CSCI 403
Database Management

21 – Disks, File Organization, and B-Trees

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This Lecture

- How the files are stored on rotational media
- Strategies for reading/writing/storing database records
- B-Tree indexes

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Rotational Media

HARD DISK DRIVES

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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. These float extremely close to the platters and detect or modify magnetic domains as the spinning disk brings them under the heads.

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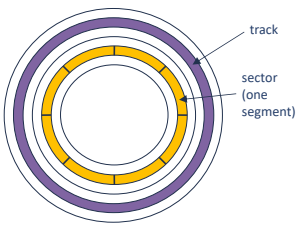
Data Organization

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.

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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)

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Key Insight

- A program can do almost anything with a block of data *in memory* on a modern CPU in much less time than 10 ms
  - That is, compared to a read, time to process the data is negligible
- Disk I/O is thus the primary bottleneck for database query latency

How is a database table stored on a drive?

FILE ORGANIZATION

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 a 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 1/100th number of blocks: only search 10,000 ≈ 2^{14} blocks
  - Cost is ~140ms to search index + 10ms to lookup referenced block

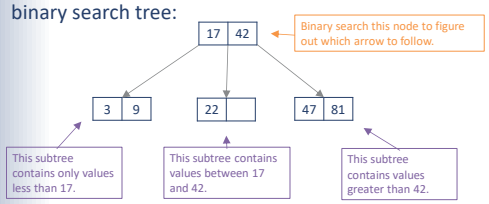
Additional Levels

- 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

Database Access Performance

Actual indexed query performance (e.g., flowers) tends to be better than our 30ms example:

- Indexes tend to be on small keys, blocks have gotten large (4 – 16 Kb) – so can fit way more than 100 keys into an index block (e.g. 4Kb -> 1024 integer keys)
- Caching of important disk blocks in memory speeds up repeated accesses – whole indices or even tables can fit in memory!
  - First read may take 10-20ms
  - Subsequent reads may be sub-millisecond
- Clever disk tricks:
  - Striping
  - Storing indices on different drive than data
  - Sharding