11. Query Execution

[Most of the content is drawn from book Elmasri/Navathe]

A query can be expressed in different way;

(1) $\pi_{\text{fname, dname, salary}}($
$\sigma_{\text{salary >= 30000 AND employee.dno = department.dno}}$
(employee x department))

(2) $\pi_{\text{fname, dname, salary}}(\sigma_{\text{salary >= 30000}}$ (employee)
* department)

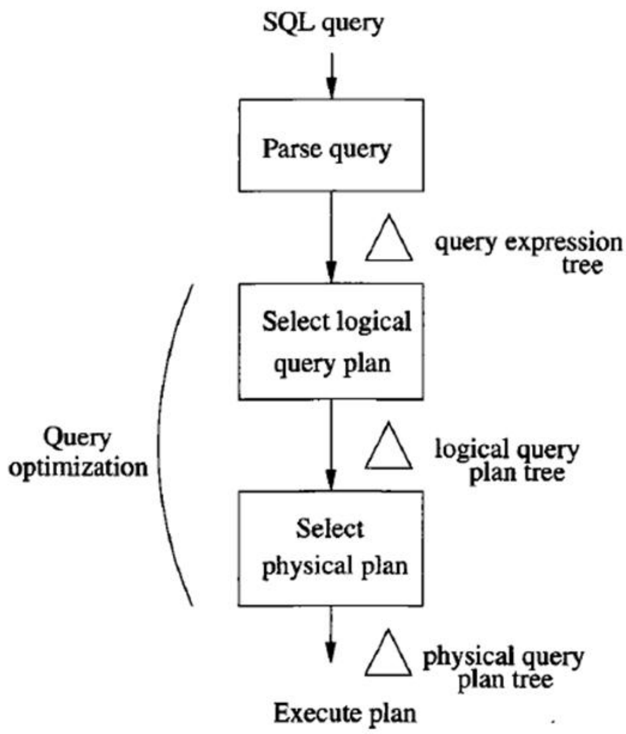
(3) $\sigma_{\text{salary >= 30000}}(\pi_{\text{fname, dname, salary}}$
(employee * department))

<u>Which is more efficient to execute?</u>

DBMS attempts executing efficient queries in most optimal way; regardless of how they have been expressed by the user. DBMS provide a dedicated module, "Query Optimizer" that has prime responsibility of figuring out answer of above question itself.

<u>Query Execution</u>

Various steps showed here in the diagram drawn from book[1]



<u>Parsing and Parse Tree generation:</u>
Checks for syntax errors, checks for correct references to tables and attributes; and finally produces "<u>query parse tree</u>" typically in terms of relational algebra.

<u>Select Logical Query Plan (Query rewriting)</u>:

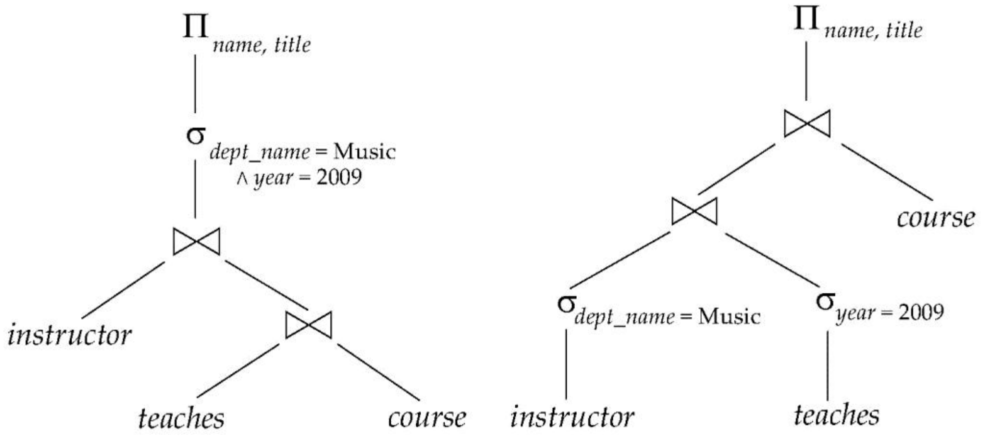
Using certain heuristic rules queries is rewritten or expressed differently that would be more efficient; following are some of optimization parameters-

- If a JOIN expressed in terms of CROSS PRODUCT be expressed as JOIN
- Can some operations be combined or split
- Will re-ordering of operations will lead to better plan – attempts pushing selection as below as possible in parse tree.

Outcome of the step is an Evaluation Tree in terms of relational operations (note that order of operations also gets specified in evaluation tree)

[1] Garcia-Molina, Hector. Database systems: the complete book. Pearson Education India, 2008.

Here is an example from book [2] –



(a) Initial expression tree (b) Tree after multiple transformations

Select Physical Query Plan:

At this level most appropriate algorithm is selected for performing operations in the "logical plan" and in that order.

Final outcome of this step is "code for executing the query"

Note: plan might be saved for further execution of the query - "prepared statements"

Algorithms for query execution

Parameters used in cost of algorithm:

- N: number of records in a relation
- Rs: record size
- B: number of blocks in a relation
- BF (Blocking factor): number of records in a block
- Selection Cardinality S = N / distinct values for an attributes
- Selectivity: S / N
- H: height of B+-tree index tree
- Join Selectivity (js) describe later

Sorting Algorithms:

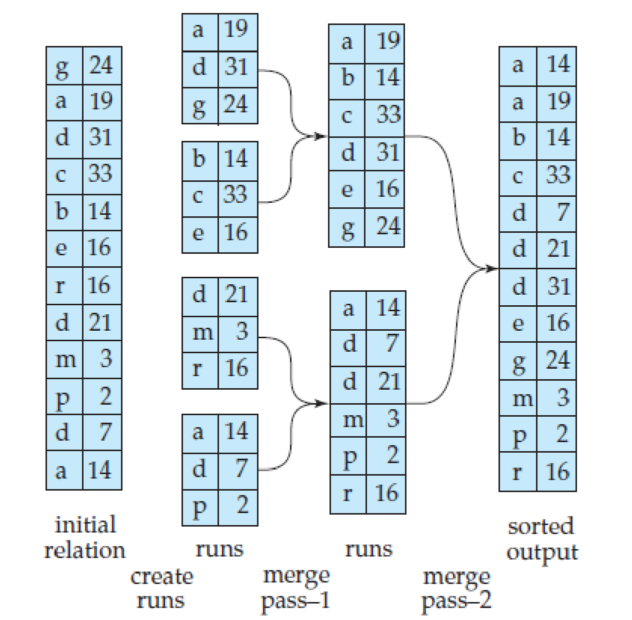
Sorting is one of the common physical task done while answering this query; sorting typically required in

- In executing ORDER BY
- In duplicate removal
- In Sort-Merge technique for JOIN
- In performing various set operations like UNION, INTERSECTION

[2] Database System Concepts, 6th ed; Silberschatz, Korth and Sudarshan

External sorting is common techniques for sorting large files. It uses sort-merge strategy. In this case sorting is done in chunks (typically of size available main memory for the sort); then sorted chunks are merged in one, and final sorted file is produced.

Diagram below from book[2] captures the intuition of sort-merge algorithm -



Sort-Phase

```
i = 0;
repeat
    read M blocks of the relation, or the rest of the relation,
        whichever is smaller;
    sort the in-memory part of the relation;
    write the sorted data to run file R_i;
    i = i + 1;
until the end of the relation
```

Merge-Phase

```
read one block of each of the N files R_i into a buffer block in memory;
repeat
    choose the first tuple (in sort order) among all buffer blocks;
    write the tuple to the output, and delete it from the buffer block;
    if the buffer block of any run R_i is empty and not end-of-file(R_i)
        then read the next block of R_i into the buffer block;
until all input buffer blocks are empty
```

<u>Algorithms for SELECTION operation</u>:

Simple Selections

(S1) <u>Linear Search</u>: brute force search on data file; often referred as *table scan*.

Cost Estimate: *B/2* for key attributes; B for non-key attributes

(S2) <u>Binary Search</u> on data file: requires file to be ordered.

Cost Estimate: For key attribute: $log_2(B)$; and
for non-key attribute: $log_2(B) + \lceil S/BF \rceil - 1$

(S3a) Using a primary (B+-tree) index (Key)

For example: answering query $\sigma_{ssn=12345}(EMP)$; and relation having primary index on SSN.

Cost Estimate: *H+1*;

(S4) Using primary (B+-tree) index for range search

For example answering of queries like $\sigma_{ssn < 56756}(EMP)$

Approach: for query like above, reach to the leaf node that matches with ssn=56756, and then collect all preceding records.

Cost Estimate: $H + B/2$; H_i to reach to first/last leaf node meeting the condition. This is very rough assuming that half the records (B/2 blocks) will meet the selection criteria.

(S5) Using a clustering (B+-tree) index to retrieve multiple records

For example answering of queries like $\sigma_{dno=5}(EMP)$

Cost Estimate: $H + \lceil S/BF \rceil$

(S6) Using a secondary (B+-tree) index;

Cost for key attribute based index and search: $H + 1$

Cost for non-key attribute based index and search: since index is not clustered, separate block is read for each matched value; selectivity is used here,
cost estimate: $H + S$

For range search: let us say (again it is very rough estimate), let say half of the first level nodes are scanned, and half the file records by the index are accessed;
cost estimate: $H + B_{i1}/2 + N/2$

Selections with conjunctive conditions

(S7) Conjunctive selection using an individual index:

If any of the attribute has an index; use any of the approach S2 to S6 (whichever is applicable); and do sequential search n accessed record on other attribute.

For example dno=5 and salary > 50000; we can perform index search on dno while linear for salary on selected records for dno=5

(S8) Conjunctive selection using a composite index

If we have composite index on both; then can directly use it as any of approach S2 to S6, whichever is applicable

Other example, we may have index on ssn, pno in works_on relation

(S9) Conjunctive selection by intersection of record pointers

if we have individual indexes on multiple attributes; first, we have individual records selected using respective indexes; and then compute intersection. Restriction on remaining attributes can be done by sequential scan in result of intersection.

> While performing conjunctive selections; access path on attribute with low selectivity is desirable to be executed first

Selections with disjunctive conditions

Selections based on disjunctive conditions are hard to execute; if any of the participating attribute does not have access path; then we are forced to have "table scan".

There is hardly any optimization can be done in such cases.

If access paths for all attributes are there, then individual index based selections can be union-ed.

Having these many options available for performing selection; DBMS does some cost analysis and choose most efficient approach for evaluating the query.

Many things play role- record size, index availability, index size, number of records, selectivity, available memory, etc.

Cost formulas are defined for implemented algorithms, and used by query optimizer

Join Algorithms

Join examples used here

OJ1: $R \underset{\boxed{R.A = S.B}}{\bowtie} S$

OJ2: $EMP \underset{\boxed{E.DNO = D.DNO}}{\bowtie} DEP$

OJ3: $EMP \underset{\boxed{ssn = mgrssn}}{\bowtie} DEP$

Join Selectivity:

Join Selectivity (js) is defined as the ratio of number of tuples in join result with the number rows in corresponding cross product: |R JOIN S| / |R CROSS S| = |R JOIN S| / (|R| * |S|)

Its value can be anything from 0 to 1; js=1 if no join condition; it is zero if there no match at all. If A is key in R, then every tuple in S can atmost be joined with one tuple in R; consider more specific situation, S.B is FK referring into R.A; then size of JOIN will be <= |S|; and

js will be <= (|S|)/(|R|*|S|) , will <= 1/|R|; if attribute S.B has NOT NULL constraint; then size of JOIN result will be |S|, and js = 1/|R|.

Join selectivity helps in estimating size of join resultant relation.

(J1) Nested block join

This is brute-force and default technique for join.

It goes as following one for every block in a relation R, scan every block in other relation S; cases in which join condition is met, joined tuple is computed and added to the result.

Cost Estimate: $B_R + B_R \times B_S \ + \ (js \times |R| \times |S| / BF_{RS})$

Last part of cost is for writing result file.

If available memory is also accounted for, Let us say available memory is M blocks, cost of nested block comes as following-

Cost Estimate: $B_R + \lceil B_R/(M-2) \rceil \times B_S + (\, js \times |R| \times |S|/BF_{RS})$

Important question, which relation should be used in outer loop?

Normally the relation that has lesser tuples, resulting lesser cost; sample calculation follows.

(J2) Single loop Join

When we have index on one relation in join (on attribute of that relation in join condition) ; for example we having index on SSN in join operation OJ3 above.

We need to have one scan on relation without index, and have index lookup for find matched tuple from other relation. In example OJ3, we can have sequential scan on DEP and index look on EMP (ssn)

Following are cost estimates for different types of indexes; suppose R is scanned and index lookup is done in S

Secondary index: $B_R + (|R| \times (H_{BS} + S_{BS})) + (\, js \times |R| \times |S|/BF_{RS})$

Clustered index (non-key): $B_R + (|R| \times (H_{BS} + S_{BS}/BF_S)) + (\, js \times |R| \times |S|/BF_{RS})$

Primary index (key attribute index): $B_R + (|R| \times (H_{BS} + 1)) + (\, js \times |R| \times |S|/BF_{RS})$

Note: Notation H_{BS} represents height of b+-index on attribute B in relation S, and S_{BS} denotes Selectivity of attribute B in relation S. BF_{RS} represents Blocking Factor of joined relation RS.

Hashing: $B_R + (|R| \times hf) + (\, js \times |R| \times |S|/BF_{RS})$

Here *hf* is number of block accesses to retrieve a record, given its hash key value. hf = 1 for static hashing and 2 for dynamic hashing

(J3) Sort-Merge Join

If records of R and S are already sorted on A and B respectively, this could turn out to be efficient

Simultaneous scan of both files and generated combined tuples for matches yields join results

Cost Estimate (assuming that records of both relations are already sorted):
$B_R + B_S \; + \; (\, js \times |R| \times |S|/BF_{RS})$

(J3) Partition Hash

- Same hash function is used for both the attributes A in R and B in S.
- Done in two steps-

- First, a single pass through the file with fewer records (say, R) and hashes its records to the various partitions of R; this is called the *partitioning phase*. Partitioning phase because, the records of R are partitioned into the hash buckets.
- Next is *probing phase*, in this, let us say few or all buckets of hash table of R (HR) is in the primary memory, scan buckets one by one from HR. For each record in a bucket, we search (probed) into S sing the same hash function. And if found in S, produce the joined tuple.

Below is an worked example for cost in Join, we can roughly infer following from the sample calculations –

(1) It is better to a smaller relation in outer loop – in both cases
(2) If sufficient memory is available, a nested join may turn out to be better than single loop join.

<u>A worked example for cost for JOIN</u>

OJ2 : $EMP \bowtie_{E.DNO=D.DNO} DEP$

$N_E = 10000$ $\quad N_D = 125$

$B_E = 2000$ $\quad B_D = 13$

$H_{SSN} = 4.$ $\quad H_{MGRSSN} = 2$

$H_{DNO} = 2.$ $\quad H_{DNO} = 1$

$JS = \frac{10000.}{125 \times 10000}$ 1/125 $\quad BF_{ED} = 4$ records/block

J1

EMP in outer loop

(1) $C_{J1} = B_E + (B_E \times B_D) + (JS * N_E * N_D)/BF_{ED}$

$= 2000 + 2000 \times 13 + \left(\frac{1}{125} \times \frac{10000 * 125}{4}\right) = 30,500$

2500

(2) DEP in outer loop

$= 13 + (13 \times 2000) + \frac{1}{125} \times \frac{10000 \times 125}{4} = 28,513$

J2

(3) EMP in outer loop $\quad \swarrow$ primary index

$CJ2 = B_E + (N_E * (\overset{1}{H_{DNO}} + 1)) + 2500 =$

$= 2000 + 10000 \times 2 + 2500 = 24500$

(4) DEP is outer loop (

~~13 + (125~~

clustered index

$$B_D + \left(N_D * \left(H_{\substack{DNO\\EMP}} + \text{Selectivity of DNO in E}\right)\right) + 2500$$

$$= 13 + \left(125 * \left(2 + \underbrace{\frac{10000}{125}}_{80}\right)\right) + 2500$$

$$= \boxed{12763}$$

w/ Memory, M blocks - 10 blocks

2a) 1) Cost J1 for DEP is outer loop

$$= B_D + \left\lceil \frac{B_D}{M-2} \right\rceil * B_E + 2500$$

$$= 13 + 2 * 2000 + 2500 = 6513$$

Algorithms for PROJECT

PROJECT is straight forward as subset of attributes needs to be selected.

However project might produce duplicate tuples; therefore duplicate removal might be needed. You should not that duplicate removal is not needed in SQL unless it has been asked for (DISTINCT keyword).

Duplication removal can be done by sorting or hashing.

Algorithms for SET operations

Set operations—UNION, INTERSECTION, SET DIFFERENCE, and CARTESIAN PRODUCT are often expensive; particularly cross product.

For set operations Sort-Merge is effective technique.

Hashing is again effective technique.

Heuristics for query optimizations

Parser produces initial parse tree without any optimization.

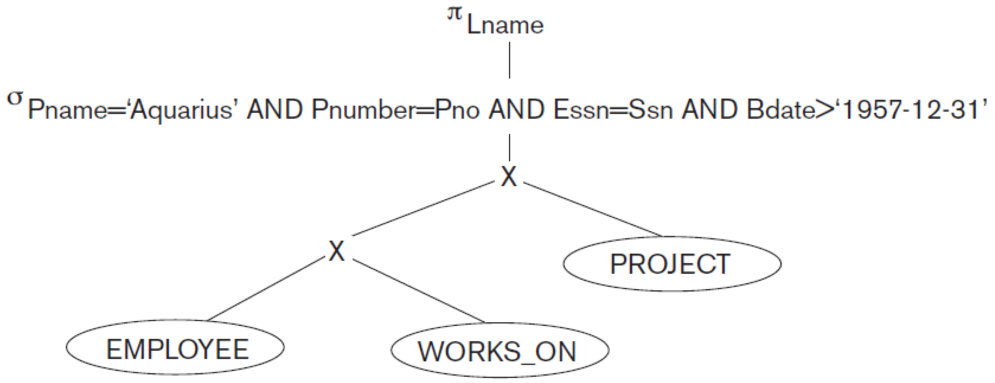
Let us say SQL Query for

> Find the last names of employees born after 1957 who work on a project named 'Aquarius'

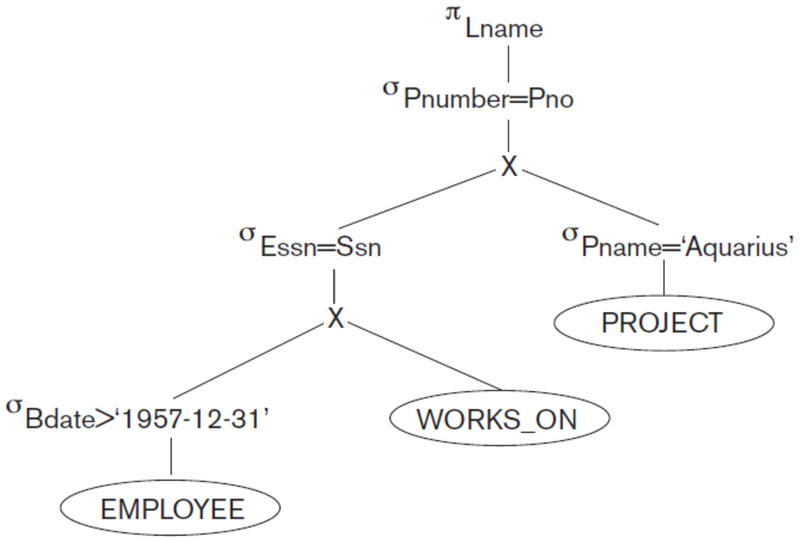
Say expressed SQL as

SELECT lname from employee, works_on, project
WHERE pname='aquarius' and pnumber=pno and essn=ssn and
bdate > '1957-12-31';

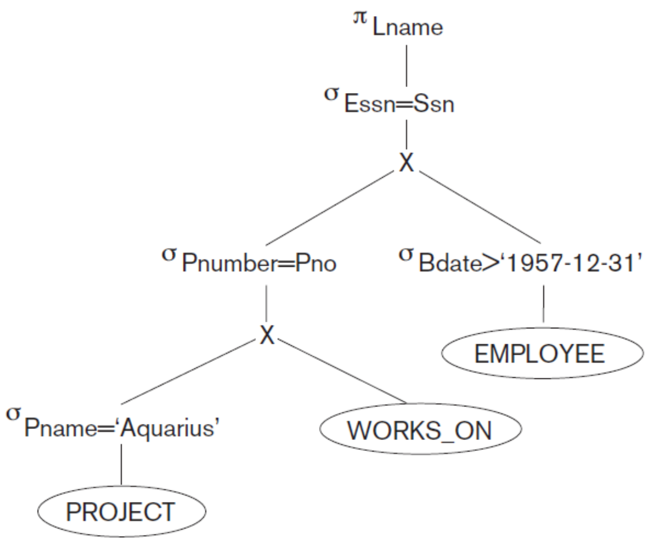
(a) Initial query tree for SQL query above: without any optimization, just translation



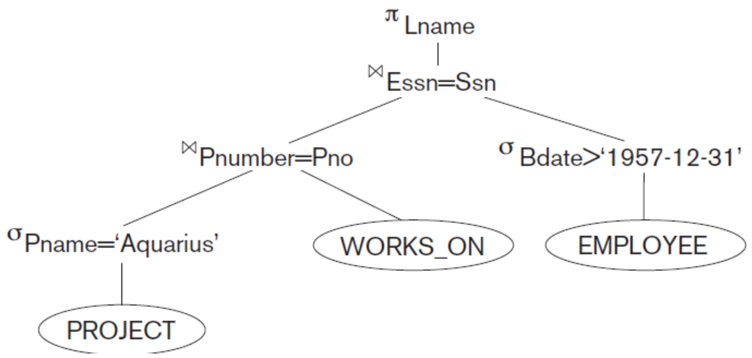
(b) Below is tree after moving SELECT operations down the query tree



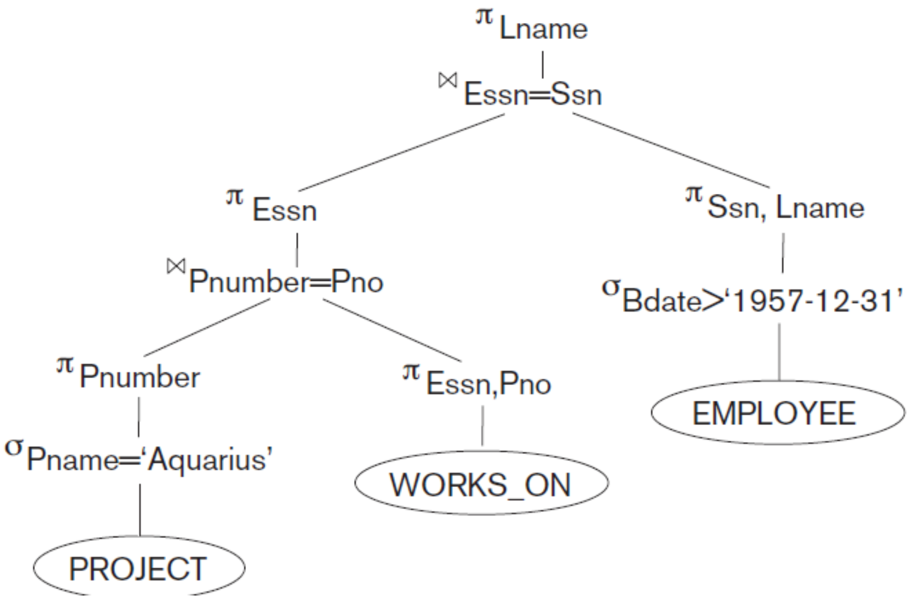
(c) Below is tree after applying the more restrictive SELECT operation first.



(d) Below is tree after replacing CARTESIAN PRODUCT and SELECT with JOIN operations.



(e) Below is tree after moving PROJECT operations down the query tree, and is final optimized tree at logical level.



General Transformation Rules for Relational Algebra Operations.

Below is representative list of rules drawn from book elmasri/navathe-

1. Cascading of σ

   $\sigma_{c_1 \text{ AND } c_2 \text{ AND} \ldots \text{AND } c_n}(R) \equiv \sigma_{c_1}(\sigma_{c_2}(\ldots(\sigma_{c_n}(R))\ldots))$

2. Commutativity of σ

   $\sigma_{c_1}(\sigma_{c_2}(R)) \equiv \sigma_{c_2}(\sigma_{c_1}(R))$

3. Cascade of π

   $\pi_{\text{List}_1}(\pi_{\text{List}_2}(\ldots(\pi_{\text{List}_n}(R))\ldots)) \equiv \pi_{\text{List}_1}(R)$

4. Commuting σ with π

   $\pi_{A_1, A_2, \ldots, A_n}(\sigma_c(R)) \equiv \sigma_c(\pi_{A_1, A_2, \ldots, A_n}(R))$

5. Commutativity of $\bowtie$ (and $\times$)
   $R \bowtie_c S \equiv S \bowtie_c R$
   $R \times S \equiv S \times R$
6. Commuting σ with $\bowtie$ (and $\times$)
   $\sigma_c (R \bowtie S) \equiv (\sigma_c (R)) \bowtie S$
   Alternative if condition c can be split into c1 and c2 drawing attributes from R and S only, can be expressed as
   $\sigma_c (R \bowtie S) \equiv (\sigma_{c_1} (R)) \bowtie (\sigma_{c_2} (S))$
7. Commuting π with $\bowtie$ (and $\times$)
   If set of attributes L = {a1,a2, an} from R and {b1,b2,..bm} from S, and attributes in condition c is from L, then can be expressed as
   $\pi_L (R \bowtie_c S) \equiv (\pi_{A_1, \ldots, A_n} (R)) \bowtie_c (\pi_{B_1, \ldots, B_m} (S))$
   If attributes in c not there in L, then can be added to respective side, and can be rewritten
8. <u>Commutativity of set operations</u>. The set operations ∪ and ∩ are commutative but − is not.
9. Associativity of $\bowtie$, ×, ∪, and ∩. If θ stands for any of these, can be expressed as
   $(R \,\theta\, S) \,\theta\, T \equiv R \,\theta\, (S \,\theta\, T)$
10. Commuting σ with set operations. If θ stands for any one from ∪, ∩, and −, can be expressed as -
    $\sigma_c (R \,\theta\, S) \equiv (\sigma_c (R)) \,\theta\, (\sigma_c (S))$
11. Converting a (σ, ×) sequence into $\bowtie$
    $(\sigma_c (R \times S)) \equiv (R \bowtie_c S)$
12. The π operation commutes with ∪
    $\pi_L (R \cup S) \equiv (\pi_L (R)) \cup (\pi_L (S))$

<u>Outline of a Heuristic Algebraic Optimization Algorithm</u>

1. SELECT operations with conjunctive conditions into a cascade of SELECT operations. This permits a greater degree of freedom in moving SELECT operations down in different branches of the tree
2. Move each SELECT operation as far as down the query tree as is permitted by the attributes involved in the select condition.
3. If a condition involves attributes from multiple relation then it is likely to be a join condition
4. Move more restrictive selects down so that intermediate results are smaller; we can say most restrictive condition is the one that has less *selectivity*
5. Replace Cartesian products with JOIN

The main intuition of query optimization is order the operations such that they minimize the size intermediate results – preform selection and projection as early as possible.

EXPLAIN command of SQL

- You can get a fair idea how query planner work by observing various execution plans by using EXPLAIN command in Postgres

  EXPLAIN SELECT fname, dname, salary FROM employee NATURAL JOIN department WHERE salary > 50000;

  Below are some screen shot for few queries – try interpreting the output

```
pmjat=> explain select * from employee natural join department;
                                QUERY PLAN
----------------------------------------------------------------------
 Hash Join  (cost=1.04..2.24 rows=8 width=131)
   Hash Cond: ("outer".dno = "inner".dno)
   ->  Seq Scan on employee  (cost=0.00..1.08 rows=8 width=99)
   ->  Hash  (cost=1.03..1.03 rows=3 width=34)
         ->  Seq Scan on department  (cost=0.00..1.03 rows=3 width=34)
(5 rows)
```

```
pmjat=> explain select * from employee e, department d where e.dno = d.dno;
                                QUERY PLAN
----------------------------------------------------------------------
 Hash Join  (cost=1.04..2.24 rows=8 width=133)
   Hash Cond: ("outer".dno = "inner".dno)
   ->  Seq Scan on employee e  (cost=0.00..1.08 rows=8 width=99)
   ->  Hash  (cost=1.03..1.03 rows=3 width=34)
         ->  Seq Scan on department d  (cost=0.00..1.03 rows=3 width=34)
(5 rows)
```

A blog https://use-the-index-luke.com/sql/explain-plan/postgresql/operations provides a basic introduction to postgresql "explain" operations.

```
pmjat=> explain select * from employee e, department d where e.ssn = d.mgrssn;
                                QUERY PLAN
------------------------------------------------------------------------
 Merge Join  (cost=2.25..2.33 rows=3 width=133)
   Merge Cond: ("outer".ssn = "inner".mgrssn)
   ->  Sort  (cost=1.20..1.22 rows=8 width=99)
         Sort Key: e.ssn
         ->  Seq Scan on employee e  (cost=0.00..1.08 rows=8 width=99)
   ->  Sort  (cost=1.05..1.06 rows=3 width=34)
         Sort Key: d.mgrssn
         ->  Seq Scan on department d  (cost=0.00..1.03 rows=3 width=34)
(8 rows)
```

```
pmjat=> explain select ssn, fname, salary, pno,hours from employee e, works_on w
 where e.ssn = w.essn;
                               QUERY PLAN
-----------------------------------------------------------------------
 Merge Join  (cost=2.72..3.01 rows=17 width=46)
   Merge Cond: ("outer".ssn = "inner".essn)
   ->  Sort  (cost=1.20..1.22 rows=8 width=34)
         Sort Key: e.ssn
         ->  Seq Scan on employee e  (cost=0.00..1.08 rows=8 width=34)
   ->  Sort  (cost=1.52..1.56 rows=17 width=26)
         Sort Key: w.essn
         ->  Seq Scan on works_on w  (cost=0.00..1.17 rows=17 width=26)
(8 rows)
```

```
pmjat=> explain select ssn, fname, salary, pno,hours from employee e, (select *
from works_on) as w where e.ssn = w.essn;
                              QUERY PLAN
----------------------------------------------------------------------
 Merge Join  (cost=2.72..3.01 rows=17 width=46)
   Merge Cond: ("outer".ssn = "inner".essn)
   ->  Sort  (cost=1.20..1.22 rows=8 width=34)
         Sort Key: e.ssn
         ->  Seq Scan on employee e  (cost=0.00..1.08 rows=8 width=34)
   ->  Sort  (cost=1.52..1.56 rows=17 width=26)
         Sort Key: works_on.essn
         ->  Seq Scan on works_on  (cost=0.00..1.17 rows=17 width=26)
(8 rows)
```