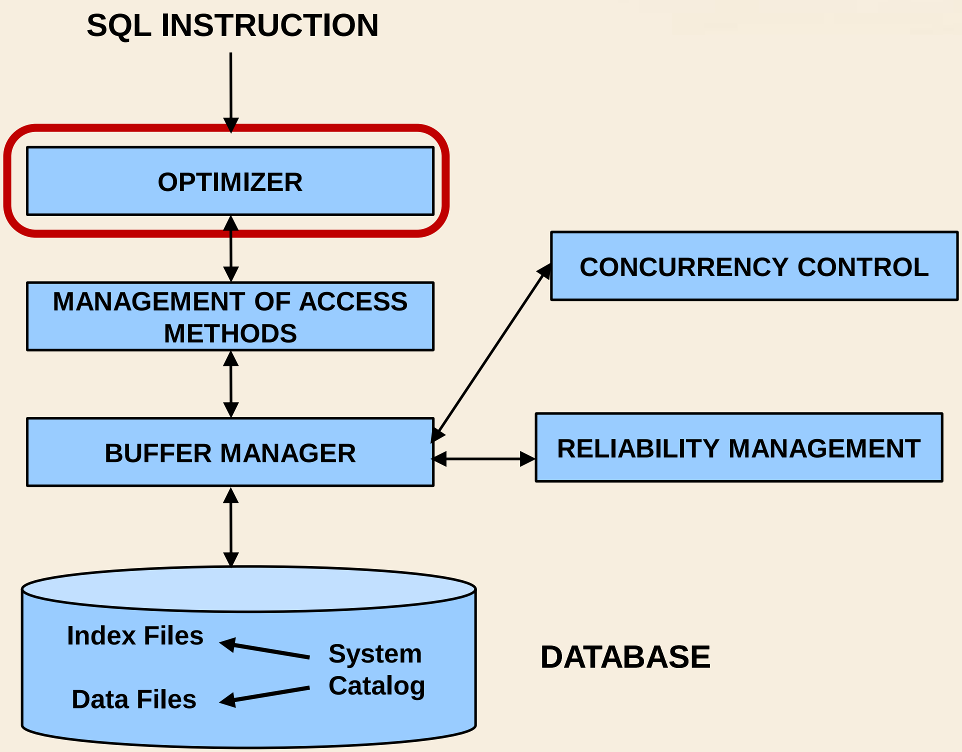
Database Management Systems

Query optimization

DBMS Architecture



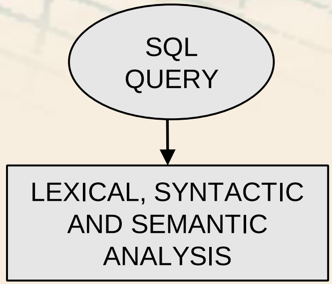
Query optimizer

- It selects an efficient strategy for query execution
  - It is a fundamental building block of a relational DBMS
- It guarantees the *data independence* property
  - The form in which the SQL query is written does not affect the way in which it is implemented
  - A physical reorganization of data does not require rewriting SQL queries

Query optimizer

- It automatically generates a *query execution plan*
  - It was formerly hard-coded by a programmer
- The automatically generated execution plan is usually more efficient
  - It evaluates many different alternatives
  - It exploits statistics on data, stored in the system catalog, to make decisions
  - It exploits the best known strategies
  - It dynamically adapts to changes in the data distribution

Query optimizer



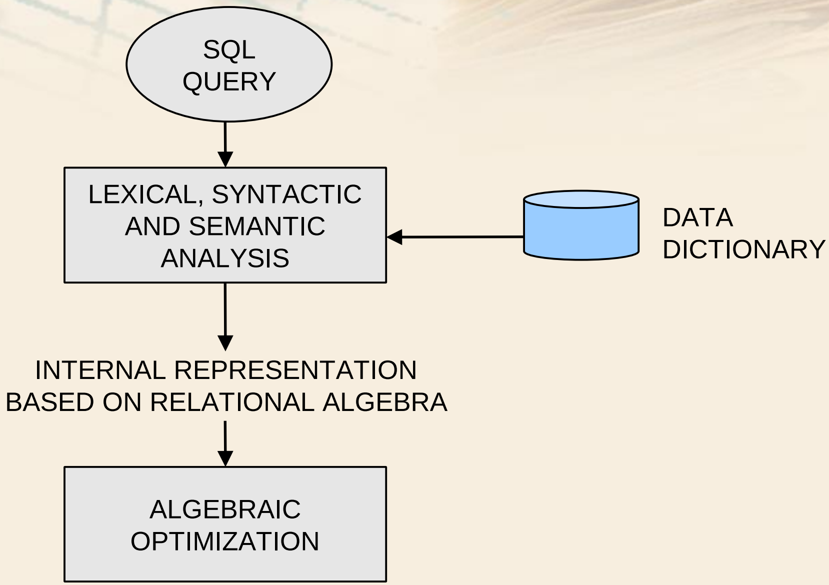
Lexical, syntactic and semantic analysis

- Analysis of a statement to detect
  - Lexical errors
    - e.g., misspelled keywords
  - Syntactic errors
    - errors in the grammar of the SQL language
  - Semantic errors
    - references to objects which do not actually exist in the database (e.g, attributes or tables)
    - information in the data dictionary is needed

Lexical, syntactic and semantic analysis

- Output
  - Internal representation in (extended) *relational algebra*
- Why relational algebra?
  - It explicitly represents the order in which operators are applied
    - It is *procedural* (different from SQL)
  - There is a corpus of theorems and properties
    - exploited to modify the initial query tree

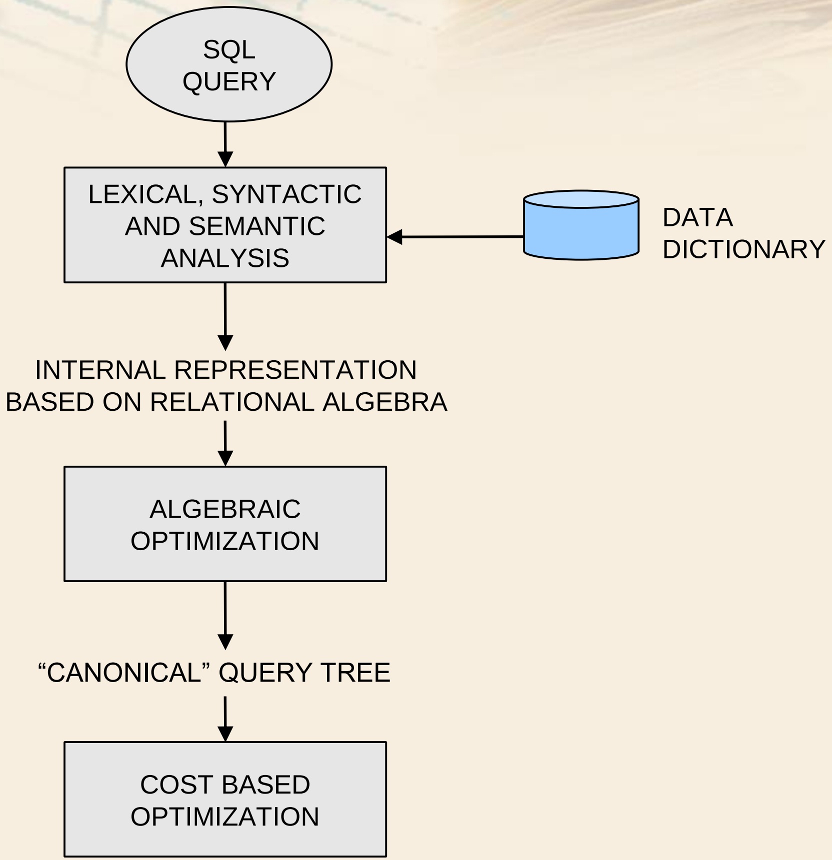
Query optimizer



Algebraic optimization

- Execution of algebraic transformations considered to be always beneficial
  - Example: anticipation of selection with respect to join
- Should eliminate the difference among different formulations of the same query
- This step is usually independent of the data distribution
- Output
  - Query tree in "canonical" form

Query optimizer



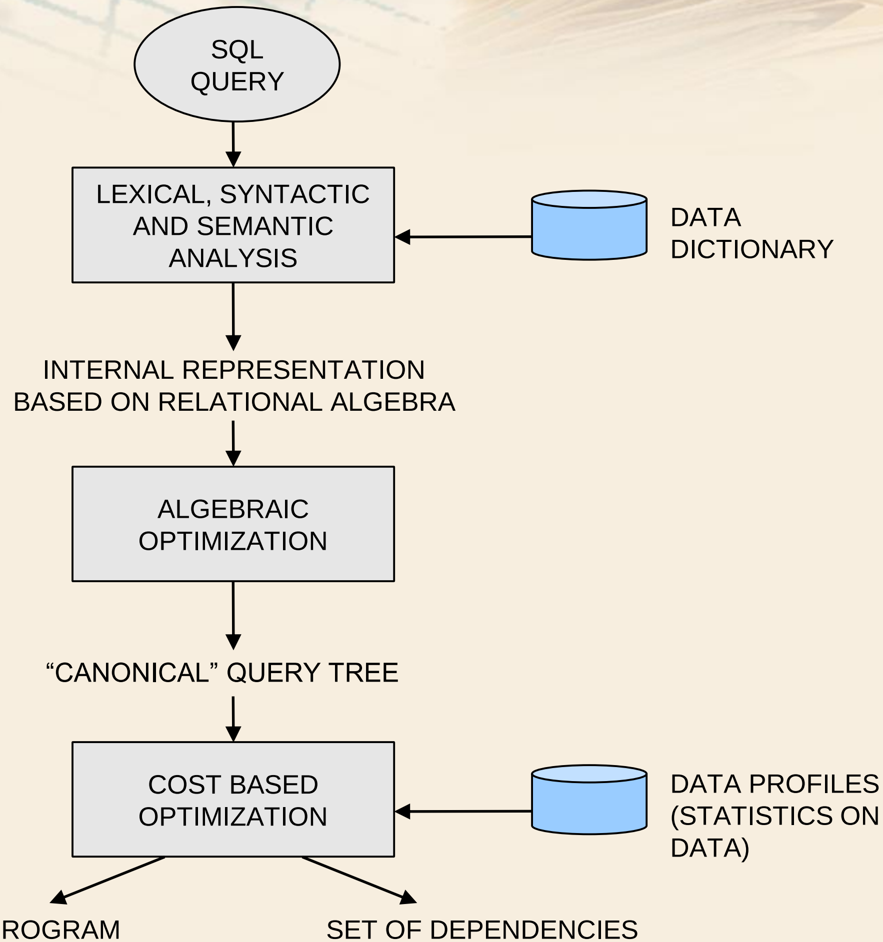
Cost based optimization

- Selection of the "best" execution plan by evaluating *execution cost*
  - Selection of
    - the best access method for each table
    - the best algorithm for each relational operator among available alternatives
  - Based on a cost model for access methods and algorithms
- Generation of the code implementing the best strategy

Cost based optimization

- Output
  - Access program in executable format
    - It exploits the internal structures of the DBMS
  - Set of dependencies
    - conditions on which the validity of the query plan depends
      - e.g., the existence of an index

Query optimizer



Execution modes

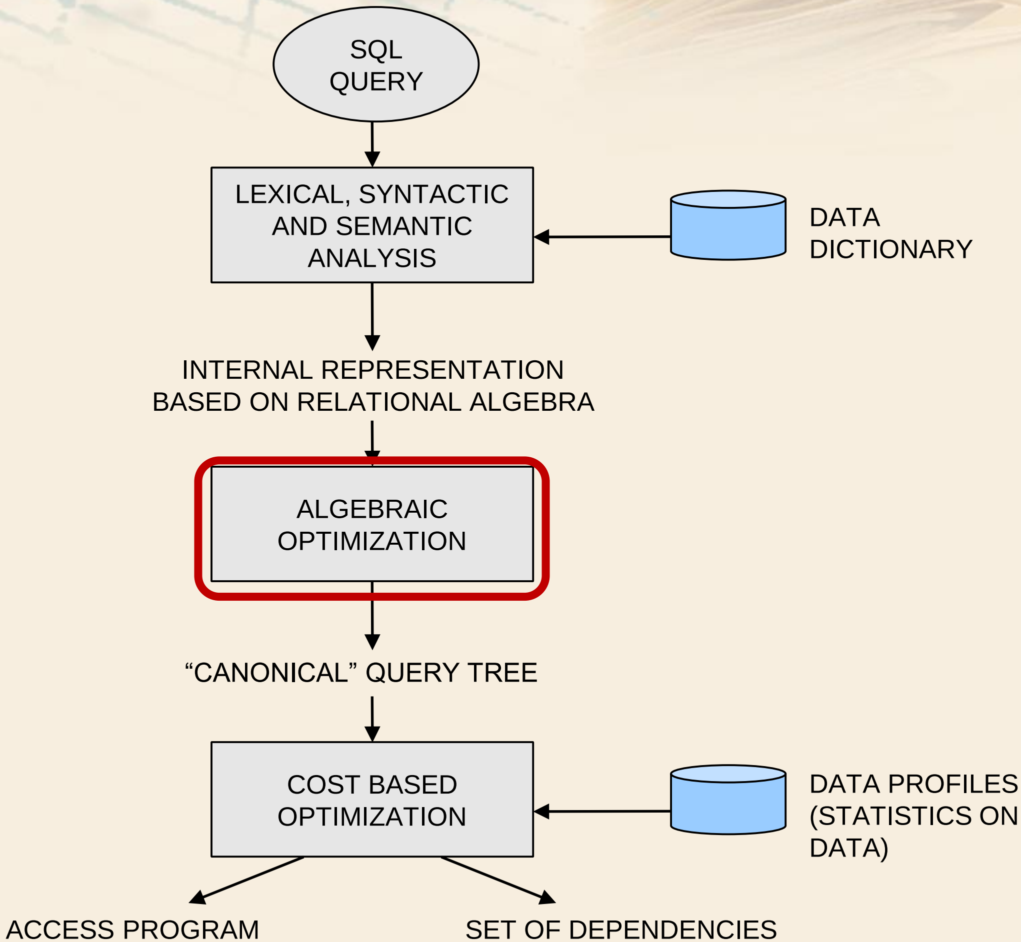
- Compile and go
  - Compilation and *immediate* execution of the statement
  - No storage of the query plan
  - Dependencies are not needed

Execution modes

- Compile and store
  - The access plan is stored in the database together with its dependencies
  - It is executed *on demand*
  - It should be recompiled when the data structure changes

Algebraic optimization

Algebraic optimization



Algebraic optimization

- It is based on equivalence transformations
  - Two relational expressions are *equivalent* if they both produce the same query result for any arbitrary database instance
- Interesting transformations
  - reduce the size of the intermediate result to be stored in memory
  - prepare an expression for the application of a transformation which reduces the size of the intermediate result

Transformations

1. Atomization of selection
   - $\sigma_{F1 \land F2}(E) \equiv \sigma_{F2}(\sigma_{F1}(E)) \equiv \sigma_{F1}(\sigma_{F2}(E))$

Transformations

1. Atomization of selection
   - $\sigma_{F1 \wedge F2} (E) \equiv \sigma_{F2} (\sigma_{F1} (E)) \equiv \sigma_{F1} (\sigma_{F2} (E))$
2. Cascading projections
   - $\pi_{X}(E) \equiv \pi_{X} (\pi_{X,Y}(E))$

Transformations

1. Atomization of selection
   - $\sigma_{F1 \wedge F2}(E) \equiv \sigma_{F2}(\sigma_{F1}(E)) \equiv \sigma_{F1}(\sigma_{F2}(E))$
2. Cascading projections
   - $\pi_X(E) \equiv \pi_X(\pi_{X,Y}(E))$
3. Anticipation of selection with respect to join (pushing selection down)
   - $\sigma_F(E_1 \bowtie E_2) \equiv E_1 \bowtie (\sigma_F(E_2))$
   - F is a predicate on attributes in E_2 only

Transformations

4. Anticipation of projection with respect to join
   - $\pi_L(E_1 \bowtie_p E_2) \equiv \pi_L((\pi_{L1,J}(E_1)) \bowtie_p (\pi_{L2,J}(E_2)))$
     - $L1 = L$ - Schema(E_2)
     - $L2 = L$ - Schema(E_1)
     - J = set of attributes needed to evaluate join predicate p

Transformations

5. Join derivation from Cartesian product
   - $\sigma_F (E_1 \times E_2) \equiv E_1 \bowtie_F E_2$
   - predicate F only relates attributes in E_1 and E_2

Transformations

5. Join derivation from Cartesian product
   - $\sigma_F (E_1 \times E_2) \equiv E_1 \bowtie_F E_2$
   - predicate F only relates attributes in E_1 and E_2
6. Distribution of selection with respect to union
   - $\sigma_F(E_1 \cup E_2) \equiv (\sigma_F (E_1)) \cup (\sigma_F (E_2))$

Transformations

5. Join derivation from Cartesian product
   - $\sigma_F (E_1 \times E_2) \equiv E_1 \bowtie_F E_2$
   - predicate F only relates attributes in E_1 and E_2
6. Distribution of selection with respect to union
   - $\sigma_F(E_1 \cup E_2) \equiv (\sigma_F (E_1)) \cup (\sigma_F (E_2))$
7. Distribution of selection with respect to difference
   - $\sigma_F(E_1 - E_2) \equiv (\sigma_F (E_1)) - (\sigma_F (E_2))$

     $\equiv (\sigma_F (E_1)) - E_2$

Transformations

8. Distribution of projection with respect to union
   - $\pi_X(E_1 \cup E_2) \equiv (\pi_X(E_1)) \cup (\pi_X(E_2))$

Transformations

8. Distribution of projection with respect to union
   - $\pi_X(E_1 \cup E_2) \equiv (\pi_X(E_1)) \cup (\pi_X(E_2))$

- Can projection be distributed with respect to difference?

$$\pi_X (E_1 - E_2) \equiv (\pi_X(E_1)) - (\pi_X(E_2))$$

8. Distribution of projection with respect to union
   - $\pi_X(E_1 \cup E_2) \equiv (\pi_X(E_1)) \cup (\pi_X(E_2))$

- Can projection be distributed with respect to difference?

  ~~$\pi_X (E_1 - E_2) \equiv (\pi_X(E_1)) - (\pi_X(E_2))$~~

  - This equivalence *only* holds if X includes the primary key or a set of attributes with the same properties (unique and not null)

9. Other properties
   - $\sigma_{F1 \vee F2}(E) \equiv (\sigma_{F1}(E)) \cup (\sigma_{F2}(E))$
   - $\sigma_{F1 \wedge F2}(E) \equiv (\sigma_{F1}(E)) \cap (\sigma_{F2}(E))$

Transformations

10. Distribution of join with respect to union
    - $E \bowtie (E_1 \cup E_2) \equiv (E \bowtie E_1) \cup (E \bowtie E_2)$

- All binary operators are commutative and associative *except for difference*

Example

- Tables

  EMP (Emp#, ………, Dept#, Salary)

  DEPT (Dept#, DName,……………)

- SQL query

```
SELECT DISTINCT DName
FROM   EMP, DEPT
WHERE EMP.Dept#=DEPT.Dept#
AND Salary > 1000;
```

Example: Algebraic transformations

$$\pi_{DName}\ (\sigma_{EMP.Dept\#=DEPT.Dept\#\ \wedge\ Salary\ >1000}\ (EMP \times DEPT))$$

Example: Algebraic transformations

$$\pi_{DName}\ (\sigma_{EMP.Dept\#=DEPT.Dept\#\ \land\ Salary\ >1000}\ (EMP \times DEPT))$$

Prop #1 ⬇

$$\pi_{DName}(\sigma_{Salary\ >1000}\ (\sigma_{EMP.Dept\#=DEPT.Dept\#}\ (EMP \times DEPT))$$

Example: Algebraic transformations

$$\pi_{DName}\ (\sigma_{EMP.Dept\#=DEPT.Dept\#\ \wedge\ Salary\ >1000}\ (EMP \times DEPT))$$

Prop #1 ⇓

$$\pi_{DName}(\sigma_{Salary\ >1000}\ (\sigma_{EMP.Dept\#=DEPT.Dept\#}\ (EMP \times DEPT))$$

Prop #5 ⇓

$$\pi_{DName}(\sigma_{Salary\ >1000}\ (EMP \bowtie DEPT)$$

Example: Algebraic transformations

$$\pi_{DName}(\sigma_{Salary > 1000} (EMP \bowtie DEPT)$$

Prop #3

$$\pi_{DName}(\sigma_{Salary > 1000} (EMP)) \bowtie DEPT)$$

Example: Algebraic transformations

$$\pi_{DName}(\sigma_{Salary > 1000}(EMP \bowtie DEPT)$$

Prop #3

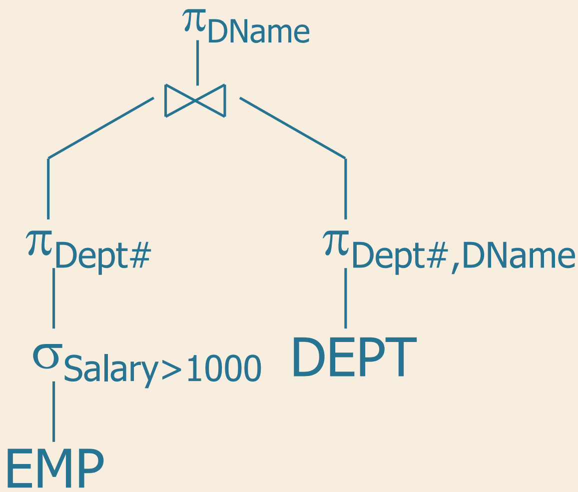
$$\pi_{DName}(\sigma_{Salary > 1000}(EMP)) \bowtie DEPT)$$

Prop #2 and #4

$$\pi_{DName}((\pi_{Dept\#}(\sigma_{Salary > 1000}(EMP)) \bowtie (\pi_{Dept\#,DName}(DEPT)))$$

Example: Query tree

- Final query tree

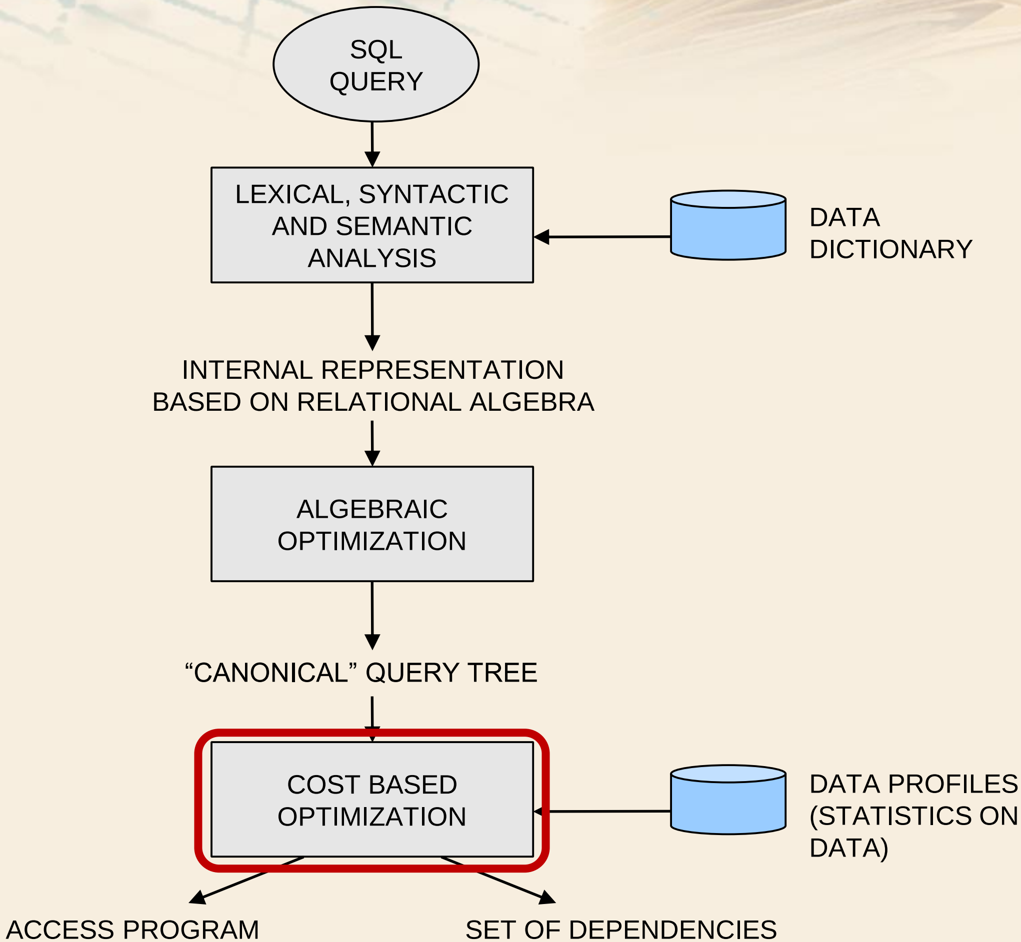


Example: Cardinalities

- Cardinality (EMP) ≈ 10,000
- Cardinality (DEPT) ≈ 100
- Cardinality (EMP where Salary > 1000) ≈ 50

Cost based optimization

Cost based optimization



Cost based optimization

- It is based on
  - Data profiles
    - statistical information describing data distribution for tables and intermediate relational expressions
  - Approximate cost formulas for access operations
    - Allow evaluating the cost of different alternatives for executing a relational operator

Data profiles

Table profiles

- Quantitative information on the characteristics of tables and columns
  - cardinality (# of tuples) in each table T
    - also estimated for intermediate relational expressions
  - size in bytes of tuples in T
  - size in bytes of each attribute A_j in T
  - number of distinct values of each attribute in T
    - cardinality of the active domain of the attribute
  - min and max values of each attribute A_j in T

Table profiles

- Table profiles are stored in the data dictionary
- Profiles should be periodically refreshed by re-analyzing data in the tables
  - Update statistics command
  - Executed on demand
    - immediate execution during transaction processing would overload the system

Data profiles

- Table profiles are exploited to estimate the size of intermediate relational expressions
  - For the selection operator

$$\text{Card}\,(\sigma_{A_i = v}(T)) \approx \text{Card}\,(T) / \text{Val}\,(A_i \text{ in } T)$$

    - Val (A_i in T) = # of distinct values of A_i in T (active domain)

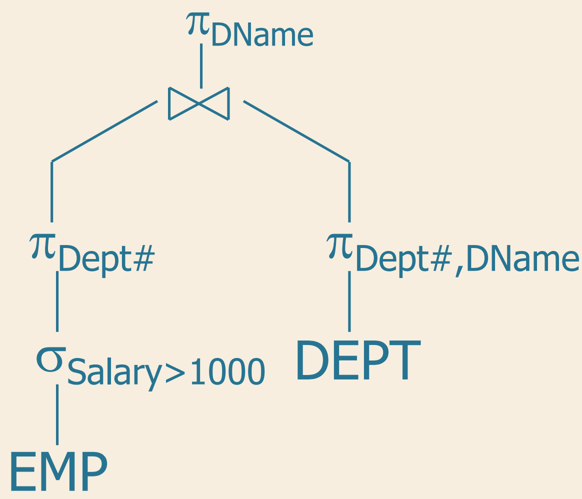
  It holds only under the hypothesis of *uniform distribution*

Database Management Systems

Access operators

Query tree

- Internal representation of the relational expression as a query tree



Query tree

- Leaves correspond to the physical structures
  - tables, indices
- Intermediate nodes are operations on data supported by the given physical structure
  - e.g., scan, join, group by

Sequential scan

- Executes sequential access to all tuples in a table
  - also called full table scan
- Operations performed during a sequential scan
  - Projection
    - discards unnecessary columns
  - Selection on a simple predicate (A_i=v)
  - Sorting based on an attribute list
  - Insert, update, delete

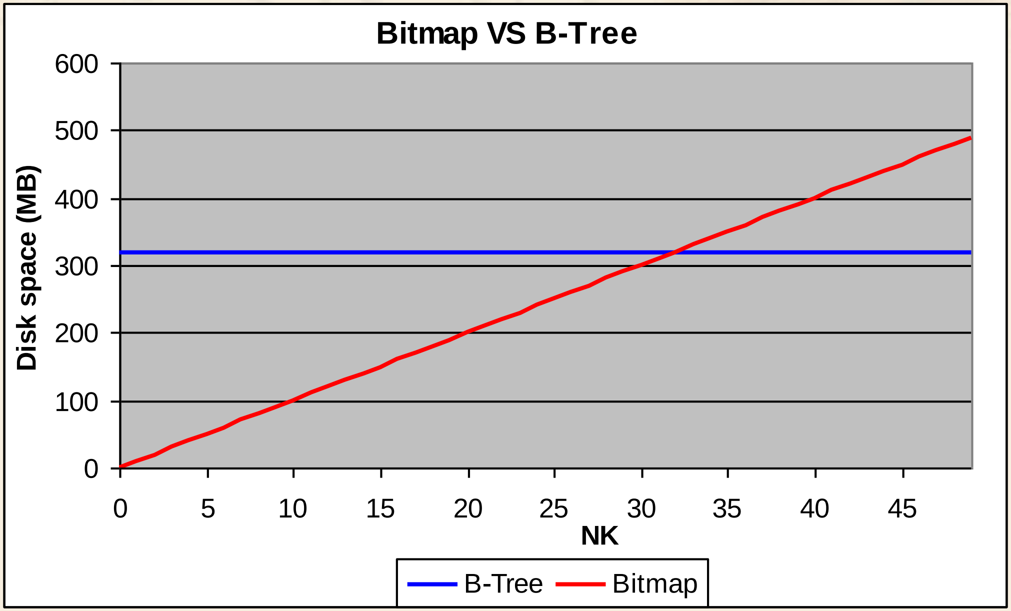
Sorting

- Classical algorithms in computer science are exploited
  - e.g., quick sort
- Size of data is relevant
  - memory sort
  - sort on disk

Predicate evaluation

- If available, it may exploit *index* access
  - B^+-tree, hash, or bitmap
- Simple equality predicate $A_i=v$
  - Hash, B^+-tree, or bitmap are appropriate
- Range predicate $v_1 \le A_i \le v_2$
  - *only* B^+-tree is appropriate
- For predicates with *limited selectivity* full table scan is better
  - if available, consider bitmap

B+-tree versus bitmap



B-tree NR×*Len*(Pointer)

Bitmap NR × NK × 1 bit

Len(*Pointer*) = 4×8 bit

Courtesy of Golfarelli, Rizzi, "Data warehouse, teoria e pratica della progettazione", McGraw Hill 2006

Predicate evaluation

- Conjunction of predicates $A_i = v_1 \wedge A_j = v_2$
  - The *most selective* predicate is evaluated first
    - Table is read through the index
  - Next the other predicates are evaluated on the intermediate result
- Optimization
  - First compute the *intersection* of bitmaps or RIDs coming from available indices
  - Next table read and evaluation of remaining predicates

Example: Predicate evaluation

- Which female students living in Piemonte are exempt from enrollment fee?

RID	Gender	Exempt	Region
1	M	Y	Piemonte
2	F	Y	Liguria
3	M	N	Puglia
4	M	N	Sicilia
5	F	Y	Piemonte

Gender	Exempt	Piemonte
0	1	1
1	1	0
0	0	0
0	0	0
1	1	1

RID 5

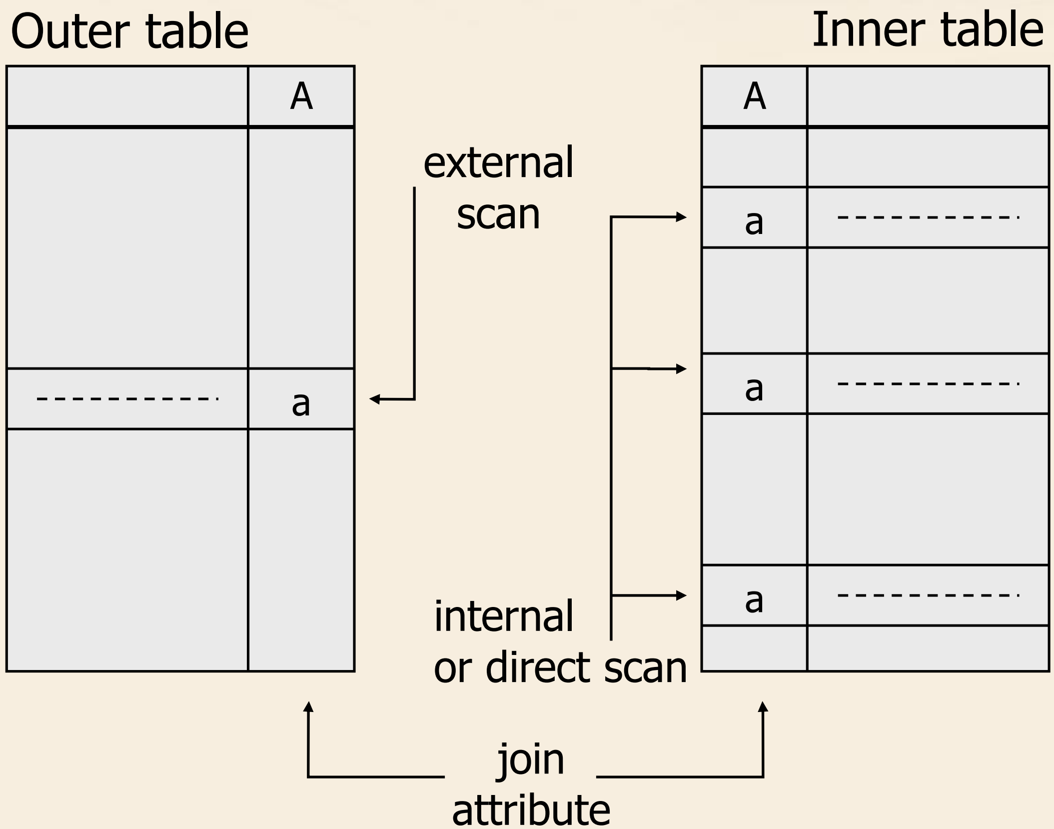
Predicate evaluation

- Disjunction of predicates $A_i = v_1 \vee A_j = v_2$
  - Index access can be exploited *only* if all predicates are supported by an index
    - otherwise full table scan

Join operation

- A critical operation for a relational DBMS
  - connection between tables is based on values
    - instead of pointers
  - size of the intermediate result is typically larger than the smaller table
- Different join algorithms
  - Nested loop
  - Merge scan join
  - Hash join
  - Bitmapped join

Nested loop



Outer table
Inner table
A
A
a
a
a
a
external scan
internal or direct scan
join attribute

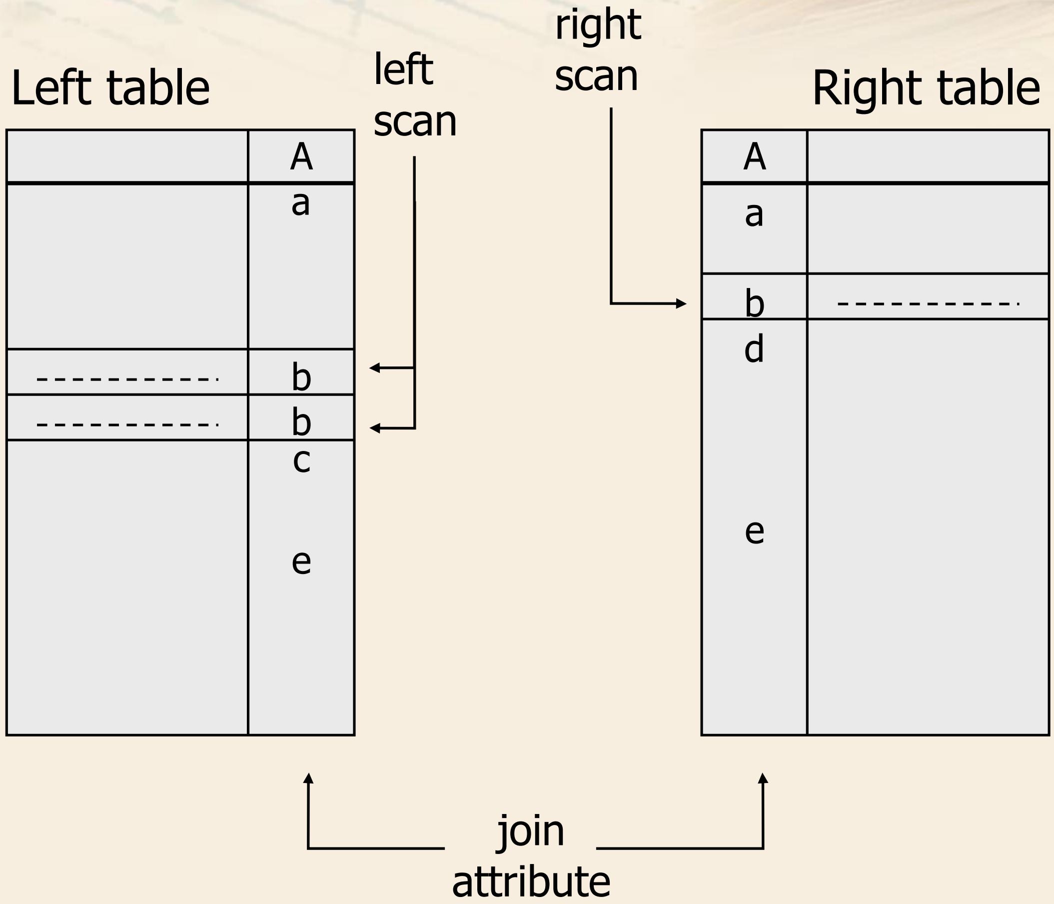
Nested loop

- A single full scan is done on the outer table
- For each tuple in the outer table
  - a full scan of the inner table is performed, looking for corresponding values
- Also called “brute force”

Nested loop

- Efficient when
  - inner table is small and fits in memory
    - optimized scan
  - join attribute in the inner table is indexed
    - index scan
- Execution cost
  - The nested loop join technique is *not symmetric*
  - The execution cost depends on which table takes the role of inner table

Merge scan

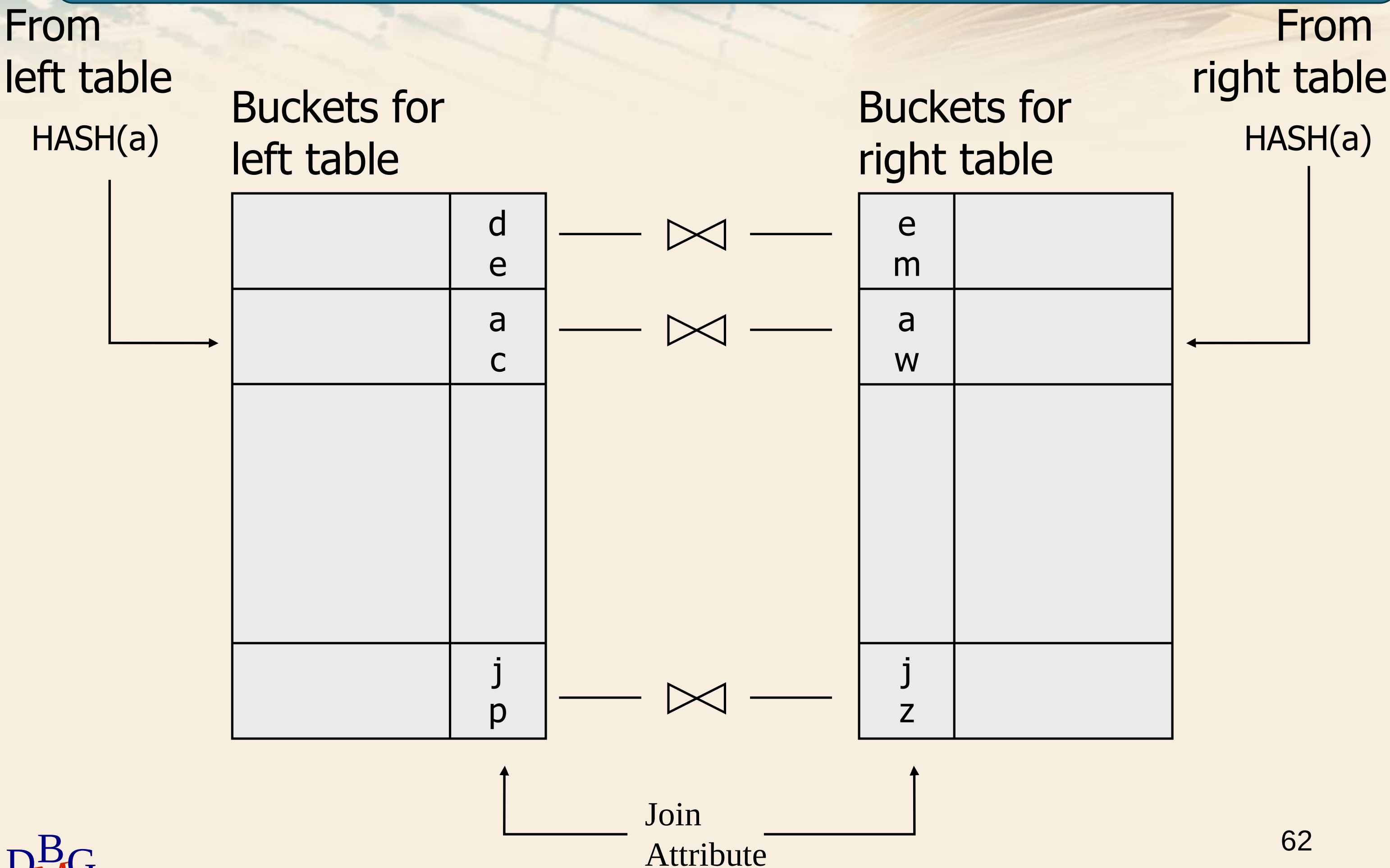


Left table
left scan
right scan
Right table
A
a
b
b
c
e
A
a
b
d
e
join attribute

Merge scan

- Both tables are sorted on the join attributes
- The two tables are scanned in parallel
  - tuple pairs are generated on corresponding values
- Execution cost
  - The merge scan technique is *symmetric*
  - requires sorting both tables
    - may be sorted by a previous operation
    - may be read through a clustered index on join attributes
- More used in the past
  - efficient for large tables, because sorted tables may be stored on disk

Hash Join



From
left table
HASH(a)
Buckets for
left table
d
e
a
c
j
p
Buckets for
right table
e
m
a
w
j
z
From
right table
HASH(a)
Join
Attribute

Hash join

- Application of the same hash function to the join attributes in both tables
  - Tuples to be joined end up in the same buckets
    - collisions are generated by tuples yielding the same hash function result with different attribute value
  - A local sort and join is performed into each bucket
- Very fast join technique

Bitmapped join index

- Bit matrix that precomputes the join between two tables A and B
  - One column for each RID in table A
  - One row for each RID in table B
- Position (i, j) of the matrix is
  - 1 if tuple with RID j in table A joins with tuple with RID i in table B
  - 0 otherwise
- Updates may be slow

RID	1	2	…	n
1	0	0	…	1
2	0	1	…	0
3	0	0	…	1
4	1	0	…	0
…	…	…	…	0

Bitmapped join

- Typically used in OLAP queries
  - joining several tables with a large central table
- Example
  - Exam table, joined to Student and Course tables
- Exploits one or more bitmapped join indices
  - One for each pair of joined tables
- Access to the large central table is the last step

Bitmapped join

- Complex queries may exploit jointly
  - bitmapped join indices
  - bitmap indices for predicates on single tables

Example: Bitmapped join

- Average score of male students for exams of courses in the first year of the master degree
  - STUDENT (Reg#, SName, Gender)
  - COURSE (Course#, CName, CourseYear)
  - EXAM (Reg#, Course#, Date, Grade)

```
SELECT AVG (Grade)
FROM   STUDENT S, EXAM E, COURSE C
WHERE E.Reg# = S.Reg#
AND E.Course# = C.Course#
AND CourseYear = '1M'
AND Gender = 'M';
```

Bitmapped join

… FROM EXAM E, COURSE C
WHERE E.Course# = C.Course#
AND CourseYear = ‘1M’ …

Bitmap for CourseYear attribute

RID	…	1M	…	…
1	0	1	…	0
2	0	0	…	0
3	0	0	…	1
4	0	1	…	0
5	1	0	…	0

RIDs 1 and 4

Bitmapped join index
for Course-Exams join

RID	1	…	4	…
1	0	…	1	1
2	0	…	1	0
3	0	…	0	1
4	1	…	0	0
…	…	…	…	…

1		4		RID_{CY}
0		1		1
0		1		1
0	OR	0	=	0
1		0		1
…		…		…

Bitmapped join

RID_{CY}		RID_G		RID
1		1		1
1	AND	0	=	0
0		0		0
1		1		1
…		…		…

RIDs of Exam table for tuples to be read

bitmap for Course-Exam predicates and join

bitmap for Student-Exam predicates and join

Group by

- Sort based
  - Sort on the group by attributes
  - Next compute aggregate functions on groups
- Hash based
  - Hash function on the group by attributes
  - Next sort each bucket and compute aggregate functions
- *Materialized views* may be exploited to improve the performance of aggregation operations

Execution plan selection

Cost based optimization

- Inputs
  - Data profiles
  - Internal representation of the query tree
- Output
  - "Optimal" query execution plan
  - Set of dependencies
- It evaluates the cost of different alternatives for
  - reading each table
  - executing each relational operator
- It exploits approximate cost formulas for access operations

General approach to optimization

- The search for the optimal plan is based on the following dimensions
  - The way data is read from disk
    - e.g., full scan, index
  - The execution order among operators
    - e.g., join order between two join operations
  - The technique by means of which each operator is implemented
    - e.g., the join method
  - When to perform sort (if sort is needed)

General approach to optimization

- The optimizer builds a *tree of alternatives* in which
  - each internal node makes a decision on a variable
  - each leaf represents a complete query execution plan

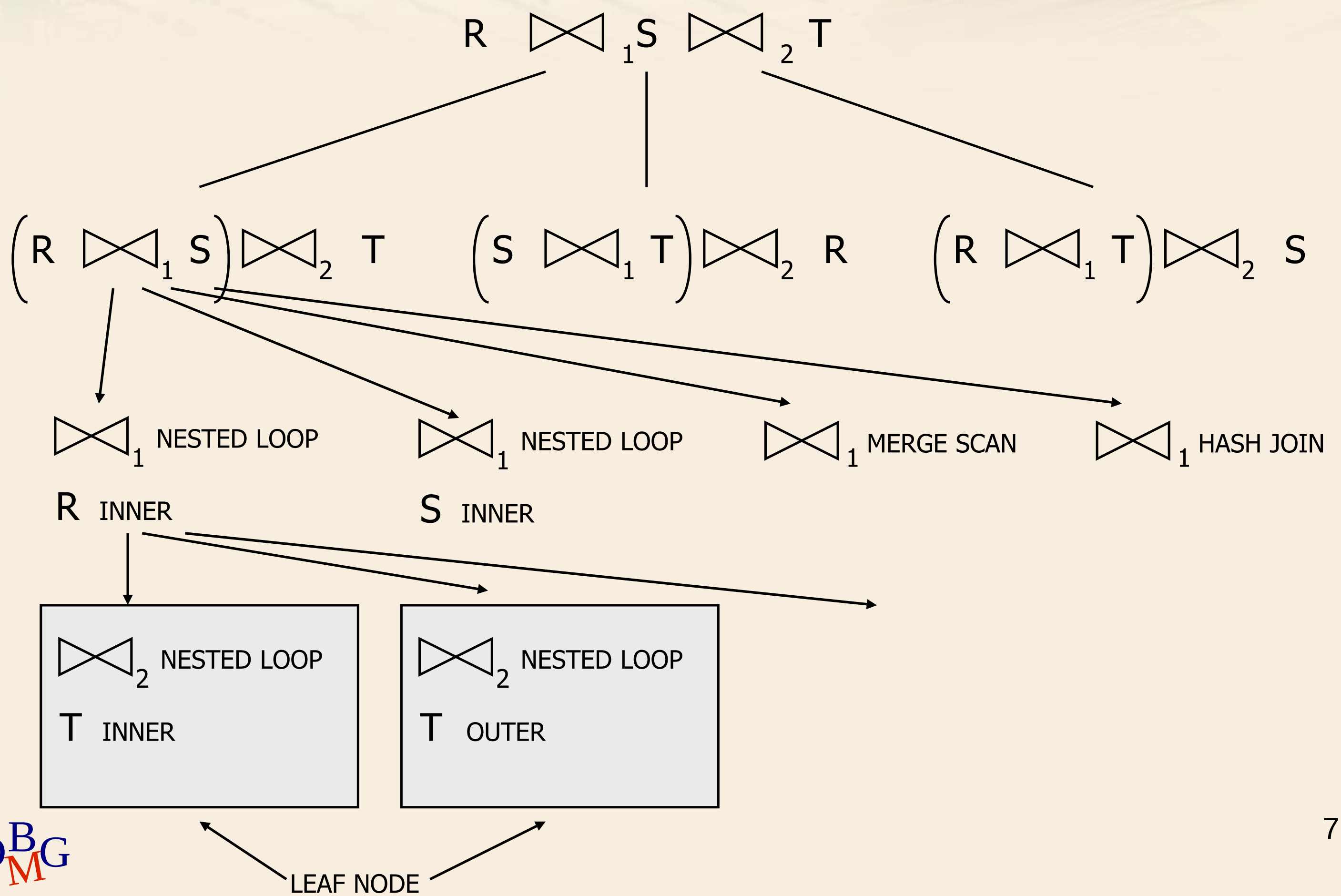
Example

- Given 3 tables
  - R, S, T
- Compute the join

$$R \bowtie S \bowtie T$$

- Execution alternatives
  - 4 join techniques to evaluate (for both joins)
  - 3 join orders
  - In total, at most
    - 4 * 4 * 3 = 48 different alternatives

Example



R ⋈1 S ⋈2 T
(R ⋈1 S) ⋈2 T
(S ⋈1 T) ⋈2 R
(R ⋈1 T) ⋈2 S
⋈1 NESTED LOOP
R INNER
⋈1 NESTED LOOP
S INNER
⋈1 MERGE SCAN
⋈1 HASH JOIN
⋈2 NESTED LOOP
T INNER
⋈2 NESTED LOOP
T OUTER
LEAF NODE

Best execution plan selection

- The optimizer selects the leaf with the lowest cost
- General formula

  $$C_{Total} = C_{I/O} \times n_{I/O} + C_{cpu} \times n_{cpu}$$

  - $n_{I/O}$ is the number of I/O operations
  - n_{cpu} is the number of CPU operations
- The selection is based on operation research optimization techniques
  - e.g., branch and bound

Best execution plan selection

- The final execution plan is an approximation of the best solution
- The optimizer looks for a solution which is of the same order of magnitude of the "best" solution
  - For compile and go
    - it stops when the time spent in searching is comparable to the time required to execute the current best plan