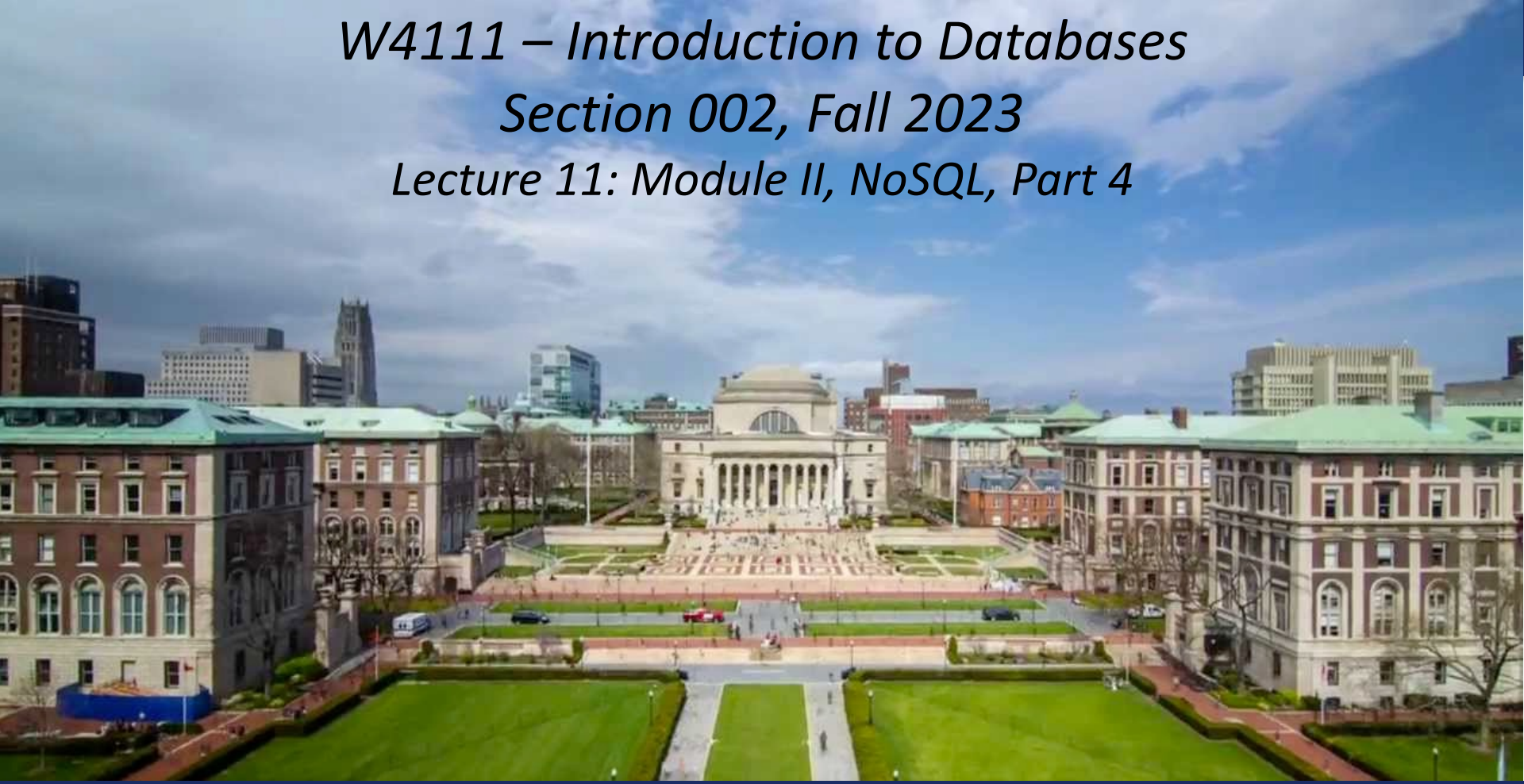
W4111 – Introduction to Databases
Section 002, Fall 2023
Lecture 11: Module II, NoSQL, Part 4



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Contents

Contents

- Module II (DBMS Implementation) Final Topics
  - Query Processing (chapter 15)
  - Query Optimization (chapter 16)
  - Transactions
    - Transactions (chapter 17)
    - Concurrency Control (chapter 18)
    - Recovery (chapter 19)
- Relational Database Design Theory, aka Normalization
- ~~Begin Module IV – Data Analysis~~
  - ~~Concepts~~
  - ~~CQRS example~~
  - ~~GoT Applications~~

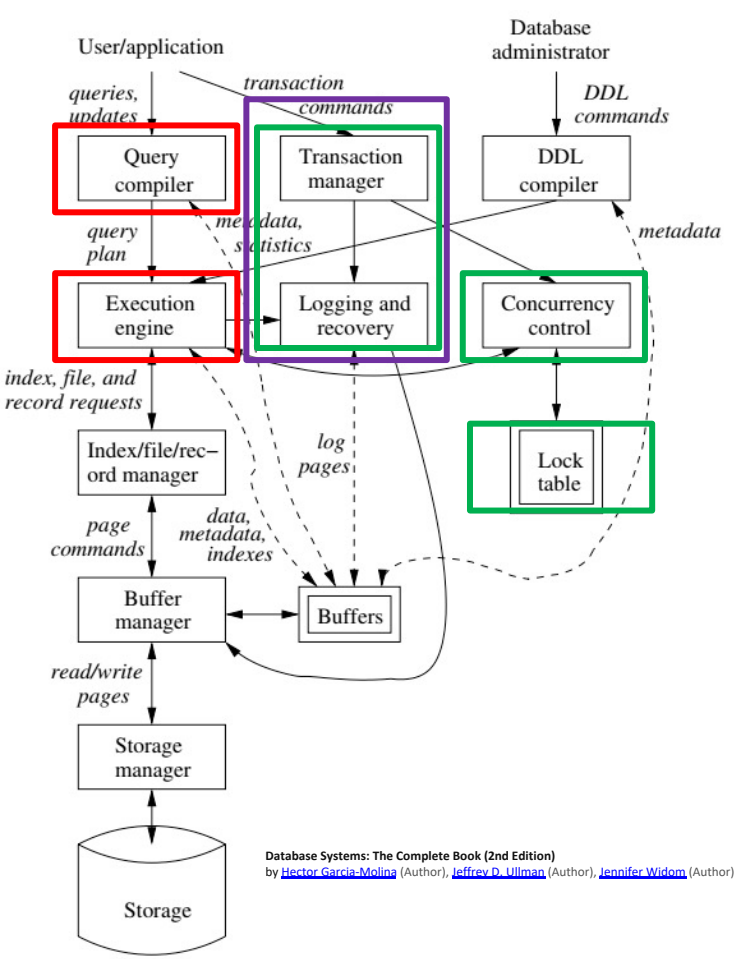
- Each of these chapters is an entire semesters (or more) topic.
- We will cover core concepts in class.
- HW/Final will ask questions that require some independent reading of book slides or material.
- Lecture will rely mostly on slides.

Query Processing

Query Processing

Transactions

- Find things quickly.
- Load/Save quickly.
- Transactions
- Durability



Database Systems: The Complete Book (2nd Edition)
by Hector Garcia-Molina (Author), Jeffrey D. Ullman (Author), Jennifer Widom (Author)

Query Compilation

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Preview of Query Compilation

To set the context for query execution, we offer a very brief outline of the content of the next chapter. Query compilation is divided into the three major steps shown in Fig. 15.2.

a) *Parsing*. A *parse tree* for the query is constructed.

b) *Query Rewrite*. The parse tree is converted to an initial query plan, which is usually an algebraic representation of the query. This initial plan is then transformed into an equivalent plan that is expected to require less time to execute.

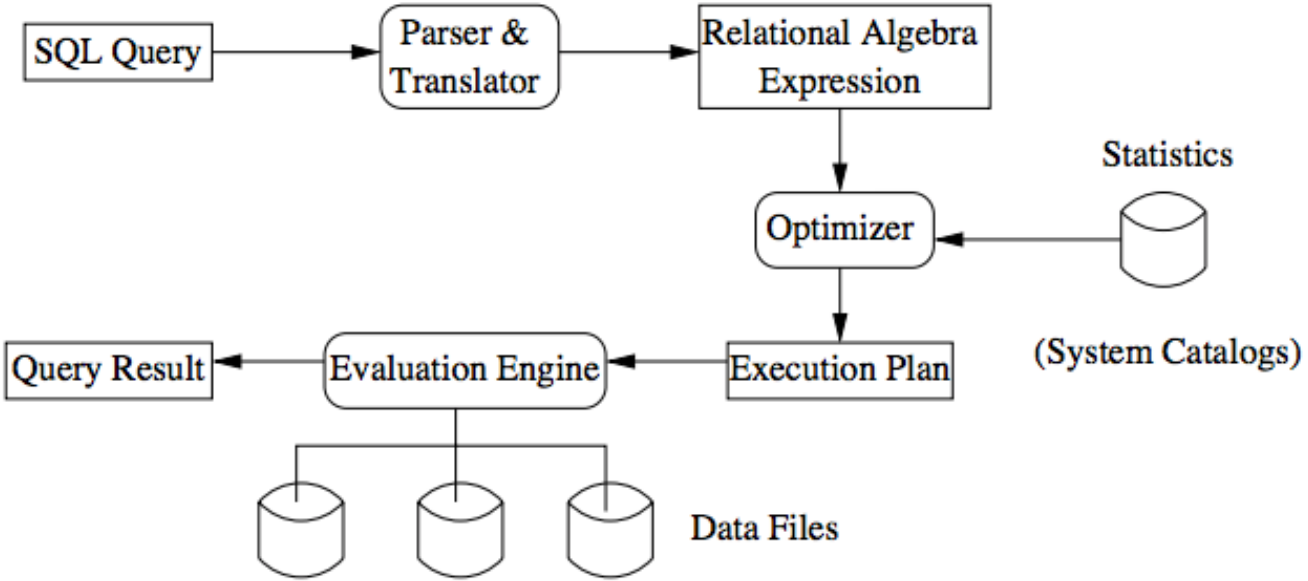
c) *Physical Plan Generation*. The abstract query plan from (b), often called a *logical query plan*, is turned into a *physical query plan* by selecting algorithms to implement each of the operators of the logical plan, and by selecting an order of execution for these operators. The physical plan, like the result of parsing and the logical plan, is represented by an expression tree. The physical plan also includes details such as how the queried relations are accessed, and when and if a relation should be sorted.

Parsing and Execution

- Parser/Translator
  - Verifies syntax correctness and generates a *parse tree.*
  - Converts to *logical plan tree* that defines how to execute the query.
    - Tree nodes are *operator(tables, parameters)*
    - Edges are the flow of data “up the tree” from node to node.
- Optimizer
  - Modifies the logical plan to define an improved execution.
  - Query rewrite/transformation.
  - Determines *how* to choose among multiple implementations of operators.
- Engine
  - Executes the plan
  - May modify the plan to *optimize* execution, e.g. using indexes.

Query Processing Overview

Basic Steps in Processing an SQL Query



Chapter 15: Query Processing

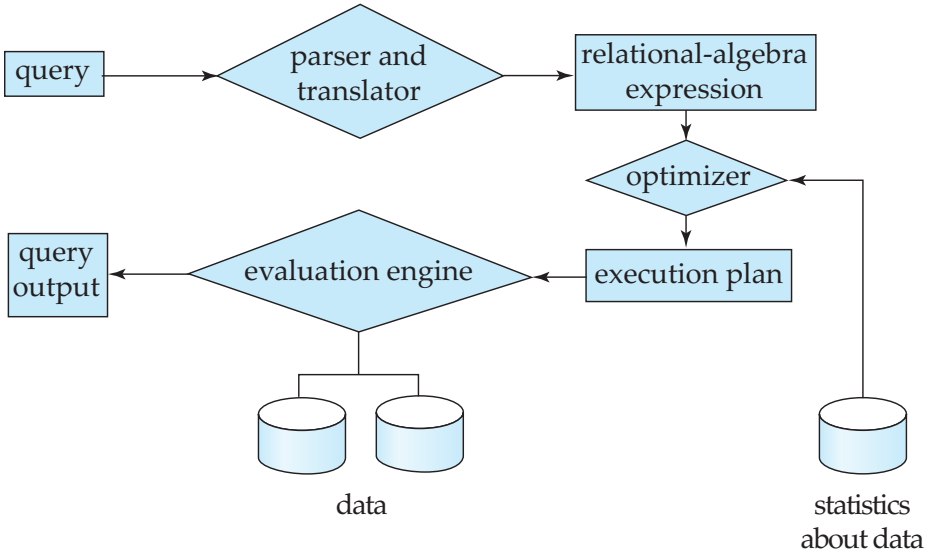
Database System Concepts, 7th Ed.

Chapter 15: Query Processing

- Overview
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations
- Evaluation of Expressions

Basic Steps in Query Processing

1. Parsing and translation
2. Optimization
3. Evaluation



Basic Steps in Query Processing (Cont.)

- Parsing and translation
  - translate the query into its internal form. This is then translated into relational algebra.
  - Parser checks syntax, verifies relations
- Evaluation
  - The query-execution engine takes a query-evaluation plan, executes that plan, and returns the answers to the query.

Basic Steps in Query Processing: Optimization

- A relational algebra expression may have many equivalent expressions
  - E.g., $\sigma_{salary<75000}(\Pi_{salary}(instructor))$ is equivalent to $\Pi_{salary}(\sigma_{salary<75000}(instructor))$
- Each relational algebra operation can be evaluated using one of several different algorithms
  - Correspondingly, a relational-algebra expression can be evaluated in many ways.
- Annotated expression specifying detailed evaluation strategy is called an **evaluation-plan**. E.g.,:
  - Use an index on *salary* to find instructors with salary < 75000,
  - Or perform complete relation scan and discard instructors with salary ≥ 75000

Basic Steps: Optimization (Cont.)

- **Query Optimization**: Amongst all equivalent evaluation plans choose the one with lowest cost.
  - Cost is estimated using statistical information from the database catalog
    - e.g.. number of tuples in each relation, size of tuples, etc.
- In this chapter we study
  - How to measure query costs
  - Algorithms for evaluating relational algebra operations
  - How to combine algorithms for individual operations in order to evaluate a complete expression
- In Chapter 16
  - We study how to optimize queries, that is, how to find an evaluation plan with lowest estimated cost

Measures of Query Cost

- Many factors contribute to time cost
  - *disk access, CPU*, and network *communication*
- Cost can be measured based on
  - **response time**, i.e. total elapsed time for answering query, or
  - total **resource consumption**
- We use total resource consumption as cost metric
  - Response time harder to estimate, and minimizing resource consumption is a good idea in a shared database
- We ignore CPU costs for simplicity
  - Real systems do take CPU cost into account
  - Network costs must be considered for parallel systems
- We describe how estimate the cost of each operation
  - We do not include cost to writing output to disk

Measures of Query Cost

- Disk cost can be estimated as:
  - Number of seeks * average-seek-cost
  - Number of blocks read * average-block-read-cost
  - Number of blocks written * average-block-write-cost
- For simplicity we just use the **number of block transfers** *from disk and the* **number of seeks** as the cost measures
  - t_T – time to transfer one block
    - Assuming for simplicity that write cost is same as read cost
  - t_S – time for one seek
  - Cost for b block transfers plus S seeks
    $b * t_T + S * t_S$
- t_S and t_T depend on where data is stored; with 4 KB blocks:
  - High end magnetic disk: t_S = 4 msec and t_T =0.1 msec
  - SSD: t_S = 20-90 microsec and t_T = 2-10 microsec for 4KB

Measures of Query Cost (Cont.)

- Required data may be buffer resident already, avoiding disk I/O
  - But hard to take into account for cost estimation
- Several algorithms can reduce disk IO by using extra buffer space
  - Amount of real memory available to buffer depends on other concurrent queries and OS processes, known only during execution
- Worst case estimates assume that no data is initially in buffer and only the minimum amount of memory needed for the operation is available
  - But more optimistic estimates are used in practice

Selection Operation

- **File scan**
- Algorithm **A1** (**linear search**). Scan each file block and test all records to see whether they satisfy the selection condition.
  - Cost estimate = b_r block transfers + 1 seek
    - b_r denotes number of blocks containing records from relation r
  - If selection is on a key attribute, can stop on finding record
    - cost = (b_r/2) block transfers + 1 seek
  - Linear search can be applied regardless of
    - selection condition or
    - ordering of records in the file, or
    - availability of indices
- Note: binary search generally does not make sense since data is not stored consecutively
  - except when there is an index available,
  - and binary search requires more seeks than index search

Selections Using Indices

- **Index scan** – search algorithms that use an index
  - selection condition must be on search-key of index.
- **A2** (**clustering index, equality on key**). Retrieve a single record that satisfies the corresponding equality condition
  - $Cost = (h_i + 1) * (t_T + t_S)$
- **A3** (**clustering index, equality on nonkey**) Retrieve multiple records.
  - Records will be on consecutive blocks
    - Let b = number of blocks containing matching records
  - $Cost = h_i * (t_T + t_S) + t_S + t_T * b$

Selections Using Indices

- **A4** (**secondary index, equality on key/non-key**).
  - Retrieve a single record if the search-key is a candidate key
    - $Cost = (h_i + 1) * (t_T + t_S)$
  - Retrieve multiple records if search-key is not a candidate key
    - each of n matching records may be on a different block
    - Cost = $(h_i + n) * (t_T + t_S)$
      - Can be very expensive!

Selections Involving Comparisons

- Can implement selections of the form $\sigma_{A \leq V}(r)$ or $\sigma_{A \geq V}(r)$ by using
  - a linear file scan,
  - or by using indices in the following ways:
- **A5** (**clustering index, comparison**). (Relation is sorted on A)
  - For $\sigma_{A \geq V}(r)$ use index to find first tuple $\geq v$ and scan relation sequentially from there
  - For $\sigma_{A \leq V}(r)$ just scan relation sequentially till first tuple $> v$; do not use index
- **A6** (**clustering index, comparison**).
  - For $\sigma_{A \geq V}(r)$ use index to find first index entry $\geq v$ and scan index sequentially from there, to find pointers to records.
  - For $\sigma_{A \leq V}(r)$ just scan leaf pages of index finding pointers to records, till first entry $> v$
  - In either case, retrieve records that are pointed to
  - requires an I/O per record; Linear file scan may be cheaper!

Implementation of Complex Selections

- **Conjunction:** $\sigma_{\theta 1 \wedge \theta 2 \wedge \ldots \theta n}(r)$
- **A7** (**conjunctive selection using one index**).
  - Select a combination of θ_i and algorithms A1 through A7 that results in the least cost for $\sigma_{\theta i}(r)$.
  - Test other conditions on tuple after fetching it into memory buffer.
- **A8** (**conjunctive selection using composite index**).
  - Use appropriate composite (multiple-key) index if available.
- **A9** (**conjunctive selection by intersection of identifiers**).
  - Requires indices with record pointers.
  - Use corresponding index for each condition, and take intersection of all the obtained sets of record pointers.
  - Then fetch records from file
  - If some conditions do not have appropriate indices, apply test in memory.

Algorithms for Complex Selections

- **Disjunction:** $\sigma_{\theta 1 \vee \theta 2 \vee \ldots \theta n}(r)$.
- **A10** (**disjunctive selection by union of identifiers**).
  - Applicable if *all* conditions have available indices.
    - Otherwise use linear scan.
  - Use corresponding index for each condition, and take union of all the obtained sets of record pointers.
  - Then fetch records from file
- **Negation:** $\sigma_{\neg\theta}(r)$
  - Use linear scan on file
  - If very few records satisfy $\neg\theta$, and an index is applicable to θ
    - Find satisfying records using index and fetch from file

Sorting

- We may build an index on the relation, and then use the index to read the relation in sorted order. May lead to one disk block access for each tuple.
- For relations that fit in memory, techniques like quicksort can be used.
  - For relations that don't fit in memory, **external sort-merge** is a good choice.

Join Operation

- Several different algorithms to implement joins
  - Nested-loop join
  - Block nested-loop join
  - Indexed nested-loop join
  - Merge-join
  - Hash-join
- Choice based on cost estimate
- Examples use the following information
  - Number of records of *student*: 5,000 *takes*: 10,000
  - Number of blocks of *student*: 100 *takes*: 400

Nested-Loop Join

- To compute the theta join $r \bowtie_\theta s$

  for each tuple t_r **in** r **do begin**
    for each tuple t_s **in** s **do begin**
      test pair (t_r, t_s) to see if they satisfy the join condition θ
      if they do, add $t_r \cdot t_s$ to the result.
    end
  end

- r is called the **outer relation** and s the **inner relation** of the join.
- Requires no indices and can be used with any kind of join condition.
- Expensive since it examines every pair of tuples in the two relations.

Nested-Loop Join (Cont.)

- In the worst case, if there is enough memory only to hold one block of each relation, the estimated cost is

  $n_r * b_s + b_r$ block transfers, plus $n_r + b_r$ seeks

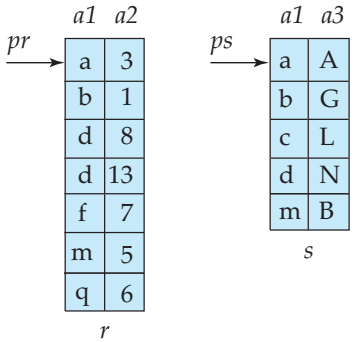
- If the smaller relation fits entirely in memory, use that as the inner relation.
  - Reduces cost to $b_r + b_s$ block transfers and 2 seeks
- Assuming worst case memory availability cost estimate is
  - with *student* as outer relation:
    - 5000 * 400 + 100 = 2,000,100 block transfers,
    - 5000 + 100 = 5100 seeks
  - with *takes* as the outer relation
    - 10000 * 100 + 400 = 1,000,400 block transfers and 10,400 seeks
- If smaller relation (*student*) fits entirely in memory, the cost estimate will be 500 block transfers.
- Block nested-loops algorithm (next slide) is preferable.

Indexed Nested-Loop Join

- Index lookups can replace file scans if
  - join is an equi-join or natural join and
  - an index is available on the inner relation's join attribute
    - Can construct an index just to compute a join.
- For each tuple t_r in the outer relation *r,* use the index to look up tuples in *s* that satisfy the join condition with tuple t_r.
- Worst case: buffer has space for only one page of *r*, and, for each tuple in *r*, we perform an index lookup on *s.*
- Cost of the join: $b_r (t_T + t_S) + n_r * c$
  - Where *c* is the cost of traversing index and fetching all matching *s* tuples for one tuple or *r*
  - *c* can be estimated as cost of a single selection on *s* using the join condition.
- If indices are available on join attributes of both *r* and *s,* use the relation with fewer tuples as the outer relation.

Merge-Join

1. Sort both relations on their join attribute (if not already sorted on the join attributes).
2. Merge the sorted relations to join them
    1. Join step is similar to the merge stage of the sort-merge algorithm.
    2. Main difference is handling of duplicate values in join attribute — every pair with same value on join attribute must be matched
    3. Detailed algorithm in book



Merge-Join (Cont.)

- Can be used only for equi-joins and natural joins
- Each block needs to be read only once (assuming all tuples for any given value of the join attributes fit in memory
- Thus the cost of merge join is:

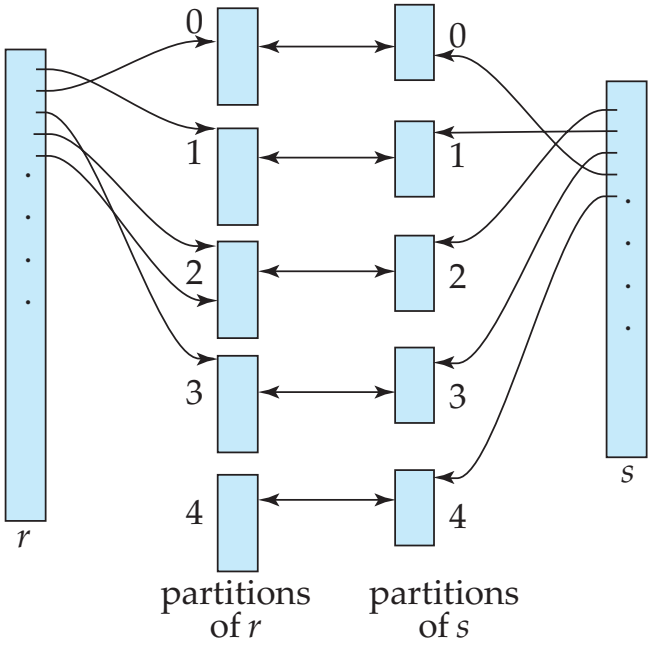
  $b_r + b_s$ block transfers $+ \lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil$ seeks

  + the cost of sorting if relations are unsorted.
- **hybrid merge-join:** If one relation is sorted, and the other has a secondary B^+-tree index on the join attribute
  - Merge the sorted relation with the leaf entries of the B^+-tree .
  - Sort the result on the addresses of the unsorted relation's tuples
  - Scan the unsorted relation in physical address order and merge with previous result, to replace addresses by the actual tuples
    - Sequential scan more efficient than random lookup

Hash-Join

- Applicable for equi-joins and natural joins.
- A hash function h is used to partition tuples of both relations
- h maps *JoinAttrs* values to {0, 1, ..., n}, where *JoinAttrs* denotes the common attributes of r and s used in the natural join.
  - $r_0, r_1, \ldots, r_n$ denote partitions of r tuples
    - Each tuple $t_r \in r$ is put in partition r_i where $i = h(t_r[JoinAttrs])$.
  - $r_0, r_1, \ldots, r_n$ denotes partitions of s tuples
    - Each tuple $t_s \in s$ is put in partition s_i, where $i = h(t_s[JoinAttrs])$.
- *Note:* In book, Figure 12.10 r_i is denoted as H_{ri}, s_i is denoted as H_{si} and n is denoted as n_h.

Hash-Join (Cont.)



Hash-Join Algorithm

The hash-join of r and s is computed as follows.

1. Partition the relation s using hashing function h. When partitioning a relation, one block of memory is reserved as the output buffer for each partition.
2. Partition r similarly.
3. For each i:
   (a) Load s_i into memory and build an in-memory hash index on it using the join attribute. This hash index uses a different hash function than the earlier one h.
   (b) Read the tuples in r_i from the disk one by one. For each tuple t_r locate each matching tuple t_s in s_i using the in-memory hash index. Output the concatenation of their attributes.

Relation s is called the **build input** and r is called the **probe input**.

Hash-Join algorithm (Cont.)

- The value n and the hash function h is chosen such that each s_i should fit in memory.
  - Typically n is chosen as $\lceil b_s/M \rceil * f$ where f is a "**fudge factor**", typically around 1.2
  - The probe relation partitions s_i need not fit in memory
- **Recursive partitioning** required if number of partitions n is greater than number of pages M of memory.
  - instead of partitioning n ways, use $M - 1$ partitions for s
  - Further partition the $M - 1$ partitions using a different hash function
  - Use same partitioning method on r
  - Rarely required: e.g., with block size of 4 KB, recursive partitioning not needed for relations of < 1GB with memory size of 2MB, or relations of < 36 GB with memory of 12 MB

Other Operations

- **Duplicate elimination** can be implemented via hashing or sorting.
  - On sorting duplicates will come adjacent to each other, and all but one set of duplicates can be deleted.
  - *Optimization:* duplicates can be deleted during run generation as well as at intermediate merge steps in external sort-merge.
  - Hashing is similar – duplicates will come into the same bucket.
- **Projection**:
  - perform projection on each tuple
  - followed by duplicate elimination.

Other Operations : Aggregation

- **Aggregation** can be implemented in a manner similar to duplicate elimination.
  - **Sorting** or **hashing** can be used to bring tuples in the same group together, and then the aggregate functions can be applied on each group.
  - Optimization: **partial aggregation**
    - combine tuples in the same group during run generation and intermediate merges, by computing partial aggregate values
    - For count, min, max, sum: keep aggregate values on tuples found so far in the group.
      - When combining partial aggregate for count, add up the partial aggregates
    - For avg, keep sum and count, and divide sum by count at the end

Evaluation of Expressions

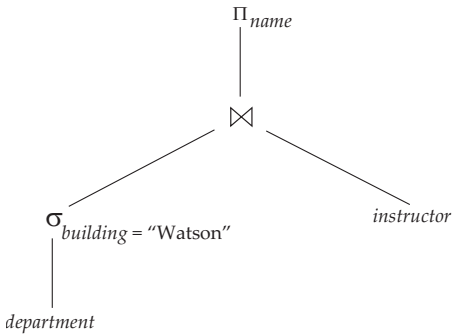
- So far: we have seen algorithms for individual operations
- Alternatives for evaluating an entire expression tree
  - **Materialization**: generate results of an expression whose inputs are relations or are already computed, **materialize** (store) it on disk. Repeat.
  - **Pipelining**: pass on tuples to parent operations even as an operation is being executed
- We study above alternatives in more detail

Materialization

- **Materialized evaluation**: evaluate one operation at a time, starting at the lowest-level. Use intermediate results materialized into temporary relations to evaluate next-level operations.
- E.g., in figure below, compute and store

$$\sigma_{building=\text{"Watson"}}(department)$$

then compute the store its join with *instructor,* and finally compute the projection on *name.*



Materialization (Cont.)

- Materialized evaluation is always applicable
- Cost of writing results to disk and reading them back can be quite high
  - Our cost formulas for operations ignore cost of writing results to disk, so
    - Overall cost = Sum of costs of individual operations + cost of writing intermediate results to disk
- **Double buffering**: use two output buffers for each operation, when one is full write it to disk while the other is getting filled
  - Allows overlap of disk writes with computation and reduces execution time

Pipelining

- **Pipelined evaluation**: evaluate several operations simultaneously, passing the results of one operation on to the next.
- E.g., in previous expression tree, don't store result of

$$\sigma_{building = \text{"Watson"}}(department)$$

  - instead, pass tuples directly to the join.. Similarly, don't store result of join, pass tuples directly to projection.
- Much cheaper than materialization: no need to store a temporary relation to disk.
- Pipelining may not always be possible – e.g., sort, hash-join.
- For pipelining to be effective, use evaluation algorithms that generate output tuples even as tuples are received for inputs to the operation.
- Pipelines can be executed in two ways: **demand driven** and **producer driven**

Pipelining (Cont.)

- In **demand driven** or **lazy** evaluation
  - system repeatedly requests next tuple from top level operation
  - Each operation requests next tuple from children operations as required, in order to output its next tuple
  - In between calls, operation has to maintain "**state**" so it knows what to return next
- In **producer-driven** or **eager** pipelining
  - Operators produce tuples eagerly and pass them up to their parents
    - Buffer maintained between operators, child puts tuples in buffer, parent removes tuples from buffer
    - if buffer is full, child waits till there is space in the buffer, and then generates more tuples
  - System schedules operations that have space in output buffer and can process more input tuples
- Alternative name: **pull** and **push** models of pipelining

Pipelining (Cont.)

- Implementation of demand-driven pipelining
  - Each operation is implemented as an **iterator** implementing the following operations
    - **open()**
      - E.g., file scan: initialize file scan
        - state: pointer to beginning of file
      - E.g., merge join: sort relations;
        - state: pointers to beginning of sorted relations
    - **next()**
      - E.g., for file scan: Output next tuple, and advance and store file pointer
      - E.g., for merge join: continue with merge from earlier state till next output tuple is found. Save pointers as iterator state.
    - **close()**

Query Optimization

Chapter 16: Query Optimization

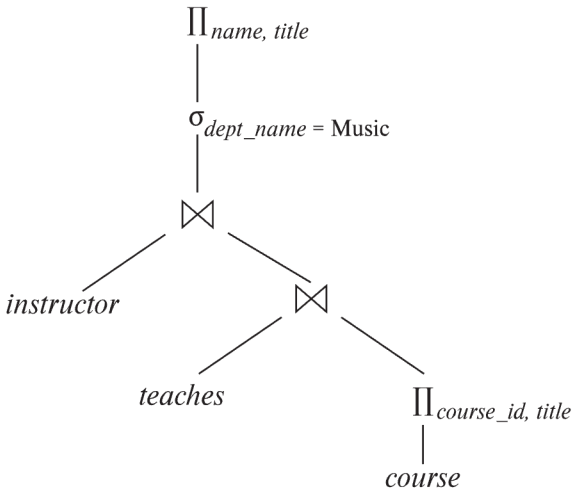
Database System Concepts, 7th Ed.

Outline

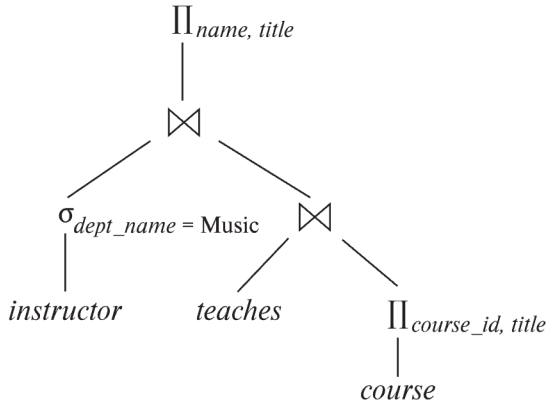
- Introduction
- Transformation of Relational Expressions
- Catalog Information for Cost Estimation
- Statistical Information for Cost Estimation
- Cost-based optimization
- Dynamic Programming for Choosing Evaluation Plans
- Materialized views

Introduction

- Alternative ways of evaluating a given query
  - Equivalent expressions
  - Different algorithms for each operation



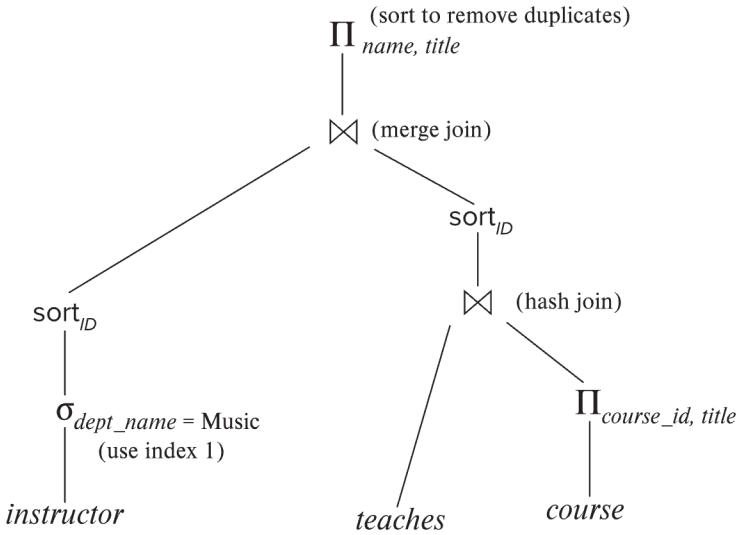
(a) Initial expression tree



(b) Transformed expression tree

Introduction (Cont.)

- An **evaluation plan** defines exactly what algorithm is used for each operation, and how the execution of the operations is coordinated.



- Find out how to view query execution plans on your favorite database

Introduction (Cont.)

- Cost difference between evaluation plans for a query can be enormous
  - E.g., seconds vs. days in some cases
- Steps in **cost-based query optimization**
  1. Generate logically equivalent expressions using **equivalence rules**
  2. Annotate resultant expressions to get alternative query plans
  3. Choose the cheapest plan based on **estimated cost**
- Estimation of plan cost based on:
  - Statistical information about relations. Examples:
    - number of tuples, number of distinct values for an attribute
  - Statistics estimation for intermediate results
    - to compute cost of complex expressions
  - Cost formulae for algorithms, computed using statistics

Viewing Query Evaluation Plans

- Most database support **explain** <query>
  - Displays plan chosen by query optimizer, along with cost estimates
  - Some syntax variations between databases
    - Oracle: **explain plan for** <query> followed by **select** * **from** table (*dbms_xplan.display*)
    - SQL Server: **set showplan_text on**
- Some databases (e.g. PostgreSQL) support **explain analyse** <query>
  - Shows actual runtime statistics found by running the query, in addition to showing the plan
- Some databases (e.g. PostgreSQL) show cost as *f..l*
  - *f* is the cost of delivering first tuple and *l* is cost of delivering all results

Generating Equivalent Expressions

Transformation of Relational Expressions

- Two relational algebra expressions are said to be **equivalent** if the two expressions generate the same set of tuples on every *legal* database instance
  - Note: order of tuples is irrelevant
  - we don't care if they generate different results on databases that violate integrity constraints
- In SQL, inputs and outputs are multisets of tuples
  - Two expressions in the multiset version of the relational algebra are said to be equivalent if the two expressions generate the same multiset of tuples on every legal database instance.
- An **equivalence rule** says that expressions of two forms are equivalent
  - Can replace expression of first form by second, or vice versa

Equivalence Rules

1. Conjunctive selection operations can be deconstructed into a sequence of individual selections.

   $$\sigma_{\theta_1 \wedge \theta_2}(E) \equiv \sigma_{\theta_1}(\sigma_{\theta_2}(E))$$

2. Selection operations are commutative.

   $$\sigma_{\theta_1}(\sigma_{\theta_2}(E)) \equiv \sigma_{\theta_2}(\sigma_{\theta_1}(E))$$

3. Only the last in a sequence of projection operations is needed, the others can be omitted.

   $$\Pi_{L_1}(\Pi_{L_2}(\ldots(\Pi_{L_n}(E))\ldots)) \equiv \Pi_{L_1}(E)$$

   where $L_1 \subseteq L_2 \ldots \subseteq L_n$

4. Selections can be combined with Cartesian products and theta joins.

   a. $\sigma_{\theta}(E_1 \times E_2) \equiv E_1 \bowtie_{\theta} E_2$

   b. $\sigma_{\theta_1}(E_1 \bowtie_{\theta_2} E_2) \equiv E_1 \bowtie_{\theta_1 \wedge \theta_2} E_2$

Equivalence Rules (Cont.)

5. Theta-join operations (and natural joins) are commutative.

$$E_1 \bowtie E_2 \equiv E_2 \bowtie E_1$$

6. (a) Natural join operations are associative:

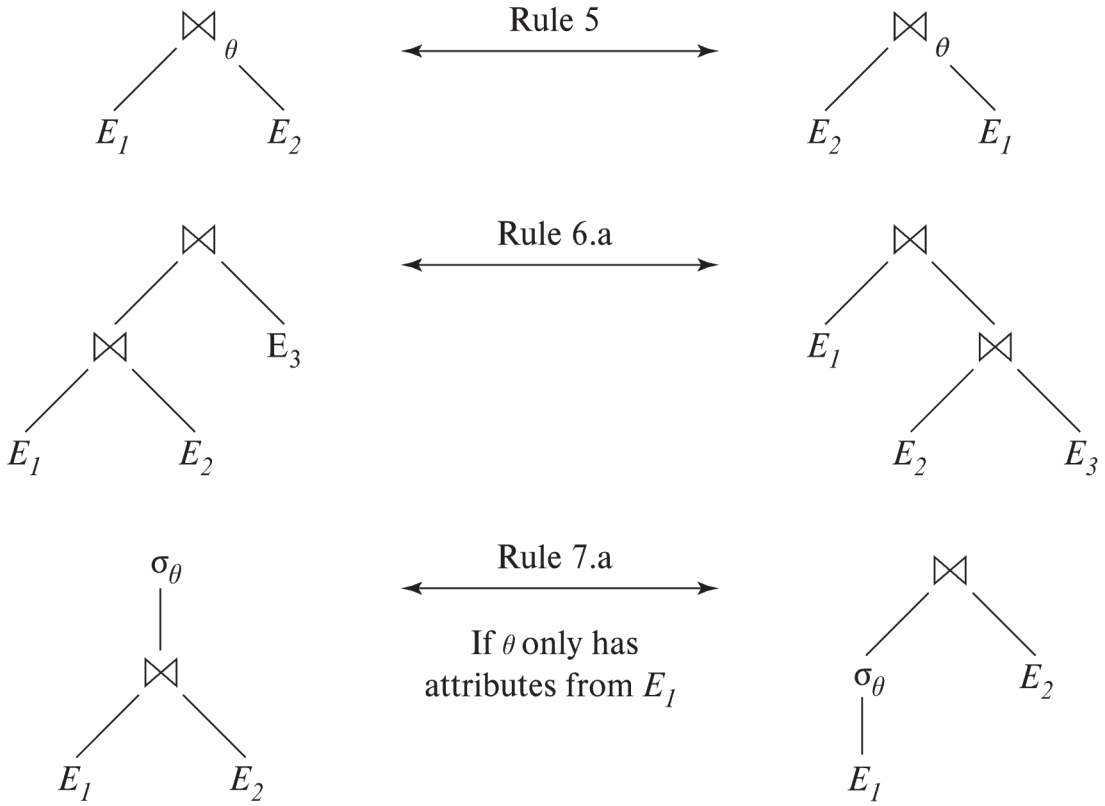
$$(E_1 \bowtie E_2) \bowtie E_3 \equiv E_1 \bowtie (E_2 \bowtie E_3)$$

(b) Theta joins are associative in the following manner:

$$(E_1 \bowtie_{\theta_1} E_2) \bowtie_{\theta_2 \wedge \theta_3} E_3 \equiv E_1 \bowtie_{\theta_1 \wedge \theta_3} (E_2 \bowtie_{\theta_2} E_3)$$

where θ_2 involves attributes from only E_2 and E_3.

Pictorial Depiction of Equivalence Rules



Equivalence Rules (Cont.)

7. The selection operation distributes over the theta join operation under the following two conditions:
   (a) When all the attributes in θ_0 involve only the attributes of one of the expressions (E_1) being joined.

$$\sigma_{\theta_0}(E_1 \bowtie_\theta E_2) \equiv (\sigma_{\theta_0}(E_1)) \bowtie_\theta E_2$$

   (b) When θ_1 involves only the attributes of E_1 and θ_2 involves only the attributes of E_2.

$$\sigma_{\theta_1 \wedge \theta_2}(E_1 \bowtie_\theta E_2) \equiv (\sigma_{\theta_1}(E_1)) \bowtie_\theta (\sigma_{\theta_2}(E_2))$$

Equivalence Rules (Cont.)

8. The projection operation distributes over the theta join operation as follows:

   (a) if θ involves only attributes from $L_1 \cup L_2$:

   $$\Pi_{L_1 \cup L_2}(E_1 \bowtie_\theta E_2) \equiv \Pi_{L_1}(E_1) \bowtie_\theta \Pi_{L_2}(E_2)$$

   (b) In general, consider a join $E_1 \bowtie_\theta E_2$.

   - Let L_1 and L_2 be sets of attributes from E_1 and E_2, respectively.
   - Let L_3 be attributes of E_1 that are involved in join condition θ, but are not in $L_1 \cup L_2$, and
   - let L_4 be attributes of E_2 that are involved in join condition θ, but are not in $L_1 \cup L_2$.

   $$\Pi_{L_1 \cup L_2}(E_1 \bowtie_\theta E_2) \equiv \Pi_{L_1 \cup L_2}(\Pi_{L_1 \cup L_3}(E_1) \bowtie_\theta \Pi_{L_2 \cup L_4}(E_2))$$

Similar equivalences hold for outerjoin operations: $\mathbin{⟗}$, $\mathbin{⟕}$, and $\mathbin{⟖}$

Equivalence Rules (Cont.)

9. The set operations union and intersection are commutative

$$E_1 \cup E_2 \equiv E_2 \cup E_1$$
$$E_1 \cap E_2 \equiv E_2 \cap E_1$$

(set difference is not commutative).

10. Set union and intersection are associative.

$$(E_1 \cup E_2) \cup E_3 \equiv E_1 \cup (E_2 \cup E_3)$$
$$(E_1 \cap E_2) \cap E_3 \equiv E_1 \cap (E_2 \cap E_3)$$

11. The selection operation distributes over $\cup$, $\cap$ and $-$.

a. $\sigma_\theta (E_1 \cup E_2) \equiv \sigma_\theta (E_1) \cup \sigma_\theta(E_2)$
b. $\sigma_\theta (E_1 \cap E_2) \equiv \sigma_\theta (E_1) \cap \sigma_\theta(E_2)$
c. $\sigma_\theta (E_1 - E_2) \equiv \sigma_\theta (E_1) - \sigma_\theta(E_2)$
d. $\sigma_\theta (E_1 \cap E_2) \equiv \sigma_\theta(E_1) \cap E_2$
e. $\sigma_\theta (E_1 - E_2) \equiv \sigma_\theta(E_1) - E_2$

preceding equivalence does not hold for $\cup$

12. The projection operation distributes over union

$$\Pi_L(E_1 \cup E_2) \equiv (\Pi_L(E_1)) \cup (\Pi_L(E_2))$$

Equivalence Rules (Cont.)

13. Selection distributes over aggregation as below
    $\sigma_\theta({}_G\gamma_A(E)) \equiv {}_G\gamma_A(\sigma_\theta(E))$
    provided θ only involves attributes in G
14. a. Full outerjoin is commutative:
    $E_1 \mathbin{⟗} E_2 \equiv E_2 \mathbin{⟗} E_1$
    b. Left and right outerjoin are not commutative, but:
    $E_1 ⟕ E_2 \equiv E_2 ⟖ E_1$
15. Selection distributes over left and right outerjoins as below, provided θ_1 only involves attributes of E_1
    a. $\sigma_{\theta_1}(E_1 ⟕_\theta E_2) \equiv (\sigma_{\theta_1}(E_1)) ⟕_\theta E_2$
    b. $\sigma_{\theta_1}(E_1 ⟖_\theta E_2) \equiv E_2 ⟖_\theta (\sigma_{\theta_1}(E_1))$
16. Outerjoins can be replaced by inner joins under some conditions
    a. $\sigma_{\theta_1}(E_1 ⟕_\theta E_2) \equiv \sigma_{\theta_1}(E_1 ⋈_\theta E_2)$
    b. $\sigma_{\theta_1}(E_1 ⟖_\theta E_1) \equiv \sigma_{\theta_1}(E_1 ⋈_\theta E_2)$
    provided θ_1 is null rejecting on E_2

Equivalence Rules (Cont.)

Note that several equivalences that hold for joins do not hold for outerjoins

- $\sigma_{year=2017}(instructor \bowtie teaches) \not\equiv \sigma_{year=2017}(instructor \bowtie teaches)$
- Outerjoins are not associative

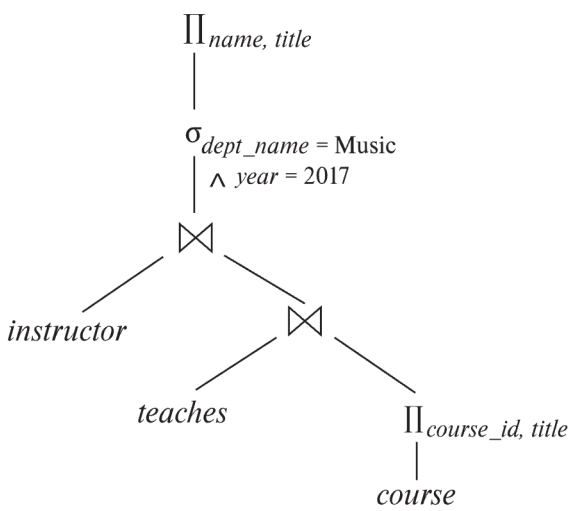
  $(r \bowtie s) \bowtie t \quad \not\equiv \quad r \bowtie (s \bowtie t)$

  - e.g. with r(A,B) = {(1,1), s(B,C) = { (1,1)}, t(A,C) = { }

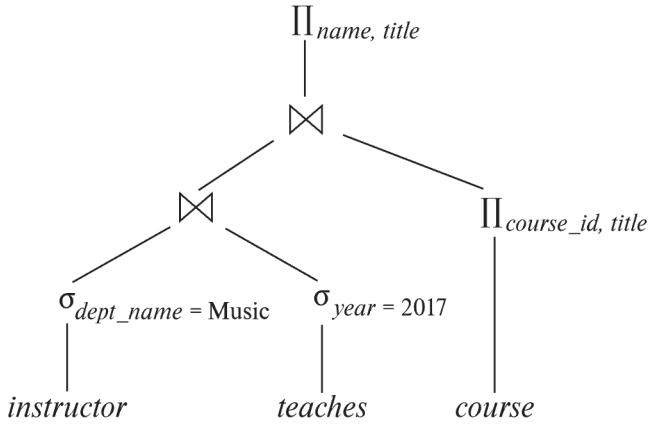
Transformation Example: Pushing Selections

- Query: Find the names of all instructors in the Music department, along with the titles of the courses that they teach
  - $\Pi_{name,\ title}(\sigma_{dept\_name=\text{'Music'}}(instructor \bowtie (teaches \bowtie \Pi_{course\_id,\ title}(course))))$
- Transformation using rule 7a.
  - $\Pi_{name,\ title}((\sigma_{dept\_name=\text{'Music'}}(instructor)) \bowtie (teaches \bowtie \Pi_{course\_id,\ title}(course)))$
- Performing the selection as early as possible reduces the size of the relation to be joined.

Multiple Transformations (Cont.)



(a) Initial expression tree



(b) Tree after multiple transformations

Join Ordering Example

- For all relations r_1, r_2, and r_3,

$$(r_1 \bowtie r_2) \bowtie r_3 = r_1 \bowtie (r_2 \bowtie r_3)$$

  (Join Associativity) $\bowtie$

- If $r_2 \bowtie r_3$ is quite large and $r_1 \bowtie r_2$ is small, we choose

$$(r_1 \bowtie r_2) \bowtie r_3$$

  so that we compute and store a smaller temporary relation.

Join Ordering Example (Cont.)

- Consider the expression

$$\Pi_{name,\ title}(\sigma_{dept\_name=\text{“Music”}}(instructor) \bowtie teaches) \bowtie \Pi_{course\_id,\ title}(course))))$$

- Could compute $teaches \bowtie \Pi_{course\_id,\ title}(course)$ first, and join result with

$$\sigma_{dept\_name=\text{“Music”}}(instructor)$$

but the result of the first join is likely to be a large relation.

- Only a small fraction of the university's instructors are likely to be from the Music department
  - it is better to compute

$$\sigma_{dept\_name=\text{“Music”}}(instructor) \bowtie teaches$$

first.

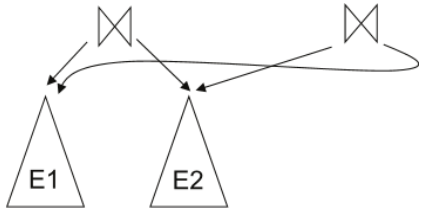
Enumeration of Equivalent Expressions

- Query optimizers use equivalence rules to **systematically** generate expressions equivalent to the given expression
- Can generate all equivalent expressions as follows:
  - Repeat
    - apply all applicable equivalence rules on every subexpression of every equivalent expression found so far
    - add newly generated expressions to the set of equivalent expressions

    Until no new equivalent expressions are generated above
- The above approach is very expensive in space and time
  - Two approaches
    - Optimized plan generation based on transformation rules
    - Special case approach for queries with only selections, projections and joins

Implementing Transformation Based Optimization

- Space requirements reduced by sharing common sub-expressions:
  - when E1 is generated from E2 by an equivalence rule, usually only the top level of the two are different, subtrees below are the same and can be shared using pointers
    - E.g., when applying join commutativity



  - Same sub-expression may get generated multiple times
    - Detect duplicate sub-expressions and share one copy
- Time requirements are reduced by not generating all expressions
  - Dynamic programming
    - We will study only the special case of dynamic programming for join order optimization

Cost Estimation

- Cost of each operator computer as described in Chapter 15
  - Need statistics of input relations
    - E.g., number of tuples, sizes of tuples
- Inputs can be results of sub-expressions
  - Need to estimate statistics of expression results
  - To do so, we require additional statistics
    - E.g., number of distinct values for an attribute
- More on cost estimation later

Choice of Evaluation Plans

- Must consider the interaction of evaluation techniques when choosing evaluation plans
  - choosing the cheapest algorithm for each operation independently may not yield best overall algorithm. E.g.
    - merge-join may be costlier than hash-join, but may provide a sorted output which reduces the cost for an outer level aggregation.
    - nested-loop join may provide opportunity for pipelining
- Practical query optimizers incorporate elements of the following two broad approaches:
  1. Search all the plans and choose the best plan in a cost-based fashion.
  2. Uses heuristics to choose a plan.

Cost-Based Optimization

- Consider finding the best join-order for $r_1 \bowtie r_2 \bowtie \ldots \bowtie r_n$.
- There are $(2(n-1))!/(n-1)!$ different join orders for above expression. With $n = 7$, the number is 665280, with $n = 10$, the number is greater than 176 billion!
- No need to generate all the join orders. Using dynamic programming, the least-cost join order for any subset of $\{r_1, r_2, \ldots r_n\}$ is computed only once and stored for future use.

Statistics for Cost Estimation

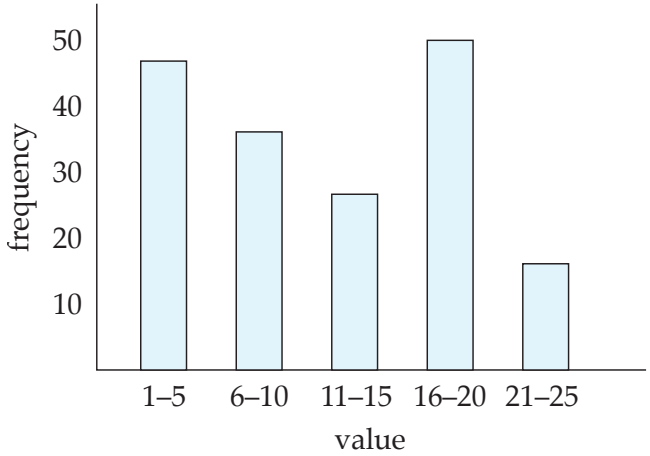
Statistical Information for Cost Estimation

- n_r: number of tuples in a relation *r.*
- b_r: number of blocks containing tuples of *r.*
- l_r: size of a tuple of *r.*
- f_r: blocking factor of *r* — i.e., the number of tuples of *r* that fit into one block.
- *V(A, r):* number of distinct values that appear in *r* for attribute *A;* same as the size of $\prod_A(r)$.
- If tuples of *r* are stored together physically in a file, then:

$$b_r = \left\lceil \frac{n_r}{f_r} \right\rceil$$

Histograms

- Histogram on attribute *age* of relation *person*



- **Equi-width** histograms
- **Equi-depth** histograms break up range such that each range has (approximately) the same number of tuples
  - E.g. (4, 8, 14, 19)
- Many databases also store *n* **most-frequent values** and their counts
  - Histogram is built on remaining values only

Histograms (cont.)

- Histograms and other statistics usually computed based on a **random sample**
- Statistics may be out of date
  - Some database require a **analyze** command to be executed to update statistics
  - Others automatically recompute statistics
    - e.g., when number of tuples in a relation changes by some percentage

Selection Size Estimation

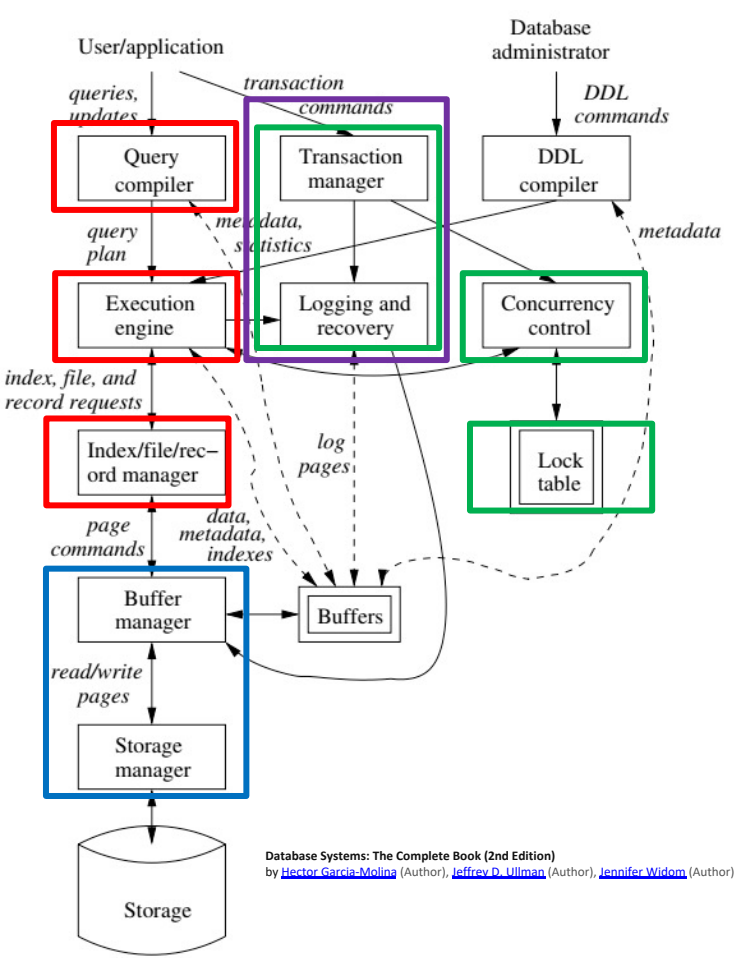
- $\sigma_{A=V}(r)$
  - n_r / $V(A,r)$: number of records that will satisfy the selection
  - Equality condition on a key attribute: *size estimate* = 1
- $\sigma_{A \leq V}(r)$ (case of $\sigma_{A \geq V}(r)$ is symmetric)
  - Let c denote the estimated number of tuples satisfying the condition.
  - If min(A,r) and max(A,r) are available in catalog
    - c = 0 if v < min(A,r)
    - c = $n_r \cdot \frac{v - \min(A,r)}{\max(A,r) - \min(A,r)}$
  - If histograms available, can refine above estimate
  - In absence of statistical information *c* is assumed to be $n_r / 2$.

Transactions

Concepts

Transactions

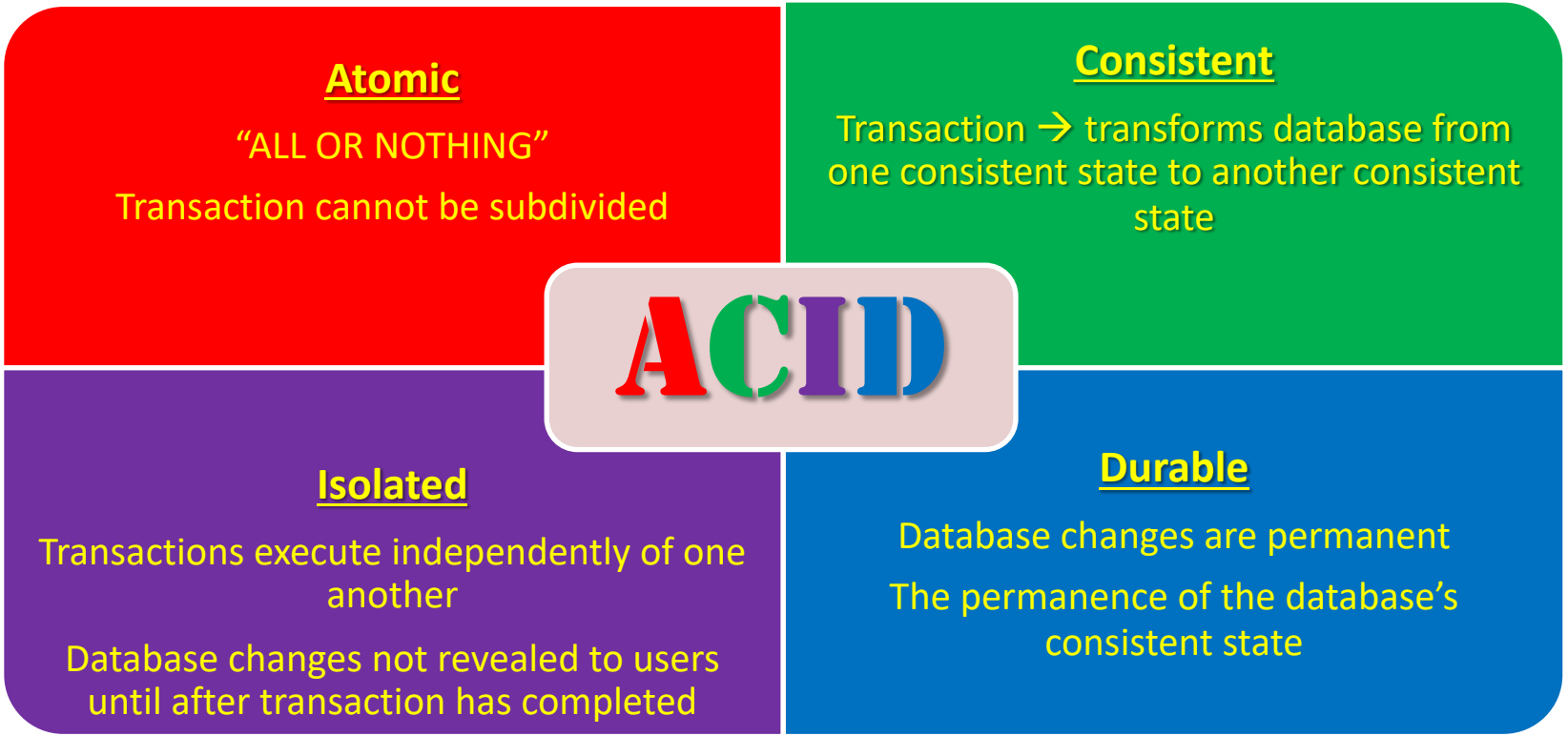
- Find things quickly.
- Load/Save quickly.
- Transactions
- Durability



Database Systems: The Complete Book (2nd Edition)
by Hector Garcia-Molina (Author), Jeffrey D. Ullman (Author), Jennifer Widom (Author)

Core Transaction Concept is ACID Properties

http://slideplayer.com/slide/9307681



ACID Properties (httpwww.tutorialspoint.com/dbms/dbms_transaction.htm)

A *transaction* is a very small unit of a program and it may contain several low-level tasks. A transaction in a database system must maintain **A**tomicity, **C**onsistency, **I**solation, and **D**urability − commonly known as ACID properties − in order to ensure accuracy, completeness, and data integrity.

- **Atomicity** − This property states that a transaction must be treated as an atomic unit, that is, either all of its operations are executed or none. There must be no state in a database where a transaction is left partially completed. States should be defined either before the execution of the transaction or after the execution/abortion/failure of the transaction.
- **Consistency** − The database must remain in a consistent state after any transaction. No transaction should have any adverse effect on the data residing in the database. If the database was in a consistent state before the execution of a transaction, it must remain consistent after the execution of the transaction as well.
- **Durability** − The database should be durable enough to hold all its latest updates even if the system fails or restarts. If a transaction updates a chunk of data in a database and commits, then the database will hold the modified data. If a transaction commits but the system fails before the data could be written on to the disk, then that data will be updated once the system springs back into action.
- **Isolation** − In a database system where more than one transaction are being executed simultaneously and in parallel, the property of isolation states that all the transactions will be carried out and executed as if it is the only transaction in the system. No transaction will affect the existence of any other transaction.

Transaction Concept

BEGIN TRANSACTION {

1. **read**(*A*)
2. *A* := *A* – 50
3. **write**(*A*)
4. **read**(*B*)
5. *B* := *B* + 50
6. **write**(*B*)

COMMIT or ROLLBACK }

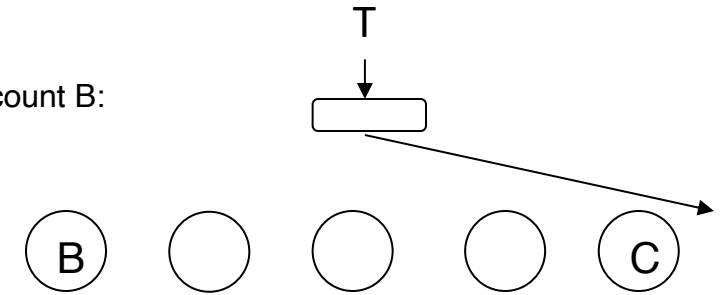
- A **transaction** is a *unit* of program execution that accesses and possibly updates various data items.
- E.g., transaction to transfer $50 from account A to account B:

  BEGIN TRANSACTION {

  1. **read**(*A*)
  2. *A* := *A* – 50
  3. **write**(*A*)
  4. **read**(*B*)
  5. *B* := *B* + 50
  6. **write**(*B*)

  COMMIT or ROLLBACK }
- Two main issues to deal with:
  - Failures of various kinds, such as hardware failures and system crashes
  - Concurrent execution of multiple transactions

Example of Fund Transfer



- Transaction to transfer $50 from account A to account B:
  1. **read**(*A*)
  2. *A* := *A* – 50
  3. **write**(*A*)
  4. **read**(*B*)
  5. *B* := *B* + 50
  6. **write**(*B*)
- **Atomicity requirement**
  - If the transaction fails after step 3 and before step 6, money will be "lost" leading to an inconsistent database state
    - Failure could be due to software or hardware
  - The system should ensure that updates of a partially executed transaction are not reflected in the database
- **Durability requirement** — once the user has been notified that the transaction has completed (i.e., the transfer of the $50 has taken place), the updates to the database by the transaction must persist even if there are software or hardware failures.

Example of Fund Transfer (Cont.)

- **Consistency requirement** in above example:
  - The sum of A and B is unchanged by the execution of the transaction
- In general, consistency requirements include
  - Explicitly specified integrity constraints such as primary keys and foreign keys
  - Implicit integrity constraints
    - e.g., sum of balances of all accounts, minus sum of loan amounts must equal value of cash-in-hand
  - A transaction must see a consistent database.
  - During transaction execution the database may be temporarily inconsistent.
  - When the transaction completes successfully the database must be consistent
    - Erroneous transaction logic can lead to inconsistency

Example of Fund Transfer (Cont.)

T1, T2

- **Isolation requirement** — if between steps 3 and 6, another transaction T2 is allowed to access the partially updated database, it will see an inconsistent database (the sum $A + B$ will be less than it should be).

T1
T2

T1	T2
1. **read**(A)	
2. $A := A - 50$	
3. **write**(A)	
	read(A)
	read(B) print(A+B)
4. **read**(B)	
5. $B := B + 50$	
6. **write**(B)	

- Isolation can be ensured trivially by running transactions **serially**
  - That is, one after the other.
- However, executing multiple transactions concurrently has significant benefits, as we will see later.

Transaction State

- **Active** – the initial state; the transaction stays in this state while it is executing
- **Partially committed** – after the final statement has been executed.
- **Failed** -- after the discovery that normal execution can no longer proceed.
- **Aborted** – after the transaction has been rolled back and the database restored to its state prior to the start of the transaction. Two options after it has been aborted:
  - Restart the transaction
    - Can be done only if no internal logical error
  - Kill the transaction
- **Committed** – after successful completion.

Atomicity
Durability

Atomicity

A transaction is a logical unit of work that must be either entirely completed or entirely undone. (All writes happen or none of them happen)

OK. What does this mean? Consider some pseudo-code

def transfer(source_acct_id, target_acct_id, amount)

1. Check that both accounts exist.
2. IF *is_checking_account(source_acct_id)*
    1. Check that (source_acct.balance-amount) > source_account.overdraft_limit
3. ELSE
    1. Check that (source_count.balance-amount) >source_account.minimum_balance
4. Update source account
5. Update target account.
6. INSERT a record into transfer tracking table.

Atomicity

A transaction is a logical unit of work that must be either entirely completed or entirely undone. (All writes happen or none of them happen)

OK. What does this mean? Consider some pseudo-code

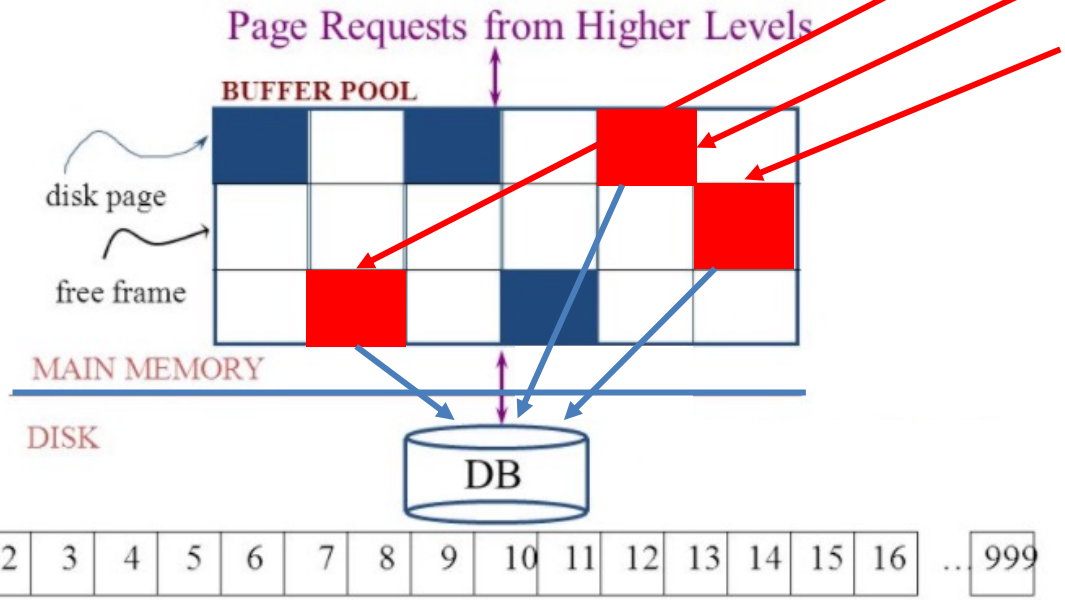
def transfer(source_acct_id, target_acct_id, amount)

1. Check that both accounts exist.
2. IF *is_checking_account(source_acct_id)*
    1. Check that (source_acct.balance-amount) > source_ac
3. ELSE
    1. Check that (source_count.balance-amount) >source_a
4. Update source account
5. Update target account.
6. INSERT a record into transfer tracking table.

Atomicty

- Transaction programs and databases are fast (milliseconds).
  What are the chances of the failure occurring in the wrong spot?
- Well, that doesn't really matter. If it happens,
  - Someone lost money and
  - There is no record off it. Someone is going to very upset.
- Even a small server can have thousands of concurrent transactions ➔
  - There will be corruptions because some transaction will be in the wrong place at the wrong time.
  - Unless we do something in the DBMS
  - Because HW and software inevitably fail
  - And sadly, SW is especially prone to failure when under load

Simplistic Approach



Begin

Update A

Update B

Update C

Commit (REQ)

Force to disk

Commit (RSP)

Simplistic Approach

There are several problems with the simplistic approach.

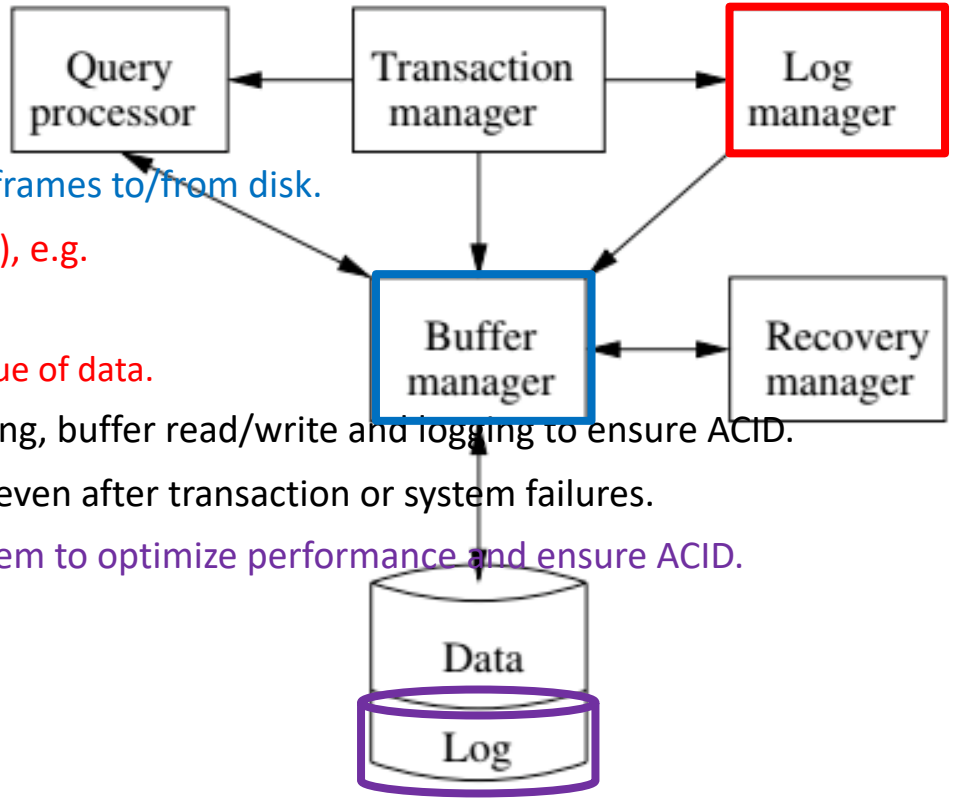
1. The approach does not solve the problem
    1. Some writes might succeed.
    2. Some might be interrupted by the failure, or require retry.
2. Writes may be random and scattered. N updates might
    1. Change a few bytes in N data frames
    2. A few bytes in M index frames

    Transaction rate becomes bottlenecked by write I/O rate, even though a relative small number of bytes change/transaction.
3. Written frames must be held in memory.
    1. Lots of transactions
    2. Randomly writing small pieces of lots of frames.
    3. Consumes lots of memory with pinned pages.
    4. Degrades the performance and optimization of the buffer.
        1. The optimal buffer replacement policy wants to hold frames that will be reused.
        2. Not frames that have been touched and never reused.

DBMS ACID Implementation

Implementation Subsystems

- *Query processor* schedules and executes queries.
- *Buffer manager* controls reading/writing blocks/frames to/from disk.
- *Log manager* journals/records events to disk (log), e.g.
  - Transaction start/commit/abort
  - Transaction update of a block and previous value of data.
- *Transaction manager* coordinates query scheduling, buffer read/write and logging to ensure ACID.
- *Recovery manager* processes log to ensure ACID even after transaction or system failures.
- *Log* is a special type of block file used by the system to optimize performance and ensure ACID.



Garcia-Molina et al., p. 846

Logging

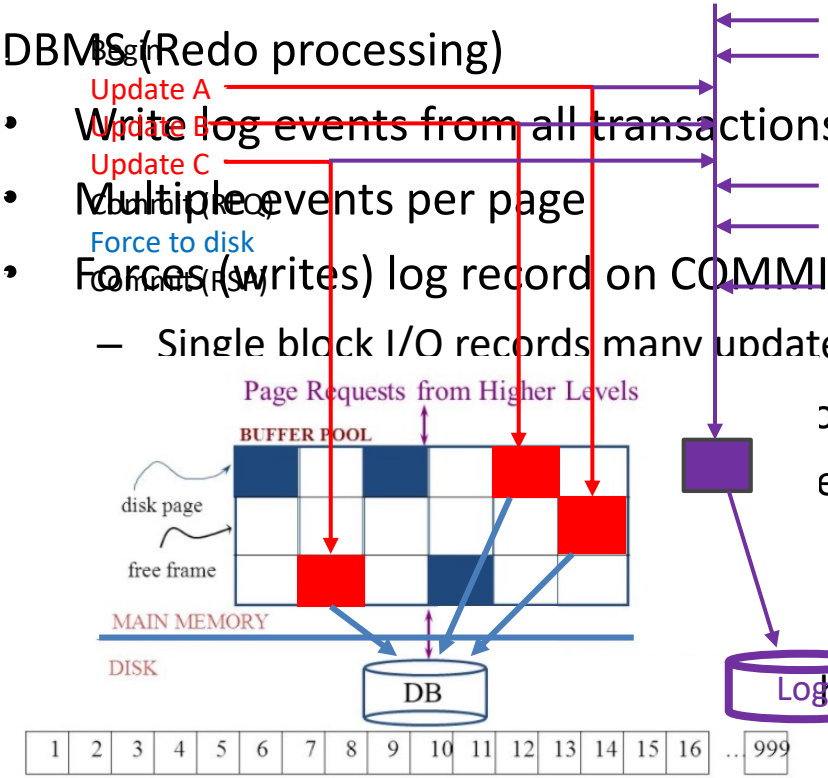
The DBMS logs every transaction event

- *Log Sequence Number* (LSN): A unique ID for a log record.
- *Prev LSN*: A link to their last log record.
- *Transaction ID number.*
- *Type*: Describes the type of database log record.
  - **Update Log Record**
    - *PageID*: A reference to the Page ID of the modified page.
    - *Length and Offset*: Length in bytes and offset of the page are usually included.
    - *Before and After Images* of records.
  - **Compensation Log Record**
  - **Commit Record**
  - **Abort Record Checkpoint Record**
  - **Completion Record** notes that all work has been done for this particular transaction.

Write Ahead Logging

DBMS (Redo processing)

- Write log events from all transactions into a single log stream.
- Multiple events per page
- Forces (writes) log record on COMMIT/ABORT
  - Single block I/O records many updates



ording a single change.

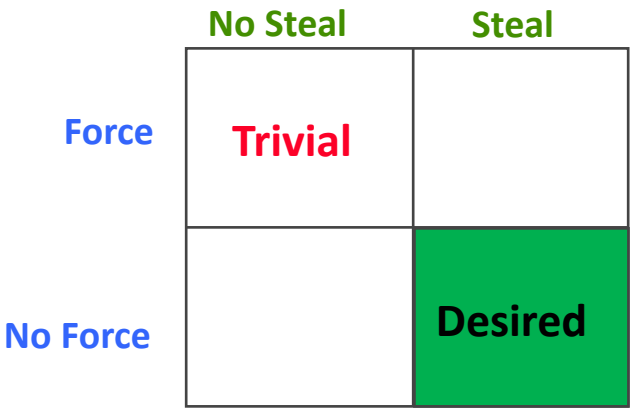
ed in one I/O versus many.

hat were not saved to disk.

Write Ahead Logging

- Force every write to disk?
  - Poor response time.
  - But provides durability.

- Steal buffer-pool frames from uncommitted transactions?
  - If not, poor performance/caching performance
  - If yes, how can we ensure atomicity? Uncommitted updates on disk



DBMS (Undo processing)

- Enable steal policy to improve cache performance by
  - Avoiding lots of pinned pages
  - Unlikely to be reused soon.
- Before stealing
  - Force log record to disk.
  - Update log entry has data record
    - Before image
    - After image
- If there is a failure
  - DBMS sequentially reads log.
  - Undoes changes to
    - modified pages, uncommitted pages
    - That were saved to disk.
  - Then resumes normal processing.

ARIES recovery involves three passes

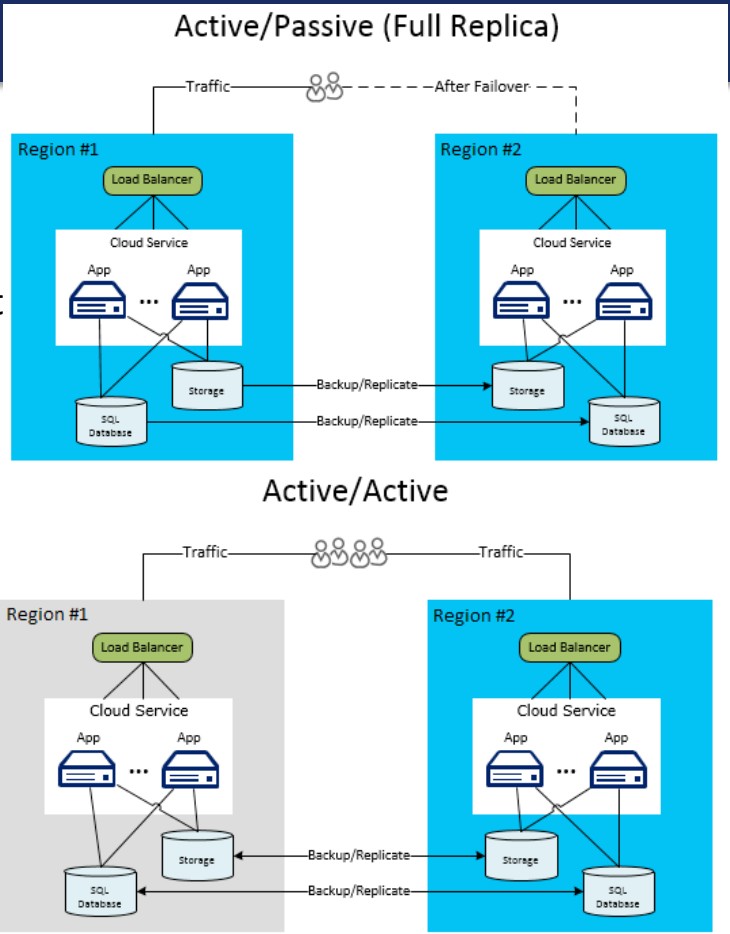
1. Analysis pass:
   - Determine which transactions to undo
   - Determine which pages were dirty (disk version not up to date) at time of
   - RedoLSN: LSN from which redo should start
2. Redo pass:
   - Repeats history, redoing all actions from RedoLSN
     (updated committed but not written changes to pages)
   - RecLSN and PageLSNs are used to avoid redoing actions already reflected on page
3. Undo pass:
   - Rolls back all incomplete transactions (with uncommitted pages written to disk).
   - Transactions whose abort was complete earlier are not undone

Durability

- Write changes to disk trivially achieves durability.
- DBMS engine uses write-ahead-logging to
  - Achieve durability
  - But with better performance through more efficient caching and I/O.
- Well, disks fail. How is that durable.
  - RAID and other solutions.
  - Disk subsystems, including entire RAID device, fail →
    - Duplex writes
    - To independent disk subsystems.
- Well, there are earthquakes, floods, etc.

Availability and Replication

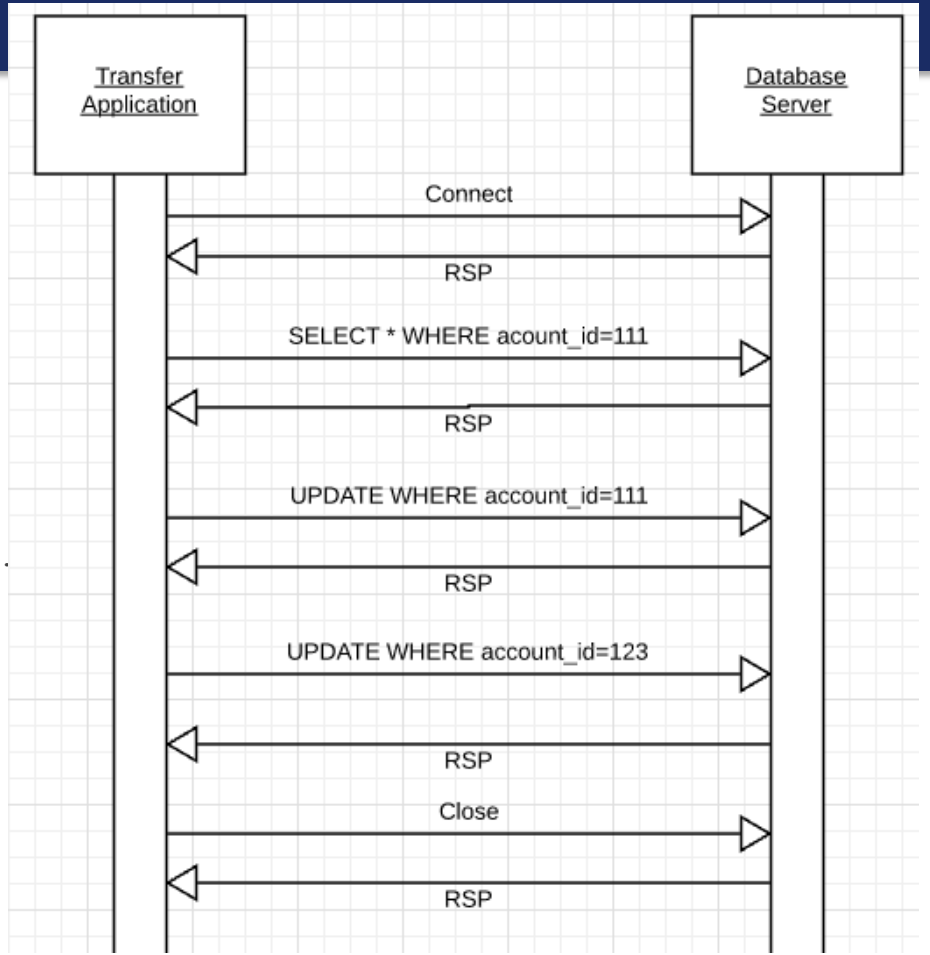
- There are two basic patterns
  - Active/Passive
    - All requests go to *master* during normal processing.
    - Updates are transactionally queued for processing at
    - Failure of *master*
      - Routes subsequent requests to *backup.*
      - Backup must process and commit updates before accepting requests.
  - Active/Active
    - Both environments process requests.
    - Some form of distributed transaction commit requir
- Multi-system communication to guarantee consis tradeoffs in CAP.
  - The system can be CAP if and only iff
  - There are never any partitions or system failures
  - Which is unrealistic in cloud/Internet systems.



Isolation

Isolation

- Transfer $50 from
  - account_id=111 to
  - account_id=123
- Requires 3 SQL statements
  - SELECT from 111 to check balance >= $50
  - UPDATE account_id=111
  - UPDATE account_id=123
- There are some interesting scenarios
  - Two different programs read the balance ($51)
  - And decide removing $50 is OK.
- DB constraints can prevent the conflict from happening, but …
  - There are more complex scenarios that constraints do not prevent.
  - Not ALL databases support constraints.
  - The "correct" execution should be that
    - One transaction responds "insufficient funds"
    - Before attempting transfer instead of after attempting.



Isolation

- Consider two **simultaneous** transfer transactions T1 and T2.
- There are two equally ***correct*** executions
  1. T1 transfers, T2 responds “insufficient funds” and does not attempt transfer
  2. T2 transfers, T1 responds “insufficient funds” and does not attempt transfer
- Each correct simultaneous execution is equivalent to a serial (sequential) execution schedule
  - (1) Execute T1, Execute T2
  - (2) Execute T2, Execute T1
- NOTE:
  - We are focusing on ***correctness*** not
  - ***Fairness:***
    - We do not care which transaction was actually submitted first.
    - And probably do not know due to networking, etc.

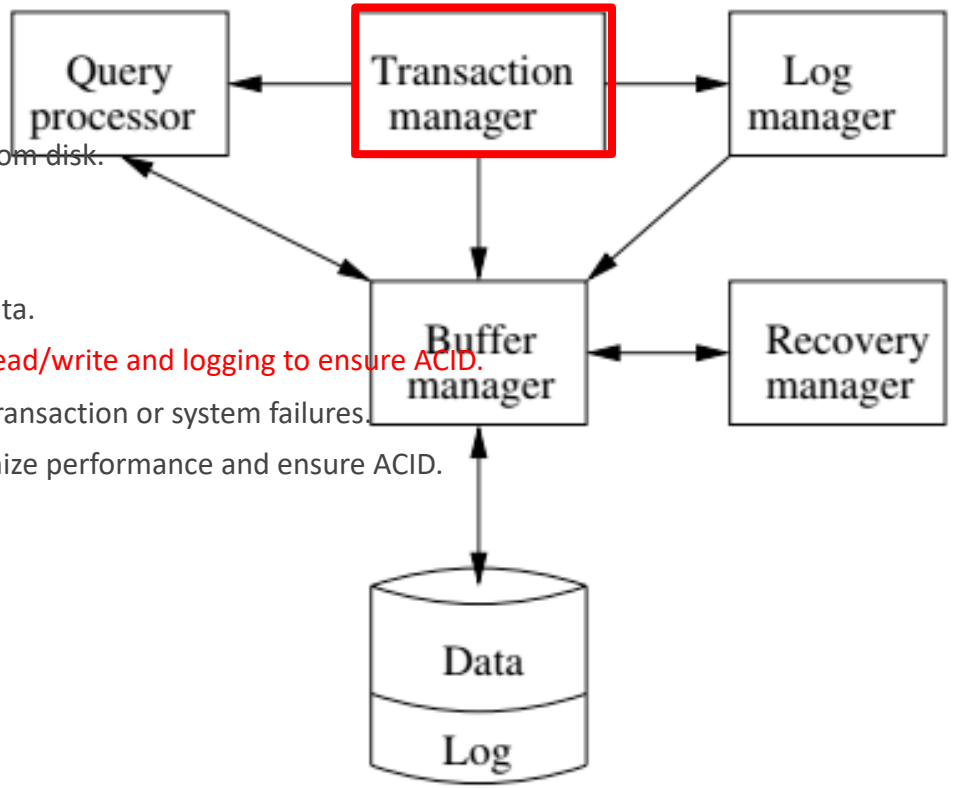
Serializability

"In concurrency control of databases,[1][2] transaction processing (transaction management), and various transactional applications (e.g., transactional memory[3] and software transactional memory), both centralized and distributed, a transaction schedule is **serializable** if its outcome (e.g., the resulting database state) is equal to the outcome of its transactions executed serially, i.e. without overlapping in time. Transactions are normally executed concurrently (they overlap), since this is the most efficient way. Serializability is the major correctness criterion for concurrent transactions' executions. It is considered the highest level of isolation between transactions, and plays an essential role in concurrency control. As such it is supported in all general purpose database systems." (https://en.wikipedia.org/wiki/Serializability)

DBMS ACID Implementation

Implementation Subsystems

- *Query processor* schedules and executes queries.
- *Buffer manager* controls reading/writing blocks/frames to/from disk.
- *Log manager* journals/records events to disk (log), e.g.
  - Transaction start/commit/abort
  - Transaction update of a block and previous value of data.
- *Transaction manager* coordinates query **scheduling**, buffer read/write and logging to ensure ACID.
- *Recovery manager* processes log to ensure ACID even after transaction or system failures.
- *Log* is a special type of block file used by the system to optimize performance and ensure ACID.



Garcia-Molina et al., p. 846

Schedule

18.1.1 Schedules

A *schedule* is a sequence of the important actions taken by one or more transactions. When studying concurrency control, the important read and write actions take place in the main-memory buffers, not the disk. That is, a database element A that is brought to a buffer by some transaction T may be read or written in that buffer not only by T but by other transactions that access A.

T_1	T_2
READ(A,t)	READ(A,s)
t := t+100	s := s*2
WRITE(A,t)	WRITE(A,s)
READ(B,t)	READ(B,s)
t := t+100	s := s*2
WRITE(B,t)	WRITE(B,s)

Figure 18.2: Two transactions

Garcia-Molina et al.

Serializable

- Assume there are three
  - concurrently executing transactions
  - T1, T2 and T3
- The transaction manager
  - Enables concurrent execution
  - But schedules individual operations
  - To ensure that the final DB state
  - Is *equivalent* to one of the following schedules
    - T1, T2, T3
    - T1, T3, T2
    - T2, T1, T3
    - T2, T3, T1
    - T3, T1, T2
    - T3, T2, T1

  Concurrent execution was *serializable.*

18.1.2 Serial Schedules

A schedule is *serial* if its actions consist of all the actions of one transaction, then all the actions of another transaction, and so on. No mixing of the actions is allowed.

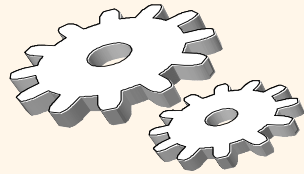
T_1	T_2	A	B
		25	25
READ(A,t)			
t := t+100			
WRITE(A,t)		125	
READ(B,t)			
t := t+100			
WRITE(B,t)			125
	READ(A,s)		
	s := s*2		
	WRITE(A,s)	250	
	READ(B,s)		
	s := s*2		
	WRITE(B,s)		250

Figure 18.3: Serial schedule in which T_1 precedes T_2

Serializability (en.wikipedia.org/wiki/Serializability)

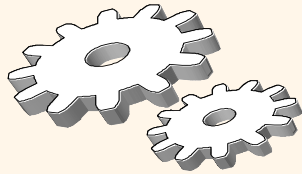
- **Serializability** is used to keep the data in the data item in a consistent state. Serializability is a property of a transaction schedule (history). It relates to the *isolation* property of a database transaction.
- **Serializability** of a schedule means equivalence (in the outcome, the database state, data values) to a *serial schedule* (i.e., sequential with no transaction overlap in time) with the same transactions. It is the major criterion for the correctness of concurrent transactions' schedule, and thus supported in all general purpose database systems.
- **The rationale behind serializability** is the following:
  - If each transaction is correct by itself, i.e., meets certain integrity conditions,
  - then a schedule that comprises any *serial* execution of these transactions is correct (its transactions still meet their conditions):
    - "Serial" means that transactions do not overlap in time and cannot interfere with each other, i.e, complete *isolation* between each other exists.
    - Any order of the transactions is legitimate, (…)
    - As a result, a schedule that comprises any execution (not necessarily serial) that is equivalent (in its outcome) to any serial execution of these transactions, is correct.

Lock-Based Concurrency Control



- *Strict Two-phase Locking (Strict 2PL) Protocol*:
  - Each Xact must obtain a S (*shared*) lock on object before reading, and an X (*exclusive*) lock on object before writing.
  - All locks held by a transaction are released when the transaction completes
    - (Non-strict) 2PL Variant: Release locks anytime, but cannot acquire locks after releasing any lock.
  - If an Xact holds an X lock on an object, no other Xact can get a lock (S or X) on that object.
- Strict 2PL allows only serializable schedules.
  - Additionally, it simplifies transaction aborts
  - (Non-strict) 2PL also allows only serializable schedules, but involves more complex abort processing

Aborting a Transaction



- If a transaction *Ti* is aborted, all its actions have to be undone. Not only that, if *Tj* reads an object last written by *Ti*, *Tj* must be aborted as well!
- Most systems avoid such *cascading aborts* by releasing a transaction's locks only at commit time.
  - If *Ti* writes an object, *Tj* can read this only after *Ti* commits.
- In order to *undo* the actions of an aborted transaction, the DBMS maintains a *log* in which every write is recorded. This mechanism is also used to recover from system crashes: all active Xacts at the time of the crash are aborted when the system comes back up.

MySQL (Locking) Isolation

13.3.6 SET TRANSACTION Syntax

```
SET [GLOBAL | SESSION] TRANSACTION
    transaction_characteristic [, transaction_characteristic] ...

transaction_characteristic:
    ISOLATION LEVEL level
  | READ WRITE
  | READ ONLY

level:
     REPEATABLE READ
   | READ COMMITTED
   | READ UNCOMMITTED
   | SERIALIZABLE
```

Scope of Transaction Characteristics

You can set transaction characteristics globally, for the current session, or for the next transaction:

- With the `GLOBAL` keyword, the statement applies globally for all subsequent sessions. Existing sessions are unaffected.
- With the `SESSION` keyword, the statement applies to all subsequent transactions performed within the current session.
- Without any `SESSION` or `GLOBAL` keyword, the statement applies to the next (not started) transaction performed within the current session. Subsequent transactions revert to using the `SESSION` isolation level.

Isolation Levels (https://en.wikipedia.org/wiki/Isolation_(database_systems)

Not all transaction use cases require 2PL and serializable execution. Databases support a a set of levels.

- **Serializable**
  - With a lock-based concurrency control DBMS implementation, serializability requires read and write locks (acquired on selected data) to be released at the end of the transaction. Also *range-locks* must be acquired when a SELECT query uses a ranged *WHERE* clause, especially to avoid the ***phantom reads*** phenomenon.
  - *The execution of concurrent SQL-transactions at isolation level SERIALIZABLE is guaranteed to be serializable. A serializable execution is defined to be an execution of the operations of concurrently executing SQL-transactions that produces the same effect as some serial execution of those same SQL-transactions. A serial execution is one in which each SQL-transaction executes to completion before the next SQL-transaction begins.*
- **Repeatable reads**
  - In this isolation level, a lock-based concurrency control DBMS implementation keeps read and write locks (acquired on selected data) until the end of the transaction. However, *range-locks* are not managed, so ***phantom reads*** can occur.
  - Write skew is possible at this isolation level, a phenomenon where two writes are allowed to the same column(s) in a table by two different writers (who have previously read the columns they are updating), resulting in the column having data that is a mix of the two transactions.[3][4]
- **Read committed**
  - In this isolation level, a lock-based concurrency control DBMS implementation keeps write locks (acquired on selected data) until the end of the transaction, but read locks are released as soon as the SELECT operation is performed (so the ***non-repeatable reads phenomenon*** can occur in this isolation level). As in the previous level, *range-locks* are not managed.
  - Putting it in simpler words, read committed is an isolation level that guarantees that any data read is committed at the moment it is read. It simply restricts the reader from seeing any intermediate, uncommitted, 'dirty' read. It makes no promise whatsoever that if the transaction re-issues the read, it will find the same data; data is free to change after it is read.
- **Read uncommitted**
  - This is the *lowest* isolation level. In this level, ***dirty reads*** are allowed, so one transaction may see *not-yet-committed* changes made by other transactions

In Databases, Cursors Define *Isolation*

- We have talked about ACID transactions

Isolation level	Dirty reads	Non-repeatable reads	Phantoms
Read Uncommitted	may occur	may occur	may occur
Read Committed	-	may occur	may occur
Repeatable Read	-	-	may occur
Serializable	-	-	-

```
InitialContext ctx = new InitialContext();
DataSource ds = (DataSource)
ctx.lookup("jdbc/MyBase");
Connection con = ds.getConnection();
DatabaseMetaData dbmd = con.getMetaData();
if (dbmd.supportsTransactionIsolationLevel(TRANSACTION_SERIALIZABLE)
{ Connection.setTransactionIsolation(TRANSACTION_SERIALIZABLE); }
```

- Isolation
  - Determines what happens when two or more threads are manipulating the data at the same time.
  - And is defined relative to where cursors are and what they have touched.
  - Because the cursor movement determines *what you are reading or have read.*
- *But, … Cursors are client conversation state and cannot be used in REST.*

Relational Database Design Normalization

Overview of Normalization

Features of Good Relational Designs

- Hypothetically, assume our schema originally had one relation that provided information about faculty and departments.
- Suppose we combine *instructor* and *department* into *in_dep,* which represents the natural join on the relations *instructor* and *department*

ID	*name*	*salary*	*dept_name*	*building*	*budget*
22222	Einstein	95000	Physics	Watson	70000
12121	Wu	90000	Finance	Painter	120000
32343	El Said	60000	History	Painter	50000
45565	Katz	75000	Comp. Sci.	Taylor	100000
98345	Kim	80000	Elec. Eng.	Taylor	85000
76766	Crick	72000	Biology	Watson	90000
10101	Srinivasan	65000	Comp. Sci.	Taylor	100000
58583	Califieri	62000	History	Painter	50000
83821	Brandt	92000	Comp. Sci.	Taylor	100000
15151	Mozart	40000	Music	Packard	80000
33456	Gold	87000	Physics	Watson	70000
76543	Singh	80000	Finance	Painter	120000

X → Y
X = (dept_name)
Y = (building, budget)

Pix Physics
Pix Physics

Piy (Watson, 70000)

- There is repetition of information
- Need to use null values (if we add a new department with no instructors)

Decomposition

- The only way to avoid the repetition-of-information problem in the i*n_dep* schema is to decompose it into two schemas – instructor and *department* schemas.
- Not all decompositions are good. Suppose we decompose

  employee(ID, name, street, city, salary)

  into

  employee1 (*ID*, *name*)

  employee2 (*name*, *street, city, salary*)

  The problem arises when we have two employees with the same name
- The next slide shows how we lose information -- we cannot reconstruct the original *employee* relation -- and so, this is a **lossy decomposition**.

Lossy Decomposition

ID	name	street	city	salary
⋮				
57766	Kim	Main	Perryridge	75000
98776	Kim	North	Hampton	67000
⋮				

employee

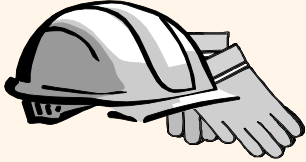
ID	name
⋮	
57766	Kim
98776	Kim
⋮	

name	street	city	salary
⋮			
Kim	Main	Perryridge	75000
Kim	North	Hampton	67000
⋮			

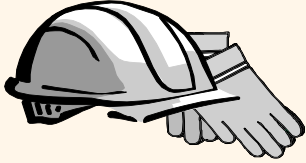
natural join

ID	name	street	city	salary
⋮				
57766	Kim	Main	Perryridge	75000
57766	Kim	North	Hampton	67000
98776	Kim	Main	Perryridge	75000
98776	Kim	North	Hampton	67000
⋮				

The Evils of Redundancy



- *Redundancy* is at the root of several problems associated with relational schemas:
  - redundant storage, insert/delete/update anomalies
- Integrity constraints, in particular *functional dependencies*, can be used to identify schemas with such problems and to suggest refinements.
- Main refinement technique: *decomposition* (replacing ABCD with, say, AB and BCD, or ACD and ABD).
- Decomposition should be used judiciously:
  - Is there reason to decompose a relation?
  - What problems (if any) does the decomposition cause?



Example (Contd.)

Wages

R	W
8	10
5	7

Hourly_Emps2

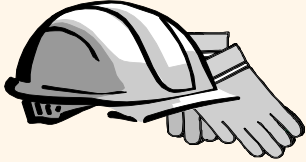
S	N	L	R	H
123-22-3666	Attishoo	48	8	40
231-31-5368	Smiley	22	8	30
131-24-3650	Smethurst	35	5	30
434-26-3751	Guldu	35	5	32
612-67-4134	Madayan	35	8	40

- Problems due to R → W :
  - *Update anomaly*: Can we change W in just the 1st tuple of SNLRWH?
  - *Insertion anomaly*: What if we want to insert an employee and don't know the hourly wage for his rating?
  - *Deletion anomaly*: If we delete all employees with rating 5, we lose the information about the wage for rating 5!

Will 2 smaller tables be better?

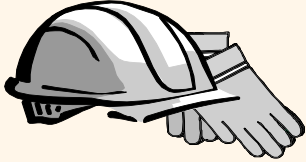
S	N	L	R	W	H
123-22-3666	Attishoo	48	8	10	40
231-31-5368	Smiley	22	8	10	30
131-24-3650	Smethurst	35	5	7	30
434-26-3751	Guldu	35	5	7	32
612-67-4134	Madayan	35	8	10	40

Functional Dependencies (FDs)



- A functional dependency X→ Y holds over relation R if, for every allowable instance *r* of R:
  - $t1 \in r$, $t2 \in r$, $\pi_X(t1) = \pi_X(t2)$ implies $\pi_Y(t1) = \pi_Y(t2)$
  - i.e., given two tuples in *r*, if the X values agree, then the Y values must also agree. (X and Y are *sets* of attributes.)
- An FD is a statement about *all* allowable relations.
  - Must be identified based on semantics of application.
  - Given some allowable instance *r1* of R, we can check if it violates some FD *f*, but we cannot tell if *f* holds over R!
- K is a candidate key for R means that K→ R
  - However, K→ R does not require K to be *minimal*!

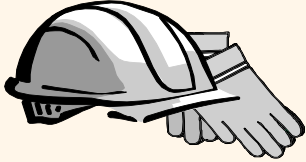
Example: Constraints on Entity Set



- Consider relation obtained from Hourly_Emps:
  - Hourly_Emps (*ssn*, *name*, *lot*, *rating*, *hrly_wages*, *hrs_worked*)
- *Notation*: We will denote this relation schema by listing the attributes: SNLRWH
  - This is really the *set* of attributes {S,N,L,R,W,H}.
  - Sometimes, we will refer to all attributes of a relation by using the relation name. (e.g., Hourly_Emps for SNLRWH)
- Some FDs on Hourly_Emps:
  - *ssn* is the key: S → SNLRWH
  - *rating* determines *hrly_wages*: R → W

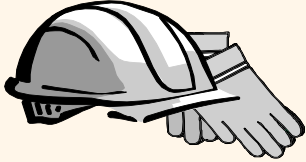
- (uni, email, last_name, first_name)
  uni and email are candidate (not NULL, unique)
  - Uni → email
  - Email → (last_name, first_name)
  - ➔ Uni → (last_name, first_name)
- Person:(uni, email, last_name, first_name),
  ContactInfo: (email, phone_number, dorm_name)
  - Uni → email
  - Email → phone_number, dorm_name
  - Uni → phone_number, dorm_name

Reasoning About FDs



- Given some FDs, we can usually infer additional FDs:
  - *ssn* → *did*, *did* → *lot* implies *ssn* → *lot*
- An FD *f* is *implied by* a set of FDs *F* if *f* holds whenever all FDs in *F* hold.
  - F^+ = *closure of F* is the set of all FDs that are implied by *F*.
- Armstrong's Axioms (X, Y, Z are sets of attributes):
  - *Reflexivity*: If $X \subseteq Y$, then $Y \rightarrow X$
  - *Augmentation*: If $X \rightarrow Y$, then $XZ \rightarrow YZ$ for any Z
  - *Transitivity*: If $X \rightarrow Y$ and $Y \rightarrow Z$, then $X \rightarrow Z$
- These are *sound* and *complete* inference rules for FDs!

Lossless Decomposition



- Let *R* be a relation schema and let R_1 and R_2 form a decomposition of R.
  - That is R = R_1 U R_2
  - *Note: This notation is confusing. This is a statement about the schema, not about the data in relations.*
- We say that the decomposition is a **lossless decomposition** if there is no loss of information by replacing R with the two relation schemas R_1 U R_2
- Formally,

$$\prod_{R_1}(r) \bowtie \prod_{R_2}(r) = r$$

- And, conversely a decomposition is lossy if

$$r \subset \prod_{R_1}(r) \bowtie \prod_{R_2}(r) = r$$

Normalization Theory

- Decide whether a particular relation R is in "good" form.
- In the case that a relation R is not in "good" form, decompose it into set of relations $\{R_1, R_2, ..., R_n\}$ such that
  - Each relation is in good form
  - The decomposition is a lossless decomposition
- Our theory is based on:
  - Functional dependencies
  - Multivalued dependencies

Functional Dependencies

- There are usually a variety of constraints (rules) on the data in the real world.
- For example, some of the constraints that are expected to hold in a university database are:
  - Students and instructors are uniquely identified by their ID.
  - Each student and instructor has only one name.
  - Each instructor and student is (primarily) associated with only one department.
  - Each department has only one value for its budget, and only one associated building.

Functional Dependencies (Cont.)

- An instance of a relation that satisfies all such real-world constraints is called a **legal instance** of the relation;
- A legal instance of a database is one where all the relation instances are legal instances
- Constraints on the set of legal relations.
- Require that the value for a certain set of attributes determines uniquely the value for another set of attributes.
- A functional dependency is a generalization of the notion of a *key.*

Functional Dependencies Definition

- Let R be a relation schema

$$\alpha \subseteq R \text{ and } \beta \subseteq R$$

- The **functional dependency**

$$\alpha \rightarrow \beta$$

holds on R if and only if for any legal relations $r(R)$, whenever any two tuples t_1 and t_2 of r agree on the attributes α, they also agree on the attributes β. That is,

$$t_1[\alpha] = t_2[\alpha] \Rightarrow t_1[\beta] = t_2[\beta]$$

- Example: Consider $r(A,B)$ with the following instance of r.

1	4
1	5
3	7

- On this instance, $B \rightarrow A$ hold; $A \rightarrow B$ does **NOT** hold,

Closure of a Set of Functional Dependencies

- Given a set F set of functional dependencies, there are certain other functional dependencies that are logically implied by F.
  - If $A \rightarrow B$ and $B \rightarrow C$, then we can infer that $A \rightarrow C$
  - etc.
- The set of **all** functional dependencies logically implied by F is the **closure** of F.
- We denote the *closure* of F by F^+.

Keys and Functional Dependencies

- K is a superkey for relation schema R if and only if $K \rightarrow R$
- K is a candidate key for R if and only if
  - $K \rightarrow R$, and
  - for no $\alpha \subset K$, $\alpha \rightarrow R$
- Functional dependencies allow us to express constraints that cannot be expressed using superkeys. Consider the schema:

  in_dep (*ID, name, salary, dept_name, building, budget*).

  We expect these functional dependencies to hold:

  dept_name → *building*

  ID → *building*

  but would not expect the following to hold:

  dept_name → *salary*

DFF Note:
- In the current data: ID → dept_name → building
- But
- In the schema, dept_name may be NULL..

Use of Functional Dependencies

- We use functional dependencies to:
  - To test relations to see if they are legal under a given set of functional dependencies.
    - If a relation *r* is legal under a set *F* of functional dependencies, we say that *r* **satisfies** *F.*
  - To specify constraints on the set of legal relations
    - We say that *F* **holds on** *R* if all legal relations on *R* satisfy the set of functional dependencies *F.*
- Note: A specific instance of a relation schema may satisfy a functional dependency even if the functional dependency does not hold on all legal instances.
  - For example, a specific instance of *instructor* may, by chance, satisfy
    name $\rightarrow$ *ID.*

Normal Forms

Boyce-Codd Normal Form

- A relation schema R is in BCNF with respect to a set F of functional dependencies if for all functional dependencies in F^+ of the form

  $$\alpha \rightarrow \beta$$

  where $\alpha \subseteq R$ and $\beta \subseteq R$, at least one of the following holds:
  - $\alpha \rightarrow \beta$ is trivial (i.e., $\beta \subseteq \alpha$)
  - α is a superkey for R

DFF Note:
- The theoretical treatment is no conveying the practical intent.
- If α is α superkey, I can set a primary key/unique constraint on α.
- Consider tables with address info in the rows.

Decomposing a Schema into BCNF

- Let R be a schema R that is not in BCNF. Let $\alpha \rightarrow \beta$ be the FD that causes a violation of BCNF.
- We decompose R into:
  - $(\alpha \cup \beta)$
  - $(R - (\beta - \alpha))$
- In our example of *in_dep*,
  - α = *dept_name*
  - β = *building, budget*

  and *in_dep* is replaced by
  - $(\alpha \cup \beta)$ = (*dept_name, building, budget*)
  - $(R - (\beta - \alpha))$ = (*ID, name, dept_name, salary*)

DFF Note – again this is baffling
- R = (id, name_last, name_first, street, city, state, zipcode)
- $\alpha \rightarrow \beta$ means zipcode → (city, state)
- $(\alpha \cup \beta)$ = (zipcode, city, state), which we call Address
- $R - (\beta - \alpha)$). = R - β + α = (id, name_last, name_first, zipcode), which we call Person
- Setting primary key ID in Address and zipcode on Address preserves the dependency and is lossless.

Note:
- This is an example only.
- Zip code does not imply city or state in real world.

BCNF and Dependency Preservation

- It is not always possible to achieve both BCNF and dependency preservation
- Consider a schema:

  dept_advisor(s_ID, i_ID, department_name)
- With function dependencies:

  $i\_ID \rightarrow dept\_name$

  $s\_ID, dept\_name \rightarrow i\_ID$
- *dept_advisor* is not in BCNF
  - *i_ID* is not a superkey.
- Any decomposition of *dept_advisor* will not include all the attributes in

  $s\_ID, dept\_name \rightarrow i\_ID$
- Thus, the composition is NOT be dependency preserving

Third Normal Form

- A relation schema R is in **third normal form (3NF)** if for all:

  $$\alpha \rightarrow \beta \text{ in } F^+$$

  at least one of the following holds:

  - $\alpha \rightarrow \beta$ is trivial (i.e., $\beta \in \alpha$)
  - α is a superkey for R
  - Each attribute A in $\beta - \alpha$ is contained in a candidate key for R.

    (**NOTE**: each attribute may be in a different candidate key)
- If a relation is in BCNF it is in 3NF (since in BCNF one of the first two conditions above must hold).
- Third condition is a minimal relaxation of BCNF to ensure dependency preservation (will see why later).

3NF Example

- Consider a schema:

  dept_advisor(s_ID, i_ID, dept_name)

- With function dependencies:

  i_ID $\rightarrow$ *dept_name*

  s_ID, dept_name $\rightarrow$ *i_ID*

- Two candidate keys = {*s_ID, dept_name*}, {*s_ID, i_ID* }
- We have seen before that *dept_advisor* is not in BCNF
- *R,* however, is in 3NF
  - *s_ID, dept_name* is a superkey
  - *i_ID* $\rightarrow$ *dept_name and i_ID* is NOT a superkey, but:
    - { *dept_name*} – {*i_ID* } = {*dept_name* } and
    - *dept_name* is contained in a candidate key

Comparison of BCNF and 3NF

- Advantages to 3NF over BCNF. It is always possible to obtain a 3NF design without sacrificing losslessness or dependency preservation.
- Disadvantages to 3NF.
  - We may have to use null values to represent some of the possible meaningful relationships among data items.
  - There is the problem of repetition of information.

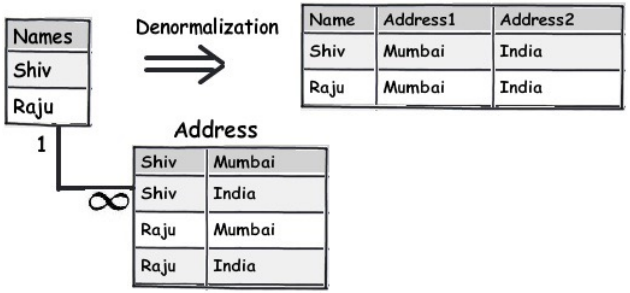
Goals of Normalization

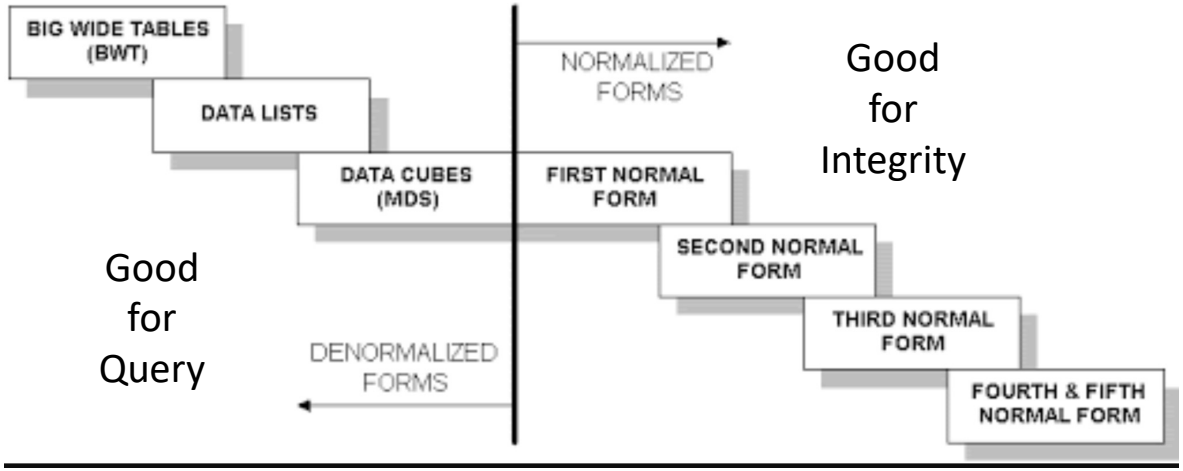
- Let R be a relation scheme with a set F of functional dependencies.
- Decide whether a relation scheme R is in "good" form.
- In the case that a relation scheme R is not in "good" form, need to decompose it into a set of relation scheme $\{R_1, R_2, ..., R_n\}$ such that:
  - Each relation scheme is in good form
  - The decomposition is a lossless decomposition
  - Preferably, the decomposition should be dependency preserving.

Denormalization for Performance

- May want to use non-normalized schema for performance
- For example, displaying *prereqs* along with *course_id,* and *title* requires join of *course* with *prereq*
- Alternative 1: Use denormalized relation containing attributes of *course* as well as *prereq* with all above attributes
  - faster lookup
  - extra space and extra execution time for updates
  - extra coding work for programmer and possibility of error in extra code
- Alternative 2: use a materialized view defined a *course* $\bowtie$ *prereq*
  - Benefits and drawbacks same as above, except no extra coding work for programmer and avoids possible errors

Wide Flat Tables





- Improve query performance by precomputing and saving:
  - JOINs
  - Aggregation
  - Derived/computed columns
- One of the primary strength of the relational model is maintaining "integrity" when applications create, update and delete data. This relies on:
  - The core capabilities of the relational model, e.g. constraints.
  - A well-design database (We will cover a formal definition – "normalization" in more detail later.
- Data models that are well designed for integrity are very bad for read only analysis queries.
  We will build and analyze wide flat tables as part of the analysis tasks in HW3, HW4 as projects.

First Normal Form

- Domain is **atomic** if its elements are considered to be indivisible units
  - Examples of non-atomic domains:
    - Set of names, composite attributes
    - Identification numbers like CS 101 that can be broken up into parts
- A relational schema R is in **first normal form** if the domains of all attributes of R are atomic
- Non-atomic values complicate storage and encourage redundant (repeated) storage of data
  - Example: Set of accounts stored with each customer, and set of owners stored with each account
  - We assume all relations are in first normal form (and revisit this in Chapter 22: Object Based Databases)

First Normal Form (Cont.)

- Atomicity is actually a property of how the elements of the domain are used.
  - Example: Strings would normally be considered indivisible
  - Suppose that students are given roll numbers which are strings of the form *CS0012* or *EE1127*
  - If the first two characters are extracted to find the department, the domain of roll numbers is not atomic.
  - Doing so is a bad idea: leads to encoding of information in application program rather than in the database.