DB 2

10 – Matching Queries and Indexes

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1 ┆ Matching Queries and Indexes

The mere presence of an index I on column $T(a)$ neither guarantees nor warrants the use of I during query evaluation. The **index has to match the query:** can I help to (significantly) reduce evaluation cost?

- Does I index the column(s) referenced in this WHERE predicate p?
- Are *all columns* referenced by this query present in I?
- Does the order of rows in I's sequence set match the row order required by this ORDER BY/GROUP BY clause?
- Accessing I will cause I/O. Do we still save overall I/O because we need to access less pages of T's heap file?

2 ┆ Indexes on Expressions

Recall table indexed and its two indexes:

```
CREATE TABLE indexed (a int PRIMARY KEY,
                      b text,
                      c numeric(3,2));
CREATE INDEX indexed_a ON indexed USING btree (a); -- 🔑
CREATE INDEX indexed_c ON indexed USING btree (c);
```

- Will the following query be supported by an index?

```
SELECT i.a
FROM   indexed AS i
WHERE  degrees(asin(i.c)) = 90 -- recall: i.c ≡ sin(i.a)
```

Indexes on Expressions

The query optimizer essentially sees the following query:

$$
\begin{array}{ll}
\textbf{SELECT} & \texttt{i.a} \\
\textbf{FROM} & \texttt{indexed } \textbf{AS} \texttt{ i} \\
\textbf{WHERE} & \blacksquare(\texttt{i.c}) = v
\end{array}
$$

- In general, the RDBMS will *not able* to form the inverse of the "black box" to rewrite the predicate into $\texttt{i.c} = \blacksquare^{-1}(v)$:
  - $\blacksquare$ may be complex and/or user-defined and the inverse might be hard to find for the system.
  - $\blacksquare$ may not be bijective and thus have no inverse at all.

Indexes on Expressions

In an **expression-based (or: function-based) index** *I*, index entries hold the value of *an expression* over the column(s) of table *T*:

$$\textbf{CREATE INDEX } I \textbf{ ON } T \textbf{ USING } \texttt{btree} \underbrace{(e)}_{\text{expression/function over columns of } T}$$

- Expression *e* is evaluated at row *insertion/update time*. 👍, if query speed is more important than update speed.
- Index *I* matches predicates of the form $e\ \theta\ v$.
- The sequence set of index *I* is ordered by *e*.
- `CREATE UNIQUE INDEX …`: can protect complex constraints.

Indexes on Expressions

Consider expression-based index people_age on the user-defined SQL function (UDF) get_age():

```
CREATE FUNCTION get_age(d_o_b date) RETURNS int AS
$$
  SELECT extract(years from age(now(), d_o_b)) :: int
$$                                -- ☝ current system time ⚠
LANGUAGE SQL;

CREATE TABLE people (name text, birthdate date);
CREATE INDEX people_age ON people
  USING btree (get_age(birthdate));  -- expression-based index

SELECT p.name AS adult                   --
FROM   people AS p                       --  } intended index use case
WHERE  get_age(p.birthdate) >= 18;       --
```

- **Q:** How do you expect the RDBMS to behave?

3 ┆ Composite (or: Concatenated) Indexes

Index I may be built over a **list of columns** c_i of table T:

```
CREATE INDEX I ON T USING btree (c₁,…,cₙ)
```

- In I's leaf level, the rows of T will be ordered *lexicographically*. Row t_1 is smaller than t_2, iff:

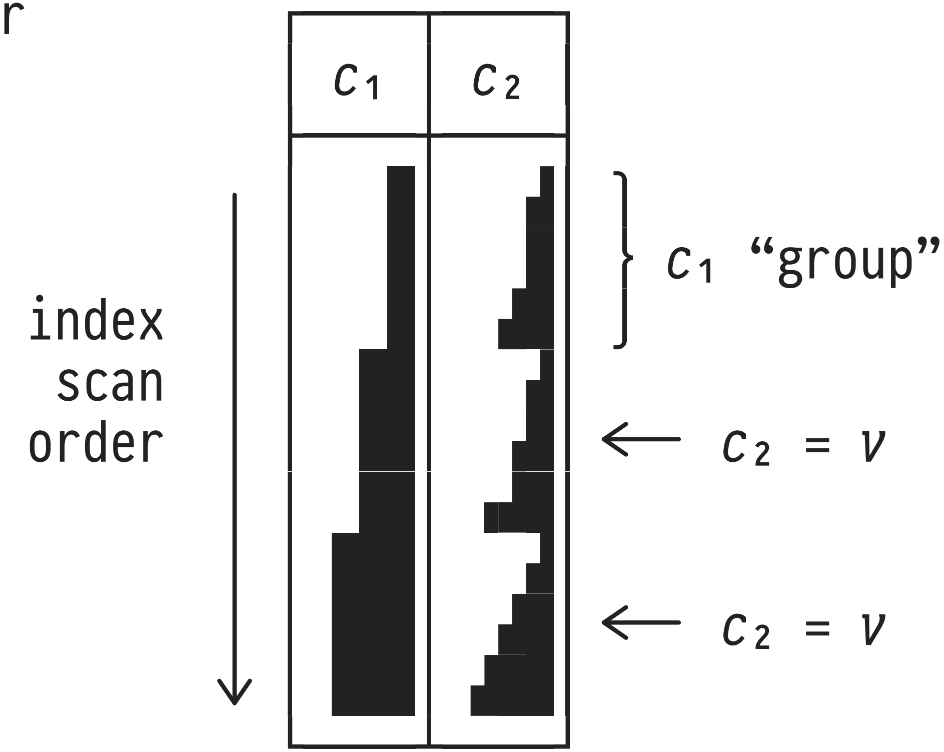
$$
\begin{array}{ll}
 & (t_1.c_1 < t_2.c_1) \\
\lor & (t_1.c_1 = t_2.c_1 \land t_1.c_2 < t_2.c_2) \\
\vdots & \\
\lor & (t_1.c_1 = t_2.c_1 \land \cdots \land t_1.c_{n-1} = t_2.c_{n-1} \land t_1.c_n < t_2.c_n)
\end{array}
$$

- ⚠️ Row order in indexes on (c_1,c_2) and (c_2,c_1) will be entirely different. **Q:** How about (c_1) and (c_1,c_2)?

Matching Queries With Composite Indexes

Entry order in (c_1, c_2) index I (▃█ ≡ magnitude of values):

- If we scan I in order, we encounter these ascending/repeating patterns of values in columns c_1/c_2:



⇛ Composite index matches a query if its filter predicate refers to a **prefix** of the column list $(c_1, \ldots, c_n)$

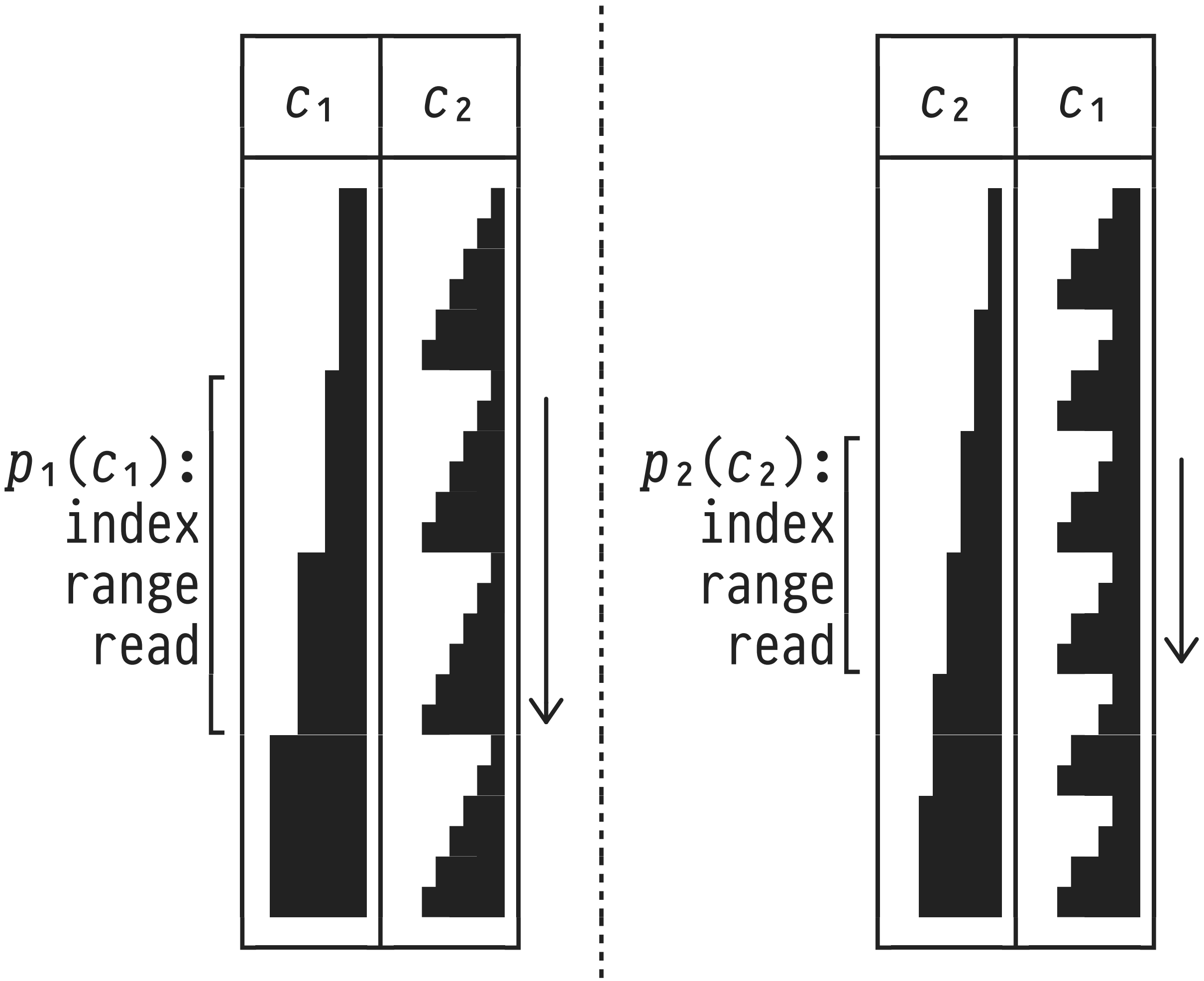
Multi-Dimensional Queries and Composite Indexes

Composite indexes are designed to support *multi-dimensional* queries whose predicates refer to *multiple* columns:

```
SELECT e(t)
FROM   T AS t
WHERE  p₁(t.c₁)   -- two dimensions:
  AND  p₂(t.c₂)   -- c₁, c₂
```

- **Q:** Shall we build a (c_1, c_2) or a (c_2, c_1) index to support this query?
- 💡 Hmm... What would PostgreSQL do?

Composite Indexes: Index for Selective Dimension First

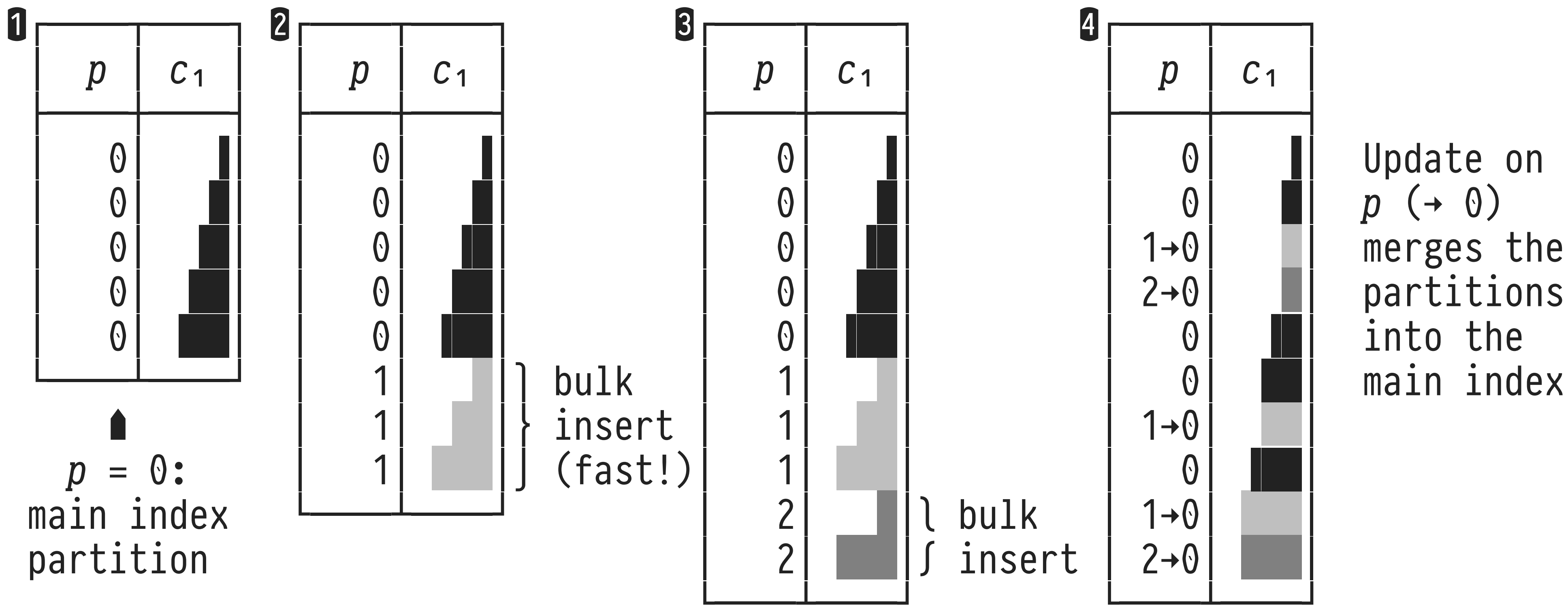


- Leading column c_i and predicate p_i define index scan range: ↓
- Aim to minimize work, i.e., index scan range: the **more selective predicate** determines choice of index (c_2, c_1)
- If you can afford one of the two indexes only, build (c_2, c_1)

⇒ Rule of thumb: "Index for '=' first!"

4 ¦ Partitioned B⁺Trees: Non-Selective Key Prefixes

Indexes in which an artificial partitioning column *p* of **low selectivity** is prepended to the index key can be useful:



Partitioned B⁺Trees: SQL Code

Simple implementation of bulk appends and delayed merging:

```
-- ❶ Prepend partition column p, build partitioned B⁺Tree I
ALTER TABLE T
  ADD COLUMN p int NOT NULL CHECK (p >= 0) DEFAULT 0;
CREATE INDEX I ON T USING btree (p,c₁);

-- ❷+❸ Fast⚡ bulk inserts (simply appends to B⁺Tree I)
INSERT INTO T(p,…) SELECT 1, …  FROM …;
INSERT INTO T(p,…) SELECT 2, …  FROM …;

-- ❹ Merge partition(s) into main partition when convenient
UPDATE T AS t
SET    p = 0
WHERE  t.p = 1;  -- or: t.p IN (‹partitions›) ┆ t.p <> 0
```

5 ┆ Multi-Dimensional Predicates and Index Combinations

Consider a SQL query with a *disjunctive* predicate:

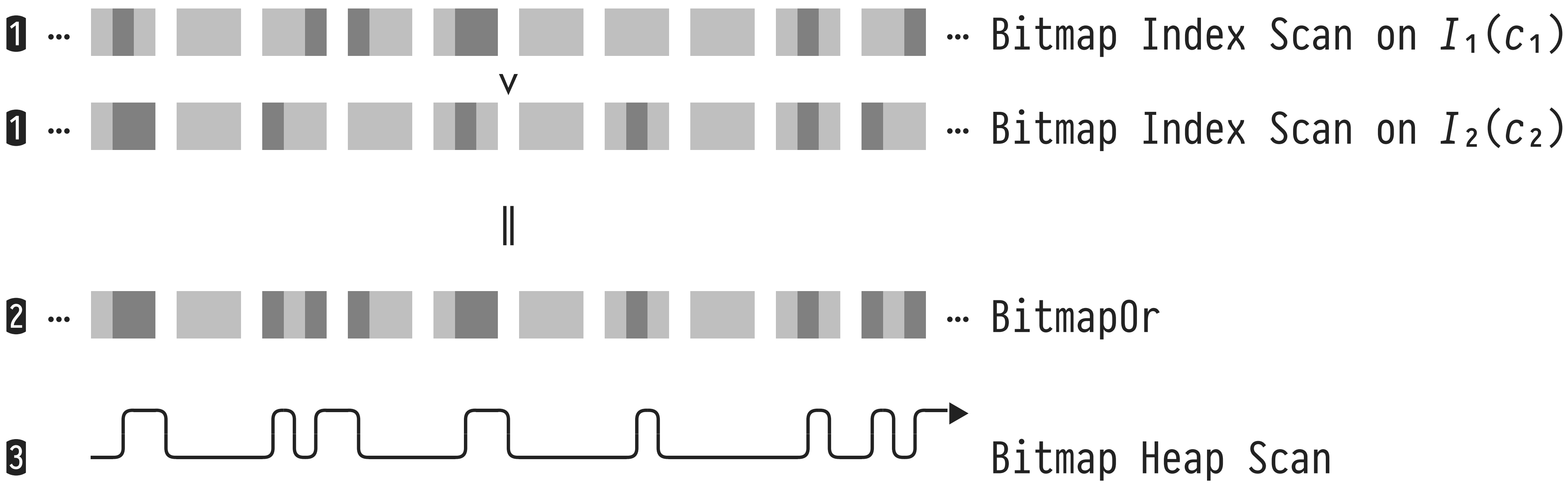
```
SELECT e(t)
FROM   T AS t
WHERE  p₁(t.c₁)  -- ⎱ disjunctive
   OR  p₂(t.c₂)  -- ⎰ predicate
```

- Neither a (c_1,c_2) nor a (c_2,c_1) index can support the disjunction: we would need to scan the *entire* index 👎 (thus: rather access T's heap file directly).

- 💡 Try to **combine separate indexes** on columns I_1 on (c_1) and I_2 on (c_2). Idea builds on Bitmap Index Scan.

Combining Indexes via Bitmap Heap Scan and BitmapOr/And

1. Perform individual Bitmap Index Scans, possibly in //, possibly multiple times on the same index.
2. Combine resulting row-/page-level bitmaps using ∨ or ∧.
3. Perform Bitmap Heap Scan with combined bitmap.



6 ┊ String Pattern Matching (**LIKE**) and Indexes

Q: Can indexes support the evaluation of SQL **string pattern matches** LIKE '%this'? **A:** Yes, but it depends on the pattern.

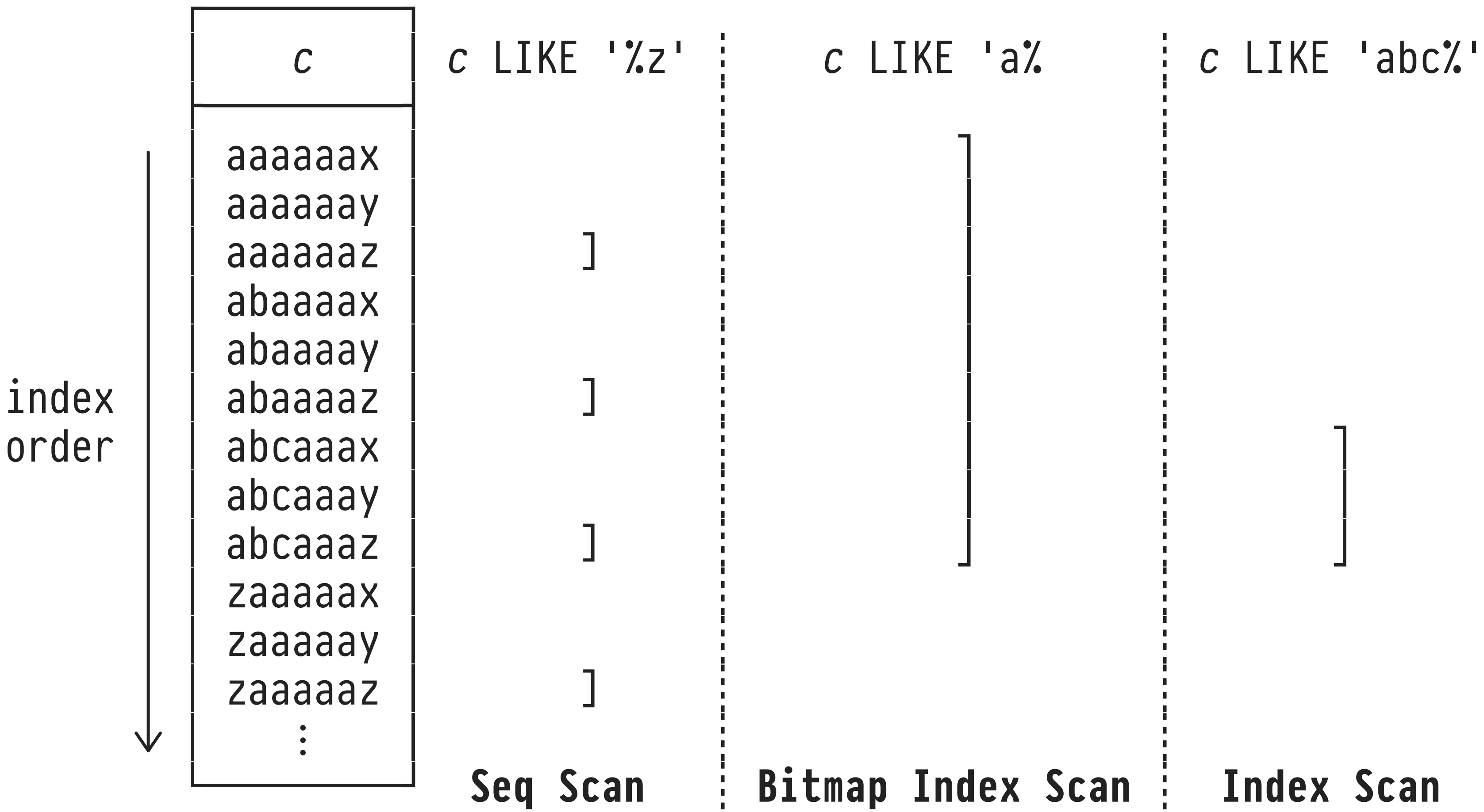
- SQL pattern matching: e LIKE 's_1%s_2' holds iff string e constains substrings $s_{1,2}$ separated by zero or more arbitrary characters (regular expressions: 's_1.*s_2').

- PostgreSQL: B$^+$ tree index on column c :: text of table T:

```
-- I₁ supports LIKE
CREATE INDEX I₁ on T USING btree (c text_pattern_ops)
-- I₂ supports =, <, >, …
CREATE INDEX I₂ on T USING btree (c)
```

Patterns, Selectivity, and Index Ranges

- Placement of wildcard % influences predicate selectivity:



7 ┆ Partial Indexes: Hot vs. Cold Rows

Sometimes, small parts of a table contain 🔥 "hot" rows while most of the table only has archival value:

Table **orders**

id	…	fulfilled	
42		☐	"hot" open orders
41		☐	
39		☐	
40		2018-06-03	closed orders only used in reporting
38		2018-05-27	
⋮		⋮	
2		2017-08-26	
1		2017-04-10	

- Lion share of rows is cold, read infrequently (*e.g.*, to create a monthly report).
- Hot row subset queried regularly, would benefit from index support.
- But: Hot rows would be distributed all over a regular index. 👎
- Predicate *p* discerns hot rows (*e.g.*, `fulfilled IS NULL`).

Partial Indexes

Build **partial index** that covers the hot row subset only:

```
CREATE INDEX I on T USING btree (c₁,c₂,…) WHERE p(cₚ)
```

- I will be small: only rows of T satisfying p are be present in the index.
- Updates on column(s) c_p may move rows into/out of I.
- I matches a query if its filter predicate q **implies** p:

```
SELECT e(t)
FROM   T AS t
WHERE  q(t)    -- q ⇒ p?
```

  - RDBMSs typically recognize trivial implications only.

8 ┆ Index-Only Query Evaluation

For some queries, **all columns** $c_1,\dots,c_n$ needed for evaluation may be present as key values in an index.

- Perform **index-only** query evaluation, do not access the tables' heap files at all.
- May even try to design wide multi-column indexes[1] with keys $c_1,\dots,c_k,c_{k+1},\dots,c_n$, in which
  - prefix $c_1,\dots,c_k$ is used to guide index search (*i.e.*, to evaluate predicates),
  - suffix $c_{k+1},\dots,c_n$ is used to evaluate other expressions.

[1] PostgreSQL v11: CREATE INDEX *I* on *T* USING btree ($c_1,\dots,c_k$) INCLUDE ($c_{k+1},\dots,c_n$), builds a B⁺Tree in which keys ($c_1,\dots,c_k$) are narrow and only the leaves carry all columns $c_1,\dots,c_n$.

Index-Only Queries?

Assume B+Tree index (a,c) on table indexed. **Q:** Can ❶…❻ be evaluated using the index only?

❶
```sql
SELECT i.c
FROM   indexed AS i
WHERE  i.a < v
```

❷
```sql
SELECT i.a
FROM   indexed AS i
WHERE  i.c < v
```

❸
```sql
SELECT i.a / i.c AS div
FROM   indexed AS i
WHERE  i.a < v AND i.c <> 0
```

❹
```sql
SELECT MAX(i.c) AS m
FROM   indexed AS i
WHERE  i.a < v;
```

❺
```sql
SELECT i.a, SUM(i.c) AS s
FROM   indexed AS i
GROUP BY i.a;
```

❻
```sql
SELECT MIN(i.b) AS m
FROM   indexed AS i
WHERE  i.a < v;
```

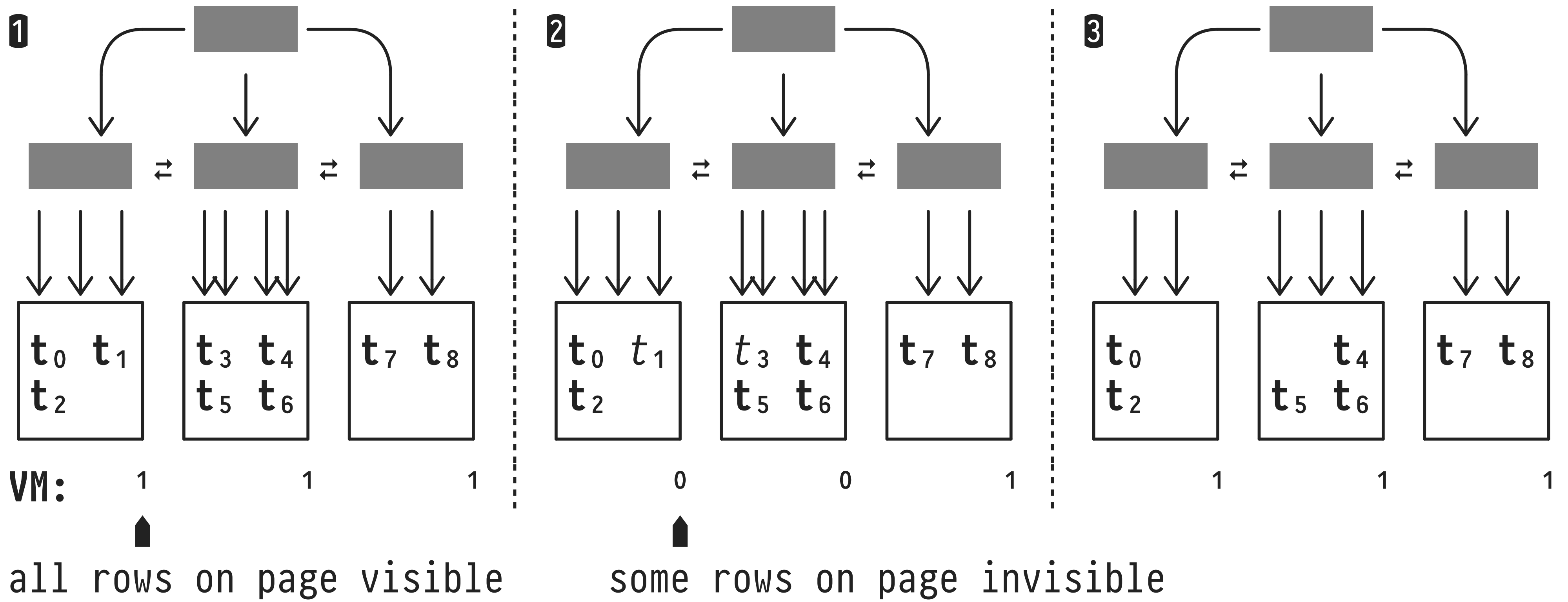
Index-Only Scans and Row Visibility

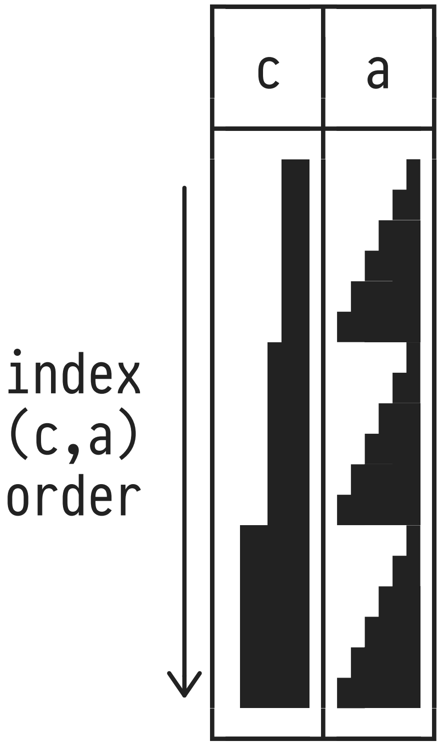
Index-only query evaluation — implemented by plan operator Index Only Scan — in PostgreSQL faces a challenge:

- Row visibility (recall timestamps xmin, xmax) is recorded in the heap file *only*.
  - **Huh?**😱 Index Only Scan needs to check the heap file whether an index entry may occur in the query result…
- Instead check the table's/heap file's **visibility map** to efficiently check that all rows of a page are visible.
  - Use Index Only Scan when no/few row visibility checks require actual heap file accesses.

Index-Only Scans and the Visibility Map (VM)

1. Original table state ($\mathbf{t}_i$: visible row).
2. After deletion of $\mathbf{t}_1$ and $\mathbf{t}_3$ (t_i: invisible row).
3. After VACUUM: dead rows removed, index updated.





B⁺Trees provide **ordered access** to rows. Query operations other than predicate filters should be able to benefit.

- For the following, assume that table `indexed` features two-column index `indexed_c_a` on `(c,a)` only.
- In an index scan, we will encounter rows *as if* they had been sorted by `ORDER BY c ASC, a ASC` (see left).

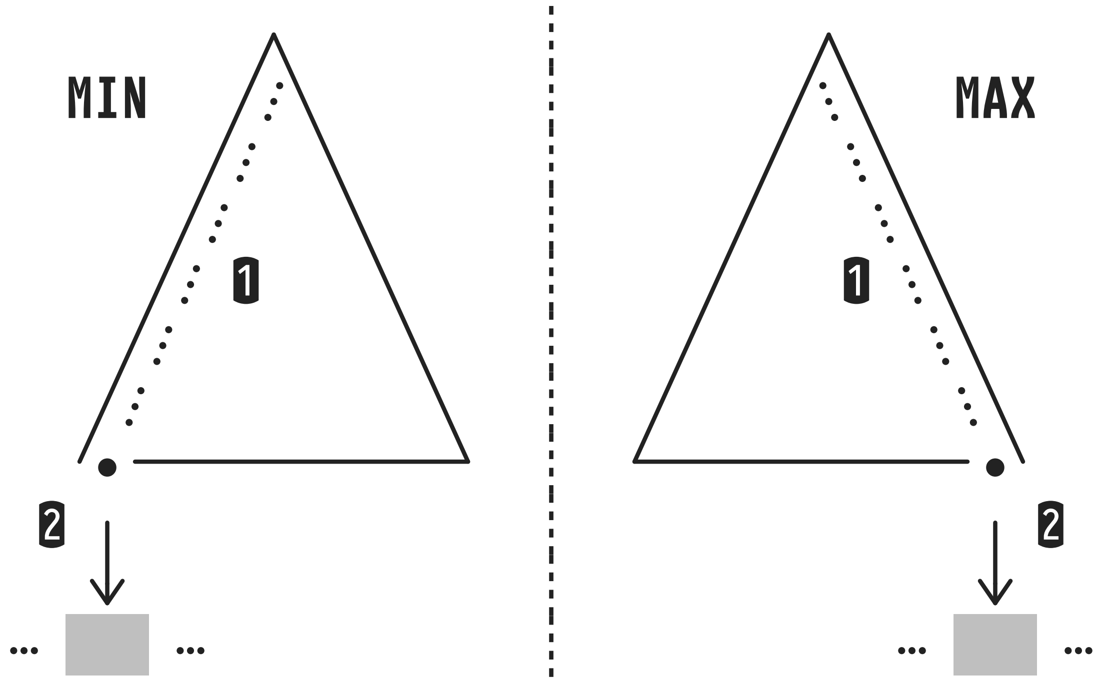
Supporting MIN/MAX With B+Trees

```
SELECT MIN(i.c) AS m  -- or: MAX(i.c)
FROM   indexed AS i
```

1. Descend on left/rightmost path

2. Initiate **Index Only Scan [Backward]**

Q: Which **Index Cond** will the scans use?



Supporting ORDER BY With B⁺Trees?

ORDER BY criteria need to match the row visit order of a (c,a) index forward/backward scan:

❶
```
SELECT i.*
FROM   indexed AS i
ORDER BY i.c
```

❷
```
SELECT i.*
FROM   indexed AS i
ORDER BY i.c DESC
```

❸
```
SELECT i.*
FROM   indexed AS i
ORDER BY i.c, i.a
```

❹
```
SELECT i.*
FROM   indexed AS i
ORDER BY i.c DESC, i.a DESC
```

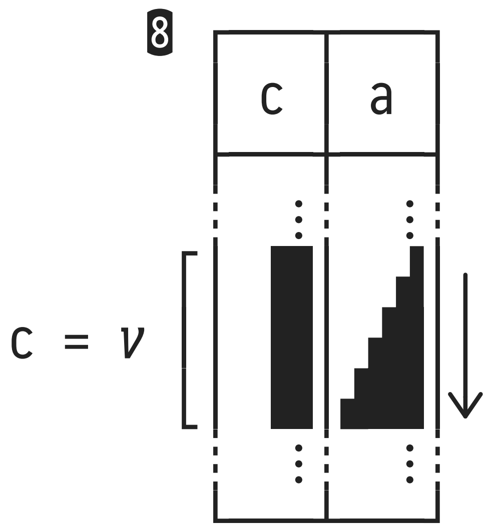
❺
```
SELECT i.*
FROM   indexed AS i
ORDER BY i.c ASC, i.a DESC
```

❻
```
SELECT i.*
FROM   indexed AS i
ORDER BY i.c
LIMIT 42 -- first 42 rows only
```

Supporting ORDER BY With B+Trees?

```
❼ SELECT   i.*
  FROM     indexed AS i
  ORDER BY i.a
```

```
❽ SELECT   .*
  FROM     indexed AS i
  WHERE    i.c = 0.0
  ORDER BY i.a
```



- **N.B.:** A range predicate on c (*e.g.*, c ⩽ v) rules out index support again.

- In ❽, PostgreSQL implements filter i.c = 0.0 with a Bitmap Index Scan, then implements ORDER BY i.a using Sort.[2]

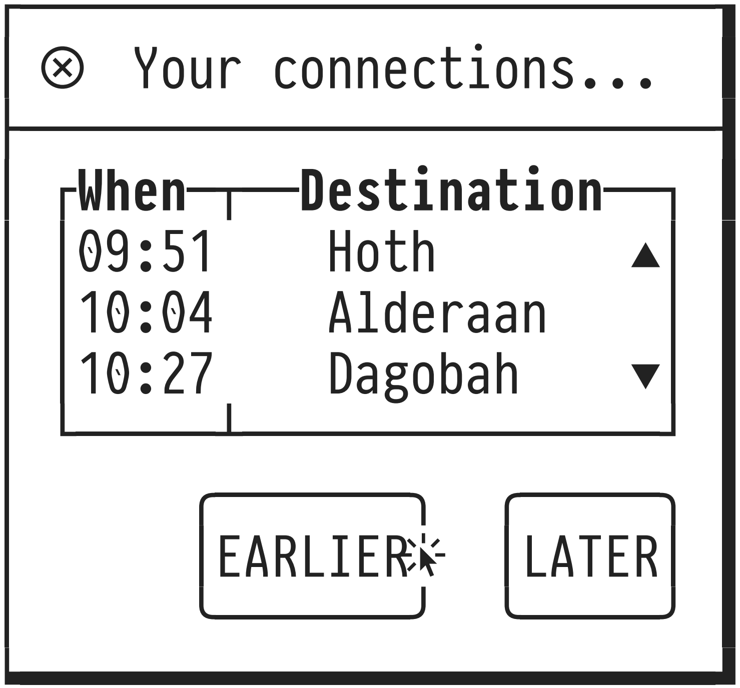
[2] Use set enable_sort = off or set enable_bitmapscan = off to see that PostgreSQL *can* be reasonable.

10 ¦ Use Case: Paging Through Table Contents

id	when	destination
1	09:51	Tatooine
2	09:51	Hoth
3	10:04	Alderaan
4	10:27	Dagobah

- Efficiently **page** through a large table or query result. Show *n* rows at a time.

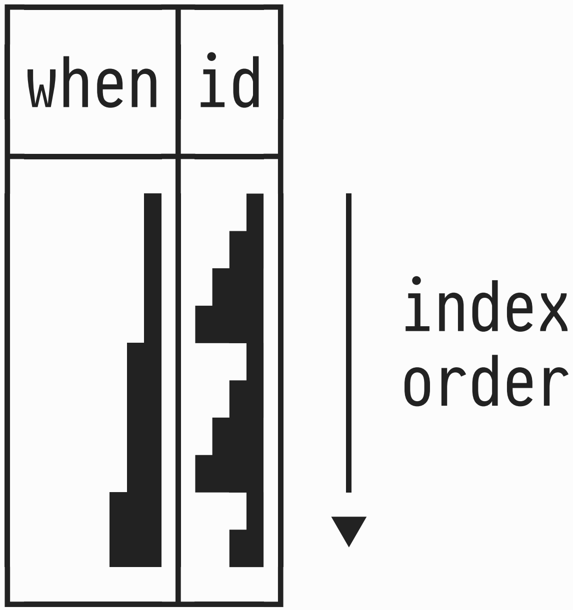
- Do not cache large table in UI (think Web browser), instead request required window of *n* rows from the DB server on demand.


Your connections...
When
Destination
09:51 Hoth
10:04 Alderaan
10:27 Dagobah
EARLIER
LATER

Indexing for Efficient "when"-Based Paging

id	when	destination
1	09:51	Tatooine
2	09:51	Hoth
3	10:04	Alderaan
4	10:27	Dagobah

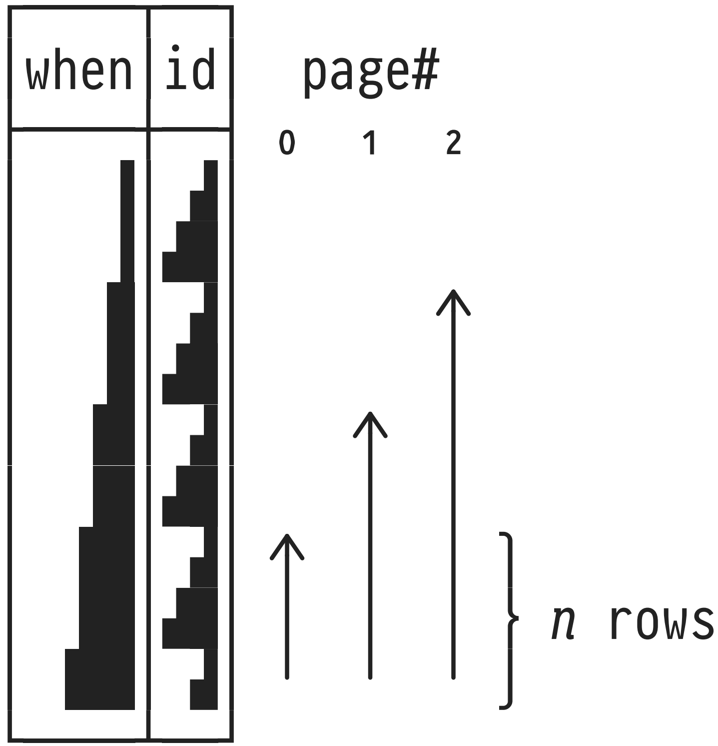
```
CREATE TABLE connections (
  id          int PRIMARY KEY,
  "when"      timestamp,
  destination text
);
CREATE INDEX connections_when_id
  ON connections("when", id);
```



Option 1: Using OFFSET and LIMIT

Parameters: *:page* ∈ {0,…} current page, *:n* rows per page.

```
SELECT c.*
FROM   connections AS c
ORDER BY c."when" DESC
OFFSET :page * :n
LIMIT  :n
```

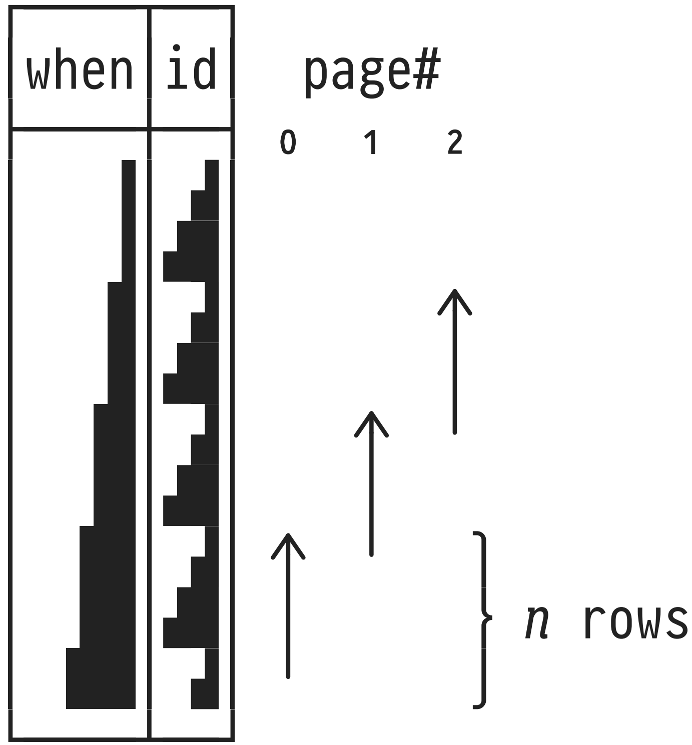


- The further we page, the wider becomes the index scan range.

⇛ Paging gets slower and slower.

Option 2: Using WHERE and LIMIT

```
SELECT c.*
FROM   connections AS c
WHERE (c."when",c.id) < (:last_when,:last_id)
ORDER BY c."when" DESC, c.id DESC
LIMIT  :n
```



- Save index keys *:last_when*, *:last_id* of last entry displayed. Pass these to RDBMS when we request next page (continue "interrupted" index scan).

⇒ Paging speed independent of page #.