An Overview of Query Optimization in Relational Systems

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What to expect from this tutorial?

- **Query Optimization *in practice***
  - Framework
  - A few key ideas
  - Active areas of work
- **No cool theorems**
- **Provide a perspective that helps place your work in a systems context**

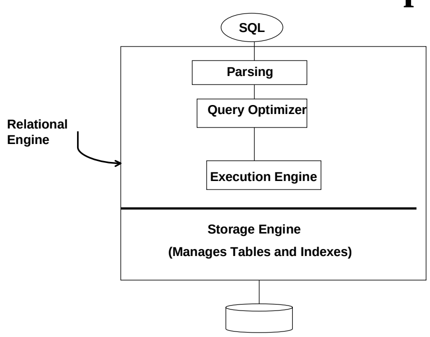
Why Query Optimization?

- **SQL is a high level language (“declarative”)**
  - Physical data independence
- **Needs to be compiled into a program over *relational query engine***
- **Query optimization compiles the query into a program that takes the “least” resources**
  - Acid test of data independence

Outline

- ***Preliminaries***
  - Relational query engine
  - “Programs” over relational query engines (operator trees)
- **Query Optimization Framework**
- **System R optimizer**
- **Modern Optimizers**
- **How to interact with Optimizers**
- **Active Areas of work**
- **Conclusion**

Relational DBMS Components



Storage Structures

- **Tables**
- **Indexes**
  - Columns
    - Single column, Multiple columns
  - Type
    - B+ indexes, Bitmap indexes, Hash indexes
  - Clustering
    - Clustered, Non-clustered
  - Implied “index-evaluable” predicate

Implementation Operators for Scan and Selection

- **Scan([index], table, predicate)**
  - Sequential Scan
  - Indexscan: Which index(es) to use?
  - Always push down "index-evaluable" predicates
- **Filter(table, predicate)**

Implementation Operators for Join

- **Join([method], outer, inner, join-predicate)**
  - Asymmetric
  - Effect of physical properties of input streams (e.g., sorted input)
  - Physical properties of output stream (e.g., sorted)
  - Pipelined v.s. Blocking (Nested Loop v.s. Sort-Merge)

Join Operators

- **Join(Sort-Merge, R1, R2, R1.a = R2.a)**
  - Can exploit sorted order on R1.a
  - Output is a sorted order
  - Blocking
- **Join(Nested-Loop, R1, R2, R1.a = R2.b)**
  - Sorted inputs of no consequence
  - Output has the same sort order as R1.a
  - Pipelined

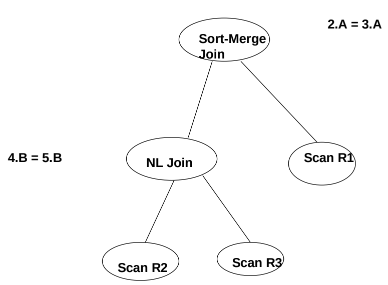
Generic View of Operators

- **Input: One or more data streams**
- **Output: One data stream**
- **Implementation**
  - open()
  - getnext()
  - close()
- **Pipelined/Blocking**

Operator Trees

- **An algebraic expression tree consisting of selection and join can be realized**
  - using an *operator tree* consisting of *scan, filter* and *join* nodes
  - root node is the output of algebraic expression
  - leaf nodes are scans on stored relations
  - child node is an input data stream to its parent
- **(Sequential) Operator tree same as**
  - annotated Query Tree
  - execution Plan (or, simply plan)

Example of an Operator Tree



Execution of an Operator Tree

- Demand-driven architecture is the simplest
- open() is propagated from the root
- getnext() at the root is propagated
- If getnext() at the root fails to return a new tuple, then no more answers for the query

Properties of Trees

- **Edge properties**
  - Size of the data stream
  - Physical properties (e.g., sorted order)
- **Node properties**
  - Cost of an operator
  - Pipelined v.s. blocking
- **Cost of tree = sum of costs of nodes**
- **How to *estimate* the edge and node properties?**

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Goal of Query Optimization

- **Multiple ways to compile a SQL query over the relational engine**
  - Algebraic properties
  - Implementations for each operator
  - Costs of the alternatives may be widely different
- **Find the program with least cost**
  - Query optimization as a planning problem?

A Framework for Query Optimization

- **Equivalence Transformations**
  - Algebraic properties
  - Implementation options
- **Estimation Model**
  - Needs to estimate cost of an operator tree (incrementally)
- **Search Algorithm**
  - Fast, Memory-efficient

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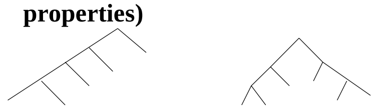
SPJ Queries

Select A.a, B.b, C.c
From A, B, C
Where A.x = B.x and B.y = C.y
Order By A.a

Algebraic Transformations

- **Select and Join commute**
  - Filter(Join(A,B), a) = Join(Filter(A,a), B)
- **Joins are associative and commutative :**
  - Join(Join(A,B), C) = Join (Join(B,A), C)
  - Join(Join(A,C), B) = Join(Join(A,B), C)
  - Many equivalent expressions
- **Linear join trees (restricted use of AC properties)**



Implementation Transformations

- **Scan**
  - B+ tree index scan
  - (Sargable) Predicate: Between and its degenerate forms
- **Filter**
  - Any Boolean expression
- **Join**
  - Sort-Merge, Nested-loop, Indexed Nested-loop

Estimation Model

- **Goal: *Estimate* the *cost* of an operator tree**
  - Number of tuples, Number of distinct values, cost of sub-expressions
- **System-R used a bottom-up computation. For every node:**
  - Computes these parameters of the operator for the given parameters of the input data streams
  - Derives properties of the output data streams
- **Propagates estimates up the tree**
  - For base tables, this information is computed by "run statistics"

Deriving Statistics

- **Consider a "normal" form of SPJ query: Q = Filter(Cartesian-Product(R1,….Rn), f)**
- **Selectivity is fraction of data that satisfies predicate**
  - Size of Q = Selectivity(f) * Size-of(R1)* ..*Size-of(Rn)
- **Compute selectivity of a filter expression**
  - (a) Determine selectivity of atomic predicates using statistics (a > 3, a=b)
  - (b) Derive the selectivity of a Boolean expression from (a)

Selectivity Estimates for Atomic Predicates

- **Selections**
  - Column = v
    - F = 1/(#column)
  - Column Between [a1,a2]
    - F = (a2-a1)/(Hkey - Lkey)
- **Joins**
  - Column1 = Column2
    - F = 1/max(#column1, #column2)

Selectivity Estimates for Boolean Expressions

- **P1 AND P2**
  - F(P1 AND P2) = F(P1)* F(P2)
- **NOT P1**
  - F(NOT P1) = 1- F(P1)
- **P1 OR P2**
  - F(P1 OR P2) = F(P1) + F(P2) - F(P1)*F(P2)
- **Interesting issue:**
  - There are multiple ways to derive statistics for the same expression

Cost Estimates

- **What to measure?**
  - Throughput
  - IO cost + w * CPU cost
  - IO cost = Page Fetches
- **Examples of Scan cost**
  - S: # of Pages(R)
  - CI: F * (# of Pages(R) + # of Index Pages)
  - NCI: F * (# of Tuples(R) + # of Index Pages)
- **Interesting Issue**
  - Effect of database buffers?

Cost Estimates (Join)

- **Nested Loop Join**
  - Cost-of(N1) + Size-of(N1) * Scan-cost(N2)
  - Scan-cost(N2) depends on indexes used
- **Sort-Merge Join**
  - Sort(N1) + Sort(N2) + Scan(Temp1) + Scan(Temp2)

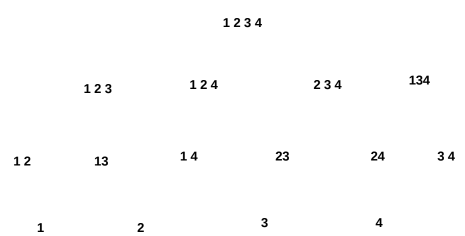
Search Strategy

- **Need to order joins (linearly)**
- **Naïve strategy:**
  - Generate all n! permutations of joins
- **Prohibitively expensive for a large number of joins**
  - Overlapping subproblems, use of optimal substructures
  - Ideal for dynamic programming

Dynamic Programming

- **Goal: Find the optimal plan for Join(R_1,..R_n, R_{n+1})**
  - For each S in {R_1,..R_n, R_{n+1}} do
  - Find Optimal plan for Join(Join(R_1,..R_n), S)
  - Endfor
  - Pick the plan with the least cost
- **Principle of Optimality:**
  - Optimal plan for a larger expression is derived from optimal plan of one of its sub-expressions
- **Complexity**
  - Enumeration cost drops from O(n!) to O(n2^n)
  - May need to store O(2^n) partial plans
  - Significantly more efficient than the naïve scheme

Example

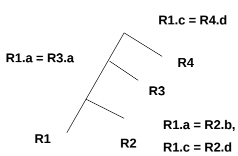


Search Control Features

- **Avoid Cartesian product**
  - Defer all Cartesian products as late as possible to avoid “blow-up”
    - Don’t consider (R1 X R2) Join R3 if (R1 Join R3) Join R2 is feasible
- **Recognize “interesting orders” as violation of principle of optimality:**
  - Cost-of(SM (R1,R2)) > Cost-of (NL(R1,R2))
  - But, Cost-of (SM(SM(R1,R2)), R3) may be much less expensive than other options

Handling Interesting Orders

- **Identify all columns that may exploit sorted order (by examining join predicates)**
- **Collapse into equivalent groups**
- **One optimal partial plan for each interesting order**
- **Example:**



Key Ideas from System R

- **Cost model based on**
  - access methods
  - size and cardinality of relations
- **Enumeration exploits**
  - dynamic programming
  - one optimal plan for each equivalent expression
  - violation of principle of optimality handled using interesting order

Limitations of System R

- **Cost Model**
  - one aggregate number for every column (inaccurate)
  - independence assumption
- **Transformation**
  - limited to join ordering
- **Enumeration**
  - limited to single block queries

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  - *Cost Estimation*
  - Transformations
  - Enumeration Architectures
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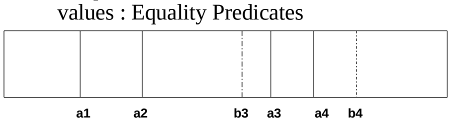
Selectivity Estimation Models

- **Estimate selectivity by executing the query on a "sampled" database**
- **Pre-compute Statistical Descriptors**
  - Histograms : Range Predicates
  - Frequent Values, Number of distinct values : Equality Predicates



Number of Steps = k

Height of each step = n/k

Histograms for Derived Columns

- **Filter**
  - Filter acts as a mask
  - Interpolate count in a partial bucket using uniformity assumption
  - Filter with host variables hard to handle
- **Join**
  - "Normalize" two histograms
  - "Join" two histograms
- **Shortcomings:**
  - Cannot capture correlation
    - Month = Jan and Item = Jacket
    - Needs multi-dimensional histograms
  - Not effective for equality queries

Various Histogram Structures

- **Equi-depth:**
  - All buckets have same number of values
  - Adjacent values co-located in buckets
- **V-Optimal**
  - Groups contiguous sets of frequencies
  - Minimizes variance of the frequency approximation
  - "Optimal" for a subset of range queries
- **A General Framework [PIHS96]**
  - Assign a metric to each value
  - How to partition the metric space?
  - What information is kept for each bucket?
  - What assumptions are made of values within a bucket

Building Statistics

- **Advantage**
  - Optimization sensitive to available statistics
- **Disadvantage**
  - Expensive to collect and maintain
  - "Auto-maintain" statistical descriptors
- **Use of sampling**
  - Must take into account data layout
  - Needs "block" sampling
  - Not effective for number of distinct value
  - How sensitive is optimization to accuracy of statistics?

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Transformations

- **SQL is the target**
- **SQL identity may *not* be a good way to think about transformations**
  - Use algebraic framework
- **May add, not just commute operators**
- **Finding transformations is easy, finding a good one is hard**
  - Broadly applicable
  - Interaction with other transformations

Case Studies of Transformations

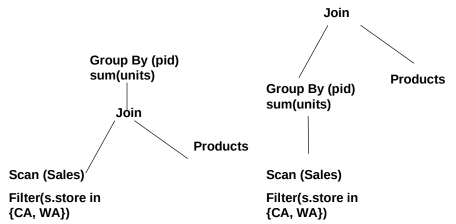
- **Commuting group by and join**
- **Commuting join and outer-join**
- **Optimize multi-block queries**
  - Collapse multi-block query to a single block query
  - Optimize across multiple query blocks

Commuting Group By and Join

- **Traditionally, execution of group-by follows execution of joins**
- **“Pushing down” group by past a join:**
  - Group By “collapses” an equivalence class
  - Therefore, may reduce cost of subsequent joins
  - Can be pipelined with index scans
- **Application needs to be cost based since**
  - The cost of group by itself may be increased
  - Access methods on base tables may no longer be useful for the join
- **Related to Optimization of *Select Distinct* queries**

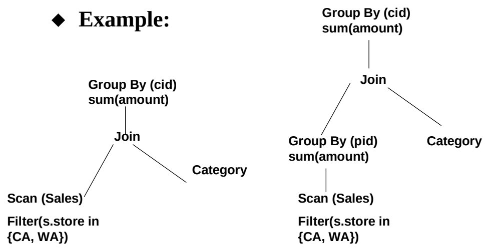
Commuting Group By and Join

- **Schema:**
  - Product(pid, unitprice, ..)
  - Sales(tid, date, store, pid, units)
- **Example :**



Introducing Group By

- **Schema:**
  - Sales(tid, date, store, pid,amount)
  - Category(pid,cid)
- **Example:**



Applicability of Group By/Join Transformations

- **Schema constraints, arbitrary aggregation functions**
- **No schema constraints, but properties of aggregate functions**
  - Agg(S1 U S2) = f(Agg(S1), Agg(S2))
  - May sometime require use of derived columns
- **Related to collapsing multi-block queries into a single block query**

Multi-Block Queries

- **Single Block Query**

  Select columns
  From base-tables
  Where conditions
  Group By columns
  Order By columns
- **Multi-block structure arises due to**
  - views with aggregates
  - table expressions
  - nested sub-queries
- **Divide and Conquer**
  - leverage single block optimization techniques

Example of A Nested Subquery

Select Emp.Name
From Emp
Where Emp.Dept# IN
(Select Dept.Dept#
From Dept
Where Dept.Loc = "Denver"
AND Emp.Emp# = Dept.Mgr)

Example of A View

Create View DepAvgSal as
(Select E.did, Avg(E.Sal) as avgsal
From Emp E
Group By E.did)

Select E.eid, E.sal
From Emp E, Dept D, DepAvgsal V
Where E.did = D.did
And E.did = V.did
And E.age < 30 and D.budget > 100k
And E.sal > V.avgsal

Merging Nested Subquery

- **Think of "IN" as a semi-join between Emp and Dept on**
  - Emp.Dept# = Dept.Dept#
  - Emp.Emp# = Dept.Mgr
- **Convert Semi-join to Join**

Select Emp.Name
From Emp
Where Emp.age < 30 And Emp.Dept# IN
(Select Dept.Dept#
From Dept
Where Dept.Loc = "Denver" And Emp.Emp# =Dept.Mgr)

Result of Merging

Query:

Select Emp.Name
From Emp
Where Emp.Dept# IN
(Select Dept.Dept# From Dept
Where Dept.Loc = "Denver" And Emp.Emp# = Dept.Mgr)

Transformed Query:

Select Emp.Name
From Emp, Dept
Where Emp.Dept# = Dept.Dept#
And Emp.Emp# = Dept.Mgr And Dept.Loc = "Denver"

Nested Subqueries (2)

- **Presence of aggregates in the nested sub-query requires careful treatment**
- **Key Observations:**
  - For each outer tuple, create the "count" of matching inner tuple and compare to D.parking
  - If outer matches no inner tuple, then the outer produces an output tuple ("count bug")

Select D.Name
From Dept D
Where D.parking < =
(Select count(E.Emp#)
From Emp E
Where E.Dept# = D. Dept #)

Merging Nested Subqueries (2)

- **Results in a left outerjoin between the parent and the child block (preserves tuples of the parent)**
  - B1 OJ B2 OJ B3 …..
- **Outerjoin reduces to a join for sum(), average(), max(), min()**
- **Transformed Query:**

Select D.Name	Select D.name
From Dept D	From Dept D LOJ Emp E
Where D.parking <	ON (E.Dept# = D.Dept#)
Select count(E.Emp#)	Group By D.Dept#
From Emp E	Having D.parking
Where E.Dept# = D. Dept #	< count(E.Emp#)

Optimization Across Blocks

- **Collapsing into a single block query is not always feasible or beneficial**
- **We can still optimize by sideways information passing across blocks**
- **Idea similar to semi-join**
  - Outer provides inner with a list of potentially required bindings
  - Helps restrict inner's computation
  - "Once only" invocation of inner for each binding

Example of Query with View

Create View DepAvgSal as (
Select E.did, Avg(E.Sal) as avgsal
From Emp E
Group By E.did)

Select E.eid, E.sal
From Emp E, Dept D, DepAvgsal V
Where E.did = D.did
And E.did = V.did
And E.age < 30 and D.budget > 100k
And E.sal > V.avgsal

Example of SIP

Select E.eid, E.sal
From Emp E, Dept D, DepAvgsal V
Where E.did = D.did
And E.did = V.did
And E.age < 30 and D.budget > 100k
And E.sal > V.avgsal

- **DepAvgsal needs to be evaluated only for cases where V.did IN**

  Select E.did
  From Emp E, Dept D
  Where E.did = D.did
  And E.age < 30 and D.budget > 100k

Result of SIP

Supporting Views

(1) *Create view ED as (Select E.eid, E.did, E.sal*
From Emp E, Dept D
Where E.did = D.did
And E.age < 30 and D.budget > 100k)

(2) *Create View LAvgSal as (*
Select E.did, Avg(E.Sal) as avgsal
From Emp E, ED
Where E.did = ED.did
Group By E.did)

Transformed Query

Select ED.eid, ED.sal
From ED, Lavgsal
Where E.did = ED.did and ED.sal > Lavgsal.avgsal

More Comments on Transformations

- **Summary of Multi-Block Transformations**
  - SIP (semi-join) techniques result in use of views
  - Merging views related to commuting Group By and Join
  - Nested Sub-query => Single Block transformations result in J/OJ expressions
- **SQL semantics is tricky**
- **Applicability conditions are complex**
- **Transformations must be cost based**

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Enumeration Architectures

- **Stress on extensibility (for optimizer developers)**
- **Key features**
  - Explicit representation of transformations as rules
  - Explicit representation of " properties" of plans
    - sort-order, estimated costs
  - Rule engine
- **Examples: Starburst, Volcano**
- **Framework != Optimizer**

Starburst v.s. Volcano

- **Starburst**
  - Heuristic application of algebraic transformations
  - "Core" cost-based single-block join enumeration
- **Volcano**
  - No distinction among transformations
  - Cost-based
  - More difficult search control problem

Starburst Overview

- **QGM for representation of queries**
- **Rewrite Rule Engine**
  - Condition -> action rules where LHS and RHS are arbitrary C functions on QGM representation
  - Rule classes for search control
  - Conflict resolution schemes
  - Customizable search control for rule classes
- **Plan Optimizer**
  - Handles implementation alternatives
  - LOLEPOP (operator)
  - STAR (implementation alternatives)
  - GLUE (achieving required properties)

Volcano Overview

- **Query as an algebraic tree**
- **Transformation Rules**
  - Logical rules, Implementation rules
- **Optimization Goal**
  - Logical Expression, Physical Properties, Estimated Cost
- **Top-down algorithm**
  - Sub-expressions optimized on demand
    - An equivalence class table is maintained
  - Enumerate possible moves
    - Implement operator (LOLEPOP)
    - Enforce property (GLUE)
    - Apply Transformation Rules
  - Select "move" based on promise
  - Branch and bound

Distributed Systems

- **Optimization in Distributed Systems**
  - Communication cost v.s. local processing time
- **Evolution of Distributed Systems**
  - Scalability concerns => Parallel systems
  - Distributed information => Replicated sites

Parallel Database Systems

- **Objective is to minimize response time**
- **Forms of parallelism**
  - Independent, Pipelined, Partitioned
- **Scheduling of operators becomes an important aspect of optimization**
- **Can scheduling be separated from the rest of the query optimization?**

Parallel Database Systems

- **Two step approach:**
  - Generate a sequential plan
  - Apply a scheduling algorithm to "parallelize" the plan
- **The first phase should take into account cost of communication (e.g., repartitioning cost)**
  - Influences partitioning attribute
- **Scheduling algorithm assigns processors to operators**
  - *Symmetric schedule:* assigns each operator equally to each processor
    - suboptimal when communication costs are considered

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Interacting with Optimizer

- **Information on the plan chosen by the optimizer**
  - Showplan (MS), Visual Explain (IBM)
  - Load plan information in tables
- **Optimizer hints to control the nature of plans**
- **Optimization Level**
  - How exhaustive is the search for the "optimal" plan? (greedy v.s. DP join enumeration)
- **Statistics**
  - *Update Statistics*
  - Manual update to statistics (distinct values, frequent values, highest values)

Optimizer Hints

- **Give partial control of execution back to the application developer**
- **Can specify**
  - Join ordering, Join methods, Choice of Indexes
- **Liability**
  - Hard to maintain as software is upgraded or database statistics changes
- **Example**

  Select emp-id
  From Emp (index = 0)
  Where hire-date > '10/1/94'

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Active Areas

- **OLAP**
- **Optimization for ADT**
- **Content Based Retrieval**
- **Old-fashioned problems**

OLAP

- **Spreadsheet paradigm drives the querying model**
- ***Complex* ad-hoc queries over *large* databases**
- **Stress on use of**
  - Indexes
  - Multi-pass SQL
  - Materialized Views
  - Top-k Queries
  - "Helper Constructs"
  - Data Partitioning, Parallelism

Using Indexes

- **Selection**
  - Use single or multi-column indexes
- **Join**
  - Join indexes, Use two clustered indexes
- **Projection**
  - Use as a vertical projection
- **Group By**
  - On-the-fly aggregation
- **Index AND-ing**
  - data scan for fewer pages
  - avoid data scan altogether
- ***How to use the right set of indexes?***

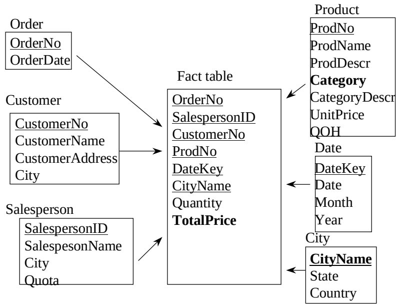
Multi-Pass SQL

- **Backends always cannot digest complex SQL**
- **Middleware ("ROLAP") tool optimizes SQL generation**
  - Creates and maintains materialized views
  - Tuned to backends
  - Defines appropriate temporary relations

Materialized Views

- **View Definitions**
  - Must consider aggregation as part of view definitions
- **Optimization Problem**
  - Choose an equivalent expression over materialized views and tables
  - Appropriate access methods
- **Reminders**
  - Need for a cost-based choice
    - Multiple materialized views may apply
    - Using base table may be better than using cached results!
  - "2-step" algorithms can be significantly worse

Materialized Views over Star Schema



Dominance among Views

- **Use a *more specific* view that and can answer the query**
- **Dominance is a partial order**
- **Need cost-based optimization**
  - Consider a query on (category, state)
  - The view on (product, state)
    - dominates (product, city)
    - does not dominate (category, city)
  - (product, state) and (category,city) are *candidate materialized views* to answer the query

Top K Queries

- **Find k best restaurants in Seattle by … where …**
- **If k is small compared to result size then optimal query plan may be different**
  - Use nested loop instead of sort-merge
  - Use non-clustered index scan instead of sort
  - Alternative row blocking techniques
- Commercial databases provide constructs

Helper Constructs

- **Ensuring "Optimality" of plans not feasible**
- **Provide constructs in language that help optimizer**
  - Does not extend expressivity
  - But, may result in significant performance enhancement
- **Example: Each subtotal requires a separate aggregate query**

	MODEL	
Y E A R		Sum by Year
	Sum By Model	

CUBE and ROLLUP

- **Rollup (order of columns matters)**
  - ***Group By*** product,store,city ***Rollup***
    - Group by product, store, city; Group by product, store; Group by product
- **Cube (order of columns does not matter)**
  - ***Group By*** product,store,city ***Cube***
  - One aggregation on each subset of {product, store, city}:
    - Group by product, store, city; Group by store, city; Group by city, product
    - Cube = A set of Roll-up operations

Optimization for ADT

- **Independent user-defined functions**
  - Select * From Stocks Where stocks.*fluctuation* > .6
  - Associate a per-tuple CPU and IO cost with udf
  - New issues in enumeration
    - Udfs are harder than selections, but easier than relations
- **Relationship among udfs**
  - E.g., Spatial datablade supports related spatial indexes
  - Use rules to specify semantic relationships
  - Cost-based semantic Query Optimization
  - New issues in costing and enumeration
    - Don't generate all equivalent expressions
    - How to use costs uniformly across ADT-s
    - "Mix and match" or "ADT-specific" optimization?

Content Based Retrieval

- **Fuzzy matches**
  - Associate a degree of match with selection
- **Top k fuzzy matches**
  - Only interested in “top 10” matches with a suspect’s sketch
  - Match may involve multiple features
  - How to exploit the specification of for reducing the cost of data access?
  - Related to near neighbor search
- **Relationship to IR work**

Old-fashioned Problems

- **Compile Time v.s. Run time optimization**
  - Choose plan and Exchange
- **Resource governer**
  - Adapting optimization to memory constraints
- **Sensitivity of the cost model**
  - How detailed a cost model needs to be?
- **Client-Server issues**
- **Object models**

Concluding Remarks

- **Many factors determine performance**
  - Query Processing engine
  - Query Optimizer
  - Physical database design
  - Settings of the “knobs”
- **Many open problems**
  - Architectural framework is important
  - Oversimplification may render results useless
  - Need to pay attention to SQL semantics

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