☺
  - Sometimes it can't find a fast way to run your query
  - Also depends on sophistication of the planner itself
    - e.g. if planner doesn't know how to optimize certain queries, or if executor doesn't implement very advanced algorithms

# Table Data Storage



- Databases usually store each table in its own file
- File IO is performed in fixed-size blocks or pages
  - Common page size is 4KB or 8KB; can often tune this value
  - Disks can read/write entire pages faster than small amounts of bytes or individual records
  - Also makes it *much* easier for the database to manage pages of data in memory
    - The buffer manager takes care of this very complicated task
- Each block in the file contains some number of records
- Frequently, individual records can vary in size…
  - (due to variable-size types: **`VARCHAR`**, **`NUMERIC`**, etc.)

# Table Data Storage (2)



- Individual blocks have internal structure, to manage:
  - Records that vary in size
  - Records that are deleted
  - Where and how to add a new record to the block, if there is space for it
- The table file itself also has internal structure:
  - Want to make sure common operations are fast!
    - “I want to insert a new row.  Which block has space for it, or do I have to allocate a new block at the end of the file?”

# Record Organization



- Should table records be organized in a specific way?
- Example: records are kept in sorted order, using a key
  - Called a sequential file organization
  - Would be much faster to find records based on the key
  - Would be much faster to do range queries as well
  - *Definitely* complicates the storage of records!
    - Can't predict order records will be added or deleted
    - Requires periodic reorganization to ensure that records remain physically sorted on the disk
- Could also hash records based on some key
  - Called a hashing file organization
  - Again, speeds up access based on specific values
  - Similar organizational challenges arise over time…

# Record Organization (2)



- More advanced commercial DBs support tables with sequential or hashing file organizations…
  - A few even support very advanced storage layouts, such as <u>multitable clustering file organization</u>
    - If two tables will be joined a lot, interleave their records together in a single file
    - Records that would be equijoined are stored next to each other
- By far, the most common file organization is random! ☺
  - Called a <u>heap file organization</u>
  - Every record can be placed anywhere in the table file, wherever there is space for the record
  - Just about all databases provide heap file organization
  - Usually perfectly sufficient, except for most demanding tasks

# Heap Files and Queries



- Given that DBs normally use heap file organization, how does the DB evaluate a query like:

```
SELECT * FROM account
WHERE account_id = 'A-591';
```

- A simple approach:
  - Search through the entire table file, looking for all rows where value of *account_id* is A-591
  - This is called a <u>file scan</u>, for obvious reasons
- This will be slow, but it's all we can do so far…
- Need a way to optimize accesses like this

# Table Indexes



- Most queries use a small number of rows from a table
  - Need a faster way to look up those values, besides scanning through entire data file
- Approach: build an <u>index</u> on the table
  - Each index is associated with a specific column or set of columns in the table, called the <u>search key</u> for the index
  - Queries involving those columns can often be made *much* faster by using the index on those columns
  - (Queries not using those columns will still use a file scan ☹)
- Index is always structured in some way, for fast lookups
- Index is much smaller than the actual table itself
  - Much faster to search within the index (fewer IO operations)

# Index Characteristics



- Many different varieties of indexes, with different access characteristics
  - What kind of lookup is most efficient for the kind of index?
  - How costly is it to find a particular item, or a set of items?
    - e.g. a query retrieving records with a range of values
- Indexes do impose both a time and space overhead
  - **Indexes must be kept up to date!** Frequently, they *slow down* update operations, while making selects faster.
- Different kinds of indexes impose different overheads:
  - How much time to add a new item to the index?
  - How much time to delete an item from the index?
  - How much additional space does the index take up?

# Index Characteristics (2)



- Two major categories of indexes:
  - Ordered indexes keep values in a sorted order
  - Hash indexes divide values into bins, using a hash function
- Many variations within these two categories!
- Example: dense vs. sparse indexes
  - A dense index includes every single value from the source column(s). Faster lookups, but a larger space overhead.
  - A sparse index only includes some of the values. Lookups require searching more records, but index is smaller.
- The indexes we are covering today are dense indexes
  - Heap files are in random order, so an index won't help us very much unless it includes every value from the table

# Index Implementations



- Indexes are usually stored in files separate from the actual table data
  - Indexes are also read/written as blocks
    - (Same reasons as before…)
- Indexes use <u>record pointers</u> to reference specific records in the table file
  - Simply consists of the block number the record is in, and the offset of the record within that block
- <u>Index records</u> contain values (or hashes), and one or more pointers to table records with those values

# Index Implementations (2)



- Virtually all databases provide ordered indexes, using some kind of balanced tree structure
  - $B^+$-tree and B-tree indexes, typically referred to as "btree" indexes
- Some databases also provide hash indexes
  - More complex to manage than ordered indexes, so not very common in open-source databases
- Several other kinds of indexes as well:
  - Bitmap indexes – to speed up queries on multiple keys
    - Also less common in open-source databases
  - R-tree indexes – to make spatial queries very fast
    - With ubiquity of geospatial data, quite common these days

# $B^+$-Tree Indexes



- A *very* widely used ordered index storage format
- Manages a balanced tree structure
  - Every path from root to leaf is the same length
  - Generally remains efficient for selects, even with inserts and deletes occurring
- Can consume significant space, since individual nodes can be up to half empty!
- Index updates for insert and delete can be slow…
  - Tree structure must be updated properly
- Performance benefits on queries more than outweigh these costs!

# $B^+$-Tree Indexes (2)



- Each tree node has up to *n* children
  - Simplification: *n* is fixed for the entire tree
- Each node stores *n* pointers and *n* – 1 values

| $P_1$ | $K_1$ | $P_2$ | $K_2$ | $P_3$ | … | $P_{n-1}$ | $K_{n-1}$ | $P_n$ |
|---|---|---|---|---|---|---|---|---|

  - $K_i$ are search-key values, $P_i$ are record pointers
  - Values are kept in sorted order: if $i < j$ then $K_i < K_j$
  - All nodes (except root) must be at least half full
- Size of *n* depends on block size, search-key size, and record pointer size, but it is usually large!
  - Example: 4KB blocks, 4B record pointers, 4B integer keys
  - *n* will be >500! $B^+$-tree indexes are shallow, broad trees.

# $B^+$-Tree Leaf Nodes



- For leaf nodes:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $P_1$ | $K_1$ | $P_2$ | $K_2$ | $P_3$ | … | $P_{n-1}$ | $K_{n-1}$ | $P_n$ |

$P_i$ points to record(s) with key value $K_i$

$P_n$ points to next leaf in sequence (i.e. leaf whose first value is $K_n$)

  - Pointer $P_i$ refers to record(s) with search-key value $K_i$
  - If search key is a candidate key, $P_i$ points to the record with key value $K_i$
  - If search key isn't a candidate key, $P_i$ points to a collection of pointers to all records with key value $K_i$
- No two leaves have overlapping ranges
  - Leaves can be arranged in sequential order
  - Pointer $P_n$ points to the next leaf in sequential order

# $B^+$-Tree Non-Leaf Nodes



- For non-leaf nodes:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $P_1$ | $K_1$ | $P_2$ | $K_2$ | $P_3$ | … | $P_{n-1}$ | $K_{n-1}$ | $P_n$ |

$P_1$ is subtree with values $< K_1$

$P_i$ is subtree with key values $K_{i-1} \le K < K_i$

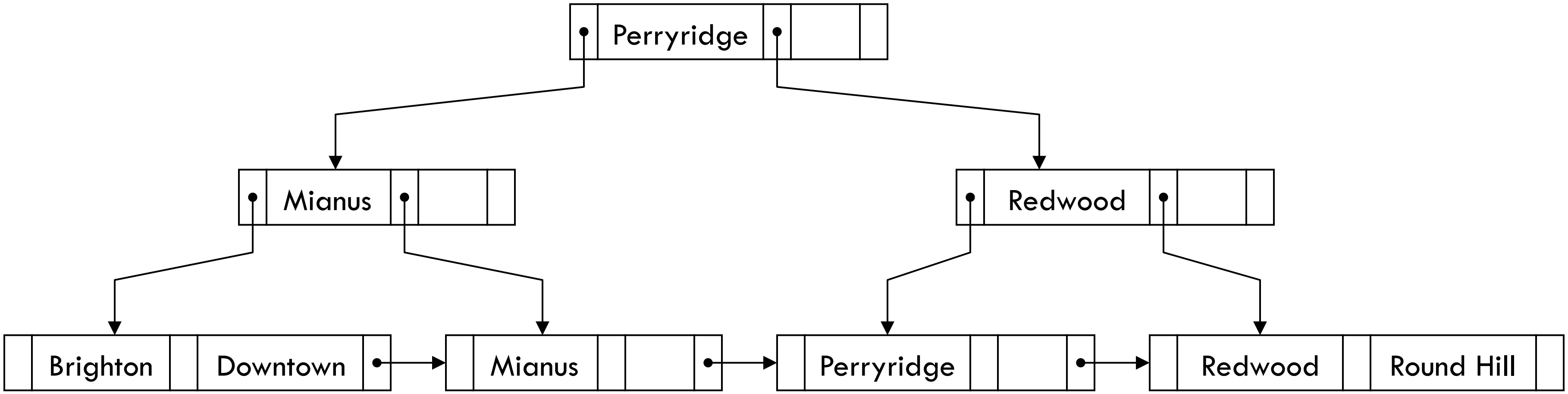
$P_n$ is subtree with values $\ge K_{n-1}$

  - All pointers $P_i$ refer to other $B^+$-tree nodes
- For $1 < i < n$:
  - Pointer $P_i$ points to subtree containing search-key values of at least $K_{i-1}$, but less than $K_i$
- For $i = 1$ or $i = n$:
  - Pointer $P_1$ points to subtree containing search-key values less than $K_1$
  - Pointer $P_n$ points to subtree containing search-key values at least $K_{n-1}$

# Example $B^+$-Tree



- A simple $B^+$-tree, with $n = 3$




- Queries are straightforward
- Inserts may require a node to be split
- Deletes may require nodes to be merged

# B$^+$-Trees and String Keys

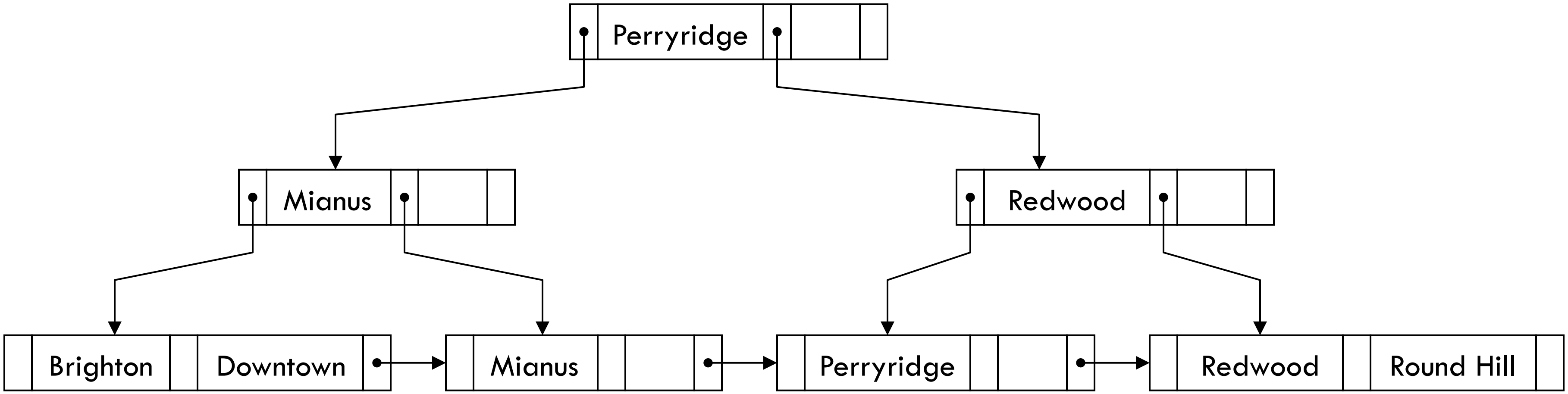


- String columns are problematic for indexing
  - Frequently specified to have large/variable-size values
  - Large keys reduce branching factor of each node, increasing tree depth and access cost
  - Large keys can also interfere with tree restructuring
- Simple solution: don't use the entire string! ☺
  - Can use <u>prefix compression</u> technique
  - Non-leaf nodes only store a prefix of the search string
  - Size of prefix must be large enough to distinguish reasonably well between values in each subtree
    - Otherwise, can't effectively narrow down records to consider

# $B^+$-Trees and B-Trees



- In $B^+$-trees, key values appear in multiple nodes




- B-tree indexes have a slightly different structure
  - Each key value only appears once in the hierarchy
  - Non-leaf nodes must also refer to records with each key value, as well as to subtrees
  - Slightly more complex structure, but saves space

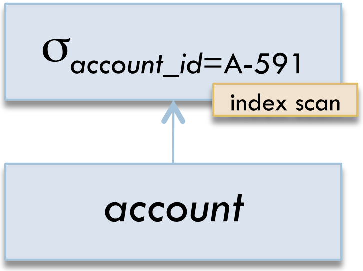
# Indexes and Queries



- Indexes provide an alternate <u>access path</u> to specific records in a table
  - If looking for a specific value or range of values, use the index to find where to start looking in the table file
- Query planner looks for indexes on relevant columns when optimizing your query
- Query from before:

```
SELECT * FROM account
WHERE account_id='A-591';
```

*Execution Plan:*




- If there is an index on *account_id* column, planner can use an index scan instead of a file scan
  - Execution plan is annotated with these kinds of details

# Keys and Indexes



- Databases create many indexes automatically
  - DB will create an index on the primary key columns, and sometimes on foreign key columns too
  - Makes it much faster for DB to enforce key and referential integrity constraints
- Many of your queries already use these indexes!
  - Lookups on primary keys, and joins on primary/foreign key columns
- Sometimes queries use columns that don't have indexes
  - e.g. `SELECT * FROM account WHERE balance >= 3000;`
- How do we tell what indexes the DB uses for a query?
- How do we create additional indexes on our tables?

# **EXPLAIN** Yourself



- Most databases have an **EXPLAIN**-type command
  - Performs query planning and optimization phases, then outputs details about the execution plan
  - Reports, among other things, what indexes are used
- MySQL **EXPLAIN** command:

```
EXPLAIN SELECT * FROM account
WHERE account_id = 'A-591';
```

| id | select_type | table | type | possible_keys | key | key_len | ref | rows | Extra |
|---|---|---|---|---|---|---|---|---|---|
| 1 | SIMPLE | account | const | PRIMARY | PRIMARY | 17 | const | 1 | |

  - This query uses primary key index to look up the record
  - MySQL knows that the result will be one row, or no rows

# MySQL **EXPLAIN** (2)



- More interesting result with a different account ID:

```
EXPLAIN SELECT * FROM account
  WHERE account_id = 'A-000';
```

| id | select_type | table | ... | Extra |
|---|---|---|---|---|
| 1 | SIMPLE | NULL | ... | Impossible WHERE noticed after reading const tables |

  - MySQL planner uses the primary key index to discern that the specified ID doesn't appear in the *account* table!

- Another query against *account*:

```
EXPLAIN SELECT * FROM account
  WHERE balance >= 3000;
```

| id | select_type | table | type | possible_keys | key | key_len | ref | rows | Extra |
|---|---|---|---|---|---|---|---|---|---|
| 1 | SIMPLE | account | ALL | NULL | NULL | NULL | NULL | 60 | Using where |

  - No index available to use for this column ☹

# Adding Indexes to Tables



- If many queries reference columns that don't have indexes, and performance becomes an issue:
  - Create additional indexes on a table to help the DB
- Usually specified with **CREATE INDEX** commands
- To speed up queries on account balances:

```
CREATE INDEX idx_balance ON account (balance);
```

  - Database will create the index file and populate it from the current contents of the *account* relation
    - *(this could take some time for really large tables…)*
- Can also create multi-column indexes
- Can specify many options, such as the index type
  - Virtually all databases create **BTREE** indexes by default

# Adding Indexes to Tables (2)



- MySQL allows you to specify indexes in the **`CREATE TABLE`** command itself…
  - *…not many other DBs support this, so it's not portable.*
- Any drawbacks to putting an index on account balances?
  - It's a bank.  Account balances change all the time.
  - Will definitely incur a performance penalty on updates *(but, it probably won't be terribly substantial…)*

# Verifying Index Usage



- <u>Very important</u> to verify that your new index is actually being used!
  - If your query doesn't use the index, best to get rid of it!

```
EXPLAIN SELECT * FROM account
  WHERE balance >= 3000;
+----+-------------+---------+------+---------------+------+---------+------+------+-------------+
| id | select_type | table   | type | possible_keys | key  | key_len | ref  | rows | Extra       |
+----+-------------+---------+------+---------------+------+---------+------+------+-------------+
|  1 | SIMPLE      | account | ALL  | idx_balance   | NULL | NULL    | NULL |   60 | Using where |
+----+-------------+---------+------+---------------+------+---------+------+------+-------------+
```

- Hmm, MySQL doesn't use the index for this query. ☹
  - If other expensive queries use it, makes sense to keep it (e.g. the rank query would use this index)
  - Otherwise, just get rid of it and keep your updates fast

# Indexes on Large Values



- Large keys seriously degrade index performance
- Example:  B-trees and $B^+$-trees
  - Biggest benefit is very large branching factor of each node
  - Large key-values will dramatically reduce the branching factor, deepening the tree and increasing IO costs
- Can specify indexes on only the first *N* characters/bytes of a string/LOB value

```
CREATE INDEX idx_name ON customer (cust_name(5));
```

  - Only uses first five characters for customer-name index
  - If most values differ in first *N* bytes, index will be much smaller and faster for both updates and queries
  - If values don't differ much, index won't do much good

# Indexes and Performance Tuning



- Adding indexes to a schema is a common task in many database projects
- As a performance-tuning task, usually occurs after DB contains some data, and queries are slow
  - **<u>Always</u> avoid premature optimization!**
  - **<u>Always</u> find out what the DB is doing first!**
- Indexes impose an overhead in both space and time
  - Speeds up selects, but slows down all modifications
- Always need to verify that a new index is actually being used by the database. *If not, get rid of it!*

# Administrivia



- Next time:  SQL Query Evaluation II
  - Overview of how most relational algebra operators are implemented, including common-case optimizations

- Midterm time is a-comin'…
  - Next Monday, October 27, is midterm review
  - Come to class, watch the video, get the slides, whatever.
  - Midterm will be available towards end of next week
  - No assignment due the week of the midterm