Databases

Lecture 11

Query Optimization in Relational Databases

Evaluating Relational Algebra Operators

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SQL Statements Execution

- client application - SQL statement execution request
  - for any query - minimum response time !
- statement execution - stages:
  - client: generate SQL statement (non-procedural language), send it to server
  - server:
    - analyze SQL statement (syntactically)
    - translate statement into an internal form (relational algebra expression)
    - transform internal form into an optimal form
    - generate a procedural execution plan
    - evaluate procedural plan, send result to client

non procedural ⇒ just describe the result

- the following operators are necessary in the querying process:
  - selection: $\sigma_C(R)$
  - projection: $\pi_\alpha(R)$
  - cross-product: $R_1 \times R_2$
  - union: $R_1 \cup R_2$
  - set-difference: $R_1 - R_2$
  - intersection: $R_1 \cap R_2$
  - theta join: $R_1 \otimes_\Theta R_2$
  - natural join: $R_1 * R_2$
  - left outer join: $R_1 \ltimes_\mathrm{C} R_2$
  - right outer join: $R_1 \rtimes_\mathrm{C} R_2$
  - full outer join: $R_1 \bowtie_\mathrm{C} R_2$
  - left semi join: $R_1 \rhd R_2$
  - right semi join: $R_1 \lhd R_2$
  - division: $R_1 \div R_2$
  - duplicate elimination: $\delta(R)$
  - sorting: $S_{\{list\}}(R)$
  - grouping: $\gamma_{\{list1\}\ group\ by\ \{list2\}}(R)$

- an SQL query can be written in multiple ways
- example for a relational database
- primary keys are underlined, foreign keys are written in blue

  programs[<u>id</u>, pname, pdescription]

  groups[<u>id</u>, program, yearofstudy, gdescription]

  students[<u>cnp</u>, lastname, firstname, sgroup, gpa, addr, email]
- query: find students (lastname, firstname, year of study, program name, gpa) in a given program (e.g., with id = 2, can be a parameter), with a gpa >= 9 (can be a parameter):

a)

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM students st, groups gr, programs pr
WHERE st.sgroup = gr.id AND gr.program = pr.id
  AND program = 2 and gpa >= 9
```

b)

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM (students st INNER JOIN groups gr ON
  st.sgroup = gr.id)
  INNER JOIN programs pr ON gr.program = pr.id
WHERE program = 2 AND gpa >= 9
```

c)

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM
   (
    (SELECT lastname, firstname, sgroup, gpa
     FROM students
     WHERE gpa >= 9) st
    INNER JOIN
    (SELECT * FROM groups WHERE program = 2) gr
       ON st.sgroup = gr.id
   )
   INNER JOIN
   (SELECT id, pname FROM programs WHERE id = 2) pr
   ON gr.program = pr.id
```

- the previous query versions are equivalent (they provide the same answer)
- equivalent relational algebra expressions:

programs[id, pname, pdescription]
groups[id, program, yearofstudy, gdescription]
students[cnp, lastname, firstname, sgroup, gpa, addr, email]

a.

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM students st, groups gr, programs pr
WHERE st.sgroup = gr.id AND gr.program = pr.id
  AND program = 2 and gpa >= 9
```

$$\boxed{\pi_\beta}(\boxed{\sigma_C}(\underbrace{students \times groups \times programs}_{\text{a lot of entries}}))$$

b)

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM (students st INNER JOIN groups gr ON
  st.sgroup = gr.id)
  INNER JOIN programs pr ON gr.program = pr.id
WHERE program = 2 AND gpa >= 9
```

$$\pi_\beta(\sigma_{C1}((students \otimes_{C2} groups) \otimes_{C3} programs))$$

c)

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM
   (
    (SELECT lastname, firstname, sgroup, gpa
     FROM students
     WHERE gpa >= 9) st
   INNER JOIN
    (SELECT * FROM groups WHERE program = 2) gr
       ON st.sgroup = gr.id
   )
   INNER JOIN
   (SELECT id, pname FROM programs WHERE id = 2) pr
   ON gr.program = pr.id
```

$$\boxed{\pi_{\beta}}(((\boxed{\pi_{\beta 1}}(\sigma_{C2}(students))) \otimes_{\boxed{C3}} (\sigma_{\boxed{C4}}(groups))) \otimes_{\boxed{C5}} (\boxed{\pi_{\beta 2}}(\sigma_{C6}(programs))))$$

- an evaluation tree can be constructed for a relational algebra expression
- problems:
    - which version is better?
    - when generating the execution plan:
        - which parameters are optimized?
        - what information is required?
    - what can the optimizer (DBMS component) do?

Relational Algebra Operators - Evaluation

- operands for relational operators:
  - database tables (can have attached indexes)
  - temporary tables (obtained by evaluating some relational operators)
- several evaluation algorithms could be used for a relational algebra operator
- when generating the execution plan:
  - choose the algorithm with the lowest complexity (for the current database context); take into account data from the system catalog, statistical information

* algorithms

Table Scan

- many operators require a full scan of the entire table
- b_R - number of blocks storing a table's records
  - sequential search algorithm - approximately $b_R/2$ blocks are necessary (on average) when performing a sequential search on a key value
  - all blocks must be brought into main memory when performing a sequential search on a non-key field
- high transfer time for large tables

Index Seek

- searching for a key value K_0
- condition of the form: $K = K_0$
- search:
  - explicit (searching a table, evaluating a join)
  - implicit (checking a key constraint)
- examine an index (stored as a B-tree, B+ tree) created:
  - via a key constraint
  - with the CREATE INDEX statement
- obs: K can be a simple or composite key

Index Scan

- evaluating $\sigma_c(R)$, where condition C is of the form:
  - A < v, A <= v, A > v, A >= v, A IS NULL, A IS NOT NULL – index built for a key A
  - A = v, A < v, A <= v, A > v, A >= v, A IS NULL, A IS NOT NULL – index built for a non-key field A
- partial / total index scan – obtain desired records' addresses
- get records from the relation; some blocks can be read multiple times

- a join can be defined as a cross-product followed by a selection
- joins arise more often in practice than cross-products
- in general, the result of a cross-product is much larger than the result of a join
- it's important to implement the join without materializing the underlying cross-product, by applying selections and projections as soon as possible, and materializing only the subset of the cross-product that will appear in the result of the join

Cross Join

- this algorithm is used to evaluate a cross-product:
  - R CROSS JOIN S
  - R INNER JOIN S ON C (C evaluates to TRUE)
  - SELECT ... FROM R, S ..., no join condition between R and S
- b_R, b_S
  - the number of blocks storing R and S, respectively
- m, n
  - the number of blocks from R and S that can simultaneously appear in the main memory (there are m+n buffers for the 2 tables)

Cross Join

- the following algorithm can be used to generate the cross-product $\{(r, s) \mid r \in R, s \in S\}$:
- `for every group of max. m blocks in R:`
  - `read the group of blocks from R into main memory; let` M_1 `be the set of records in these blocks`
  - `for every group of max. n blocks in S:`
    - `read the group of blocks from S into main memory; let` M_2 `be the set of records in these blocks`
    - `for every r ∈` M_1`:`
      - `for every s ∈` M_2`: add (r, s) to the result`

Cross Join

- algorithm complexity: total number of read blocks (from the 2 tables):

$$b_R + \left\lceil \frac{b_R}{m} \right\rceil * b_S \qquad (1)$$

(number of blocks in R; for every group of max. m blocks in R, read S)

- to minimize this value, m should be maximized (the other operands are constants); one buffer can be used for S (so n = 1), while the remaining space can be used for R (m max.)
- switch the 2 relations (in the algorithm and when computing the complexity) => complexity:

$$b_S + \left\lceil \frac{b_S}{n} \right\rceil * b_R \qquad (2)$$

- choose better version
- obs.: if b_R <= m or b_S <= n => complexity $b_R + b_S$

Nested Loops Join

- the Cross Join algorithm can be used to evaluate a join between 2 tables
- for every element (r, s) in the cross-product, evaluate the condition in the join operator
- elements (r, s) that don't meet the join condition are eliminated

Indexed Nested Loops Join

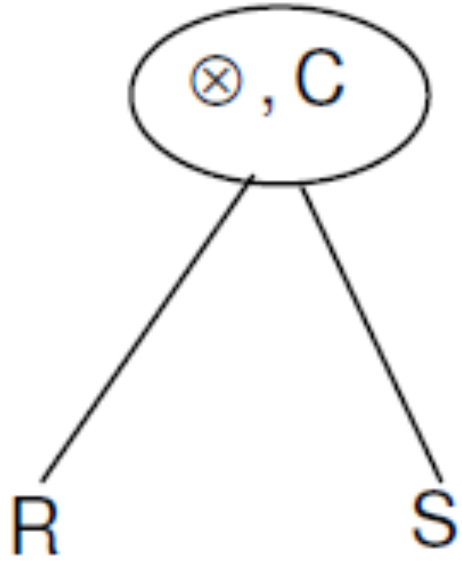
- this algorithm is used to evaluate $R \otimes_C S$, where C ≡ (R.A=S.B), and there is an index on A (in R) or on B (in S)
- in the algorithm description below, we assume there is an index on column B in table S
- `for every block in R:`
  - `read the block into main memory; let M be the set of records in the block`
  - `for every r ∈ M:`
    - `determine v =` $\pi_A(r)$
    - `use the index on B in S to determine records s ∈ S with value v for B; for every such record s, the pair (r,s) is added to the result`
- obs.: depending on the type of index - at most 1 / multiple matching records in S

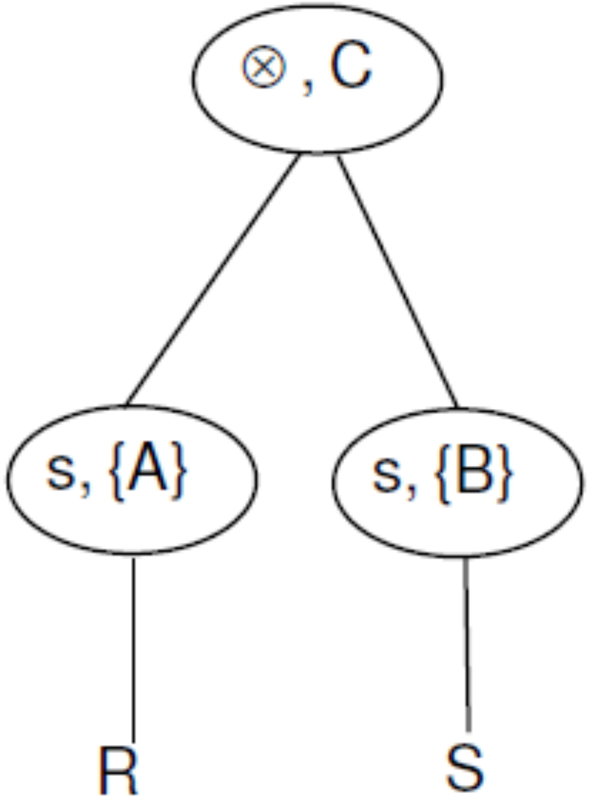
Merge Join

- this algorithm is used to evaluate $R \otimes_C S$, where C ≡ (R.A=S.B), and there are no indexes on A (in R) and B (in S)
- `sort R and S on the columns used in the join: R on A, S on B`
- `scan obtained tables; let r in R and s in S be 2 current records`
  - `if r.A = s.B: add (r', s') to the result; r' is in the set of all consecutive records in R with A = r.A, analogous for s' and S; next(r); next(s) (get a record with the next value for A and B)`
  - `if r.A < s.B: next(r) (determine record in sorted R with the next value for A)`
  - `if r.A > s.B: next(s) (determine record in sorted S with the next value for B)`

Merge Join

- this algorithm replaces an evaluation tree with another evaluation tree:





Hash Join

- this algorithm is used to evaluate $\mathrm{R} \otimes_{\mathrm{C}} \mathrm{S}$, where C ≡ (R.A = S.B)

1. partitioning phase

- hash R and S on the join column, use the same hash function *h*

=> partitions

2. probing phase

- tuples in partition R_x are compared only with tuples in partition S_x (tuples in partition R_1 cannot join with tuples in partition S_2, for instance, as they have a different hash value)

Outer Joins

- adapt condition join algorithms

Operations on Sets of Records: R ∪ S, R – S, R ∩ S

- adapt previous algorithms
- e.g., intersection:
    - sort R using all columns, sort S using all columns
    - scan sorted R and S, write in the result only the tuples in R that also appear in S

Relational Algebra Equivalences

- SQL statement - transformed into a relational algebra expression (based on a set of transformation rules for the clauses that appear in the statement)
- transform relational expression (such that the evaluation algorithm has a lower complexity)
- certain transformation rules are used (mathematical properties of the relational operators)

* $\sigma_C(\pi_\alpha(R)) = \pi_\alpha(\sigma_C(R))$

- selection reduces the number of records for projection; in the second expression, the projection operator analyzes fewer records
- optimization - algorithm that evaluates both operators in a single pass of R

* perform one pass instead of 2:

$$\sigma_{C1}(\sigma_{C2}(R)) = \sigma_{C1\ \mathrm{AND}\ C2}(R)$$

* replace cross-product and selection by condition join (a number of condition join algorithms don't evaluate the cross-product):

$$\sigma_C(R \times S) = R \otimes_C S$$

, where C - join condition between R and S

* R and S - compatible schemas:

$$\sigma_C(R \cup S) = \sigma_C(R) \cup \sigma_C(S)$$
$$\sigma_C(R \cap S) = \sigma_C(R) \cap \sigma_C(S)$$
$$\sigma_C(R - S) = \sigma_C(R) - \sigma_C(S)$$

* $\sigma_C(R \times S)$

particular cases:

- C contains only attributes from R:

$$\sigma_C(R \times S) = \sigma_C(R) \times S$$

- C = C1 AND C2, C1 contains only attributes from R, C2 - only attributes from S:

$$\sigma_{C1 \text{ AND } C2}(R \times S) = \sigma_{C1}(R) \times \sigma_{C2}(S)$$

- C = C1 AND C2, C2 - join condition between R and S:

$$\sigma_{C1 \text{ AND } C2}(R \times S) = \sigma_{C1}(R \otimes_{C2} S)$$

* $\pi_{\alpha}(R \cup S) = \pi_{\alpha}(R) \cup \pi_{\alpha}(S)$

* $\pi_{\alpha}(R \otimes_{C} S) = \pi_{\alpha}(\pi_{\alpha 1}(R) \otimes_{C} \pi_{\alpha 2}(S))$

- $\alpha 1$: attributes in R that appear in α or C
- $\alpha 2$: attributes in S that appear in α or C

* associativity and commutativity for some relational operators

- associativity and commutativity for ∪ and ∩
- associativity for the cross-product and the natural join
- "equivalent" results (same records, but different column order) when commuting operands in × and certain join operators
  - R × S = S × R – when using the Cross Join algorithm, the order of the data sources is important

* transitivity of some relational operators for the join operators - additional filters could be applied before the join:

- (A>B AND B>3) $\equiv$ (A>B AND B>3 AND A>3)
- example: A is in R, B is in S:

$$\mathrm{R}\otimes_{\mathrm{A>B\ AND\ B>3}}\mathrm{S} = (\sigma_{\mathrm{A>3}}(\mathrm{R}))\otimes_{\mathrm{A>B}}(\sigma_{\mathrm{B>3}}(\mathrm{S}))$$

- (A=B AND B=3) $\equiv$ (A=B AND B=3 AND A=3)
- example: A is in R, B is in S:

$$\mathrm{R}\otimes_{\mathrm{A=B\ AND\ B=3}}\mathrm{S} = (\sigma_{\mathrm{A=3}}(\mathrm{R}))\otimes_{\mathrm{A=B}}(\sigma_{\mathrm{B=3}}(\mathrm{S}))$$

* evaluating $\sigma_C(R)$, where C $\equiv$ $(\mathrm{R.A} \in \delta(\pi_{\{\mathrm{B}\}}(S)))$; avoid evaluating C for every record of R; the initial evaluation is equivalent to:

$$\mathrm{R} \otimes_{\mathrm{R.A=S.B}} (\delta(\pi_{\{\mathrm{B}\}}(\mathrm{S})))$$

- consider again the query described on the database:
  programs[id, pname, pdescription]
  groups[id, program, yearofstudy, gdescription]
  students[cnp, lastname, firstname, sgroup, gpa, addr, email]
- query: find students (lastname, firstname, year of study, program name, gpa) in a given program (e.g., with id = 2), with a gpa >= 9:

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM students, groups, programs
WHERE students.sgroup = groups.id AND
  groups.program = programs.id AND
  program = 2 and gpa >= 9
```

- denote by:

C $\equiv$ (students.sgroup = groups.id AND groups.program = programs.id AND program = 2 and gpa >= 9)

β = {lastname, firstname, yearofstudy, pname, gpa} – attributes in the SELECT clause

- the corresponding relational expression:

$$\pi_{\beta}(\sigma_{C}(students \times groups \times programs))$$

- carry out the following transformations, using previously discussed rules:
- associativity for ×:

$$students \times groups \times programs = \ (students \times groups) \times programs$$ or

$$students \times groups \times programs = \ students \times (groups \times programs)$$

- commute σ with × (use a particular case); the transitivity of the equality operator:

(groups.program = programs.id AND program = 2)

≡ (groups.program = programs.id AND program = 2 AND programs.id = 2)

students.sgroup = groups.id	AND	groups.program = programs.id	AND	program = 2	AND	gpa >= 9	AND	programs.id = 2
C1		C2		C3		C4		C5

$$\sigma_C(students \times groups \times programs) =$$
$$\sigma_{C1\ AND\ C2}((\sigma_{C4}(students) \times \sigma_{C3}(groups)) \times \sigma_{C5}(programs))$$ or
$$\sigma_{C1\ AND\ C2}(\sigma_{C4}(students) \times (\sigma_{C3}(groups) \times \sigma_{C5}(programs)))$$

- replace selection and cross-product with condition join:

$$= ((\sigma_{C4}(students)) \otimes_{C1} (\sigma_{C3}(groups))) \otimes_{C2} (\sigma_{C5}(programs))$$

or

$$= (\sigma_{C4}(students)) \otimes_{C1} ((\sigma_{C3}(groups)) \otimes_{C2} (\sigma_{C5}(programs)))$$

- choose a version based on statistical information from the database; we consider the first version:

$$\Rightarrow e = \pi_{\beta}(((\sigma_{C4}(students)) \otimes_{C1} (\sigma_{C3}(groups))) \otimes_{C2} (\sigma_{C5}(programs)))$$

- commute π with join:

$\beta 1$ = {lastname, firstname, gpa, sgroup} - useful for β and join

$\beta 2$ = {id, program, yearofstudy} - useful for β and join

$\beta 3$ = {id, pname} - useful for β and join

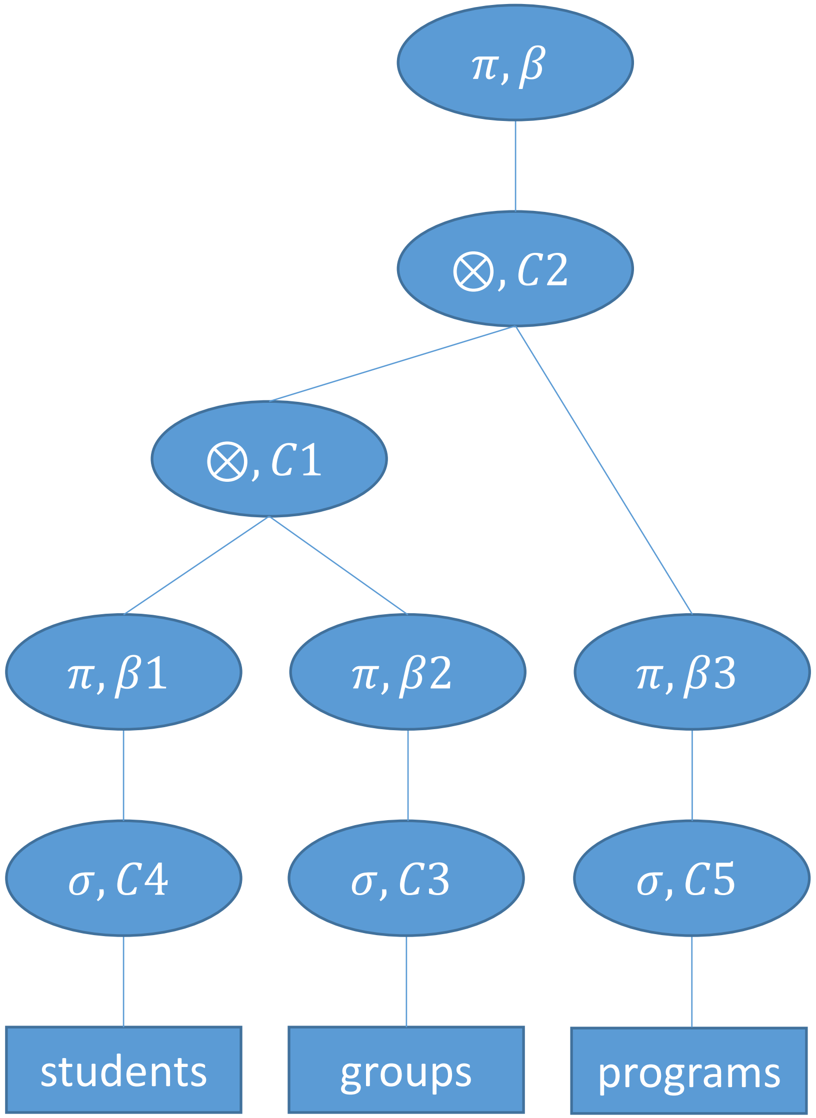
$$e = \pi_{\beta}(((\pi_{\beta 1}(\sigma_{C4}(students))) \otimes_{C1} (\pi_{\beta 2}(\sigma_{C3}(groups)))) \otimes_{C2} (\pi_{\beta 3}(\sigma_{C5}(programs))))$$

- the last expression corresponds to the statement:

```
SELECT lastname, firstname, yearofstudy, pname, gpa
FROM
  (
   (SELECT lastname, firstname, gpa, sgroup FROM students WHERE gpa >= 9) st
   INNER JOIN
   (SELECT id, program, yearofstudy FROM groups WHERE program = 2) gr
      ON st.sgroup = gr.id
  )
  INNER JOIN
  (SELECT id, pname FROM programs WHERE programs.id = 2) pr
  ON gr.program = pr.id
```

- an evaluation tree can be constructed for the last version of the relational algebra expression

- using information from the system catalog and possibly statistical information, an execution plan can be generated from the last version of the expression; every relational operator is replaced by an evaluation algorithm



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