Recap

- Data-savviness is the future!
- Notion of a DBMS
- The relational data model and algebra: bags and sets
- SQL Queries
- SQL Modifications
- SQL DDL
- Database Design
- Views
- Constraints and triggers
- Next: indexes



Index

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Indexes

- Indexes help you look for data matching certain characteristics
 - Much like an index in a book! Or a library!
- An index on an attribute A allows you to find tuples with a specific value for A
 - Think of indexes as data structures or dictionaries storing "index key-value" pairs
 - Index key = values of A
 - Value = locations of tuples
 - Q: what is the correspondence for an index in a book?
 - This may be useful, for example, to find tuples with
 - $\bullet A = a$
 - A <= a
 - $a \le A \le b$



Why Indexes?

- Often your relations are pretty large
 - millions, billions, trillions of tuples
- Scanning through all the tuples to find those that match a certain condition can be time-consuming
 - SELECT * FROM Film WHERE rental_duration = 5 AND rental_rate = 2.99;
 - Naive approach: Go through all 10000 tuples in Film, verify if rental_duration and rental_rate are 5 and 2.99
 - Or: with an index on rental_duration: go through 100 tuples with rental_duration 5
 - Or: with a multi-dimensional index on rental_duration and rental_rate, go through 10 tuples with values 5 and 2.99 respectively



Also Useful for Joins!

```
SELECT * FROM Film, FilmActor
WHERE Film.film_id = FilmActor.film_id;
```

- Say Film has 10,000 tuples and FilmActor has 50,000 tuples
 - Roughly 5 actors per film (say)
- Q: If you have no indexes, need to consider how many pairs of tuples?
 - $10,000 * 50,000 = 5 * 10^8$
- Q: How would you use indexes here?
 - For each film in Film, look up tuples in FilmActor, or vice versa
 - Goes from 5 * 10^8 to 5 * 10^4 tuples considered



Also Useful for Joins!

```
SELECT * FROM Film, FilmActor

WHERE Film.film_id = FilmActor.film_id

AND rental_duration = 5 AND rental_rate = 2.99
```

- Say we had indexes for FilmActor.film_id, Film.film_id, and Film.rental_duration. Q: How would you use indexes here?
 - Lookup films with rental_duration 5 = 100 tuples
 - For each one, look up FilmActor = 100 * 5 tuples matched
 - Verify if rental_rate = 2.99



Declaring Indexes

CREATE INDEX rentIndex ON Film (rental_duration)

Allow for lookups based on rental_duration

CREATE INDEX rentReleaseIndex ON Film (rental_duration, release_year)

- Imagine this to be a "index key-value" pair dictionary based on concatenating attribute values
- Allow for lookups based on pairs of rental_duration and release_year
- Or just for rental_duration
- Q:Why not release_year only?

DROP INDEX rentReleaseIndex

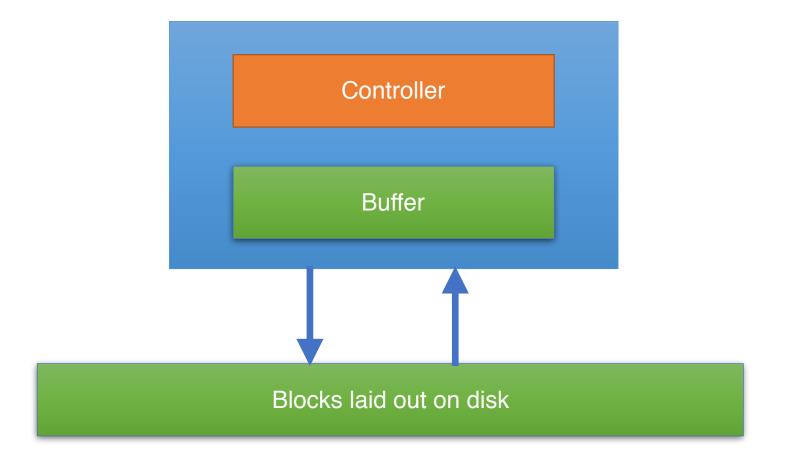


Indexes Seem Magical...

- Q: what are downsides of indexes?
- A: the maintenance costs during updates, deletes, inserts
- If an index is not maintained, it may lead to inaccurate query results
- e.g., if a new tuple is inserted but it is not reflected in the index, it won't be returned as part of queries



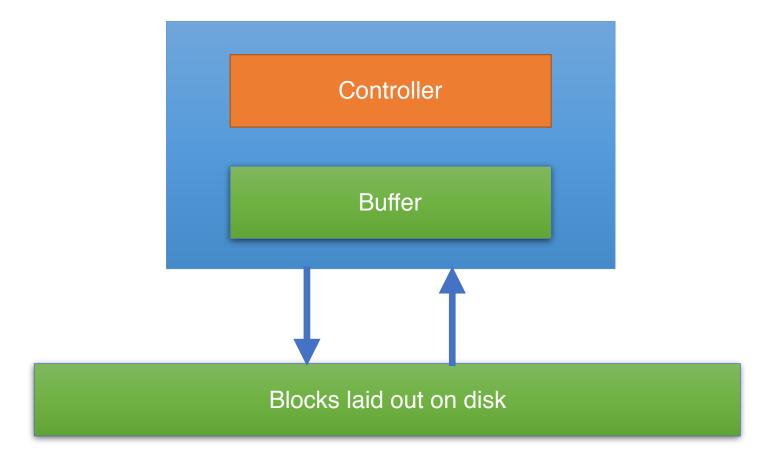
Aside: A Mental Model for a Database



- Data is laid out on blocks/ pages on stable storage (e.g., disk)
- Each block may have many 100s-1000s of tuples
- Data is retrieved a block at a time
- Stored in main-memory buffers
- Written back to stable storage



Aside: A Mental Model for a Database



- Usually, computation is cheap relative to I/O
- So main cost in SQL queries is the cost of fetching the blocks and writing them out



OK, Going Back to Indexes...

- Which indexes should we create?
- Answer: it depends!
- Many databases automatically create indexes for PRIMARY KEY or UNIQUE attributes. Several reasons:
 - It also helps enforcing the constraints! Updating the index can serve as a check for the constraint
 - Many queries lookup based on these attributes
 - SELECT * FROM Film, FilmActor WHERE Film.film_id = FilmActor.film_id
 - It is a high-cardinality attribute (as many values as number of tuples!)



Why does cardinality matter?

- Databases retrieve data as "blocks"
- Say you are indexing based on attribute A, with 100 distinct values. You have 10,000 tuples. Each block contains 100 tuples.
- Q: How many blocks do we have?
- A: 100 blocks
- Assuming that the tuples with a given value of A (A = a) are randomly distributed, every block, on average, every block has one tuple with A=a.
- Thus, we can't avoid looking at all blocks => the index doesn't help.
- Q:What if we had a 1000 distinct values instead of 100? How many blocks would we have to look at then?
- A: 10 blocks, so there may be some savings.



Why does cardinality matter?

- Databases retrieve data as "blocks"
- Say you are indexing based on attribute A, with 100 distinct values. You have 10,000 tuples. Each block contains 100 tuples.
- However, if you know anything about disks, you will know that reading sequentially is much much faster than jumping across the disk
 - Even reading I in 10 blocks may not be enough to justify gains
 - Usually, I in 100 is enough to justify gains
- So, indexes on low cardinality attributes are not a great idea
- Exception: if data is "clustered" on that attribute
 - If we knew that all values of A = a are together (as opposed to randomly shuffled),
 we can simply read one block



How Do We Decide?

- Good to create attributes used often in WHERE clauses
- Good to create on key attributes (but usually done by default)
- Good on attributes that are "clustered"
- Not very good on attributes where there are many tuples per value of attribute
- Not very good on tables that are modified more often than queried

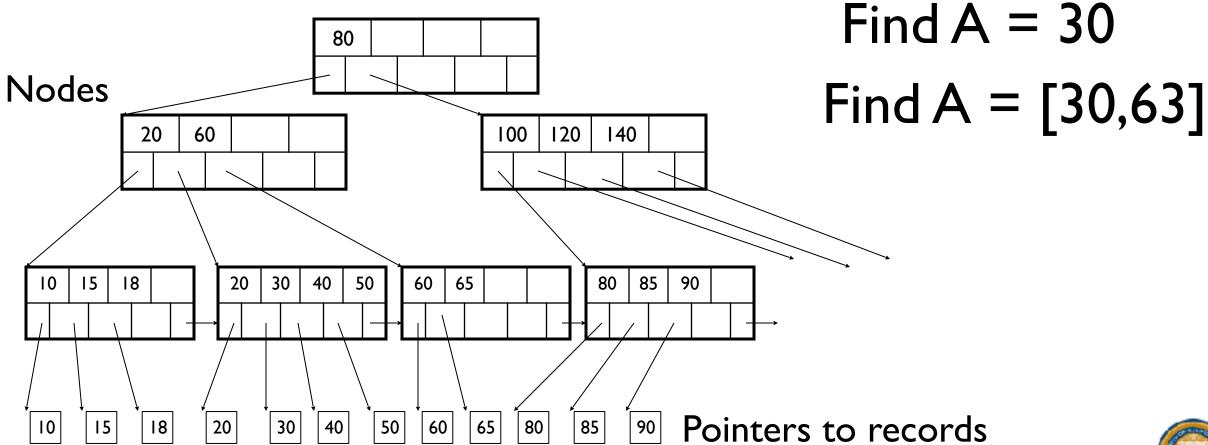


Types of Indexes: B+ Tree

- The most popular type of index in databases are B+Trees
- A generalization of binary trees
- Properties:
 - High fanout
 - Each "node" is a block
 - If "b" is fanout is ~ 1000 , $b^4 = 10^12$
 - Self-balancing
 - Maintains a certain fill-factor (usually half) by splitting nodes and percolating changes to maintain balance
 - We won't worry about those algorithms in this class



At least halfway filled, except root



Types of Indexes: B+ Tree

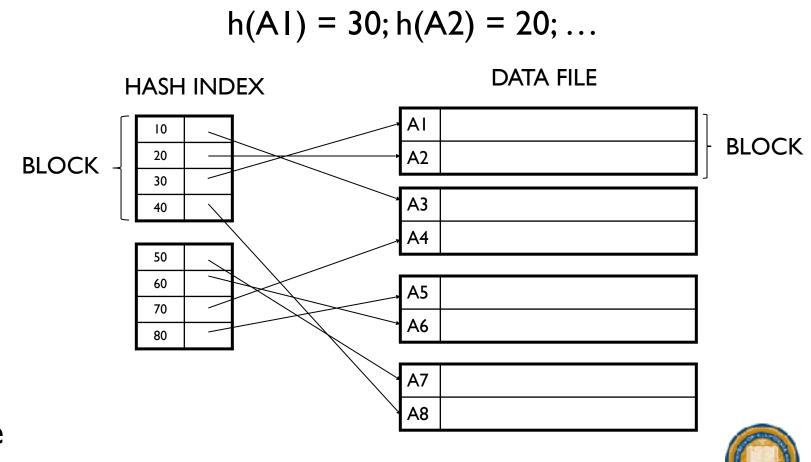
- Logarithmic complexity
 - For searching (as we saw)
 - For insert, delete, update (not covered)
- In practice, depth of tree = number of nodes (blocks) retrieved is small

- Can handle both value lookups as well as range lookups
- In PostgreSQL this is the default index type



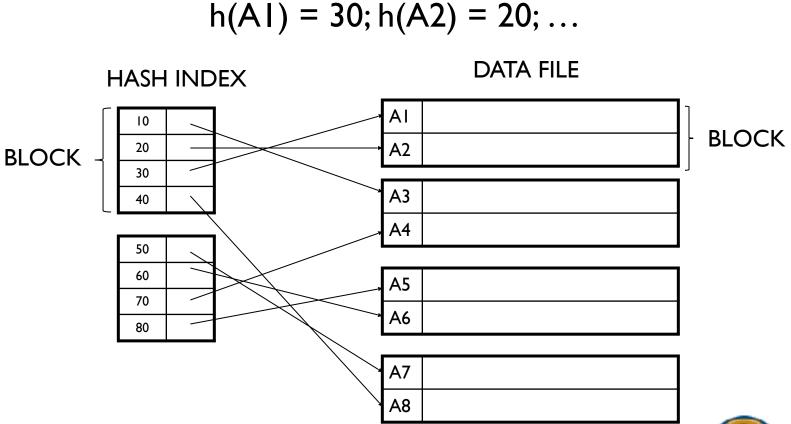
Types of Indexes: Hash Indexes

- Like hash-based dictionaries or maps in programming languages
 - A hash function applied to value a, i.e., h(a) yields location where pointers for tuples with A = a are found
- Main challenge: how to "extend" the hash table as values of A grow
 - See linear or extendible hashing



Types of Indexes: Hash Indexes

- Constant complexity O(I)
- Can only handle value lookups, not range lookups
 - Why?
- In PostgreSQL done as follows:
 - CREATE INDEX
 <name> ON
 USING hash (column);





Other Types of Indexes

- Inverted Indexes: valuable for keyword search (more later, hopefully!)
 - In PostgreSQL, known as GIN indexes
- R-Tree: valuable for range-based lookups in k-dimensions
 - e.g., searching for things in rectangular range in a map
 - In PostgreSQL, a special case of a GIST index
- Lots of other types of indexes!
 - Partial indexes
 - Indexes on expressions
 - . . .



Indexes Summary

- Indexes are great!
- They speed up certain types of queries
- But we should use them carefully
 - Only on high cardinality = "selective" attributes like keys
 - Or on frequently queried but rarely updated attributes
- Lots of different types of indexes: but B+trees are most popular; hash indexes are a close second

