NetApp

GIN, BTREE_GIN, GIST, BTREE_GIST, HASH & BTREE indexes on JSONB data

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PROBLEMS WITH IMPLEMENTATION OF JSON DATA

JSON - light and dark side of the force

- Frontend and backend developers love the flexibility of JSON.
- JSON minimizes the need for app changes due to schema changes.
- JSON standardized for IoT devices.

- Data quality checks - absolute freedom might be a big challenge.
- Problems with data cleansing and transformation.
- Business intelligence, ML, and reporting need structured and standardized data.

- But the full decomposition of JSON can be a complex and painful task.
- Databases must handle JSON data, there is no escape.

Clients struggle with implementing JSONB

- Articles are often shallow, repeating documentation.
- Very trivial examples - create a table, create a index, insert 3 rows, try explain, celebrate.
- Even AIs are not helpful with deeper and more complicated topics.

- Clients develop with small inadequate datasets.
- Tests are often too simple, just guessing production use cases.
- PostgreSQL dev instance has inadequate configuration.

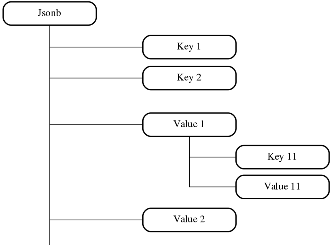
- Confusion about TOAST tables, compression, and storage.
- Doubts about design - partitions vs 1 big table.
- Developers are obsessed with forcing indexes.

HOW IS JSONB DATA STORED IN POSTGRESQL

JSONB implementation

- JSONB is a binary tree, structure reflects levels of JSON object.
- Stores keys and values in separate nodes, 2 children per key-value pair.
- Keys and values of one level are grouped together for quicker access to keys.
- Keys on the one level are stored in order to speed up search.
- Array has one child node for each element, stored in array order.

- Many interesting comments in PostgreSQL source code:
- src/include/utils/jsonb.h
- src/backend/utils/adt/jsonbsubs.c, jsonb_gin.c, jsonb_util.c, jsonb.c, jsonb_op.c



(Image from the article Jsonb: few more stories about the performance)

WHAT WAS TESTED AND HOW

What was tested

- Different types of indexes for different use cases.
- Different compression and storage methods.
- One big table vs partitioned tables.

- Influence of PostgreSQL settings - memory, costs.
- Performance under different loads - multiple simultaneous sessions.
- Influence of parallelism.
- Influence of data distribution and selectivity.

- User defined statistics on JSONB columns.
- Full decomposition vs one big JSONB column.
- Deep dive into internals of indexes. Analysis of code.

Dataset for tests

- GitHub Archive events - www.gharchive.org
- Separate .gz files for each hour - YYYY-MM-DD-HH24.json.gz
- Python scripts for downloading, importing, analyzing, and testing.
- Multiple local and AWS RDS testing environments.
- Tested in PostgreSQL 15 and 16.
- One big JSONB column with all the data

```
CREATE TABLE github_events (
                id SERIAL PRIMARY KEY NOT NULL,
                jsonb_data JSONB);
```


GitHub events - JSON record

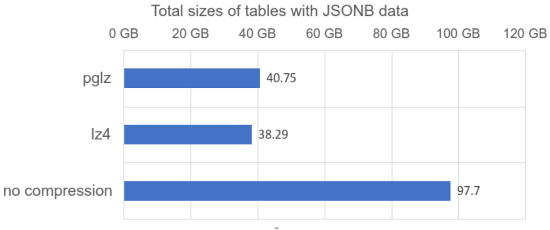

```
{   "id": "26167585827",
    "repo": {   "id": 581592468,
                "url": "https://api.github.com/repos/tiwabs/tiwabs_audio_door_tool",
                "name": "tiwabs/tiwabs_audio_door_tool" },
    "type": "PushEvent",
    "actor": {  "id": 48737497,
                "url": "https://api.github.com/users/tiwabs",
                "login": "tiwabs",
                "avatar_url": "https://avatars.githubusercontent.com/u/48737497?",
                "gravatar_id": "",
                "display_login": "tiwabs"  },
    "public": true,
    "payload": {"ref": "refs/heads/master",
                "head": "3ca247941f269bcedeb17e5b12e9b3b74b1c4da2",
                "size": 1,
                "before": "0dd5471667b12084b8fc88b1bca299780382d50a",
                "commits":
                    [
                        {   "sha": "3ca247941f269bcedeb17e5b12e9b3b74b1c4da2",
                            "url": "https://api.github.com/repos/tiwabs/....12e9b3b74b1c4da2",
                            "author": { "name": "Tiwabs", "email": "mrskielz@gmail.com" },
                            "message": "fix(export): export nametable if export succed",
                            "distinct": true }
                    ],
                "push_id": 12149772587,
                "distinct_size": 1 },
    "created_at": "2023-01-01T13:39:55Z" }
```


DIFFERENT COMPRESSION ALGORITHMS AND STORAGE

Different compression and storage methods

- Used 1 week of data from January 2023.
- In total 17,474,101 rows.

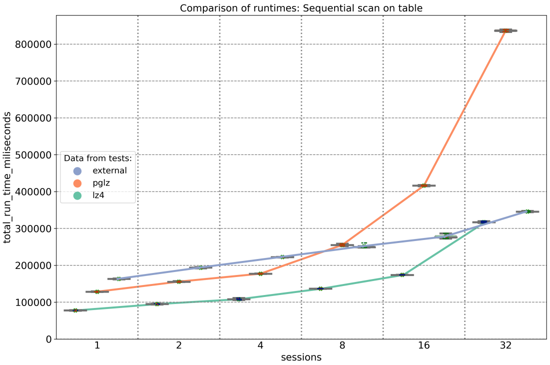
- 3 tables, different compression / storage methods:
- pglz: 41 GB
- lz4: 38 GB
- external storage with no compression: 98 GB



PGLZ vs LZ4 vs no compression - test 1

- Aggregation query over all records using sequential scan on the table.
- No parallel workers, no JIT.
- Query selected keys from the beginning of the JSONB structure.
- Machine with i7, 8 cores, 32 GB RAM, SSD 500GB.

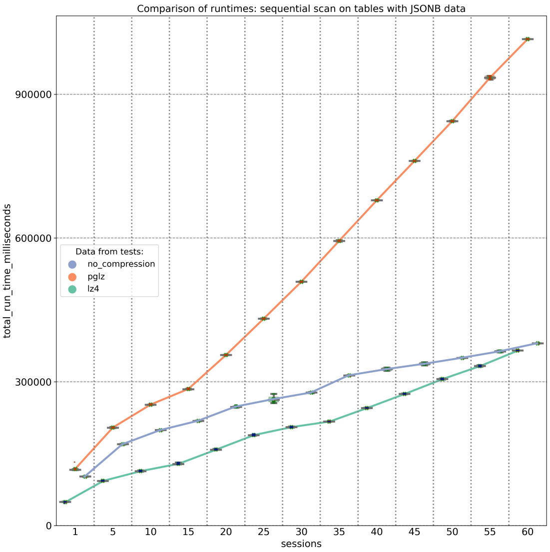
- PGLZ slower than no compression with 8 sessions on 8 cores.
- With 16, 32, and 64 sessions on 8 cores, PGLZ became a serious performance bottleneck.



PGLZ vs LZ4 vs no compression - test 2

- Aggregation query over all records using sequential scan on the table.
- No parallel workers, no JIT.
- Query selected keys from all parts of the JSONB structure.
- Machine with i7, 20 cores, 32 GB RAM, SSD 500GB.

- PGLZ slower than no compression right from the beginning.
- LZ4 outperforms both PGLZ and not compressed data significantly.



PGLZ vs LZ4 vs no compression - summary

- The difference in performance between PGLZ and LZ4 is significant.
- PGLZ becomes a serious bottleneck under high parallel load.
- This is the reason why in the past people used uncompressed data.
- LZ4 outperforms both PGLZ and not compressed data significantly.

- But these results are anecdotal, cannot be blindly generalized.
- Always test your specific use case with your specific data.
- To convert data you cannot simply copy them between tables with different compression setting.
- Already compressed data are simply copied as they are.
- Data must be cast to text and then back to JSONB.

Disk intensive operations - throughput matters

- The same problem occurs on ALL clouds; we just tested it on AWS.

- On AWS RDS SSD 300GB with 3,000 IOPS, the throughput of 125 MiBps was a real disaster.
- All disk-intensive operations were 4x to 5x slower than on the local PC.

- With SSD 500GB and 12,000 IOPS, and a throughput of 500 MiBps, we finally got reasonable results.
- But auto-scaling of the disk can also slow down your actions by 5x or more.

- Never try to save money on a cloud instance by using a slow, small disk.
- Do not rely only on the auto-scaling of the disk.

GIN INDEXES

GIN indexes

- GIN indexes generally showed very stable performance even under high load.
- But for their usage proper settings are crucial.
- Set Shared_buffers to 25% of RAM and effective_cache_size to around 50% of RAM.

- GIN indexes do not support parallelism, neither for creation nor for usage.
- Parallelism can be a significant factor in using or not using GIN indexes.

- If parallel workers are available, the planner can choose parallel sequential scan on the table.
- If all parallel workers are in use, the planner uses GIN indexes for new queries.
- Set Max_parallel_workers_per_gather = 0 at least for the query.

GIN indexes - parameters tuning

- SSD: random_page_cost = 1.1, effective_io_concurrency = 200.
- Set random_page_costs <= seq_page_cost (=1) if the database is fully cached in memory.
- Different values of work_mem had minimal impact if the query used GIN index scan.

- PostgreSQL code: src/backend/optimizer/path/costsize.c
- cpu_tuple_cost, cpu_index_tuple_cost, cpu_operator_cost ???
- parallel_setup_cost, parallel_tuple_cost ???

- The code says ”measured on an arbitrary scale”.
- Especially *cpu_tuple_cost* is used incredibly often in the code.
- Its value influences the planner’s decisions significantly.

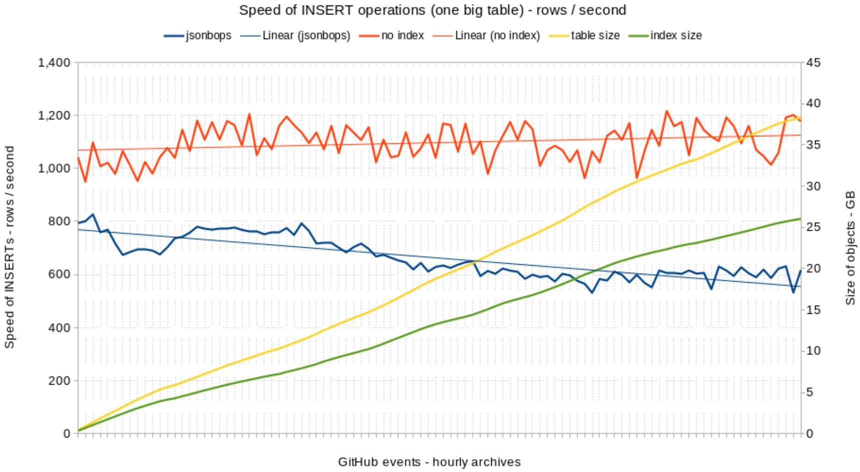
GIN indexes - updates of the index

- It can take hours to create a new GIN index on the whole column with existing data.
- Setting *maintenance_work_mem* has a rather small impact on the speed of creating a GIN index.
- Disk IO is the main factor affecting the speed of creating a GIN index.

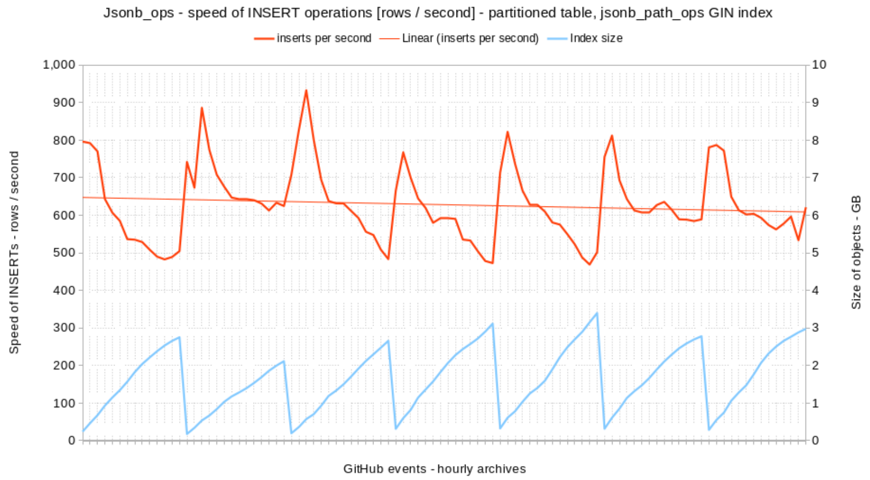
- Updates of GIN indexes become significantly slower as the table size grows.
- The index is rebuilt when the *gin_pending_list_limit* is reached or during vacuuming.
- Default value of *gin_pending_list_limit* is 4MB = 512 data pages.

- The size of the table matters.
- The speed of inserting rows per second can decrease by up to 50%.
- Partitioning can help significantly. However, disk IO is again the main factor.

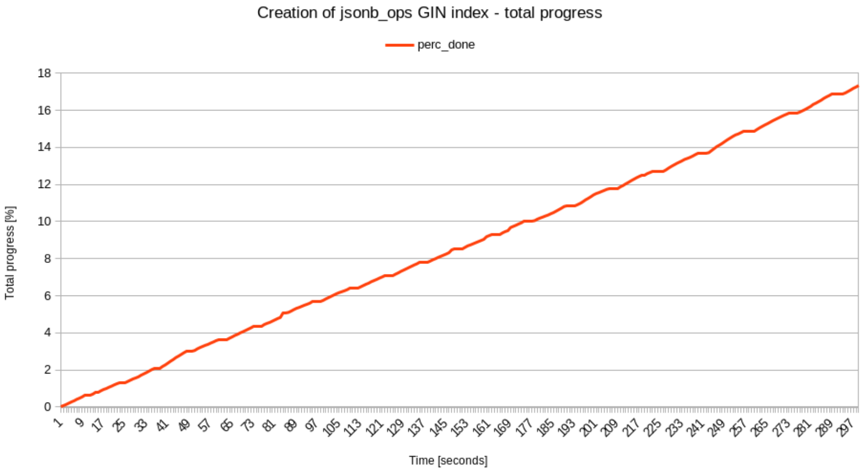
GIN indexes - speed of inserts - one big table



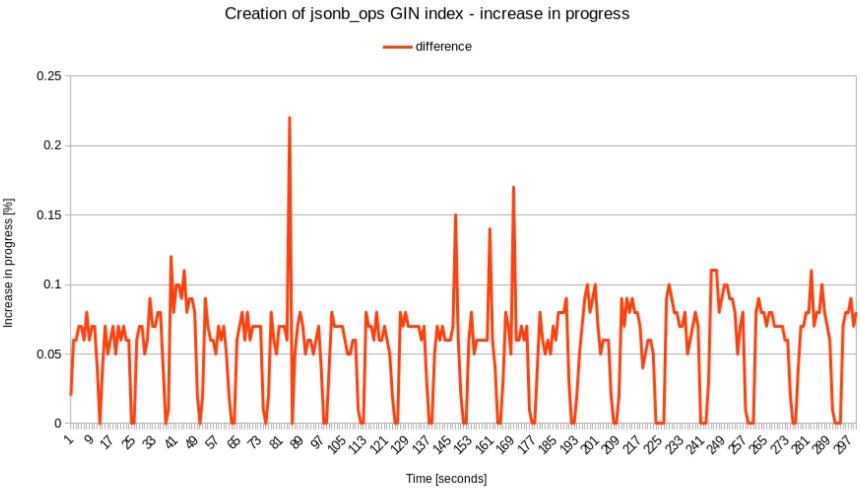
GIN indexes - speed of inserts - partitions



GIN indexes - creation - total progress



GIN indexes - creation - difference in progress



Gin Indexes inspection - pending pages and tuples

- We can use extensions to get some deeper information about GIN indexes
- pgstattuple:
  - pgstatginindex()
- pageinspect:
  - gin_page_opaque_info() - basic info about page
  - gin_metapage_info() - details for metapage
  - gin_leafpage_items() - details for leaf page

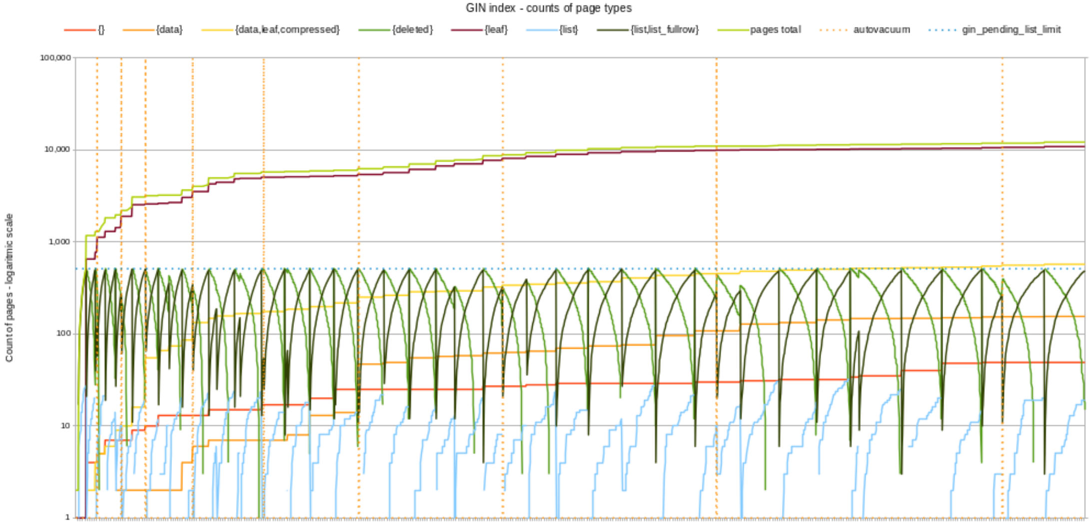
```
SELECT * FROM pgstatginindex('index_name');

 version | pending_pages | pending_tuples
---------+---------------+----------------
       2 |           414 |           1853
```

```
SELECT *
FROM gin_metapage_info(
    get_raw_page('index_name', 0))\gx

pending_head     : 292675
pending_tail     : 339992
tail_free_size   : 220
n_pending_pages  : 414
n_pending_tuples : 1853
n_total_pages    : 339200
n_entry_pages    : 312283
n_data_pages     : 24533
n_entries        : 52572205
version          : 2

--> but before VACUUM these
values are only estimates!
```


Gin Indexes inspection - deeper dive into pages stats

```
-- How to get proper count of pages?

pg_class: 339986, metapage: 339200 - both are estimates, just taken differently


-- Let's calculate the proper count of pages from the size of data files

SELECT pg_relation_size('index_name') / 8192;
-> 357105 pages


-- Now we can get statistics about GIN index pages

WITH pages AS (
    SELECT *
    FROM generate_series(0,
        (SELECT pg_relation_size('index_name') / 8192) -1) as pagenum)
SELECT
    (SELECT flags
    FROM gin_page_opaque_info(
            get_raw_page('index_name', pagenum))) as flags,
    count(*) as pages
FROM pages GROUP BY flags ORDER BY flags;
```


GIN indexes - rebuild of index during insertion of data



GIN indexes - equality of value - operators @? and @@

- *GIN index with jsonb_ops* operator class is the most versatile but also the biggest.
- It allows searching for *equality* of values on multiple *unknown* levels of keys.
- The @? and @@ operators can be used with * and ** wildcards.
- Example: WHERE jsonb_data @@ '$.** == "python3" '
- The size of the jsonb_ops GIN index on the whole column can reach 80% of the table size.

- The operator class *jsonb_path_ops* works only with fully known jsonpath.
- It allows searching for *equality* of values on multiple *known* levels of keys.
- The @? and @@ operators cannot use wildcards, the jsonpath must be known.
- Example: WHERE jsonb_data @@ '$.payload.pull_request.head.repo.topics[*] == "python3"'
- The GIN index with jsonb_path_ops on the whole column can reach 30% of the table size.

GIN indexes - operator @>

- If the second object is contained in the first one - an exact match of the key(s) and value(s).
- Works with both operator classes.
- Works for nested objects and arrays.
- Allows searching for *equality of multiple values* in one condition.

- Searching for values from lists of values - events from specific users, a specific repository.
- Run times are in dozens or hundreds of milliseconds.
- Very stable performance even with multiple sessions running in parallel.

- Limitation - the path must be known.
- This will find data: WHERE jsonb_data @> '{"payload":{"commits":[{"author":{"name": "Jane Joy"}}]}}'
- This will not find: WHERE jsonb_data @> '{"commits":[{"author":{"name": "Jane Joy"}}]}'

GIN indexes - other operators

- Operators `?`, `?|`, and `?&`.
- They are used to look for the existence of key(s) on the *top level*.
- These operators only work with the *jsonb_ops* operator class.

- The usage of the GIN index depends on statistics.
- If a key is present in the majority of records, the GIN index is not used.
- If the table is very small, the GIN index is not used.

- The GIN index is only used for keys that are not present in the majority of records.
- Useful for a very dynamic schema or a table that stores many different JSON datasets.

GIN indexes - SQL\JSON operators and methods

- SQL\JSON contains multiple amazing methods, but GIN index does not work for them.
- like_regex - tests if the string value returned by jsonpath matches a regular expression:
  WHERE jsonb_data @? '$.description ? (@ like_regex ".*Michigan.*")'

- starts with - tests if the string value returned by jsonpath starts with a specific string:
  WHERE jsonb_data @? '$.laureates[*].firstname ? (@ starts with "Jo")'

- exists - tests if a key exists in the JSONB schema at a given level:
  WHERE jsonb_data @? '$.laureates[*].firstname ? (exists (@))'

- The PostgreSQL community should consider creating indexes for these operators.

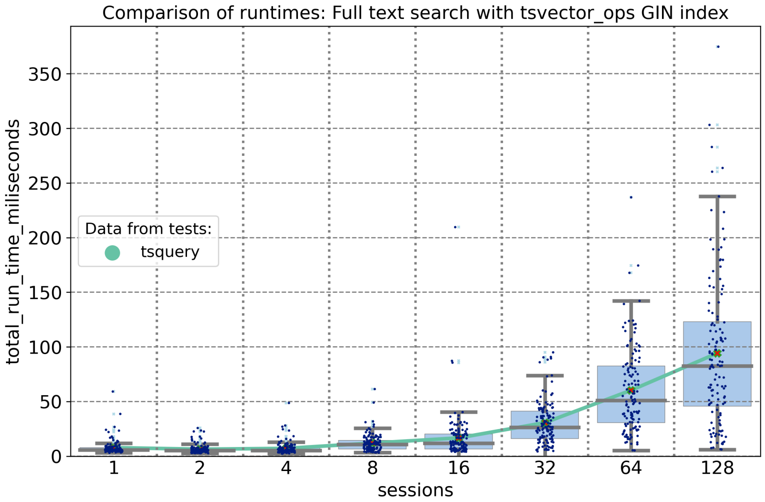
GIN indexes - full text search

- GIN index with *tsvector_ops* operator class allows full text search.
- The function *jsonb_to_tsvector* converts JSONB data into tsvector.
- Example: WHERE jsonb_to_tsvector('english', jsonb_data, '"string"') @@ to_tsquery('search_string')

- Full text search works for *equality* of words/synonyms.
- You can combine words using AND/OR.

- The tsvector_ops index on the whole column can be larger than the table.
- It only makes sense to create an index on free text columns.
- It speeds up search by at least 100 times.
- Performance is very stable under high load.

GIN indexes - full text search - commit messages



GIN indexes - LIKE search

- *Gin_trgm_ops* operator class allows string search using LIKE.
- The index over the whole column does not distinguish keys and values.
- It still performs an *equality* search behind the scenes - *equality of trigrams*.
- Creating an index on free text columns is the only scenario where it makes sense.

- The size of the gin_trgm_ops GIN index on the whole column can reach 50% of the table size.
- It significantly speeds up search, even up to 1000x.
- The performance is very stable under high load.

GIN indexes - partitions

- Partitioned tables showed multiple advantages over one big table.

- Query run times using GIN indexes are faster on partitioned tables, approximately 5 times faster.

- Loading data into partitioned tables is faster.
- Updates of GIN indexes on partitions are faster.

- Partitioning also makes GIN indexes more efficient in case of very uneven data distribution.
- Bloat of partial GIN indexes due to the values with very high frequency is much lower.

BTREE_GIN INDEXES

BTREE_GIN indexes

- The BTREE_GIN extension combines the BTREE and GIN indexes.
- It adds GIN operator classes with BTREE behavior.
- The BTREE text_pattern_ops does not work with BTREE_GIN indexes.
- You can use any GIN operator class with the BTREE_GIN index.

- The BTREE_GIN index can have multiple columns.
- It will optimize the search for any combination of these columns.
- The order of columns does not seem to be important.

- The runtime with the BTREE_GIN index was better than with the GIN index + filter search.
- The run times of the tested use cases were in the range of hundreds of milliseconds.
- The performance was stable even with many parallel sessions.

GIST INDEXES

GIST indexes

- For indexing geo data, you need GIST indexes.
- Most commonly in GeoJSON format.
- Usually - Type (Point), coordinates [longitude (+/- 0-180), latitude (+/- 0-90)].

```
-- NASA meteorites dataset

{ "id": "1",
"fall": "Fell",
"mass": "21",
"name": "Aachen",
"year": "1880-01-01T00:00:00.000",
"reclat": "50.775000",
"reclong": "6.083330",
"nametype": "Valid",
"recclass": "L5",
"geolocation": {
    "type": "Point",
    "coordinates": [ 6.08333, 50.775 ] } }
```


GIST indexes - PostGIS example

- Let’s create a GIST index based on GEOMETRY(point, 4326) PostGIS data type.
- EPSG code 4326 is for WGS 84 spacial reference system.

```
-- you can create a GIST index on a GEOMETRY column manually:

CREATE INDEX ON nasa_meteorits USING GIST(
    ST_SETSRID(ST_MakePoint(
        cast(jsonb_data->'geolocation'->'coordinates'->>0 as float),
        cast(jsonb_data->'geolocation'->'coordinates'->>1 as float) ), 4326) );

-- or use PostGIS extension function st_geomfromgeojson
-- expects a GeoJSON object as input, recognizes content automatically:
-- meteorites: { "type": "Point", "coordinates": [ 6.08333, 50.775 ] }
-- earthquakes: { "geometry": { "type": "Point", "coordinates": [ -104.024, 31.646, 6.8514 ] }}

CREATE INDEX ON nasa_meteorits USING GIST(
    ST_GeomFromGeoJSON(jsonb_data->'geolocation') );
```


GIST indexes - BTREE_GIST extension

- The BTREE_GIST extension allows you to combine GIST and BTREE indexes.
- You cannot create a GIST index on a whole JSONB column.
- However, you can combine multiple columns into a BTREE_GIST index using different operator classes.

- The intarray extension implements the gist__int_ops and gist__intbig_ops operator classes for arrays.
- There is the gist_trgm_ops operator class for performing LIKE search over strings.
- And the tsvector_ops operator class for creating a GIST index for full-text search.

GIST indexes - BTREE_GIST extension

- Earthquakes dataset - United States Geological Survey (earthquake.usgs.gov).
- GIST index on JSONB column combining multiple extracted values.
- Geolocation, magnitude as a number, place as a trigram, and magnitude type as a list of values.
- Optimizes all variants of queries using these columns.
- Quick to create - 1 minute on a 1 GB dataset. Size is 20% of the table size.

```
CREATE INDEX ON jsonimport USING gist (
    ST_GeomFromGeoJSON(jsonb_data->'geolocation'),
    ((jsonb_data->'properties'->>'mag')::numeric),
    (jsonb_data->'properties'->>'place') gist_trgm_ops,
    (jsonb_data->'properties'->>'magType') );
```


HASH INDEXES

HASH indexes

- HASH indexes allow only equality search, not range search.
- Support only single-column indexes and do not allow uniqueness checking.
- Can be smaller and quicker than BTREE indexes, but only on some data.

- In my tests, the performance of HASH and BTREE indexes on unique data was almost the same.
- On non-unique data, HASH indexes were still very quick, but at least 5x slower than BTREE indexes.
- However, HASH indexes have been bigger in size than BTREE indexes - 2x to 3x.

- HASH indexes are extremely sensitive to the data distribution.
- *Require unique or nearly unique data* with a low number of rows per hash bucket.
- Many repeated values lead to a big number of overflow bucket pages and bad performance.

HASH indexes

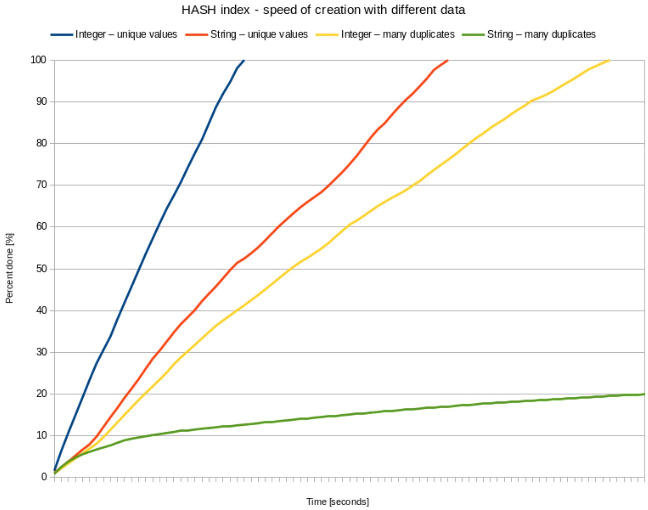
- Always check PostgreSQL statistics on the data before deciding to use a HASH index.
- For JSONB data, create user defined statistics for the keys you want to index.

- In pg_stats, a value of *n_distinct = -1* indicates fully unique values.
- If n_distinct != -1, check the values in *most_common_vals* and *most_common_freqs*.
- If the values in most_common_freqs are 0.1 or higher, a HASH index is not a good choice.
- You can avoid NULLs and empty strings by using a partial index.

HASH index - creation / reindex

- Numbers are processed quicker than strings.
- Unique data is processed very quickly.
- Non-unique strings with many duplicates are processed extremely slowly.

- Unique integers: 30 seconds,
  highly duplicate integers: 1.5 minute.
- Unique strings: 1 minute,
  highly duplicate strings: 55 minutes.



HASH indexes - internal structure

- Extension *pageinspect* contains functions for inspecting the index.
- Function *hash_page_type* returns the type of the page.

- If all values are unique, index contains: metapage (0), bucket pages, bitmap page (last).
- If there are duplicates, overflow pages are added after the bitmap page.

- The bitmap pages maintain the map of free and in-use overflow pages.
- Free overflow pages, not attached to any bucket, are kept and reused.

- There are other functions to inspect content of pages.
- Hash_metapage_info, hash_bitmap_info, hash_page_items, hash_page_stats.

HASH indexes - maintenance

- HASH indexes are not automatically maintained.
- Empty overflow pages are never removed from the index.
- Shrinking requires REINDEX or VACUUM FULL.

- HASH indexes can be useful only in very specific cases.
- BTREE indexes seem to be a much better choice.

BTREE INDEXES

BTREE indexes

- BTREE indexes are very small and quick, making them an ideal first choice.
- They allow parallel index build and scan.
- They can be created in minutes, even on large tables.

- BTREE indexes support equality and range queries using operators such as <, <=, =, >=, and >.
- When combined with *text_pattern_ops* (for each column), they can be used for prefix-LIKE queries.

- Some transformations must be encapsulated into immutable functions.
- Conditions in queries must contain the exact indexed expression.

- Partial BTREE indexes can be very useful for dynamic schemas.
- Whenever possible, use LIMIT to improve the delivery of results significantly.

SIZES OF INDEXES

Summary of results - sizes of indexes

Table - lz4 TOAST compression, 17.5 M rows	38 GB	
GIN index - jsonb_ops - whole JSONB column	25 GB	66 %
GIN index - jsonb_path_ops - whole JSONB column	16 GB	42 %
GIN index - gin_trgm_ops - whole JSONB column	16 GB	42 %
GIN index - tsvector_ops - jsonb_to_tsvector, ”string” values	34 GB	90 %
GIN index - tsvector_ops - just commit messages	0.5 GB	1.5 %
GIN index - gin_trgm_ops - just commit messages	1 GB	3 %
BTREE_GIN index - ’payload’ jsonb_ops + created_at	23 GB	60 %
BTREE_GIN index - ’payload’ jsonb_path_ops + created_at	15 GB	40 %
BTREE index on ”created_at” timestamp	120 MB	0.2 %
HASH index on ”created_at” timestamp	0.5 GB	1.5 %

JSON DECOMPOSITION

JSON object decomposition - test with Github events

- Github events schema has 936 unique jsonpaths.
- Some keys contain different data types in different records.
- Schema contains 12 embedded arrays with another JSONB objects -> additional 12 tables.

- Main table would have 807 columns. (Jsonpaths without array elements)
- In total: text 604, number 105, boolean 70, datetime 28 columns.
- I tried to create and fill the main table: *”row is too big: size 9088, maximum size 8160”*

- I would have to put some big nested JSONB objects into separate tables too.
- Decomposition is huge task on its own prone to multiple additional errors.

JSON object decomposition

- A table with hundreds of columns is hard to use.
- The theoretical limit is 1600 columns in the tuple.
- However, the tuple must fit into one data page (8KB).

- A full jsonpath as a column name can easily exceed 63 characters.
- A table with many columns requires careful design due to data types padding.
- Columns must fit into 8-byte blocks - a 64-bit CPU reads a block of 8 bytes.

JSON object decomposition

- Nested composed data types can make the solution even more complex.
- They use extended storage, i.e. TOAST.
- This way you just convert one binary object into another.
- Queries require encapsulation of top-level keys into parentheses.
- Only after really trying it you will realize how big challenge it can be.

JSON object decomposition - use GENERATED columns

- Manual decomposition is not worth the trouble.
- You can use *GENERATED columns* for some frequently used jsonpaths.
- This way you avoid a lot of manual work.

```
ALTER TABLE github_events
ADD COLUMN actor_login text
GENERATED ALWAYS AS ((jsonb_data->'actor'->>'login')) STORED;
```


STATISTICS

Statistics for the whole JSONB object

- The planner seems to be able to deduce statistics for top-level keys.
- For specific jsonpaths use *CREATE STATISTICS* command.
- This way you will have always up-to-date statistics for your use cases.

- Command *CREATE STATISTICS* only prepares statistics object.
- Statistics are gathered by first *ANALYZE* command and later by system as usual.

Statistics for the whole JSONB object

```
CREATE STATISTICS github_actor_login
ON ( ((jsonb_data -> 'actor'::text) ->> 'login'::text) )
FROM github_events;

CREATE STATISTICS github_created_at_ts
ON ( json_datetime_to_timestamp((jsonb_data ->> 'created_at'::text)) )
FROM github_events;
```

- View *pg_stats_ext_exprs* shows statistics.
- Columns n_distinct, most_common_vals, and most_common_freqs, correlation as in pg_stats.

Understand your data and use cases

- Indexes are not the ”silver bullet” for everything.
- Don’t be obsessed with forcing PostgreSQL to use indexes.

- The usage of indexes depends on frequency, selectivity, and correlation.
- In some use cases, a parallel sequential scan can be better than an index scan.

- The runtime of queries depends on data distribution - sorting in memory vs on disk.
- On multi-tenant systems, things are even more complicated.

- Understand your data and use cases to use the right tools!
- Make sure that your PostgreSQL has proper settings.

- Thank you for your attention!
- Questions?

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