The DB2 Universal Database Optimizer

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Agenda

- **Overview of Query Processing**
- **Query ReWrite**
- **Plan Selection Optimization**
  - Elements of Optimization
    - Execution Strategies
    - Cost model & plan properties
    - Search strategy
  - Parallelism
  - Special strategies for OLAP & BI
  - Engineering considerations
- **Conclusions and Future**

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Many platforms, but one codebase!
- Software: Unix/Linux (AIX, HP,Sun, Linux), Windows, Sequent, OS/2
- Hardware: Uni, SMP, MPP, Clusters, NUMA

Database volume ranges continue to grow: 1GB to >100TB

Increasing query complexity:
- OLTP → DSS → OLAP / ROLAP
- SQL generated by query generators, naive users

Managing complexity
- Fewer skilled administrators available
  - distributed systems
  - database design can be complex
- Too many knobs !
  - configuration parameters
  - flavors of optimization

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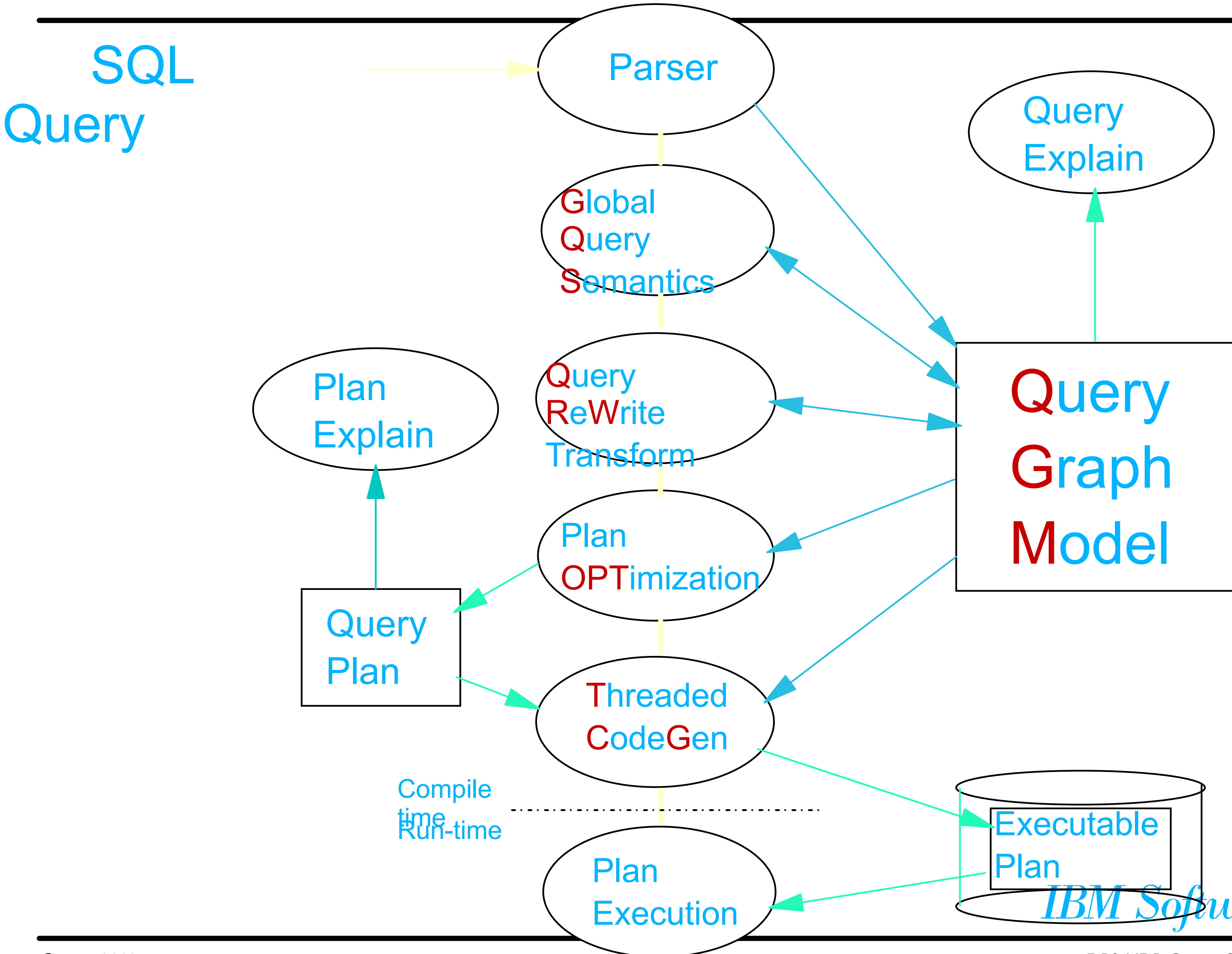
Query Compiler Overview



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Elements of Query Compilation

Parsing
- Analyze "text" of SQL query
- Detect syntax errors
- Create internal query representation

Semantic Checking
- Validate SQL statement
- View analysis
- Incorporate constraints, triggers, etc.

Query Optimization
- Modify query to improve performance (Query Rewrite)
- Choose the most efficient "access plan" (Query Optimization)

Code Generation
- Generate code that is
  - executable
  - efficient
  - re-locatable

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Query Graph Model (QGM)

- **Captures the entire semantics of an SQL query to be compiled**
- **"Headquarters" for all knowledge about compiling a query**
- **Represents internally that query's:**
  - ✓ **Entities (e.g. tables, columns, predicates,...)**
  - ✓ **Relationships (e.g. "ranges-over", "contains", ...)**
- **Has its own schema**
  - Entity-Relationship (ER) model
- **Visualized as a Data Flow Model**
  - **Boxes (nodes) represent table operations**
  - **Rows flow through the graph**
- **Implemented as a C++ library**
  - Facilitates construction, use, and destruction of QGM entities
- **Designed for flexibility**
  - Easy extension of SQL Language (i.e. SELECT over IUDs)

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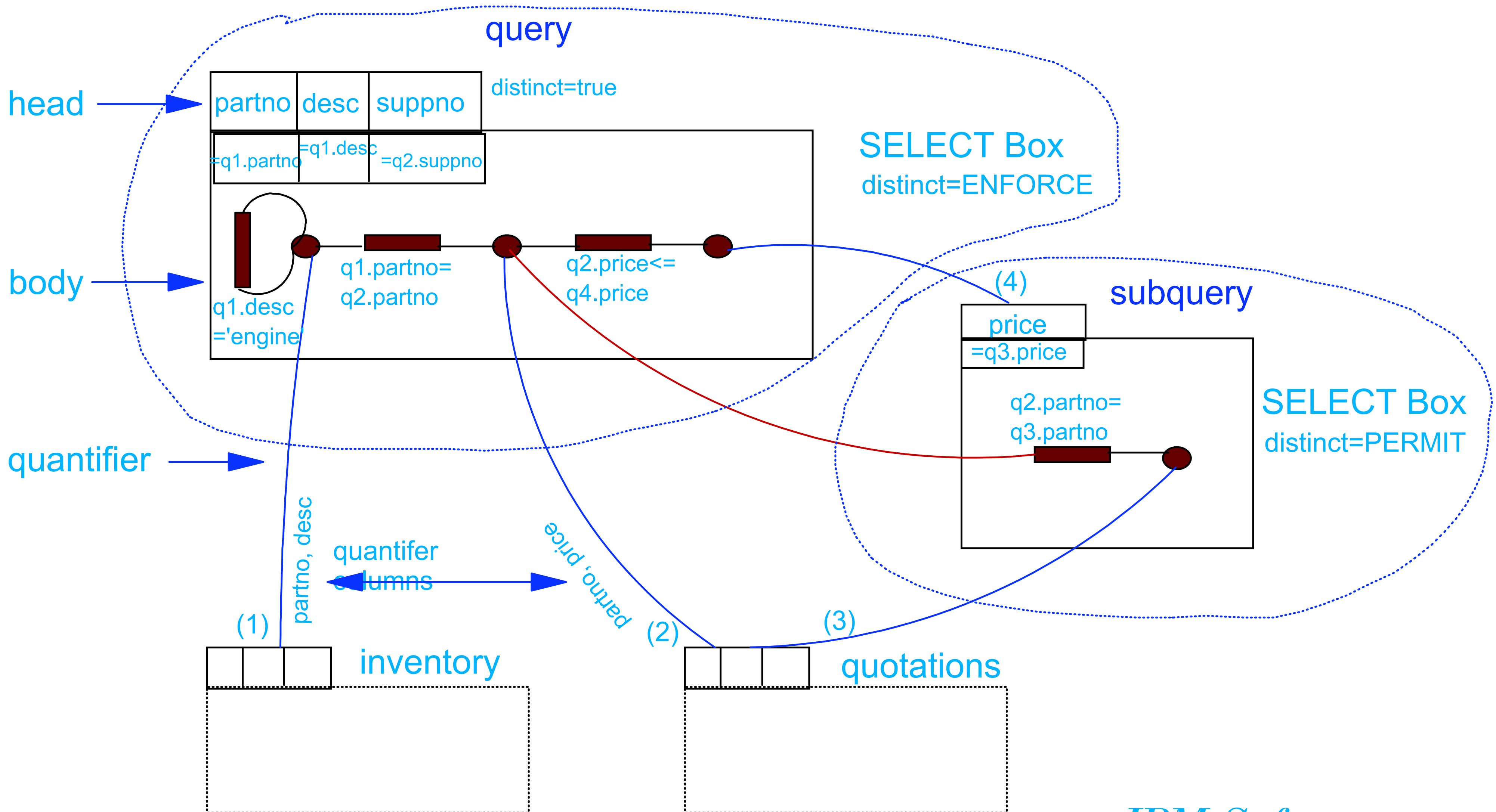
Example QGM for a Query

```
SELECT DISTINCT q1.partno, q1.descr, q2.suppno
FROM inventory q1, quotations q2
WHERE q1.partno = q2.partno
      AND q1.descr = 'engine'
      AND q2.price <= ALL
            ( SELECT q3.price
              FROM quotations q3
              WHERE q2.partno = q3.partno
            );
```

QGM Graph (after Semantics)



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Query Rewrite - An Overview

What is Query Rewrite?

- Rewriting a given SQL query into a **semantically equivalent** form that
  - may be processed more efficiently
  - gives the Optimizer more latitude

Why?

- **Same query may have multiple representations in SQL**
- **Complex queries often result in redundancy, especially with views**
- **Query generators**
  - **often produce suboptimal queries that don't perform well**
  - **don't permit "hand optimization"**

Based on Starburst Query Rewrite

- **Rule-based query rewrite engine**
- **Transforms legal QGM into more efficient QGM**
- **Some transformations aren't always universally applicable**
- **Has classes of rules**
- **Terminates when no rules eligible or budget exceded**

Query Rewrite - A VERY Simple Example

Original Query:

select **distinct** custkey, name from TPCD.CUSTOMER

After Query Rewrite:

select custkey, name from TPCD.CUSTOMER

Rationale:

custkey is unique, distinct is redundant

Query Rewrite - Operation Merge

- **Goal: give Optimizer maximum latitude in its decisions**
- **Techniques:**
  - view merge
    - makes additional join orders possible
    - can eliminate redundant joins
  - subquery-to-join transformation
    - removes restrictions on join method/order
    - improves efficiency
  - redundant join elimination
    - satisfies multiple references to the same table with a single scan

Query Rewrite: Subquery-to-Join Example:

Original Query:

```
SELECT ps.*
FROM    tpcd.partsupp ps
WHERE ps.ps_partkey IN
             (SELECT p_partkey
              FROM tpcd.parts
              WHERE p_name LIKE 'forest%');
```

Rewritten Query:

```
SELECT ps.*
FROM parts, partsupp ps
WHERE ps.ps_partkey = p_partkey AND
             p_name LIKE `forest%';
```

NOTE: Unlike Oracle, DB2 can do this transform, even if p_partkey is NOT a key!

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Query Rewrite - Operation Movement

- **Goal: minimum cost / predicate**
- **Techniques:**
  - Distinct Pushdown
    - Allow optimizer to eliminate duplicates early, or not
  - Distinct Pullup
    - to avoid duplicate elimination
  - Predicate Pushdown
    - apply more selective and cheaper predicates early on;
    - e.g., push into UNION, GROUP BY

Query Rewrite - Predicate Pushdown Example

Original query:

```
CREATE VIEW lineitem_group(suppkey, partkey, total)
AS SELECT l_suppkey, l_partkey, sum(quantity)
     FROM    tpcd.lineitem
     GROUP BY l_suppkey, l_partkey;

SELECT *
FROM lineitem_group
WHERE suppkey = 1234567;
```

Rewritten query:

```
CREATE VIEW lineitem_group(suppkey, partkey, total)
AS SELECT l_suppkey, l_partkey, sum(quantity)
     FROM     tpcd.lineitem
   WHERE    l_suppkey = 1234567
   GROUP BY l_suppkey, l_partkey;


SELECT *
FROM lineitem_group;
```

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Query Rewrite - Predicate Translation

- **GOAL: optimal predicates**
- **Examples:**

  - Distribute NOT
    - ... WHERE NOT(COL1 = 10 OR COL2 > 3)
      becomes
    - ... WHERE COL1 <> 10 AND COL2 <= 3
  - Constant expression transformation:
    - ...WHERE COL = YEAR(`1994-09-08')
      becomes
    - ... WHERE COL = 1994
  - Predicate transitive closure
    given predicates:
    - T1.C1 = T2.C2, T2.C2 = T3.C3, T1.C1 > 5
      add these predicates...
    - T1.C1 = T3.C3 AND T2.C2 > 5 AND T3.C3 > 5
  - IN-to-OR conversion for Index ORing
  - and many more...

Optimizer Key Objectives

- **Extensible (technology from Starburst)**
  - Clean separation of execution "repertoire", cost eqns., search algorithm
  - Cost & properties modularized per operator
    ==> easier to add new operators, strategies
  - Adjustable search space
  - Object-relational features (user-defined types, methods)
- **Parallel (intra-query)**
  - CPU and I/O (e.g., prefetching)
  - (multi-arm) I/O (i.e., striping)
  - Shared-memory (i.e., SMP)
  - Shared-nothing (i.e. MPP with pre-partitioned data)
- **Powerful / Sophisticated**
  - OLAP support
    - Star join
    - ROLLUP
    - CUBE
  - Recursive queries
  - Statistical functions (rank, linear recursion, etc.)
  - and many more...

What does the Query Optimizer Do?

Generates & Evaluates alternative

- Operation order
  - joins
  - predicate application
  - aggregation
- Implementation to use:
  - table scan vs. index scan
  - nested-loop join vs. sorted-merge join
- Location (in partitioned environments)
  - co-located
  - re-direct each row of 1 input stream to appropriate node of the other stream
  - re-partition both input streams to a third partitioning
  - broadcast one input stream to all nodes of the other stream

Estimates the execution of that plan

- number of rows resulting
- CPU, I/O, and memory costs
- Communications costs (in partitioned environments)

Selects the best plan, i.e. with minimal

- total resource consumption (normally)
- elapsed time (in parallel environments, OPTIMIZE FOR N ROWS)

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Inputs to Optimizer

System catalogs
- Schema, including constraints
- Statistics on tables, columns, indexes, etc.

Configuration parameters, e.g.
- speed of CPU
  - determined automatically at database creation time
  - runs a timing program
- storage device characteristics
  - used to model random and sequential I/O costs
  - set at table-space level
  - overhead (seek & average rotational latency)
  - transfer_rate
- communications bandwidth
  - to factor communication cost into overall cost, in partitioned environments

Memory resources
- buffer pool(s)
- sort heap

Concurrency Environment
- average number of users
- isolation level / blocking
- number of available locks

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Major Aspects of Query Optimization

1. Alternative Execution Strategies (methods)

- ★ Rule-based generation of plan operators
- ★ Creates alternative
  - ➤ Access paths (e.g. indexes)
  - ➤ Join orders
  - ➤ Join methods

2. Cost Model

- ★ Number of rows, based upon
  - ➤ Statistics for table
  - ➤ Selectivity estimate for predicates
- ★ Properties & Costs
  - ➤ Determined per operator type
  - ➤ Tracked per operator instance (cumulative effect)
- ★ Prunes plans that have
  - ➤ Same or subsumed properties
  - ➤ Higher cost

3. Search Strategy

- ★ Dynamic Programming vs. Greedy
- ★ Bushy vs. Deep

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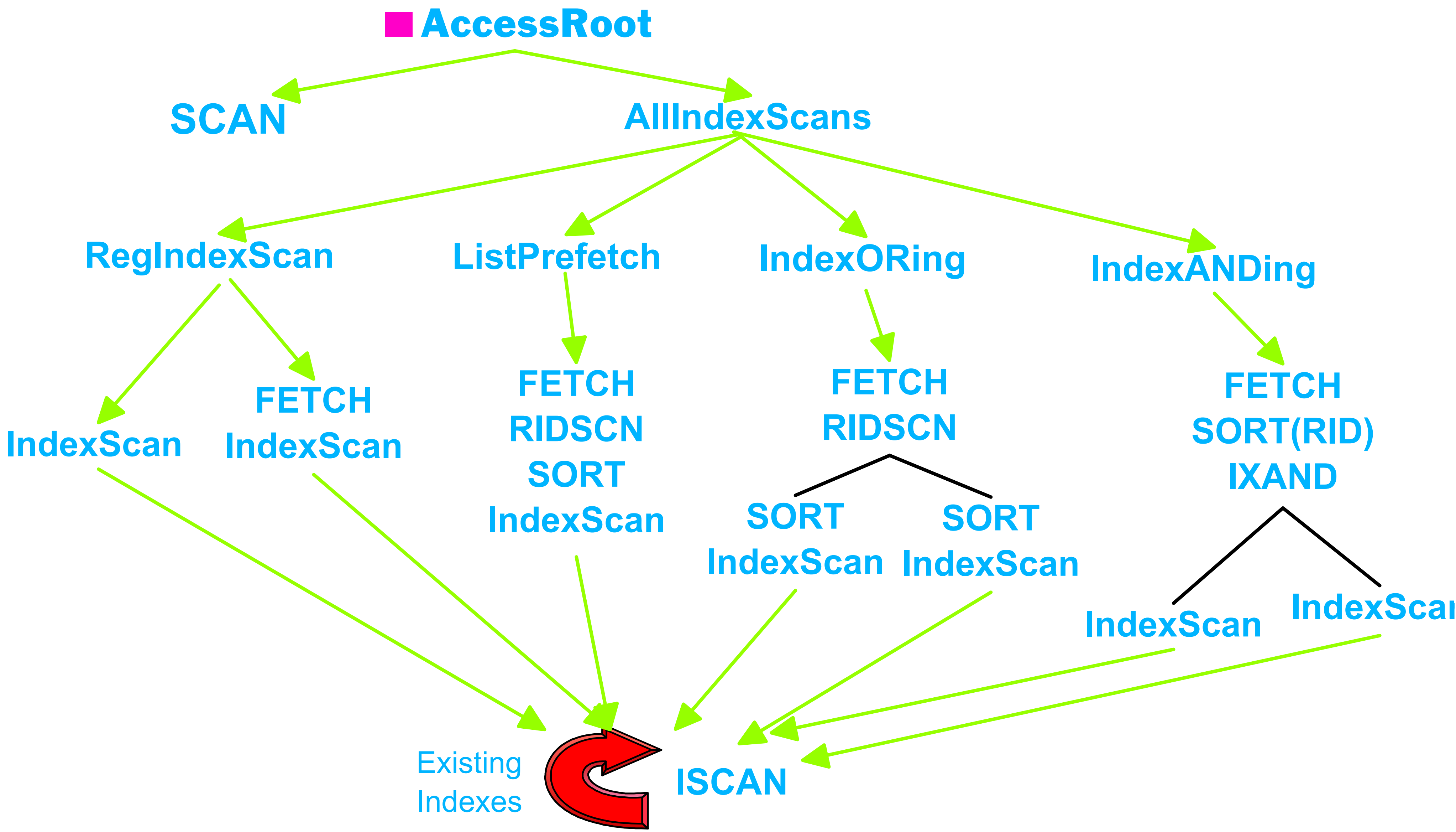
Generation of Table Access Alternatives



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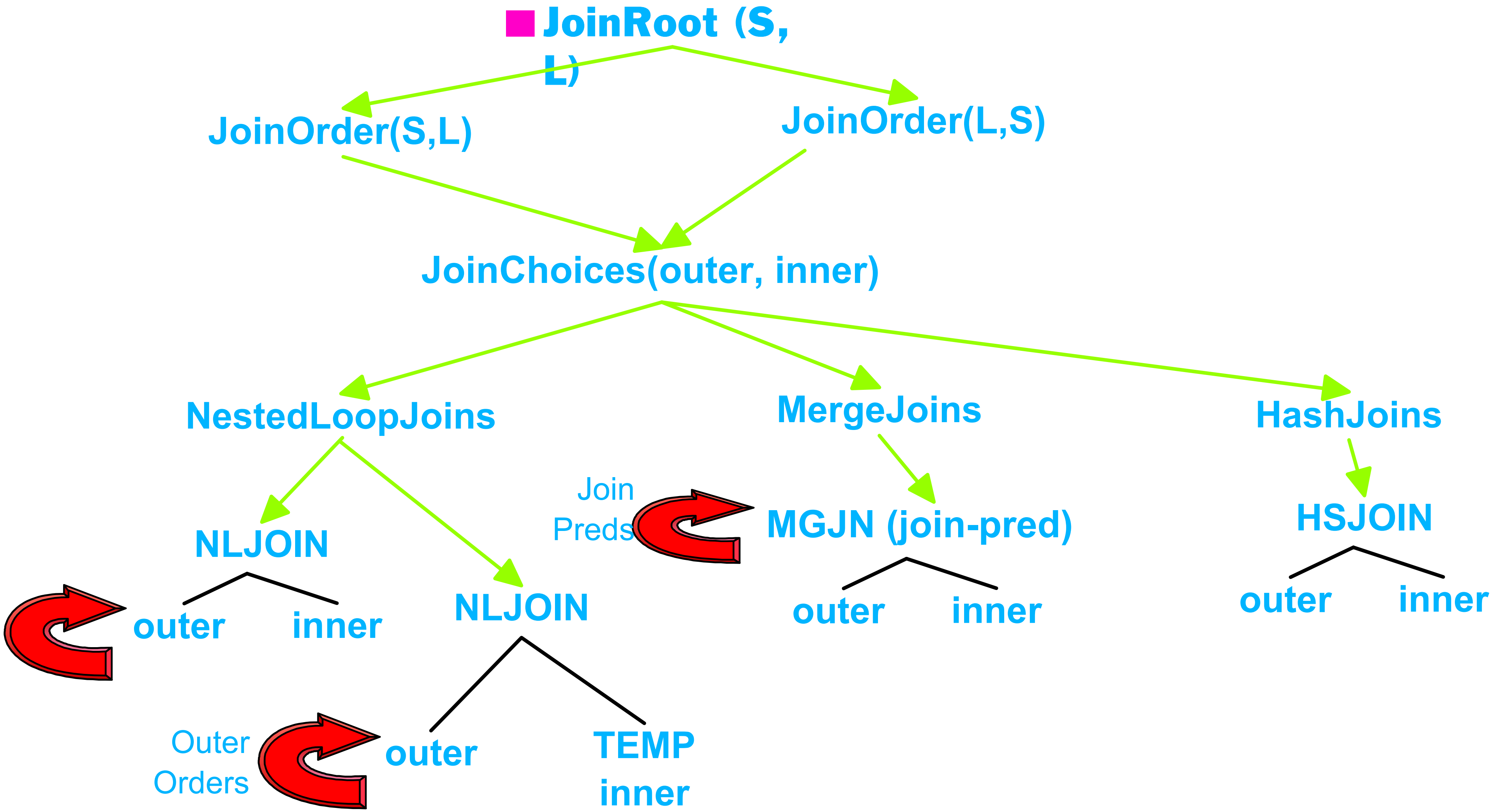
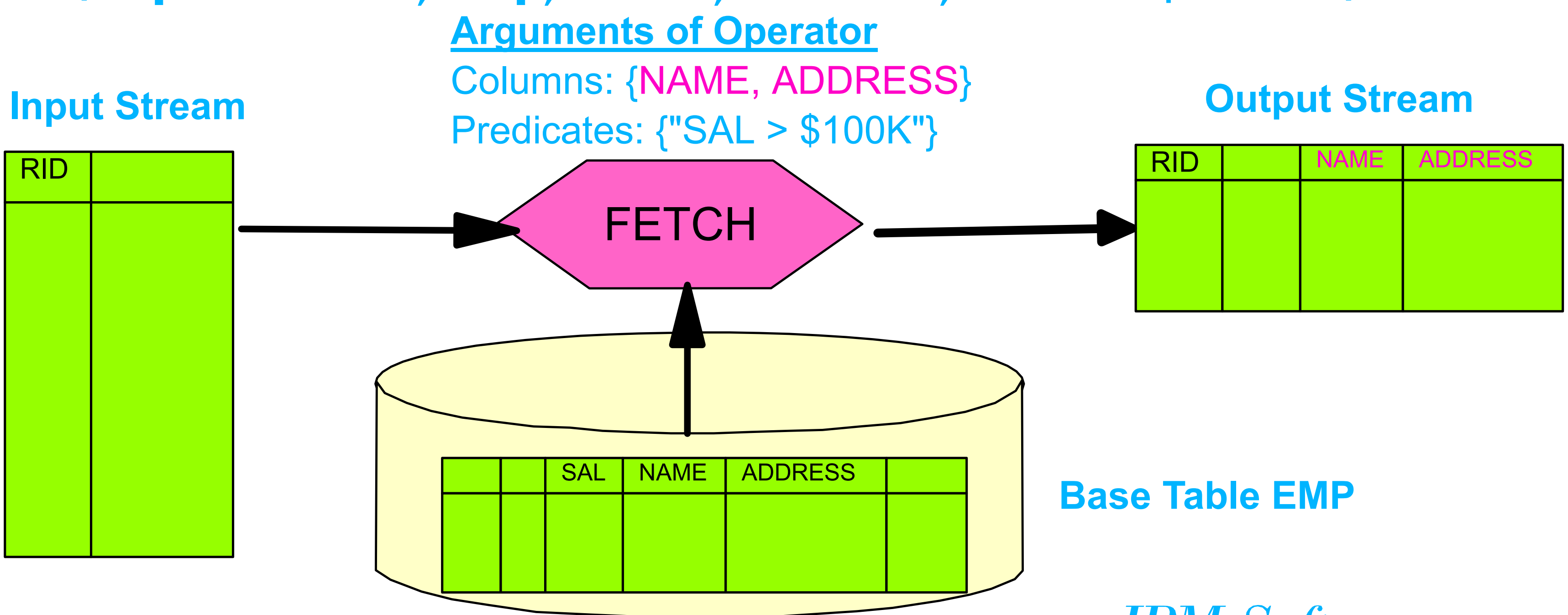
Generation of Join Alternatives



Atomic Object: LOw-LEvel Plan OPerator (LOLEPOP)

- **Database operator, interpreted at execution time**
- **Operates on, and produces, tables (visualized as in-memory streams of rows)**
- **Examples:**
  - Relational algebra (e.g. JOIN, UNION)
  - Physical operators (e.g. SCAN, SORT, TEMP)
- **May be expressed as a function with parameters, e.g. FETCH(<input stream>, Emp, {Name, Address}, {"SAL > $100K"})**



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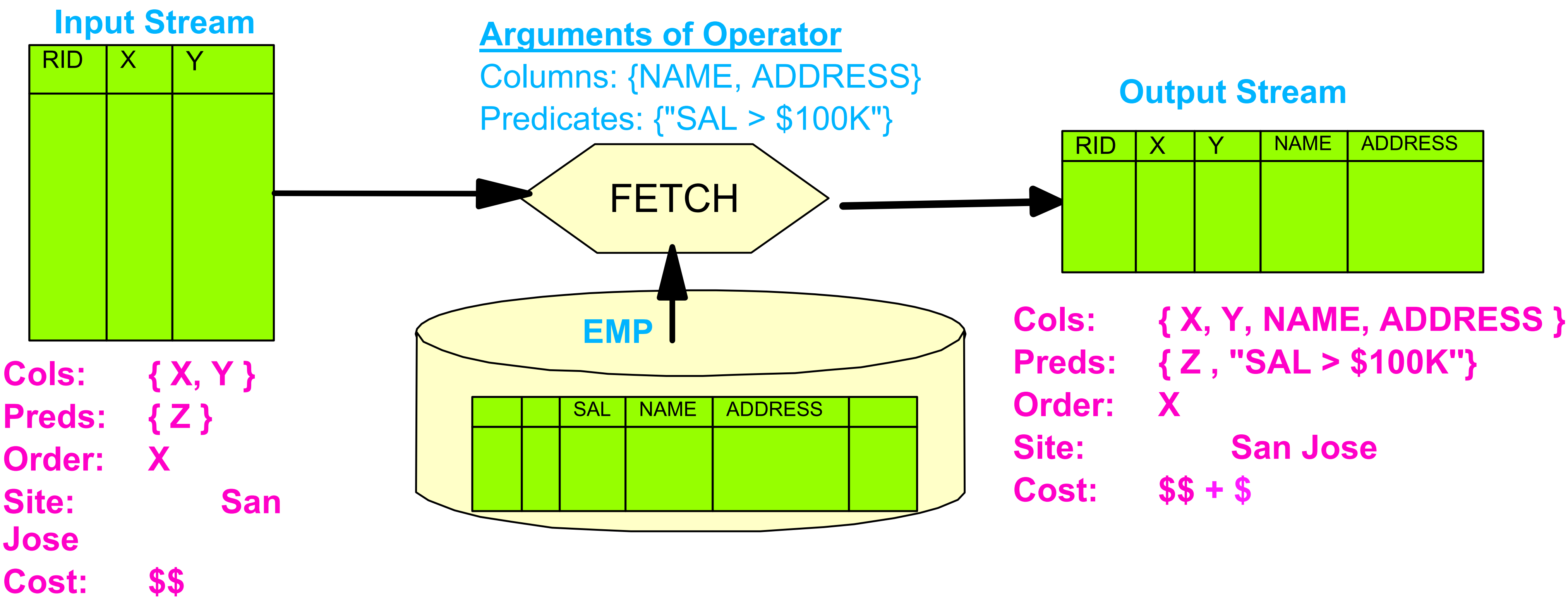
Properties of Plans



- **Give <u>cumulative, net result</u> (including cost) of work done in plan instance**
- **Initially obtained from statistics in catalogs for stored objects**
- **Altered by effect of LOLEPOP type (e.g., SORT alters ORDER property)**
- **Specified in Optimizer by property and cost functions for each LOLEPOP**

Example Properties

- **Relational ("What?")**
  - Tables (quantifiers) accessed
  - Columns accessed
  - Predicates applied
  - Correlation columns referenced
  - Keys -- columns on which rows distinct
  - Functional dependencies
- **Physical ("How?")**
  - Columns on which rows ordered
  - Columns on which rows partitioned (partitioned environment only)
  - Physical site (DataJoiner only)
- **Derived ("How much?")**
  - Cardinality (estimated number of rows)
  - Maximum provable cardinality
  - Estimated cost, including separated:
    - Total cost
    - CPU (# of instructions)
    - I/O
    - Re-scan costs
    - 1st-row costs (for OPTIMIZE FOR N ROWS)
- **Flags, e.g. Pipelined, Halloween, etc.**

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Optimizer Cost Model

- **Differing objectives: Minimize...**
  - Elapsed time, in parallel environments, OPTIMIZE FOR N ROWS
  - Total resources, otherwise
- **Combines components of estimated**
  - CPU (# of instructions)
  - I/O (random and sequential)
  - Communications (# of IP frames)
    - Between nodes, in partitioned environments
    - Between sites, in DataJoiner environments
- **Detailed modeling of**
  - Buffer needed vs. available, hit ratios
  - Rescan costs vs. build costs
  - Prefetching and big-block I/O
  - Non-uniformity of data
  - Operating environment (via configuration parameters)
  - First tuple costs (for OPTIMIZE FOR N ROWS)

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Catalog Statistics Used by the Optimizer

- **Basic Statistics**
  - no. of rows/pages in table
  - for each column in a table, records
    - # distinct data values, avg. length of data values, data range information
  - for each index on a table,
    - # key values, # levels, # leaf pages, etc.
- **Non-uniform distribution statistics ("WITH DISTRIBUTION")**
  - N most frequent values (default 10)
    - good for equality predicates
  - M quantiles (default 20)
    - good for range predicates
  - N and M set by DBA as DB configuration parameters
  - N and M can differ per column (new in V8.1!)
- **Index clustering (DETAILED index statistics)**
  - empirical model: determines curve of I/O vs. buffer size
  - accounts for benefit of large buffers
- **User-defined function (UDF) statistics**
  - can specify I/O & CPU costs
    - per function invocation
    - at function initialization
    - associated with input parameters

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Modifying Catalog Statistics

- **Statistics values are...**
  - readable in the system catalogs
    - e.g., HIGH2KEY, LOW2KEY
  - updateable, e.g.
    - UPDATE SYSSTAT.TABLES
      SET CARD = 1000000
      WHERE TABNAME = `NATION'
- **Implications:**
  - Can simulate a non-existent database
  - Can "clone" a production database (in a test environment)
- **Tools**
  - DB2LOOK captures the statistics & table DDL to replicate an environment

Extensible Search Strategy

- **Breadth-first, ottom-up generation of plans**
- **Parameterized search strategy**
  - Dynamic Programming (provably optimal, but expensive)
    1. Build plans to access base tables
    2. For j = 2 to # of tables:

    Build j-way joins from best plans containing j-1, j-2, ... , 2, 1 tables
  - Greedy (more efficient for large queries)
- **Parameterized search space**
  - Composite inners or not (actually, maximum # of quantifiers in smaller set)
  - Cartesian products (no join predicate) or not
  - Disable/enable individual rules generating strategies (e.g. hash joins)
- **Interfaces to add/replace entire search strategy**
- **Controlled by "levels of optimization"**

Top-Down vs. Bottom-Up Conundrum

Bottom-up (System R, DB2, Oracle, Informix)

- Plans MUST be costed bottom-up (need input costs)
- Dynamic programming REQUIRES breadth-first enumeration to pick best
- Can't pick best plan until it's costed

Top-down (Volcano, Cascades, Tandem, SQL Server)

- Operators may REQUIRE certain properties (e.g. order or partitioning)
- Limit strategies based upon context of use

Solution in DB2:

- Plans built bottom-up, BUT...
- Pre-processing amasses candidate future requirements:
  - "Interesting" orders, e.g. for joins, GROUP BY, ORDER BY
  - "Interesting" partitions, in partitioned environment
  - Used to lump together "un-interesting" properties for pruning
- Operators requiring certain properties:
  1. Call "get-best-plan" to find a plan with those properties
  2. If none found, augment all plans with "glue" to get desired properties, e.g. add SORT to get desired Order, and pick cheapest
- Hence, <u>could</u> build a top-down (demand-driven) enumerator, using get-best-plan!

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Query Optimization Level

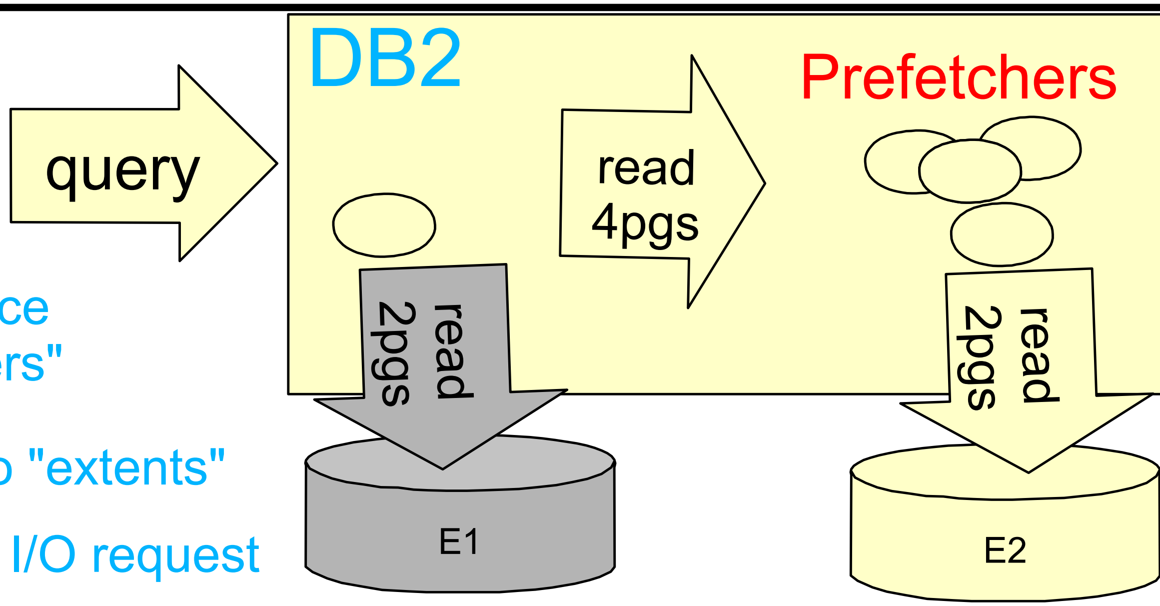
- **Optimization requires**
  - processing time
  - memory
- **Users can control resources applied to query optimization**
  - (similar to the -O flag in a C compiler)
  - special register, for dynamic SQL
    - set current query optimization = 1
  - bind option, for static SQL
    - bind tpcc.bnd queryopt 1
  - database configuration parameter, for default
    - update db cfg for <db> using dft_queryopt <n>
- **static & dynamic SQL may use different values**

Query Optimization Level Meaning

- **Use greedy join enumeration**
  - 0 - minimal optimization for OLTP
    - use index scan/nested loop join
    - avoid some query rewrite
  - 1 - low optimization
    - rough approximation of Version 1
  - 2 - full optimization, limit space/time
    - use same query transforms & join strategies as class 7
- **Use dynamic programming join enumeration**
  - 3 - moderate optimization
    - rough approximation of DB2 for MVS/ESA
  - 5 - self-adjusting full optimization (default)
    - uses all techniques with heuristics
  - 7 - full optimization
    - similar to 5, without heuristics
  - 9 - maximal optimization
    - spare no effort/expense
    - considers all possible join orders, including Cartesian products!

I/O Parallelism (multiple arms)

- Parallelism achieved by
  - User defining tablespace over multiple "containers" (disks)
  - DB2 breaking table into "extents"
  - DB2 breaking prefetch I/O request into multiple I/O requests



price	product_id	quarter_id	region_id
10.50	a1	q1	r1
12.00	a1	q1	r3
12.00	a1	q2	r2
11.99	b12	q1	r2
10.50	a1	q2	r2
15.75	cc2	q2	r3
14.50	a2	q3	r1
12.95	b12	q1	r4

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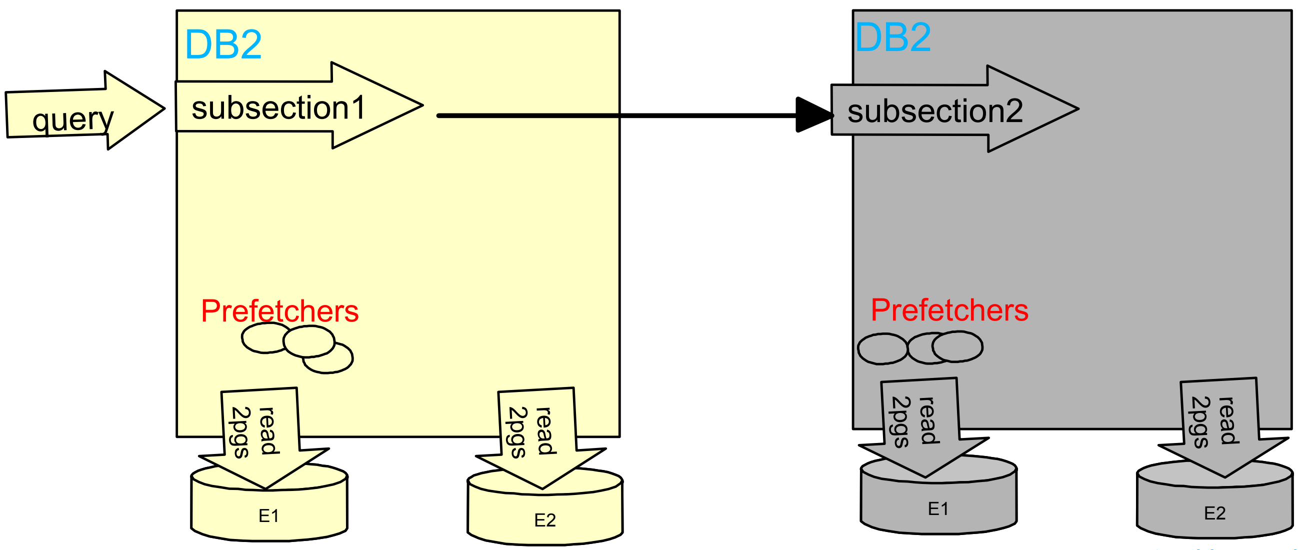
Inter-Partition Parallelism

- System configured with autonomous DB2 instances called "nodes"
  - ➡ typically with own CPU, memory, disks
  - ➡ connected by high-speed switch
  - ➡ can use logical nodes as well
- Tables partitioned among nodes via "partitioning key" column(s)



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11.99	b12	q1	r2
10.50	a1	q2	r2
12.95	b12	q1	r4

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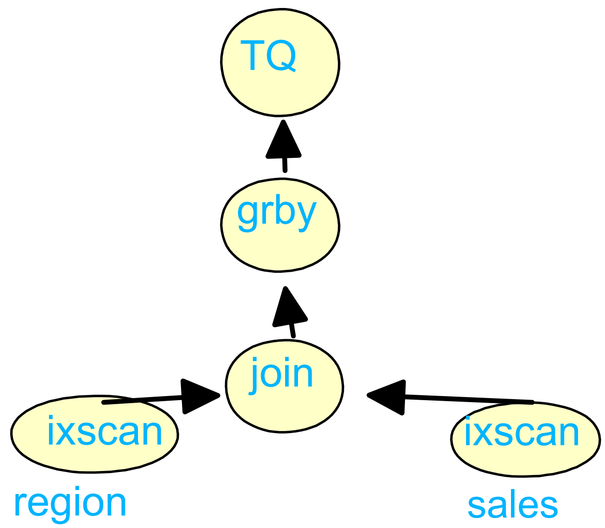
Optimizing Inter-Partition Parallelism

- Query (section) divided into parts (subsections) based upon...
  - How data is partitioned
  - Query's semantics
- All nodes assumed equal
- Function is shipped to data
  - Dynamic repartitioning might be required
- Goal of query optimization:
  - Minimize elapsed time

select rname, sum(price),
from sales s, region r
where r.region_id = s.region_id
group by rname, r.region_id



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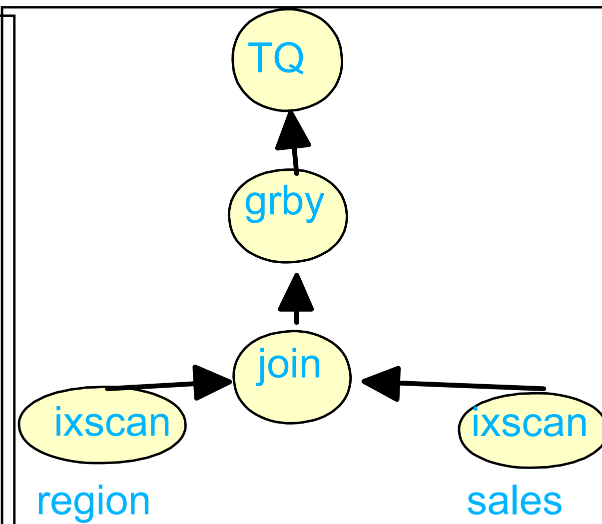
14.50	a2	q3	r1

region_id	rname
r3	Northeast
r1	Mideast
r5	SouthEast



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11.99	b12	q1	r2
10.50	a1	q2	r2
12.95	b12	q1	r4

region_id	rname
r6	Southwest
r2	Midwest
r4	Nthwest

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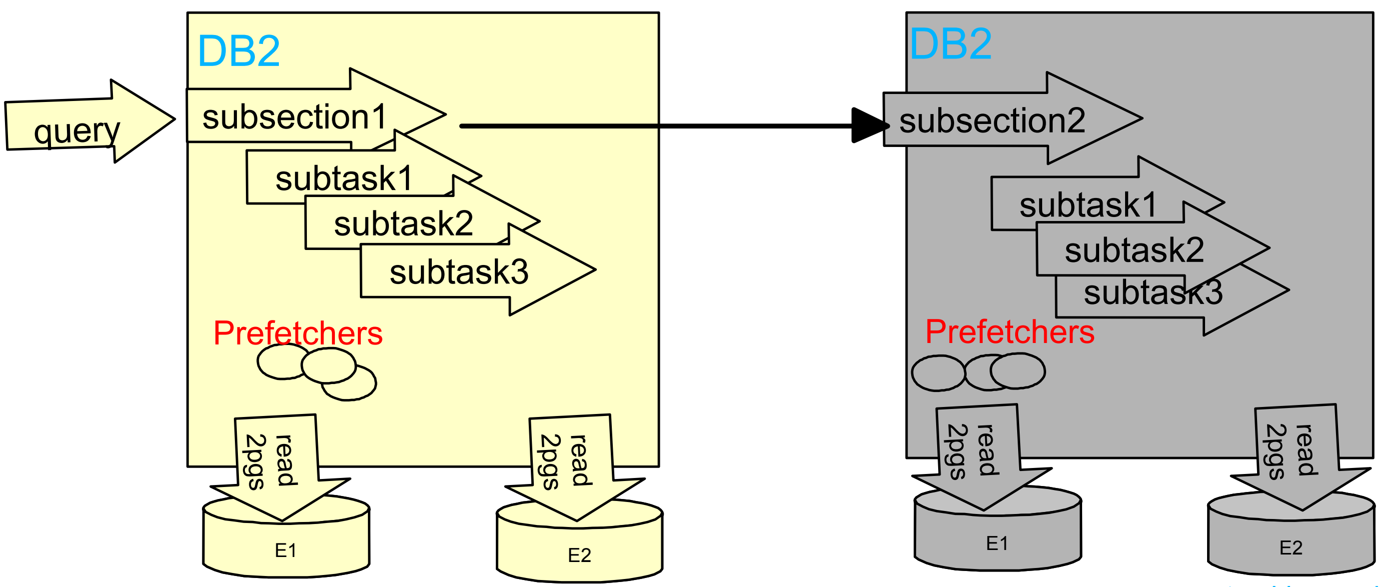
Intra-Partition Parallelism

- Exploits multiple processors of a symmetric multiprocessor (SMP)
- Multiple agents work on a single plan fragment
- Workload is dynamically balanced at run-time
- Post-optimizer parallelizes best serial/partitioned plan
- Degree of parallelism determined by compiler and run-time, bounded by config. parm.



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12.95	b12	q1	r4

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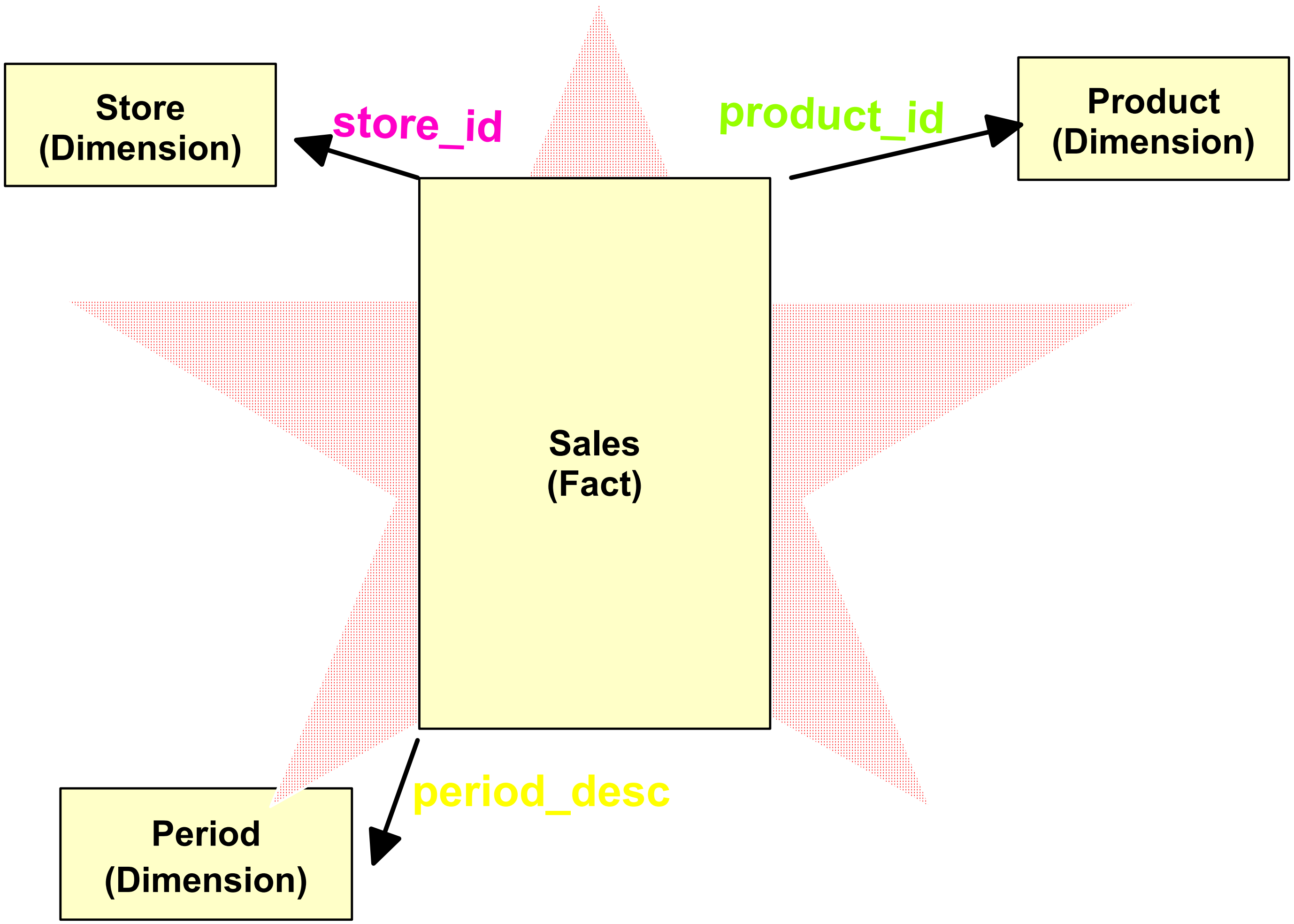
An OLAP Query to a Star Schema:



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Why are Special Strategies Needed?

- Optimizer avoids Cartesian joins (since no join predicates)
- Typically there are no join predicates between dimension tables
- So some table must join with Fact table
- Predicates on any one dimension insufficient to limit # of rows
- Large intermediate result (millions to 100s of millions) for next join!
- Therefore, intersection of limits on many dimensions are needed!

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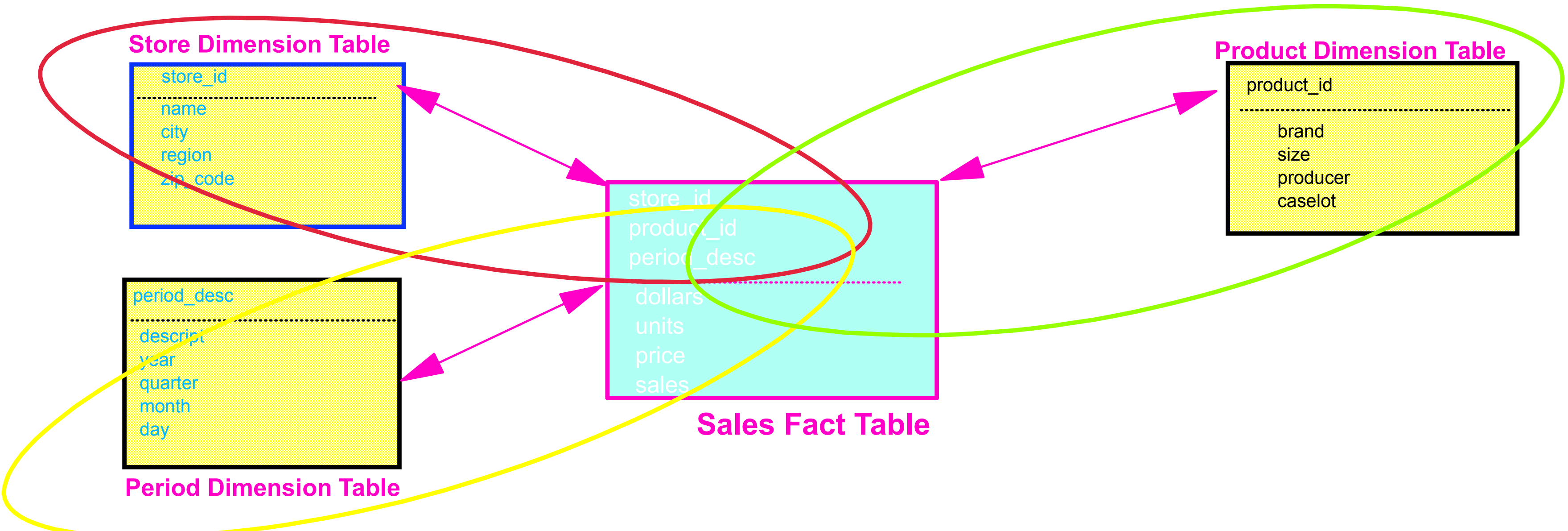
Why are Special Strategies Needed?

1. City = 'San Jose': 10s of millions of sales in San Jose stores!
2. Month = 'December': 100s of millions of sales in December!
3. Brand = 'Levi Dockers': millions of Levi's Dockers!



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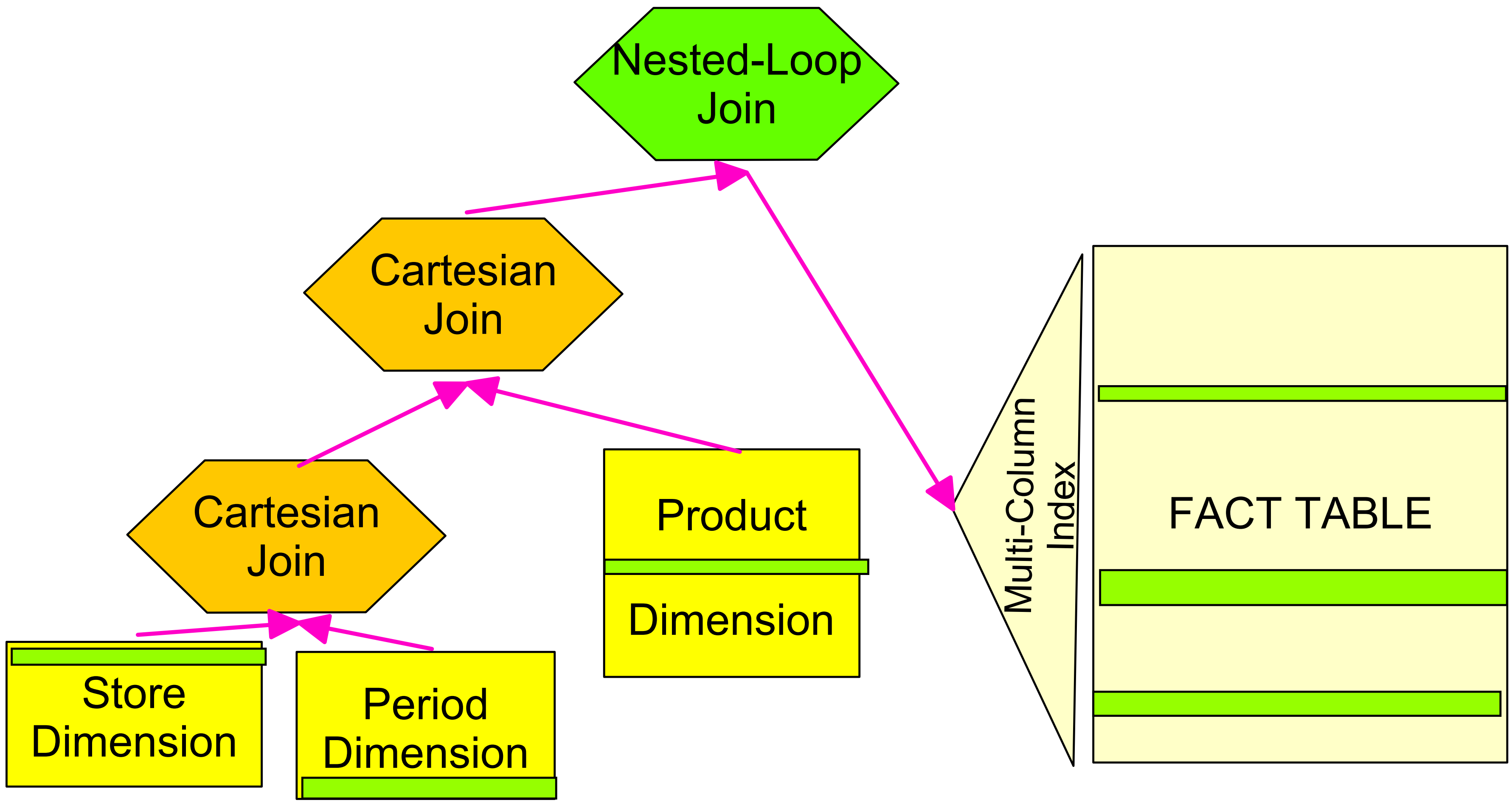
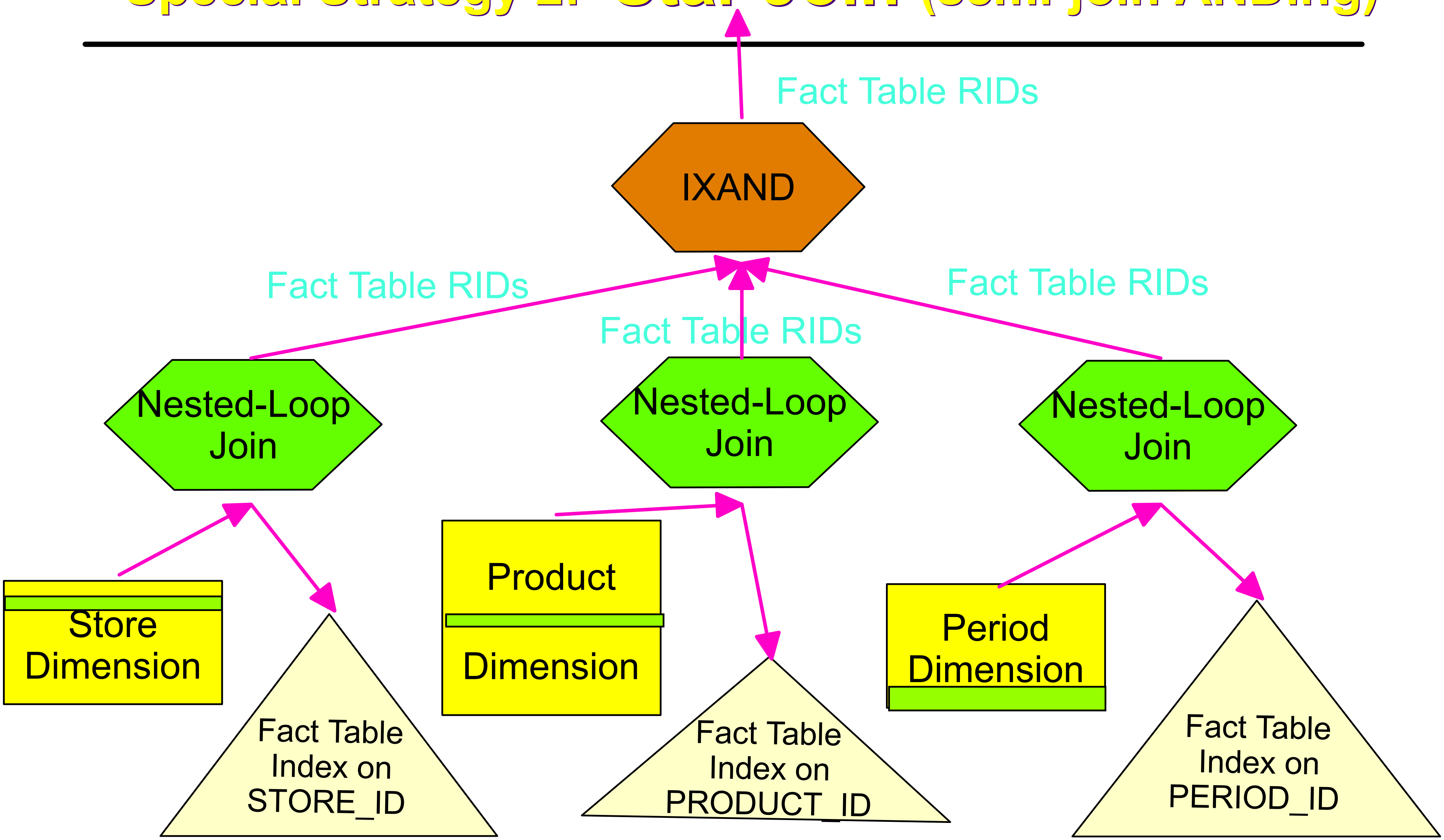
Special Strategy 1:
Cartesian-Join of Dimensions



Special Strategy 2: Star Join (semi-join ANDing)



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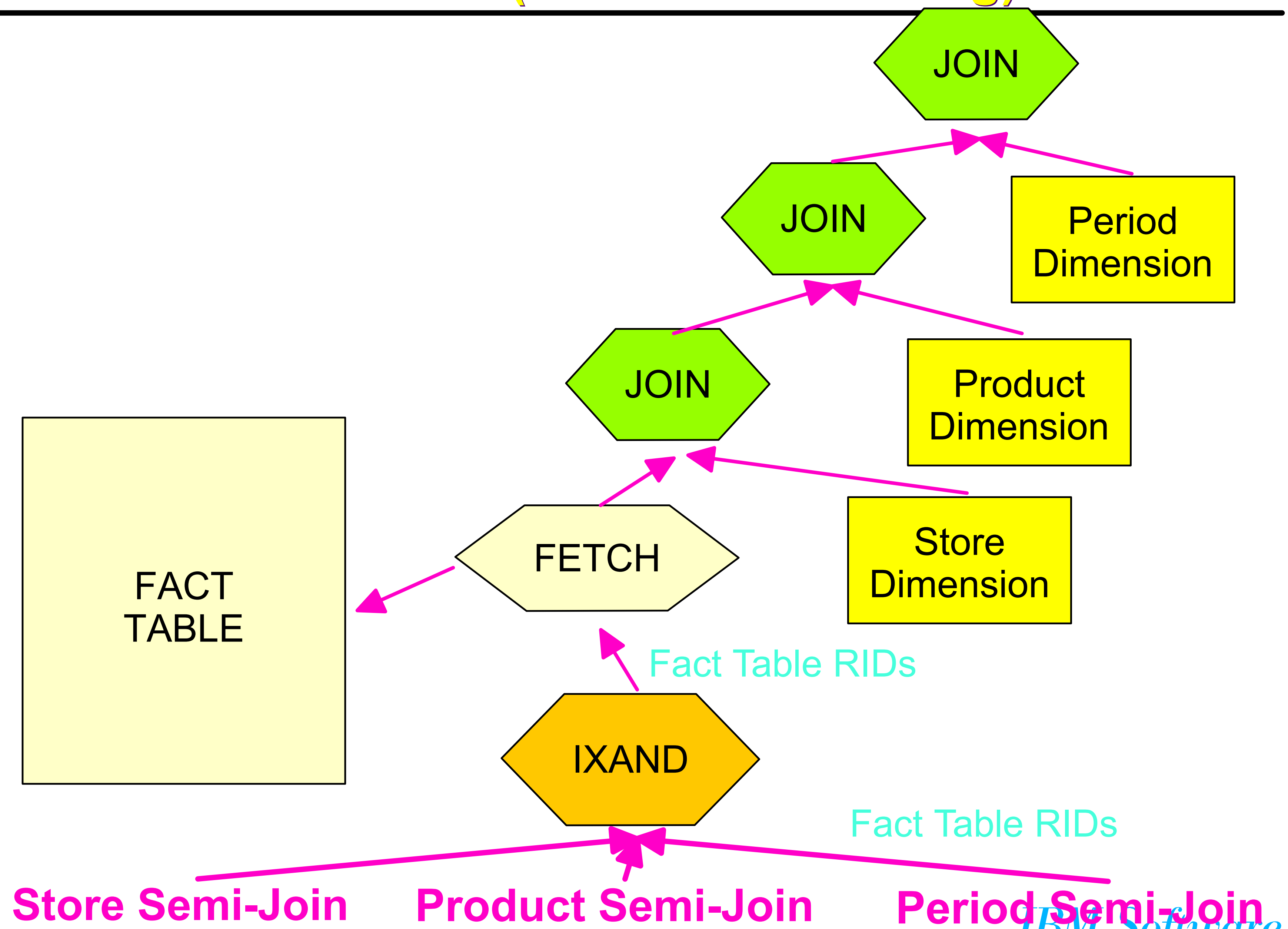
Special Strategy 2:
Star Join (Fetch & Re-Joining)



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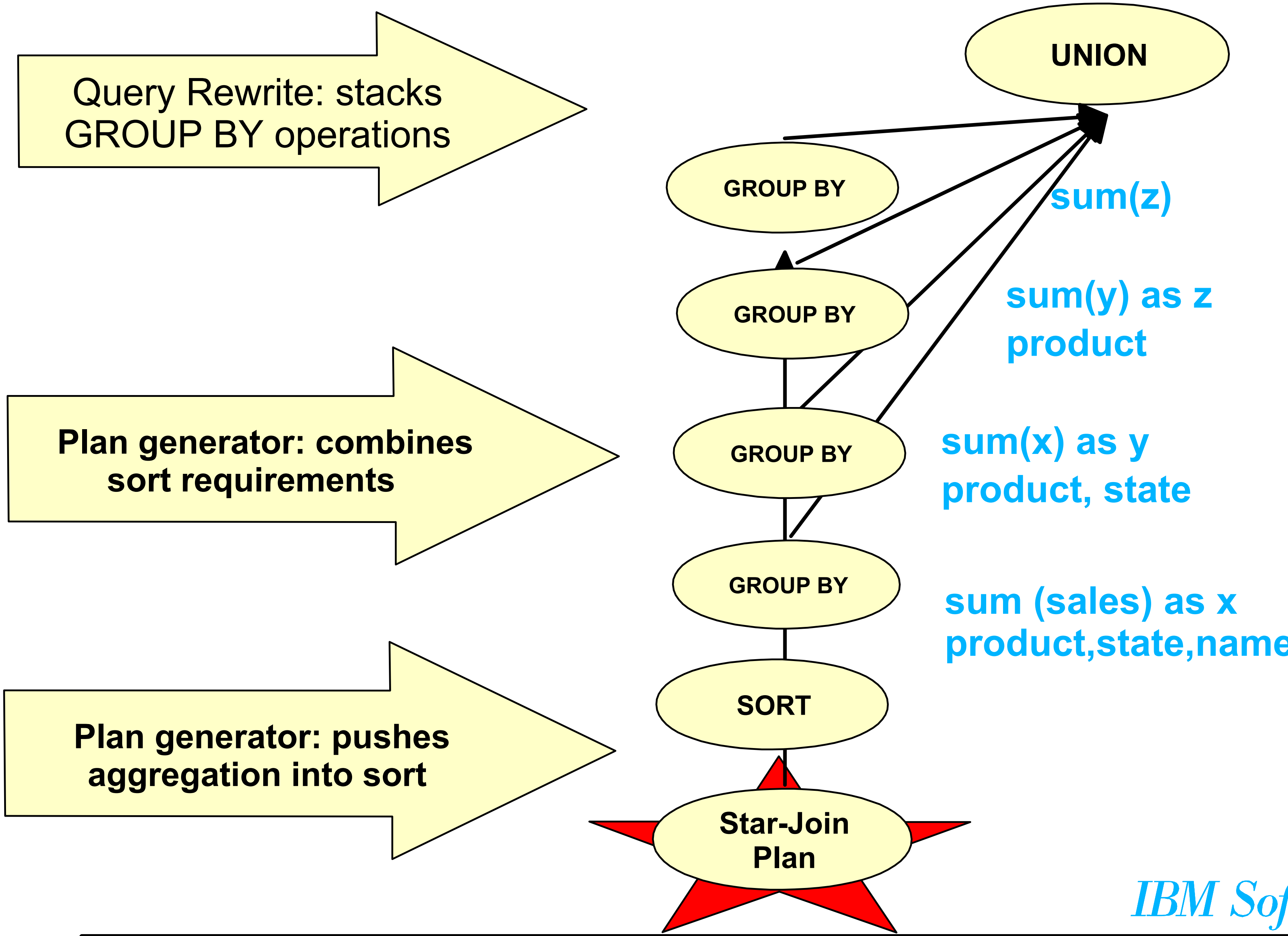
DB2 UDB ROLAP optimization: ROLLUP



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Product-Quality Query Optimizers Must:
Support ALL of SQL

- **Subqueries, including expressions of subqueries**
- **Correlation (very complex!)**
- **IN lists**
- **LIKE predicates, with wildcard characters (*,%)**
- **Cursors and WHERE CURRENT OF CURSOR statements**
- **IS NULL and IS NOT NULL**
- **Enforcement of constraints (column, referential integrity)**
- **EXCEPT, INTERSECT, UNION**
  - ALL
  - DISTINCT
- **Lots more...**

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Product-Quality Query Optimizers Must:
Address High-Performance Aspects

- **No limits on number of tables, columns, predicates, ...**
- **Efficient utilization of space**
  - representation of sets of objects using bit-vectors
  - location and sharing of sub-plans
  - garbage collection
- **Multi-column indexes, each with start and/or stop key values**
- **Ascending/Descending sort orders (by column)**
- **Implied predicates (T.a = U.b AND U.b = V.c ==> T.a = V.c)**
- **Clustering and "density" of rows for page FETCH costing**
- **Optional TEMPs and SORTs to improve performance**
- **Non-uniform distribution of values**
- **Sequential prefetching of pages**
- **Random vs. sequential I/Os**
- **OPTIMIZE FOR N ROWS**

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Product-Quality Query Optimizers Must:
Deal with Details

- "Halloween problem" on UPDATE/INSERT/DELETE, e.g.

  UPDATE Emp SET salary = salary *1.1
  WHERE salary > 120K

  If an ascending index on salary is used, and no TEMP,
  - Everyone gets an infinite raise!
  - UPDATE never completes!
- Differing code pages (e.g., Kanji, Arabic, ...), esp. in indexes
- Isolation levels
- Lock intents

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Summary & Future

- **Industry-Leading Optimization**
- **Extensible**
- **Optimizes for Parallel**
  - I/O accesses
  - Within a node (SMP)
  - Between nodes (MPP)
- **Powerful for complex OLAP & BI queries**
- **Industry-Strength Engineering**
- **Portable**
  - Across HW & SW platforms
  - Databases of 1 GB to > 100 TB
- **Continuing "technology pump" of improvements from Research**

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Appendix:

More Query ReWrite Examples

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Query Rewrite - Shared Aggregation Example

Original Query:

```
SELECT SUM(O_TOTAL_PRICE) AS OSUM,
       AVG(O_TOTAL_PRICE) AS OAVG
       FROM ORDERS;
```

Rewritten Query:

```
SELECT OSUM, OSUM/OCOUNT AS OAVG
FROM (SELECT SUM(O_TOTAL_PRICE) AS OSUM,
             COUNT(O_TOTAL_PRICE) AS OCOUNT
      FROM ORDERS) AS SHARED_AGG;
```

- ➡ Reduces query from 2 sums and 1 count to 1 sum and 1 count!

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Query Rewrite - Correlated Subqueries Example

- **Original Query:**

```
SELECT PS_SUPPLYCOST  FROM PARTSUPP
WHERE PS_PARTKEY <> ALL
          (SELECT L_PARTKEY FROM LINEITEM
           WHERE PS_SUPPKEY = L_SUPPKEY)
```

- **Rewritten Query:**

```
SELECT PS_SUPPLYCOST FROM PARTSUPP
WHERE  NOT EXISTS
          (SELECT 1 FROM LINEITEM
            WHERE PS_SUPPKEY = L_SUPPKEY
                AND PS_PARTKEY = L_PARTKEY)
```

➡ Pushes down predicate to enhance chances of binding partitioning key for each correlation value (here, from PARTSUPP)

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Query Rewrite - Decorrelation Example

Original Query:

```
SELECT SUM(L_EXTENDEDPRICE)/7.0
FROM LINEITEM, PART P
 WHERE P_PARTKEY = L_PARTKEY  AND
                P_BRAND = 'Brand#23'  AND
                P_CONTAINER = 'MED BOX'  AND
                L_QUANTITY < (SELECT 0.2 * AVG(L1.L_QUANTITY)
                              FROM TPCD.LINEITEM L1
                              WHERE L1.L_PARTKEY = P.P_PARTKEY)
```

Rewritten Query:

```
WITH GBMAGIC AS  (SELECT DISTINCT P_PARTKEY FROM PART P
                  WHERE P_BRAND = 'Brand#23' AND P_CONTAINER = 'MED BOX'),
 CTE AS    (SELECT  0.2*SUM(L1.L_QUANTITY)/COUNT(L1.L_QUANTITY)  AS AVGL_LQUANTITY,
                  P.PARTKEY FROMLINEITEM L1, GBMAGIC P
              WHERE L1.L_PARTKEY = P.P_PARTKEY GROUP BYP.P_PARTKEY)
SELECT SUM(L_EXTENDEDPRICE)/7.0 AS AVG_YEARLY
FROM  LINEITEM, PART P  WHERE P_PART_KEY = L_PARTKEY
    AND P_BRAND = 'Brand#23' AND P_CONTAINER = 'MED_BOX'
    AND L_QUANTITY < (SELECT AVGL_QUANTITY FROM CTE
                        WHERE P_PARTKEY = CTE.P_PARTKEY);
```

- This SQL computes the avg_quantity per unique part and can then broadcast the result to all nodes containing the lineitem table.

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Explaining Access Plans

Visual Explain

- accessible through DB2 Control Center
- graphical display of query plan
- uses optimization information captured by the optimizer
- invoke with either:
  - SET CURRENT EXPLAIN SNAPSHOT
  - EXPLSNAP bind option
  - EXPLAIN statement with snapshot option

Explain tables

- EXPLAIN statement / bind option
- superset of DB2 for MVS/ESA
- SET CURRENT EXPLAIN MODE
- optionally, generate report with DB2EXFMT tool

EXPLAIN utility (DB2EXPLN)

- explains bound packages into a flat file report
- similar to Version 1 but with many enhancements to usability
- less detailed information than EXPLAIN or Visual Explain

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Intra-partition Parallelism - How?

Data parallelism

- Partition data
- Assign partition to query task
- Easier to load balance
- User not required to partition data
  - e.g. range, hash, etc
- Data dynamically assigned to query tasks
  - Assign range of pages or rows
  - Assign new range when range is consumed
  - Provides dynamic load balancing
  - Support table and index scans

Functional parallelism

- divide query task by function
- assign functional task to different execution units
- requires data partitioning
- harder to load balance
  - ensure execution units are equally busy
- Single co-ordinator process services application requests
- Multiple sub-ordinator processes return data through local table queue

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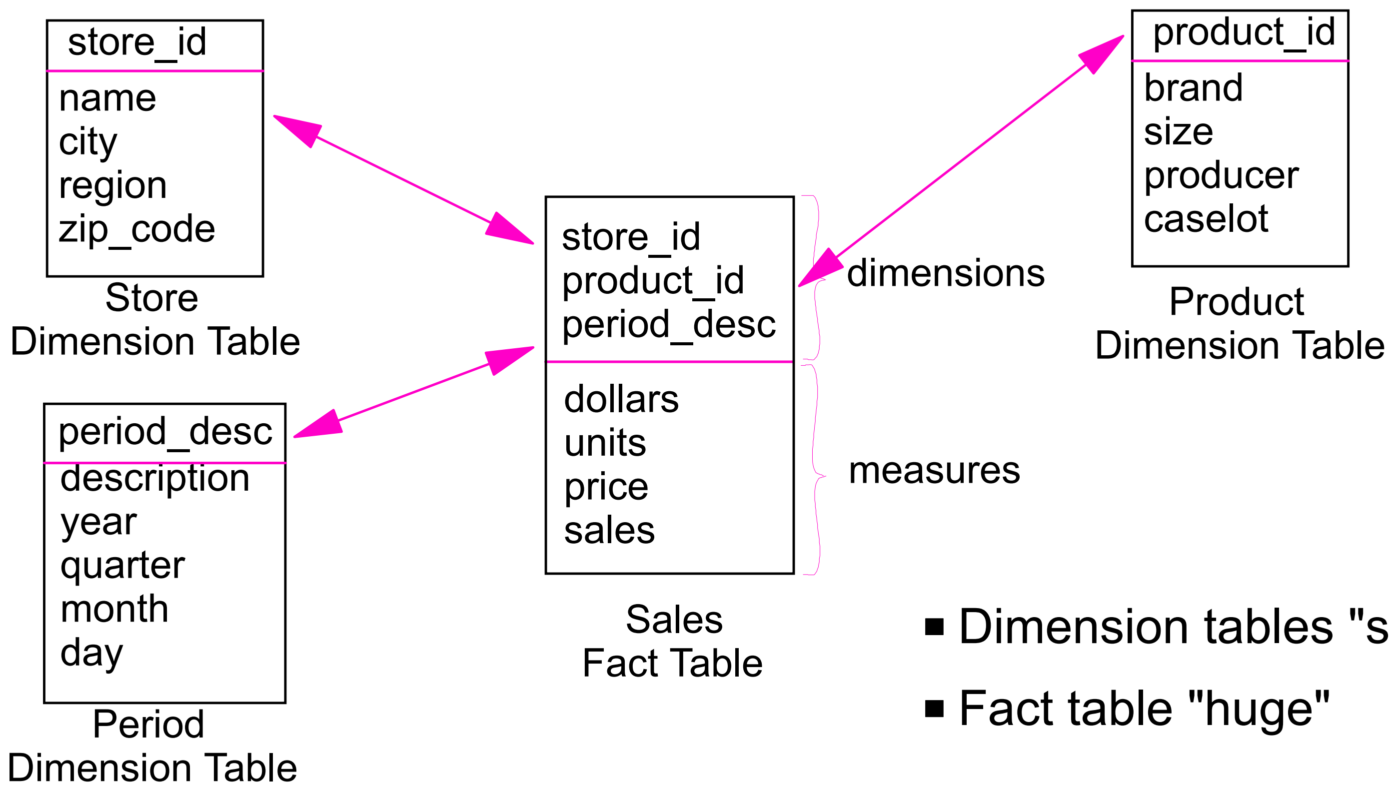
OLAP Schema

Typically uses a "STAR" structure



- Dimension tables "small"
- Fact table "huge"

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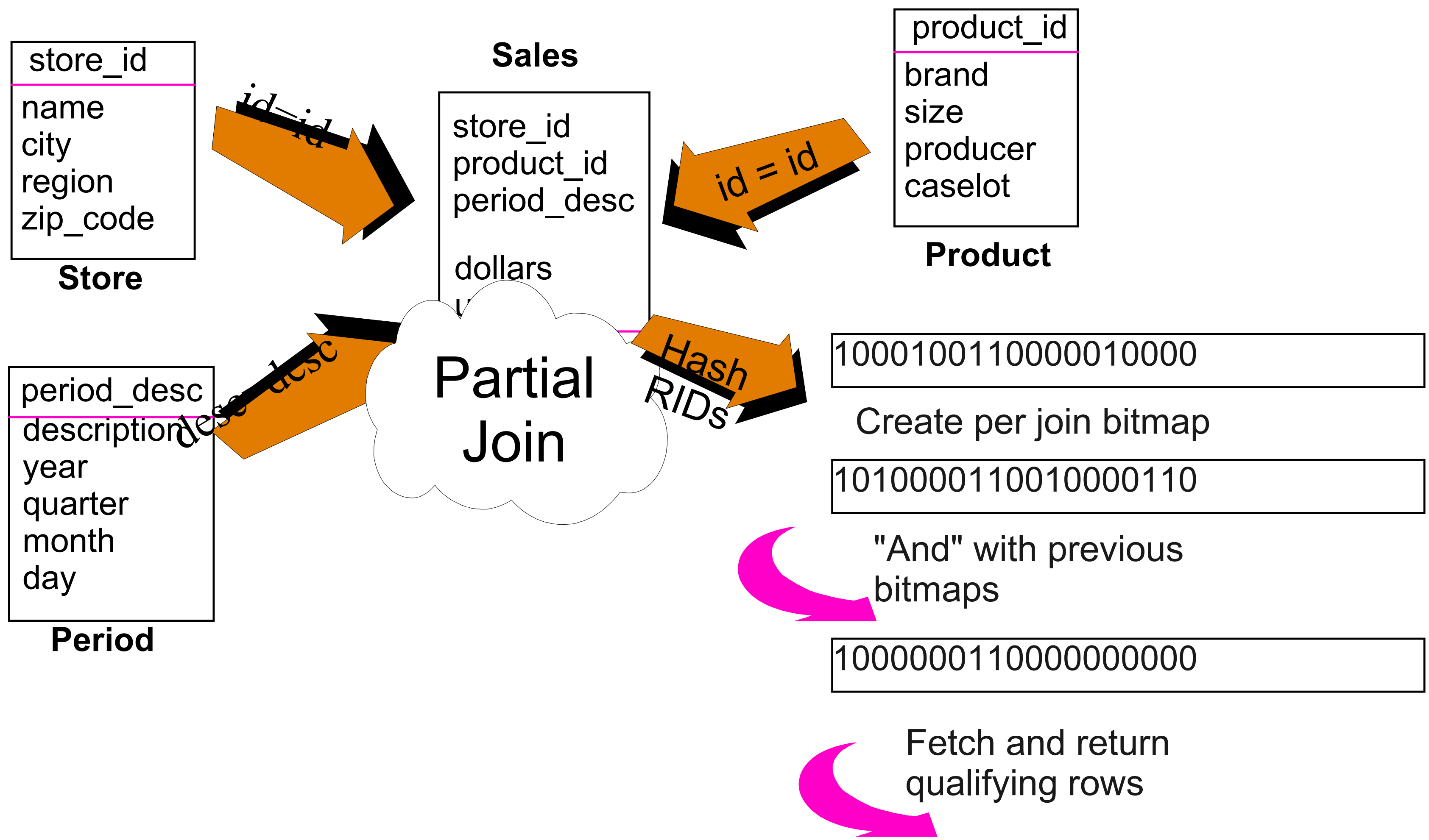
■ Filter the fact table



Dynamic Bitmap Index ANDing

- **Takes advantage of indexes to apply "AND" predicates**

- **Selection is cost based, competing with:**
  - Table scans
  - Index ORing
  - List prefetch

- **Works by:**
  - Hashing Row IDentifier (RID) values for qualifying rows of each index scan
  - Dynamically build bitmap using hashed RIDs
  - "AND" together bitmaps in a build-and-probe fashion
  - Last index scan probes bitmap and returns qualifying RID
  - Fetch qualifying rows

- **Advantages:**
  - Can apply multiple ANDed predicates to different indexes, and get speed of index scanning

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Dynamic Bitmap Index ANDing

- **Count All products with price > $2500 and units > 10**