# CSCI 403 DATABASE MANAGEMENT

Guest Lecture – Dinesh Mehta
Disks, File Organization, and B-Trees

## This Lecture

- How the database internally optimizes your query
  - *Query trees*
  - *Algebraic manipulations*
  - *Heuristic execution*
- How you can manually "tune" your database queries
  - *The EXPLAIN command*
  - *Indexes*

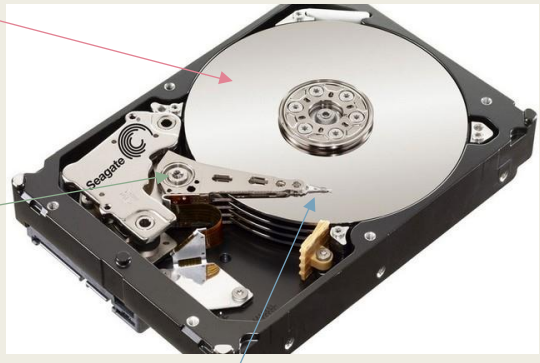

# HARD DISK DRIVES

Rotational Media

## Hard Drive Basics

Thin metal platters coated with a magnetic material, rotating at high speed. Data bits are stored as differently oriented magnetic domains.

Stepper motor assembly. The read/write heads are on the end of an array of arms which can swing to different distances from the disk center, thus accessing different "tracks".




Read/write heads, one per platter side. Float extremely close to the platters and detect or modify magnetic domains as the spinning disk brings them under the heads.

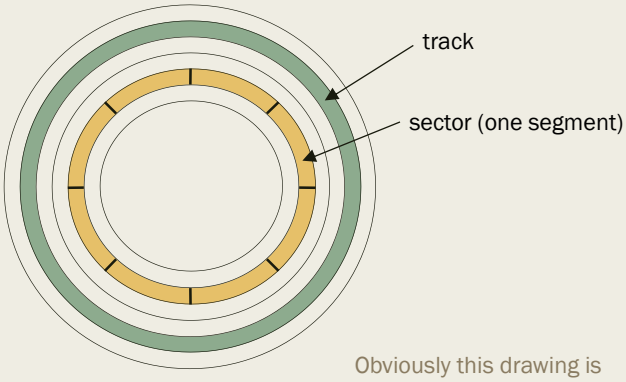
# Data Organization

Data is stored in **tracks**, which are further broken into **sectors**.

Sectors typically hold between 512 – 4096 bytes.

At the hardware level, an entire sector is read or written at one time. However, from the operating system perspective, an entire **block** is read/written. A block is a higher level abstraction which may encompass multiple sectors.

For the rest of this discussion, we'll assume a block == a sector.




Obviously this drawing is highly notional, as HDDs pack many more tracks and sectors onto a platter.

# Access Time

- A block can be read or written extremely fast… once found.
- The cost to read a block is mostly due to the *access time,* the sum of:
  - *Seek time – time to move read/write heads to the right track*
  - *Rotational latency – time to rotate until block is under read/write head*
- Some numbers:
  - *Typical average seek time for a drive: 9ms*
  - *Rotational latency for a high-end server drive (15,000 RPM): 2ms*
- Notes:
  - *Caching, buffering, and other clever optimizations make these numbers hard to measure exactly*
  - *Newer storage technologies (SSD, Optane, etc.) have completely different performance characteristics (for now, HDDs are still dominant in DB storage)*

## Key Insight

- Can do almost anything with a block of data in memory on a modern CPU in much less time than 10 ms
- Disk I/O is thus the primary bottleneck for database query latency

# FILE ORGANIZATION

How is a database table stored on a drive?

# Organizing Records

- While a key facet of the modern database is data abstraction, the data ultimately has to be stored somewhere/somehow
  - *Intersection of hardware, software, and algorithms*
  - *HDD technology has shaped the technology for 40+ years*
- Many approaches to this in various databases
- We'll explore a popular approach organized around primary keys
  - *This scheme will lead us to the idea of a hierarchical index and B-Trees*
  - *Note that PostgreSQL (and probably others) use different schemes*

# Ordered Storage by Primary Key

- Store multiple records in each *block*
  - *Within blocks, order by primary key*
  - *Maintain an list of blocks as well, ordered by primary key of first record in block*
- Note we can now do binary search ($O(\log_2 n)$) lookups:
  - *Find a block holding a particular key*
  - *Find a particular record within a block*
- Issues:
  - *Insertion/deletion – what to do when out of room / how to fill gaps?*
  - *Scaling: is it fast enough?*
  - *What if we want to search by something other than primary key?*

# Issue 1: Insertion/Deletion

- When inserting a record, if no room:
  - *Must move records aside to make room*
  - *This is expensive if we keep everything closed up tight*
  - *Solution: keep some "spare" room around:*
    - If no room, split block into two blocks – now each is half full and insert is cheap
    - Good performance, worst-case 2x storage requirement
- Similarly, when deleting, blocks may become largely empty:
  - *Requires lots of disk access for relatively few records stored*
  - *Solution: merge adjacent blocks when less than half full*

# Issue 2: Scaling/Performance

- Suppose we have a table with:
  - *100M records*
  - *100 records per block (max)*
- Assume a disk with 10ms access time
- What is cost to find a record given a primary key value?
  - *1M ≈ $2^{20}$ blocks, so binary search → must read 20 blocks in worst case*
  - *10ms/block × 20 blocks = 200ms*
- OK, that sounds fast, but consider a modern transaction processing system (e.g., stock trading) handling thousands of queries per second!

# Second Level Index

- Obviously this is not fast enough. What to do?
- Solution: create an index, a kind of table storing primary keys together with pointers to the blocks containing them.
  - *Each record represents the first key in a block*
  - *We can now stuff ~100 or more* index *records into a block*
- How does this help?
  - *Now search 1/100$^{th}$ number of blocks: only search 10,000 ≈ 2$^{14}$ blocks*
  - *Cost is ~140ms to search index + 10ms to lookup referenced block*

# Additional Levels

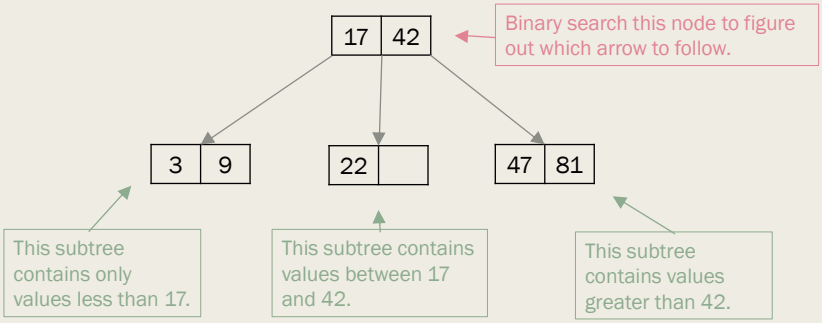
- 150ms still not good enough:
  - *Make another index indexing the second level index*
  - *Another 100x reduction → 70ms + 10ms + 10ms cost*
- Repeat again until all keys (at top level) fit into one block. Cost ~30ms
- Cost of searching with hierarchical index no longer $O(\log_2 n)$, more like $O(\log_{100} n)$

➢ Generalizing this approach leads to the B-Tree data structure
  - *By default, all indices in PostgreSQL use B-Trees*
  - *Not limited to primary keys!*

# B-TREES

## B-Tree Data Structure

- A balanced search tree with a high number of keys in each node
- Basic structure allows efficient searching much like binary search tree:



# B-Tree Rules (Knuth)

- For an order-*m* B-Tree:
  - *Every node has at most* m *children*
  - *Every non-leaf node (except root) has at least* ⌈m/2⌉ *children*
  - *The root has at least 2 children unless it is itself a leaf*
  - *A non-leaf node with* k *children has* k − 1 *keys*
  - *All leaves appear on the same level*
- For *n* keys:

  Best case height is: $\lceil \log_m(n+1) \rceil$  Worst case: $\left\lfloor \log_{m/2}\left(\frac{n+1}{2}\right) \right\rfloor$

# Insertion

- Values are always inserted at a leaf node:
  - *If leaf has no room, split the leaf and promote the median value to the parent node (becomes the separator between the two new children)*
  - *If parent leaf in turn has no room, recursively split/promote*
  - *If splitting/promotion reaches root and root has no room, split root and add a level to the tree*

# Deletion

- If value is in leaf, remove, then rebalance if underflow (too few keys in node)
- If internal node, then find nearest leaf descendant to replace it with – rebalance leaf if this results in underflow
- Rebalancing:
  - *If right sibling exists and has more than minimum # of elements, do a left rotation to borrow one element*
  - *Otherwise, if left sibling, etc.*
  - *Else both the node and its sibling are small enough to merge*
    - Have to pull separating element from parent into merged node
    - This can cause underflow in parent – deal with recursively

# FINAL THOUGHTS

# Kinds of Indexes

- Earlier section described data itself being stored in a sorted order (by primary key)
  - *Some databases (e.g., MS SQL Server) do this ("clustered index")*
  - *Indices other than primary key are called "Secondary indexes"*
    - Tiny extra overhead because secondary index must store some kind of row pointer(s) to correct block on disk
    - Extra lookup of actual data block since not stored in index
  - *PostgreSQL only has secondary indexes*
    - Tradeoff - more flexibility
- Other considerations: indexes on non-unique columns
- We'll talk more about indexing in practice when we talk about query optimization