Postgres 12 в этюдах

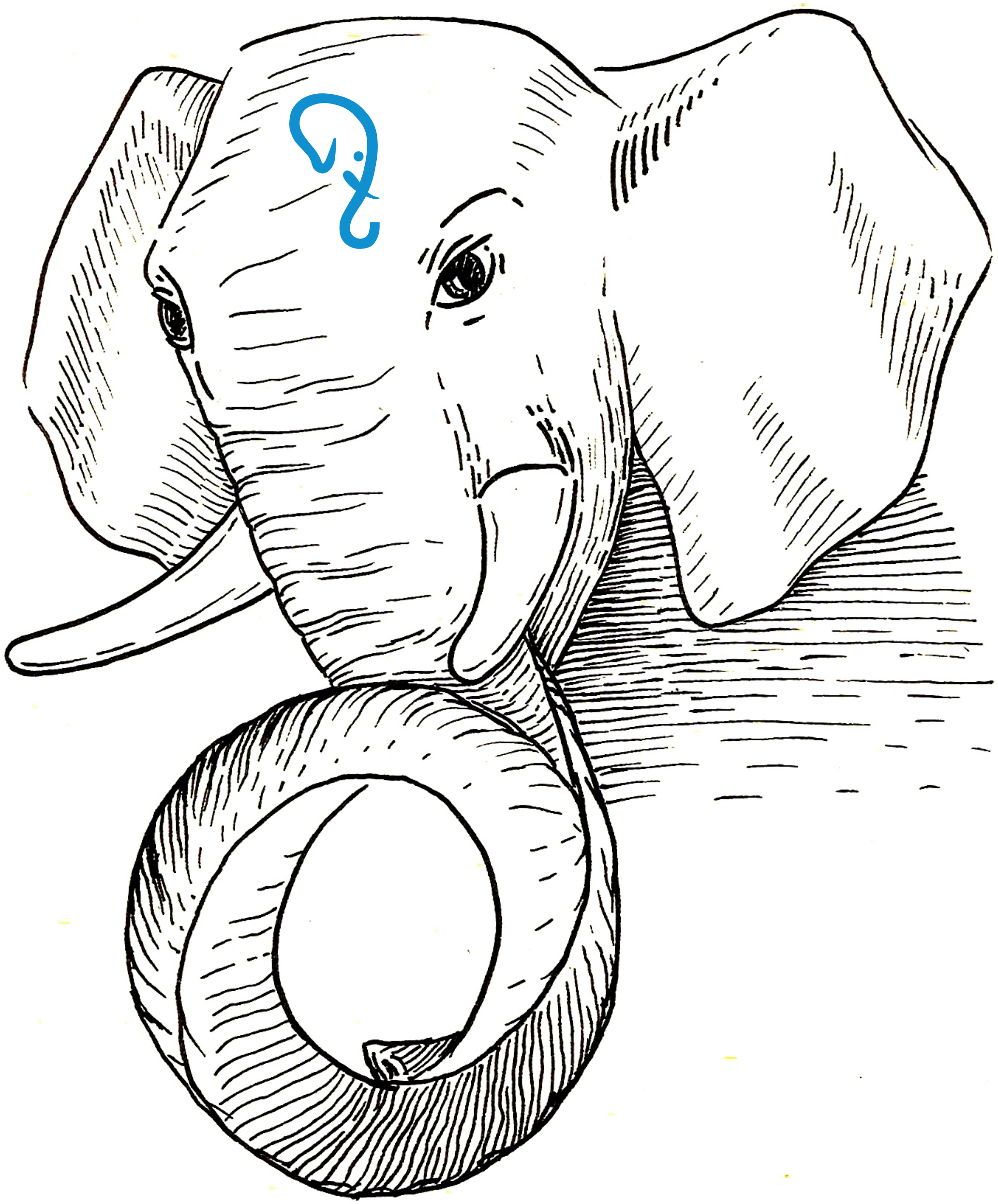
Олег Бартунов, CEO Postgres Professional

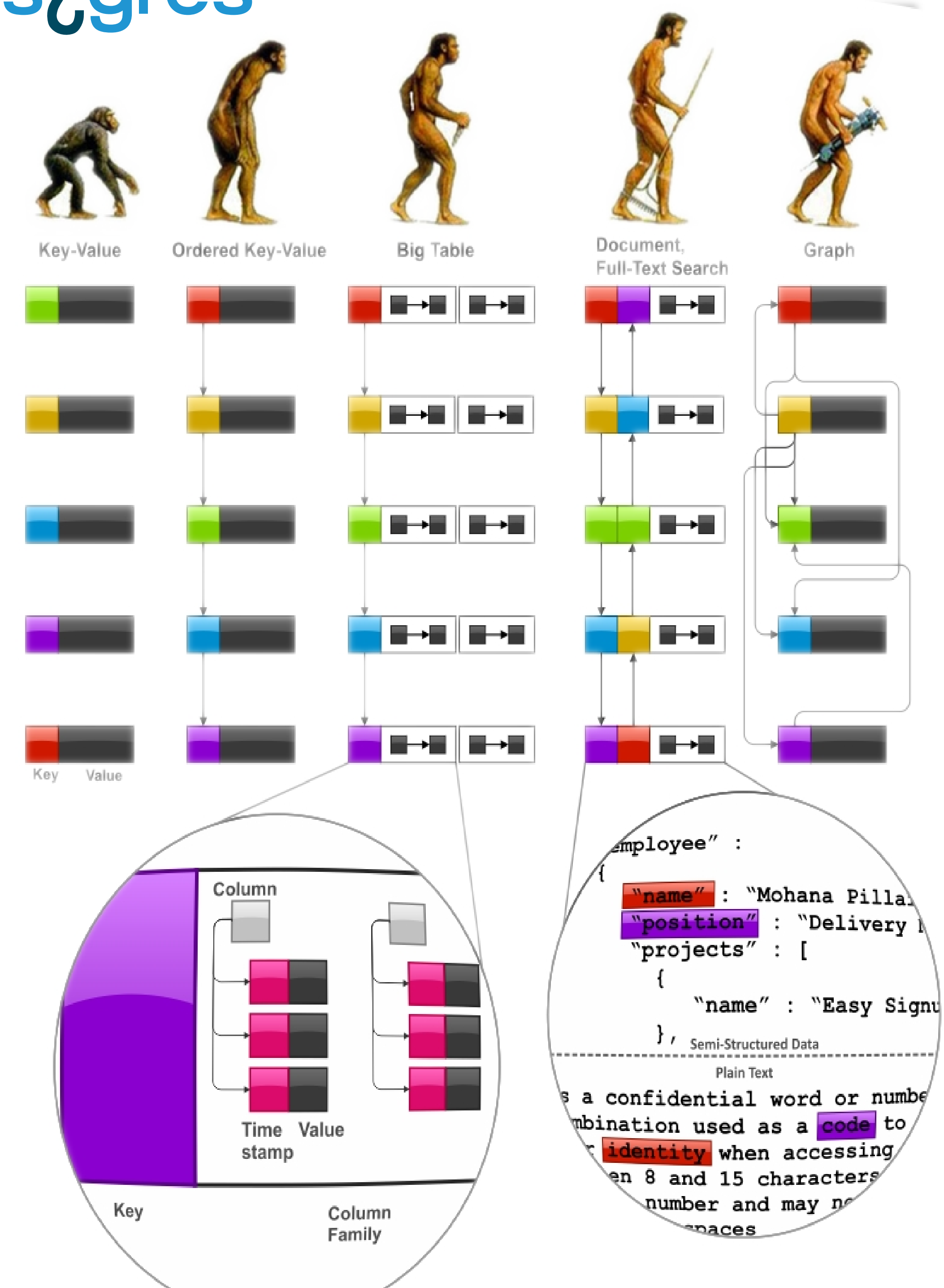
HL
Saint HighLoad++
Профессиональная конференция разработчиков высоконагруженных систем

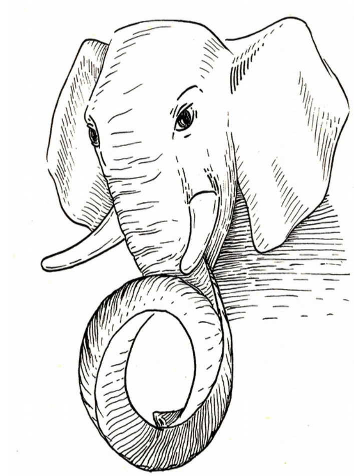
Agenda

- SQL/JSON
- Controllable CTE
- KNN
- Indexes:
  covering GiST, less WAL, concurrent reindex ….
- Pluggable storage
- Partitioning improvements
- Other features

SQL/JSON in PostgreSQL







SQL/JSON - 2019

- JSONPATH
  SQL/JSON - 2016
- PostgreSQL 12

JSONB - 2014

- Binary storage
- Nesting objects & array
- Indexing

JSON - 2012

- Textual storage
- JSON verification

HSTORE - 2003

- Perl-like hash storage
- No nesting
- Indexing

SQL/Foundation recognizes JSON after 8 years

jsonpath (committed)

Jsonpath provides an ability to operate (in standard specified way) with json structure at SQL-language level

- Dot notation – $.a.b.c
  $ - the current context element
- Array - [*]
- Filter ? - $.a.b.c ? (@.x > 10)
  @ - current context in filter expression
- Methods - $.a.b.c.x.type()
  type(), size(), double(), ceiling(), floor(), abs(), datetime(), keyvalue()
- *lax* and *strict* modes to facilitate matching of the (sloppy) document structure and path expression

```
'$.floor[*].apt[*] ? (@.area > 40 && @.area < 90)'
```

JSONPATH: [lax] vs strict

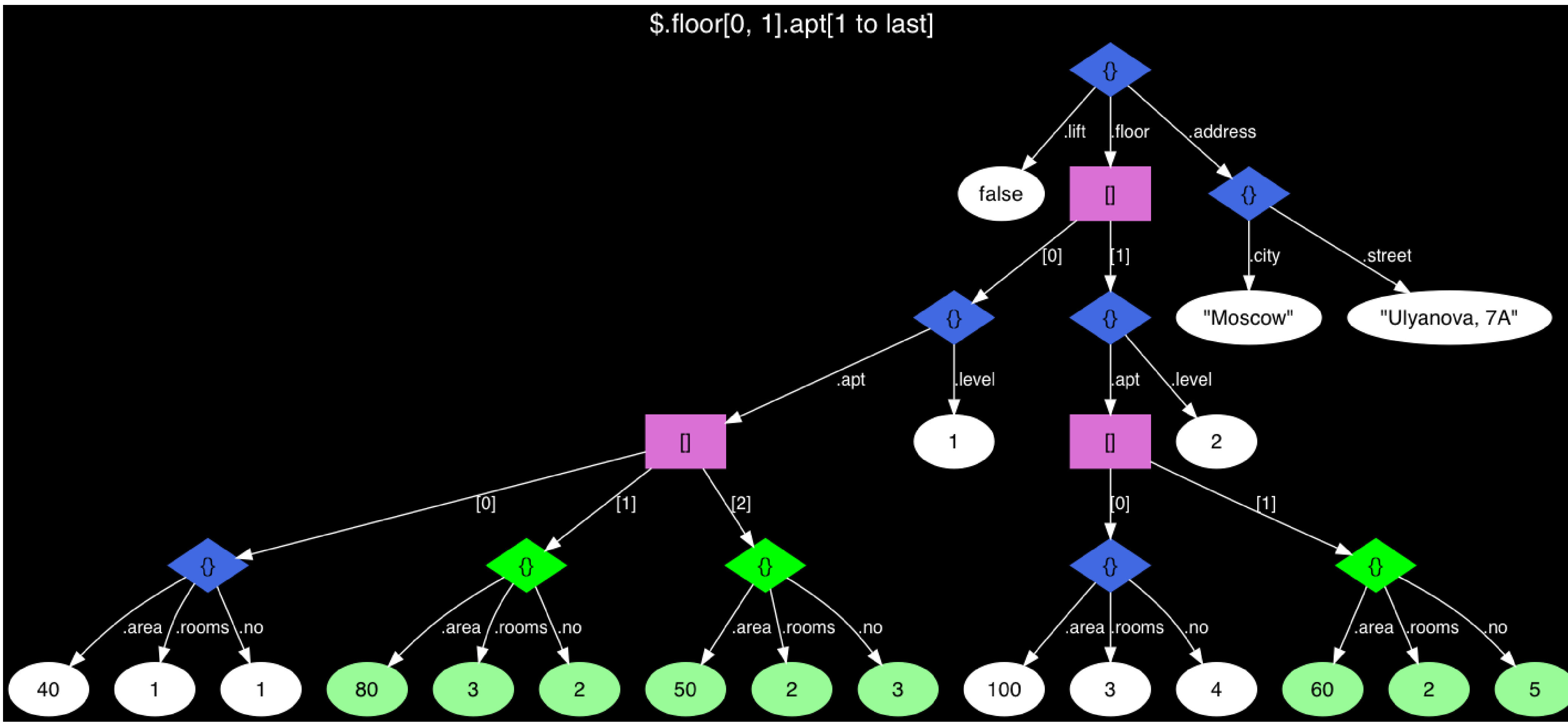
```
– lax:missing keys ignored
select jsonb '{"a":1}' @? 'lax $.b ? (@ > 1)';
 ?column?
----------
 f
(1 row)
select jsonb '{"a":1}' @? 'strict $.b ? (@ > 1)';
 ?column?
----------
 (null)
(1 row)

– lax: arrays unwrapped
select jsonb '[1,2,[3,4,5]]' @? 'lax $[*] ? (@ == 5)';
 ?column?
----------
 t
(1 row)
select jsonb '[1,2,[3,4,5]]' @? 'strict $[*] ? (@[*] == 5)';
 ?column?
----------
 t
(1 row)
```

Why JSON path is a type ?

- Standard permits only string literals in JSON path specification.
- WHY a data type ?
- To accelerate JSON path queries using existing indexes for jsonb we need boolean operators for json[b] and jsonpath.
- Implementation as a type is much easier than integration of JSON path processing with executor (complication of grammar and executor).
- In simple cases, expressions with operators can be more concise than with SQL/JSON functions.
- It is Postgres-way to use operators with custom query types (tsquery for FTS, lquery for ltree, jsquery for jsonb,...)

```
{
        "address": {
                "city": "Moscow",
                "street": "Ulyanova, 7A"
        },
        "lift": false,
        "floor": [
                {
                        "level": 1,
                        "apt": [
                                {"no": 1, "area": 40, "rooms": 1},
                                {"no": 2, "area": 80, "rooms": 3},
                                {"no": 3, "area": 50, "rooms": 2}
                        ]
                },
                {
                        "level": 2,
                        "apt": [
                                {"no": 4, "area": 100, "rooms": 3},
                                {"no": 5, "area": 60, "rooms": 2}
                        ]
                }
        ]
}
```

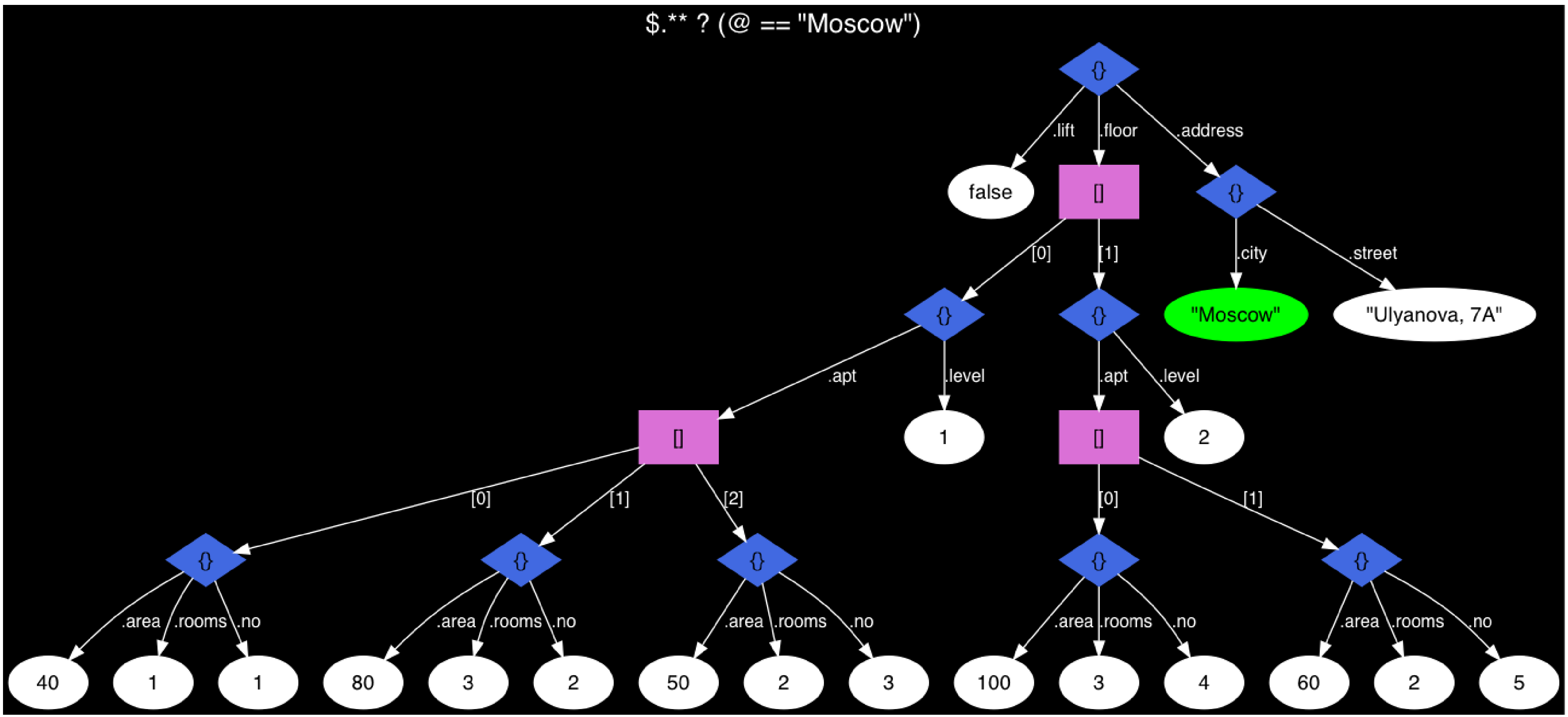
$.floor[0,1].apt[1 to last]



$.floor[0, 1].apt[1 to last]

```
SELECT jsonb_path_query_array(js, '$.floor[0, 1].apt[1 to last]')
FROM house;


SELECT jsonb_agg(apt)
FROM (SELECT apt->generate_series(1, jsonb_array_length(apt) - 1)
FROM (SELECT js->'floor'->unnest(array[0, 1])->'apt'
FROM house) apts(apt)) apts(apt);
```

Extension: wildcard search



$.** ? (@ == "Moscow")

```
SELECT jsonb_path_exists(js, '$.** ? (@ == "Moscow")') FROM house;
```

```
WITH RECURSIVE t(value) AS
(SELECT * FROM house
 UNION ALL
    ( SELECT
        COALESCE(kv.value, e.value) AS value
      FROM
        t
      LEFT JOIN LATERAL jsonb_each(
        CASE WHEN jsonb_typeof(t.value) = 'object' THEN t.value ELSE NULL END
      ) kv ON true
      LEFT JOIN LATERAL jsonb_array_elements(
        CASE WHEN jsonb_typeof(t.value) = 'array' THEN t.value ELSE NULL END
      ) e ON true
      WHERE
        kv.value IS NOT NULL OR e.value IS NOT NULL)
)
SELECT EXISTS (SELECT 1 FROM t WHERE value = '"Moscow"');
```

jsonpath (committed)

The jsonpath functions for jsonb:

- **`jsonb_path_exists()`** `=> boolean`
  Test whether a JSON path expression returns any SQL/JSON items (operator @?).
- **`jsonb_path_match()`** `=> boolean`
  Evaluate JSON path predicate (operator @@).
- **`jsonb_path_query()`** `=> setof jsonb`
  Extract a sequence of SQL/JSON items from a JSON value.
- **`jsonb_path_query_array()`** `=> jsonb`

  Extract a sequence of SQL/JSON items wrapped into JSON array.
- **`jsonb_path_query_first()`** `=> jsonb`

  Extract the first SQL/JSON item from a JSON value.

jsonpath (committed)

All `jsonb_path_xxx()` functions have the same signature:

```
jsonb_path_xxx(
    js jsonb,
    jsp jsonpath,
    vars jsonb DEFAULT '{}',
    silent boolean DEFAULT false
)
```

- "vars" is a jsonb object used for passing jsonpath variables:

```
SELECT jsonb_path_query_array('[1,2,3,4,5]', '$[*] ? (@ > $x)',
                              vars => '{"x": 2}');
 jsonb_path_query_array
------------------------
 [3, 4, 5]
```

- "silent" flag enables suppression of errors:

```
SELECT jsonb_path_query('[]', 'strict $.a');
ERROR:  SQL/JSON member not found
DETAIL:  jsonpath member accessor can only be applied to an object

SELECT jsonb_path_query('[]', 'strict $.a', silent => true);
 jsonb_path_query
------------------
(0 rows)
```

jsonpath (committed)

Jsonpath function examples:

- ```
  jsonb_path_exists('{"a": 1}', '$.a') => true
  jsonb_path_exists('{"a": 1}', '$.b') => false
  ```
- ```
  jsonb_path_match('{"a": 1}', '$.a == 1') => true
  jsonb_path_match('{"a": 1}', '$.a >= 2') => false
  ```
- ```
  jsonb_path_query('{"a": [1,2,3,4,5]}',
                   '$.a[*] ? (@ > 2)') => 3, 4, 5 (3 rows)
  jsonb_path_query('{"a": [1,2,3,4,5]}',
                   '$.a[*] ? (@ > 5)') =>  (0 rows)
  ```
- ```
  jsonb_path_query_array('{"a": [1,2,3,4,5]}',
                         '$.a[*] ? (@ > 2)') => [3, 4, 5]
  jsonb_path_query_array('{"a": [1,2,3,4,5]}',
                         '$.a[*] ? (@ > 5)') => []
  ```
- ```
  jsonb_path_query_first('{"a": [1,2,3,4,5]}',
                         '$.a[*] ? (@ > 2)') => 3
  jsonb_path_query_first('{"a": [1,2,3,4,5]}',
                         '$.a[*] ? (@ > 5)') => NULL
  ```
  ```

jsonpath (committed)

Boolean jsonpath operators for jsonb:

- `jsonb @? jsonpath` (exists)
  Test whether a JSON path expression returns any SQL/JSON items.

  ```
  jsonb '[1,2,3]' @? '$[*] ? (@ == 3)'   => true
  ```

- `jsonb @@ jsonpath` (match)
  Get the result of a JSON path predicate.

  ```
  jsonb '[1,2,3]' @@ '$[*] == 3'   => true
  ```

- Operators are interchangeable:

  ```
  js @? '$.a'        <=>  js @@ 'exists($.a)'
  js @@ '$.a == 1' <=>  js @? '$ ? ($.a == 1)'
  ```

jsonpath (indexes)

Boolean jsonpath operators are supported by GIN `jsonb_ops` and `jsonb_path_ops`:

```
CREATE INDEX ON house USING gin (js);

EXPLAIN (COSTS OFF)
SELECT * FROM house
WHERE js @? '$.floor[*].apt[*] ? (@.rooms == 3)'
```

```
                                  QUERY PLAN
--------------------------------------------------------------------------------
 Bitmap Heap Scan on house
   Recheck Cond: (js @? '$."floor"[*]."apt"[*]?(@."rooms" == 3)'::jsonpath)
   ->  Bitmap Index Scan on house_js_idx
         Index Cond: (js @? '$."floor"[*]."apt"[*]?(@."rooms" ==
3)'::jsonpath)
(4 rows)
```

- *JsQuery(https://github.com/postgrespro/jsquery, branch sqljson) provides jsonb_path_value_ops, jsonb_value_path_ops GIN opclasses for more operators.*

jsonpath (committed)

- `.datetime()` item method not supported in PG12:

```
-- behavior required by standard
SELECT jsonb_path_query('"13.03.2019"', '$.datetime("DD.MM.YYYY")');
 jsonb_path_query
------------------
 "2019-03-13"
(1 row)

-- behavior of PG12
SELECT jsonb_path_query('"13.03.2019"', '$.datetime("DD.MM.YYYY")');
ERROR:  bad jsonpath representation
```

- Arithmetic errors in filters suppressed:

```
-- behavior required by standard
SELECT jsonb_path_query('[1,0,2]', '$[*] ? (1 / @ >= 1)');
jsonb_path_query
------------------
 1
(1 row)
```

SQL/JSON (доп.материалы)

- Презентация по SQL/JSON
  http://www.sai.msu.su/~megera/postgres/talks/sqljson-china-2018.pdf
- Введение в SQL/JSON
  https://github.com/obartunov/sqljsondoc/blob/master/README.jsonpath.md
- Посты про SQL/JSON
  https://obartunov.livejournal.com/tag/sqljson

Postgres PROFESSIONAL

CTE

CTE

- A CTEs (Common Table Expression) is a temporary tables existing for just one query, that can be referenced from a primary query. Useful to break complex query to a readable parts — easy read and maintain.
- Most databases consider CTEs as views and optimize overall query
- Postgres implementation — always materialize CTEs
  - CTE uses work_mem, beware large results of CTEs
  - Optimization fence like <OFFSET 0>

    «*CTEs are also treated as optimization fences; this is not so much an optimizer limitation as to keep the semantics sane when the CTE contains a writable query.», Tom Lane, 2011*

    Logically equivalent queries (subselects and WITH) executed with different plans !

CTE

```
WITH RECURSIVE x(i) — idea by Graeme Job
AS (
    VALUES(0)
UNION ALL
    SELECT i + 1 FROM x WHERE i < 101
),
Z(Ix, Iy, Cx, Cy, X, Y, I)
AS (
    SELECT Ix, Iy, X::float, Y::float, X::float,
Y::float, 0
    FROM (SELECT -2.2 + 0.031 * i, i FROM x) AS
xgen(x,ix)
    CROSS JOIN
        (SELECT -1.5 + 0.031 * i, i FROM x) AS
ygen(y,iy)
    UNION ALL
    SELECT Ix, Iy, Cx, Cy, X*X – Y*Y + Cx AS X,
Y*X*2 + Cy, I + 1
    FROM Z
    WHERE X*X + Y*Y < 16.0  AND I < 27
),
Zt (Ix, Iy, I)
AS (
    SELECT Ix, Iy, MAX(I) AS I
    FROM Z
    GROUP BY Iy, Ix
    ORDER BY Iy, Ix
)
SELECT array_to_string(
    array_agg(
        SUBSTRING(' .,,,-----++++%%%%@@@@#### ',
                  GREATEST(I,1),1)),''
    )
FROM Zt
GROUP BY Iy
ORDER BY Iy;
```

CTE

- Writable CTEs always executed
- Non-referenced CTEs never executed

```
WITH yy AS
	(
		SELECT * FROM cte WHERE y > 1
	),
not_executed AS
	(
		SELECT * FROM cte
	),
always_executed AS
	(
		INSERT INTO cte VALUES(2,2) RETURNING *
	)
SELECT FROM yy WHERE x=2;
```

```
        QUERY PLAN
----------------------------
 CTE Scan on yy
   Filter: (x = 2)
   CTE yy
     ->  Seq Scan on cte
           Filter: (y > 1)
   CTE always_executed
     ->  Insert on cte cte_1
           ->  Result
(8 rows)
```

CTE is a black box for optimizer

- Break a really complex query to the well readable parts

```
CREATE TABLE cte AS SELECT x, x AS y FROM generate_series(1,10000000) AS x;
CREATE INDEX ON cte(x,y);
               Table "public.cte"
 Column |  Type   | Collation | Nullable | Default
--------+---------+-----------+----------+---------
 x      | integer |           |          |
 y      | integer |           |          |
Indexes:
    "cte_x_y_idx" btree (x, y)

-- subselects

SELECT * FROM
    (SELECT * FROM cte WHERE y>1) AS t
WHERE x=2;

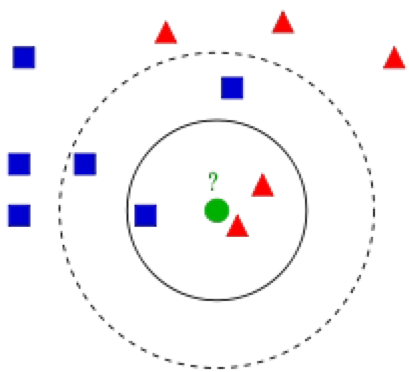
– CTE

WITH yy AS (
    SELECT * FROM cte
    WHERE y>1
)
SELECT * FROM  yy
WHERE  x=2;
```

CTE is a black box for optimizer

```
WITH yy AS ( – always materialized and cannot inlined into a parent query
    SELECT * FROM cte
    WHERE y>1
)
SELECT * FROM  yy
WHERE  x=2;

 CTE Scan on yy (actual time=0.099..3672.842 rows=1 loops=1)
   Filter: (x = 2)
   Rows Removed by Filter: 9999998
   CTE yy
     ->  Seq Scan on cte (actual time=0.097..1355.367 rows=9999999 loops=1)
           Filter: (y > 1)
           Rows Removed by Filter: 1
 Planning Time: 0.088 ms
 Execution Time: 3735.986 ms
(9 rows)

SELECT * FROM (SELECT * FROM cte WHERE y>1) as t WHERE X=2;
                                     QUERY PLAN
-------------------------------------------------------------------------------------
 Index Only Scan using cte_x_y_idx on cte (actual time=0.013..0.013 rows=1 loop
   Index Cond: ((x = 2) AND (y > 1))
   Heap Fetches: 0
 Planning Time: 0.058 ms
 Execution Time: 0.025 ms
(5 rows)
```

SURPRISE: CTE is 150 000 slower than subselect !

PG12: Controllable CTE materialization

```
WITH cte_name  AS [NOT] MATERIALIZED
```

- Writable WITH query always materialized
- Recursive WITH query always materialized

- No fencing (new default)

```
WITH yy AS (
    SELECT * FROM cte
    WHERE y=2
)
SELECT * FROM  yy
WHERE  x=2;

               QUERY PLAN
------------------------------------------
 Index Only Scan using cte_x_y_idx on cte
   Index Cond: ((x = 2) AND (y = 2))
(2 rows)
```

- Old behavior

```
WITH yy AS MATERIALIZED (
    SELECT * FROM cte
    WHERE y=2
)
SELECT * FROM  yy
WHERE  x=2;

        QUERY PLAN
---------------------------
 CTE Scan on yy
   Filter: (x = 2)
   CTE yy
     ->  Seq Scan on cte
           Filter: (y = 2)
(5 rows)
```

PG12: Controllable CTE materialization

```
WITH cte_name  AS [NOT] MATERIALIZED
```

- If a WITH query is referred to multiple times, CTE “materialize” its result to prevent double execution, use EXPLICIT NOT MATERIALIZED

```
WITH yy AS  ( SELECT * FROM cte WHERE y > 1) SELECT (SELECT count(*) FROM
yy WHERE x=2), (SELECT count(*) FROM yy WHERE x=2);
                                  QUERY PLAN
---------------------------------------------------------------------------
 Result (actual time=3922.274..3922.275 rows=1 loops=1)
   CTE yy
     ->  Seq Scan on cte (actual time=0.023..1295.262 rows=9999999 loops=1)
           Filter: (y > 1)
           Rows Removed by Filter: 1
   InitPlan 2 (returns $1)
     ->  Aggregate (actual time=3109.687..3109.687 rows=1 loops=1)
           ->  CTE Scan on yy (actual time=0.027..3109.682 rows=1 loops=1)
                 Filter: (x = 2)
                 Rows Removed by Filter: 9999998
   InitPlan 3 (returns $2)
     ->  Aggregate (actual time=812.580..812.580 rows=1 loops=1)
           ->  CTE Scan on yy yy_1 (actual time=0.016..812.575 rows=1
loops=1)
                 Filter: (x = 2)
                 Rows Removed by Filter: 9999998
 Planning Time: 0.136 ms
 Execution Time: 3939.848 ms
(17 rows)
```

PG12: Controllable CTE materialization

```
WITH cte_name  AS [NOT] MATERIALIZED
```

- If a WITH query is referred to multiple times, CTE “materialize” its result to prevent double execution, use EXPLICIT NOT MATERIALIZED

```
 WITH yy AS NOT MATERIALIZED  ( SELECT * FROM cte WHERE y > 1) SELECT
(SELECT count(*) FROM yy WHERE x=2), (SELECT count(*) FROM yy WHERE x=2);
                                               QUERY PLAN
----------------------------------------------------------------------------
 Result (actual time=0.035..0.035 rows=1 loops=1)
   InitPlan 1 (returns $0)
     ->  Aggregate (actual time=0.024..0.024 rows=1 loops=1)
           ->  Index Only Scan using cte_x_y_idx on cte (actual
time=0.019..0.020 rows=1 loops=1)
                 Index Cond: ((x = 2) AND (y > 1))
                 Heap Fetches: 1
   InitPlan 2 (returns $1)
     ->  Aggregate (actual time=0.006..0.006 rows=1 loops=1)
           ->  Index Only Scan using cte_x_y_idx on cte cte_1 (actual
time=0.004..0.005 rows=1 loops=1)
                 Index Cond: ((x = 2) AND (y > 1))
                 Heap Fetches: 1
 Planning Time: 0.253 ms
 Execution Time: 0.075 ms
(13 rows)
```

Efficient K-nearest neighbour search in PostgreSQL

Knn-search: The problem

- What are the closest restaurants near Park Inn Пулковская, Санкт-Петербург ?
- What happens in the world near the launch of Sputnik ?
- Reverse image search, search by image
- …………
- GIS, Science (high-dimensional data)



K-nearest neighbour search

- 10 closest events to the launch of Sputnik ?

```
SELECT id, date, event FROM events
ORDER ABS(date - '1957-10-04'::date) ASC LIMIT 10;
   id   |    date    |                                 event
--------+------------+-----------------------------------------------------------------
  58136 | 1957-10-04 | "Leave It to Beaver," debuts on CBS
  58137 | 1957-10-04 | U.S.S.R. launches Sputnik I, 1st artificial Earth satellite
 117062 | 1957-10-04 | Gregory T Linteris, Demarest, New Jersey, astronaut, sk: STS 83
 117061 | 1957-10-04 | Christina Smith, born in Miami, Florida, playmate, Mar, 1978
 102671 | 1957-10-05 | Lee "Kix" Thompson, saxophonist, Madness-Baggy Trousers
 102670 | 1957-10-05 | Larry Saumell, jockey
  58292 | 1957-10-05 | Yugoslav dissident Milovan Djilos sentenced to 7 years
  58290 | 1957-10-05 | 11th NHL All-Star Game: All-Stars beat Montreal 5-3 at Montreal
  31456 | 1957-10-03 | Willy Brandt elected mayor of West Berlin
  58291 | 1957-10-05 | 12th Ryder Cup: Britain-Ireland, 7 -4 at Lindrick GC, England
(10 rows)
```

- Slow: Index is useless, full heap scan, sort, limit

```
Limit (actual time=54.481..54.485 rows=10 loops=1)
   Buffers: shared hit=1824
   ->  Sort (actual time=54.479..54.481 rows=10 loops=1)
         Sort Key: (abs((date - '1957-10-04'::date)))
         Sort Method: top-N heapsort  Memory: 26kB
         Buffers: shared hit=1824
         ->  Seq Scan on events (actual time=0.020..25.896 rows=151643 loops=1)
               Buffers: shared hit=1824
 Planning Time: 0.091 ms
 Execution Time: 54.513 ms
(10 rows)
```

Knn-search: Existing solutions

- Traditional way to speedup query
  - Indexes are very inefficient (no predicate)
  - Constrain data space (range search)
    - Incremental search → to many queries
    - Need to know in advance size of neighbourhood, how ?
      1Km is ok for Paris, but too small for Siberia
    - Maintain 'density map' ?

Knn-search: What do we want !

- We want to avoid full table scan – read only <right> tuples
  - So, we need index
- We want to avoid sorting – read <right> tuples in <right> order
  - So, we need special strategy to traverse index
- We want to support tuples visibility
  - So, we should be able to resume index traverse

Knn-search: What do we want !

- We want to avoid full table scan – read only <right> tuples
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- We want to support tuples visibility
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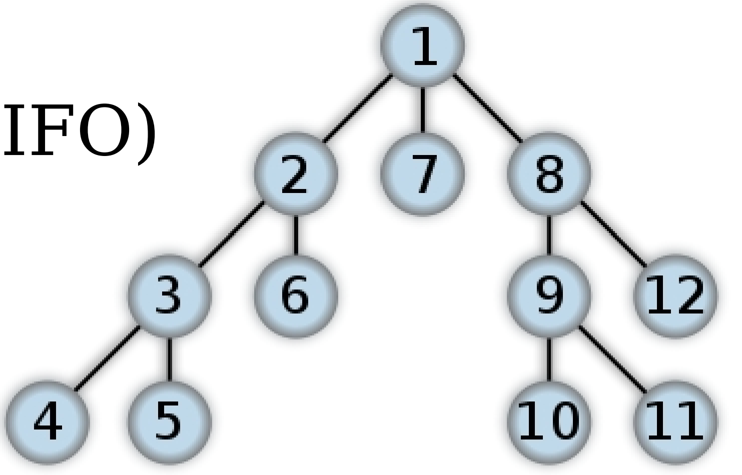
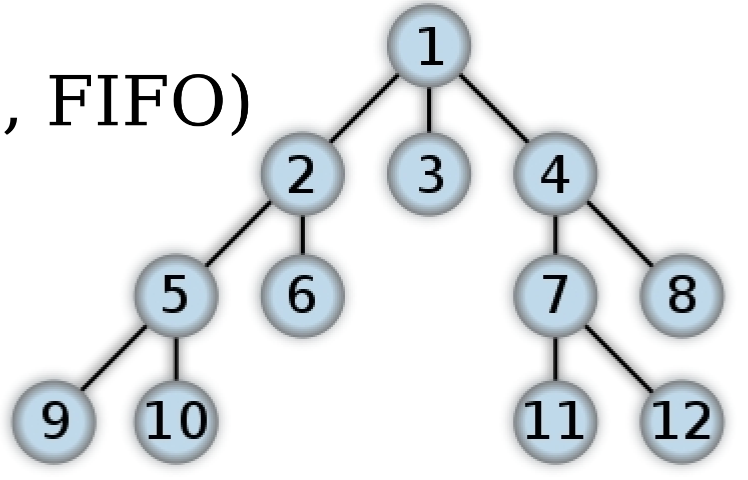
Knn-search: Index traverse

- Depth First Search (stack, LIFO)

  R-tree search



- Breadth First Search (queue, FIFO)



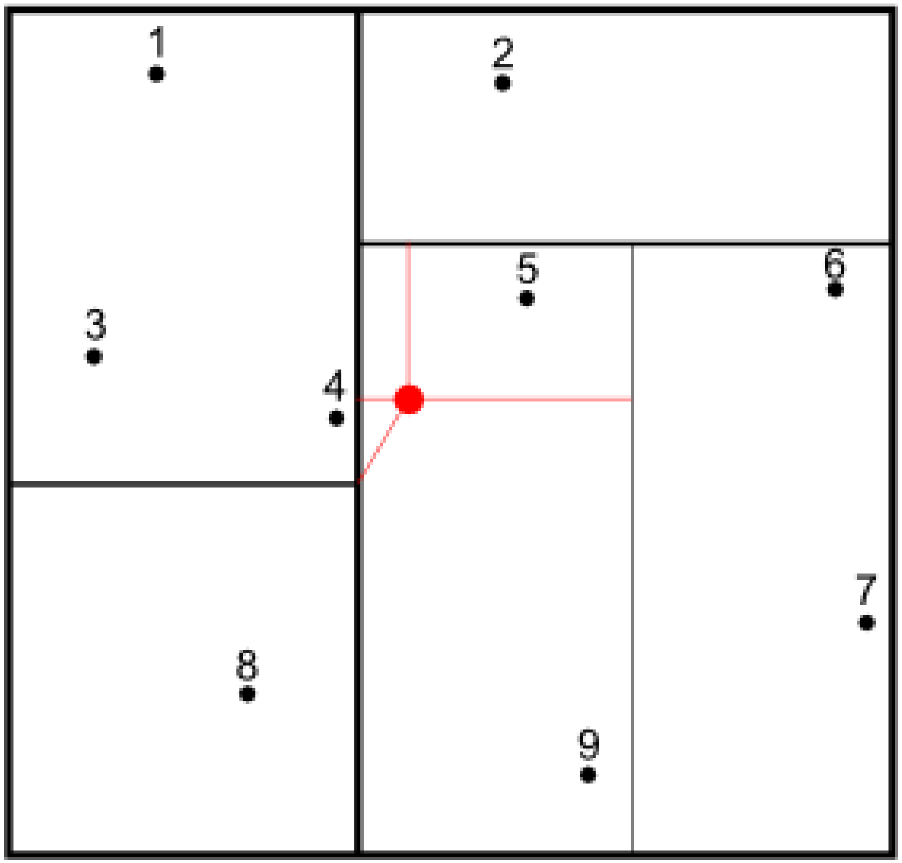
- Both strategies are not good for us – full index scan

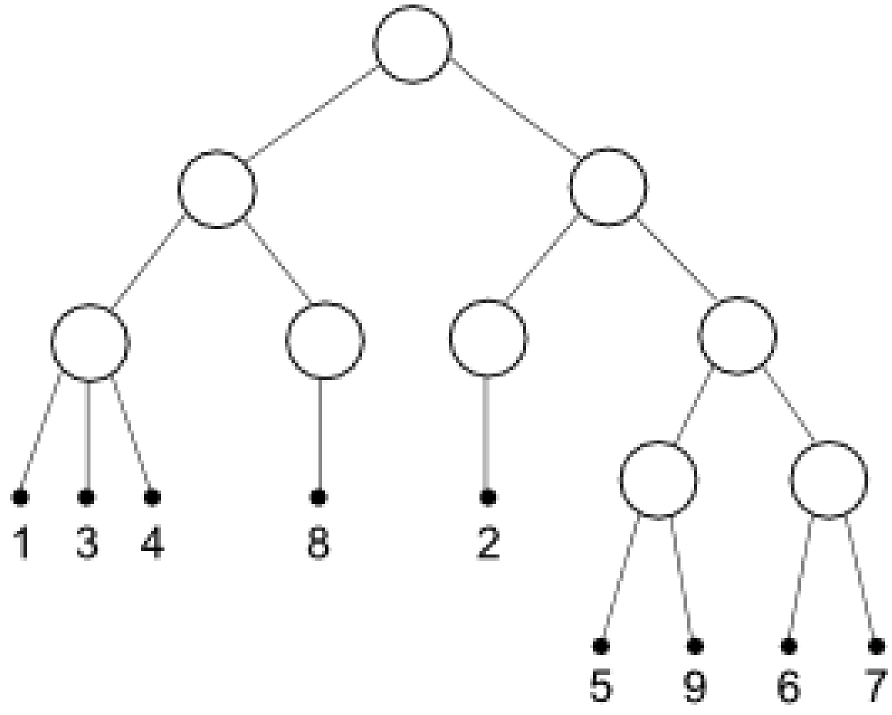
Knn-search: Index traverse

- Best First Search (PQ, priority queue). Maintain order of items in PQ according their distance from given point
  - Distance to MBR (rectangle for Rtree) for internal pages
    - minimum distance of all items in that MBR
  - Distance = 0 for MBR with given point
  - Distance to point for leaf pages
- Each time we extract point from PQ we output it – it is next closest point ! If we extract rectangle, we expand it by pushing their children (rectangles and points) into the queue.
- We traverse index by visiting only interesting nodes !

Knn-search: Index traverse

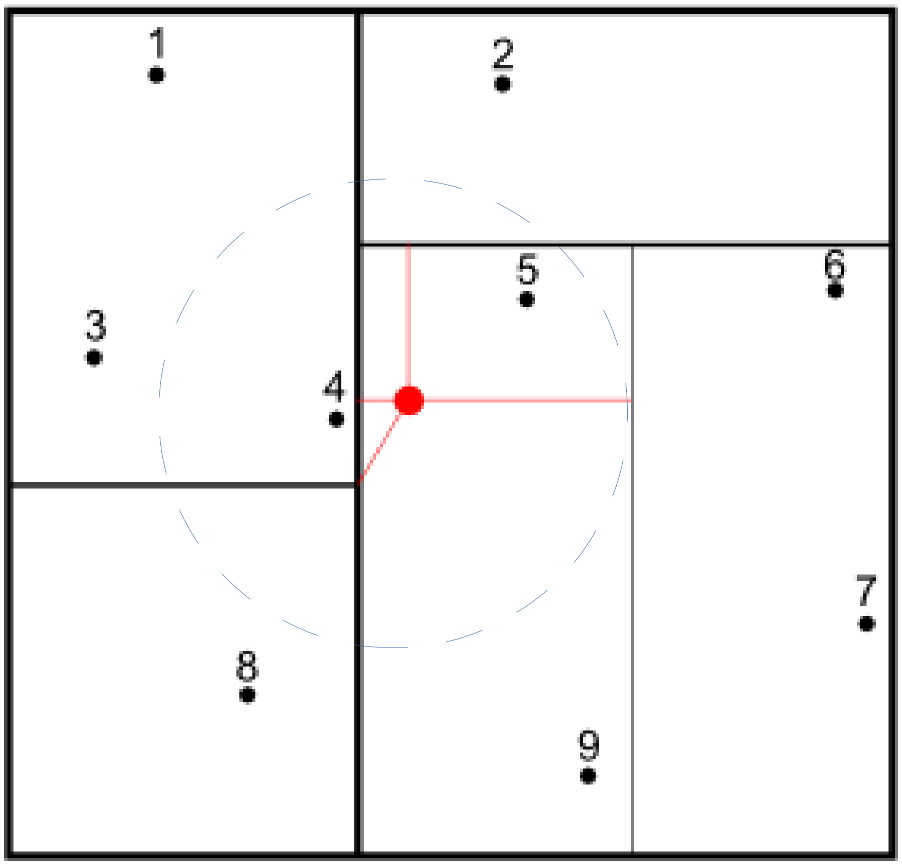
- Simple example – non-overlapped partitioning





Knn-search: Index traverse

- Example – non-overlapped partitioning



- Priority Queue

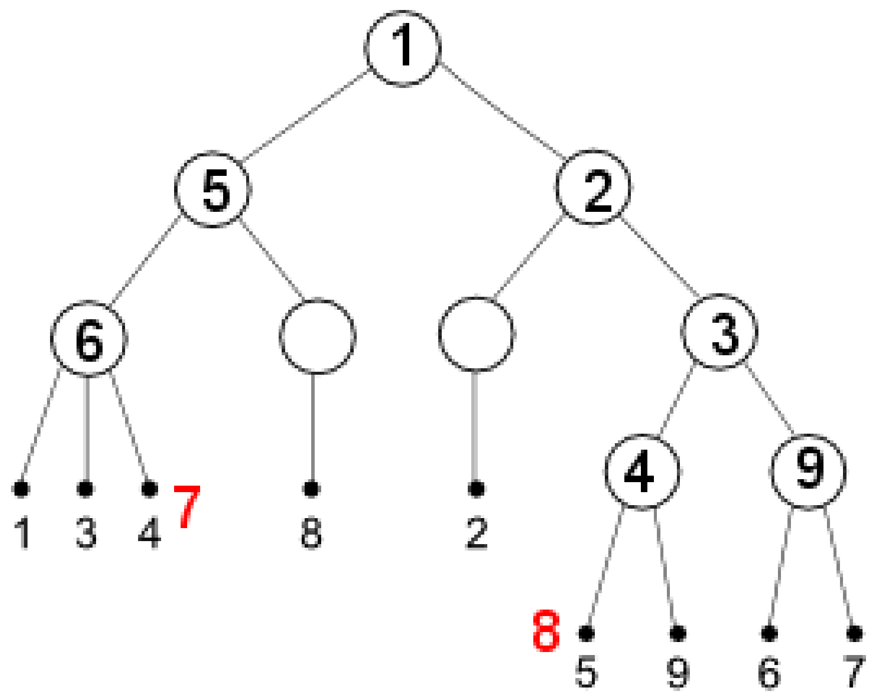
- 1: {1,2,3,4,5,6,7,8,9}
- 2: {2,5,6,7,9}, {1,3,4,8}
- 3: {5,6,7,9}, {1,3,4,8}, {2}
- 4: {5,9}, {1,3,4,8}, {2}, {6,7}
- 5: {1,3,4,8}, 5, {2}, {6,7}, 9
- 6: {1,3,4}, {8}, 5, {2}, {6,7}, 9
- 7: 4, {8}, 5, {2}, {6,7}, 3, 1, 9

  we can output 4 without visit other rectangles !

- 8: 5, {2}, {6,7}, 3, 8, 1, 9
- 9: {6,7}, 3, 2, 8, 1, 9
- 10: 3, 2, 8, 1, 9, 6, 7

Knn-search: Index traverse

- Example – non-overlapped partitioning



- Priority Queue
  - 1: {1,2,3,4,5,6,7,8,9}
  - 2: {2,5,6,7,9}, {1,3,4,8}
  - 3: {5,6,7,9}, {1,3,4,8}, {2}
  - 4: {5,9}, {1,3,4,8}, {2}, {6,7}
  - 5: {1,3,4,8}, 5, {2}, {6,7}, 9
  - 6: {1,3,4}, {8}, 5, {2}, {6,7}, 9
  - **7: 4**, {8}, 5, {2}, {6,7}, 3, 1, 9
  - 8: 5, {2}, {6,7}, 3, 8, 1, 9

Knn-search: Performance

- SEQ (no index) – base performance
  - Sequentially read full table + Sort full table (can be very bad, sort_mem !)
- DFS – very bad !
  - Full index scan + Random read full table + Sort full table
- BFS – the best for small k !
  - Partial index scan + Random read k-records
    - T(index scan) ~ Height of Search tree ~ log(n)
  - Performance win BFS/SEQ ~ Nrelpages/k, for small k. The more rows, the more benefit !
  - Can still win even for k=n (for large tables) - no sort !

K-nearest neighbour search

```
SELECT id, date, event FROM events
ORDER ABS(date - '1957-10-04'::date) ASC LIMIT 10;
Limit (actual time=54.481..54.485 rows=10 loops=1)
   Buffers: shared hit=1824
   ->  Sort (actual time=54.479..54.481 rows=10 loops=1)
         Sort Key: (abs((date - '1957-10-04'::date)))
         Sort Method: top-N heapsort  Memory: 26kB
         Buffers: shared hit=1824
         ->  Seq Scan on events (actual time=0.020..25.896 rows=151643 loops=1)
               Buffers: shared hit=1824
 Planning Time: 0.091 ms
 Execution Time: 54.513 ms
(10 rows)
```

KNN-GiST (Btree-GiST)

```
SELECT id, date, event FROM events
ORDER BY date <-> '1957-10-04'::date ASC LIMIT 10;
                                        QUERY PLAN
----------------------------------------------------------------------------------------------
 Limit (actual time=0.128..0.145 rows=10 loops=1)
   ->  Index Scan using events_date_idx1 on events (actual time=0.128..0.142 rows=10 loops=1)
         Order By: (date <-> '1957-10-04'::date)
 Planning Time: 0.155 ms
 Execution Time: 0.186 ms
(5 rows)
```

KNN SP-GiST (committed)

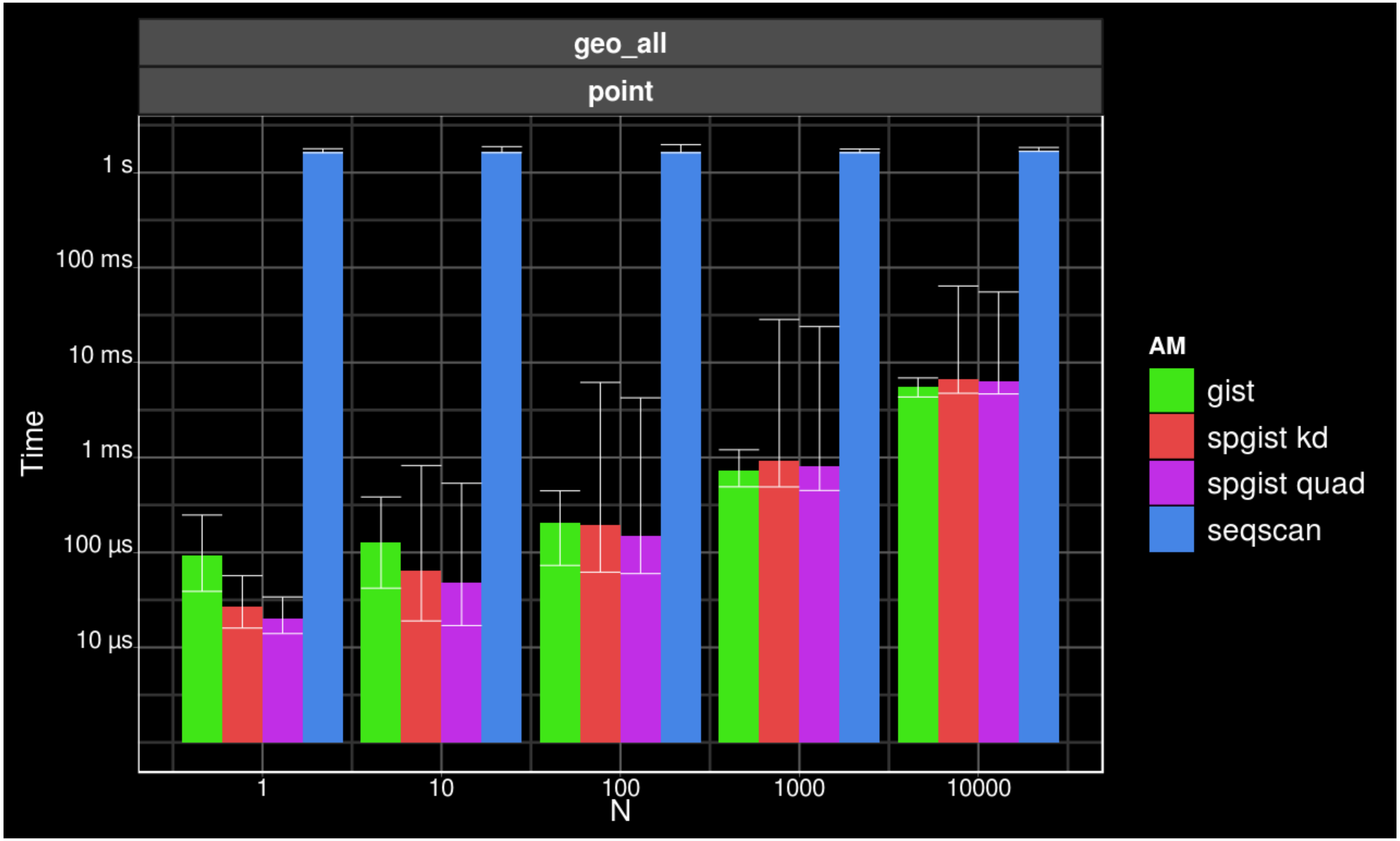
```
SELECT *
FROM knn_test
ORDER BY p <-> point(:x,:y) LIMIT :n;
```

	GiST		SP-GiST	
n	time, ms	buffers	time, ms	buffers
10	0,12	14	0,07	18
100	0,27	110	0,2	118
1000	1,58	1231	1,51	1264

KNN-SPGiST (committed)

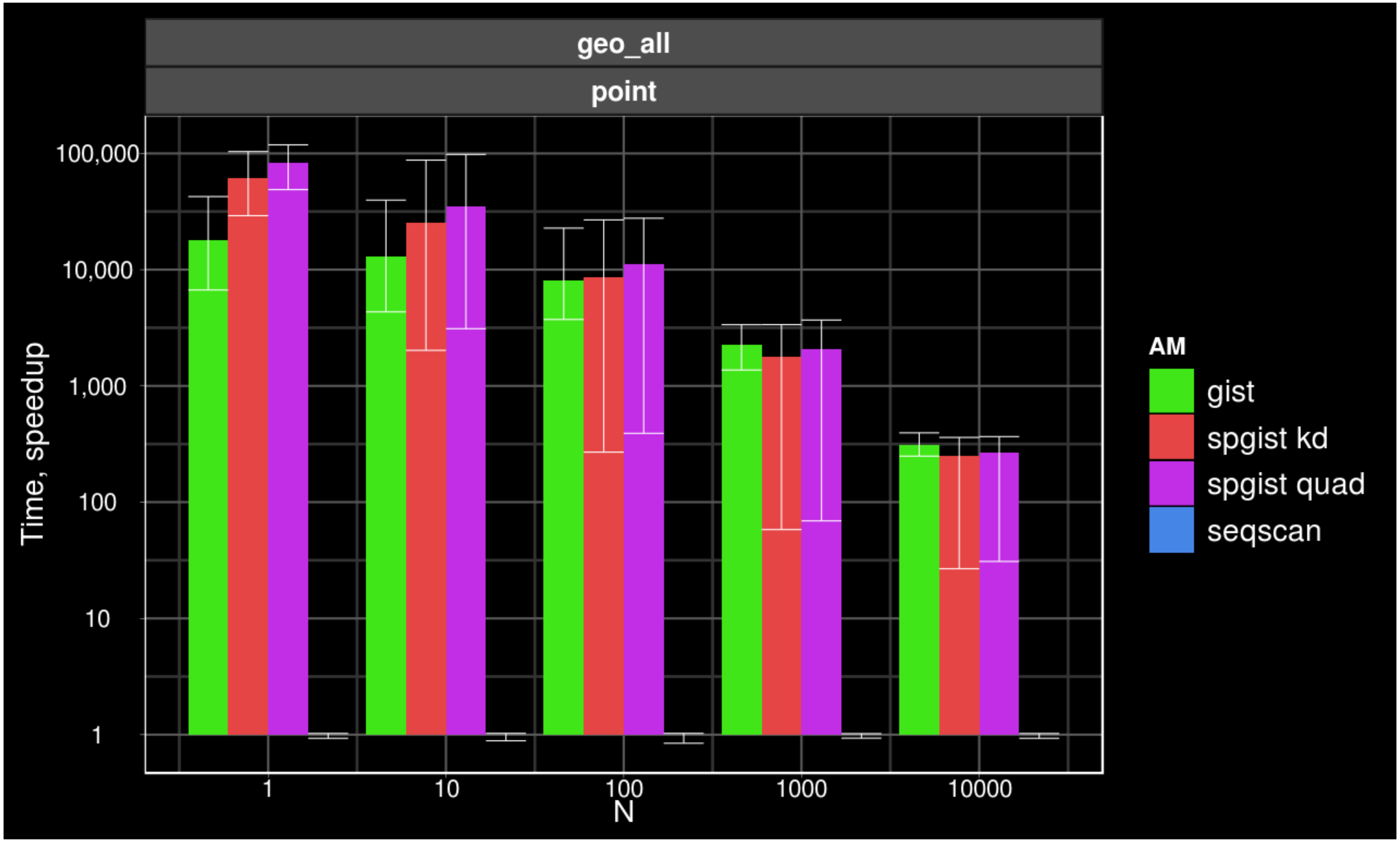
7240858 points (geonames)

SELECT point, point <-> ? FROM geo_all ORDER BY 2 LIMIT ?
KD-tree, Quad-tree



KNN-SPGiST (committed)

KNN Speedup



KNN B-tree (in-progress)

```
SELECT * FROM events
ORDER BY date <-> '2000-01-01'::date ASC
LIMIT 100;
```

	KNN B-tree		btree_gist		union		seq scan	
k	time, ms	buffers	time, ms	buffers	time, ms	buffers	time, ms	buffers
1	0.041	4	0.079	4	0.060	8	41.1	1824
10	0.048	7	0.091	9	0.097	17	41.8	1824
100	0.107	47	0.192	52	0.342	104	42.3	1824
1000	0.735	573	0.913	650	2.970	1160	43.5	1824
10000	5.070	5622	6.240	6760	36.300	11031	54.1	1824
100000	49.600	51608	61.900	64194	295.100	94980	115.0	1824

Covering GiST

- Include non-indexed columns into index to greatly improve Index-only scan (index should contains all columns from query)
  - Index is smaller than composite index
  - No need opclass for column

- PG11: INCLUDE for B-tree
  One index for UNIQUE/PRIMARY and INCLUDE to use Index-only scan

```
CREATE TABLE foo (id int, col1 text, col2 text,  primary key (id) include (col1,col2));
```

- PG12: INCLUDE for GiST

```
CREATE INDEX ON mowboxes USING  gist(bounds) INCLUDING (ip);
```

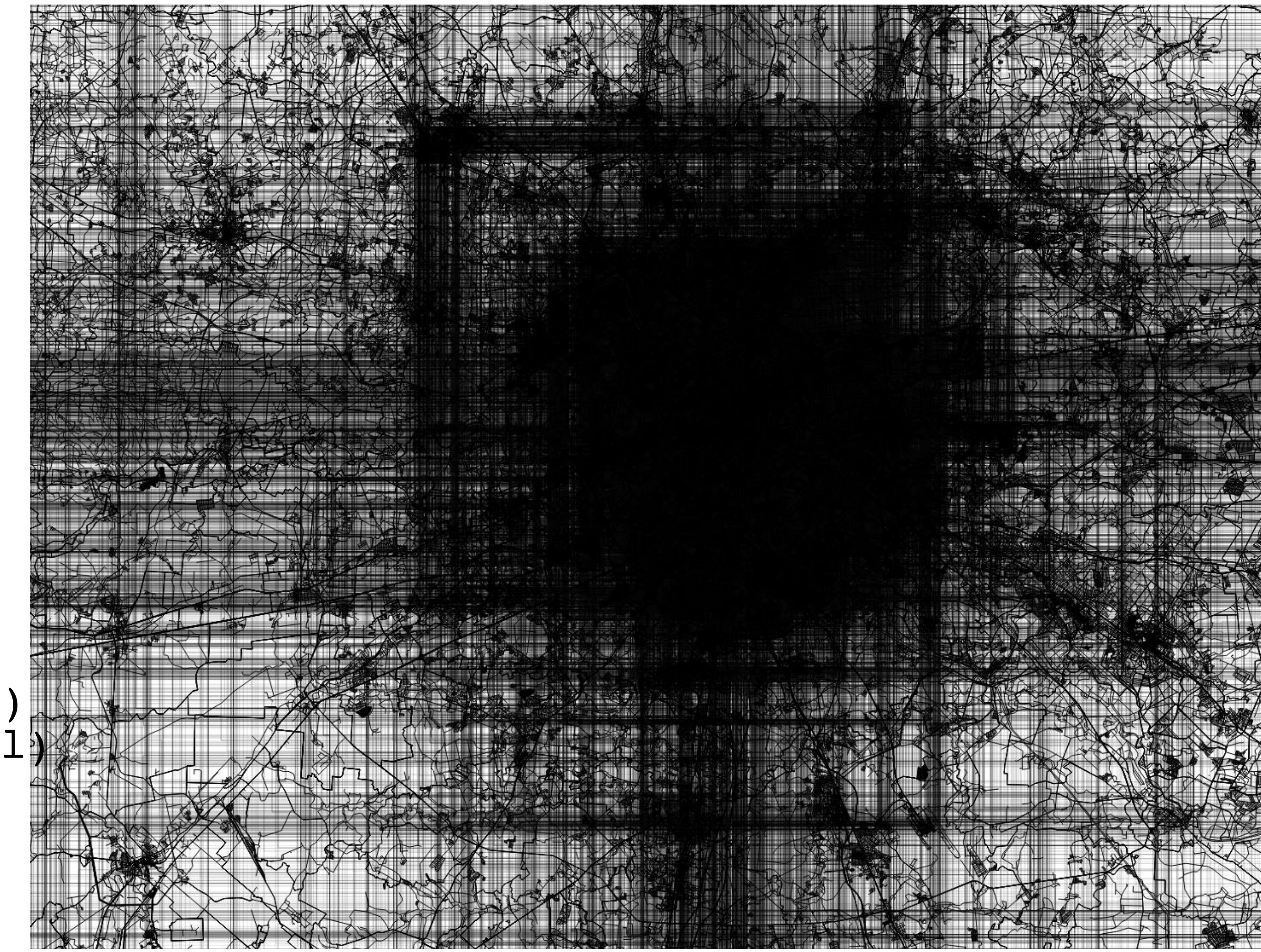
Covering GiST

Test data — 7803499 boxes with additional columns

```
\d mowboxes

  Column   |  Type
-----------+----------
 Ip        | cidr
 num       | integer
 center    | point
 bounds    | box
 Tsbounds  | tsrange

Indexes:
gist (bounds)
gist (bounds,ip)
gist (bounds)INCLUDE(ip)
gist (bounds)INCLUDE(all)
```



```
SELECT ip,bounds  FROM mowboxes WHERE bounds @>  some::point
```

Covering GiST

Test data — 7803499 boxes with additional columns

```
\d mowboxes

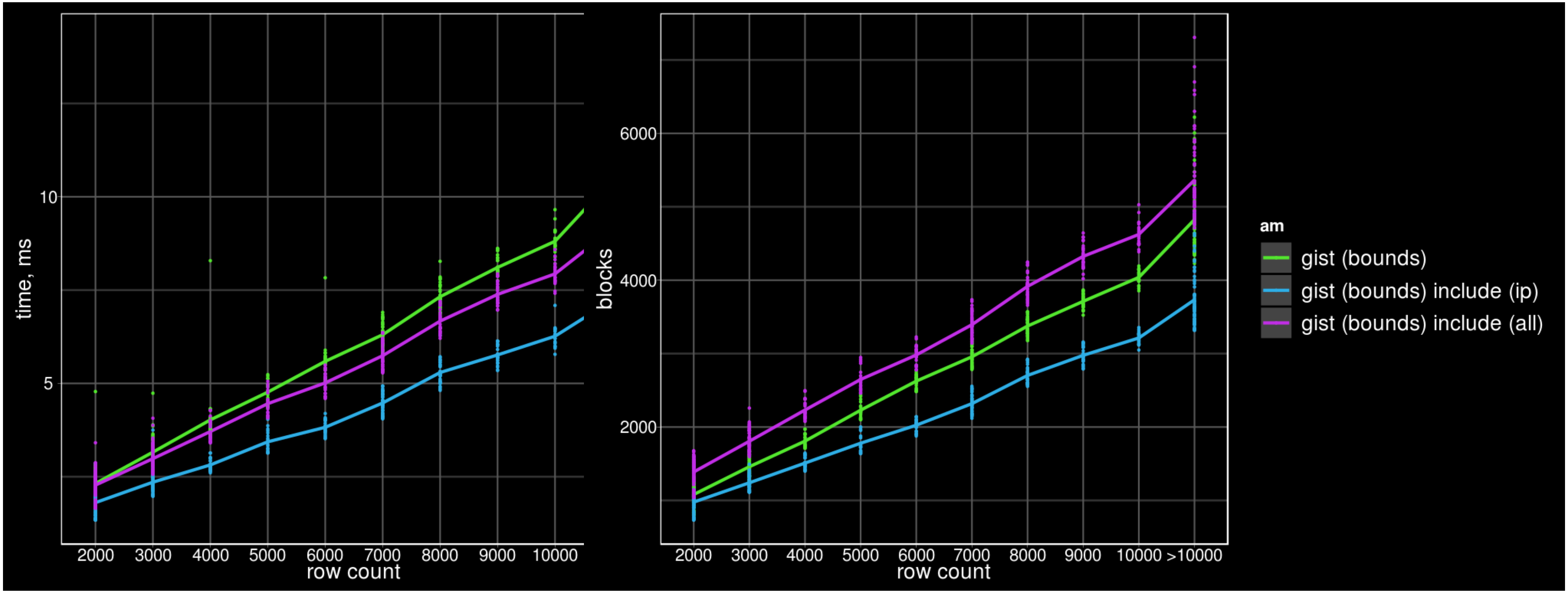
  Column   |  Type
----------+---------
 Ip        | cidr
 num       | integer
 center    | point
 bounds    | box
 Tsbounds  | tsrange

Indexes:
gist (bounds)                  665 MB
gist (bounds,ip)               876 MB
gist (bounds)INCLUDE(ip)       788 MB
gist (bounds)INCLUDE(all)     1498 MB
```

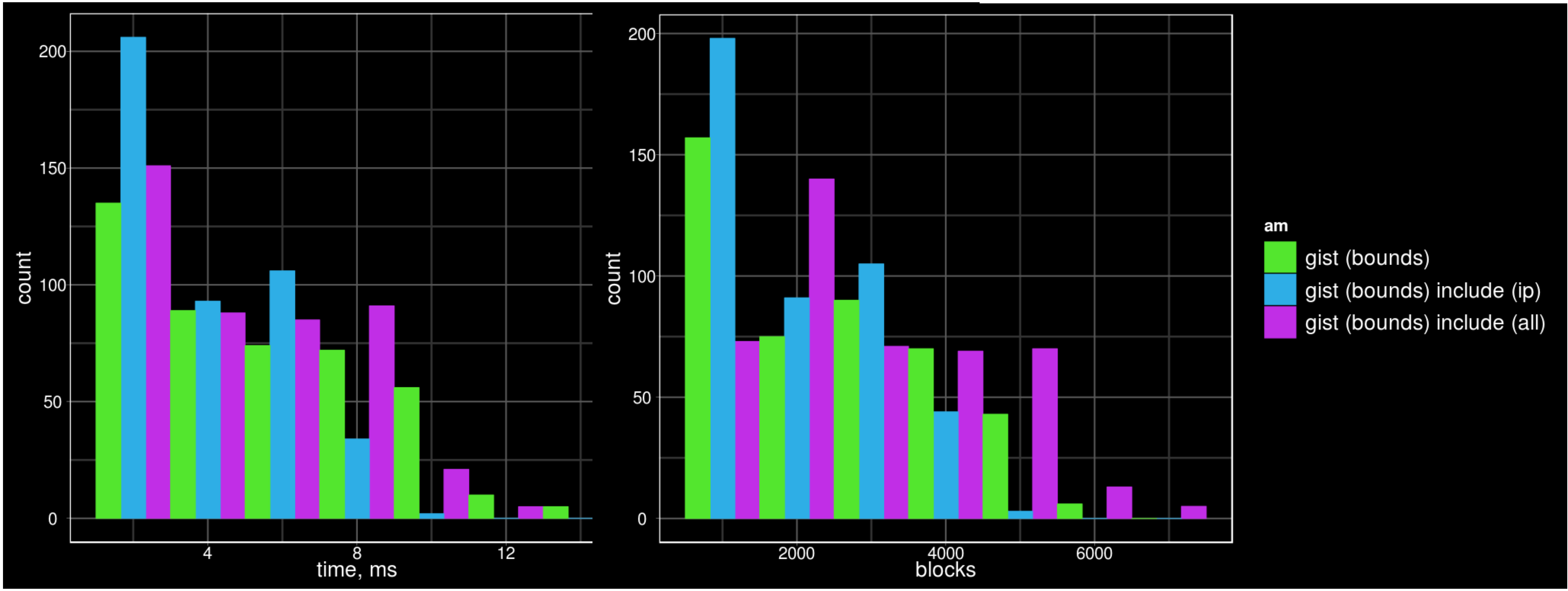
TEST QUERY (POINTs from (37.0, 55.0) - (47.5, 65.0) , step 0.5):

SELECT ip,bounds FROM mowboxes WHERE bounds @> POINT::point

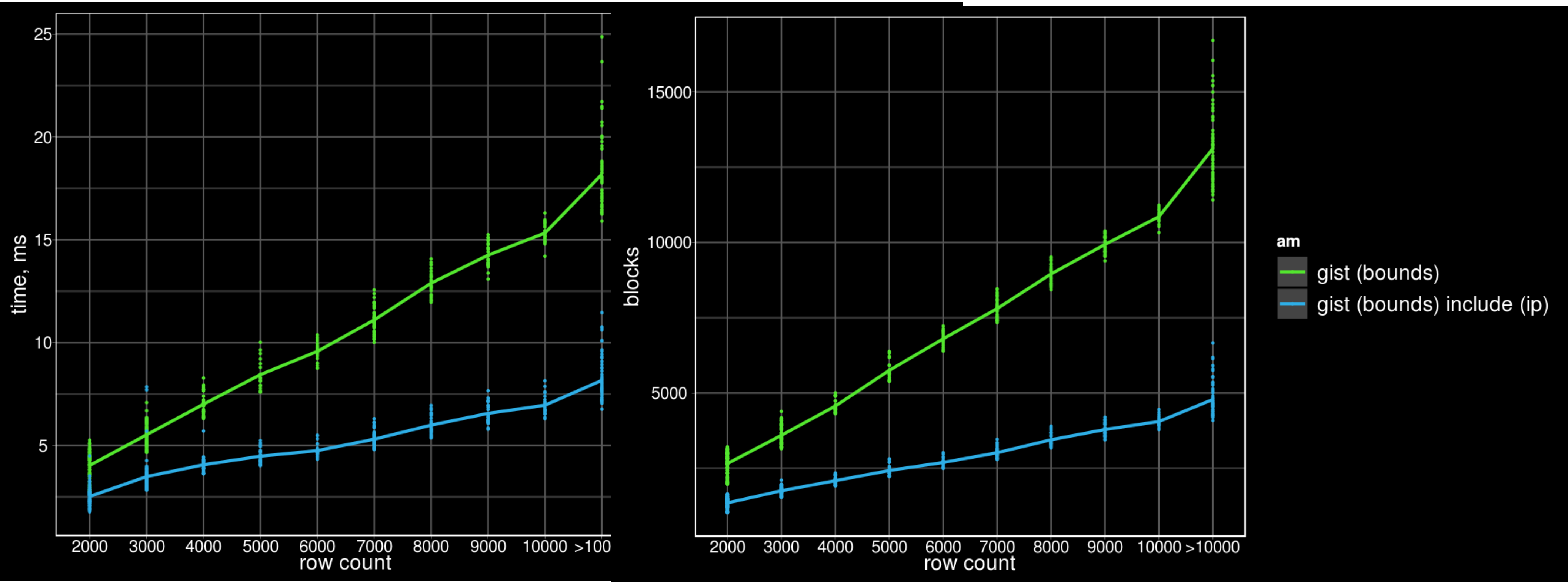
Covering GiST



Covering GiST



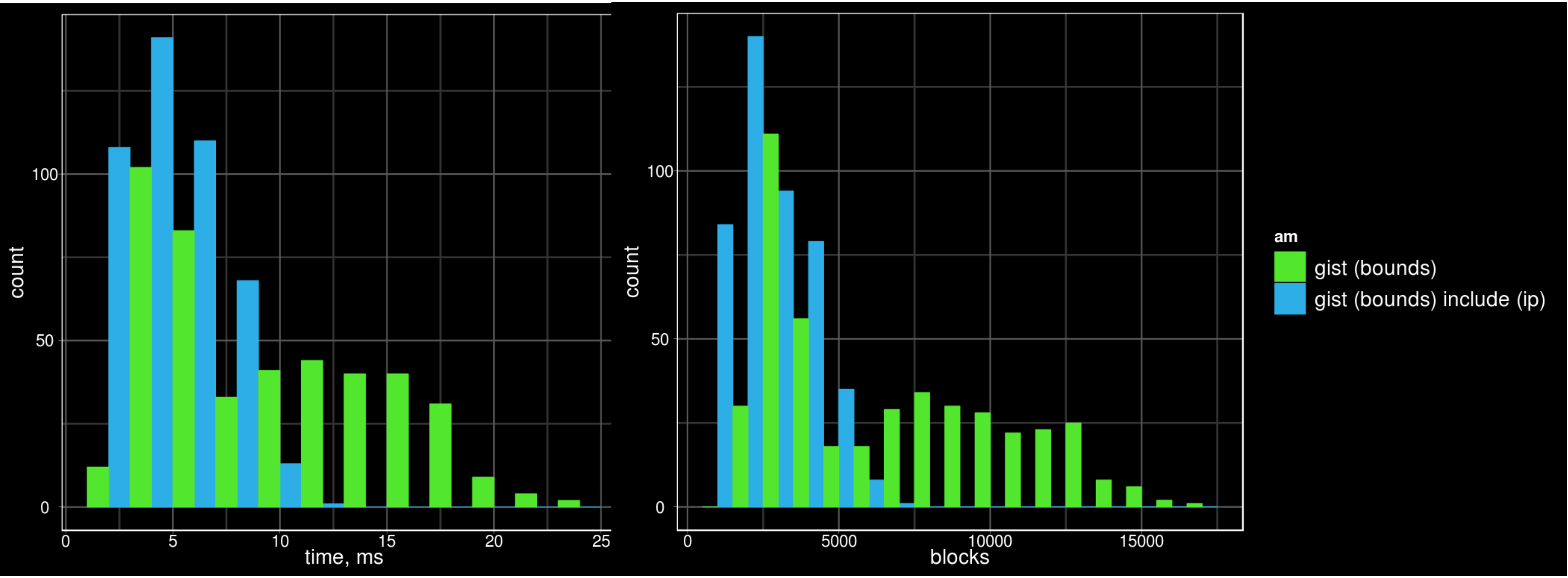
Covering GiST (randomize)



Randomize table:

CREATE TABLE mowboxes_rnd AS SELECT * FROM mowboxes ORDER BY random();

Covering GiST (randomize)



Randomize table:

CREATE TABLE mowboxes_rnd AS SELECT * FROM mowboxes ORDER BY random();

Covering GiST improves utility and performance of index-only scan

Generate less WAL during GiST, GIN and SP-GiST index build

Instead of WAL-logging every modification during the build separately, first build the index without any WAL-logging, and make a separate pass through the index at the end, to write all pages to the WAL. This significantly reduces the amount of WAL generated, and is usually also faster, despite the extra I/O needed for the extra scan through the index. WAL generated this way is also faster to replay.

IMDB database in json format: 4189128 rows, 2938 MB

CREATE INDEX ON imdb USING gin(jb jsonb_path_ops);

BEFORE:
TIME: 205115.236 ms, WAL: 3201 MB

AFTER:
TIME: 133554.225 ms, WAL: 406 MB

Useful functions:
pg_current_wal_lsn(),   pg_size_pretty(pg_wal_lsn_diff());

REINDEX CONCURRENTLY

```
REINDEX [ ( VERBOSE ) ] { INDEX | TABLE | SCHEMA | DATABASE | SYSTEM }
            [ CONCURRENTLY ] name
```

- Not the SYSTEM tables
- Longer build and more resources, but no lock for insert, update, delete operations
- Failed REINDEX may leave invalid indexes (manual drop)
- Temporal name for indexes: <name>_ccnew, <name>_ccold

Report progress of CREATE INDEX/REINDEX operations

- Infrastructure of progress reporting:

  pg_stat_progress_cluster
  pg_stat_progress_vacuum
  pg_stat_progress_create_index

```
select relid::regclass, phase,
format('lockers: %s/%s (%s)', lockers_done, lockers_total, current_locker_pid) as lockers,
format('blocks: %s/%s', blocks_done, blocks_total) as blocks,
format('tuples: %s/%s', tuples_done, tuples_total) as tuples,
format('partitions: %s/%s', partitions_done, partitions_total) as partitions
from pg_stat_progress_create_index
\watch 0,1
```

```
imdb   | waiting for reader snapshots | lockers: 0/1 (23097) | blocks: 314490/314491 | tuples: 0/0 | partitions: 0/0
jb     | building index               | lockers: 0/0 (0)     | blocks: 171478/175168 | tuples: 0/0 | partitions: 0/0

imdb   | waiting for reader snapshots | lockers: 0/1 (23097) | blocks: 314490/314491 | tuples: 0/0 | partitions: 0/0
jb     | building index               | lockers: 0/0 (0)     | blocks: 173329/175168 | tuples: 0/0 | partitions: 0/0

imdb   | waiting for reader snapshots | lockers: 0/1 (23097) | blocks: 314490/314491 | tuples: 0/0 | partitions: 0/0
jb     | building index               | lockers: 0/0 (0)     | blocks: 174894/175168 | tuples: 0/0 | partitions: 0/0

imdb   | waiting for reader snapshots | lockers: 0/1 (23097) | blocks: 314490/314491 | tuples: 0/0 | partitions: 0/0
jb     | building index               | lockers: 0/0 (0)     | blocks: 175097/175168 | tuples: 0/0 | partitions: 0/0
```

Stonebraker «Navigating database Universe»

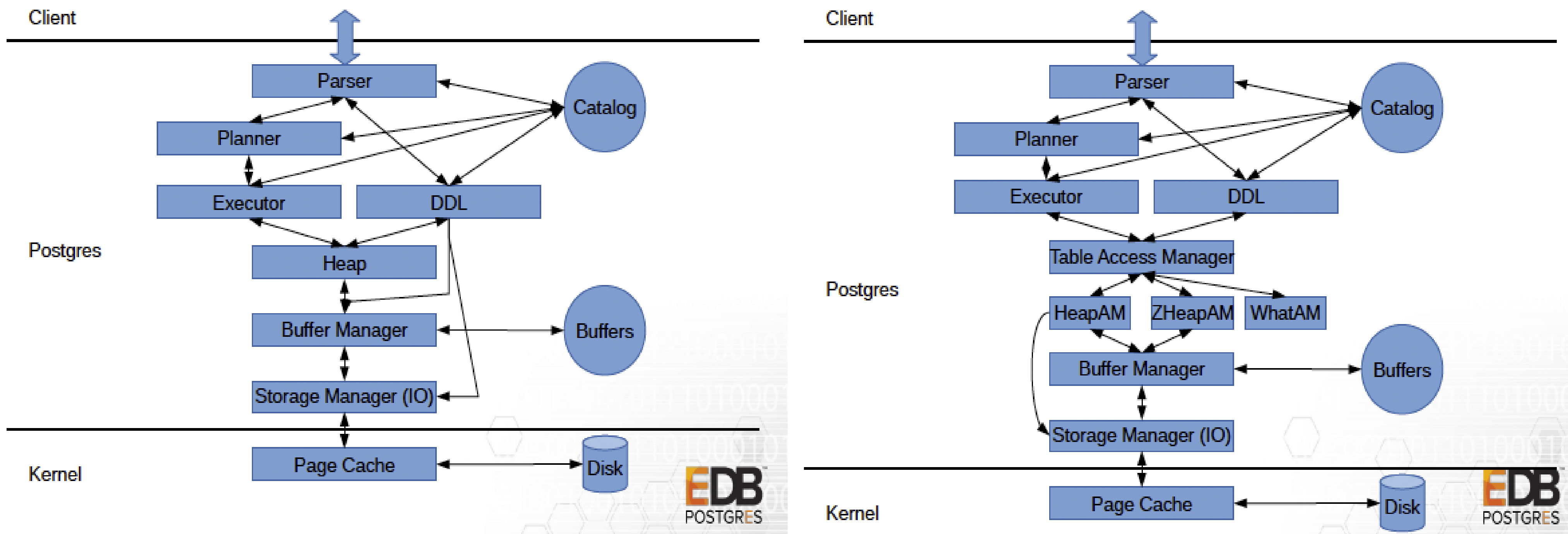
#2: Get the Implementation Right

- **Leverage a few simple ideas:** Early relational implementations
  - System R storage system dropped links
  - Views (protection, schema modification, performance)
  - Cost-based optimizer
- **Leverage a few simple ideas:** Postgres
  - User-defined data types and functions (adopted by most everybody)
  - Rules/triggers
  - No-overwrite storage
- **Leverage a few simple ideas:** Vertica
  - Store data by column
  - Compressed up the ging gong
  - Parallel load without compromising ACID

Historical Winners

Pluggable storage

- Better Postgres extensibility
  - Storage is about tables/mat.views
  - Replace hardcoded *heap* by Table Access Manager
  - Several Table AMs coexists, could be added online
  - Examples: columnar, append-only, ZHeap, in-memory..



Andres Freund, http://anarazel.de/talks/2018-10-25-pgconfeu-pluggable-storage/pluggable.pdf

Pluggable storage

- Better Postgres extensibility
  - Table access method
    CREATE ACCESS METHOD ... TYPE TABLE

```
\dA+
                              List of access methods
  Name   | Type  |       Handler        |               Description
---------+-------+----------------------+----------------------------------------
 brin    | Index | brinhandler          | block range index (BRIN) access method
 btree   | Index | bthandler            | b-tree index access method
 gin     | Index | ginhandler           | GIN index access method
 gist    | Index | gisthandler          | GiST index access method
 hash    | Index | hashhandler          | hash index access method
 heap    |       | heap_tableam_handler | heap table access method
 spgist  | Index | spghandler           | SP-GiST index access method
(7 rows)
```

Pluggable storage

- Better Postgres extensibility
  - CREATE EXTENSION my_storage;
  - CREATE TABLE ... USING my_storage;
  - SET default_table_access_method = 'my_storage';

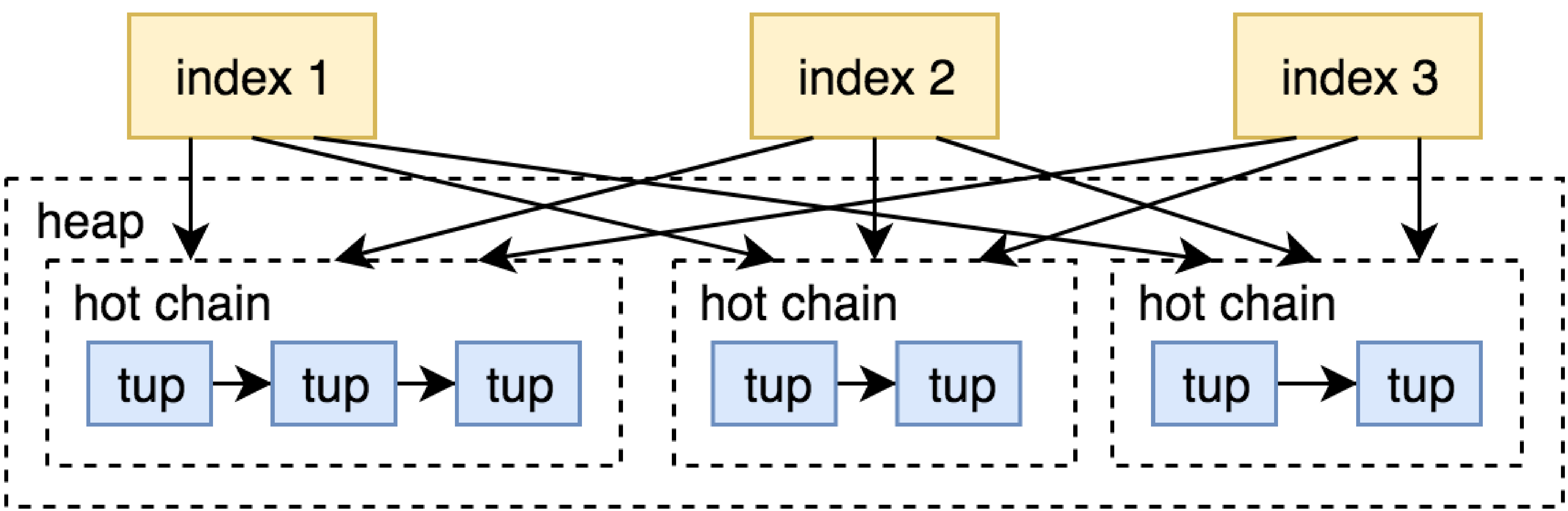
```
 =# CREATE TABLE bar() USING HEAP;
CREATE TABLE
=# show default_table_access_method;
 default_table_access_method
-----------------------------
 heap
(1 row)
```

Pluggable storage (in-progress)

- Support for INSERT/UPDATE/DELETE, triggers etc.
- Support for custom maintenance (own vacuum).
- Support for table rewrite.
- Support for custom tuple format.
- Support for custom tuple storage.
- Index-heap relationship must be the same. Only HOT-like update OR insertion to EVERY index.
- Row must be identified by 6-byte TID.
- System catalog must be heap.

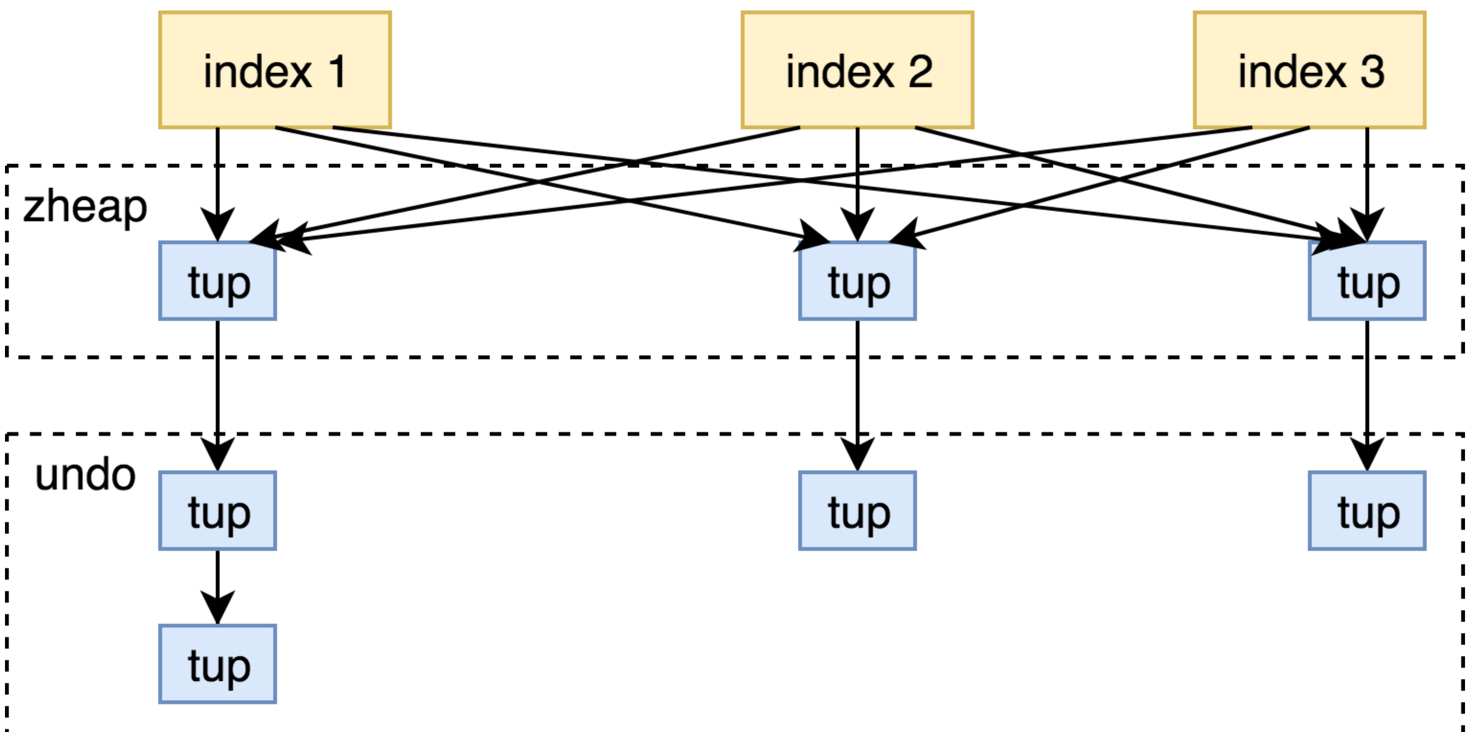
ZHeap (in-progress)

- MVCC implementation:
  - Oracle, MySQL, SQL Server: old versions are in other place
  - MVCC in Postgres: all row versions are in table
    - Table bloat, write amplification



ZHeap (in-progress)

- ZHeap — new storage for PostgreSQL with UNDO (No Vacuum storage)
  - The old versions of rows are in undo log
  - Reverse all changes made by aborted transactions



ZHeap (in-progress)

- ZHeap — new storage for PostgreSQL with UNDO
  - In-place updates (when possible) — less bloat
    - But, In-place update don“t need an extra space for new tuple on page as HOT, only if new tuple is wider.
    - In-place update like a HOT update (can“t modify any indexed columns)
  - Reclame space after transaction (committed or aborted)
  - Avoid non-modification data writes, like hint-bits
  - Shorter tuple header (no xmin,xmax, cmin,cmax)
    - UNDO log contains most of data for MVCC
    - Zheap is smaller on disk

Partitioning improvements

- Generalized expression syntax for partition bounds

  The expression is evaluated once at the table creation time so it can involve even volatile expressions such as CURRENT_TIMESTAMP.

```
CREATE TABLE part (ts timestamp)PARTITION BYRANGE(ts);

CREATE TABLE part1 PARTITION OF part FOR VALUES
FROM ('2018-01-01') TO (current_timestamp + '1 day');
```

```
                                   Partitioned table "public.part"
 Column |            Type             | Collation | Nullable | Default | Storage
| Stats target | Description
--------+-----------------------------+-----------+----------+---------+---------
+--------------+-------------
 ts     | timestamp without time zone |           |          |         | plain
|              |
Partition key: RANGE (ts)
Partitions: part1 FOR VALUES FROM ('2018-01-01 00:00:00') TO ('2019-04-05
16:07:12.253855')
```

Partitioning improvements

- Run-time partition pruning for MergeAppend

```
# EXPLAIN ANALYZE  SELECT * FROM news
  WHERE category = (SELECT category FROM hot_category)
  ORDER BY ts LIMIT 10;

 Limit  (cost=36.79..37.26 rows=10 width=12) (actual time=0.035..0.044 rows=10
loops=1)
   InitPlan 1 (returns $0)
     ->  Seq Scan on hot_category  (cost=0.00..35.50 rows=2550 width=4)
(actual time=0.011..0.012 rows=1 loops=1)
   ->  Merge Append  (cost=1.29..46833.10 rows=1000000 width=12)
(actual time=0.033..0.040 rows=10 loops=1)
         Sort Key: news_cat1.ts
         ->  Index Scan using news_cat1_ts_idx on news_cat1
             (cost=0.42..11302.75 rows=333333 width=12)
             (actual time=0.016..0.021 rows=10 loops=1)
               Filter: (category = $0)
         ->  Index Scan using news_cat2_ts_idx on news_cat2
             (cost=0.42..11302.77 rows=333334 width=12)
             (never executed)
               Filter: (category = $0)
         ->  Index Scan using news_cat3_ts_idx on news_cat3
             (cost=0.42..11302.75 rows=333333 width=12)
             (never executed)
               Filter: (category = $0)
```

Partitioning improvements

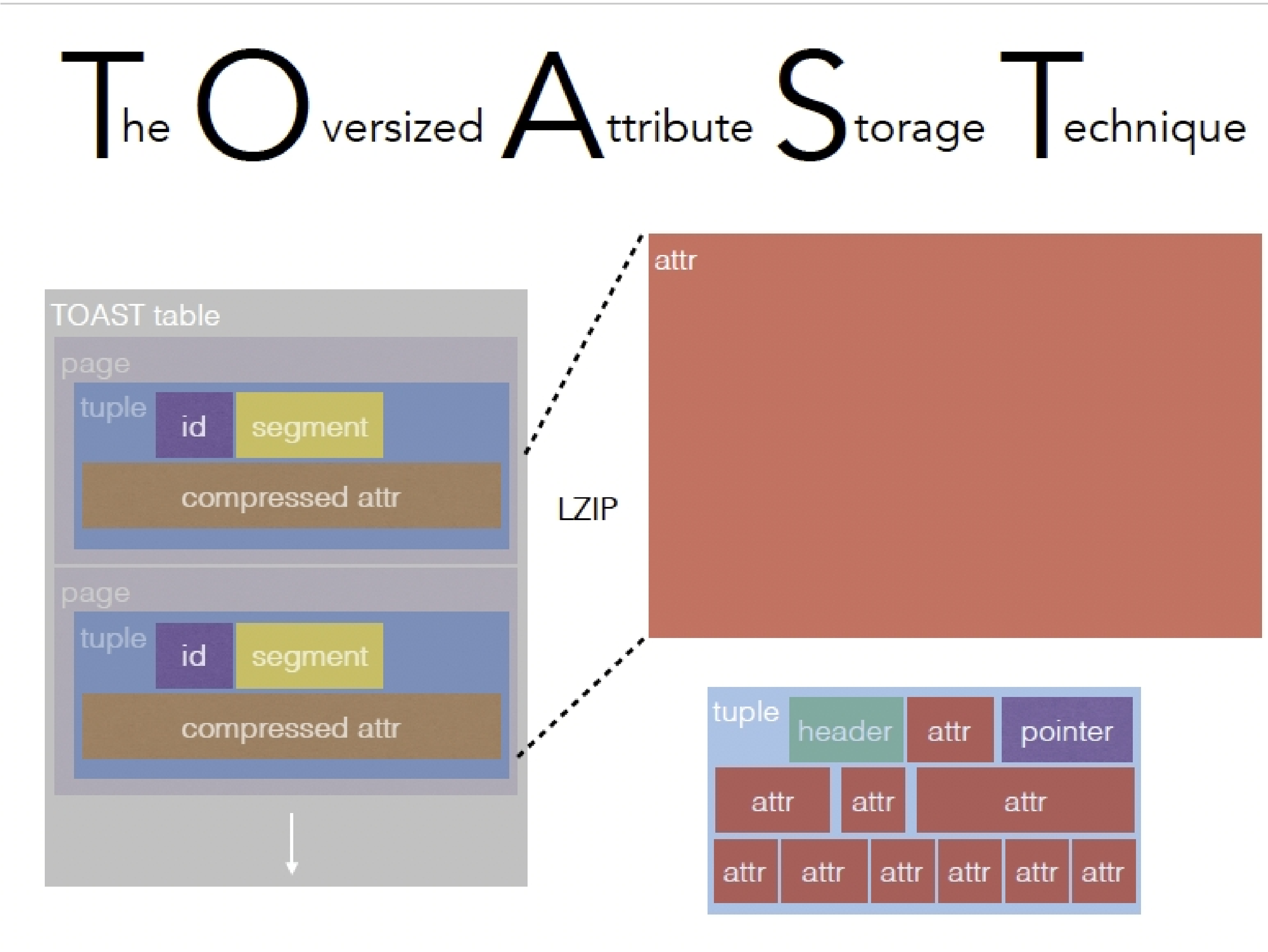
- Reduce partition tuple routing overheads
  - Inserts into 10k partitions table:

PG11	PG12	Single Table
96	17729	19121

- Speed up planning when partitions can be pruned at plan time
  - «For queries that can be proven at plan time to access only a small number of partitions, this patch improves the practical maximum number of partitions from under 100 to perhaps a few thousand.»
- Support foreign keys that reference partitioned tables
  - «Previously, while primary keys could be made on partitioned tables, it was not possible to define foreign keys that reference those primary keys. Now it is possible to do that.»
- Use Append rather than MergeAppend for scanning ordered parts.
- \dP — display info about partition tables, indexes

support for partial TOAST decompression

«When asked for a slice of a TOAST entry, decompress enough to return the slice instead of decompressing the entire object.»



1. Compress and slice by segments
2. Store in separate table

1. Retrieve all segments and decompress

Now: decompress only first needed segments

support for partial TOAST decompression

«When asked for a slice of a TOAST entry, decompress enough to return the slice instead of decompressing the entire object.»

```
CREATE TABLE slicingtest ( id serial primary key, a text);

INSERT INTO slicingtest (a) SELECT repeat('xyz123', 10000) AS a
FROM generate_series(1,10000);

SELECT sum(length(substr(a, 0, 20))) FROM slicingtest;
```

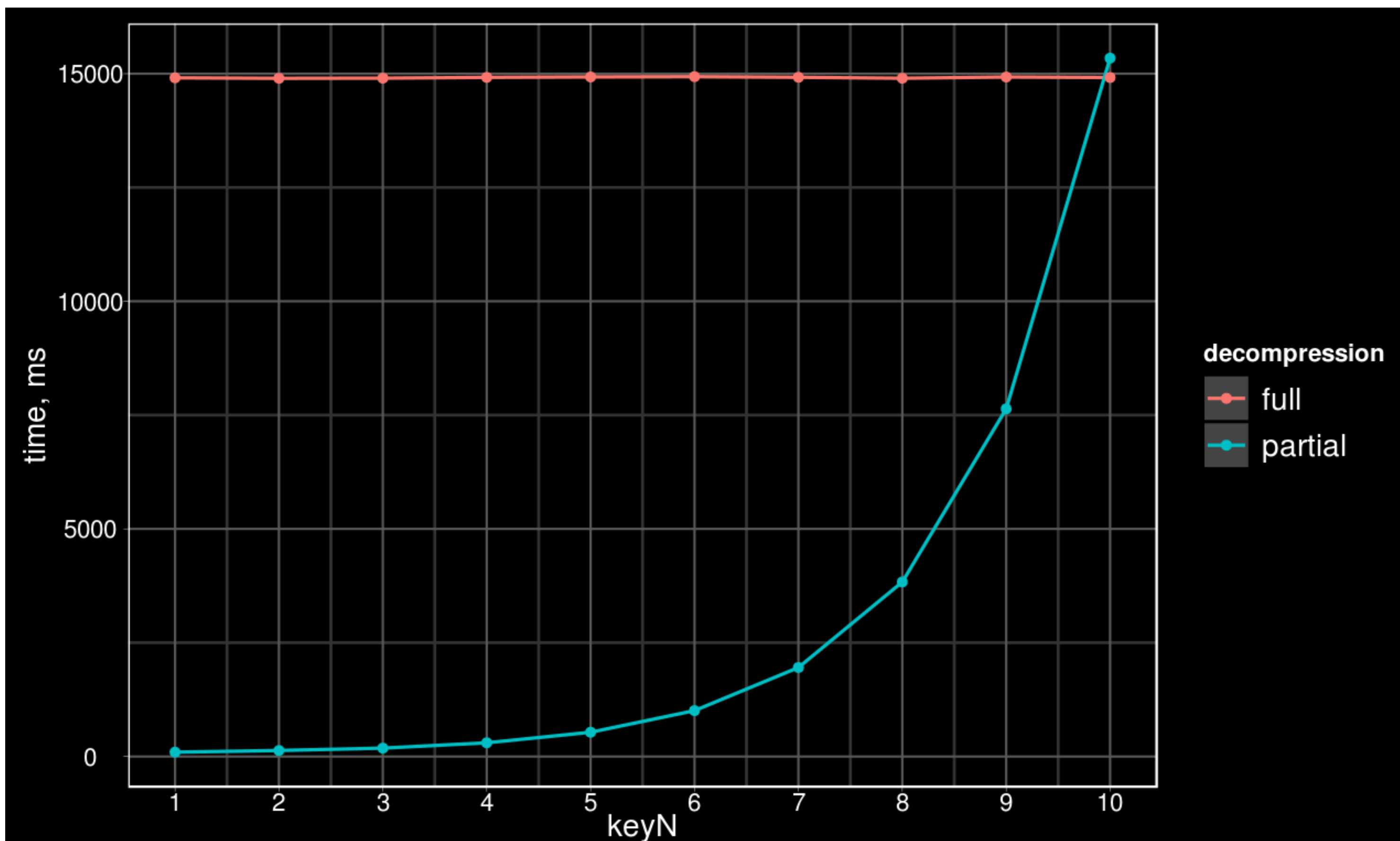
PG11: 400 ms, PG12: 10 ms

support for partial TOAST decompression (jsonb)

- Quick experiment

```
CREATE TABLE t(jb jsonb);
-- {"key1": 2^10 "a" , ... "key10": 2^19 "a" }
INSERT INTO t SELECT (
      SELECT jsonb_object_agg('key' || i, repeat('a', pow(2, i + 9)::int)
)  FROM generate_series(1,10) i) FROM generate_series(1,1000);

SELECT jb->'key1'
FROM t;
```



multivariate MCV lists

Add support for multivariate MCV lists

Introduce a third extended statistic type, supported by the CREATE STATISTICS command - MCV lists, a generalization of the statistic already built and used for individual columns.

Compared to the already supported types (n-distinct coefficients and functional dependencies), MCV lists are more complex, include column values and allow estimation of much wider range of common clauses (equality and inequality conditions, IS NULL, IS NOT NULL etc.). Similarly to the other types, a new pseudo-type (pg_mcv_list) is used.

CREATE STATISTICS <name> (mcv) ON <col1>,<col2>... FROM <table>;

pg_catalog.pg_statistic_ext

multivariate MCV lists

```
CREATE TABLE test (a INT, b INT, c INT);
INSERT INTO test SELECT i/10000, i/10000, i/10000
FROM generate_series(1,1000000) s(i);
ANALYZE test;

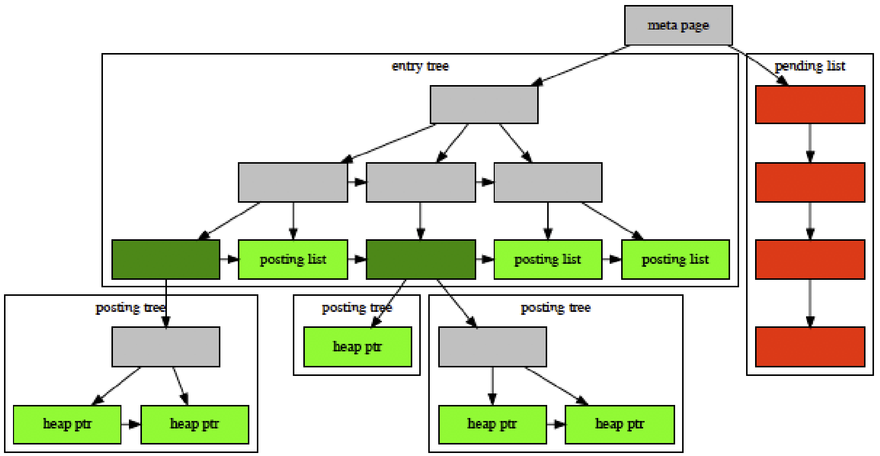
SELECT * FROM test WHERE (a = 0) AND (b = 0) AND (c = 0);
-------------------------------------------------------
 Seq Scan on test  (cost=0.00..22906.00 rows=1 width=12)
   Filter: ((a = 0) AND (b = 0) AND (c = 0))
(2 rows)
```

WRONG, should be 10 000 !

```
CREATE STATISTICS mcv_lists_stats (mcv) ON a, b, c FROM test;
ANALYZE test;
SELECT * FROM test WHERE (a = 0) AND (b = 0) AND (c = 0);
-----------------------------------------------------------
 Seq Scan on test  (cost=0.00..22906.00 rows=10100 width=12)
   Filter: ((a = 0) AND (b = 0) AND (c = 0))
(2 rows)
```

Figures in Documentation

Figure 65.1. GIN Internals



65.4.1. GIN Fast Update Technique

Updating a GIN index tends to be slow because of the intrinsic nature of inverted indexes: inserting or updating one heap row can cause many inserts into the index (one for each key extracted from the indexed item). As of PostgreSQL 8.4, GIN is capable of postponing much of this work by inserting new tuples into a temporary, unsorted list of pending entries. When the table is vacuumed or autoanalyzed, or when `gin_clean_pending_list` function is called, or if the pending list becomes larger than gin_pending_list_limit, the entries are moved to the main GIN data structure using the same bulk insert techniques used during initial index creation. This greatly improves GIN index update speed, even counting the additional vacuum overhead. Moreover the overhead work can be done by a background process instead of in foreground query processing.

The main disadvantage of this approach is that searches must scan the list of pending entries in addition to searching the regular index, and so a large list of pending entries will slow searches significantly. Another disadvantage is that, while most updates are fast, an update that causes the pending list to become "too large" will incur an immediate cleanup cycle and thus be much slower than other updates. Proper use of autovacuum can minimize both of these problems.

If consistent response time is more important than update speed, use of pending entries can be disabled by turning off the `fastupdate` storage parameter for a GIN index. See CREATE INDEX for details.

65.4.2. Partial Match Algorithm

Generated columns

This is an SQL-standard feature that allows creating columns that are computed from expressions rather than assigned, similar to a view or materialized view but on a column basis.

This implements one kind of generated column: stored (computed on write). Another kind, virtual (computed on read), is planned for the future, and some room is left for it.

CREATE TABLE … (…, b int GENERATED ALWAYS AS (expr) STORED);

Expression should be IMMUTABLE

CREATE TABLE ...(…, b int GENERATED ALWAYS AS IDENTITY(…));
CREATE TABLE ...(…, b int GENERATED BY DEFAULT AS IDENTITY(…));

INT, BIGINT, SMALLINT

Add SETTINGS option to EXPLAIN, to print modified settings.

```
explain (SETTINGS ON) select count(*) from imdb;
                              QUERY PLAN
----------------------------------------------------------------------------
 Aggregate  (cost=366855.10..366855.11 rows=1 width=8)
   ->  Seq Scan on imdb  (cost=0.00..356382.28 rows=4189128 width=0)
 Settings: max_parallel_workers_per_gather = '0', parallel_tuple_cost = '0'
(3 rows)
```

PostgreSQL version in log (committed)

```
2019-02-02 09:23:11.711 MSK [59708] LOG:  starting
PostgreSQL 12devel on x86_64-apple-darwin17.7.0, compiled
by Apple LLVM version 10.0.0 (clang-1000.11.45.5), 64-bit
2019-02-02 09:23:11.715 MSK [59708] LOG:  listening on
IPv6 address "::1", port 5434
2019-02-02 09:23:11.715 MSK [59708] LOG:  listening on
IPv6 address "fe80::1%lo0", port 5434
2019-02-02 09:23:11.715 MSK [59708] LOG:  listening on
IPv4 address "127.0.0.1", port 5434
2019-02-02 09:23:11.716 MSK [59708] LOG:  listening on
Unix socket "/tmp/.s.PGSQL.5434"


.........................................................
```

Locking B-tree leafs immediately in exclusive mode (committed)

test	original, TPS	patched, TPS
unordered inserts	409 591	412 765
ordered inserts	252 796	314 541
duplicate inserts	44 811	202 325

Function to promote standby servers (committed)

How to promote a standby?

- Trigger file
- pg_ctl promote
- **SELECT pg_promote();**

Step towards managing cluster in pure SQL!

Speedup of relation deletes during recovery (committed)

Relation delete or truncate:

- Causes sequential scan of shared_buffers
- Slow with large shared_buffers
- Especially bad for standby, because of single-process recovery

Now, instead of

```
DELETE tab1; DELETE tab2; … DELETE tabN;
```

it's better to do

```
BEGIN;
DELETE tab1; DELETE tab2; … DELETE tabN;
COMMIT;
```

Single pass over shared_buffers instead of N.

Less replication lag!

Add log_statement_sample_rate parameter (committed)

- Logging all the statements consumes much of resources
- Logging only long statements may distort your picture
- Sample logging is the solution!

```
log_statement_sample_rate = 1 ; log every statement
log_statement_sample_rate = 0 ; log no statements
log_statement_sample_rate = 0.5 ; log half of statement
log_statement_sample_rate = 0.1 ; log one tenth of
                                ; statement
```

Enable/disable (offline) checksums

```
pg_checksums --help
pg_checksums enables, disables or verifies data checksums in a PostgreSQL database cluster.

Usage:
  pg_checksums [OPTION]... [DATADIR]

Options:
 [-D, --pgdata=]DATADIR  data directory
  -c, --check            check data checksums (default)
  -d, --disable          disable data checksums
  -e, --enable           enable data checksums
  -N, --no-sync          do not wait for changes to be written safely to disk
  -P, --progress         show progress information
  -v, --verbose          output verbose messages
  -r RELFILENODE         check only relation with specified relfilenode
  -V, --version          output version information, then exit
  -?, --help             show this help, then exit

If no data directory (DATADIR) is specified, the environment variable PGDATA
is used.
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СПАСИБО ЗА ВНИМАНИЕ !