Database Systems I

CMPT 354 Summer 2024

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Announcements (Wed. July 24)

- A3 grade released
- Exam II grade releasing soon When?
- Expect sample questions for Exam III in the weekend
- A5 dues on next Monday

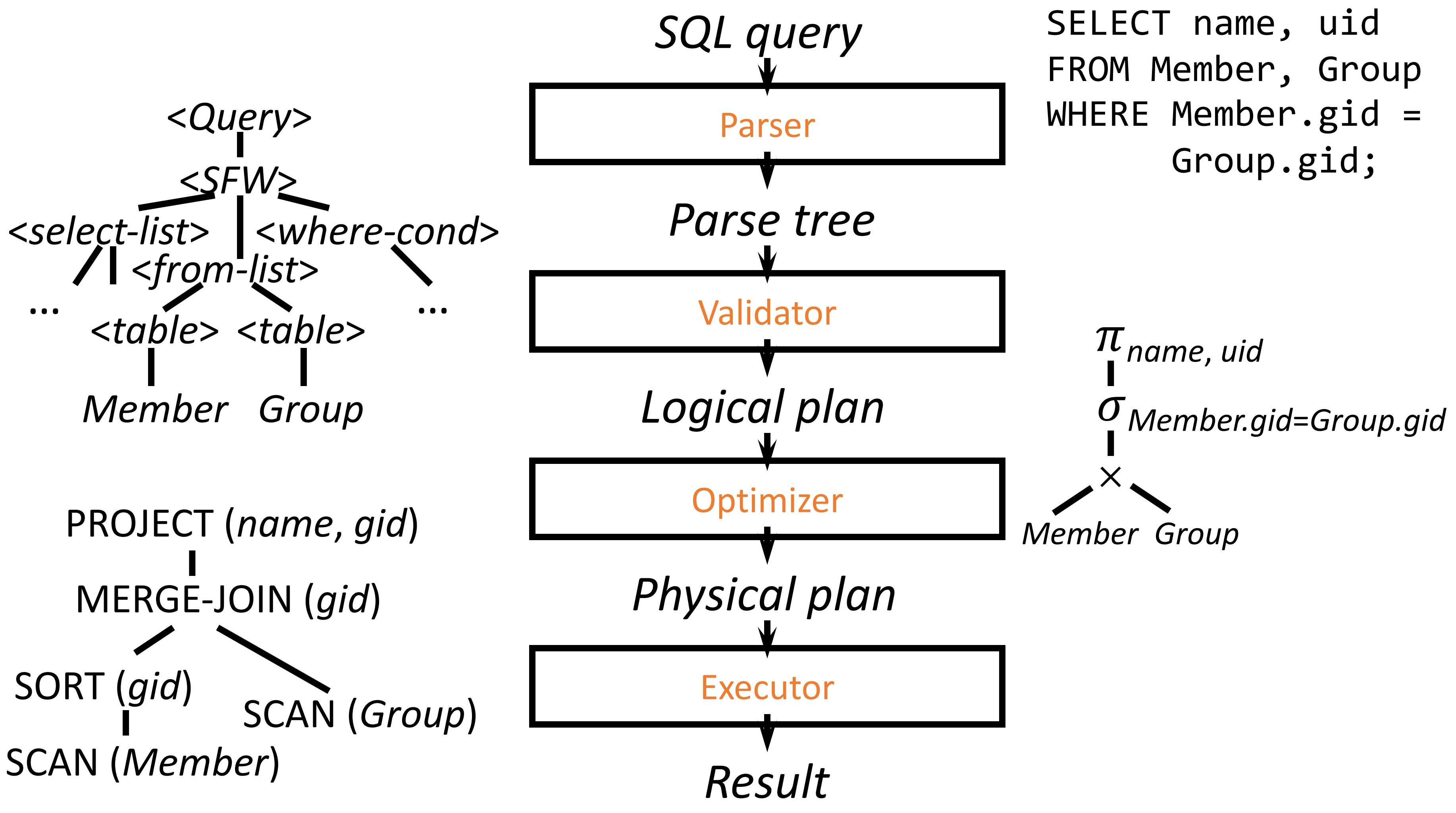
Overview

- Many ways to process the same query
  - Scan? Sort? Hash? Use an index?
  - All have different performance characteristics and/or make different assumptions about data
- **Best choice depends on the situation**
  - **Implement all alternatives**
  - **Let the query optimizer choose at run-time**

Outline

- System view of query processing
  - Logical plan and physical plan
- Cost calculation of the physical plan
  - Cardinality estimation
- Search space and search strategy
  - Transformation rules
  - Other heuristics

A query's trip through the DBMS



Parsing and validation

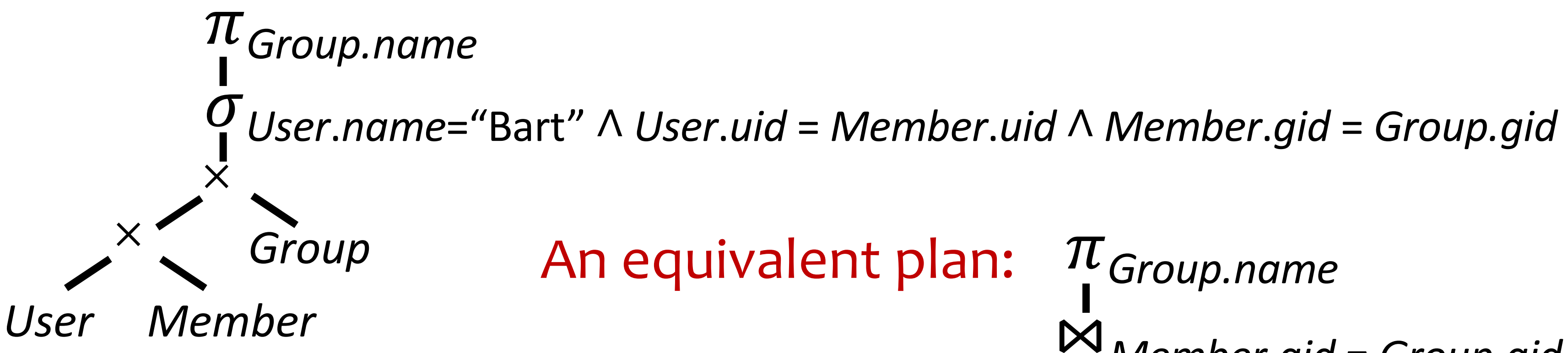
- Parser: SQL → parse tree
  - Detect and reject syntax errors
- Validator: parse tree → logical plan

Parser creates AST, the validator checks that everything in the tree complies with the restrictions (types, existing tables, etc)

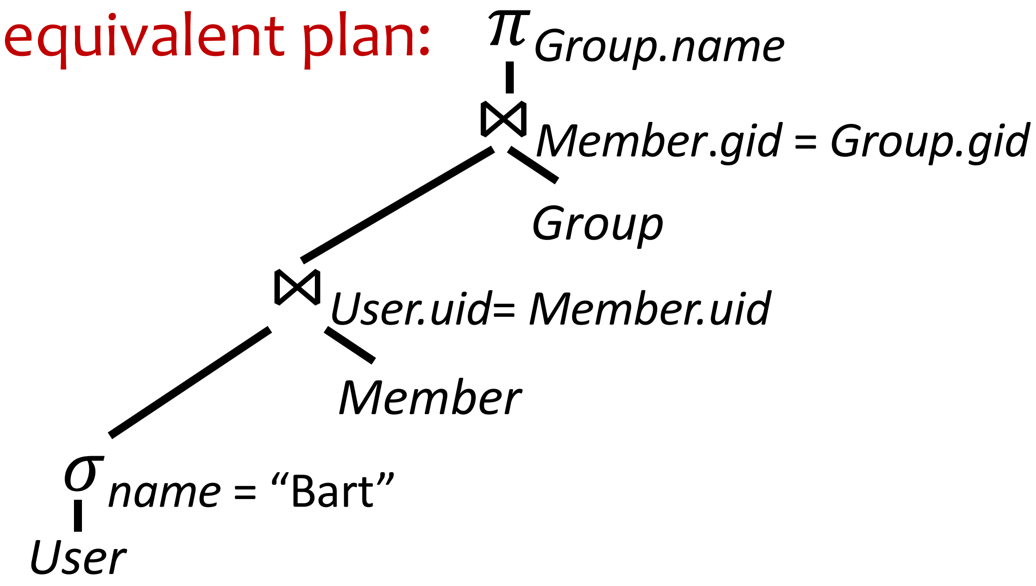
  - Detect and reject semantic errors
    - Nonexistent tables/views/columns?
    - Insufficient access privileges?
    - Type mismatches?
      - Examples: AVG(name), name + pop, User UNION Member
  - Also
    - Resolve column references
    - Expand *, Expand view definitions
  - Information required for semantic checking is found in system catalog (which contains all schema information)

Logical plan

- Nodes are logical operators (often relational algebra operators)
- There are many equivalent logical plans



An equivalent plan:

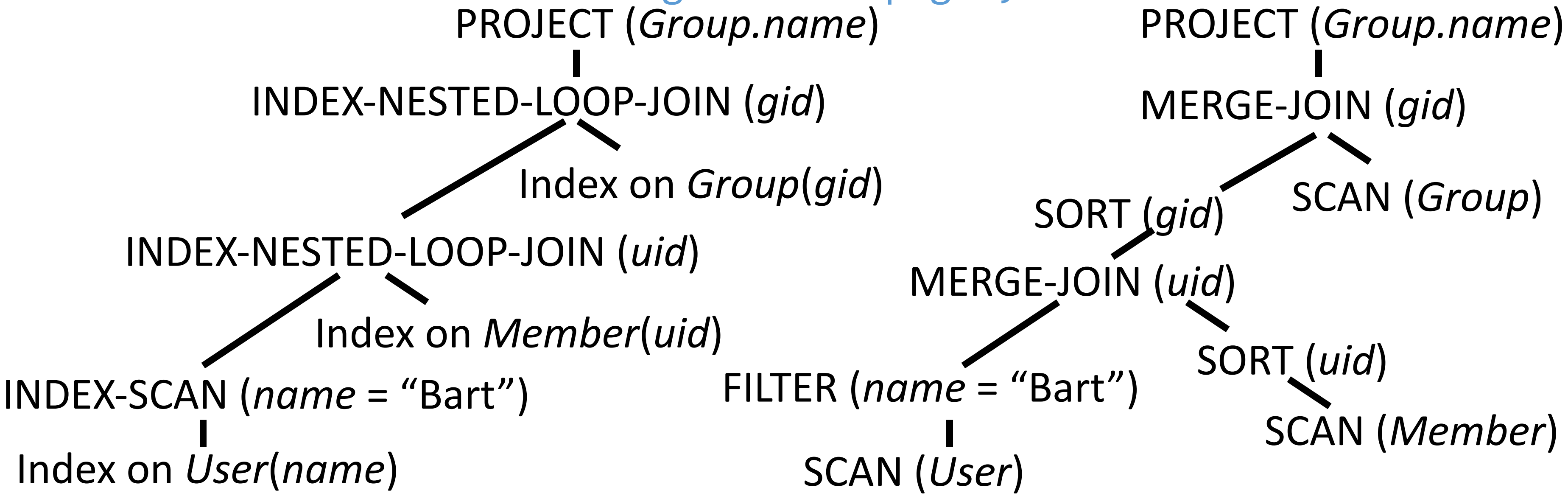


Physical (execution) plan

- A complex query may involve multiple tables and various query processing algorithms
  - E.g., table scan, index nested-loop join, sort-merge join, hash-based duplicate elimination… (covered in Lec 16)
- A physical plan for a query tells the DBMS query processor how to execute the query
  - A tree of physical plan operators
  - Each operator implements a query processing algorithm
  - Each operator accepts one or more input tables/streams and produces a single output table/stream

Examples of physical plans

```sql
SELECT Group.name
FROM User, Member, Group
WHERE User.name = 'Bart'
AND User.uid = Member.uid AND Member.gid = Group.gid;
```

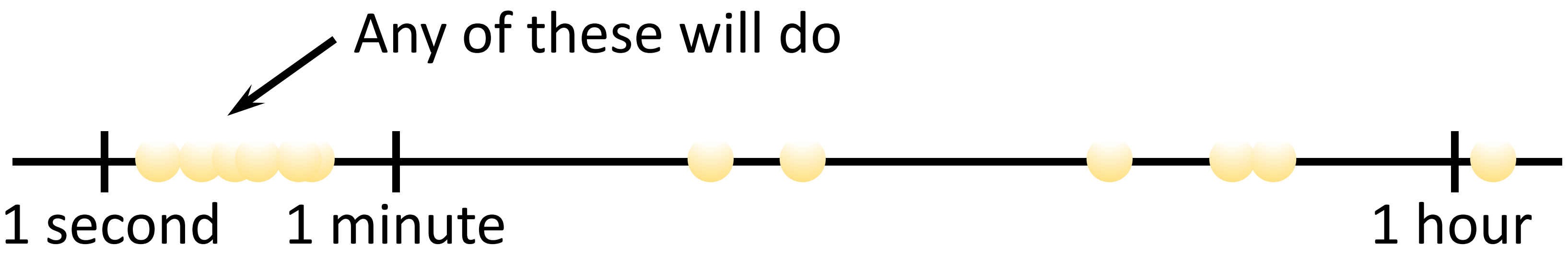


- Many physical plans for a single query
  - Equivalent results, but different costs and assumptions!

☞DBMS query optimizer picks the “best” possible physical plan

Query optimization: how to pick the physical plan?

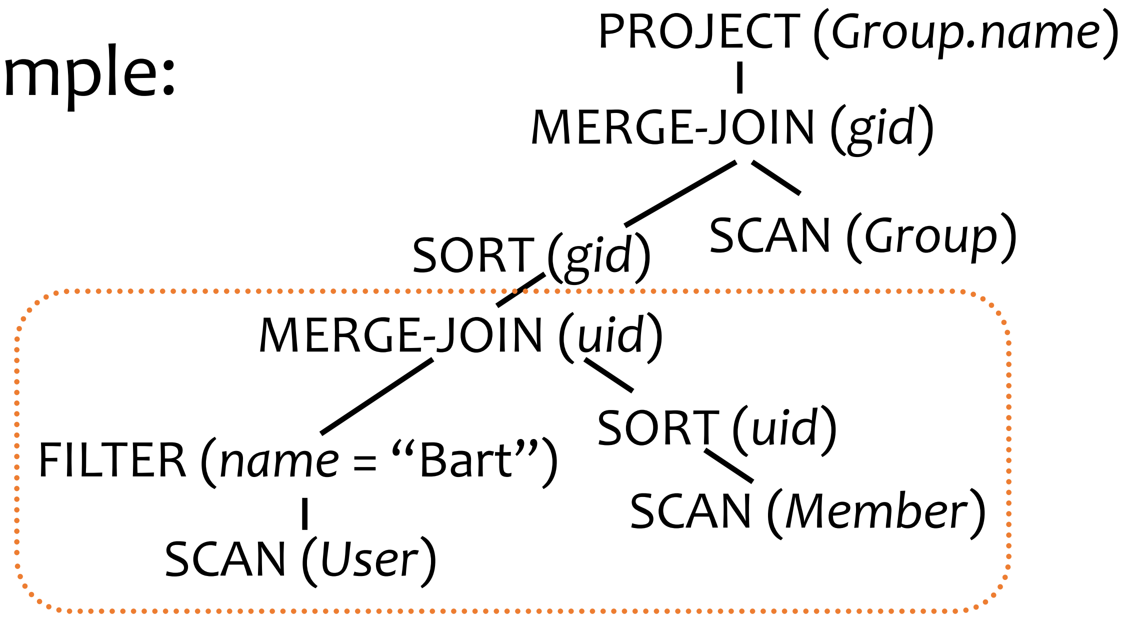
- One logical plan → "best" physical plan
- Questions
  - How to estimate costs
  - How to enumerate possible plans
  - How to pick the "best" one
- Often the goal is not getting the optimum plan, but instead avoiding the horrible ones



Cost estimation

Physical plan example:

Input to SORT(*gid*):



- We have: cost estimation for each operator
  - Example: SORT(*gid*) takes $O(B(\text{input}) \times \log_M B(\text{input}))$
    - But what is $B(\text{input})$?
- We need: size of intermediate results

Cardinality estimation

Cardinality estimation for:

- Equality predicates
- Range predicates
- Joins
- Other operators refer to the textbook

http://www.learningresources.com/product/estimation+station.do

Selections with equality predicates

- Q: $\sigma_{A=v}R$
- Suppose the following information is available
  - Size of R: $|R|$
  - Number of distinct A values in R: $|\pi_A R|$

Assumptions are unrealistic, but they work in practice.

- Assumptions
  - Values of A are uniformly distributed in R
  - Values of v in Q are uniformly distributed over all $R.A$ values
- $|Q| \approx {}^{|R|}/_{|\pi_A R|}$
  - Selectivity factor of $(A = v)$ is ${}^{1}/_{|\pi_A R|}$

Conjunctive predicates

- Q: $\sigma_{A=u \wedge B=v} R$
- Additional assumptions
  - $(A = u)$ and $(B = v)$ are independent
    - Counterexample: major and advisor
  - No "over"-selection

    What is over-selection?
    - Counterexample: A is the key
- $|Q| \approx {}^{|R|}/_{|\pi_A R| \cdot |\pi_B R|}$
  - Reduce total size by all selectivity factors

Negated and disjunctive predicates

- Q: $\sigma_{A \neq v} R$
  - $|Q| \approx |R| \cdot \left(1 - {}^{1}/_{|\pi_A R|}\right)$
    - Selectivity factor of $\neg p$ is $(1 -$ selectivity factor of $p)$
- Q: $\sigma_{A=u \,\vee\, B=v} R$
  - $|Q| \approx |R| \cdot \left({}^{1}/_{|\pi_A R|} + {}^{1}/_{|\pi_B R|}\right)$?

    When you sum, you will overcount.
    Must apply inclusion-exclusion to avoid this.
    - No!
  - $|Q| \approx |R| \cdot \left({}^{1}/_{|\pi_A R|} + {}^{1}/_{|\pi_B R|} - {}^{1}/_{|\pi_A R||\pi_B R|}\right)$
    - Inclusion-exclusion principle

Range predicates

- Q: $\sigma_{A>v} R$
- Not enough information!
  - Just pick, say, $|Q| \approx |R| \cdot {}^{1}/_{3}$
- With more information
  - Largest $R.A$ value: $\text{high}(R.A)$
  - Smallest $R.A$ value: $\text{low}(R.A)$
  - $|Q| \approx |R| \cdot \frac{\text{high}(R.A) - v}{\text{high}(R.A) - \text{low}(R.A)}$
  - In practice: sometimes the second highest and lowest are used instead

Two-way equi-join

- Q: $R(A, B) \bowtie S(A, C)$
- Assumption: containment of value sets
  - Every tuple in the "smaller" relation (one with fewer distinct values for the join attribute) joins with some tuple in the other relation
  - That is, if $|\pi_A R| \leq |\pi_A S|$ then $\pi_A R \subseteq \pi_A S$
  - Certainly not true in general
  - But holds in the common case of foreign key joins
- $|Q| \approx \frac{|R| \cdot |S|}{\max(|\pi_A R|, |\pi_A S|)}$
  - Selectivity factor of $R.A = S.A$ is $1/_{\max(|\pi_A R|, |\pi_A S|)}$

Example

- Database:
  - User(<u>uid</u>, name, age, pop), Member(<u>gid,uid</u>,date), Group(<u>gid</u>, gname)
  - $|User|$=1000 rows, | Group |=100 rows, $|Member|$=50000 rows
  - $|\pi_{\text{name}}(User)| = 50$
  - $|\pi_{\text{uid}}(Member)| = 500$

- Estimate size $|User \bowtie Member| =?$
  - $|\pi_{\text{uid}}(User)| = 1000$
  - $|\pi_{\text{uid}}(Member)| = 500$
  - 1000*50000/max(500,1000)=50000

Multiway equi-join

- Q: $R(A, B) \bowtie S(B, C) \bowtie T(C, D)$
- What is the number of distinct C values in the join of R and S?
- Assumption: preservation of value sets
  - A non-join attribute does not lose values from its set of possible values
  - That is, if A is in R but not S, then $\pi_A(R \bowtie S) = \pi_A R$
  - Certainly not true in general
  - But holds in the common case of foreign key joins (for value sets from the referencing table)

Multiway equi-join (cont'd)

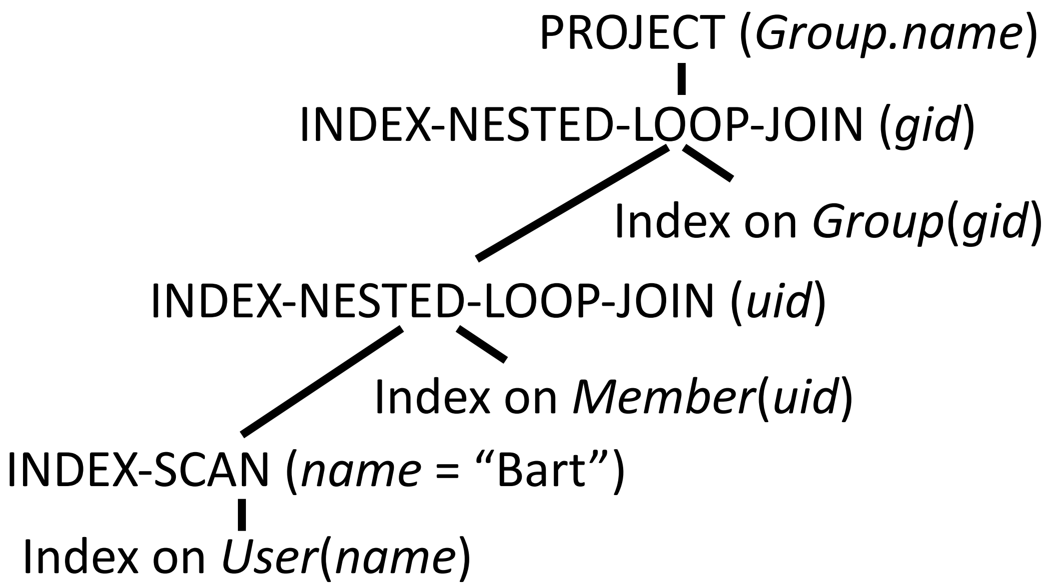
- Q: $R(A,B) \bowtie S(B,C) \bowtie T(C,D)$
- Start with the product of relation sizes
  - $|R| \cdot |S| \cdot |T|$
- Reduce the total size by the selectivity factor of each join predicate
  - $R.B = S.B$: ${}^{1}/_{\max(|\pi_B R|,|\pi_B S|)}$
  - $S.C = T.C$: ${}^{1}/_{\max(|\pi_C S|,|\pi_C T|)}$
  - $|Q| \approx \dfrac{|R|\cdot|S|\cdot|T|}{\max(|\pi_B R|,|\pi_B S|)\cdot\max(|\pi_C S|,|\pi_C T|)}$

Cost estimation example

- $Q: R(A,B) \bowtie S(B,C) \bowtie T(C,D)$
  - $|R| = 1000, |\pi_B R| = 20$
  - $|S| = 2000, |\pi_B S| = 50, |\pi_C S| = 100$
  - $|T| = 5000, |\pi_C T| = 500$
- Estimation method 1: $(R \bowtie S) \bowtie T$
  - $|R \bowtie S| = \frac{|R| \cdot |S|}{\max(|\pi_B R|, |\pi_B S|)} = \frac{1000 \times 2000}{50} = 40\text{K}$
  - $|(R \bowtie S) \bowtie T| = \frac{|R \bowtie S| \cdot |T|}{\max(|\pi_C (R \bowtie S)|, |\pi_C T|)} = \frac{40000 \times 5000}{500} = 400\text{K}$
- Estimation method 2: $R \bowtie (S \bowtie T)$
  - $|S \bowtie T| = \frac{|S| \cdot |T|}{\max(|\pi_C S|, |\pi_C T|)} = \frac{2000 \times 5000}{500} = 20\text{K}$
  - $|R \bowtie (S \bowtie T)| = \frac{|R| \cdot |S \bowtie T|}{\max(|\pi_B (R)|, |\pi_B (S \bowtie T)|)} = \frac{1000 \times 20000}{50} = 400\text{K}$

More example

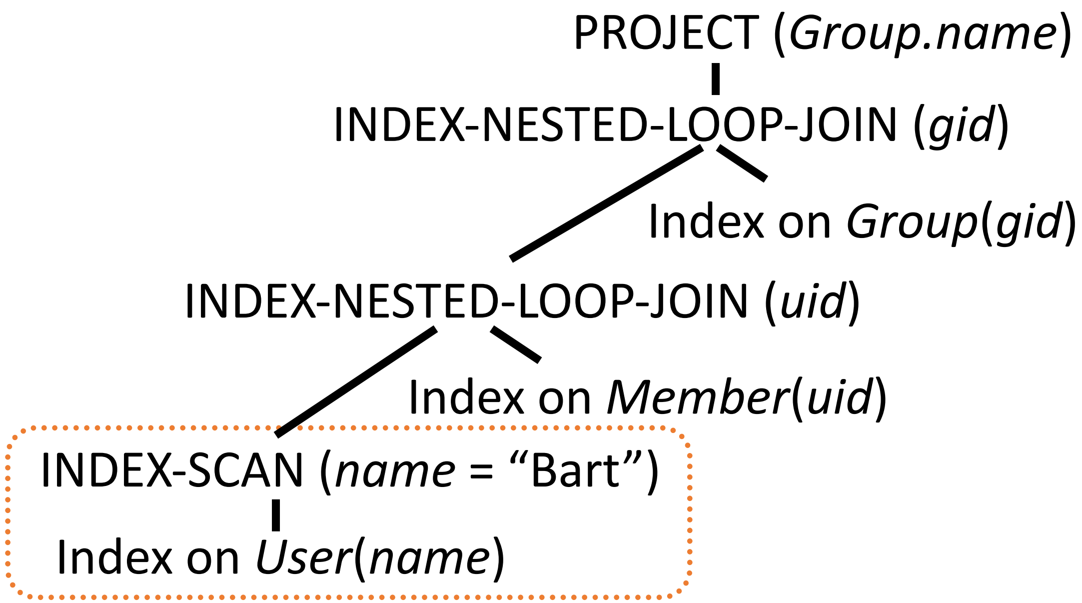
Physical plan example:



- System requirements:
  - Each disk/memory block can hold up to 10 rows (from any table);
  - All tables are stored compactly on disk (10 rows per block);
  - 8 memory blocks are available for query processing: M=8
- Database:
  - User(uid, age, pop), Member(gid,uid,date), Group(gid, gname)
  - $|User|$=1000 rows, $|Group|$=100 rows, $|Member|$=50000 rows
  - #of blocks: B(User) = 1000/10 = 100; B(Group) = 100/10 = 10; B(Member) = 50000/10=5k

More example

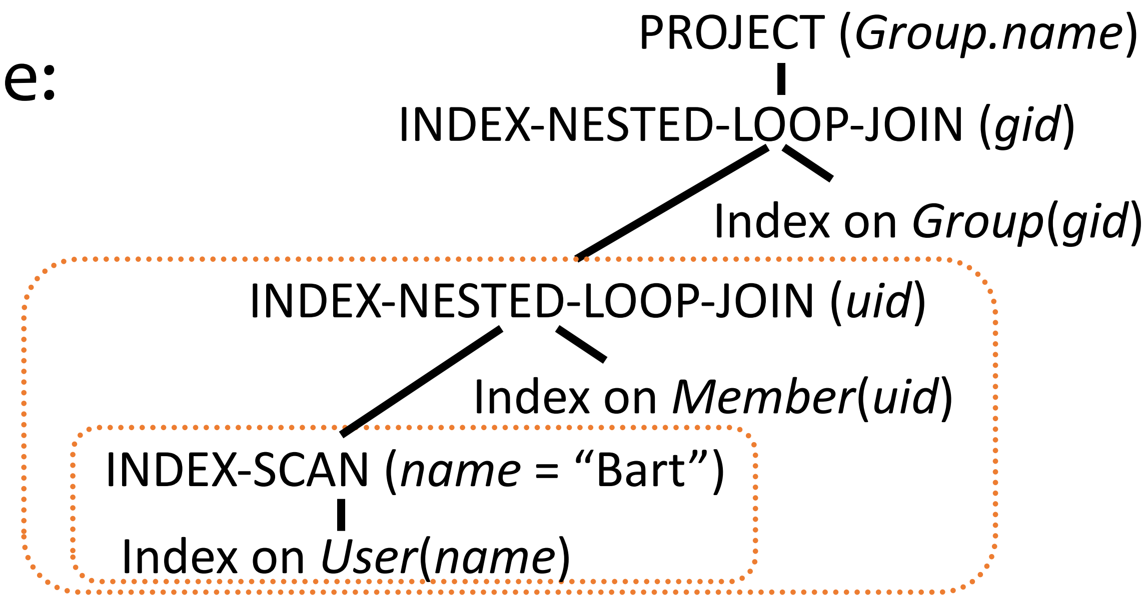
Physical plan example:



- Given $|User|$=1000, $|\pi_{name}\ (User)|$ = 50
- $|\sigma_{name=\text{“}Bart\text{”}}(User)|$ = 1000 / 50 = 20 records
- INDEX-SCAN on User
  - IO COST: index lookup (~4 IOs, depending on the height of the index tree)

More example

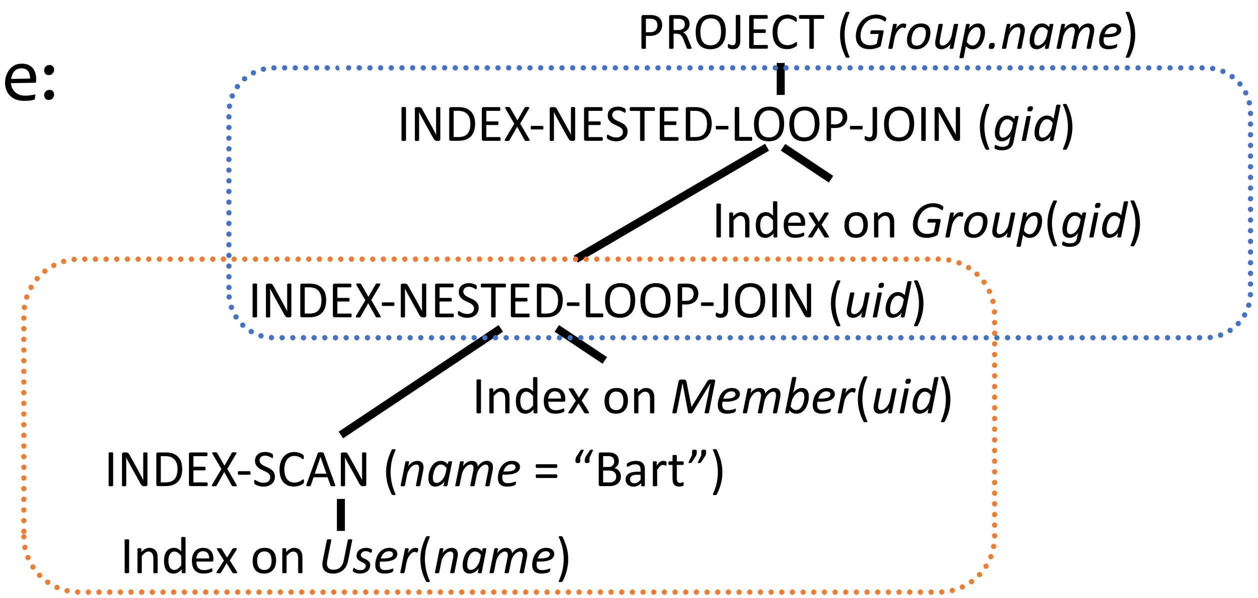
Physical plan example:



- Given $|User|$=1000, $|\pi_{name}(User)|$ = 50, $|\sigma_{name=\text{"Bart"}}(User)|$ = 1000/50 = 20 records
- INDEX-SCAN on User
  - IO COST: index lookup (4 IOs, depending on the height of the index tree)
- JOIN: For each record with name = "Bart", probe the index on $Member(uid)$
  - IO cost: $B(R)$ + $|R|$ $\cdot$ (index lookup + record fetch)
  - 20 rows are not clustered → in the worst case, 20 blocks of data to be retrieved
  - 20 + 20 * (4 IOs for index + record fetches)

More example

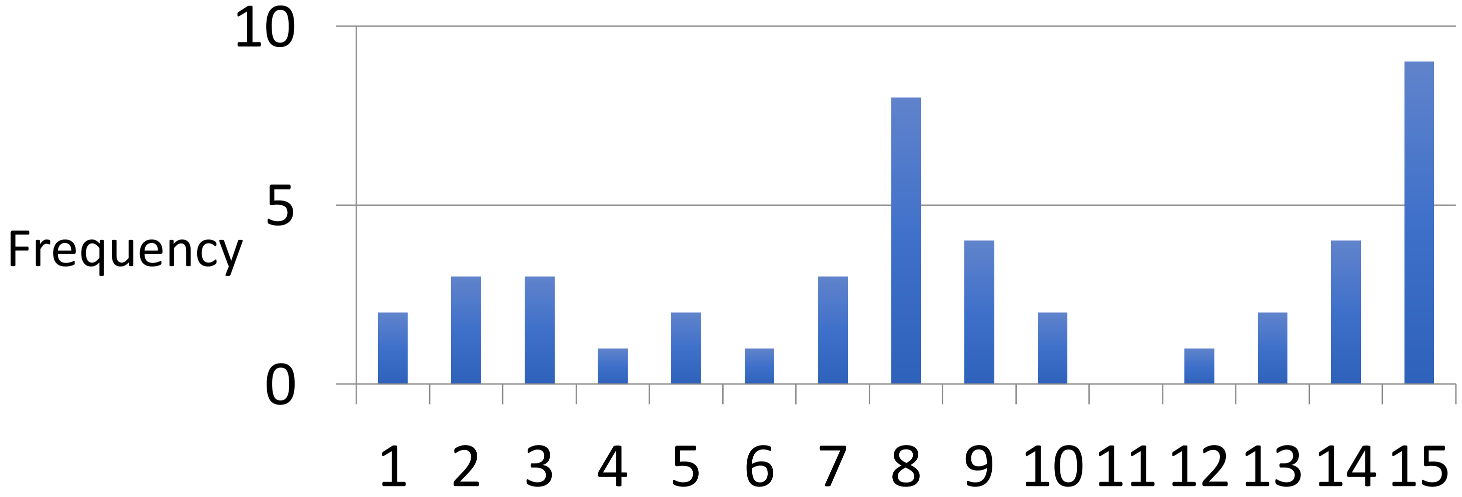
Physical plan example:



- Given $|\pi_{uid}(\sigma_{name=\text{“Bart”}}(User))|$ = 20, $|\pi_{uid}(Member)|$ = 500, $|\pi_{uid}(Group)|$ = 100
- $|JOIN(uid)| \approx \frac{|R|\cdot|S|}{\max(|\pi_A R|,|\pi_A S|)} = \frac{20\cdot 50k}{\max(20,500)} = \frac{1000k}{500} = 2k$
- Assume preservation of value sets: $|\pi_{gid}(User \bowtie Member)| = |\pi_{gid} Member|$, but how about $|\pi_{gid}(\sigma_{name=\text{“Bart”}}(User) \bowtie Member)|$?
  - Depending on the distribution, here we assume $|\pi_{gid}(\sigma_{name=\text{“Bart”}}(User) \bowtie Member)|$ = 50
- $|JOIN(gid)| \approx \frac{|R|\cdot|S|}{\max(|\pi_A R|,|\pi_A S|)} = \frac{2k\cdot 100}{\max(50,100)} = \frac{200k}{100} = 2k$

Cost estimation: summary

- Using similar ideas, we can estimate the size of projection, deduplication, union, difference, aggregation (with grouping)
- Lots of assumptions and very rough estimation
  - Accurate estimate is not needed
  - Maybe okay if we overestimate or underestimate consistently
- Not covered: better estimation using histograms and machine learning



Outline

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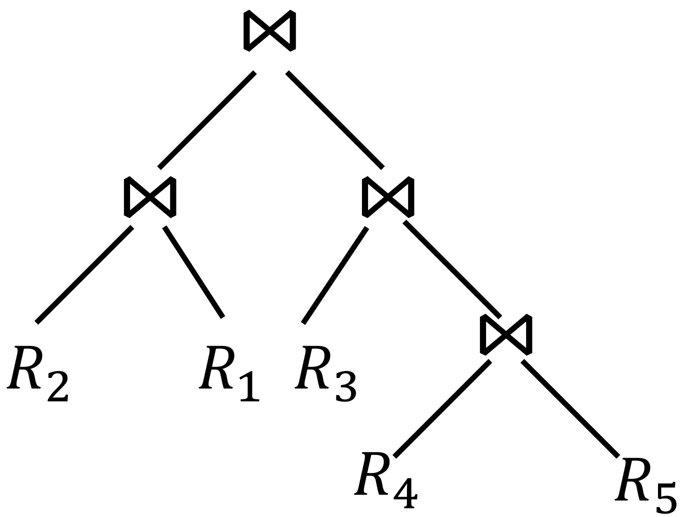
- **Search space and search strategy**
  - **Transformation rules**
  - **Other heuristics**

Search space

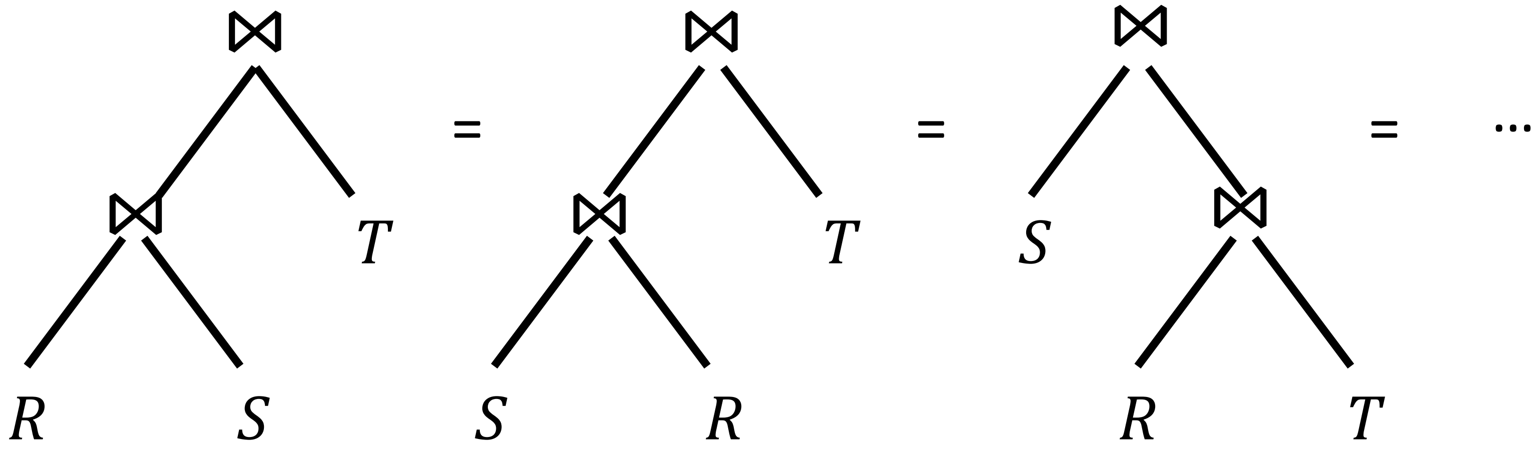
- Huge!
- "Bushy" plan example:



- Just considering different join orders, there are $\frac{(2n-2)!}{(n-1)!}$ bushy plans for $R_1 \bowtie \cdots \bowtie R_n$
  - 30240 for $n = 6$
- And there are more if we consider:
  - Multiway joins
  - Different join methods
  - Placement of selection and projection operators

Plan enumeration in relational algebra

- Do we need to exam all the logical plans?
  - No
- Apply relational algebra equivalences to find a cheaper logical plan
  - ☞Join reordering: $\times$ and $\bowtie$ are associative and commutative (except column ordering, but that is unimportant)



More relational algebra equivalences

- Convert σ_p-$\times$ to/from $\bowtie_p$: $\sigma_p(R \times S) = R \bowtie_p S$
  - Example: $\sigma_{\text{User.uid}=\text{Member.uid}}(User \times Member) = User \bowtie Member$
- Merge/split σ's: $\sigma_{p_1}\left(\sigma_{p_2} R\right) = \sigma_{p_1 \wedge p_2} R$
  - Example: $\sigma_{\text{age}>20}(\sigma_{\text{pop}>0.5}\, User) = \sigma_{\text{age}>20\, \wedge\, \text{pop}>0.5}\, User)$
- Merge/split π's: $\pi_{L_1}\left(\pi_{L_2} R\right) = \pi_{L_1} R$, where $L_1 \subseteq L_2$
  - Example: $\pi_{age}\,(\pi_{age,pop} User) = \pi_{age}\,(User)$

More relational algebra equivalences

- Push down/pull up σ:
  $\sigma_{p \wedge p_r \wedge p_s}(R \bowtie_{p'} S) = (\sigma_{p_r} R) \bowtie_{p \wedge p'} (\sigma_{p_s} S)$, where
  - p_r is a predicate involving only R columns
  - p_s is a predicate involving only S columns
  - p and p' are predicates involving both R and S columns
  - Example

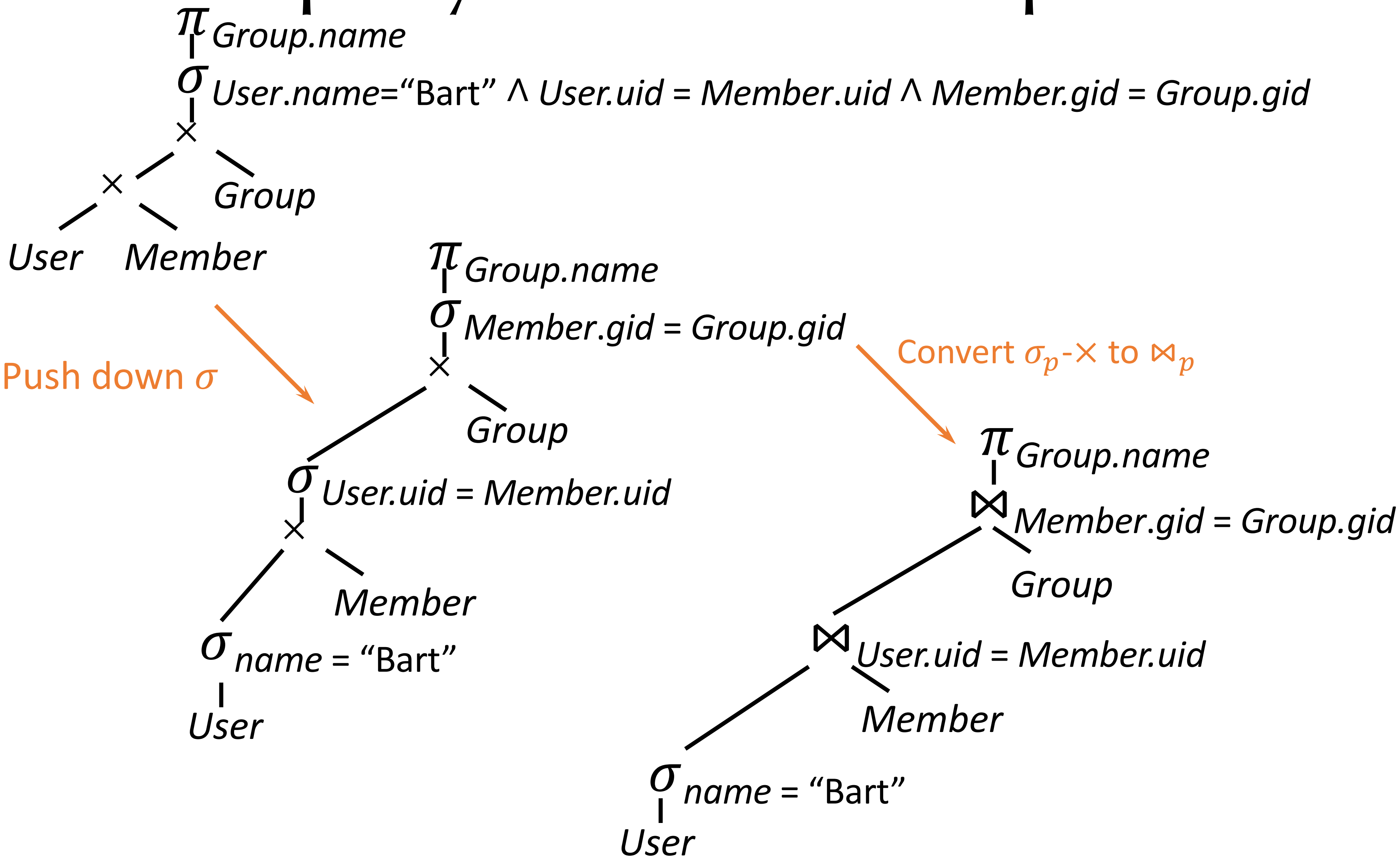
$$\sigma_{\text{U1.name=U2.name} \wedge \text{U1.pop>0.5} \wedge \text{U2.pop} > 0.5} (\rho_{\text{U1}} User \bowtie_{\text{U1.uid} \neq \text{U2.uid}} \rho_{\text{U2}} User)$$
$$= (\sigma_{\text{pop>0.5}} (\rho_{\text{U1}} User)) \bowtie_{\text{U1.uid} \neq \text{U2.uid} \wedge \text{U1.name=U2.name}} (\sigma_{\text{pop>0.5}} (\rho_{\text{U2}} User))$$

More relational algebra equivalences

- Push down π: $\pi_L(\sigma_p R) = \pi_L\left(\sigma_p(\pi_{LL'} R)\right)$, where
  - L' is the set of columns referenced by p that are not in L
  - Example:
  - $\pi_{age}(\sigma_{\text{pop}>0.5} User) = \pi_{age}(\sigma_{\text{pop}>0.5}\,(\pi_{age,pop}\, User))$

- Many more (seemingly trivial) equivalences…
  - Can be systematically used to transform a plan to new ones

Relational query rewrite example



Heuristics-based query optimization

- Start with a logical plan
- Push selections/projections down as much as possible
  - Why? Reduce the size of intermediate results
  - Why not?
- Join smaller relations first, and avoid cross product
  - Why? Reduce the size of intermediate results
  - Why not?
- Convert the transformed logical plan to a physical plan (by choosing appropriate physical operators)

SQL query rewrite

- More complicated—subqueries and views divide a query into nested “blocks”
  - Processing each block separately forces particular join methods and join order
  - Even if the plan is optimal for each block, it may not be optimal for the entire query
- Unnest query: convert subqueries/views to joins

☞We can then deal with each select-project-join(-aggregation) block

  - Where the clean rules of relational algebra apply

SQL query rewrite example

- ```
  SELECT name
  FROM User
  WHERE uid = ANY (SELECT uid FROM Member);
  ```
- ```
  SELECT name
  FROM User, Member
  WHERE User.uid = Member.uid;
  ```
  - Wrong—
- ```
  SELECT name
  FROM (SELECT DISTINCT User.uid, name
        FROM User, Member
        WHERE User.uid = Member.uid);
  ```
  - Right—assuming `User.uid` is a key
  ```

Dealing with correlated subqueries

- ```
  SELECT gid FROM Group
  WHERE name LIKE 'Springfield%'
  AND min_size > (SELECT COUNT(*) FROM Member
                  WHERE Member.gid = Group.gid);
  ```
- ```
  SELECT gid
  FROM Group, (SELECT gid, COUNT(*) AS cnt
               FROM Member GROUP BY gid) t
  WHERE t.gid = Group.gid AND min_size > t.cnt
  AND name LIKE 'Springfield%’;
  ```
- New subquery is inefficient (it computes the size for every group)
- Suppose a group is empty?

Heuristics- vs. cost-based optimization

- Heuristics-based optimization
  - Apply heuristics to rewrite plans into cheaper ones
- Cost-based optimization
  - Rewrite logical plan to combine “blocks” as much as possible
  - Optimize query block by block
    - Enumerate logical plans (already covered)
    - Estimate the cost of plans
    - Pick a plan with acceptable cost
  - Focus: select-project-join blocks

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