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Gin, Btree_gin, GiST, Btree_gist, Hash and Btree indexes on JSONB data

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credativ GmbH

- Founded 1999 in Jülich, Germany
- Close ties to Open-Source Community
- More than 40 Open-Source experts
- Consulting, development, training, support (3rd-level / 24x7)
- Open-Source infrastructure with Linux, Kubernetes, Proxmox
- Open-Source databases with PostgreSQL
- DevSecOps with Ansible, Puppet, Terraform and others
- Since 2025 independent owner-managed company again

Josef Machytka

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- Professional Service Consultant - PostgreSQL specialist at credativ GmbH
- 30+ years of experience with different databases
- PostgreSQL (13y), BigQuery (7y), Oracle (15y), MySQL (12y), Elasticsearch (5y), MS SQL (5y)
- 10+ years of experience with Data Ingestion pipelines, Data Analysis, Data Lake and Data Warehouse
- 2+ years of practical experience with different LLMs / AI including their architecture and principles
- From Czechia, living now 11 years in Berlin

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All My Slides:

Recoded talks:

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Problems with implementation of JSON data

JSON – light and dark side of the force

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- Frontend and backend developers love the flexibility of JSON.
- JSON minimizes the need for app changes due to schema changes.
- IoT devices use JSON - W3C Web of Things Working Group standardized JSON for IoT.

- 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

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- Articles are often too shallow, repeating documentation.
- Very trivial examples - create a table, insert 3 rows, try explain, celebrate.
- Even ChatGPT-4o is 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.

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What was tested

What was tested

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- 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

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- GitHub Archive events - www.gharchive.org
- Separate .gz files for each hour - YYYY-MM-DD-HH24.json.gz

- One big JSONB column with all the data

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

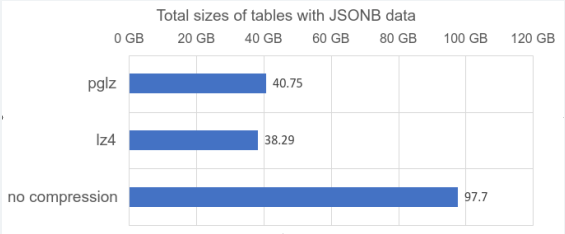
GitHub events - JSON record


```
{   "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" }
```

GitHub events – testing details

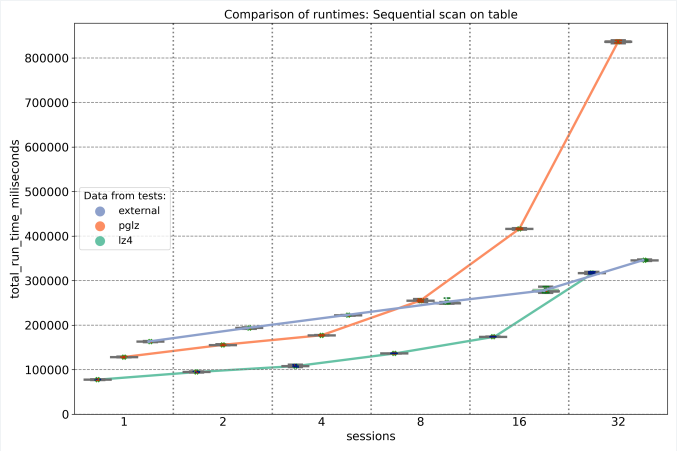
- Tested in PostgreSQL 15 and 16
- Python scripts for downloading, importing, analyzing, and testing
- Multiple local and AWS RDS testing environments
- Different CPUs, all with 8 cores and 32 GB RAM

- Used 1 week of data from January 2023
- In total 17,474,101 rows
- 3 tables, different compression methods:
  - pglz: 41 GB
  - lz4: 38 GB
  - external storage with no compression: 98 GB



Performance testing - sequential scan on the table

- Aggregation query over all records using sequential scan on the table, without parallelism
- The old compression method, pglz, was already 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



Disk intensive operations - throughput matters

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- 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

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GIN indexes

GIN indexes

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- Showed very stable performance even under high load
- But for their usage proper settings are crucial
- Shared_buffers -> 25% of RAM, effective_cache_size -> 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

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- 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 - how they are measured?
  - parallel_setup_cost, parallel_tuple_cost - how are these measured?

  - 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

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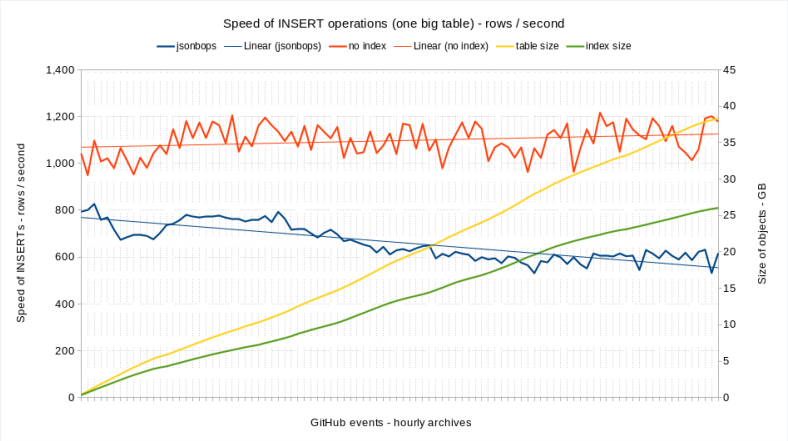
- It can take hours to create a new GIN index on the whole column with existing data
- *maintenance_work_mem* had only small impact on the speed of creating a GIN index
- Disk IO is the main factor affecting the speed of creating a GIN index

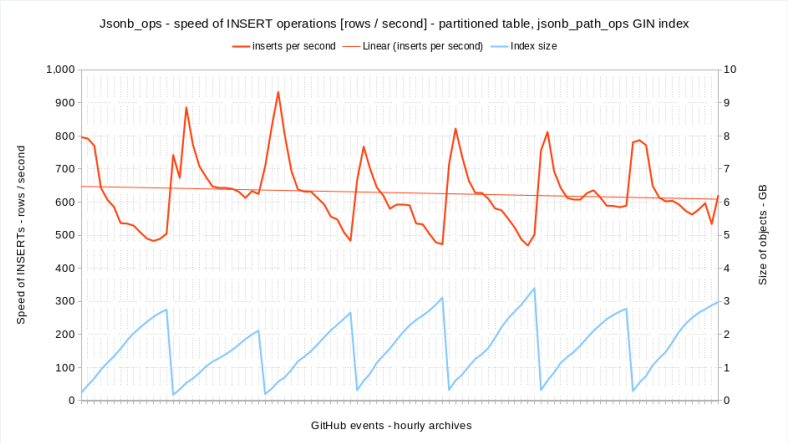
- Updates of GIN indexes become significantly slower as the table size grows
- The index is rebuilt when the *gin_pending_list_limit* is reached or during vacuuming
- Default value of *gin_pending_list_limit* is 4MB = 512 data pages

- 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

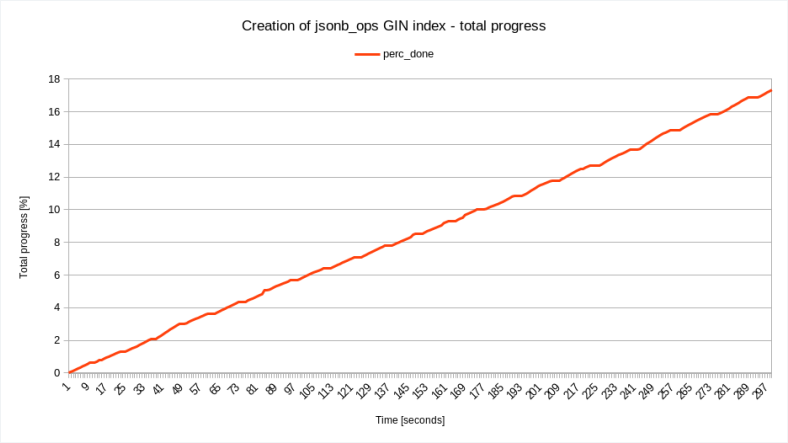
GIN indexes - speed of inserts - one big table



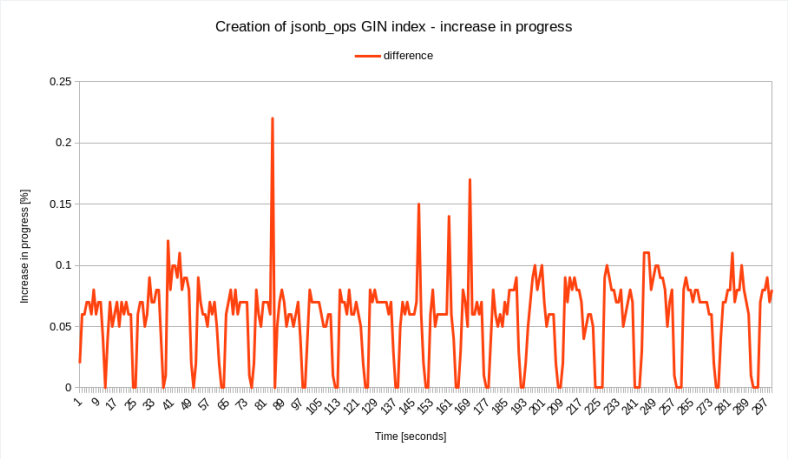
GIN indexes - speed of inserts - partitions



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

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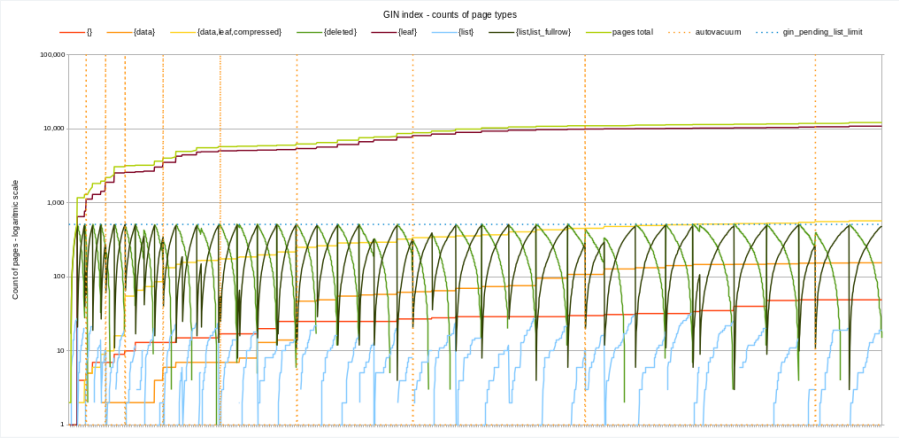
```
-- How to get proper count of pages?
pg_class: 339986, metapage: 339200 - both are estimates, just taken differently


-- 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 @@

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- *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 @>

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- 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

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- 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

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- 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

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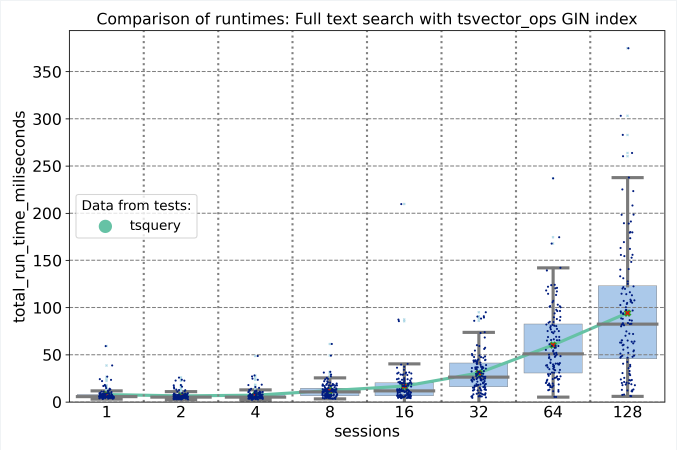
- GIN index with tsvector_ops operator class allows full text search
- The function *jsonb_to_tsvector* converts JSONB data into tsvector
- Example: WHERE jsonb_to_tsvector('english', jsonb_data, '"string"') @@ to_tsquery('search_string')

- 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

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- *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

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- 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

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BTREE_GIN indexes

BTREE_GIN indexes

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- The BTREE_GIN extension combines the BTREE and GIN indexes
  - It adds GIN operator classes with BTREE behavior
  - Any GIN operator class works 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

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GIST indexes

GIST indexes

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- 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

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

```
-- we 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

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- The BTREE_GIST extension allows to combine GIST and BTREE indexes
- We cannot create a GIST index on a whole JSONB column
- We can combine multiple columns into a BTREE_GIST with different operator classes

- intarray extension: gist__int_ops and gist__intbig_ops operator classes for arrays
- gist_trgm_ops operator class for performing LIKE search over strings
- tsvector_ops operator class for creating a GIST index for full-text search

GIST indexes – BTREE_GIST extension

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- 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') );
```

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HASH indexes

HASH indexes

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- 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

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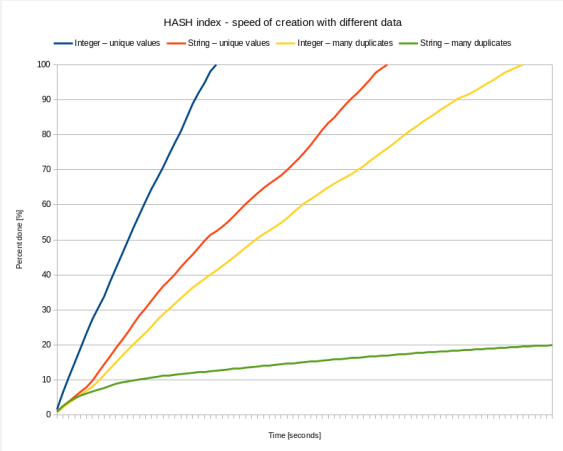
- Always check PostgreSQL statistics on the data before deciding to use a HASH index
- For JSONB data, create user defined statistics for the keys you want to index

- 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

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- 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

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- 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

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BTREE indexes

BTREE indexes

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- Very small and quick -> ideal first choice
- Allow parallel index build and scan
- Can be created in minutes, even on large tables

- Support equality and range queries: <, <=, =, >=, and >
- With *text_pattern_ops* (for each column), 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
- LIMIT improves delivery of results significantly

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Sizes of indexes

Summary of results – sizes of indexes

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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 %

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JSON decomposition

JSON object decomposition - test with Github events

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

- Main table would need 807 columns (jsonpaths without array elements)
- In total: text 604, number 105, boolean 70, datetime 28 columns
- I tried the main table: *"ERROR: row is too big: size 9088, maximum size 8160"*

- Some big nested JSONB objects would need separate tables too
- Decomposition is huge task on its own, prone to many errors

JSON object decomposition

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

- Full jsonpath as a column name can easily exceed 63 characters
- 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
- Alignment/padding can waste space for many small columns

JSON object decomposition

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- 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

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- 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;
```

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Statistics

Statistics for the whole JSONB object

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- 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

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- 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!

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All my slides

Recorded talks