DB 2

14 – Query Optimization

Summer 2018

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1 ┆ One Query — Millions of Plans

Q: Given a SQL query *Q*, what is *the optimal* (*a reasonable*)[1] plan to evaluate it? — **A:** It depends:

- Can we **simplify** (flatten, unnest) *Q*?
- How can we **access the tables** referenced in *Q*?
- How do **CPU and (sequential, random) I/O cost** compare?
- What is the **selectivity of the predicates** used in *Q*?
- Which plan **operator implementations** are applicable?
- Can we **regroup/reorder the joins** in *Q*?

[1] Here: focus on reducing the overall query evaluation time. The optimum is, generally, not reached.

Excerpt of the TPC-H Benchmark (at Scale Factor *SF*)

o_orderkey	o_custkey	o_totalprice	o_clerk	…
o	*c*			

orders (≈ *SF* × 1.5×10^6 rows)

l_orderkey	l_linenumber	l_partkey	l_quantity	l_extendedprice	…
o					

lineitem (≈ *SF* × 6×10^6 rows)

c_custkey	c_name	c_acctbal	c_nationkey	…
c			*n*	

customer (≈ *SF* × 150000 rows)

n_nationkey	n_name	n_regionkey	…
n		*r*	

nation (25 rows)

r_regionkey	r_name	…
r		

region (5 rows)

Q_{14}: Three-Way Join Against a TPC-H Instance

Price and quantity of parts orderd by customer #001:

```
SELECT l.l_partkey, l.l_quantity, l.l_extendedprice
FROM   lineitem AS l JOIN orders AS o        -- } l ⋈ o
         ON (l.l_orderkey = o.o_orderkey)  -- }          } ⋈ c
       JOIN customer AS c                  --
         ON (o.o_custkey = c.c_custkey)    --
WHERE  c.c_name = 'Customer#001';
```

- Above SQL syntax suggests the **join order** (l ⋈ o) ⋈ c.
- Commutativity and associativity of ⋈ enable the RDBMS to **reorder** the joins—based on *estimated evaluation costs*.
  - … unless we insist on the syntactic order. 🙉

2 ⁞ Pre-Processing: Query Normalization

Transform the input SQL query such that it features SELECT-FROM-WHERE (SFW) blocks of the following shape:

```
  SELECT [DISTINCT] e, …, e
  FROM      𝔸, …, 𝔸                   -- 𝔸 ≡ base table or (query)
[ WHERE     p AND … AND p ]           -- p ≡ predicate in DNF
[ GROUP BY g, …, g                    -- ⎫ e, p, g, o ≡
 [ HAVING   p AND … AND p ] ]         -- ⎬   atomic expression or
[ ORDER BY o, …, o ]                  -- ⎭   scalar (subquery)
[ OFFSET    n ]                       -- ⎱ n, m ≡ integer literal
[ LIMIT     m ]                       -- ⎰
```

- Query clauses in [...] may be missing.

3 ┆ Pre-Processing: Query Unnesting

Nested SQL queries suggest a (naïve, inefficient) nested-loop-style evaluation strategy. Consider:

```
SELECT c.c_name                                      ❶
FROM   customer AS c,
  ⍋ ⎰ (SELECT n.n_nationkey, n.n_name
    ⎱  FROM   nation AS n) AS t
WHERE c.c_nationkey = t.n_nationkey
  AND strpos(c.c_address, t.n_name) > 0
```

```
SELECT o.o_orderkey                    ❷
FROM   orders AS o
WHERE  o.o_custkey IN
    ⎧ (SELECT c.c_custkey
  ⍋ ⎨  FROM   customer AS c
    ⎩  WHERE  c.c_name = '…')
```

- 💡 If possible, **unnest** ⍋ queries and “inline” into parent query ⇒ ⍋ can participate in join reordering.

Pre-Processing: Query Unnesting

Perform **query unnesting** on the level of

- the operator-based plan representation of the query,[2] or
- the internal AST representation of SQL. Re ❷:

```
SELECT e₁                                  SELECT DISTINCT e₁
FROM   q₁,…,qᵢ                             FROM   q₁,…,qᵢ,qᵢ₊₁,…,qₙ
WHERE  p₁                            ≜*    WHERE  p₁
  AND  e₂ IN (SELECT e₃                      AND  e₂ = e₃
              FROM   qᵢ₊₁,…,qₙ               AND  p₃
              WHERE  p₃)
```

* Precondition: e_1 is key in the left-hand side query

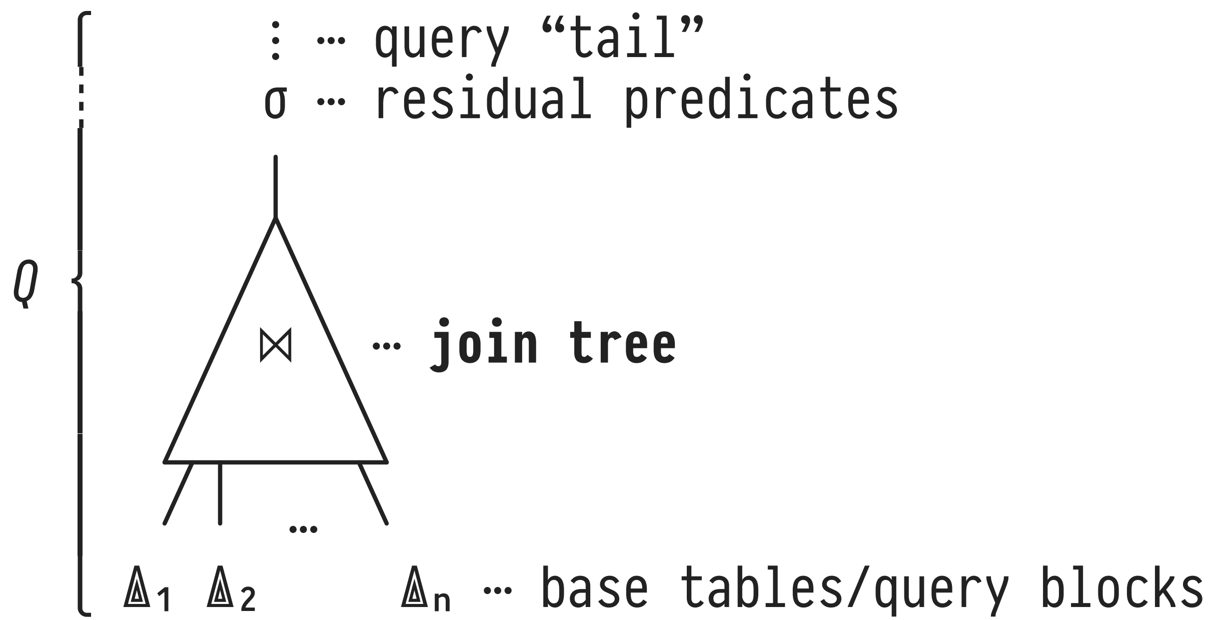
[2] See *Unnesting Arbitrary Queries*, Thomas Neumann, Alfons Kemper. BTW 2015, Hamburg, Germany.

Processing a SQL query Q starts out with its FROM and WHERE clauses which describe a **join tree** over Q's inputs:

SQL

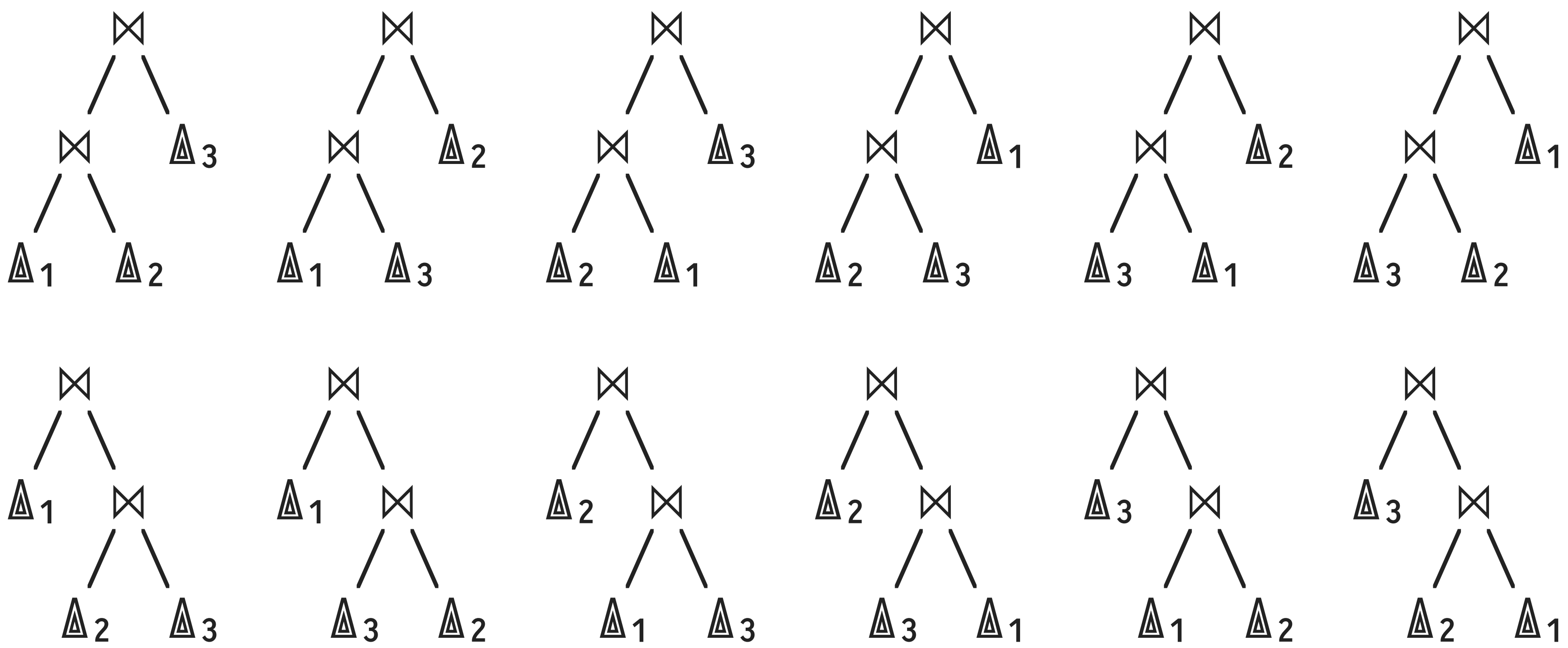
Q:
⋮
FROM $\mathbb{A}_1$, $\mathbb{A}_2$, …, $\mathbb{A}_n$
WHERE p
⋮

Canonical Plan



Join Tree Optimization

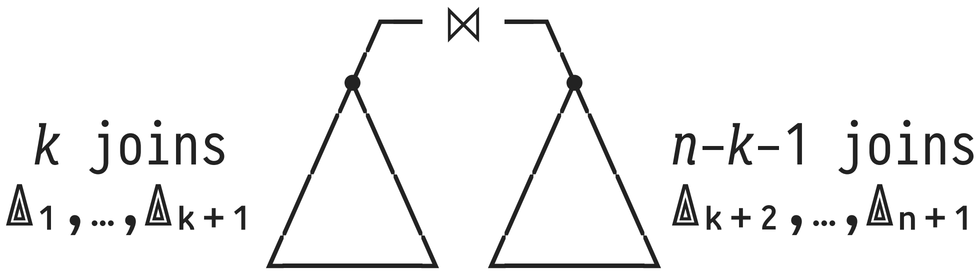
Given n join inputs, the number of possible **join tree shapes** is *huge*. Consider $n = 3$:



- Shapes based on associativity and commutativity of $\bowtie$.

How Many Possible Join Trees are There?

1. A join of $n{+}1$ inputs △ requires n binary joins. The root $\bowtie$ combines subtrees of k and $n{-}k{-}1$ joins ($0 \leqslant k \leqslant n{-}1$):[3]



\# of join tree shapes:

$$C_n = \sum_{k=0}^{n-1} C_k \times C_{n-k-1}$$

2. Orderings of the △ at the join tree leaf level: $(n{+}1)!$.
3. Join algorithm choices (a available algorithms): a^n.

[3] C_n are the *Catalan numbers*, the number of ordered binary trees with $n{+}1$ leaves. $C_0 = 1$.

How Many Possible Join Trees are There?

Number of possible join trees given n binary joins with $a = 3$ implementation choices:

# of ⟁ $(n+1)$	C_n	# of join trees
2	1	6
3	2	108
4	5	3240
5	14	136080
6	42	7384320
7	132	484989120
8	429	37829151360
9	1430	3404623622400
10	4862	347271609484800

- A search space of this size is impossible to fully explore for any query optimizer.

Join Plan Generation Through Dynamic Programming

- **Problem:** Find optimal query plan $opt[\{\mathbb{A}_1,\dots,\mathbb{A}_n\}]$ that joins n inputs $\mathbb{A}_1,\dots,\mathbb{A}_n$.

  1. **Iteration 1:** For each $\mathbb{A}_j$, find and memorize **best 1-input plan** $opt[\{\mathbb{A}_j\}]$ that accesses $\mathbb{A}_j$ only.

  2. **Iteration k > 1:** Find and memorize **best k-input plans** that join $k \leqslant n$ inputs by combining (for $1 \leqslant i < k$)
     - the best i-input plans and
     - the best $(k-i)$-input plans.

     simple lookups in $opt[\cdot]$ memo 👍

Bottom-Up Dynamic Programming (n = 3)

k Possible k-input Access/Join Plans   if $\mathbb{A}_i$ is complex

1 $opt[\{\mathbb{A}_1\}] \leftarrow prune(\{\text{Seq Scan } \mathbb{A}_1, \text{Index Scan } \mathbb{A}_1, \text{Bitmap Scan } \mathbb{A}_1, \mathbb{A}_1\})$
$opt[\{\mathbb{A}_2\}] \leftarrow prune(\{\text{Seq Scan } \mathbb{A}_2, \text{Index Scan } \mathbb{A}_2, \text{Bitmap Scan } \mathbb{A}_2, \mathbb{A}_2\})$
$opt[\{\mathbb{A}_3\}] \leftarrow prune(\{\text{Seq Scan } \mathbb{A}_3, \text{Index Scan } \mathbb{A}_3, \text{Bitmap Scan } \mathbb{A}_3, \mathbb{A}_3\})$

---

2 $opt[\{\mathbb{A}_1,\mathbb{A}_2\}] \leftarrow prune(opt[\{\mathbb{A}_1\}] \circledast opt[\{\mathbb{A}_2\}])$
$opt[\{\mathbb{A}_1,\mathbb{A}_3\}] \leftarrow prune(opt[\{\mathbb{A}_1\}] \circledast opt[\{\mathbb{A}_3\}])$
$opt[\{\mathbb{A}_2,\mathbb{A}_3\}] \leftarrow prune(opt[\{\mathbb{A}_2\}] \circledast opt[\{\mathbb{A}_3\}])$

---

3 $opt[\{\mathbb{A}_1,\mathbb{A}_2,\mathbb{A}_3\}] \leftarrow prune(opt[\{\mathbb{A}_1\}] \circledast opt[\{\mathbb{A}_2,\mathbb{A}_3\}] \cup$
$opt[\{\mathbb{A}_2\}] \circledast opt[\{\mathbb{A}_1,\mathbb{A}_3\}] \cup$
$opt[\{\mathbb{A}_3\}] \circledast opt[\{\mathbb{A}_1,\mathbb{A}_2\}]\ )$

$prune(P) \equiv$ best (= minimal cost + interestingly ordered) plans in set P
$l \circledast r \equiv \{l \bowtie^{\mathrm{nl}} r,\ r \bowtie^{\mathrm{nl}} l,\quad l \bowtie^{\mathrm{mj}} r,\ r \bowtie^{\mathrm{mj}} l,\quad l \bowtie^{\mathrm{hj}} r,\ r \bowtie^{\mathrm{hj}} l\}$

Join Plan Generation (Notes)

- **Access plan choices** (*access*(·)):
  - Consider sequential/index scans if $\mathbb{A}$ is a base table, otherwise simply consume $\mathbb{A}$'s rows.

- **Join plan choices** (_ ⊛ _):
  - Considers all viable join algorithms (given θ, available indexes, …) and left/right input orders.

- **Principle of Optimality** (*prune*(·)): A globally optimal plan is built from optimal subplans. Thus:
  - For each subset of $\{\mathbb{A}_1, \ldots, \mathbb{A}_n\}$, memorize in *opt*[·]
    1. … its overall best plan and
    2. … its best plan satisfying each **interesting order**.

(Bushy) Join Plan Generation: Pseudo Code

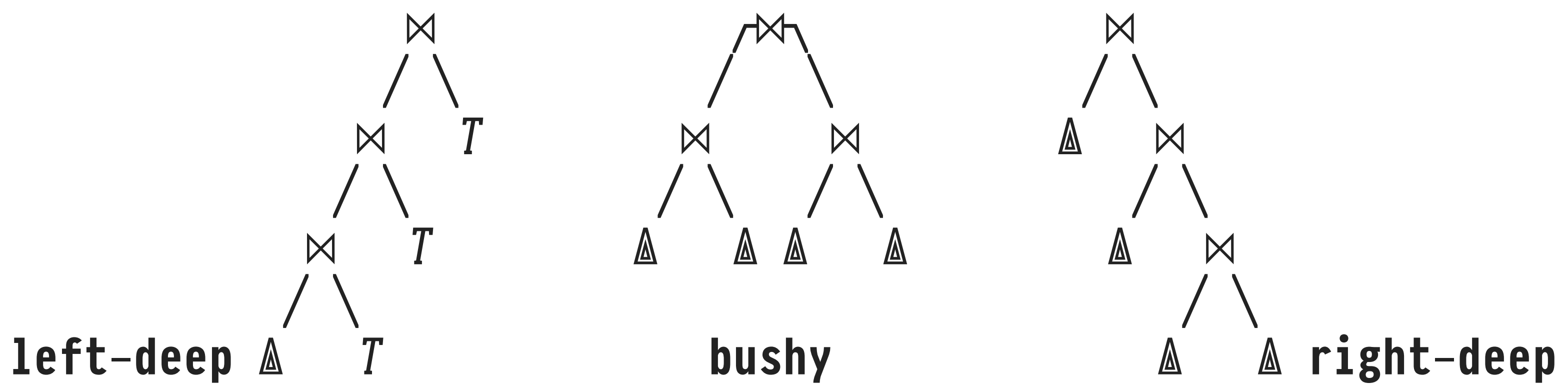
```
JoinPlan({𝔸₁,…,𝔸ₙ}):
 foreach p ∈ {𝔸₁,…,𝔸ₙ}                     } 1-input plans
  ⌊ opt[{p}] ← prune(access(p));

 for k in 2,…,n                             } k-input plans
  | foreach S ⊆ {𝔸₁,…,𝔸ₙ} with |S| = k } enumerate subsets
  |  | opt[S] ← ∅;
  |  | foreach T ⊂ S with T ≠ ∅     ⌜⋈ᵃ⌝
  |  |  ⌊ opt[S] ← opt[S] ∪ { opt[T]   opt[S \ T] };
  ⌊  ⌊  opt[S] ← prune(opt[S]);

return opt[{𝔸₁,…,𝔸ₙ}];
```

- *access*(·), *prune*(·) defined as above, ⌜⋈ᵃ⌝ builds all join algorithm choices (a ∈ {nl,mj,hj}).

Reducing the Search Space

- Avoid generating costly **Cartesian products:** don't form joins between inputs w/o join predicate ($\_ \; \theta \; \_ = \mathtt{true}$).

- Generate **left-deep** join plans only: right join input (NL⋈: inner input) is a scan over base table T.
    - Admits use of Index Nested Loop Join.
    - Straightforward Volcano-style execution (reset inner).



The query optimizer explores the vast plan search space to find the **optimal (“best”, “cheapest”) plan.**

- Typically, RDBMSs measure **plan cost** in terms of *total execution time* (time until last result row delivered).
- These total plan costs are **estimated** *before* plan execution begins (EXPLAIN: … cost=c_1..c_2← …).
- A **cost model**—measured in abstract “space$”—reflects the true costs (measured in *ms*, CPU time, # I/O ops, ...) of plans p_1, p_2:

$$\text{space\$}(p_1) < \text{space\$}(p_2) \Rightarrow \text{true cost}(p_1) < \text{true cost}(p_2)$$

PostgreSQL: Plan Cost

EXPLAIN shows estimated costs (unit: space\$) and cardinalities (# of rows):

```
                          QUERY PLAN
-----------------------------------------------------------------
            startup cost        total cost
                       ▼             ▼
Hash Join  (cost=299.00..15443.31 rows=505183 width=50)
  ⋮                                          ▲
                                        cardinality
```

- **run cost** $\stackrel{\text{def}}{=}$ **total cost** − **startup cost**[4] (not shown).
- Optimizer decisions are based on estimated **total cost**.

[4] To implement `set enable_<op> = off`, PostgreSQL sets the operator's **startup cost** to 10^9 ($\equiv \infty$).

Cost Model Configuration

Model Configuration	Default	Description
seq_page_cost	1.0	I/O cost of one sequential page access
random_page_cost	4.0	I/O cost of one random page access
cpu_tuple_cost	0.01	CPU cost to process a heap file row
cpu_index_tuple_cost	0.005	CPU cost to process an index leaf entry
cpu_operator_cost	0.0025	CPU function/operator evaluation cost
parallel_tuple_cost	0.1	Cost of passing one row worker→leader
parallel_setup_cost	1000.0	Shared memory setup cost

- Parameters are configurable:
  - Seek cost, thus random_page_cost » seq_page_cost. But…
  - … if DB fits in RAM, random_page_cost = seq_page_cost may be more appropriate.

Cost of Seq Scan ➊

Given an occurrence of Seq Scan with arguments

- *in*: input table,
- *pred*: (optional) filter predicate on *in*,
- *expr*: SELECT clause expression(s),

how does PostgreSQL derive *startup_cost* and *total_cost*?

```
                 in     QUERY PLAN    total_cost
---------------------------------------------------------------
Seq Scan on public.indexed i  (cost=0.00..22.75 rows=100 width=4)
  Output: (a + 1)        ◀ expr        ▲            ▲
  Filter: (i.a <= 100)   ◀ pred    startup_cost   #rows(out)
```

Cost of Seq Scan ②

Cost calculation depends on the following parameters, mostly available in PostgreSQL's internal pg_* meta data tables:

Parameter	Description	Available as…
#rows(*in*)	# rows (cardinality) of table *in*	pg_class.reltuples
#pages(*in*)	# pages in heap file of *in*	pg_class.relpages
sel(*pred*)	selectivity of filter *pred*[5]	see below

- Meta data like #rows(*in*), #pages(*in*) and others are updated whenever the system performs an ANALYZE run on table *in*.
- Predicate selectivity sel(*pred*) is estimated based on sampled table data and the syntactic structure of *pred*.

[5] sel(*pred*) ∊ {0,…,1} with sel(*pred*) = 0 ≡ no row satisfies filter *pred*.

Cost of Seq Scan ❸

$$\textbf{startup\_cost} \overset{\text{def}}{=} \overbrace{\text{startup\_cost}(\mathit{pred}) + \text{startup\_cost}(\mathit{expr})}^{\text{typically} = 0}$$

$$\begin{aligned}\text{cpu\_run\_cost} \overset{\text{def}}{=}\ & \#\text{rows}(\mathit{in}) \times (\overbrace{\text{cpu\_tuple\_cost}}^{\text{decode heap row}} + \overbrace{\text{run\_cost}(\mathit{pred})}^{\text{evaluate filter}}) \\ & + \underbrace{\#\text{rows}(\mathit{in}) \times \text{sel}(\mathit{pred})}_{= \#\text{rows}(\mathit{out})} \times \underbrace{\text{run\_cost}(\mathit{expr})}_{\text{evaluate SELECT clause}}\end{aligned}$$

$$\text{disk\_run\_cost} \overset{\text{def}}{=} \underbrace{\#\text{pages}(\mathit{in}) \times \text{seq\_page\_cost}}_{\text{sequentially read entire input heap file}}$$

$$\textbf{total\_cost} \overset{\text{def}}{=} \text{startup\_cost} + \underbrace{\text{cpu\_run\_cost} + \text{disk\_run\_cost}}_{= \textbf{run\_cost}}$$

Cost of Index Scan ❶

Modeling the cost for an Index Scan has to reflect that *two* data structures (heap file & B⁺Tree) are involved:

```
                    idx        in     QUERY PLAN
Index Scan using indexed_a on indexed i (cost=0.42..443.12 rows=10885 …
  Output: (c + '1'::numeric) ◀ expr
  Index Cond: (i.a <= 10000) ◀ pred                          #rows(out)
```

The model separately accounts for

1. the B⁺Tree descent (startup of the Index Scan),
2. the index leaf level scan, and
3. heap file access (clustered *vs.* non-clustered).

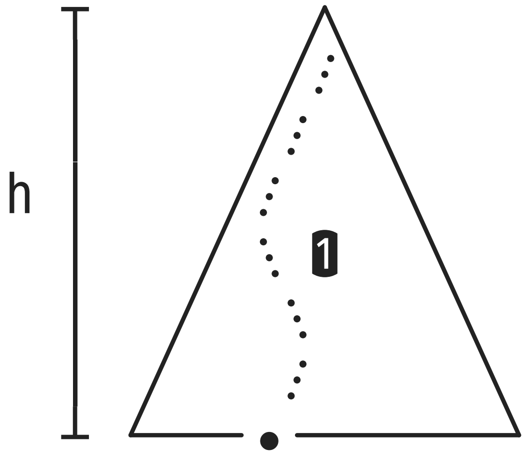
Cost of Index Scan ❷

Cost model parameters:

Parameter	Description	Available as…
#rows(*in*)	# rows (cardinality) of table *in*	pg_class.reltuples
#pages(*in*)	# pages in heap file of *in*	pg_class.relpages
sel(*pred*)	selectivity of filter *pred*	see below
h(*idx*)	height of B^{+}Tree *idx*	bt_metap(·)
#rows(*idx*)	# leaf entries in index *idx*	pg_class.reltuples
#pages(*idx*)	# pages in leaf level of *idx*	pg_class.relpages
corr(*idx*)	≈ clustering factor for index *idx*	pg_stats.correlation

- corr(*idx*) ∈ {-1.0,…,1.0} characterizes how much the physical orderings of index leaves and heap file deviate.
  - After CLUSTER *in* ON *idx*, we have corr(*idx*) = 1.0.

Cost of Index Scan ❸ (B^{+}Tree Descent)



- B^{+}Tree height $h = \log_{2 \times o}(\#\mathrm{rows}(\mathit{idx}))$

⇒ # of key comparisons during B^{+}Tree descent ❶:

$$\underbrace{\lceil \log_2(2 \times o)}_{\text{binary search in inner } B^{+}\text{Tree node with fan-out } F = 2 \times o} \times h\rceil = \lceil \log_2(\#\mathrm{rows}(\mathit{idx}))\rceil$$

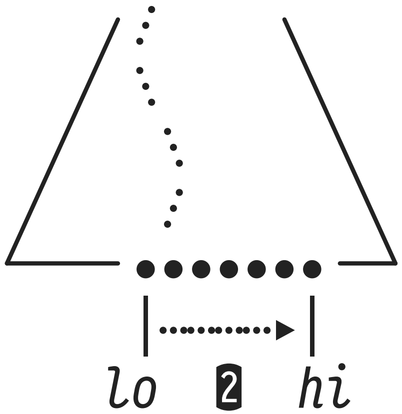
binary search in inner B^{+}Tree node with fan-out $F = 2 \times o$

startup_cost $\stackrel{\text{def}}{=}$

$$\mathrm{startup\_cost}(\mathit{pred}) + \mathrm{startup\_cost}(\mathit{expr}) + (\underbrace{\lceil \log_2(\#\mathrm{rows}(\mathit{idx}))\rceil}_{B^{+}\text{Tree descent}} + \underbrace{(h + 1)}_{⁝\, +\, \bullet} \times \underbrace{50}_{\text{index node processing}}) \times \mathrm{cpu\_operator\_cost}$$

Cost of Index Scan ❹ (Leaf Level Scan)

The index leaf level (sequence set) scan ❷ incurs CPU as well as I/O cost that contribute to the overall **run_cost:**

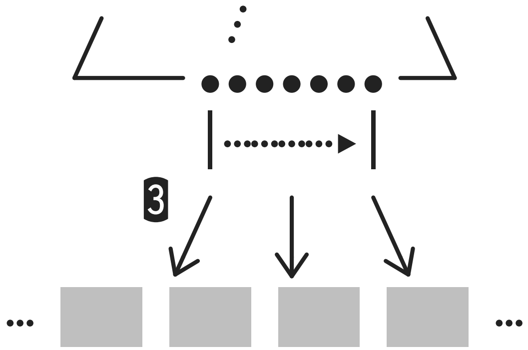


$$\text{index\_cpu\_cost} \stackrel{\text{def}}{=} \overbrace{\text{sel}(\mathit{pred}) \times \#\text{rows}(\mathit{idx})}^{\#\text{ rows in scanned range}} \times (\underbrace{\text{cpu\_index\_tuple\_cost}}_{\text{decode index leaf entry}} + \underbrace{\text{run\_cost}(\mathit{pred})}_{\text{evaluate} \leqslant \mathit{hi}})$$

$$\text{index\_IO\_cost} \stackrel{\text{def}}{=} \overbrace{\lceil \text{sel}(\mathit{pred}) \times \#\text{pages}(\mathit{idx}) \rceil}^{\#\text{ of pages} \bullet \text{ in scanned range}} \times \overbrace{\text{random\_page\_cost}}^{\text{B}^{+}\text{Tree leaves not clustered}}$$

Cost of Index Scan ➎ (Heap File Access)

Heap file accesses ❸ incur additional CPU and I/O costs (no I/O cost if we perform an Index **Only** Scan):

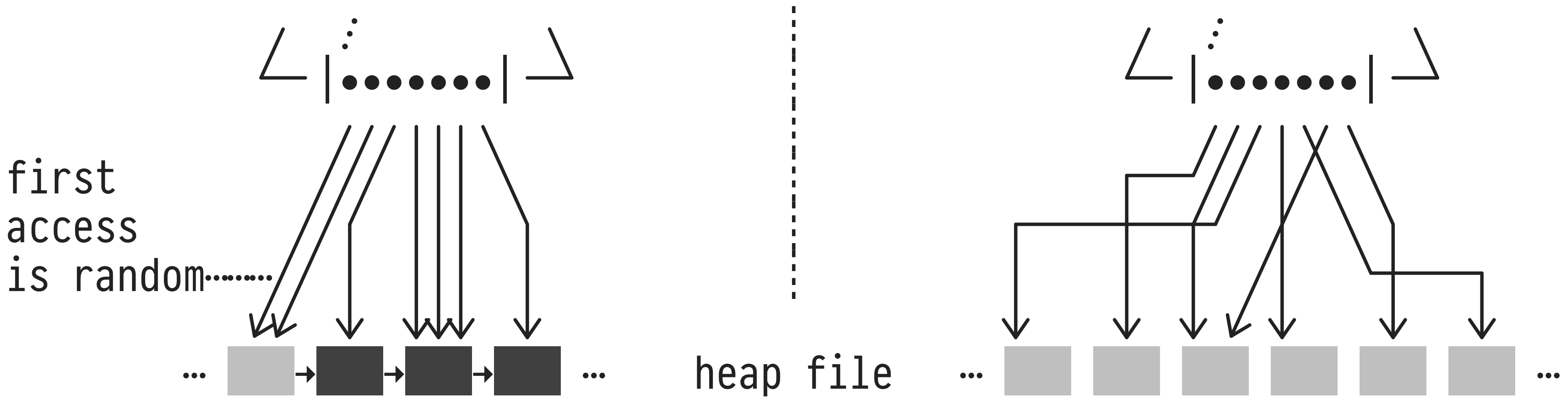


$$\mathit{heap\_cpu\_cost} \stackrel{\text{def}}{\equiv} \overbrace{\mathit{sel}(pred) \times \#\mathit{rows}(in)}^{\#\text{ rows accessed in heap file}} \times (\underbrace{\mathit{cpu\_tuple\_cost}}_{\text{decode row on}} + \underbrace{\mathit{run\_cost}(expr)}_{\text{evaluate Output}})$$

- The more **clustered** the index, the cheaper the heap I/O. Linearly interpolate between the clustered and non-clustered scenarios:

$$\mathit{heap\_IO\_cost} \stackrel{\text{def}}{\equiv} \mathit{unclustered\_IO\_cost} + \underbrace{\mathit{corr}(idx)^2}_{\approx\ \text{clustering factor} \in \{0,\dots,1\}} \times (\mathit{clustered\_IO\_cost} - \mathit{unclustered\_IO\_cost})$$

Cost of Index Scan ❻ ([Non-]Clustered Heap File Access)



$$\text{clustered\_IO\_cost} \overset{\text{def}}{=} 1 \times \text{random\_page\_cost} \; (\;) \\ + (\text{sel}(\textit{pred}) \times \#\text{pages}(\textit{in}) - 1) \times \text{seq\_page\_cost} \; (\;)$$

$$\text{unclustered\_IO\_cost} \overset{\text{def}}{=} \#\text{pages}(\textit{in}) \times \text{random\_page\_cost} \; (\;)$$

$$\textbf{total\_cost} \overset{\text{def}}{=} \textbf{startup\_cost} + \text{index\_cpu\_cost} + \text{index\_IO\_cost} \\ + \text{heap\_cpu\_cost} + \text{heap\_IO\_cost}$$

Index Correlation (Clustering Factor)

Given ordered index *idx* over column A with values $a_1 \leqslant a_2 \leqslant \dots \leqslant a_n$, where $\mathrm{pos}(a_i) \in \{1,\dots,n\}$ gives the position of a_i in the heap file for A.[6]

- **Index Correlation** $\mathrm{corr}(idx) \in \{-1,\dots,1\}$ measures how far $[\mathrm{pos}(a_1),\dots,\mathrm{pos}(a_n)]$ deviates from $[1,\dots,n]$, *i.e.*, *idx*'s clustering degree:

$$\mathrm{corr}(idx) = \frac{n \times (\sum_{i=1\dots n} i \times \mathrm{pos}(a_i)) - (\sum_{i=1\dots n} i)^2}{n \times (\sum_{i=1\dots n} i \times i) - (\sum_{i=1\dots n} i)^2}$$

[6] After `CLUSTER <table> USING` *idx*, we have $\mathrm{pos}(a_i) = i$ and thus $\mathrm{corr}(idx) = 1$.