# Query Processing

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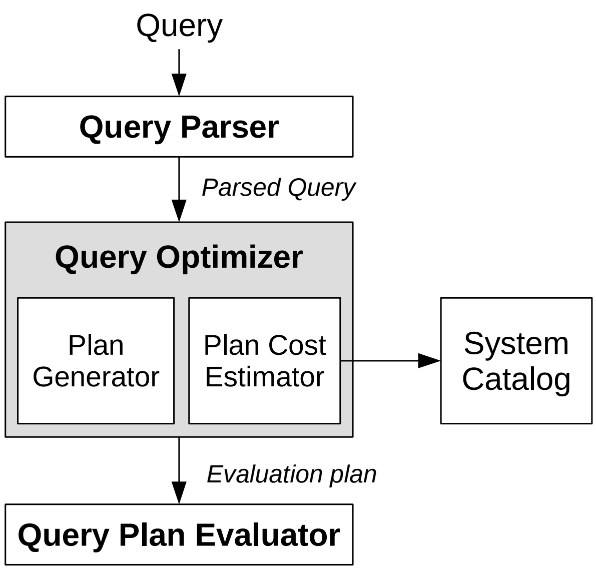
Fall 2018

Declarative queries (SQL, relational calculus) must be translated into a procedural language (relational algebra) to be executed

- Several ways (**evaluation plans**) to obtain the same answers
- Several algorithms available for each operator
- How do we find a **good** procedural query to execute?



## The system catalog (1)

Contains metadata and statistics about the database
which are used to find the best way to evaluate a query

System-wide information, such as the page size

For each table

- table name, file name and file structure
- attribute names and types
- name of indexes on the table
- integrity constraints

For each index

- index name and structure (B-tree or hash)
- attributes of the search key

## The system catalog (2)

Commonly stored statistics about tables and indexes

| | | |
|---|---|---|
| Cardinality | : | number of tuples in each table |
| Size | : | number of pages for each table |
| Index cardinality | : | number of **distinct search key values** of each index |
| Index size | : | number of pages for each index |
| Index height | : | number of non-leaf levels of each tree index |
| Index range | : | min & max values of search key in each index |

# Access paths

Access path: a way in which the rows of a table can be retrieved

- A file scan
- An index plus a **matching** selection condition

For a condition $\theta$ in CNF

- A hash index matches $\theta$ if there is a conjunct $A = \textit{value}$ for each attribute $A$ in the search key of the index
- A tree index matches $\theta$ if there is a conjunct $A$ **op** *value* for each attribute $A$ in a **prefix** of the search key of the index

where **op** $\in \{<, \leq, =, \neq, \geq, >\}$

# Examples of access paths (1)

Suppose we have a relation $R$ over attributes $A, B, C, D$ and the following selection conditions:

$\theta_1 \ : \ A = 1 \wedge B = 2 \wedge C = 0$

$\theta_2 \ : \ A = 1 \wedge B < 2 \wedge C = 0$

$\theta_3 \ : \ A = 1 \wedge C = 0$

A hash index for $R$ on the search key $(A, B, C)$

- Matches $\theta_1$, but does **not** match $\theta_2$ and $\theta_3$

A tree index for $R$ on the search key $(A, B, C)$

- Matches $\theta_1$ and $\theta_2$, but not $\theta_3$

## Examples of access paths (2)

Suppose we have a relation $R$ over attributes $A, B, C, D$

Consider the condition $A = 1 \wedge B = 2 \wedge C = 0$

An index (hash or tree) on the search key $(B, C)$

- can be used to retrieve tuples matching $B = 2 \wedge C = 0$
- retrieved tuples must be additionally filtered by $A = 1$

Consider the condition $B = 2 \wedge C = 0 \wedge D > 3$

If we have an index on $(B, C)$ and a tree index on $D$

- both indexes match (different parts of) the condition
- we can choose one of the indexes to retrieve tuples
- the conjuncts that are not matched must be checked

## Selectivity of access paths

Total number of pages retrieved when an access path is used

**Most selective** access path: retrieves the fewest pages

Selectivity depends on the conjuncts an index matches

- each conjunct acts as a filter on the table
- Reduction factor:
  the fraction of tuples satisfying a given conjunct
- can be estimated using information in the system catalog

# Evaluation of selection

Given a selection $\sigma_\theta(R)$

- If no index on $R$ matches $\theta$ we have to **scan** $R$
- If one or more indexes on $R$ match $\theta$
  1. use the **most selective** index to retrieve matching rows
  2. apply remaining conjuncts in $\theta$ to the retrieved rows

# Evaluation of projection

Scan table or index (with an appropriate search key)
and output required subset of fields for each tuple

## Duplicate elimination

Sort the table first, then do one pass to eliminate duplicates

## Projection with duplicate elimination

1. Scan $R$ and produce tuples with desired attributes
2. Sort the tuples using all attributes as sorting key
3. Scan the sorted result to discard duplicates

If $R$ has $M$ pages, this costs $O(M \log M)$ I/Os

Improvement:

- Scan in (1) can be combined with first pass of sorting
- Scan in (3) can be combined with last pass of sorting

# Join processing

Join is the most common and **expensive** operation

Several available join algorithms

- Nested Loops Join
- Block Nested Loops Join
- Index Nested Loop Join
- Sort-Merge Join
- Hash Join

# Nested Loops Join

Simplest algorithm to compute $R \bowtie_\theta S$

**for each** page $P_R$ of $R$ **do**<br>
    **for each** page $P_S$ of S **do**<br>
        **for each** tuple $r \in P_R$ **do**<br>
            **for each tuple** $s \in P_S$ **do**<br>
                **if** $rs$ satisfies $\theta$ **then**<br>
                    add $rs$ to result

$R$ is the outer relation (scanned once)<br>
$S$ is the inner relation (scanned multiple times)

If $R$ has $M$ pages and $S$ has $N$ pages, the cost is $M + M \cdot N$ I/Os<br>
If $R$ has $m$ tuples and $S$ has $n$ tuples, the CPU cost is $O(m \cdot n)$

## Block Nested Loops Join

If we have $B$ buffer pages available we can:

- read $R$ in blocks of $B-2$ pages
- use one buffer page for reading the pages of $S$
- use one buffer page for output

1. **for each** block $B_R$ of $B-2$ pages of $R$ **do**
2. **for each** page $P_S$ of S **do**
3. **for each** tuple $r \in B_R$ **do**
4. **for each tuple** $s \in P_S$ **do**
5. **if** $rs$ satisfies $\theta$ **then**
6. add $rs$ to result

If $R$ has $M$ pages and $S$ has $N$ pages, cost is $M + \left\lceil \frac{M}{B-2} \right\rceil \cdot N$ I/Os

## Index Nested Loops Join

If there is an index matching the join condition, make the indexed relation be the inner one

1. **for each** $P_R$ of $R$ **do**
2. **for each matching** page $P_S$ of S **do**
3. **for each** tuple $r \in P_R$ **do**
4. **for each tuple** $s \in P_S$ **do**
5. **if** $rs$ satisfies condition **then**
6. add $rs$ to result

Cost depends on the index and the number of matching tuples
Better than simple nested loops: it does not enumerate $R \times S$

# Sort-merge join (1)

Consider $R \bowtie_\theta S$ where $\theta$ is $R.A_1 = S.B_1 \wedge \cdots \wedge R.A_n = S.B_n$

1. Sort $R$ on $X = A_1, \ldots, A_n$ and $S$ on $Y = B_1, \ldots, B_n$
2. Set $r :=$ first tuple of $R$ and $s :=$ first tuple of $S$
3. **while** $r \neq$ EOF **and** $s \neq$ EOF **do**
4.     **while** $r[X] < s[Y]$ **do** $\{ r :=$ next$(R) \}$
5.     **while** $r[X] > s[Y]$ **do** $\{ s :=$ next$(S) \}$
6.     Set $p := s$
7.     **while** $r[X] = s[Y]$ **do**
8.         $p := s$
9.         **while** $r[X] = p[Y]$ **do**
10.             Add $rp$ to result
11.             $p :=$ next$(S)$
12.         $r :=$ next$(R)$
13.     Set $s := p$

# Sort-merge join (2)

Works only for equijoins (the condition is a conjunction of equalities)

## Cost

- Sorting $R$ costs $O(M \log M)$ if $R$ has $M$ pages
- Sorting $S$ costs $O(N \log N)$ if $S$ has $N$ pages
- **Merging phase** costs $M + N$ I/Os
  if no partition of $S$ is scanned multiple times
  otherwise $O(M \cdot N)$ in the worst case

Typically the merging phase is just a single scan of each relation

- if at least one relation has **no duplicates** in the join attributes
- this is the case for key-foreign key joins (very common)

# Hash join (1)

Consider $R \bowtie_\theta S$ where $\theta$ is $R.A_1 = S.B_1 \wedge \cdots \wedge R.A_n = S.B_n$

Partitioning phase: split $R$ and $S$ into partitions
using a hash function on the values of $\underbrace{A_1, \ldots, A_n}_{X}$ and $\underbrace{B_1, \ldots, B_n}_{Y}$

1. Choose number of buckets $k$ and appropriate hash function $h$
2. $\boxed{\begin{array}{l} \textbf{for each } r \in R \textbf{ do} \\ \quad i := h(r[X]) \\ \quad H_i^R := H_i^R \cup \{r\} \end{array}}$ $\boxed{\begin{array}{l} \textbf{for each } s \in S \textbf{ do} \\ \quad i := h(s[Y]) \\ \quad H_i^S := H_i^S \cup \{s\} \end{array}}$

Probing phase: compare tuples in each partition of $R$
**only** with tuples in the **corresponding** partition of $S$

**for** $i = 1, \ldots, k$ **do**
  read $H_i^R$ ; read $H_i^S$
  add $H_i^R \bowtie_\theta H_i^S$ to result

# Hash join (2)

Works only for equijoins (the condition is a conjunction of equalities)

## Cost

- Partioning phase: scan $R$ and $S$ once and write them out once
  Cost is $2(M + N)$ I/Os if $R$ has $M$ pages and $S$ has $N$ pages
- Probing phase: scan each partition once ($M + N$ I/Os)
  if there are no **overflows**

  Total cost is $3(M + N)$

If there are overflows, recursive partitioning is used
The cost becomes $O\big((M + N)\log(M + N)\big)$

# Other operations

## Set operations

- Expensive aspect is given by duplicate elimination
- Same technique as for projection (using sorting)

## Group by

- Typically implemented through sorting
- If there is a **tree index** matching the grouping attributes tuples can be retrieved in appropriate order without sorting

## Aggregation

- Carried out using temporary counters in main memory

# Query optimization

Query plan: relational algebra tree extended with annotations

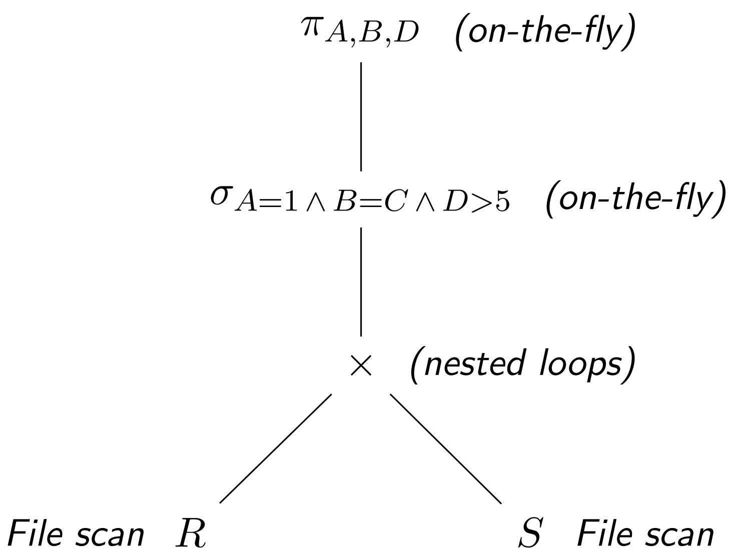
- which **access path** to use for each table
- which **implementation method** to use for each operator

Optimization involves the following steps:

1. Enumerating alternative plans to evaluate the query
2. Estimating the cost of each enumerated plan
3. Choosing the plan with the lowest estimated cost

A possible query plan for

```
SELECT A,B,D FROM R,S WHERE A=1 AND B=C AND D>5
```




## Pipelined evaluation

Pipelining: the result of an operator is passed directly to the next

Materialization: intermediate result is written to a temporary table

A unary operator is applied **on-the-fly** if its input is pipelined

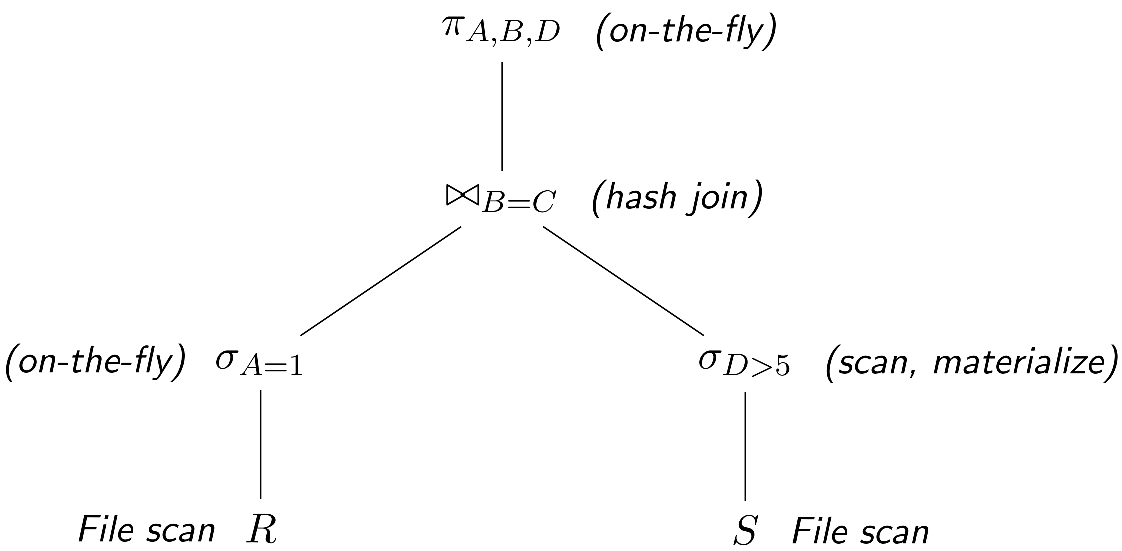
### Iterator interface

- Hides the internal implementation details of each operator
- Supports functions:

| | |
|---|---|
| **open** | initialize, allocate buffers, pass arguments in |
| **get_next** | retrieve and process tuples from input nodes |
| **close** | deallocate buffers and state information |

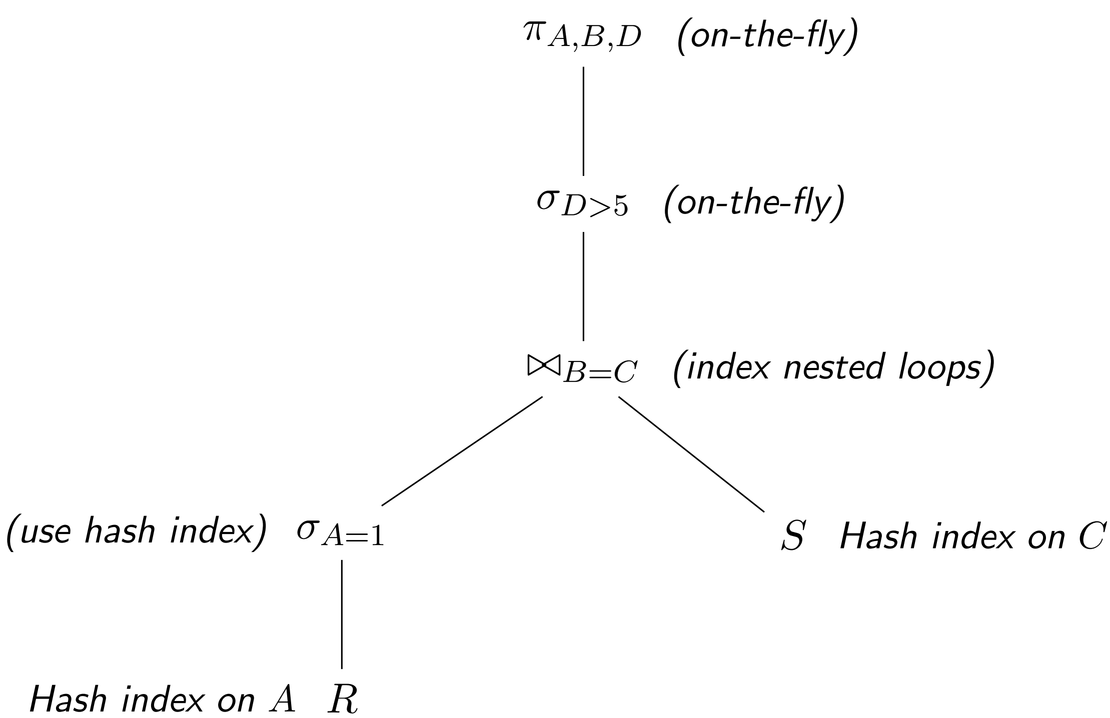
## Alternative plans

- Selections and cross-products can be combined into joins
- Joins can be extensively reordered
- Selections and projections can be pushed ahead of joins




## Using indexes

If there are indexes, other plans may be available



# Join order

Join is associate and commutative
$\Longrightarrow$ many combinations of binary joins to get same result

Linear trees: at least one child of each join node is a base table

Left-deep trees: the **right** child of each join node is a base table

Bushy trees: non-linear trees

Advantages of left-deep trees:

- if too many alternatives we need to **prune** the search space
- allow us to generate **fully pipelined** plans

# Estimating plan cost

I/O cost given by:

1. Reading the input tables (possibly more than once)
2. Materializing intermediate results (if needed)
3. Sorting final result (for duplicate elimination and ordering)

## Estimating result size

Selection: input size multiplied by reduction factor of condition

Join: max result size (= product of input tables sizes)
multiplied by reduction factor of the join condition

Reduction factors are estimated using statistics
periodically collected about (a **sample** of) the data

# Reduction factor

$RF(A = c) \simeq \frac{1}{m}$
where $m$ is the number of distinct values in $A$

$RF(A = B) \simeq \frac{1}{\max(m,n)}$
where $m$ and $n$ are the number of distinct values in $A$ and $B$

$RF(A > c) \simeq \max\big(0, \frac{H-c}{H-L}\big)$
where $H$ and $L$ are the highest and lowest values in $A$

$RF(\theta_1 \wedge \theta_2) \simeq RF(\theta_1) \cdot RF(\theta_2)$

$RF(\theta_1 \vee \theta_2) \simeq \min\big(1, RF(\theta_1) + RF(\theta_2) - RF(\theta_1) \cdot RF(\theta_2)\big)$

$RF(\neg\theta) \simeq 1 - RF(\theta)$