Distributed Queries

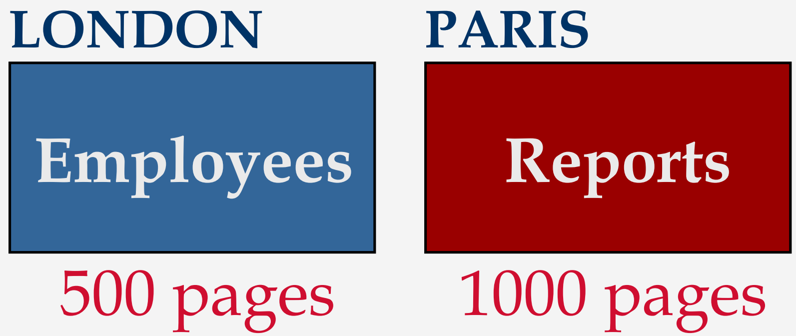
```
SELECT AVG(E.age)
FROM Employees E
WHERE E.salary > 3000
  AND E.salary < 7000
```

- Horizontally Fragmented:

Tuples with Salary < 5000 at London, >= 5000 at Paris.

  - Must compute SUM(*age*), COUNT(*age*) at both sites.
  - If WHERE contained just E.*salary*>6000, just one site.
- Vertically Fragmented: *title* and *salary* at London, *ename* and *age* at Paris, *id* at both.
  - Must reconstruct relation by join on *id*, then evaluate the query.
- Replicated: Employees copies at both sites.
  - Choice of site based on local costs, shipping costs.

Distributed Joins



- Ship to One Site: Ship Reports to London.
  - Cost: 1000 S + 4500 D (sort-merge join; cost = 3*(500+1000))
  - If result size is very large, may be better to ship both relations to result site and then join them!
- Ship Employees to Paris
  - Cost: 500 S + 4500 D

Distributed Joins

LONDON

Employees

PARIS

Reports

for Employees 1 page = 80 tuples

for Reports 1 page = 100 tuples

- Fetch as Needed, Page oriented nested loops, Employees as outer (for each Employee page fetch all Reports pages from Paris):
  - **Cost:** 500 D + 500 * 1000 (D+S)
  - **D** is cost to read/write page; **S** is cost to ship page.
  - If query was not submitted at London, must add cost of shipping result to query site.
  - Can also do INL (indexed nested loops) at London, fetching matching Reports tuples to London as needed.

Semijoin

- At London, project Employees onto join columns and ship this to Paris.
- At Paris, join Employees projection with Reports.
  - Result is called **reduction** of Reports with respect to Employees .
- Ship reduction of Reports to London.
- At London, join Employees with reduction of Reports.
- Idea: Tradeoff the cost of computing and shipping projection and computing and shipping reduction for cost of shipping full Reports relation.
- Especially useful if there is a selection on Employees, and answer desired at London.

Bloomjoin

- At London, compute a bit-vector of some size k:
  - Hash join column values into range 0 to k-1.
  - If some tuple hashes to *i*, set bit *i* to 1 (*i* from 0 to k-1).
  - Ship bit-vector to Paris.
- At Paris, hash each tuple of Reports similarly, and discard tuples that hash to 0 in Employees bit-vector.
  - Result is called **reduction** of Reports wrt Employees.
- Ship bit-vector reduced Reports to London.
- At London, join Employees with reduced Reports.
- Bit-vector cheaper to ship, almost as effective.

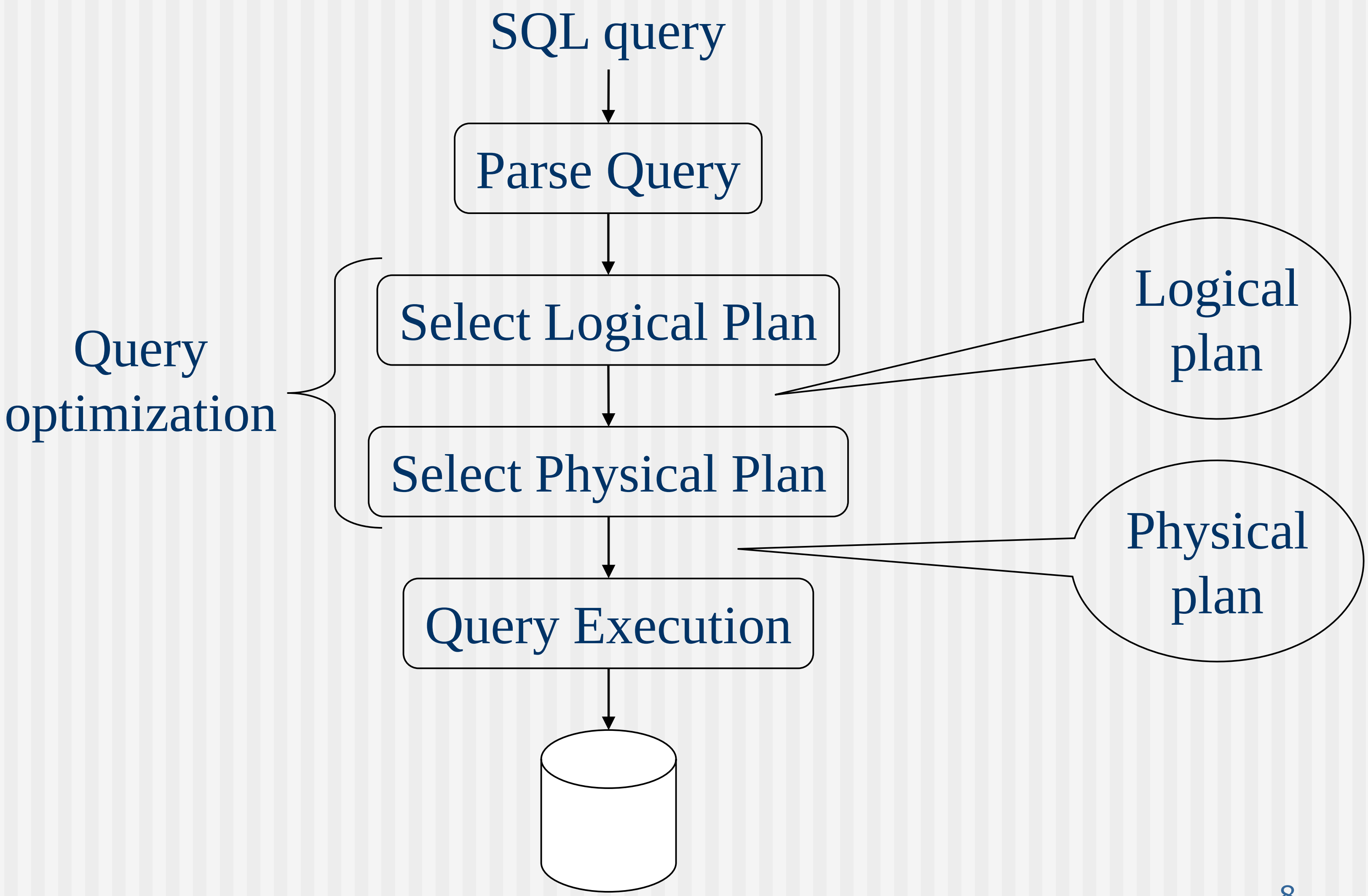
Distributed Query Optimization

- Cost-based approach; consider all plans, pick cheapest; similar to centralized optimization.
  - Difference 1: Communication costs must be considered.
  - Difference 2: Local site autonomy must be respected.
  - Difference 3: New distributed join methods.
- Query site constructs global plan, with suggested local plans describing processing at each site.
  - If a site can improve suggested local plan, free to do so.

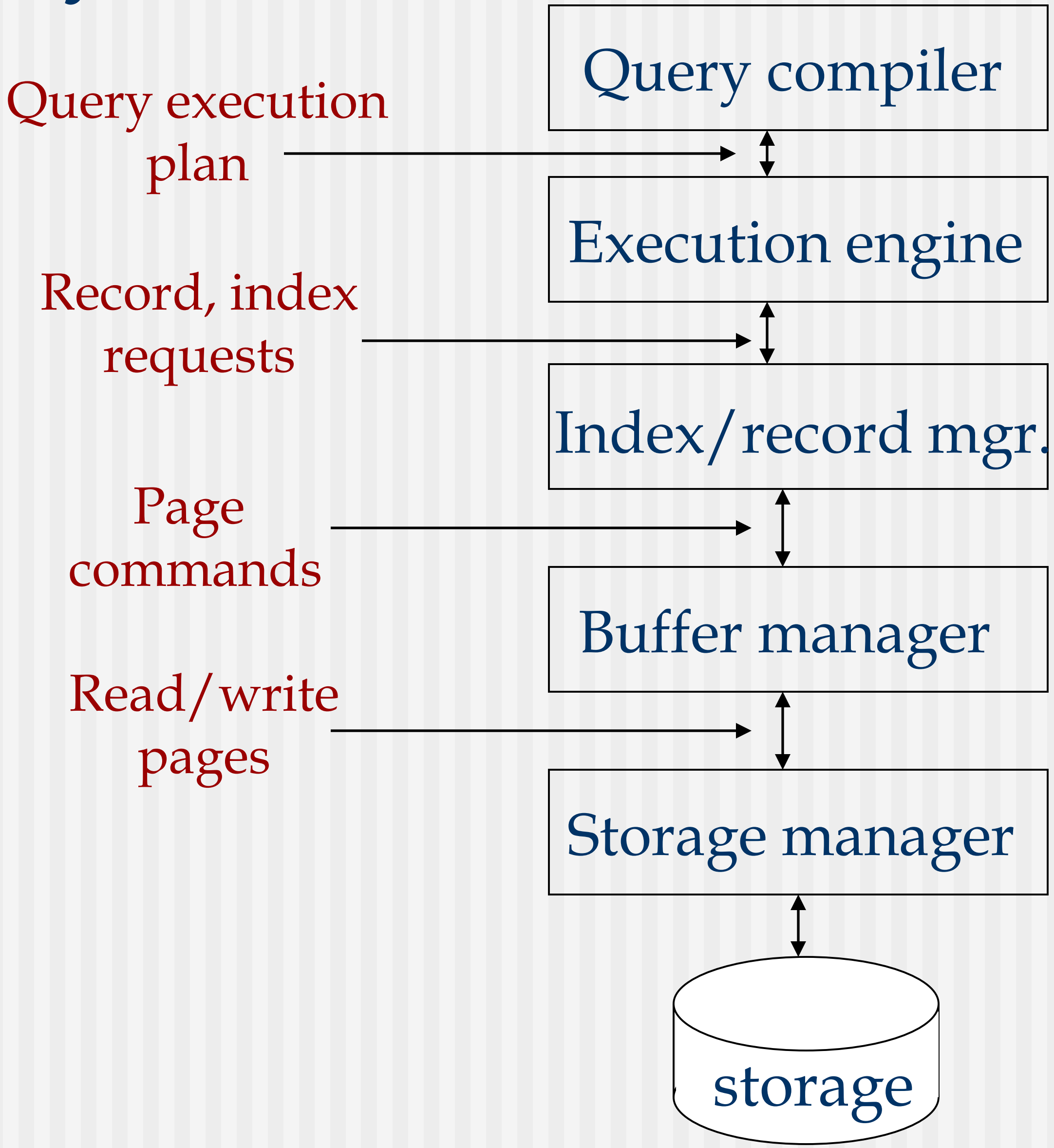
COURSE 10

Query Optimization

Architecture of Database Engine



Query Execution



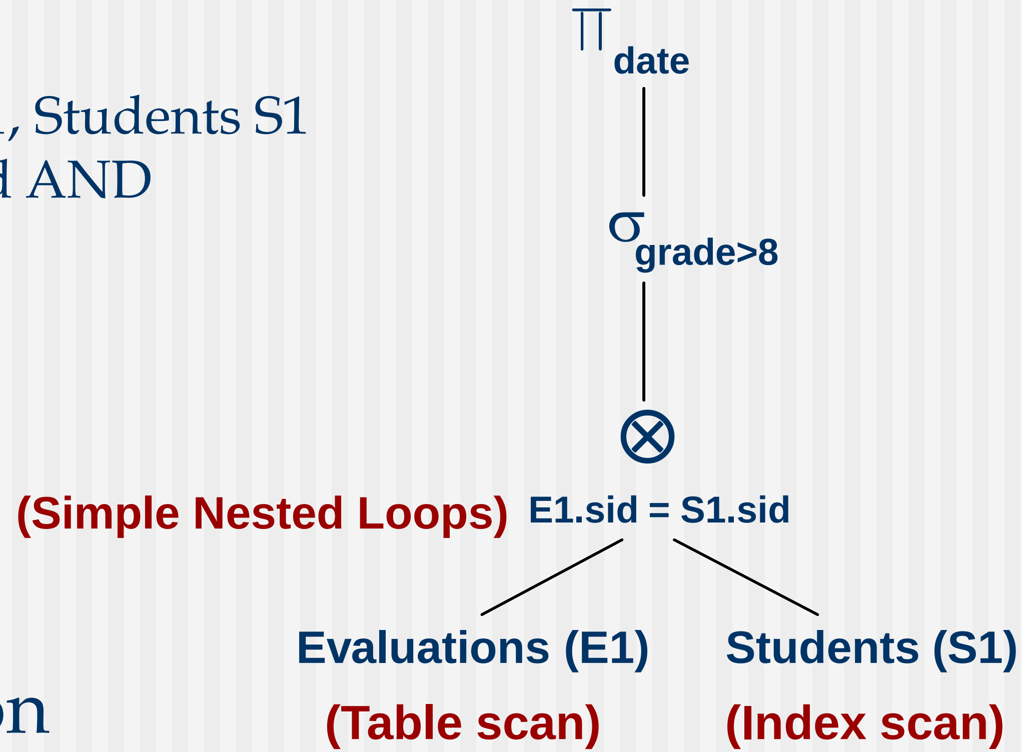
Schema for Examples

Students (<u>*sid*: integer</u>, *sname*: string, *age*: integer)
Courses (<u>*cid*: integer</u>, *name*: string, *location*: string)
Evaluations (<u>*sid*: integer, *cid*: integer</u>, *day*: date, *grade*: integer)

- Students:
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.
- Courses:
  - Each tuple is 40 bytes long, 100 tuples per page, 1 page.
- Evaluations:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.

Query Execution Plans

SELECT E1.date
FROM Evaluations E1, Students S1
WHERE E1.sid=S1.sid AND
E1.grade > 8



Query Plan:

- logical tree
- implementation choice at every node
- scheduling of operations.

Some operators are from relational algebra, and others (e.g., scan, group) are not.

The Leaves of the Plan: Scans

- Table scan: iterate through the records of the relation.
- Index scan: go to the index, from there get the records in the file
- Sorted scan: produce the relation in order. Implementation depends on relation size.
- How do we combine Operations?
  - The iterator model. Each operation is implemented by 3 functions:
    - *Open*: sets up the data structures and performs initializations
    - *GetNext*: returns the next tuple of the result.
    - *Close*: ends the operations. Cleans up the data structures.
  - Enables pipelining!
  - Contrast with data-driven materialize model.
  - Sometimes it's the same (e.g., sorted scan).

Query Optimization Process

- Parse the SQL query into a logical tree:
  - identify distinct blocks (corresponding to nested sub-queries or views).
- Query rewrite phase:
  - apply algebraic transformations to yield a cheaper plan.
  - Merge blocks and move predicates between blocks.
- Optimize each block: join ordering.
- Complete the optimization: select scheduling (pipelining strategy).

Overview of Query Optimization

- *Plan*: *Tree of R.A. ops, with choice of alg for each op.*
  - Each operator typically implemented using a `pull' interface: when an operator is `pulled' for the next output tuples, it `pulls' on its inputs and computes them.
- Two main issues:
  - For a given query, what plans are considered?
    - Algorithm to search plan space for cheapest (estimated) plan.
  - How is the cost of a plan estimated?
- Ideally: Want to find best plan.
- Practically: Avoid worst plans!

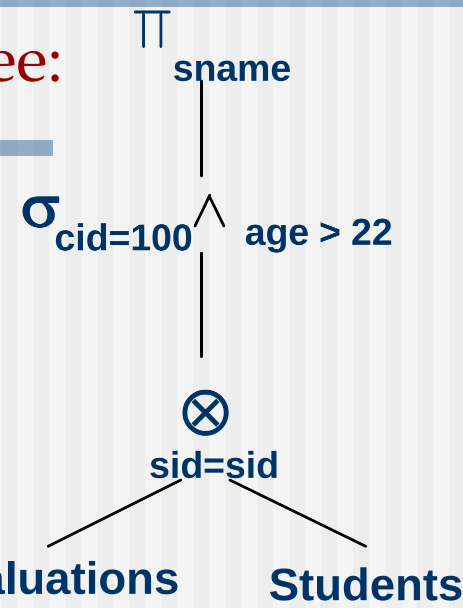
Highlights of System R Optimizer

- Impact:
  - Most widely used currently; works well for < 10 joins.
- Cost estimation: Approximate art at best.
  - Statistics, maintained in system catalogs, used to estimate cost of operations and result sizes.
  - Considers combination of CPU and I/O costs.
- Plan Space: Too large, must be reduced.
  - Only the space of *left-deep plans* is considered.
    - Left-deep plans allow output of each operator to be *pipelined* into the next operator without storing it in a temporary relation.
  - Cartesian products avoided.

Motivating Example

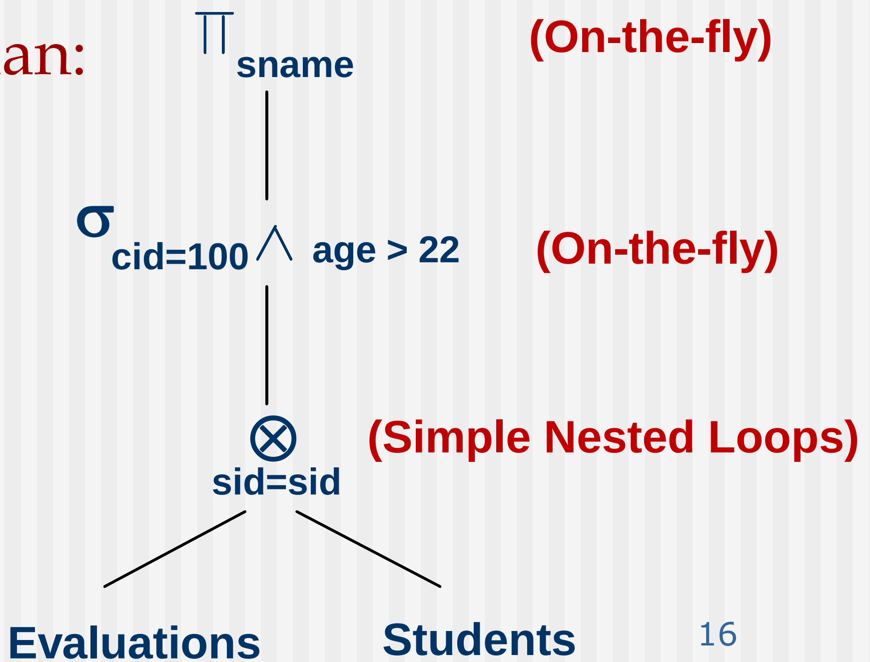
```
SELECT  S.sname
FROM  Evaluations E, Students S
WHERE  E.sid=S.sid AND
    E.cid=100 AND S.age>22
```

RA Tree:

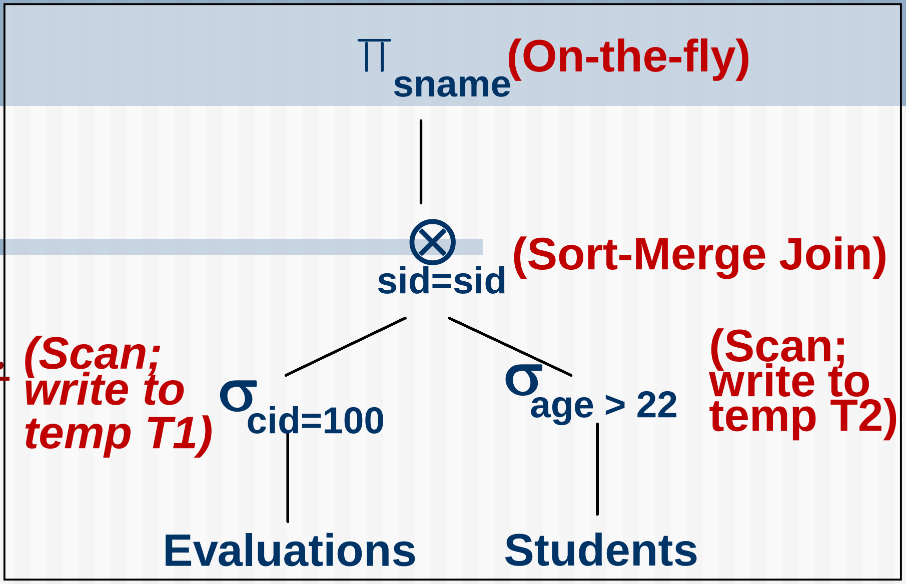


- Cost: 500+500*1000 I/Os
- By no means the worst plan!
- Misses several opportunities: selections could have been `pushed' earlier, no use is made of any available indexes, etc.
- *Goal of optimization:* To find more efficient plans that compute the same answer.

Plan:

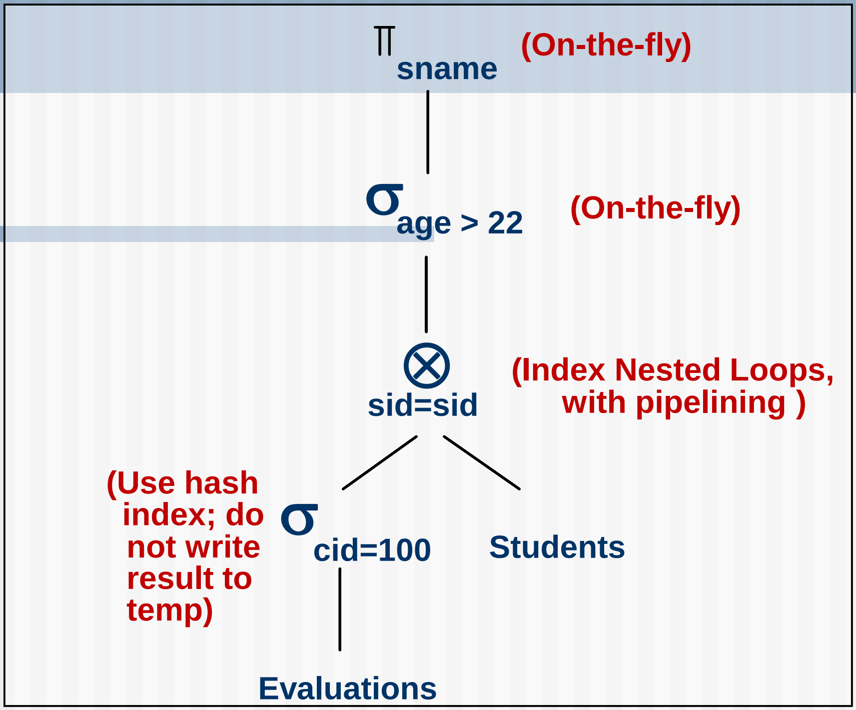


Alternative Plans 1



- ***Main difference:*** *push selects.*
- With 5 buffer pages,
- cost of plan:
  - Scan Evaluations (1000) + write temp T1 (10 pages, if we have 100 courses, uniform distribution). – *total 1010 I/Os*
  - Scan Students (500) + write temp T2 (250 pages, if we have 10 ages). – *total 750 I/Os*
  - Sort T1 (2*2*10), sort T2 (2*3*250), merge (10+250) – *total 1800 I/Os*
  - Total: 3560 page I/Os.
- If we used BNL join, join cost = 10+4*250, total cost = 2770.
- If we `push' projections, T1 has only *sid*, T2 only *sid* and *sname*:
  - T1 fits in 3 pages, cost of BNL drops to under 250 pgs, total < 2000.

Alternative Plans 2



- With clustered index on *cid* of Evaluations, we get 100,000/100 = 1000 tuples on 1000/100 = 10 pages.
- INL with ***pipelining*** (outer is not materialized).
  - Projecting out unnecessary fields from outer doesn't help.
- Join column *sid* is a key for Students.
  - At most one matching tuple, un-clustered index on *sid* OK.
- Decision not to push *age>22* before the join is based on availability of *sid* index on Students.

Cost: Selection of Evaluations tuples (10 I/Os); for each, must get matching Students tuple (1000*1.2); total *1210 I/Os*.

Query Blocks: Units of Optimization

- An SQL query is parsed into a collection of *query blocks*, and these are optimized one block at a time.
- Nested blocks are usually treated as calls to a subroutine, made once per outer tuple. (This is an over-simplification, but serves for now.)

```
SELECT  S.sname
FROM  Students S
WHERE  S.age IN
    (SELECT  MAX (S2.age)
     FROM  Students S2
     GROUP BY  S2.sname)
```

Outer block *Nested block*

For each block, the plans considered are:

- All available access methods, for each reln in FROM clause.
- All *left-deep join trees* (i.e., all ways to join the relations one-at-a-time, with the inner reln in the FROM clause, considering all reln permutations and join methods.)

Cost Estimation

- For each plan considered, must estimate cost:
  - Must estimate *cost* of each operation in plan tree.
    - Depends on input cardinalities.
    - We've already discussed how to estimate the cost of operations (sequential scan, index scan, joins, etc.)
  - Must estimate *size of result* for each operation in tree!
    - Use information about the input relations.
    - For selections and joins, assume independence of predicates.
- We'll discuss the System R cost estimation approach.
  - Very inexact, but works ok in practice.
  - More sophisticated techniques known now.

Relational Algebra Equivalences

- Allow us to choose different join orders and to \`push' selections and projections ahead of joins.

- *Selections*: $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ldots(\sigma_{cn}(R)))$ (*Cascade*)

  $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$ (*Commute*)

- *Projections*: $\pi_{a1}(R) \equiv \pi_{a1}(\ldots(\pi_{an}(R)))$ (*Cascade*)

- *Joins*: $R \otimes (S \otimes T) \equiv (R \otimes S) \otimes T$ (*Associative*)

  $(R \otimes S) \equiv (S \otimes R)$ (*Commute*)

\+ show that: $R \otimes (S \otimes T) \equiv (T \otimes R) \otimes S$

More Equivalences

- A projection commutes with a selection that only uses attributes retained by the projection.
- Selection between attributes of the two arguments of a cross-product converts cross-product to a join.
- A selection on just attributes of R commutes with $R \otimes S$. (i.e., $\sigma (R \otimes S) \equiv \sigma (R) \otimes S$)
- Similarly, if a projection follows a join $R \otimes S$, we can `push' it by retaining only attributes of R (and S) that are needed for the join or are kept by the projection.

Enumeration of Alternative Plans

- There are two main cases:
  - Single-relation plans
  - Multiple-relation plans
- For queries over a single relation, queries consist of a combination of selects, projects and aggregate ops:
  - Each available access path (file scan / index) is considered, and the one with the least estimated cost is chosen.
  - The different ops are essentially carried out together (e.g., if an index is used for a selection, projection is done for each retrieved tuple, and the resulting tuples are *pipelined* into the aggregate computation).

Cost Estimates for Single-Relation Plans

- Index I on primary key matches selection:
  - *Cost is Height(I)+1 for a B+ tree, about 1.2 for hash index.*
- Clustered index I matching one or more selects:
  - *(NPages(I)+NPages(R)) * product of RF's of matching selects.*
- Non-clustered index I matching one or more selects:
  - *(NPages(I)+NTuples(R)) * product of RF's of matching sels.*
- Sequential scan of file:
  - *NPages(R).*

+ ***Note**: Typically, no duplicate elimination on projections! (Exception: Done on answers if user says DISTINCT.)*

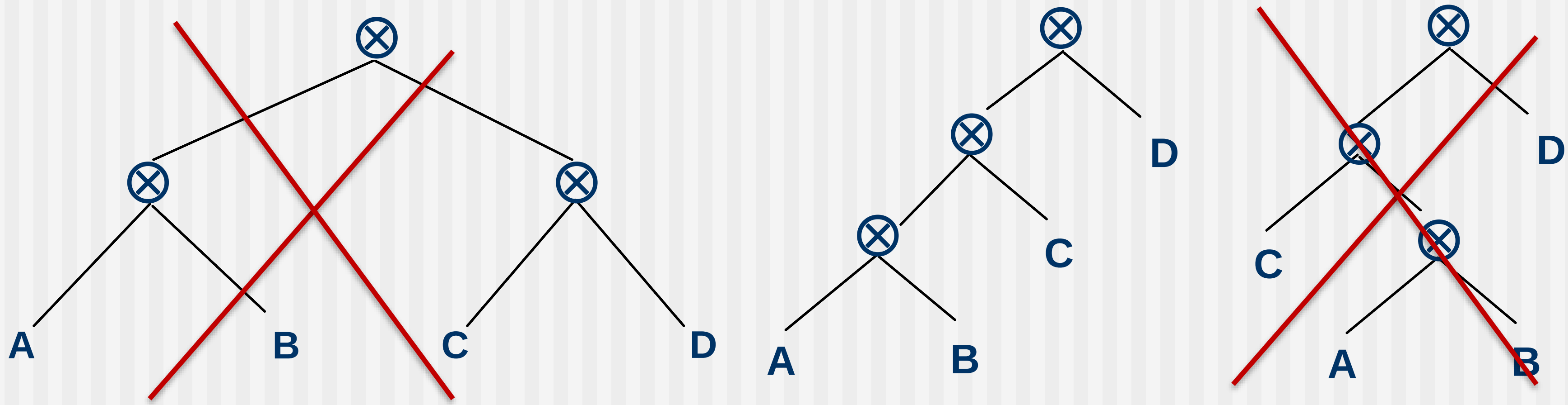
Example

```
SELECT S.sid
FROM Students S
WHERE S.age=20
```

- If we have an index on *age*:
  - (1/NKeys(I)) * NTuples(R) = (1/10) * 40000 tuples retrieved.
  - Clustered index: (1/NKeys(I)) * (NPages(I)+NPages(R)) = (1/10) * (50+500) pages are retrieved. (This is the ***cost***)
  - Unclustered index: (1/NKeys(I)) * (NPages(I)+NTuples(R)) = (1/10) * (50+40000) pages are retrieved.
- If we have an index on *sid*:
  - Would have to retrieve all tuples/pages. With a clustered index, the cost is 50+500, with un-clustered index, 50+40000.
- Doing a file scan:
  - We retrieve all file pages (500).

Queries Over Multiple Relations

- Fundamental decision in System R: *only left-deep join trees* are considered.
  - As the number of joins increases, the number of alternative plans grows rapidly; *we need to restrict the search space.*
  - Left-deep trees allow us to generate all *fully pipelined* plans.
    - -Intermediate results not written to temporary files.
    - -Not all left-deep trees are fully pipelined (e.g., SM join).



Enumeration of Left-Deep Plans

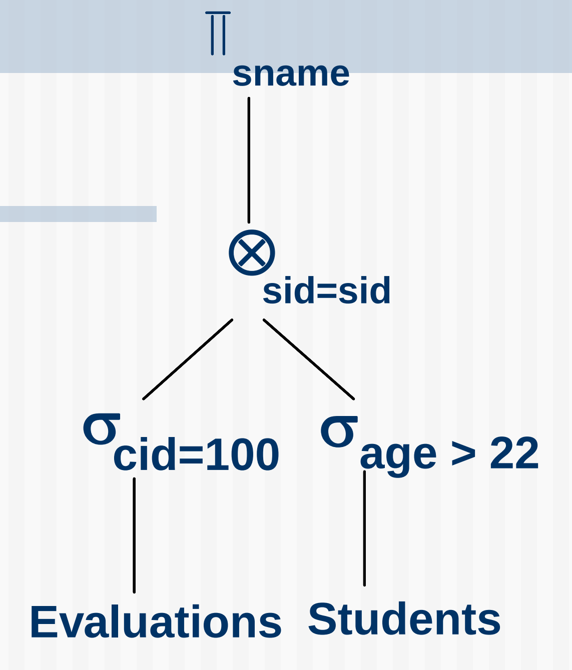
- Left-deep plans differ only in the order of relations, the access method for each relation and the join method for each join.
- Enumerated using N passes (if N relations joined):
  - Pass 1: Find best 1-relation plan for each relation.
  - Pass 2: Find best way to join result of each 1-relation plan (as outer) to another relation. *(All 2-relation plans.)*
  - Pass N: Find best way to join result of a (N-1)-relation plan (as outer) to the N'th relation. *(All N-relation plans.)*
- For each subset of relations, retain only:
  - Cheapest plan overall, plus
  - Cheapest plan for each *interesting order* of the tuples.

Enumeration of Plans (cont.)

- ORDER BY, GROUP BY, aggregates etc. handled as a final step, using either an `interestingly ordered′ plan or an additional sorting operator.
- An N-1 way plan is not combined with an additional relation unless there is a join condition between them, unless all predicates in WHERE have been used up.
  - i.e., avoid Cartesian products if possible.
- In spite of pruning plan space, this approach is still exponential in the number of tables.

Example

Students:
  B+ tree on *age*
  Hash on *sid*
Evaluations:
  B+ tree on *cid*



Pass1:

- *Students*: B+ tree matches *age>22,* and is probably cheapest. However, if this selection is expected to retrieve a lot of tuples, and index is un-clustered, file scan may be cheaper.
  - Still, B+ tree plan kept (because tuples are in *age* order).
- *Evaluations*: B+ tree on *cid* matches *cid=100*; cheapest.

Pass 2:

– We consider each plan retained from Pass 1 as the outer, and consider how to join it with the (only) other relation. (e.g., *Evaluations as outer*: Hash index can be used to get Students tuples that satisfy *sid* = outer tuple's *sid* value.)

Nested Queries

- Nested block is optimized independently, with the outer tuple considered as providing a selection condition.
- Outer block is optimized with the cost of `calling' nested block computation taken into account.
- Implicit ordering of these blocks means that some good strategies are not considered. *The non-nested version of the query is typically optimized better.*

```
SELECT  S.sname
FROM  Students S
WHERE EXISTS
   (SELECT  *
    FROM  Evaluations E
    WHERE  E.cid=103
    AND  E.sid=S.sid)
```

Nested block to optimize:

```
SELECT  *
FROM  Evaluations E
WHERE  E.cid=103
   AND  S.sid= outer value
```

Equivalent non-nested query:

```
SELECT  S.sname
FROM Sudents S,
Evaluations E
WHERE  S.sid=E.sid
  AND E.cid=103
```