Database Management Systems

Lecture 10

Evaluating Relational Operators

Query Optimization

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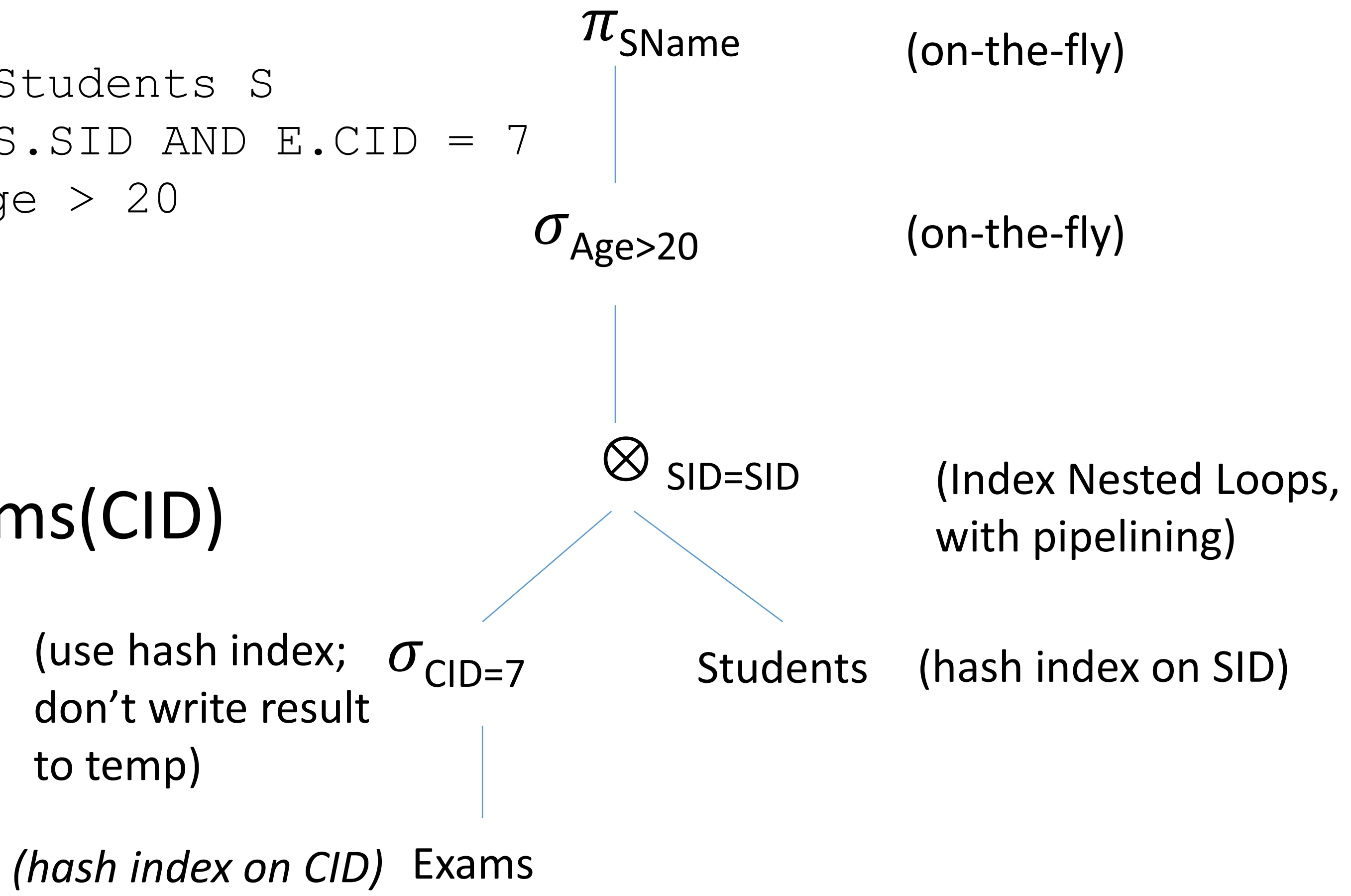
- running example - schema
  - Students (<u>SID: integer</u>, SName: string, Age: integer, RoundedGPA: integer)
  - Courses (<u>CID: integer</u>, CName: string, Description: string)
  - Exams (<u>SID: integer, CID: integer, EDate: date</u>, Grade: integer)

- Students
  - every record has 50 bytes
  - there are 80 records / page
  - 500 pages
- Courses
  - every record has 40 bytes
  - there are 100 records / page
  - 1 page
- Exams
  - every record has 40 bytes
  - there are 100 records / page
  - 1000 pages

Motivating Example
* optimizations

```
SELECT S.SName
FROM Exams E, Students S
WHERE E.SID = S.SID AND E.CID = 7
      AND S.Age > 20
```



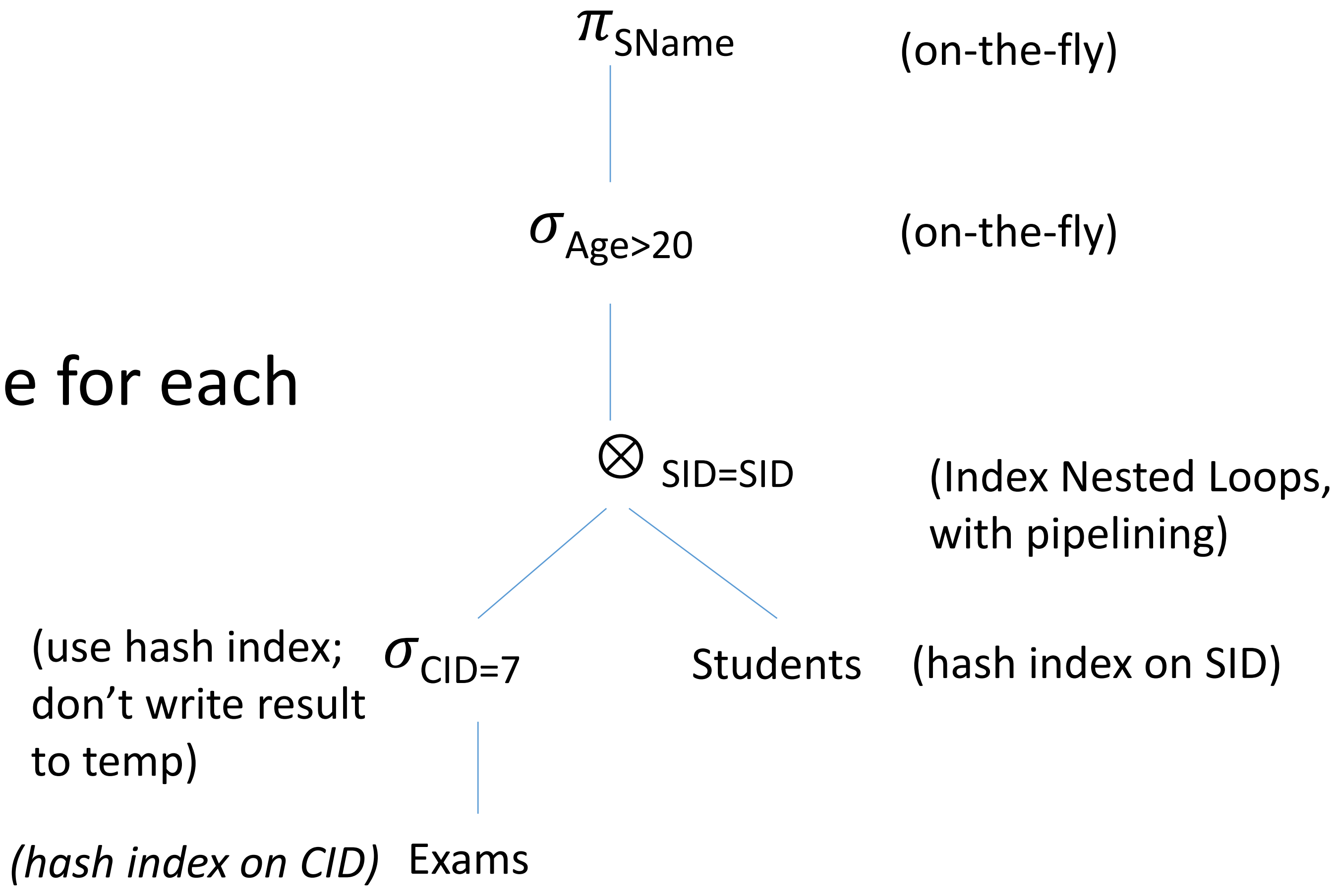
- investigate the use of indexes

- clustered static hash index on Exams(CID)
- hash index on Students(SID)

- cost
    - $\sigma_{CID=7}$
        - assume exams are uniformly distributed across all courses => 100,000 exams / 100 courses => 1,000 exams / course
        - clustered index on CID => 1,000 tuples for course with CID=7 appear consecutively within the same bucket => cost: 10 I/Os
        - the result of the selection is not materialized, the join is pipelined

Motivating Example

- cost
  - Index Nested Loops
    - find matching Students tuple for each selected exam
    - use hash index on SID
      - assume the index uses a1 => cost of 1.2 I/Os (on avg.) per exam



  - σ, π – performed on-the-fly on each tuple in the result of the join

=> **total cost** = $\underset{\sigma \text{ on Exams}}{\underline{10}} + \underset{\text{num. of Exams tuples}}{\underline{1000}} * \underset{\text{find matching Students tuple (on avg.)}}{\underline{1.2}}$ = **1210** I/Os

* can we push the selection *Age>20* ahead of the join?

IBM's System R Optimizer

- tremendous influence on subsequent relational optimizers
- design choices:
  - use statistics to estimate the costs of query evaluation plans
  - consider only plans with binary joins in which the inner relation is a base relation
  - focus optimization on SQL queries without nesting
  - don't eliminate duplicates when performing projections (unless DISTINCT is used)

Estimating the Cost of a Plan

- estimating the cost of an evaluation plan for a query block
  - for each node N in the tree:
    - estimate the cost of the corresponding operation (pipelining versus temporary relations)
    - estimate the size of N's result and whether it is sorted
      - N's result is the input of N's parent node
      - these estimates affect the estimation of cost, size, and sort order for N's parent

Estimating the Cost of a Plan

- estimating costs
    - use data about the input relations (such statistics are stored in the DBMS's system catalogs)
        - number of pages, existing indexes, etc.
- obtained estimates are at best approximations to actual sizes and costs

=> one shouldn't expect the optimizer to find the best possible plan

- optimizer - goals:
    - avoid the worst plans
    - find a good plan

Statistics Maintained by the DBMS

- updated periodically, not every time the data is changed
  - relation R
    - cardinality - *NTuples(R)*
      - the number of tuples in R
    - size - *NPages(R)*
      - the number of pages in R
  - index I
    - cardinality - *NKeys(I)*
      - the number of distinct key values for I
    - size - *INPages(I)*
      - the number of pages for I
      - B+ tree index
        - number of leaf pages

Statistics Maintained by the DBMS

- index I
  - height - *IHeight(I)*
    - maintained for tree indexes
    - the number of nonleaf levels in I
  - range - *ILow(I), IHigh(I)*
    - the minimum / maximum key value in I

Estimating Result Sizes

- query Q

  `SELECT attribute list`
  `FROM relation list`
  `WHERE` $\mathtt{term}_1 \wedge \ldots \wedge \mathtt{term}_k$
- the maximum number of tuples in Q's result:
  - $\prod |R_i|$

  where $R_i \in$ `relation list`
- each $term_j$ in the WHERE clause eliminates some candidate tuples
  - associate a reduction factor RF_j with each term $term_j$
  - RF_j models the impact $term_j$ has on the result size
- estimate the actual size of the result:
  - $\prod |R_i| * \prod RF_j$
  - i.e., the maximum result size times the product of the reduction factors for the terms in the WHERE clause

Estimating Result Sizes

- query Q

```
SELECT attribute list
FROM relation list
WHERE term_1 ∧ ... ∧ term_k
```

- assumption
  - the conditions tested by the terms in the WHERE clause are statistically independent

Estimating Result Sizes

- compute reduction factors for terms in the WHERE clause
- assumptions:
  - uniform distribution of values
  - independent distribution of values in different columns

```
SELECT attribute list
FROM relation list
WHERE term1 AND ... AND termk
```

- *column = value*
  - index I on *column*

  => RF approximated by 1/NKeys(I)
  - no index on *column*

  => RF: 1/10
    - maintain statistics on *column* (e.g., number of distinct values in *column*) to obtain a better value

Estimating Result Sizes

- *column1 = column2*
  - indexes *I1* on *column1*, *I2* on *column2*

  => RF: 1/MAX(NKeys(I1), NKeys(I2))
  - only one index I (on one of the 2 columns)

  => RF: 1/NKeys(I)
  - no indexes

  => RF: 1/10
- *column > value*
  - index I on *column*

  => RF: (IHigh(I) - *value*) / (IHigh(I) - ILow(I))
  - no index on *column* or *column* not of an arithmetic type

  => a value less than 0.5 is arbitrarily chosen
  - similar formulas can be obtained for other range selections

Estimating Result Sizes

- *column IN (list of values)*

  => RF: (RF for *column = value*) * number of items in list (but at most 0.5)
- *NOT condition*

  => RF: 1 - RF for *condition*

- obtain better estimates
  - use more detailed statistics (e.g., histograms of the values in a column)

Relational Algebra Equivalences

- central role in generating alternative plans
- different join orders can be considered
- selections, projections can be pushed ahead of joins
- cross-products can be converted to joins

- selections
  - *cascading selections*
    - $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\sigma_{c2}(\ldots(\sigma_{cn}(R))\ldots))$
  - *commutativity*
    - $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$
- projections
  - *cascading projections*
    - $\pi_{a1}(R) \equiv \pi_{a1}(\pi_{a2}(\ldots(\pi_{an}(R))\ldots))$
    - a_i – set of attributes in R
    - $a_i \subseteq a_{i+1}$, for i = 1..n-1

Relational Algebra Equivalences

- joins and cross-products
  - assumption
    - fields are identified by their name, not by their position
  - *associativity*
    - $R \times (S \times T) \equiv (R \times S) \times T$
    - $R * (S * T) \equiv (R * S) * T$
  - *commutativity*
    - $R \times S \equiv S \times R$
    - $R * S \equiv S * R$
    - can choose the inner / outer relation in a join

Relational Algebra Equivalences

- joins and cross-products
  - e.g., check that R * (S * T) ≡ (T * R) * S
    - commutativity
      - R * (S * T) ≡ R * (T * S)
    - associativity
      - R * (T * S) ≡ (R * T) * S
    - commutativity
      - (R * T) * S ≡ (T * R) * S

Relational Algebra Equivalences

- can commute σ with π if σ uses only attributes retained by π
  - $\pi_a(\sigma_c(R)) \equiv \sigma_c(\pi_a(R))$
- can combine σ with $\times$ to form a join
  - $R \otimes_c S \equiv \sigma_c(R \times S)$
- can commute σ with $\times$ or a join when the selection condition includes only fields of one of the arguments (to the cross-product or join)
  - for instance:
    - $\sigma_c(R * S) \equiv \sigma_c(R) * S$
    - $\sigma_c(R \times S) \equiv \sigma_c(R) \times S$
      - condition c must include only fields from R
- in general: $\sigma_c(R \times S) \equiv \sigma_{c1}(\sigma_{c2}(R) \times \sigma_{c3}(S))$
    - c1 – attributes of both R and S
    - c2 – only attributes of R
    - c3 – only attributes of S

Relational Algebra Equivalences

- can commute π with $\times$
  - $\pi_a(R \times S) \equiv \pi_{a1}(R) \times \pi_{a2}(S)$
  - a1 – attributes in *a* that appear in R
  - a2 – attributes in *a* that appear in S
- can commute π with join
  - $\pi_a(R \otimes_c S) \equiv \pi_{a1}(R) \otimes_c \pi_{a2}(S)$
    - every attribute in *c* must appear in *a*
    - a1 – attributes in *a* that appear in R
    - a2 – attributes in *a* that appear in S
  - *a* doesn't contain all the attributes in *c* – generalization
    - eliminate unwanted fields, compute join, eliminate fields not in *a*
      - $\pi_a(R \otimes_c S) \equiv \pi_a(\pi_{a1}(R) \otimes_c \pi_{a2}(S))$
      - a1 – attributes of R that appear in either *a* or *c*
      - a2 – attributes of S that appear in either *a* or *c*

Enumeration of Alternative Plans

- query Q
  - consider a certain set of plans
  - choose the plan with the least estimated cost
    - algebraic equivalences
    - implementation techniques for Q's operators
- not all algebraically equivalent plans are enumerated (optimization costs would be too high)
- two main cases:
  - queries with one relation in the FROM clause
  - queries with two or more relations in the FROM clause

Enumeration of Alternative Plans

- <u>queries with one relation in the FROM clause</u>
  - i.e., no joins; only σ, π, grouping, aggregate operations
  - if there is only one σ or π or aggregate operation: consider implementation techniques and cost estimates discussed in previous lectures
  - if there is a combination of operations:
    - plans with / without indexes
  - example query:

```
SELECT S.RoundedGPA, COUNT(*)
FROM Students S
WHERE S.RoundedGPA > 5 AND S.Age = 20
GROUP BY S.RoundedGPA
HAVING COUNT(DISTINCT S.SName) > 5
```

$$\pi_{S.RoundedGPA,\ COUNT(*)}(\ HAVING_{COUNT\ DISTINCT\ (S.SName) > 5}(\ GROUP\ BY_{S.RoundedGPA}(\ \pi_{S.RoundedGPA,\ S.SName}(\ \sigma_{S.RoundedGPA > 5\ \wedge\ S.Age = 20}(\ Students)))))$$

Enumeration of Alternative Plans

* plans without indexes:

- apply σ, π while scanning Students
  - file scan
    - NPages(Students)
    - 500 I/Os
  - write out tuples to a temporary relation T:
    - NPages(Students) * RF(RoundedGPA > 5) * RF(Age = 20) * (size of a *pair <RoundedGPA, SName>* / size of a *Students tuple*)
    - RF for *RoundedGPA > 5*
      - 0.5
    - RF for *Age = 20*
      - 0.1
    - size of <RoundedGPA, SName>
      - about 0.8 * size of a Students tuple

Enumeration of Alternative Plans

* plans without indexes:

- apply σ, π while scanning Students
  - write out tuples to a temporary relation T:
    => 500 * 0.5 * 0.1 * 0.8 = 20 I/Os (temporary relation T)
- GROUP BY:
  - sort T in 2 passes
    - 4 * 20 = 80 I/Os
- HAVING, aggregations
  - no additional I/O
- **total cost**
  - 500 + 20 + 80 = **600 I/Os**

Enumeration of Alternative Plans

* plans that use an index:

- available indexes on Students - a2
  - hash index on <Age>
  - B+ tree index on <RoundedGPA>
  - B+ tree index on <RoundedGPA, SName, Age>
- <u>single-index access path:</u>
  - choose the index that provides the most selective access path
  - apply π, nonprimary selection terms (i.e., that don't match the index)
  - compute grouping and aggregation operations
  - example:
    - use the hash index on Age to retrieve Students with Age = 20
      - cost: retrieve index entries and corresponding Students tuples
    - apply condition *RoundedGPA > 5* to each retrieved tuple
    - retain RoundedGPA and SName

Enumeration of Alternative Plans

* plans that use an index:

- <u>single-index access path</u> – example:
  - write out tuples to a temporary relation
  - sort the temporary relation by RoundedGPA to identify groups
  - apply the HAVING condition (to eliminate some groups)
- <u>multiple-index access path</u> - *section uploaded in advance*
  - several indexes using a2 / a3 match the selection condition, e.g., I1, I2
  - retrieve $Rids_{I1}$, $Rids_{I2}$ using I1, I2
  - get tuples with rids in $Rids_{I1} \cap Rids_{I2}$ (tuples satisfying the primary selection terms of I1 and I2)
  - apply π, nonprimary selection terms
  - compute grouping and aggregation operations
  - example:
    - use the index on Age => rids of tuples with Age = 20 (R1)

Enumeration of Alternative Plans

* plans that use an index:

- multiple-index access path – example:
    - index on RoundedGPA => rids of tuples with RoundedGPA > 5 (R2)
    - retrieve tuples with rids in R1 ∩ R2
    - keep only RoundedGPA and SName
    - write out tuples to a temporary relation
    - sort the temporary relation by RoundedGPA to identify groups
    - apply the HAVING condition (to eliminate some groups)
- sorted index access path:
    - works well when the index is clustered
    - B+ tree index I with search key K
    - GROUP BY attributes – prefix of K
    - use the index to retrieve tuples in the order required by the GROUP BY clause

Enumeration of Alternative Plans

* plans that use an index:

- apply σ, π
- compute aggregation operations

- sorted index access path – example:
    - use the B+ tree index on RoundedGPA to retrieve Students tuples with RoundedGPA > 5, ordered by RoundedGPA
    - aggregations in HAVING, SELECT - computed on-the-fly
- index-only access path:
    - index I with search key K
    - all the attributes in the query are included in K

  => index-only scan, don't need to retrieve tuples from the relation

    - data entries: apply σ, perform π, sort the result (to identify groups), compute aggregate operations

  * obs. index I doesn't have to match the selections in the WHERE clause

Enumeration of Alternative Plans

* plans that use an index:

- <u>index-only access path</u>

  * obs. I – tree index, GROUP BY attributes – prefix of K

  => can avoid sorting

  - example:
    - use the B+ tree index on <RoundedGPA, SName, Age> to retrieve entries with RoundedGPA > 5, ordered by RoundedGPA
    - select entries with Age = 20
    - aggregation operations in the HAVING and SELECT clauses - computed on-the-fly

Enumeration of Alternative Plans

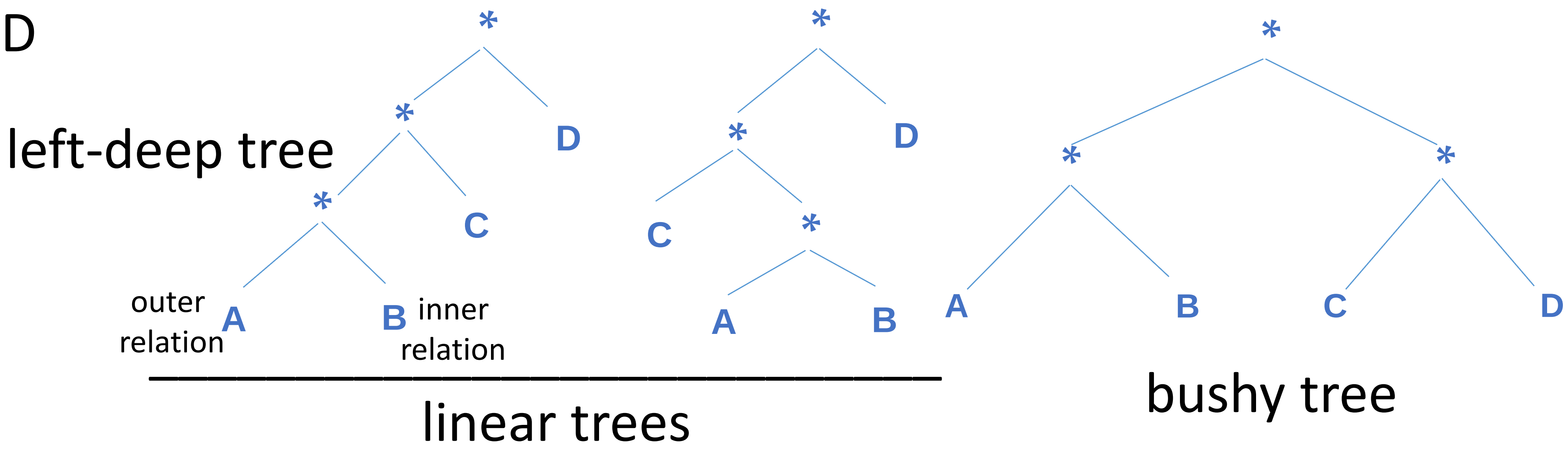
- queries with several relations in the FROM clause:
  - joins, cross-products => queries can be quite expensive
  - different join orders => intermediate relations of widely varying sizes => plans with very different costs

- class of plans considered by the optimizer
- plan enumeration

Enumeration of Alternative Plans

- <u>queries with several relations in the FROM clause</u>

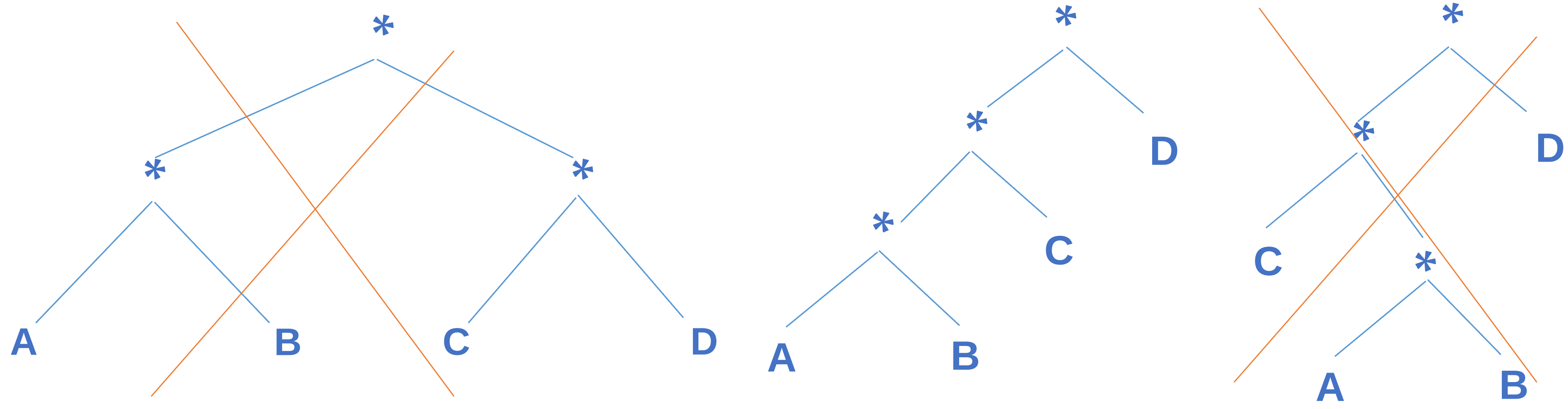
A * B * C * D



- linear trees:
  - at least one child of a join node is a base relation
- left-deep trees:
  - the right child of each join node is a base relation
- bushy tree: not linear

Enumeration of Alternative Plans

- <u>queries with several relations in the FROM clause</u>
- fundamental decision in System R:
  - only *left-deep trees* are considered



- motivation:
  - number of joins increases => number of alternative plans increases quickly => must prune the search space
  - left-deep trees generate all <u>fully pipelined plans</u> (all joins are evaluated using pipelining)

Enumeration of Alternative Plans

- <u>queries with several relations in the FROM clause</u>
- multiple passes:
  - pass 1:
    - find best 1-relation plan for each relation
  - pass 2:
    - find best way to join the result of each 1-relation plan (as the outer argument) with another relation (all 2-relation plans)

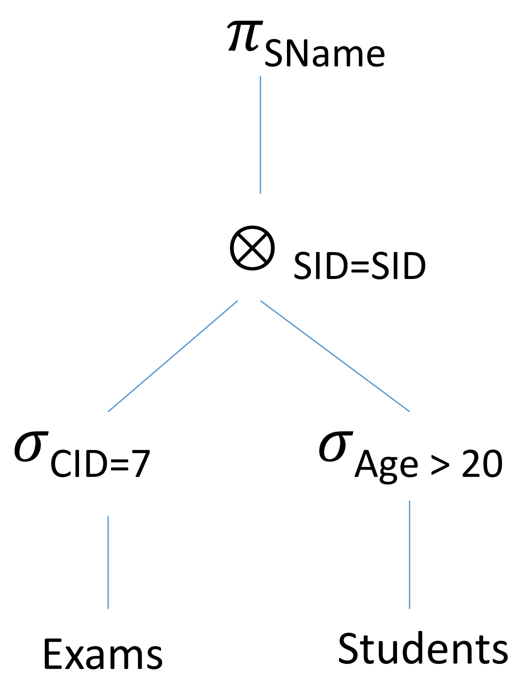
  …
  - repeat until the obtained plans contain all the relations in the query
- for each subset of relations, retain: the cheapest overall plan & the cheapest plan for each interesting ordering of tuples

Enumeration of Alternative Plans

- queries with several relations in the FROM clause
  - GROUP BY, aggregates are handled as a final step:
    - use a plan with an interesting ordering of tuples
    - use an additional sorting operator
- obs. avoid cross-products if possible

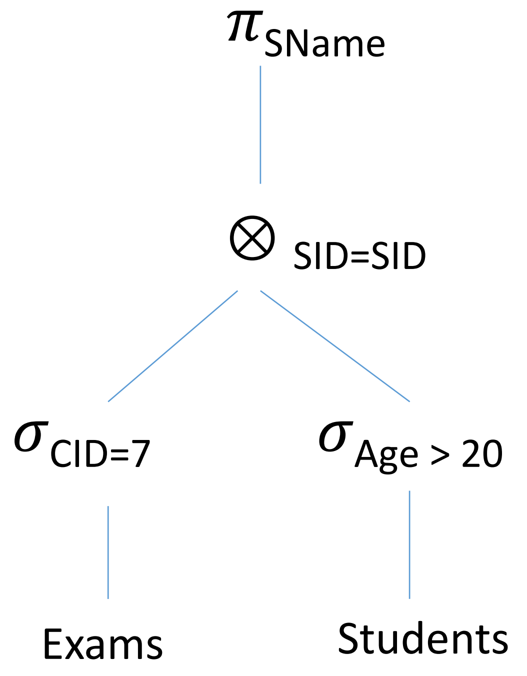
Example

- unclustered indexes using a2
- Students: B+ tree index on Age, hash index on SID
- Exams: B+ tree index on CID
- pass 1:
    - Students – 3 possible access paths:
      B+ tree index, hash index, file scan
        - *Age > 20* matches the B+ tree index on Age
        - hash index / file scan => probably much higher cost
        - keep the plan using the B+ tree index => retrieved tuples are ordered by Age
    - Exams – 2 possible access paths
        - *CID = 7* matches the B+ tree index on CID
        - better than file scan => keep the plan using the B+ tree index



Example

- Students: B+ tree index on Age, hash index on SID
- Exams: B+ tree index on CID
- pass 2:
  - consider (the result of) each plan from pass 1 as the outer argument and analyze how to join it with the other relation
  - e.g., Exams – outer argument
    - examine alternative access methods / join methods
    - access methods:
      - need Students tuples s.t. SID = *value* from outer tuple and Age > 20
      - hash index => Students tuples s.t. SID = *value* from outer tuple
      - B+ tree index => Students tuples s.t. Age > 20
    - join methods:
      - consider all available methods



Example

- Students: B+ tree index on Age, hash index on SID
- Exams: B+ tree index on CID
- pass 2:
  - consider (the result of) each plan from pass 1 as the outer argument and analyze how to join it with the other relation
  - e.g., Students – outer argument
    - access / join methods
    - access methods:
      - need Exams tuples s.t. SID = *value* from outer tuple and CID = 7
    - join methods:
      - consider all available methods
  - retain cheapest plan overall!

Nested Queries

- usually handled using some form of nested loops evaluation
- correlated query - typical evaluation strategy:
  - the inner block is evaluated for each tuple of the outer block
- some strategies are not considered
  - e.g., index on SID in Students
  - best plan could be INLJ with Exams as the outer argument, and Students as the inner one; such a plan is never considered by the optimizer
- the unnested version of the query is typically optimized better

```
SELECT  S.SName
FROM  Students S
WHERE EXISTS
   (SELECT  *
    FROM  Exams E
    WHERE  E.CID=7
     AND E.SID=S.SID)
```

Equivalent unnested query:

```
SELECT  S.SName
FROM Students S, Exams E
WHERE E.SID=S.SID AND E.CID = 7
```