QUERY OPTIMIZATION

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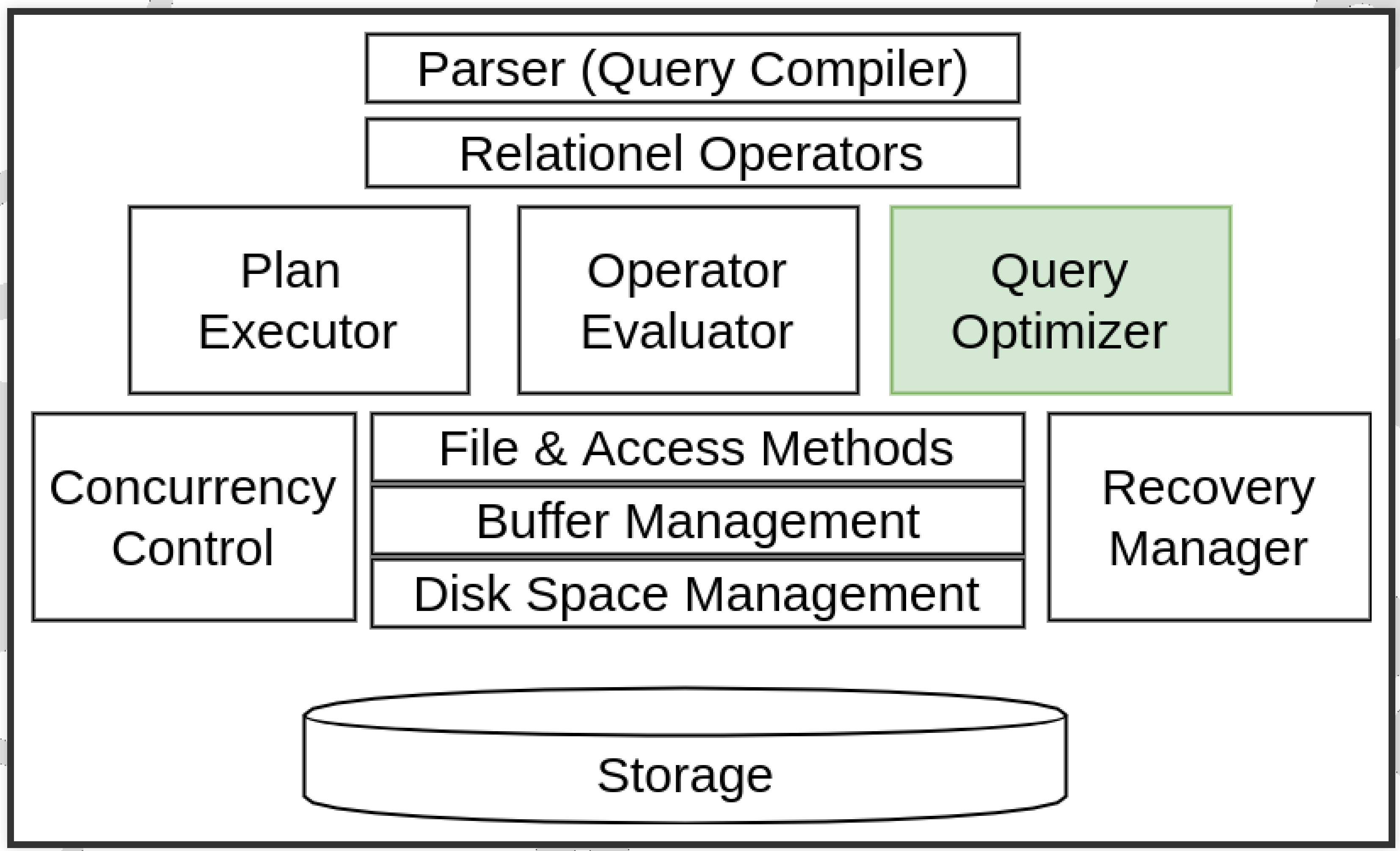
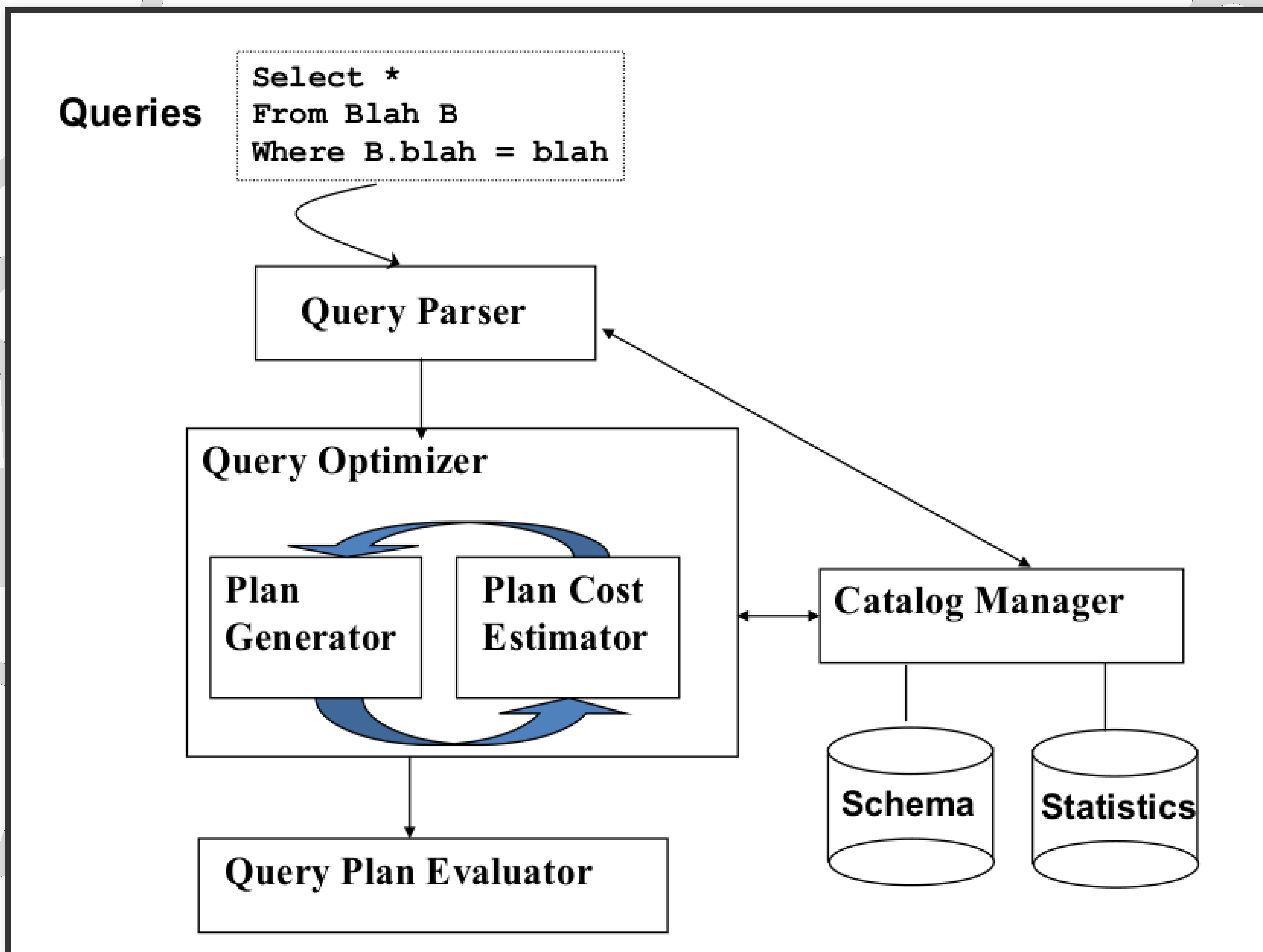
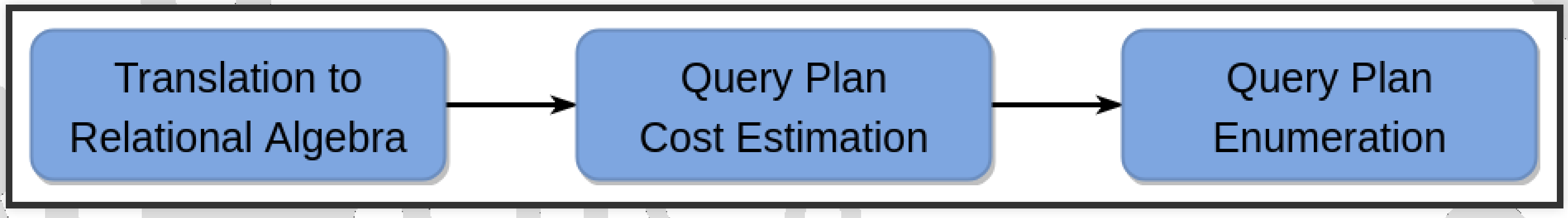


QUERY SUB-SYSTEM



ROADMAP


Translation to Relational Algebra
Query Plan Cost Estimation
Query Plan Enumeration

QUERY BLOCKS: UNITS OF OPTIMIZATION

- An SQL query is parsed into a collection of query blocks
  - optimize one block at a time.
- Nested blocks are usually treated as calls to a subroutine
  - called once per outer tuple.
  - This is an over-simplification, wait till we learn more about nested queries.

SQL EXTENDS RELATIONAL ALGEBRA

- SQL is **more** powerful than relational algebra
  - extend relational algebra to include aggregate ops: GROUP BY, HAVING

How is this query block expressed?

```
SELECT S.sname
FROM Sailors S
WHERE S.age IN (constant set from subquery)
```

$$\pi_{sname}(\sigma_{(\text{age in set from subquery})} Sailors)$$

And this query block?

```
SELECT MAX (S2.age)
FROM Sailors S2
GROUP BY S2.rating
```

$$\pi_{Max(age)}(GroupBy_{Rating}(Sailors))$$

TRANSLATING SQL TO RELATIONAL ALGEBRA

```
SELECT S.sid, MIN (R.day)
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid AND B.color = “red”
GROUP BY S.sid
HAVING COUNT (*) >= 2
```

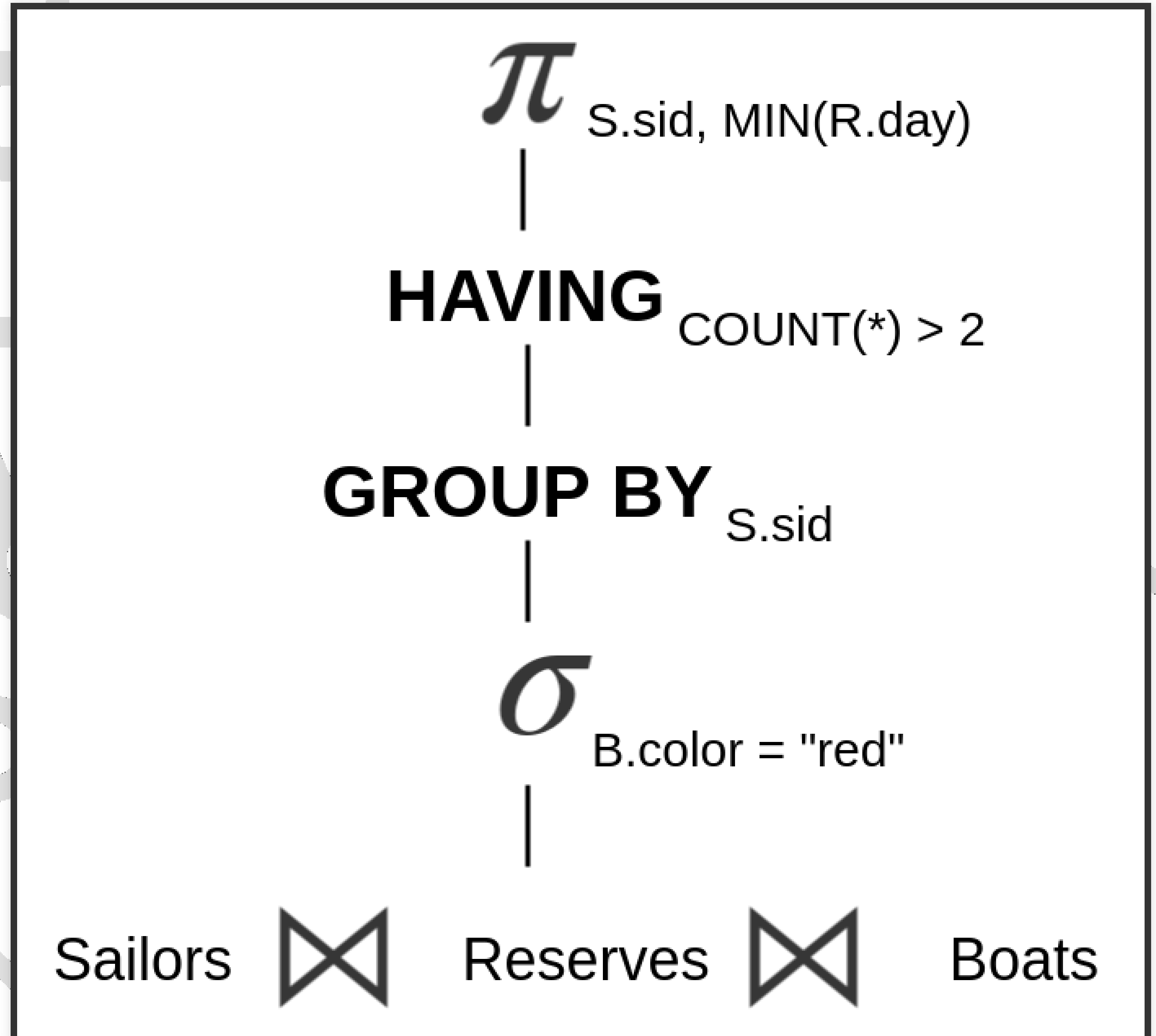
For each sailor with at least two reservations for red boats, find the sailor id and the earliest date on which the sailor has a reservation for a red boat.

TRANSLATING SQL TO RELATIONAL ALGEBRA

```sql
SELECT S.sid, MIN (R.day)
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid AND B.color = “red”
GROUP BY S.sid
HAVING COUNT (*) >= 2
```

$$\pi_{S.sid, Min(R.day)}(\\ HAVING_{COUNT(*)>2}(\\ GROUPBy_{S.sid}(\sigma_{B.color="red"}(\\ Sailors \bowtie Reserves \bowtie Boats))))$$

TRANSLATING SQL TO RELATIONAL ALGEBRA



RELATIONAL ALGEBRA EQUIVALENCES

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

Selections:

- **Cascade:** $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ldots \sigma_{cn}(R)) \ldots)$
- **Commute** $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$

Projections

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

RELATIONAL ALGEBRA EQUIVALENCES

Cartesian Product

- **Associative:** $R \times (S \times T) \equiv (R \times S) \times T$
- **Cummutative:** $R \times S \equiv S \times R$

This means we can join in any order (But… beware of the cartesian product!)

Selection between attributes of the two arguments of a cross-product converts cross-product to a join.

MORE EQUIVALENCES

Eager projection

- Rule of thumb: can project out anything not needed by operators above
- Can cascade and “push” some projections thru selection
- Can cascade and “push” some projections below one side of a join

A selection on just attributes of R commutes with $R \bowtie S$. (i.e.,
$\sigma(R \bowtie S) \equiv \sigma(R) \bowtie S$)

ELEMENTS OF QUERY OPTIMIZATION (1)

- **A closed set of operators**
  - Relational ops (table in, table out)
  - Encapsulation based on iterators
- **Plan space**
  - Based on relational equivalences
  - Different algorithms of a operator

ELEMENTS OF QUERY OPTIMIZATION (2)

- **Cost Estimation**, based on
  - Cost formulas
  - Size estimation, based on
    - Catalog information on base tables
    - Selectivity (Reduction Factor) estimation
- **A search algorithm**
  - To sift through the plan space based on cost!

EXAMPLE QUERY SCHEMA

Sailors

Sailors(sid: integer, sname: string, rating: integer, age: real)

- Each tuple is 50 bytes long, 80 tuples per page, 500 pages
- Assume **10** different ratings

Reserves

Reserves(sid:integer, bid:integer, day: date, rname: string)

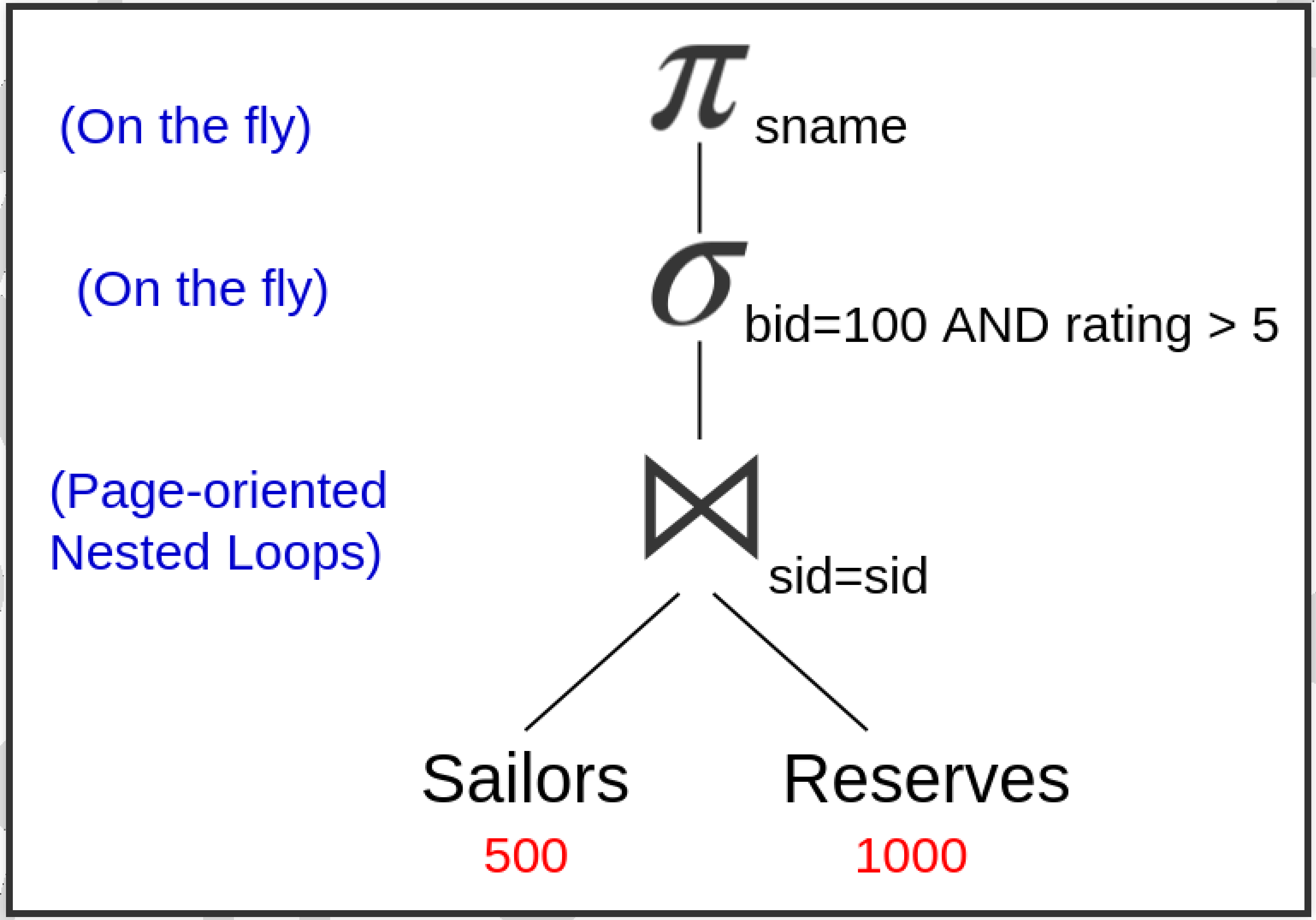
- Each tuple is 40 bytes long, 100 tuples per page, 1000 pages
- Assume **100** boats

Assume we have 5 pages in our buffer pool!

MOTIVATING EXAMPLE

```
SELECT S.sname
FROM Reserves R, Sailors S
WHERE R.sid=S.sid AND
R.bid=100 AND S.rating>5
```

MOTIVATING EXAMPLE



MOTIVATING EXAMPLE

Misses several opportunities:

- selections could have been `pushed’ earlier,
- made no use of any available indexes, etc.

Goal of optimization: To find more efficient plans that compute the same answer.

SELECTIVITY CALCULATION

Sailors: 500 pages, 80 tuples per page, 10 ratings

Selectivity of `S.rating > 5`?

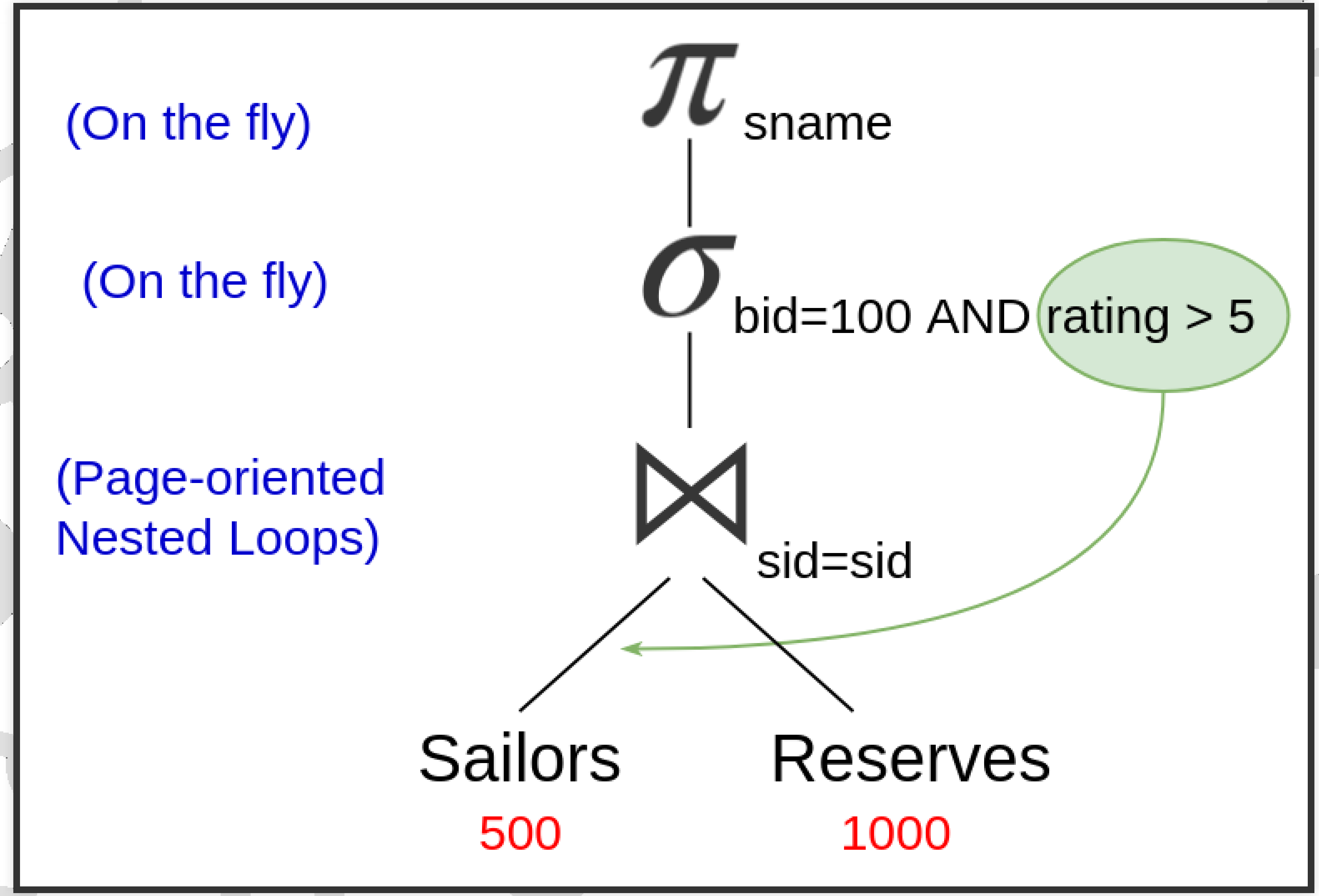
- 1/2 → 500*80/2 = 20,000 tuples
- 20,000/80 = 250 pages

Reserves: 1000 pages, 100 tuples per page, 100 boats

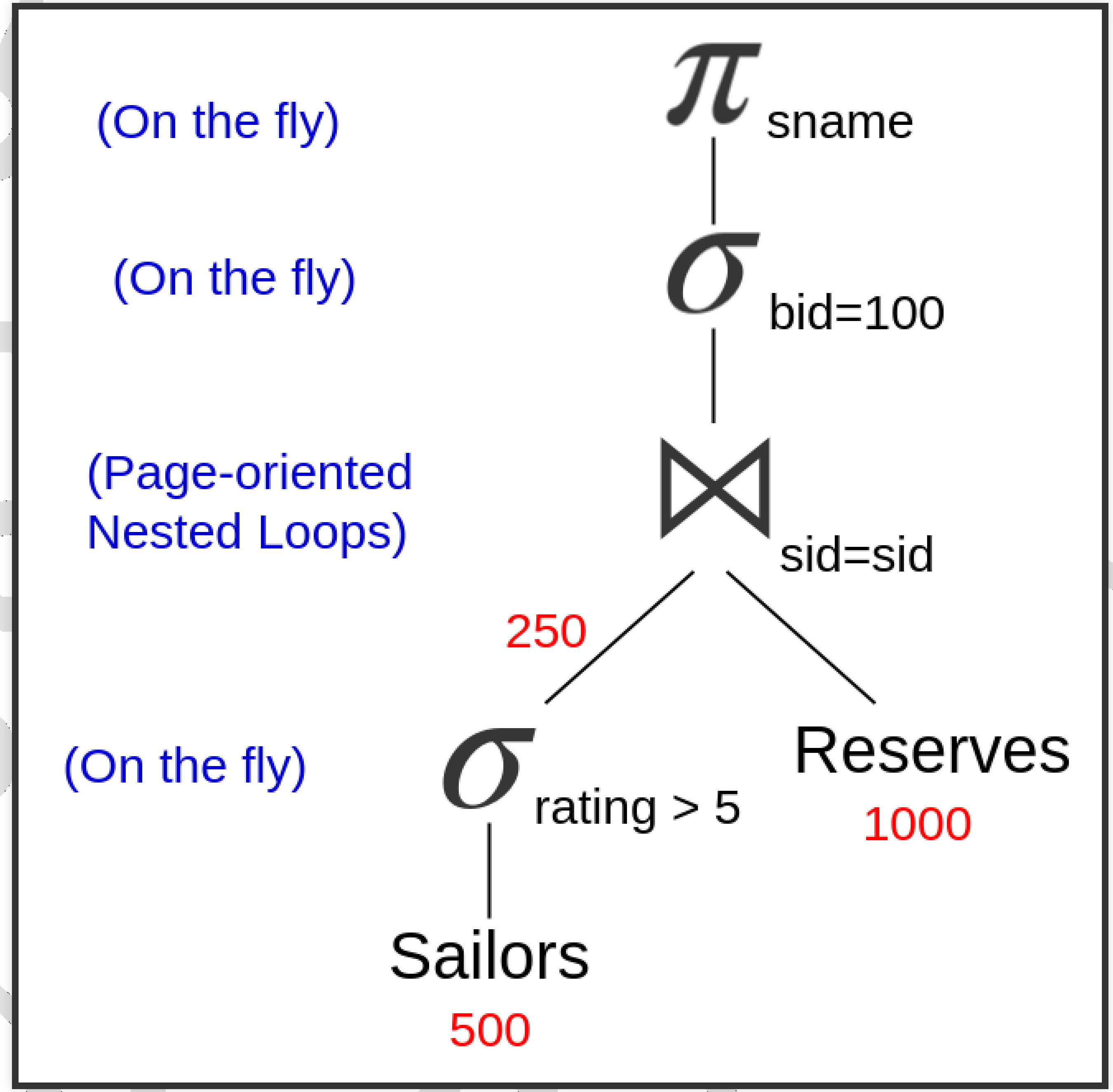
Selectivity of R.bid = 100?

- 1/100 → 1000*100/100 = 1000 tuples
- 1000/100 = 10 pages

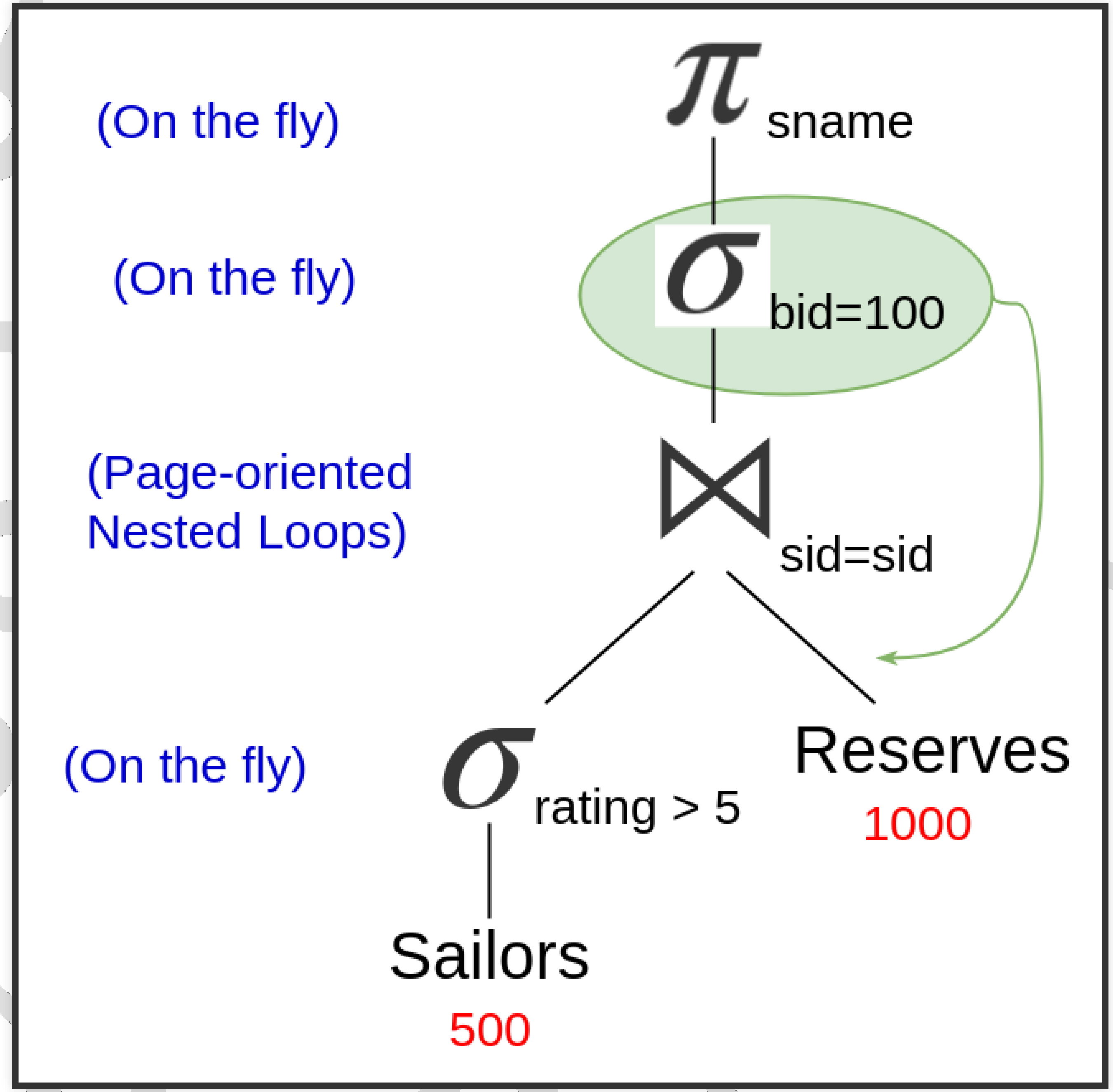
MOTIVATING EXAMPLE



MOTIVATING EXAMPLE



MOTIVATING EXAMPLE



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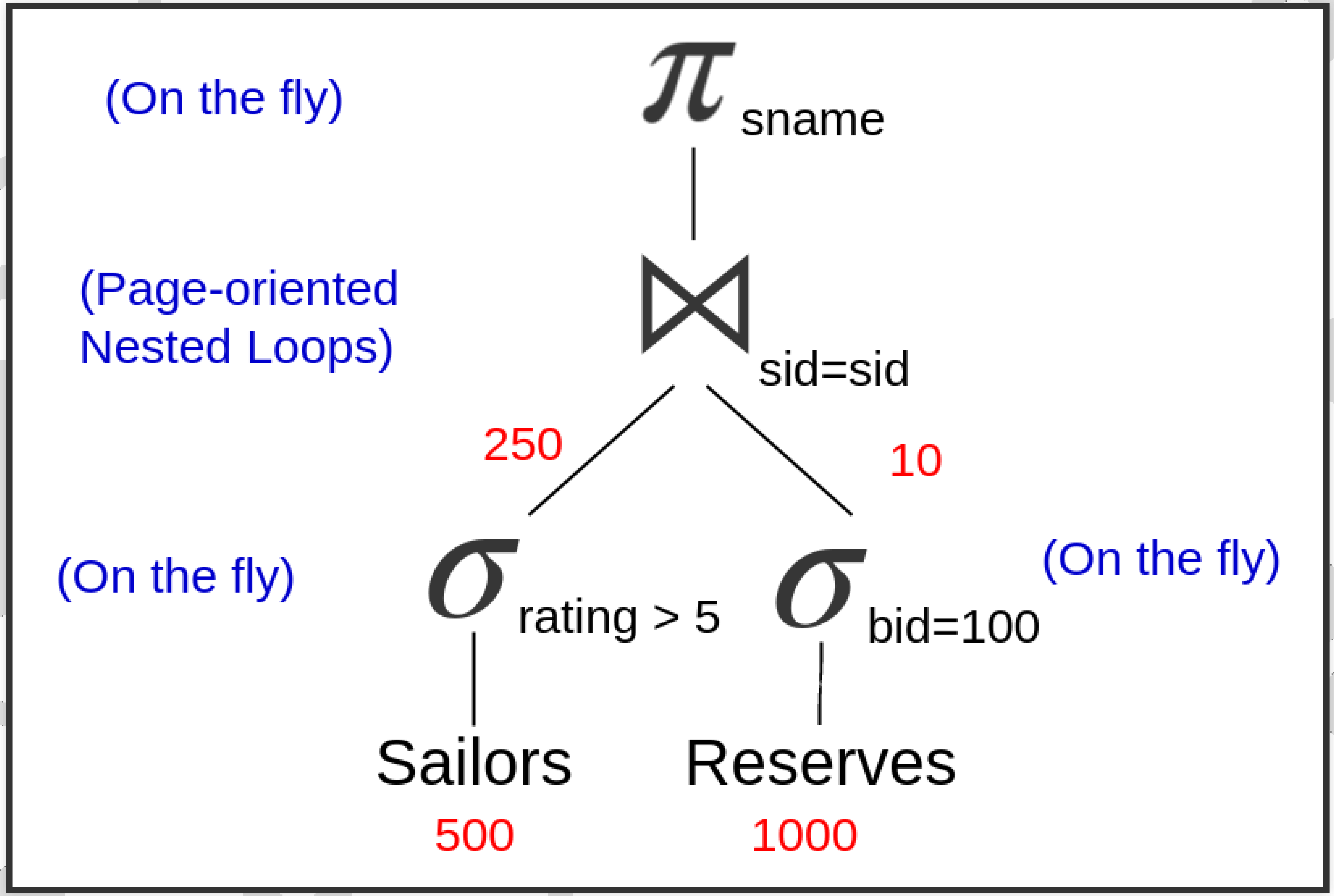

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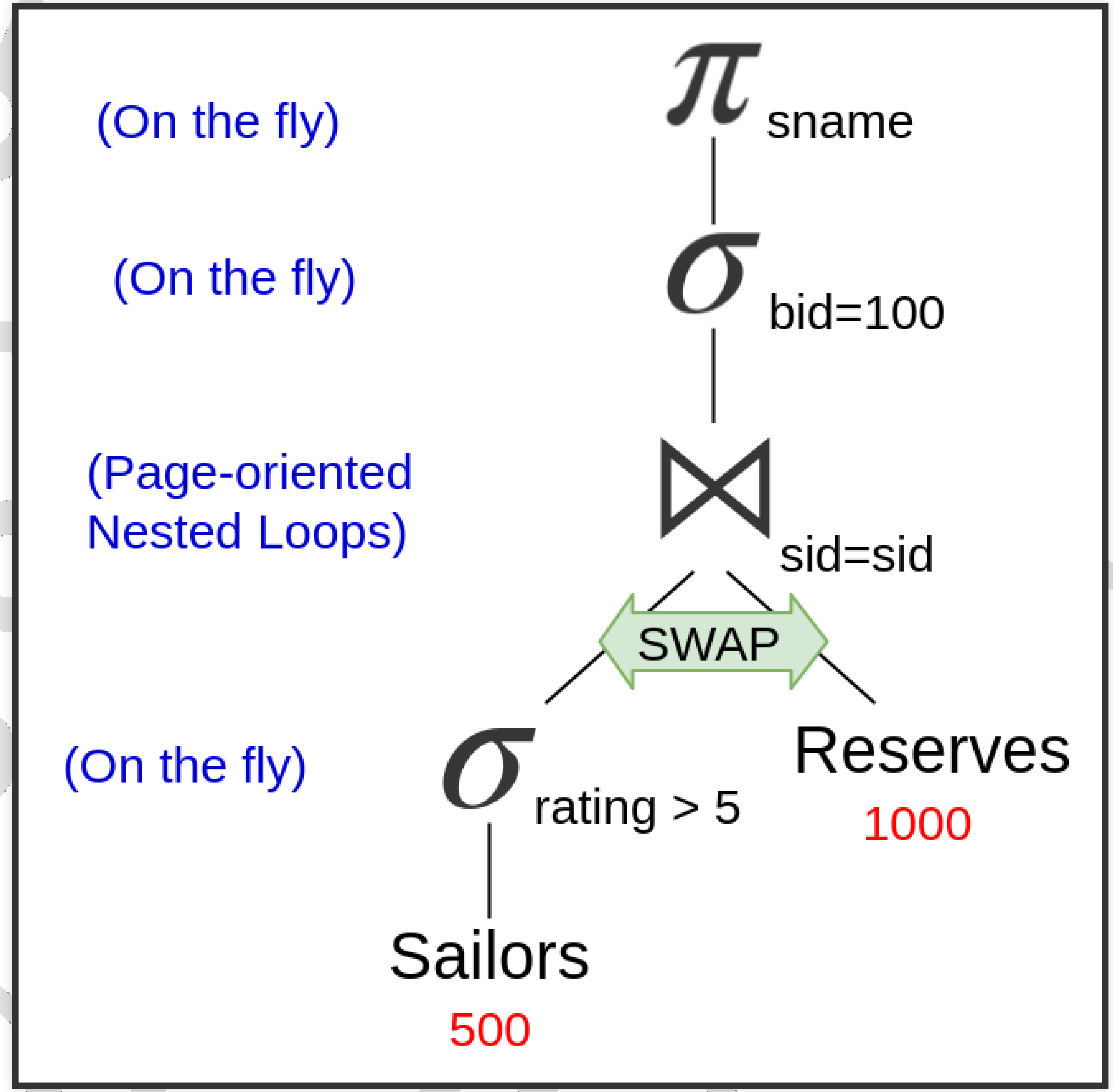

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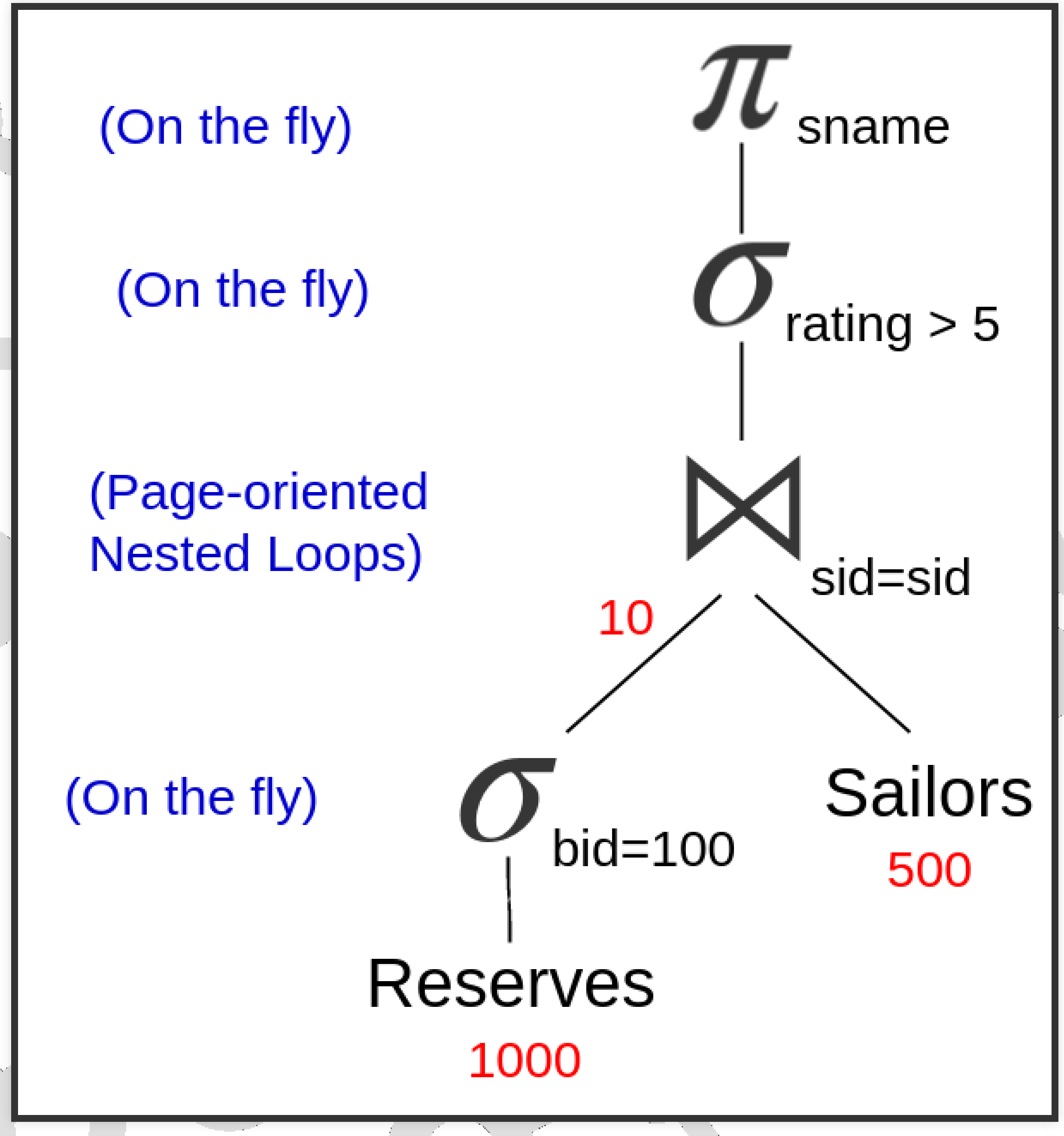

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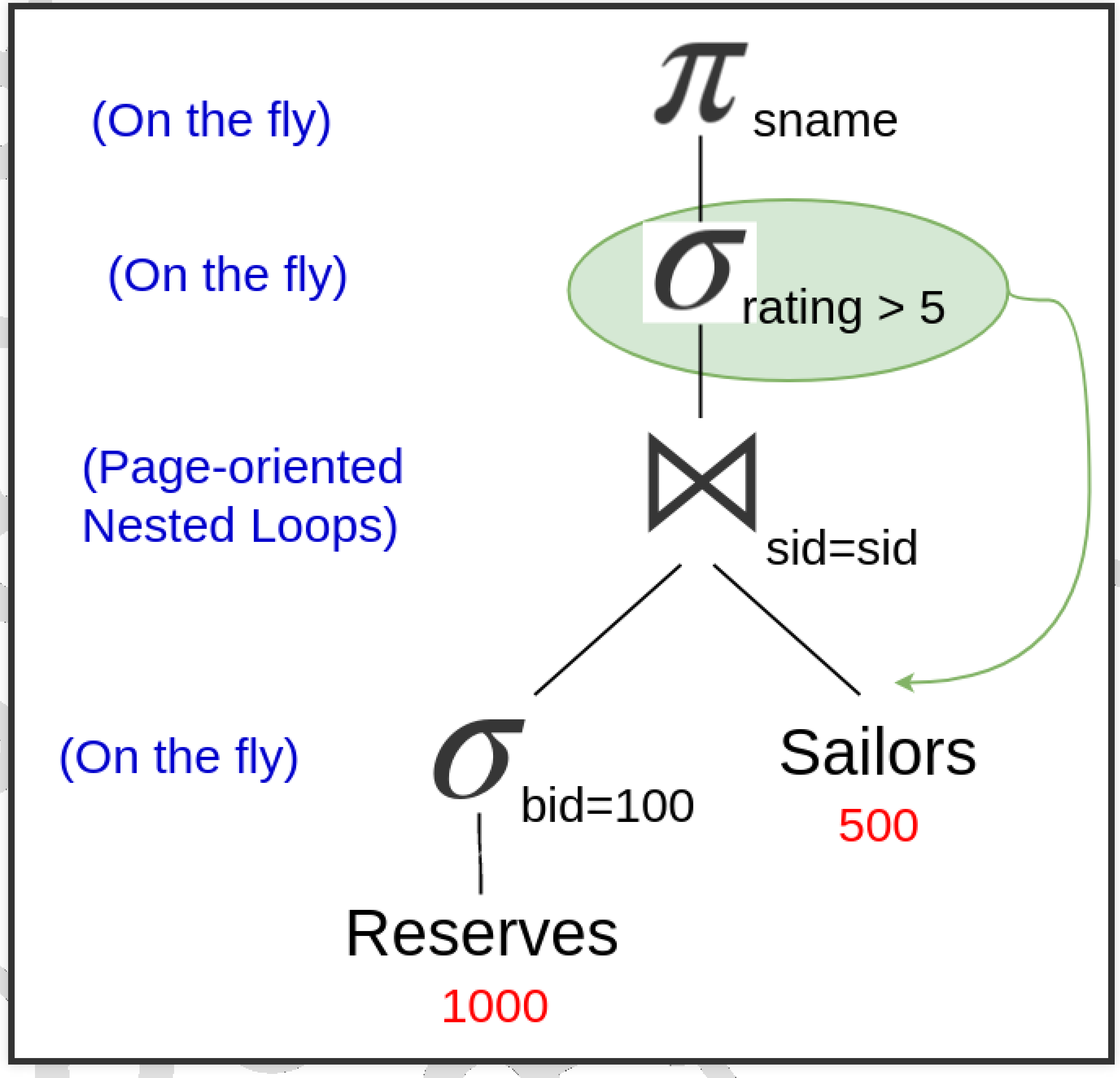

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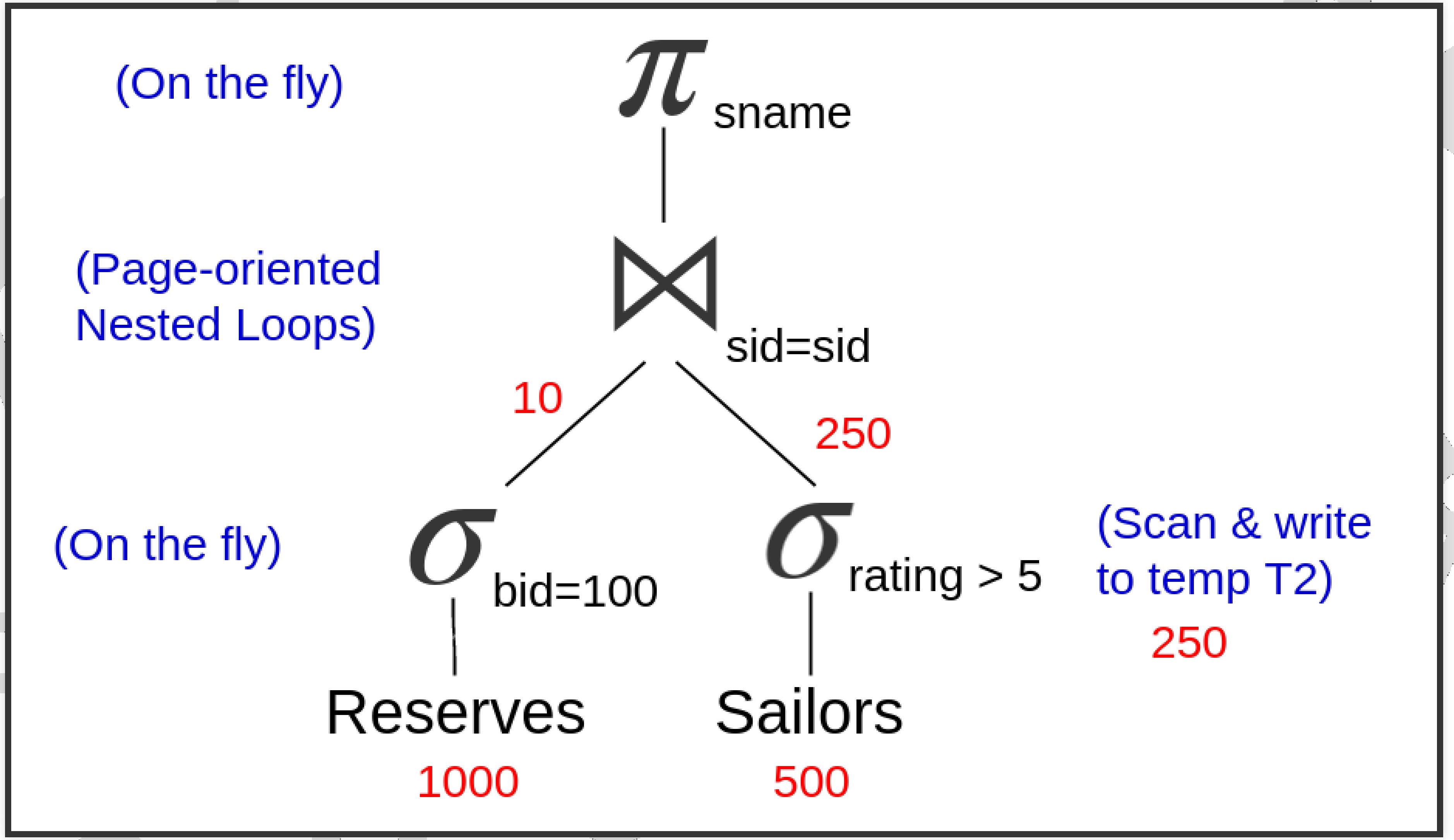

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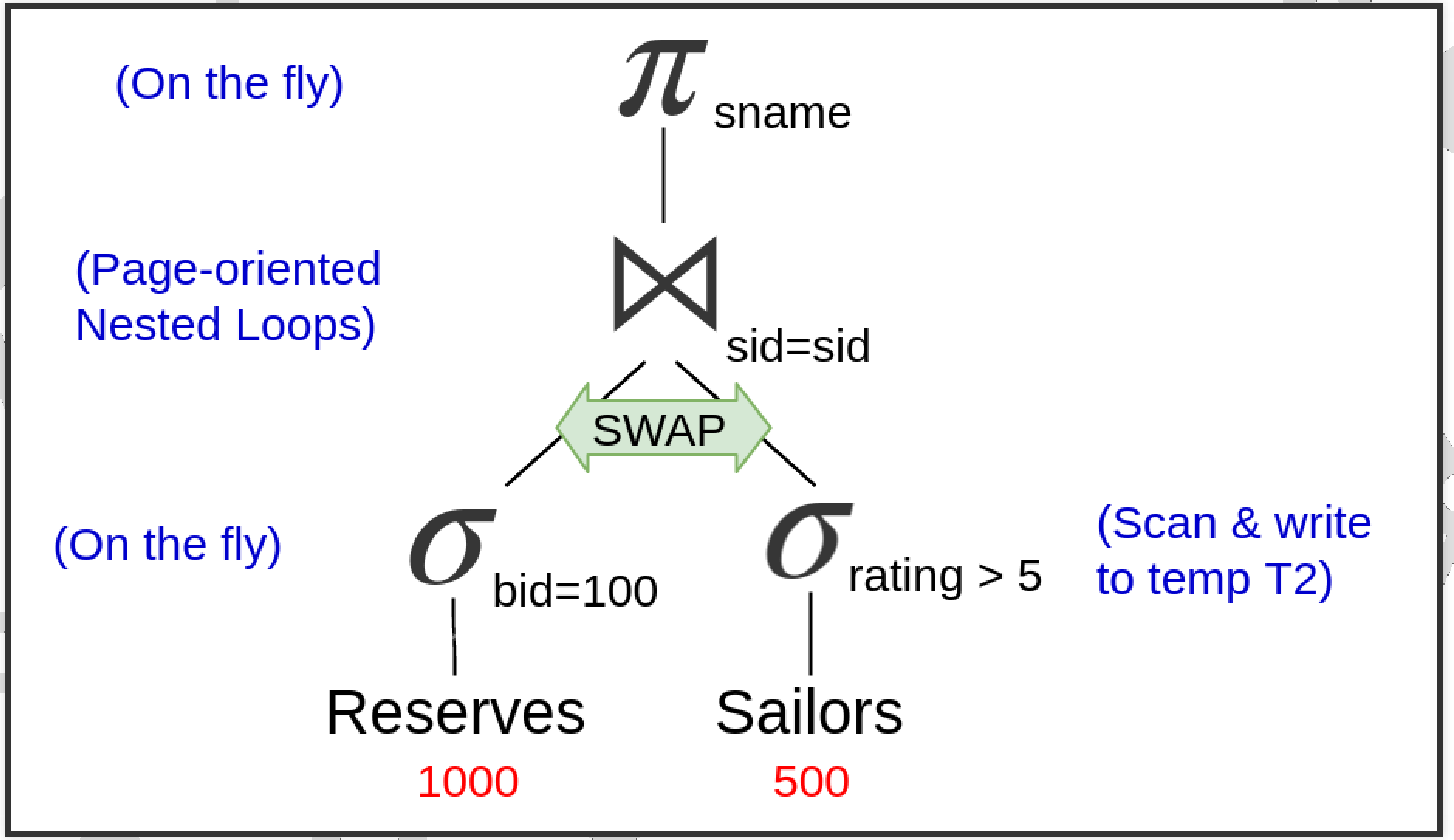
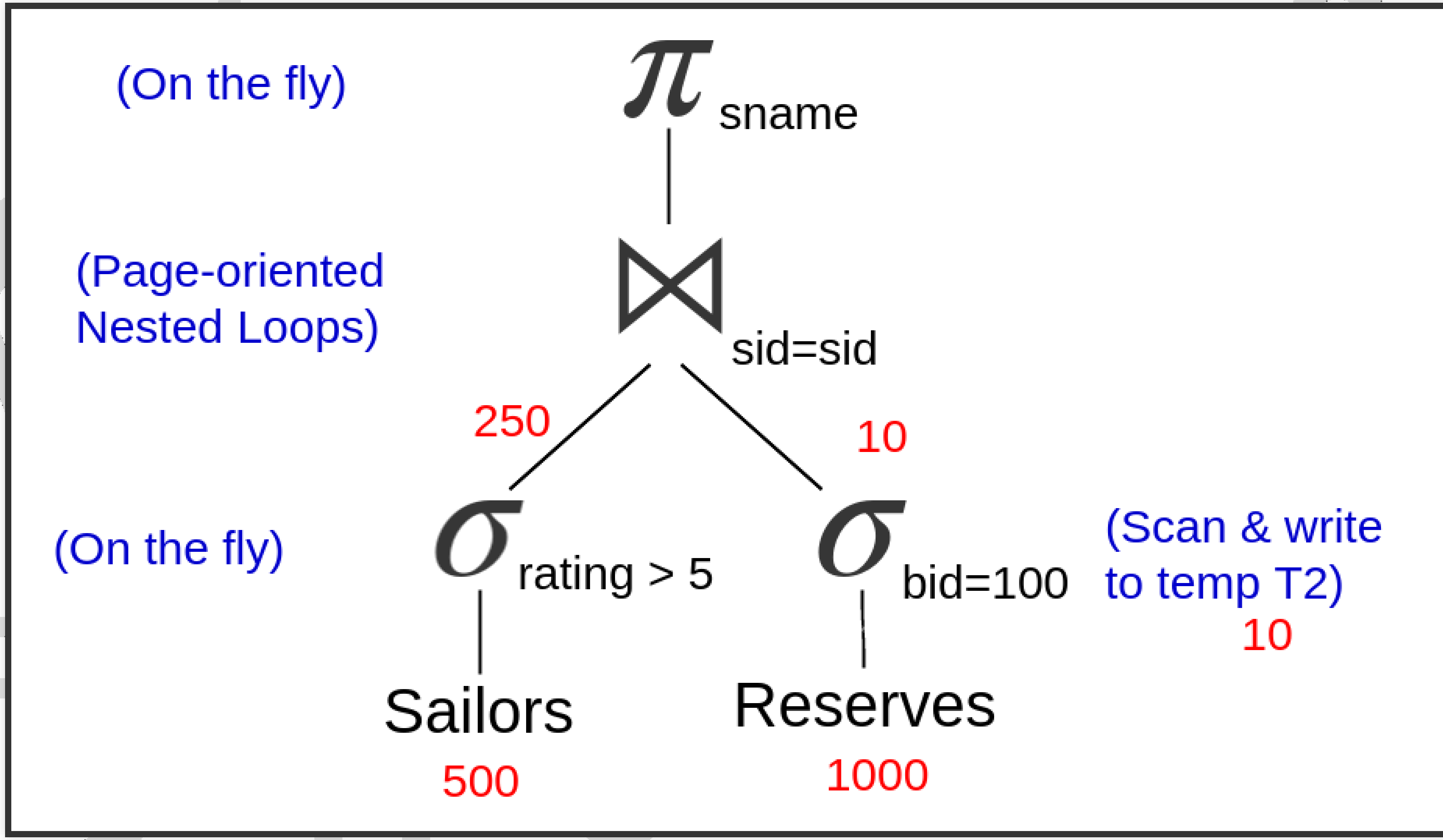
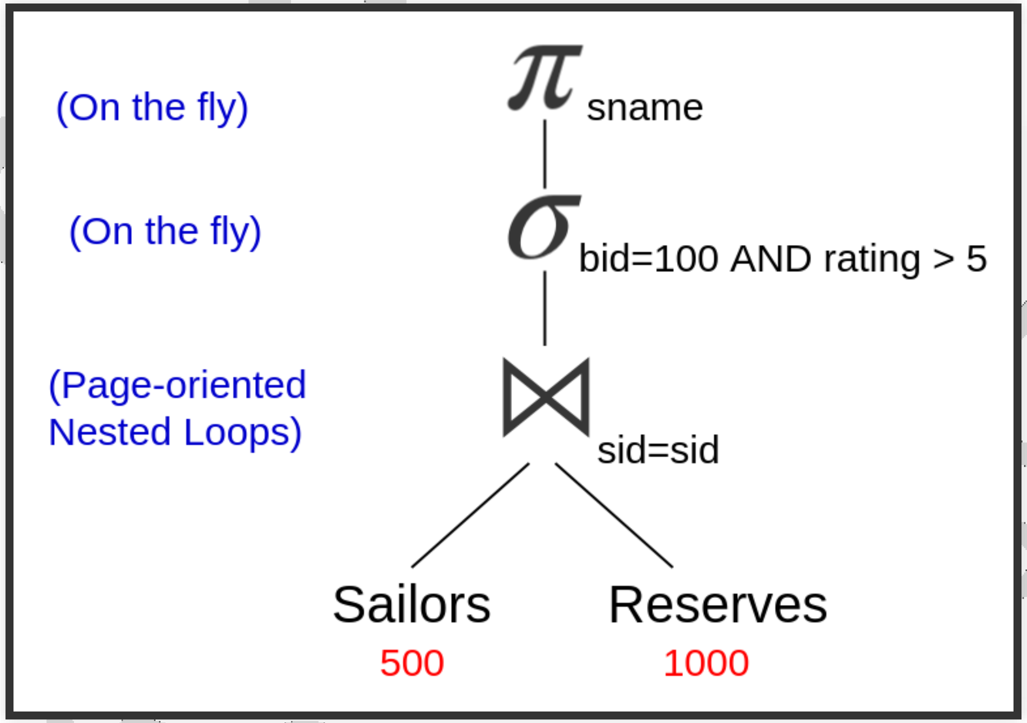


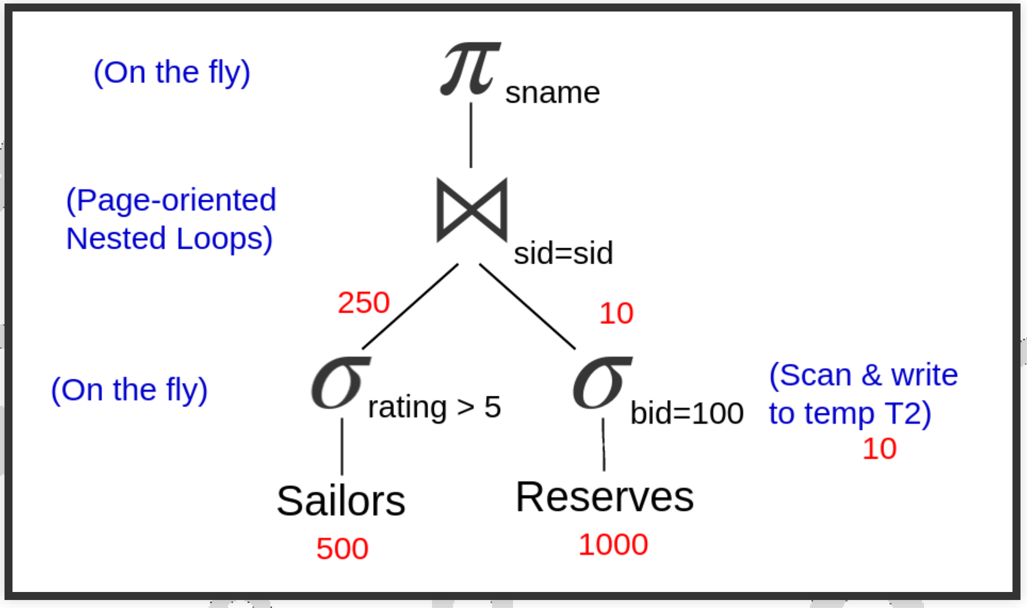
MOTIVATING EXAMPLE



MOTIVATING EXAMPLE

Original vs. optimized





Optimized query is **124x cheaper** than the original!

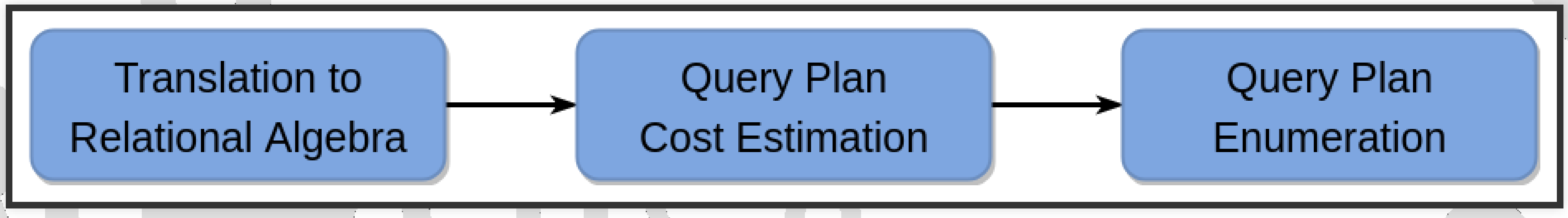
REVIEW SO FAR

- We know that there are different ways to implement an operation
  - physical operators
- We have studied how to estimate the cost of operators individually
- We also know operators could be executed in different order
  - relational algebra equivalence
- Choosing a query plan:
  - access path (index, file-scan)
  - physical operator
  - operator ordering

PROBLEMS TO BE SOLVED FOR IMPLEMENTING A QUERY OPTIMIZER

- How to estimate the cost of a query plan?
  - Size estimation and reduction factors
- Cost estimation needs statistics.
  - What statistics?
  - How to maintain them?
- How to generate alternate plans and what type of alternative plans?
- How to choose the “best” plan?

ROADMAP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HIGHLIGHTS OF SYSTEM R OPTIMIZER

- **Impact:**
  - Most widely used currently; works well for < 10 joins.
- **Cost estimation:** very inexact, but works in practice
  - Considers combination of CPU and I/O costs.
  - More sophisticated techniques known now.
- **Statistics:** maintained in system catalogs
- **Alternative plans:** only the space of *left-deep plans* is considered.
  - Cartesian products avoided in some implementations.
- **The "best" plan:** searched by *dynamic programming*

COST ESTIMATION

> To estimate the cost of query plan, we have to first estimate the cost of each operator

- The cost of an operator depends on the size of the input
- the output of one operator is the input of its parent

How to estimate the output size of an operator before we actually run it?

- In general, it is a guess of the Reduction Factor (RF)
  - **RF = output_size/input_size**
- Accuracy depends on what information we know about the input relations

THE GUESSING GAME OF RF

For an equality selection (column = value), if we know...

- only # tuples and # pages of the input:
  - System R's guess: 1/10
- If there is an index on column
  - and we know `NKeys`: # distinct key values in the index
  - System R's guess: `1/NKeys`

THE GUESSING GAME OF RF

Now how about inequality selection (e.g. column > value).

- If we only know # tuples and # pages of the input:
  - System R's guess: *a random fraction smaller than 1/2*
- If there is an index on column
  - and we know *High/Low*: the highest/lowest key values
  - System R's guess: (High – value)/(High-Low)

Q: What is the assumption of the above guesses with index?

POSTGRESQL DEFAULTS (1)

src/include/utils/selfuncs.h

```
/*
 * Note: the default selectivity estimates are not chosen entirely at random.
 * We want them to be small enough to ensure that indexscans will be used if
 * available, for typical table densities of ~100 tuples/page.  Thus, for
 * example, 0.01 is not quite small enough, since that makes it appear that
 * nearly all pages will be hit anyway.  Also, since we sometimes estimate
 * eqsel as 1/num_distinct, we probably want DEFAULT_NUM_DISTINCT to equal
 * 1/DEFAULT_EQ_SEL.
 */

/* default selectivity estimate for equalities such as "A = b" */
#define DEFAULT_EQ_SEL        0.005

/* default selectivity estimate for inequalities such as "A < b" */
#define DEFAULT_INEQ_SEL  0.3333333333333333

/* default selectivity estimate for range inequalities "A > b AND A < c" */
#define DEFAULT_RANGE_INEQ_SEL        0.005
```

POSTGRESQL DEFAULTS (1)

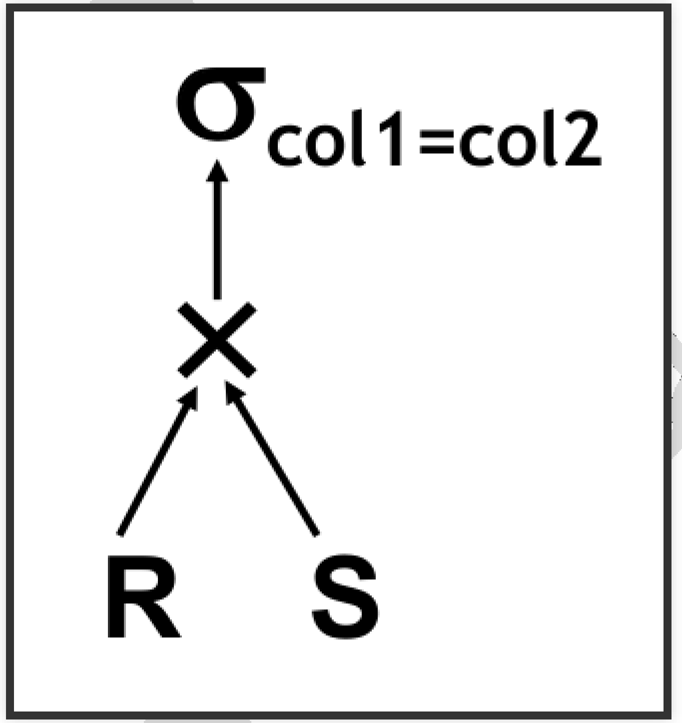
src/include/utils/selfuncs.h

```
/* default selectivity estimate for pattern-match operators such as LIKE */
#define DEFAULT_MATCH_SEL        0.005

/* default number of distinct values in a table */
#define DEFAULT_NUM_DISTINCT  200

/* default selectivity estimate for boolean and null test nodes */
#define DEFAULT_UNK_SEL                        0.005
#define DEFAULT_NOT_UNK_SEL                (1.0 - DEFAULT_UNK_SEL)
```

REDUCTION FACTORS FOR JOINS

RF for the term `col1=col2`

Its input size is the size of the cartesian product: $|R| \times |S|$



REDUCTION FACTORS FOR JOINS

Estimation of RF for Joins (term col1=col2)

If we have indices on both columns

- estimate each tuple r of R generates `NTuples(S)/Nkeys(S)` result tuples, so `|R|*|S|/Nkeys(S)`
- starting from S, yielding: `|S|*|R|/Nkeys( R )`
- If these two estimates differ, take the lower one!
  - Q: Why?

So RF = 1/MAX(NKeys(I1), NKeys(I2))

REDUCTION FACTORS FOR JOINS

The above estimations assume data are uniformly distributed. What if it is not true?

Use histogram to approximate the data distribution: Captures #tuples in ranges of values

REDUCTION FACTORS FOR JOINS

Table 1. equiwidth

No. of values	2	3	3	1	8	2	1
Value	0-0.99	1-1.99	2-2.99	3-3.99	4-4.99	5-5.99	6-6.99

Table 2. equidepth

No. of values	2	3	3	3	3	2	4
Value	0-0.99	1-1.99	2-2.99	3-4.05	4.06-4.67	4.68-4.99	5-6.99

COST ESTIMATION

For each plan considered, must estimate total cost:

- Must estimate cost of each operation in plan tree.
  - Depends on input cardinalities.
- Must estimate size of result for each operation in tree!
  - Use information about the input relations.
  - For selections and joins, assume independence of predicates.
- In System R, cost is boiled down to a single number consisting of #I/O + factor * #CPU instructions

Q: Is “cost” the same as estimated “run time”?

STATISTICS AND CATALOGS

Store necessary information about the relations and indexes in the catalogs:

- # tuples (NTuples) and # pages (NPages) per rel'n.
- # distinct key values (NKeys) for each index.
- low/high key values (Low/High) for each index
- Index height (IHeight) for each tree index.
- # index pages (INPages) for each index.

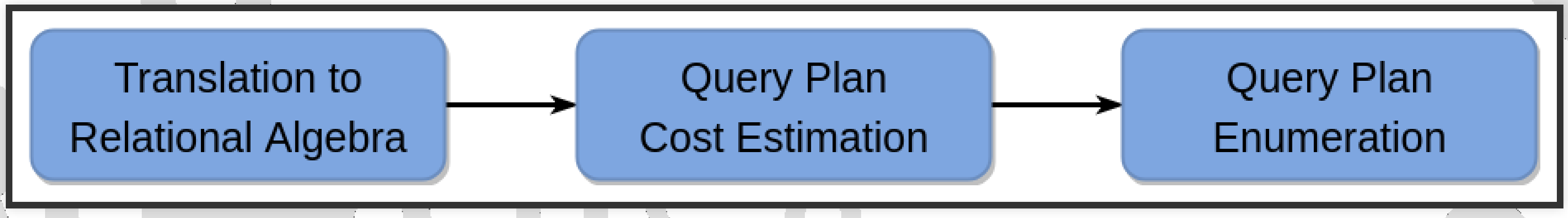
STATISTICS AND CATALOGS

Catalogs updated periodically.

- Updating whenever data changes is too expensive; lots of approximation anyway, so slight inconsistency ok.

More detailed information (e.g., histograms of the values in some field) are sometimes stored.

ROADMAP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ENUMERATION OF ALTERNATIVE PLANS

There are two main cases:

- Single-relation plans
- Multiple-relation plans

ENUMERATION OF ALTERNATIVE 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 operations 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.
- 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 selects.
- Sequential scan of file:
  - NPages(R).

Must also charge for duplicate elimination if required

EXAMPLE

```sql
SELECT S.sid
FROM Sailors S
WHERE S.rating=8
```

If we have an index on rating:

- Cardinality = (1/NKeys(I)) * NTuples(R) = (1/10) * 40000 tuples
- Clustered index: (1/NKeys(I)) * (NPages(I)+NPages(R)) = (1/10) * (50+500) = 55 pages are retrieved. (This is the cost.)
- Unclustered index: (1/NKeys(I)) * (NPages(I)+NTuples(R)) = (1/10) * (50+40000) = 401 pages are retrieved.

EXAMPLE

```sql
SELECT S.sid
FROM Sailors S
WHERE S.rating=8
```

If we have an index on sid:

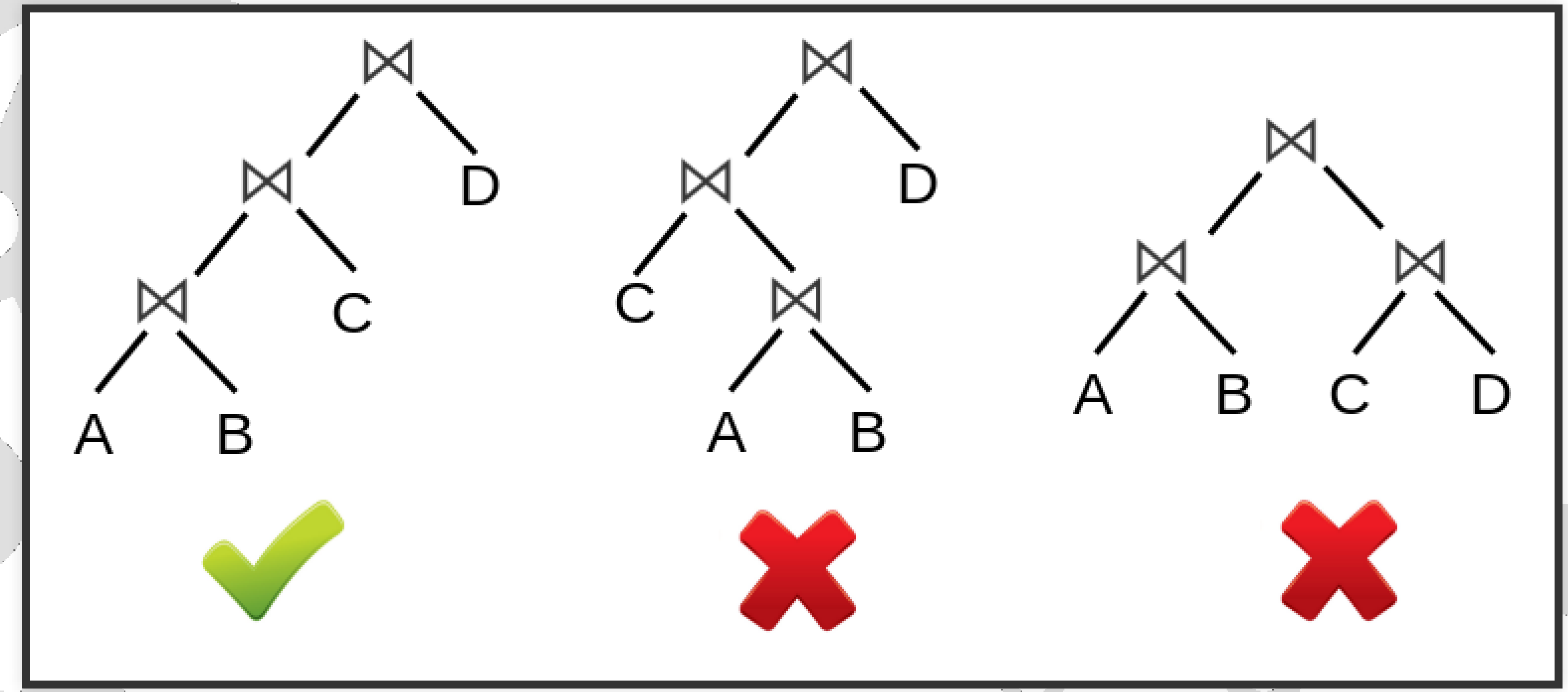
- Would have to retrieve all tuples/pages. With a clustered index, the cost is 50+500, with unclustered index, 50+40000.

Doing a file scan:

- We retrieve all file pages (500).

QUERIES OVER MULTIPLE RELATIONS

A heuristic decision in System R: only left-deep join trees are considered.



QUERIES OVER MULTIPLE RELATIONS

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 PLANS

Avoid Cartesian products:

- An N-1 way plan is not combined with an additional relation unless
  - there is a join condition between them,
  - or all predicates in WHERE have been used up.
- ORDER BY, GROUP BY, aggregates etc. handled as a final step,
  - using either an `interestingly ordered' plan
  - or an additional sort/hash operator.

In spite of pruning plan space, this approach is still exponential in the # of tables.

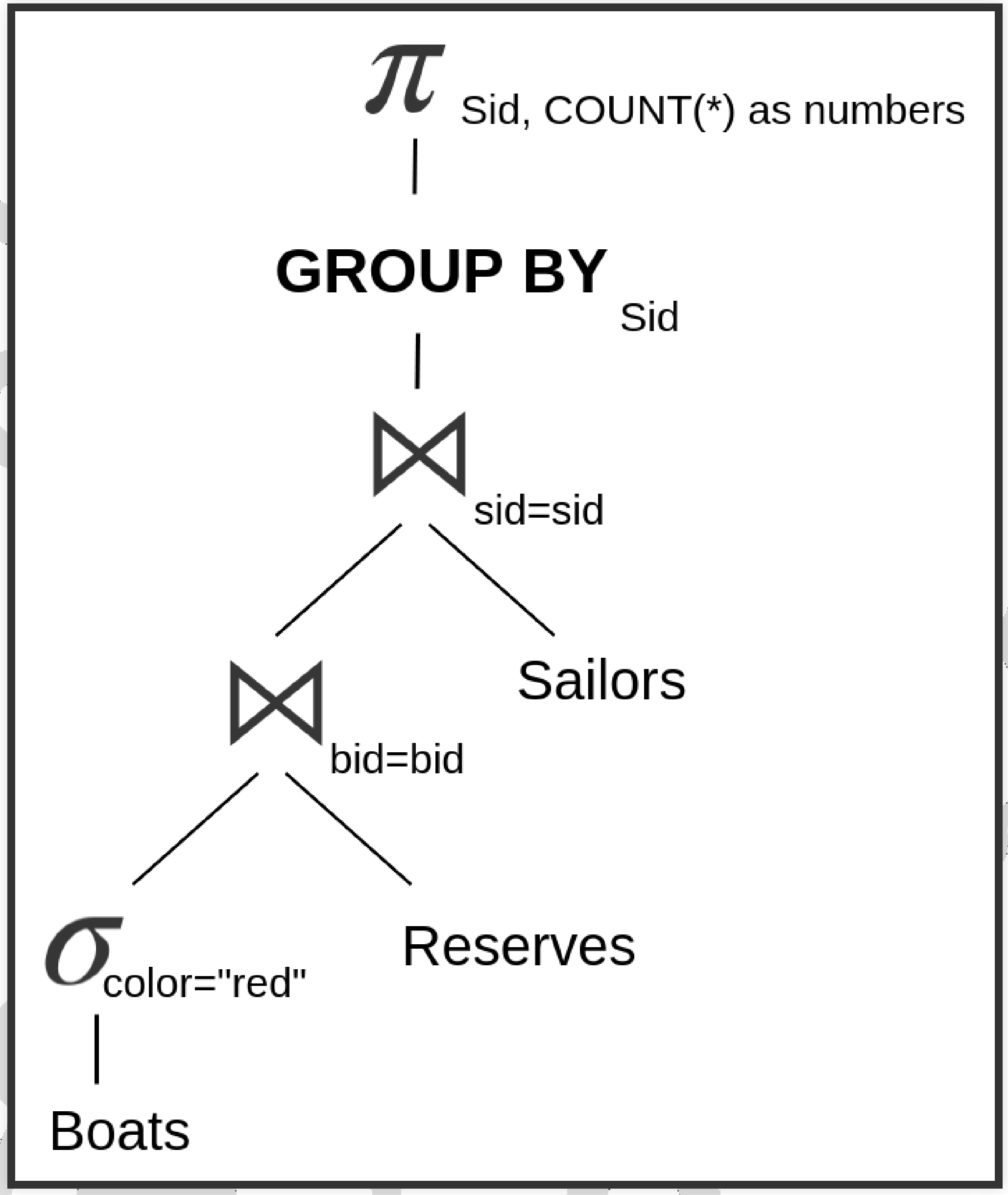
EXAMPLE

- Sailors: Hash, B+ on sid
- Reserves: Clustered B+ tree on bid, B+ on sid
- Boats: B+ on color, Hash on color

```sql
Select S.sid, COUNT(*) AS number
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
AND B.color = “red”
GROUP BY S.sid
```

We should avoid generating the same ”sub-plans” repeatedly

EXAMPLE



π Sid, COUNT(*) as numbers
GROUP BY Sid
⋈ sid=sid
⋈ bid=bid
Sailors
σ color="red"
Reserves
Boats

PASS 1

- Sailors: Hash, B+ on sid
- Reserves: Clustered B+ tree on bid, B+ on sid
- Boats: B+ on color, Hash on color

Best plan for accessing each relation regarded as the first relation in an execution plan

- Reserves, Sailors: File Scan
- Boats: Hash on color

PASS 2

Take each of the plans in pass 1 as the outer, generate plans joining another relation as the inner, using all join methods (and matching inner access methods)

Retain cheapest plan for each pair of relations

Avoid cross-product.

PASS 2

- File Scan Reserves (outer) with Boats (inner)
- File Scan Reserves (outer) with Sailors (inner)
- File Scan Sailors (outer) with Boats (inner)
- File Scan Sailors (outer) with Reserves (inner)
- Boats hash on color with Sailors (inner)
- Boats hash on color with Reserves (inner)
  - e.g. Boats hash on color with Reserves B+tree on bid using Index Nested Loop Join
  - Boats hash on color with Reserves B+tree on bid using Sort Merge Join

PASS 3 AND BEYOND

For each of the plans retained from Pass 2, taken as the outer, generate plans for the next join

- eg Boats hash on color with Reserves (bid) (inner) (sort-merge)) inner Sailors (B-tree sid) sort-merge

Then, add the cost for doing the group by and aggregate:

- This is the cost to sort the result by sid, unless it has already been sorted by a previous operator.

Then, **choose the cheapest plan**

ENUMERATION OF LEFT-DEEP PLANS

Dynamic programming

Left-deep plans differ only in

- the order of relations,
- the access method for each relation,
- and the join method for each join.

ENUMERATION OF LEFT-DEEP PLANS

Dynamic programming

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.

THE DYNAMIC PROGRAMMING TABLE

Subset of tables in FROM clause	Interesting-order columns	Best plan	Cost
{R,S}	<none>	hashjoin(R,S)	1000
{R,S}	<R.a,S.b>	sortmerge(R,S)	1500

INTERESTING ORDERS

An intermediate result has an "interesting order" if it is sorted by any of:

- ORDER BY attributes
- GROUP BY attributes
- Join attributes of *yet-to-be-added* (downstream) joins

SUMMARY

- Must understand optimization in order to understand the performance impact of a given database design (relations, indexes) on a workload (set of queries).

SUMMARY

Two parts to optimizing a query:

- Consider a set of alternative plans.
  - Good to prune search space; e.g., left-deep plans only, avoid Cartesian products.
- Must estimate cost of each plan that is considered.
  - Output cardinality and cost for each plan node.
  - Key issues: Statistics, indexes, operator implementations.

SUMMARY

Single-relation queries:

- All access paths considered, cheapest is chosen.
- Issues: Selections that match index, whether index key has all needed fields and/or provides tuples in a desired order.

SUMMARY

Multiple-relation queries:

- All single-relation plans are first enumerated.
  - Selections/projections considered as early as possible.
- Next, for each 1-relation plan, all ways of joining another relation (as inner) are considered.
- Next, for each 2-relation plan that is `retained', all ways of joining another relation (as inner) are considered, etc.
- At each level, for each subset of relations, only the best plan for each interesting order of tuples is `retained'.

SUMMARY

- Optimization is the reason for the lasting power of the relational system
- But it is primitive in some ways
- New areas: Smarter summary statistics (fancy histograms and “sketches”), auto-tuning statistics, adaptive runtime re-optimization

REFERENCES

- https://doxygen.postgresql.org/selfuncs_8h.html