Realization of DBS

12. Set-Oriented DB-Interface

Theo Härder
www.haerder.de

Goals

- Derivation of concepts for translation of descriptive queries and their
- Optimization and access module creation

Main references:

Theo Härder, Erhard Rahm: Datenbanksysteme – Konzepte und Techniken der Implementierung, Springer, 2001, Chapter 12.

Mitschang, B.: Anfrageverarbeitung in Datenbanksystemen – Entwurfs- und Implementierungskonzepte, Reihe Datenbanksysteme, Vieweg-Verlag, 1995

Goetz Graefe: Query Evaluation Techniques for Large Databases, ACM Computing Surveys 25:2, June 1993, pp. 73-170.

DBIS Datenbanken und Informationssysteme

Technische Universität Kaiserslautern

Realization of DBS

Logical Data Structures

- **Characterization of the mapping**

```
SELECT Emp.Eno, Dept.Name
FROM Dept, Emp, Skill
WHERE Emp.Job = 'Programmer' &
    Skill.Sno = Emp.Sno &
    Emp.Dno = Dept.Dno
```

Mapping functions

- views	<->	base relations
- relational expressions	<->	logical access paths
- record sets	<->	single records, currency indicators

```
FETCH Skill USING ...
FETCH NEXT Emp ...
FETCH OWNER WITHIN ...
```

- **Properties of the upper interface**
  - Access-path-independent (relational) data model
  - All facts and relationships are represented by values
  - Non-procedural (descriptive) query languages
  - Access to record sets

DBIS Datenbanken und Informationssysteme

Realization of DBS

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Examples of Descriptive SQL Queries

- **Simple query**

  SELECT Eno, EName, Salary/12
  FROM Emp
  WHERE Job = W
  AND Bonus > Salary

  Replaced by

  DECLARE C1 CURSOR FOR SELECT Eno, EName, Salary/12
  INTO :X, :Y, :Z
  FROM Emp
  WHERE Job = :W
  AND Bonus > Salary

  With operators

  OPEN C1
  FETCH C1 INTO :X, :Y, :Z
  CLOSE C1

Realization of DBS

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Evaluation of DB Statements

- **Processing steps** for the evaluation of DB statements:

1. **Lexical and syntactical analysis**
   - Creation of a query graph (QG) as reference structure for the subsequent compilation steps
   - Checking for correct syntax (parsing)
2. **Semantic analysis**
   - Checking for the existence and validity of referenced tables, views, and attributes
   - Replacement of views in the QG by their view definitions
   - Replacement of external by internal names (name resolution)
   - Conversion of external formats into internal representations
3. **Access control and integrity control**
   should already be done for performance reasons, if possible, at compile time
   - Access control requires generation of runtime actions in case of value dependencies
   - Execution of simple integrity controls
     (control of formats and conversion of data types)
   - Generation of runtime actions for more complex controls

Realization of DBS

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Evaluation of DB Statements (2)

4. Standardization and simplification
serve for more effective compilation and early error detection
- Transformation of the QG into a normal form
- Elimination of redundancies

5. Restructuring and transformation
- Restructuring aims at global improvement of the QG; transformation inserts executable operations
- Application of heuristic rules (**algebraic optimization** for QG restructuring)
- Transformation leads to replacement and aggregation of logical operators by plan operators (**non-algebraic optimization**): In most cases, there are several plan operators available for the implementation of a logical operator
- Determination of alternative access plans: Frequently, many execution sequences or access paths can be chosen
- Cost estimation and selection of the cheapest execution plans

➥ Steps 4 + 5 summarized as query optimization

6. Code generation
- Generation of a tailor-made program for the given (SQL) statement
- Creation of an executable access module
- Management of access modules in a DBMS library

Realization of DBS

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Embedding of a Set-Oriented Interface

- **Specification of the desired record set** (qualification operator)

```
SELECT   Eno, EName, Salary/12          DECLARE   C1 CURSOR FOR
FROM     Emp                            SELECT   Eno, EName, Salary/12
WHERE    Job='Operator'                 FROM     Emp
         AND Bonus>Salary               WHERE    Job=:W AND Bonus>Salary
```

- **Successive provision of qualified records** (fetch operator)

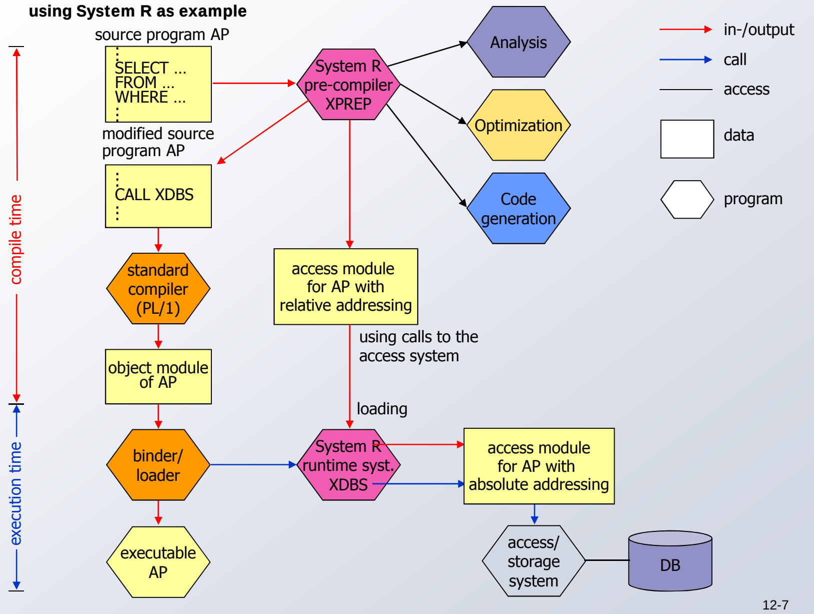
```
OPEN C1;                  →  binding of W, e.g. 'Operator',
                             activation of the cursor
FETCH C1 INTO :X, :Y, :Z; →  fetching of a record
CLOSE C1;                 →  deactivation of the cursor
```

- Possible solution**: replacement by pre-compiler**

```
DECLARE C1 ...            →  comment
OPEN C1                   →  DCL T(3) POINTER;
                             T(1) = ADDR(W)
                             CALL XDBS (AM1, 2, OPEN, ADDR(T))
FETCH C1 INTO ...         →  T(1) = ADDR(X);
                             T(2) = ADDR(Y);
                             T(3) = ADDR(Z);
                             CALL XDBS (AM1, 2, FETCH, ADDR(T));
```

Preparation and Execution of DB Statements

using System R as example



Query Optimization*

- **From query (what?) to evaluation (how?)**
  ➥ **Goal: cost-effective evaluation plan**
- **Use of a large number of methods and strategies**
  - Logical transformation of queries
  - Selection of access paths
  - Optimized storage of data on external memory
- **Key problem**
  - Exact optimization is not 'computable', in general
  - Lack of accurate statistical information
  - Broad use heuristics (rules of thumb)
- **Optimization goal**

  "either maximization of output with given resources
  or minimization of resource usage for given output

  → throughput maximization?

  → response time minimization for given query language, mix of queries of different types and given system environment!

* Jarke, M., Koch, J.: Query Optimization in Database Systems, in: ACM Comp. Surveys 16:2, 1984, pp. 111-152

Query Optimization (2)

- **Which costs are to be considered?**
  - Communication cost (# of messages, set of data to be transmitted)
    ➥ Distributed DBMS!
  - Computation cost (CPU cost, path lengths)
  - I/O cost (# of physical references)
  - Storage cost (temporary storage occupancy in DB buffer and on disk)

  ➥ Variety of costs are not independent of one another

  ➥ In centralized DBMS often "weighted function of computation- and I/O-costs"

- **What is the best approach?**

  Step 1: After compilation, find appropriate internal representation for the query (QG)

  Step 2: Apply logical restructuring to the query graph

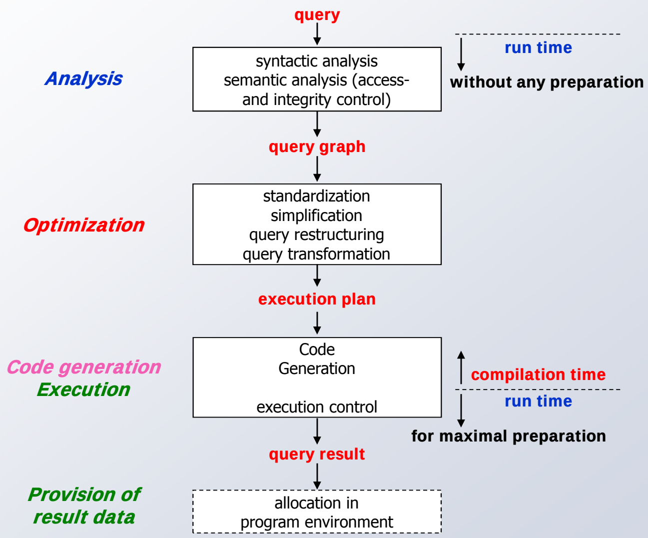
  Step 3: Map restructured query onto alternative sequences of plan operators (transformation) (➥ set of execution plans)

  Step 4: Compute cost estimates for each QEP and select the cheapest one

Realization of DBS
Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Query Processing – Cost Issues

How are the costs divided up for transaction processing?
DB system : communication system : application
When do costs incur for the query processing?



Standardization of a Query

- **Standardization**
  - Choice of a normal form
  - E.g., conjunctive normal form
  - (A11 OR ... OR A1n) AND ... AND (Am1 OR ... OR Amn)
  - Displacement of quantors
- **Transformation rules for Boolean expressions**

Commutative rules			
A **OR** B	⇔	B **OR** A	
A **AND** B	⇔	B **AND** A	
Associative rules			
(A **OR** B) **OR** C	⇔	A **OR** (B **OR** C)	
(A **AND** B) **AND** C	⇔	A **AND** (B **AND** C)	
Distributive rules			
A **OR** (B **AND** C)	⇔	(A **OR** B) **AND** (A **OR** C)	
A **AND** (B **OR** C)	⇔	(A **AND** B) **OR** (A **AND** C)	
De Morgan rules			
NOT (A **AND** B)	⇔	**NOT** (A) **OR** **NOT** (B)	
NOT (A **OR** B)	⇔	**NOT** (A) **AND** **NOT** (B)	
Double negation rule			
NOT (**NOT** (A))	⇔	A	

- **Itempotence rules for Boolean expressions**

A	**OR**	A	⇔	A
A	**AND**	A	⇔	A
A	**OR**	**NOT** (A)	⇔	TRUE
A	**AND**	**NOT** (A)	⇔	FALSE
A	**AND**	(A **OR** B)	⇔	A
A	**OR**	(A **AND** B)	⇔	A
A	**OR**	**FALSE**	⇔	A
A	**OR**	**TRUE**	⇔	TRUE
A	**AND**	**FALSE**	⇔	FALSE

Simplification of a Query

- **Equivalent expressions**
  - Can have a varying degree of redundancy
  - Usage/elimination of common sub-expressions
    - $(A_1 = a_{11}$ OR $A_1 = a_{12})$ AND $(A_1 = a_{12}$ OR $A_1 = a_{11})$
    - (Age > 25 OR (Age > 30 AND Job = 'Programmer'))
  - Simplification of expressions referring to an "empty table"
- **Constant propagation**
  - A op B AND B = const. ➥ A op const.
- **Non-satisfiable expressions**
  - A ≥ B AND B > C AND C ≥ A ➥ A > A → false
- **Use of integrity constraints (IC)**
  - ICs are true for all records of the related table
  - A is primary key: π_A → no duplicate elimination required
  - Rule: Family-Status = 'married' AND Tax-Class ≥ 3
  - ➥ Expression: (Family-Status = 'married' AND Tax-Class = 1) → false
- **Improvement of evaluation**
  - Adding of an IC to the WHERE clause does not change its truth value
  - Simpler evaluation structure, however more efficient heuristics needed

Query Restructuring

- **Most important rules for restructuring and transformation**
  - Early execution of Selection (σ) and Projection (π) without duplicate elimination
  - Aggregation of unary operator sequences (as σ and π) to a single operation
  - Evaluation of equal subtrees in the QG only once
  - Binary operator sequences (as $\cap$, $\cup$, $-$, x, $\bowtie$): minimization of intermediate results

  ➥ Selective operations (σ, π) before constructive operations (x, $\bowtie$)

- **Aggregation of operator sequences**
  - R1: $\pi_{An}(\ldots\pi_{A2}(\pi_{A1}(Tab))\ldots) \Leftrightarrow \pi_{An \ldots A1}(Tab)$
  - R2: $\sigma_{pn}(\ldots\sigma_{p2}(\sigma_{p1}(Tab))\ldots)\ldots) \Leftrightarrow \sigma_{p1 \text{ AND } p2 \ldots \text{ AND } pn}(Tab)$

- **Restructuring algorithm**

(1) Decompose complex join predicates such that they can be assigned to binary joins
(2) Divide Selections with several predicate terms in separate Selections with a single predicate term each.
(3) Execute Selections as early as possible, i.e., push down Selections to the leaves of the QG
(4) Aggregate simple Selections such that subsequent Selections (of the same table) are executed at a time
(5) Execute Projections without duplicate elimination as early as possible, i.e., push down Projections to the leaves as far as possible
(6) Aggregate simple projections (on a table) to a single operation

Realization of DBS

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Query Transformation

- **Task**
  aggregation of logical operators (one- and two-variable expressions) and their replacement by **plan operators**

- **Typical plan operators in relational systems**
  - **On a single table:**
    Selection, Projection, Sorting, Aggregation, Update operations (IUD) and ACCESS to base tables
    +
    Extensions: recursion, grouping . . .
  - **On two tables:**
    Join- and set-operations, Cartesian product

- **Adjustments in QG for the effective use of plan operators**

(1) Grouping of adjacent operators (if possible);

(2) Determination of processing sequence for binary operations;
(minimize the size of intermediate tables)

(3) Detection of common subtrees (compute them only once).

Estimation of Execution Plans – Fundamental Problems

- **Query optimization rests on “fatal” assumptions, in general**

  (1) All data elements and all attribute values are uniformly distributed

  (2) Independence of Predicates:
  - **sel(X = a and Y = b) = sel(X = a) * sel (Y= b)**

  (3) Principle of Inclusion
  - **sel(T1.X = T2.Y) = 1/max{|X|, |Y|}**

  ➥ These assumptions are wrong (in the general case)

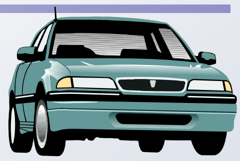
- **Example**

  (Family_Status = ‘Married’) AND (Age < 20)

➥ Linear interpolation, multiplication of probabilities

Although cost estimates are mostly wrong . . .

What is the Major Problem?



- **Correlation in predicates!**

- EXAMPLE:
  - Assume a query with the following WHERE clause:

    WHERE make = 'Honda' AND model = 'Accord',

    suppose
    - 10 makes ==> selectivity(make) = 1/10
    - 100 models ==> selectivity(model) = 1/100

  - So selectivity of both = 1/10 * 1/100 = 1/1000
    - But only Honda makes an Accord model!
    - We assumed the predicates were independent by multiplying the selectivities!
    - In fact, model and make are heavily correlated (predicate on make really adds no information)!

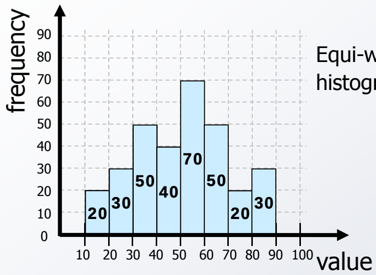
  - Effect: We underestimate cardinality by an order of magnitude!

Estimation of Execution Plans – Fundamental Problems

- **Solution?**
  - Improvement of statistics/heuristics
  - Histograms, Sampling
- **Random samplings**
  - Speed: large data set, complex algorithms
  - Example: estimation "Sales in Europe" in a TPC-H application:
    1%: 8.46 Mio. in 4 sec.
    10%: 8.51 Mio. in 52 sec.
    100%: 8.54 Mio. in 200 sec.
- **Areas of sampling usage**
  - Approximate query evaluation, estimation of response time
  - Query optimization
  - Load balancing
  - Data mining
  - Interactive query design

Realization of DBS
Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Use of Histograms



Equi-width histogram of T.a

Query 1:
SELECT *
FROM T
WHERE T.a <= 50

Query 2:
SELECT *
FROM T
WHERE T.a <= 52

- Cardinality of result for Query 1?
  sum of bucket values for *T.a <= 50* : 20 + 30 + 50 + 40 = 140
- Cardinality of result for Query 2?
  - Cardinality for *T.a <= 50* : 140
  - Cardinality for *50 < T.a <= 52* :
    uniform distribution assumption within buckets:
    ((52-50) / (60-50)) * 70 = 1/5 * 70 = 14

  ⇒ 140 + 14 = 154

Cost Model - Problems

- **Optimizer task**
  - Obtains cost estimate for each "promising" execution plan
  - Use of a weighted cost formula:

    C = #physical page accesses + W *(#calls of the access system)

    - Desired: weighted measure for I/O- and CPU utilization
    - W is the cost ratio of AS call to page access
- **Permanent problem**
  - In 1985, SQL was not standardized
  - SQL2 and SQL3 are essentially more complex
    - UDTs
    - Type and table hierarchies
    - Recursion, Constraints, Triggers, …
- **Compilation and optimization**
  - Cost-based optimizer
    - Histograms
    - but: UDTs need their own cost model
    - "Optimizing the XXX optimizer"
  - Dynamic QEPs
    - alternative plans depending on resource availability
    - "reduce the braking distance"
  - Seduction to gambling

Cost Model – Statistical Quantities

- **Statistical quantities for segments**
  - M_S number of data pages of segment S
  - L_S number of empty pages in S
- **Statistical quantities for tables**
  - N_R number of records of table R (Card(R))
  - $T_{R,S}$ number of pages in S with records of R
  - C_R clustering factor (number of records per page)
- **Statistical quantities per index** I on attributes A of a table R:
  - j_I number of attribute values / key values in the index (=Card (π_A(R))
  - B_I number of leaf pages (B*-tree)

    . . .

  → **Statistics must be maintained in the DB catalog**
- **Updating for each modification very expensive**
  - Additional write- and log operations
  - DB catalog would be the lock bottleneck
- **Alternative**
  - Initialization of statistical quantities at load- or generation time of tables and index structures
  - Periodical re-calculation of statistics by special command/service program (DB2: RUNSTATS)

Cost Model – Computational Basis

Selectivity factor SF ($0 \le SF \le 1$)
$\rightarrow$ Card ($\sigma_p(R)$) = SF(p) · Card (R)

- **Selectivity Factor SF for**

$A_i = a_i \qquad SF = \begin{cases} 1/j_i & \text{if index on } A_i \\ 1/10 & \text{otherwise} \end{cases}$

$A_i = A_k \qquad SF = \begin{cases} 1 / \mathrm{Max}(j_i, j_k) & \text{if index on } A_i, A_k \\ 1 / j_i & \text{if index on } A_i \\ 1 / j_k & \text{if index on } A_k \\ 1/10 & \text{otherwise} \end{cases}$

$A_i \ge a_i$ (or $A_i > a_i$) $\qquad SF = \begin{cases} (a_{max} - a_i) / (a_{max} - a_{min}) & \text{if index on } A_i \text{ and interpolatable} \\ 1/3 & \text{otherwise} \end{cases}$

A_i BETWEEN a_i AND a_k $\qquad SF = \begin{cases} (a_k - a_i) / (a_{max} - a_{min}) & \text{if index on } A_i \text{ and interpolatable} \\ 1/4 & \text{otherwise} \end{cases}$

A_i IN ($a_1, a_2, \ldots, a_r$) $\qquad SF = \begin{cases} r / j_i & \text{if index on } A_i \text{ and } SF < 0.5 \\ 1/2 & \text{otherwise} \end{cases}$

- **Computation of expressions**
  - SF (p(A) $\wedge$ p(B)) = SF (p(A)) · SF (p(B))
  - SF (p(A) $\vee$ p(B)) = SF (p(A)) + SF (p(B)) - SF (p(A)) · SF (p(B))
  - SF ($\neg$ p(A)) = 1 - SF (p(A))
- **Join Selectivity Factor (JSF)**
  - Card (R $\bowtie$ S) = JSF * Card(R) * Card(S)
  - for (N:1)-joins (loss-free): Card (R$\bowtie$S) = Max(Card(R), Card(S))

Creation and Selection of Execution Plans

- **Input:**
  - Optimized query graph (QG)
  - Existing storage structures and access paths
  - Cost model
- **Output: optimal execution plan (or at least “good”)**
- **Approach:**
  1. Generate all "reasonable" logical execution plans for the evaluation of the query
  2. Make the execution plans complete by adding information for physical data representation (sort sequence, access path properties, statistical information)
  3. Select the cheapest execution plan corresponding to the given cost model

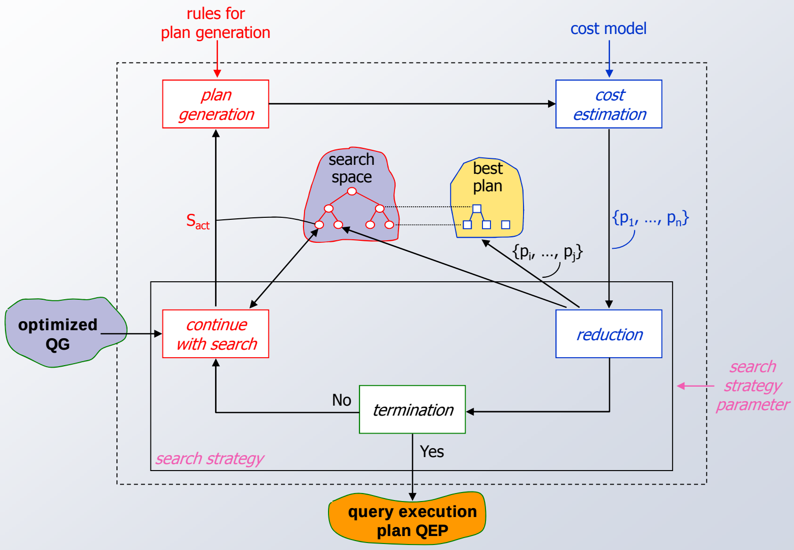
➥ Alternative execution plans for a QG primarily emerge, because various methods (implementations) exist for each plan operator and because operation sequences (e.g. in case of multi-joins) can be varied. In case of complex queries, very large search spaces with alternatives are formed (e.g. 10^{70} possible execution plans for a query with 15 joins).

- **Generation by the query optimizer**
  - ➥ Small set plans containing the optimal plan
  - ➥ Confinement by heuristics
  - Hierarchical generation based on the concept of nesting of SQL
  - Decomposition in a set of subqueries with at most two-variable expressions

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

Creation and Selection of Execution Plans (2)*

- **Interplay of components**



* Mitschang, B.: Anfrageverarbeitung in Datenbanksystemen: Entwurfs- und Implementierungskonzepte, Reihe Datenbanksysteme, Vieweg, 1995

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

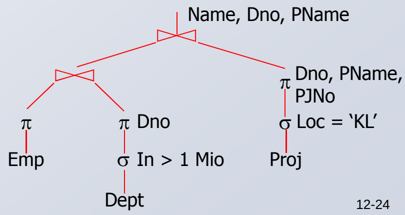
Creation and Selection of Execution Plans (3)

- **Plan generation** should
  - Always and as fast as possible find the "optimal" Plan
  - Get along with an as small as possible number of generated plans
- **Search strategies**
  - Fully enumerative
  - Restricted enumerative
  - Randomized
  - ➥ **Reduction:** certain search paths are not considered further (pruning)
- **Cost estimate**
  - Requires sufficiently accurate cost model
  - Is incrementally performed for all search methods
- **Problem representation – example**

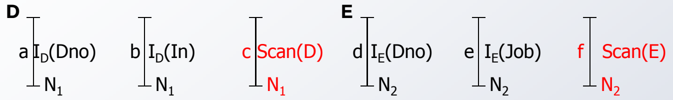
SQL:

```
SELECT  E.Eno, E.Job, J.PName
FROM    Emp E, Dept D, Proj J
WHERE   D.In > 1000000
    AND J.Loc = 'KL'
    AND D.Dno = E.Dno
    AND D.Dno = J.Dno;
```

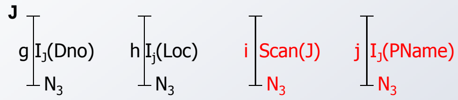
related query graph



Creation and Selection of Execution Plans (4)

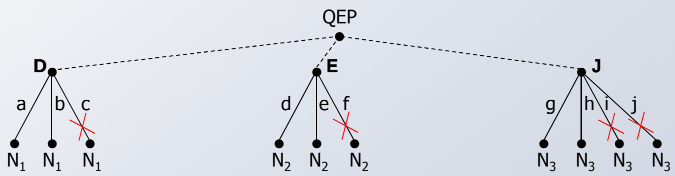


cost estimate: C (D.Dno) . . . C (E.Dno) . . .



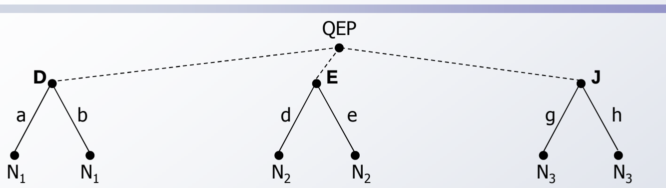
cost estimate: C (J.Dno) . . .

a) Possible access path for the single tables

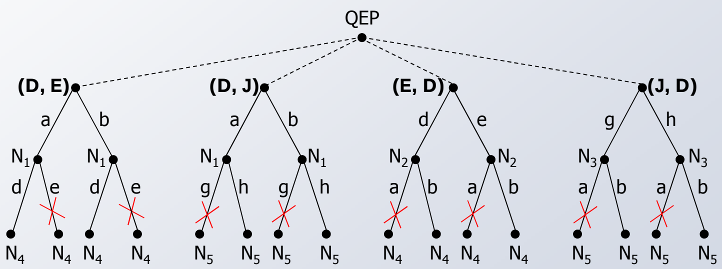


b) Solution tree for single tables: reduction by pruning of subtrees

Creation and Selection of Execution Plans (5)



b) Solution tree for single tables: after pruning



c) Extended solution tree for the Nested-Loop join with the second table
cost estimate per path: e.g. by C(C(D.Dno) + c(E.Dno) + join cost)

Code Creation

- **Optimized query graph**
  - Result of optimization phase
  - Input data structure for code generator
- **Use of the operations of the access system**
  - Direct operations (e.g. INSERT <record>)
  - Scan operations (example SYSTEM R)
    - CALL RSS (OPEN, SCAN_STRUCTURE, RETURN_CODE)
    - CALL RSS (NEXT, SCAN_STRUCTURE, RETURN_CODE)
    - SCAN_STRUCTURE is complex data structure for the handing-over of in-/output values, search arguments, etc.

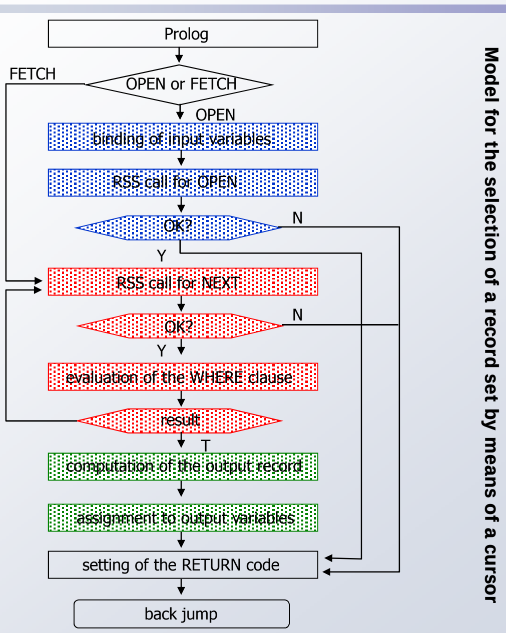
➞ **These operations are base operations for the code generation**

- **Classification of SQL statements**
  - Each class is described by a base process (e.g., by means of a cursor)
  - Skeleton of a base process is called 'model'
  - Processing step in the model is called 'fragment' (as code stored in a library)

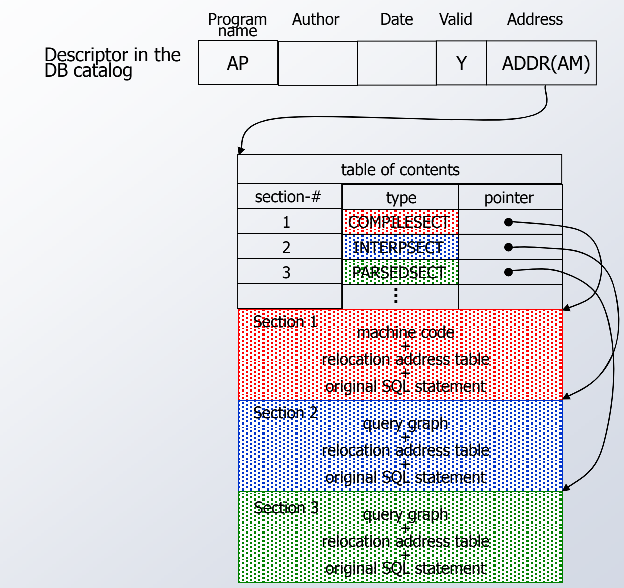
➞ **Classification happens according to the kind of access actions**

- **Provision of models and fragments**
  - 4 models for simple queries (query blocks)
  - In total: 30 models with 5-10 fragments each (<100 fragments)

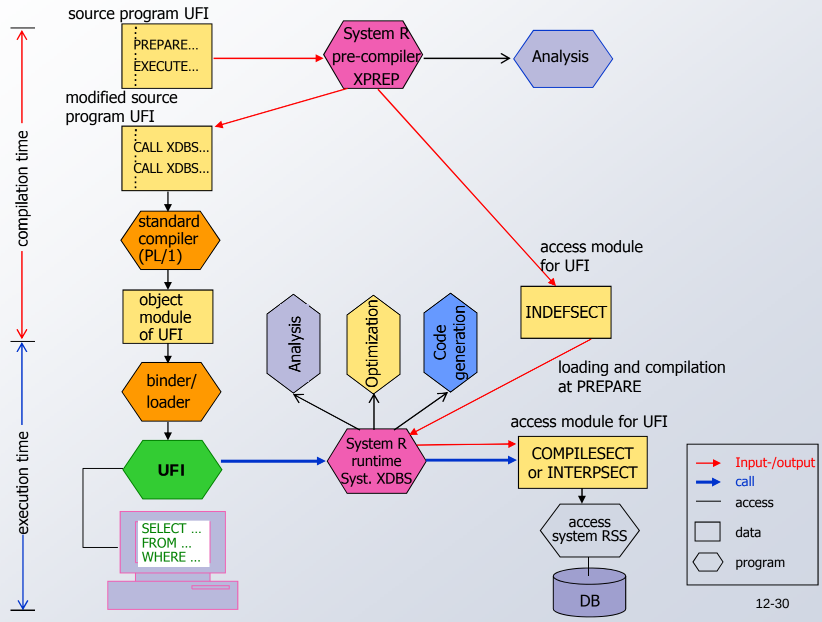
Flow Diagram for an Access Module



Structure of an Access Module



Preparation, Compilation and Execution of Ad-hoc Queries



Spectrum of Binding Times in System R

Statement type	Section type	Analysis	Optimization	Code generation	Execution
normal operations (Query, Insert, Delete, Update)	COMPILESECT	compile time	compile time	compile time	run time
non-optimizable operations (Create/ Drop Table, etc.)	INTERPSECT	compile time			run time
operations on temporary objects	PARSEDSECT	compile time	run time	run time	run time
dynamically defined statements (Prepare, Execute)	INDEFSECT	run time	run time	run time	run time

Realization of DBS

Descriptive DB languages
Evaluation of DB statements
Host language embedding
Query optimization
Estimation of execution plans
Creation of execution plans
Code creation
Ad-hoc queries

DBIS Datenbanken und Informationssysteme
© 2011 AG DBIS

Summary

- **Interpretation of a DB statement**
  - General program (Interpreter) accepts statements of the DB language as input and creates result by means of calls to the access system
  - High overhead at run time (esp. for repeated statement executions)
- **Compilation, code creation, and execution of a DB statement**
  - For each DB statement, a tailor-made program is created (compile time) which is evaluated at run time and thereby derives the result by means of calls to the access system
  - Compilation overhead is avoided as far as possible at run time
- **Query optimization: core problem**
  of compilation of set-oriented DB languages
  - "Fatal" assumptions
    - uniform distribution of all attribute values
    - independence of predicates, principle of inclusion
  - Cost estimates for execution plans
    - CPU time and I/O overhead
    - no. of messages and data volumes to be transmitted (distributed case)
  - Good heuristics for the selection of execution plans is very important
- **Cost model**
  - Minimization of cost in dependency of the system state
  - Problem: Update of statistical quantities