Self-Managing DBMS Technology at Microsoft

Surajit Chaudhuri
Microsoft Research

Acknowledgement

- SQL Product Unit
- AutoAdmin Research Team

Easy Solutions

- **Throw more hardware**
  - **Use this with caution**
  - **Where do you throw hardware?**
- **Rules of Thumb approach**
  - **Finding them is harder than you think**
  - **May simply not exist – oversimplified wrong solutions are not helpful**

Microsoft's Early Focus on Self-Managing Technology

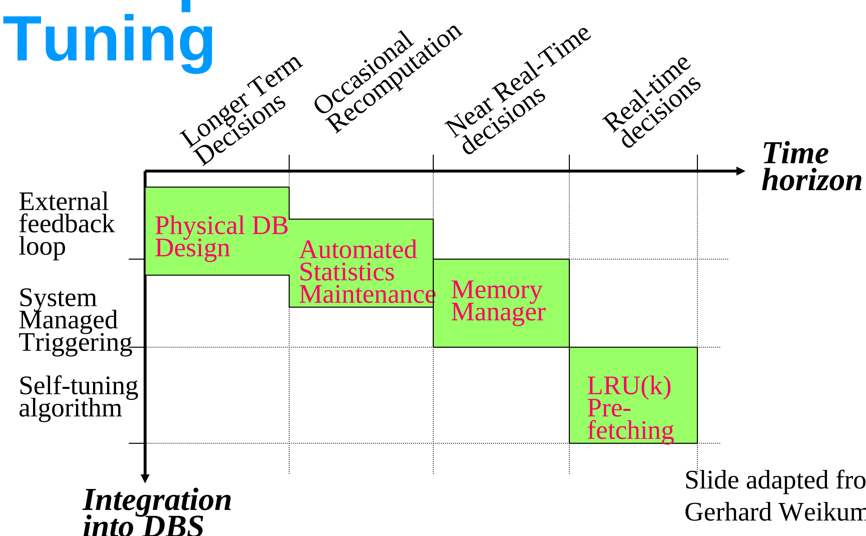
- **1998: SQL Server 7.0 launch towards a self-tuning database system:**
  - Eliminate outright many knobs and provide adaptive control
    - Dynamic Memory Management
    - Auto Stats, Auto Parallelism and Space Management
    - Index Tuning Wizard
- **1996: AutoAdmin Project at Microsoft Research – exclusive focus on self tuning**

Surajit Chaudhuri Microsoft

Key Pillars

- "Observe-Predict-React" Feedback cycle
  - Powerful Monitoring Framework (useful in itself)
  - Local Models for estimating Target (Predict Phase)
  - What-If functionality is a key component of "React"
- Key Characteristics
  - Robustness
  - Transparency

The Spectrum for Self-Tuning



Slide adapted from Gerhard Weikum

Monitoring SQL Server Activities

Microsoft

Monitoring Tools

- Microsoft Operations Manager
  - Track Connectivity, Free space, Long Running Jobs, PERFMON
  - Reporting
- Best Practices Analyzer
  - Detect common oversights in managing a SQL Server installation
  - Simple UI, Rules metadata (70+), Reporting
  - File Compression, File Placement, Index frag
- Dedicated Admin connection in SS 2005
  - Connect even to a “hung” server (uses reserved scheduler, port & resources)

Surajit Chaudhuri

Microsoft

SQL Profiler

- SQL Trace
  - Server side component of the auditing engine
  - Pick Events (plan compilations, index usage,..), Data Columns, Filters
- SQL Profiler
  - GUI tool for SQL Trace
- Event log
  - heap where events are logged
- Trace must be stopped to be queried

Surajit Chaudhuri

Need for More Transparency

- Majority of case time is spent diagnosing the problem (allocation errors, perf degradation)
  - 60% in data collection, 40% in data analysis
- Dependence on Repros
  - Difficult to ID some performance issues
  - Unacceptable to many customers
  - End User experience
- Help requested for cases which don't resolve within 30 mins
  - Full dump requested on ~40%

Surajit Chaudhuri

Dynamic Management Views in SQL Server 2005

- Simple queries now solve many scenarios (Live in memory stats)
  - low level system (server-wide) info such as memory, locking & scheduling
  - Transactions & isolation
  - Input/Output on network and disks
  - Databases and database objects
- Populate a Data Warehouse

Surajit Chaudhuri

Example: Dynamic Management Views

- Sys.dm_exec_requests – currently running requests
- Sys.dm_exec_query_stats
  - One row per query plan currently in the cache
    - Min, max, avg, last;
      - Physical reads, logical reads, physical writes;
    - Execution count; First and last execution times
- “Performance Statistics” Trace event
  - Log “query_stats” for plans which are removed from the cache

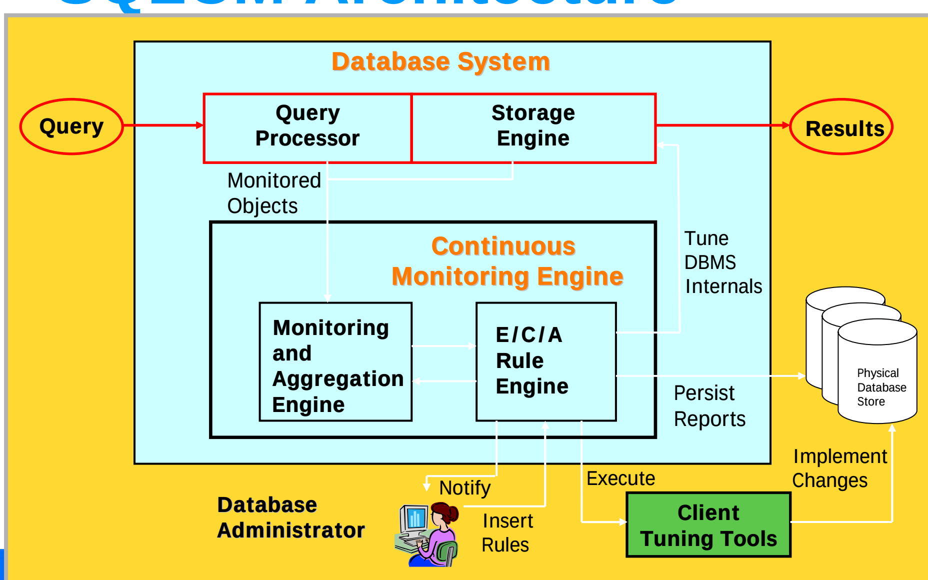
Surajit Chaudhuri

SQLCM Research Project

- SQLCM is implemented inside the DB server
- Grouping/Aggregation can be processed inside the server
  - Actions based on monitored data allow modifications in server behavior
- The programming model to specify monitoring tasks is ECA rules
  - Rules are interpreted, dynamic
  - Expressiveness limited ⇒ low and controllable overhead
- Overcomes problems with push and pull

Surajit Chaudhuri

SQLCM Architecture



Surajit Chaudhuri

Key Ideas in SQLCM

- Logical Query Signature:
  - Extracts tree structure
  - Exact match between signatures
  - Signature cached with query plan
- Lightweight Aggregation Table (LAT) :
  - A set of grouping attributes, Aggregation functions
  - A memory-constraint (in terms of rows/bytes)
  - An ordering column used for eviction
  - LAT-counters may age over time
- Status: AutoAdmin research prototype. Technical details in IEEE ICDE 2003)

Surajit Chaudhuri Microsoft

Workload Analysis

- Variety of tasks leverage workload
  - DBA (ad-hoc analysis)
  - Physical design tuning tools
  - Approximate query processing
- Workload typically gathered by logging events on server
- Workloads can be very large
  - Few DBAs can eyeball 1GB workload file!
  - Few tools can scale
- Need infrastructure for summarizing and analyzing workloads

Surajit Chaudhuri Microsoft

Approaches to Workload Analysis

- Populate a schematized database
- Model as multi-dimensional analysis problem
  - Good for ad-hoc analysis using SQL and OLAP
  - Insufficient support for summarization
- Summarizing Workload:
  - Random sampling
  - Application specific workload clustering (SIGMOD 2002)
    - Plug-in "distance" function, adapt K-Mediod clustering
  - Novel declarative primitives (VLDB 2003)

Surajit Chaudhuri

Estimating Progress of SQL Query Execution

- Decision support systems need to support long running SQL queries
- Today's DBMS provides little feedback to DBA during query execution
- Goal: Provide reliable progress estimator during query execution
  - Accuracy, Fine Granularity, Low Overhead, Monotonicity, Leverage feedback from execution
  - Status: AutoAdmin Research Project and prototype: technical details in SIGMOD 2004

Surajit Chaudhuri

Modeling Total Work

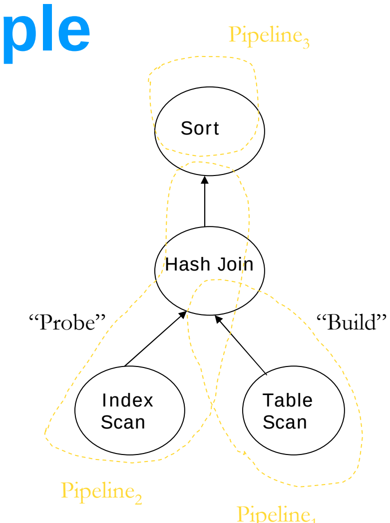
- Want a simpler model than query optimizer's cost estimate
- Query execution engines use iterator model
- Total work = Total number of GetNext() calls
- Let N_i be total number of GetNext() calls for Op_i
- Let K_i be total number of GetNext() calls for Op_i thus far
- Estimator

$$gnm = \frac{\sum_i c_i \cdot K_i}{\sum_i c_i \cdot N_i}$$

where c_i is relative weight of Op

- Problem: Estimating N_i during query execution

Example

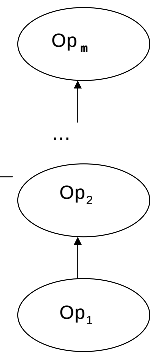


K_i of each operator can be observed exactly during execution

Problem: Estimating N_i (in particular for Hash Join, Sort operators)

Single-Pipeline Queries

- Driver Node: Operator that is "source" of tuples for the pipeline (leaf node)
- Estimator: dne = $\frac{K_1}{N_1}$
- Driver node hypothesis: $\frac{K_1}{N_1} \approx \frac{\sum_i K_i}{\sum_i N_i}$
  - Estimate of N_1 is usually more accurate
  - N_1 may dominate other N_i's, e.g., TPC-H queries
  - Work done per tuple does not vary significantly



Pipeline

Other Key Considerations

- Leverages execution information
  - Observed cardinalities (K_i's)
  - Algebraic properties of operators
  - Internal state of the operator
- Spills due to insufficient memory
  - Model as a new (runtime) pipeline
- Trade-off between guaranteeing monotonicity and accuracy
- Non-uniform weights of operators

Recap of Monitoring Highlights

- Transparency of current server state crucial for easing DBA tasks, supported by DMVs
- Online aggregation of server state can support a monitoring framework (SQLCM)
- Logging of workloads as well as server events using SQL Profiler is crucial for offline analysis
- Tool to estimate progress of queries

Surajit Chaudhuri

Self-Tuning Memory Management

Dynamic Self Tuning Memory Manager

- **SQL 7.0 pioneered idea of dynamic self-tuning memory**
  - Sufficient memory set aside so that Windows and other applications can run without hiccups
  - Amount depends on system load
- **Observe:**
  - Query Windows for the amount of free physical memory periodically
  - Considers page life expectancy for the buffer pool

Surajit Chaudhuri

Self-Tuning Memory Manager

- **Predict:** Available memory compared to required threshold of Target Pages (PERFMON values consulted)
  - No explicit model-based prediction
  - Takes physical memory size into account
- **React:**
  - Keep a given number of free pages (for new allocation requests) at all times
  - Grab if low page life expectancy
  - If memory pressure from OS, free up buffers

Surajit Chaudhuri

Memory Management by Query Execution Engine

- Among competing queries
- Within a query
  - Among parallel threads
  - Nodes of a plan
  - Phases within an operator
- Give each query, once admitted to execution, adequate memory
  - Waiting memory, Waiting operators
  - Preempt on demand

Surajit Chaudhuri

Resolving Memory Pressure

- Identifying Memory Pressure
  - OS level clues not so useful
  - Cache hit ratio, Low Page life expectancy in buffer pool, Free list stalls/s, Physical disk, Memory Grant request queue
- Dig for the cause before adding memory
  - Recompilations, poor physical design – lack of indexes, excessive de-normalization, sloppy SQL update code

Surajit Chaudhuri

Examples of Self-Tuning Features in Storage Engine

Microsoft

Automatic Checkpointing

- Uniform time interval is not ideal
  - Based on number of records in the log
  - Specified recovery interval – max time SQL Server should take for restart
- Log manager estimates if it is time for checkpointing
- For simple recovery model
  - Log 70% full
  - Restart may take more than recovery interval

Surajit Chaudhuri

Microsoft

Storage Engine

- Expanding and Shrinking a Database
  - Specify initial, max sizes and the growth rates
  - Proportional allocation of extents in a filegroup
  - Autoshrink invokes shrink with a free space threshold
- Read-ahead depth for pre-fetching/Write-behind depth for bulk write
- Lock escalation
- Online index creation in SQL Server 2005

Query Engine

- Compilation efficiency
  - Use of Procedure Cache
    - Initial cost based on compilation cost
    - Lazywriter sweep for maintenance
  - Conservative Auto-parameterization
    - Select fname, lname, sal from emp where eid = 6
    - Select fname, lname, sal from emp where eid = @e
- Degree of Parallelism dynamically chosen based on runtime conditions
  - CPU, concurrency, memory
- Auto-select exhaustiveness of optimization

Self-Tuning for Statistics Management

Why Statistics Management?

- Having “right” statistics is crucial for good quality plans.
  - When to build statistics?
  - Which columns to build statistics on?
  - How to build statistics on any column efficiently?

Auto Statistics in SQL Server

- Created dynamically at query compilation time
- On single table columns for which optimizer needs to estimate distribution
- Uses sampling of data to create statistics
- Statistics auto-maintained
- Novel feature supported since SQL Server 7.0

Uniform vs. Block-Level Sampling

- Uniform random sampling is too expensive.
- Block-level sampling:
  - Pick a few blocks at random and retain all tuples in those
- Block level sampling is efficient but tuples may be placed in blocks arbitrarily
  - Reduced quality of the resulting estimate

AutoUpdate of Statistics

- Triggered by Query Optimization
  - Involves only a subset of the columns in the query
- Refreshed when a certain fraction (roughly) of the rows have been modified
  - Uses rowmodctr information to check if threshold has been reached
- Statistics that are auto-created are aged and retired if appropriate.

Lazy Scheduling

- AutoStat and its refresh adds to the cost of the query compilation
- For some applications with large tables, this presents a choice between a poor plan and a high cost of compilation
- SQL Server 2005 offers asynchronous auto stats
  - The “current” query will be optimized with the existing statistics
  - However, an asynchronous task to build the statistics will be posted

Frontiers for Further Thinking

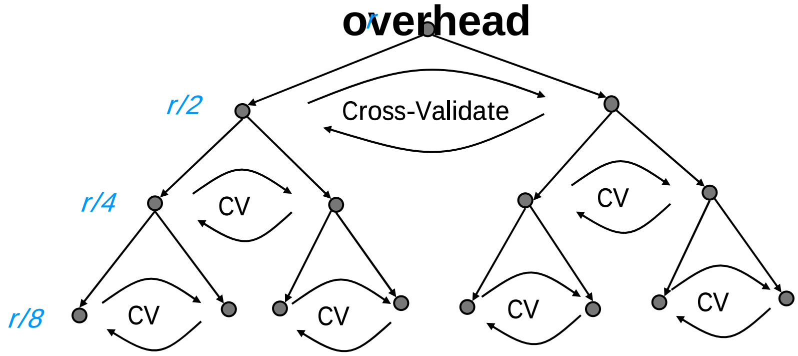
- Determining the appropriate Block Level Sampling
- Identifying the interesting subset of statistics for a query
- Statistics on views and query expressions
- Leveraging execution feedback
- Remaining slides in this part are on some research ideas being pursued at Microsoft

Adaptive 2-phase approach for Block Level Sampling

- Get initial sample
- While sorting get error estimate for *r/2*, *r/4*, *r/8* … etc.
- Find the best-fit curve of the form c/sqrt(r) through these points
  - Read off the required sample size
  - Experimentally found to almost always reach the error target or very close.
- AutoAdmin research prototype, SIGMOD 2004

Cross-Validation and Sorting

A way to get lots of estimates at little overhead



Surajit Chaudhuri

Recommending Base-Table Statistics

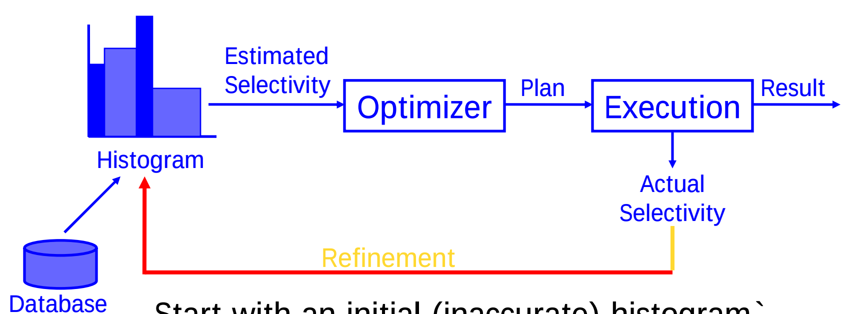
- Find subset as good as having all statistics (“essential” set)
  - Depends on workload, data distribution, optimizer…
- Determining an essential set is non-trivial.
  - “Chicken-and-egg” problem: cannot tell if additional statistics are necessary until we actually build them!
  - Need a test for equivalence *without* having to build any new statistics

Surajit Chaudhuri

Our Contribution: MNSA

- Research Prototype: [IEEE ICDE 2000]
- Builds essential sets of statistics.
  - t-Optimizer-Cost equivalence:Cost (Q, All-stats) and Cost (Q, Current-stats) are within t% of each other.
  - Varies magic numbers using monotonicity property.
  - If cost differ => need more statistics => choose stats for more expensive operators.

Exploiting Execution Feedback: Self-tuning Histograms



Start with an initial (inaccurate) histogram`
and refine it based on feedback

Self Tuning Histograms: STGrid and STHoles

- Assume uniformity and independence until execution feedback shows otherwise (no data set examination)
- Exploit workload to allocate buckets.
- Query feedback captures uniformly dense regions
- Differences: Bucket structure and refining
  - STGrid: Multidimensional Grid [SIGMOD'99].
  - STHoles: Bucket nesting [SIGMOD'01].

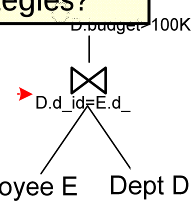
Surajit Chaudhuri

Are base-table statistics sufficient?

- **Statistics are usually propagated through complex query plans.**

Can we do better than current strategies?

```
SELECT E.name
FROM Employee E, Dept D
WHERE E.d_id=D.d_id AND
      D.budget>100K
```

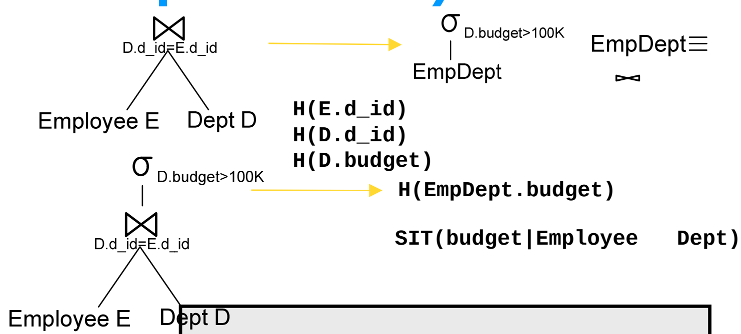


H(Employee.d_id)
H(Dept.d_id)
H(Dept.budget)

Surajit Chaudhuri

[SIGMOD'02, ICDE'03, VLDB'03, SIGMOD'04]

Statistics on Views (Query Expressions)

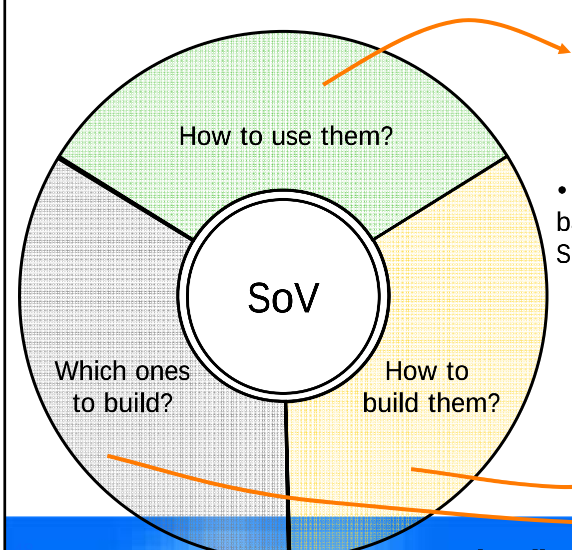


We do not need to materialize EmpDept!
(We just need the histogram)

Surajit Chaudhuri

Microsoft

SoV/SIT Challenges



Leverages view matching techniques to incorporate SITS into an existing optimizer

• Workload and feedback based technique to identify SITs to materialize

•Online based on execution feedback

•Sweep algorithms to efficiently materialize classes of SITs

Surajit Chaudhuri

Microsoft

Self-Tuning Physical Database Design

Microsoft

Microsoft SQL Server Milestones

- SQL Server 7.0: Ships index tuning wizard (1998): Industry's first
- SQL Server 2000: Integrated recommendations for indexes and materialized (indexed) Views: Industry's first
- SQL Server 2005: Integrated recommendations for indexes, materialized views, and partitioning, offering time bound tuning, Industry's first
- Results of collaboration between AutoAdmin Research and the SQL Server teams

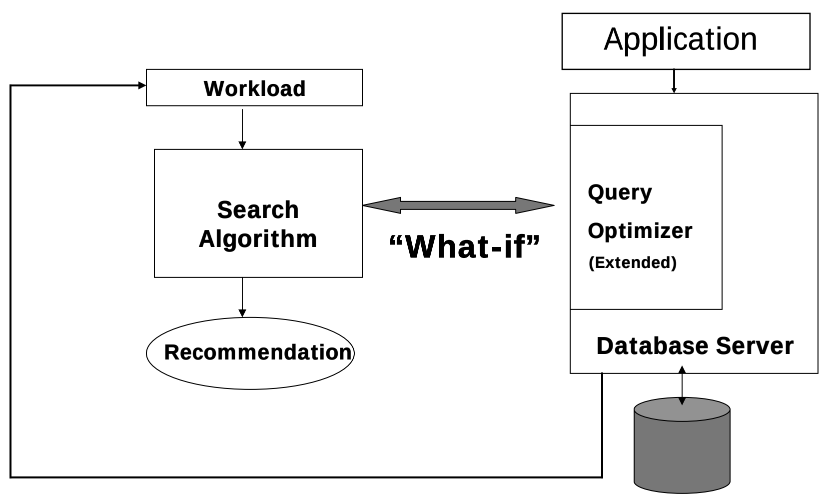
Surajit Chaudhuri

Microsoft

Key Insights

- Robustness was a design priority
- Every system is different – track workloads (VLDB 1997)
- “What-If” API for DBMS (SIGMOD 1998) is key to driving selection of physical design
- Efficient search for physical design (VLDB 1997, 2000, 2004)
- Significant thinking on system usability (VLDB 2004)

“What-If” Architecture Overview



"What-If" Analysis of Physical Design

- Estimate quantitatively the impact of physical design on workload
  - e.g., if we add an index on T.c, which queries benefit and by how much?
- Without making actual changes to physical design
    - Time consuming
    - Resource intensive
- Search efficiently the space of hypothetical designs

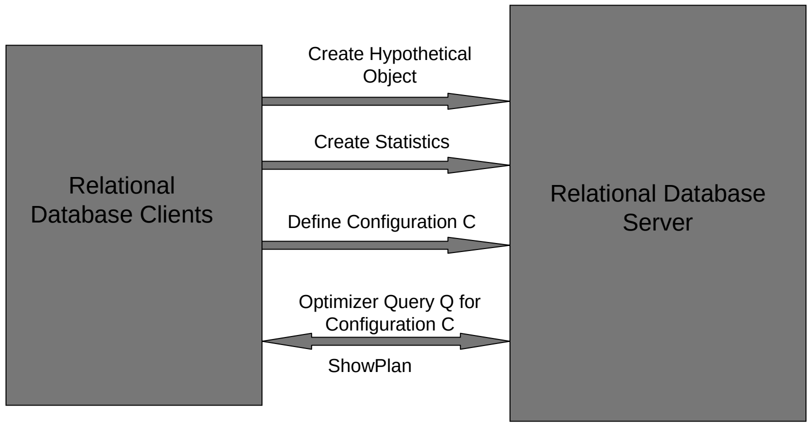
Surajit Chaudhuri

Realizing "What-If" Indexes

- Query Optimizer decides which plan to choose given a physical design
- Query optimizer does not require physical design to be materialized
  - Relies on statistics to choose right plan
    - Sampling based techniques for building statistics
- Sufficient to fake existence of physical design

Surajit Chaudhuri

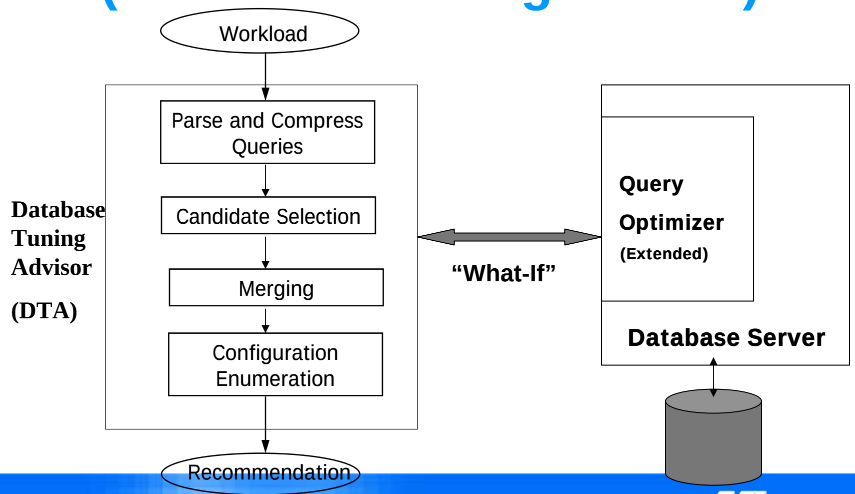
Using What-If Analysis



Physical Database Design: Problem Statement

- Workload
  - queries and updates
- Configuration
  - A set of indexes, materialized views and partitions from a search space
  - Cost obtained by “what-if” realization of the configuration
- Constraints
  - Upper bound on storage space for indexes
- Search: Pick a configuration with lowest cost for the given database and workload.

Database Tuning Advisor (aka Index Tuning Wizard)



Surajit Chaudhuri

Some Key Ideas

- Prefiltering of search space
  - Adapt cost-based frequent itemset idea from data mining (VLDB 2000)
- Quantitative analysis at per query level to isolate candidates
- Watch out for over-fitting
  - View Merging
- Search Efficiency crucial
  - Server bears the cost of "searching" as we ping the optimizer,
- Robustness – unaffected by most optimizer changes

Surajit Chaudhuri

DTA for Microsoft SQL Server 2005

- Time bound tuning
  - Complete tuning in batch window
- Range partitioning recommendations
  - Integrated Recommendation with Indexes and MVs
  - Manageability: Can recommend "Aligned" partitioning
- User-specified configuration (USC)
  - Exposes "What-if" analysis
  - Manageability: Allows specifying partial configuration for tuning
- Input/Output via XML
  - Public schema: http://schemas.microsoft.com/sqlserver/2004/07/dta/dtaschema.xsd
  - More scriptable
  - Easy for ISVs to build value added tools on top

Surajit Chaudhuri

Microsoft

DTA: Microsoft SQL Server 2005

- Production/Test Server Tuning
  - Exploit test server to reduce tuning load on production server
  - Recommendation same as if tuning done on production server
  - Servers need not be H/W identical
- Improved Performance and Scalability
  - Workload compression
  - Reduced statistics creation
  - Exploit multiple processors on server
  - Scaling to large schema
  - Multi-database tuning
- Recommends online indexes
- Drop-only mode
  - Clean up unused indexes, MVs
- More details in VLDB 2004 paper

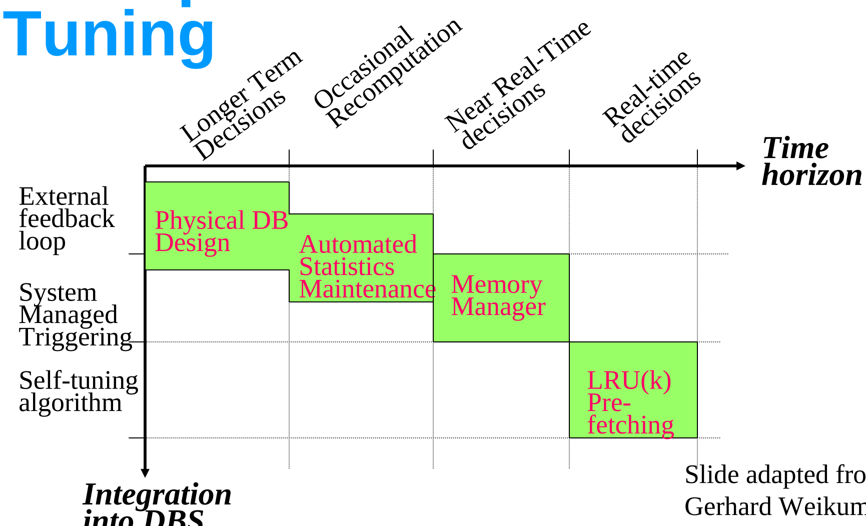
Surajit Chaudhuri

Microsoft

Lessons for Self-Tuning and Rethinking System Design

Microsoft

The Spectrum for Self-Tuning



Slide adapted from Gerhard Weikum

Surajit Chaudhuri

Microsoft

Principles for Self Tuning

- Complex problems have simple, easy to understand wrong answers
- "Observe-Predict-React" cycle can only be implemented locally
  - Develop self-tuning, adaptive algorithms for individual tuning tasks
  - Need robust models – when and how
- Global knowledge necessary for identification of bottlenecks
- Watch out for too many Tuning parameters

Surajit Chaudhuri

Rethinking Systems: Wishful Thinking?

- **VLDB 2000 Vision paper (Chaudhuri and Weikum 2000)**
- **Enforce Layered approach and Strong limits on interaction (narrow APIs)**
  - **Package as components of modest complexity**
  - **Encapsulation must be equipped with self-tuning**
- **Featurism can be a curse**
  - **Don't abuse extensibility - Eliminate 2nd order optimization**

Surajit Chaudhuri

Final Words

- **Self-Tuning servers crucial for bounding cost**
  - Policy based adaptive control "observe-predict-react"
  - Monitoring infrastructure
  - Leveraging Workload
  - What-if analysis
  - Deep understanding of local systems
- **Microsoft SQL Server encapsulates significant self-tuning technology**
- **Ongoing work in SQL Server and AutoAdmin research projects**

Microsoft SQL Server Self Tuning Technology Talks

- Vivek Narasayya "Database Tuning Advisor for Microsoft SQL Server 2005" (Industrial Session 4, Thu)
- David Campbell "Production Database Systems: Making Them Easy is Hard Work" (industrial Session 6, Thu)

Self-Tuning Overview Papers

- Chaudhuri S., Christensen E., Graefe G., Narasayya V., and Zwilling, M. Self-Tuning Technology in Microsoft SQL Server. *IEEE Data Eng. Bull. 22(2): 20-26 (1999)*
- Chaudhuri S. and Weikum G., Rethinking Database System Architecture: Towards a Self-tuning, RISC-style Database System. *VLDB 2000*.
- AutoAdmin Research Project Website: http://research.microsoft.com/dmx/AutoAdmin
- SQL Product Home http://www.microsoft.com/sql

Surajit Chaudhuri

Self-Tuning Physical Design

- Chaudhuri S. and Narasayya V., An Efficient Cost-Driven Index Selection Tool for Microsoft SQL Server. *VLDB 1997.*
- Chaudhuri, S. and Narasayya V., AutoAdmin "What-If" Index Analysis Utility. *SIGMOD*, 1998.
- Chaudhuri S. and Narasayya V. , Index Merging. *ICDE 1999*.
- Agrawal S., Chaudhuri S. and Narasayya V., Automated Selection of Materialized Views and Indexes for SQL Databases. *VLDB 2000.*
- Agrawal S., Narasayya V., and Yang, B. Integrating Vertical and Horizontal Partitioning into Automated Physical Database Design. *SIGMOD 2004*.
- Agrawal S., Chaudhuri S., Kollar L., Marathe A., Narasayya V. and Syamala M. Database Tuning Advisor for Microsoft SQL Server 2005. *VLDB 2004.*

Surajit Chaudhuri

Statistics Management

- Aboulnaga, A. and Chaudhuri, S., Self-Tuning Histograms: Building Histograms Without Looking at Data. *SIGMOD* 1999.
- Chaudhuri S. and Narasayya V. , Automating Statistics Management for Query Optimizers. *ICDE 2000.*
- Bruno N., Chaudhuri S. and Gravano L. STHoles: A Multidimensional Workload-Aware Histogram. *SIGMOD 2001*.
- Bruno N., and Chaudhuri S. Exploiting Statistics on Query Expressions for Optimization. *SIGMOD 2002*.
- Bruno N., and Chaudhuri S. Efficient Creation of Statistics over Query Expressions. *ICDE 2003.*
- César A. Galindo-Legaria, Milind Joshi, Florian Waas, Ming-Chuan Wu, Statistics on Views. *VLDB 2003*
- Bruno N. and Chaudhuri S. Conditional Selectivity for Statistics on Query Expressions. *SIGMOD 2004.*
- Chaudhuri S., Das G., and Srivastava U. Effective Use of Block-Level Sampling in Statistics Estimation. *SIGMOD 2004.*

Monitoring and Workload Analysis and Management

- Chaudhuri S., König, A., and Narasayya V. SQLCM: A Continuous Monitoring Framework for Relational Database Engines. *ICDE 2004.*
- Chaudhuri S., Narasayya V., and Ramamurthy, R. Estimating Progress of Execution for SQL Queries. *SIGMOD 2004.*
- Chaudhuri S., Gupta A., and Narasayya V. Compressing SQL Workloads. *SIGMOD* 2002.
- Chaudhuri S., Ganesan P., and Narasayya V. Primitives for Workload Summarization and Implications for SQL. *VLDB 2003*