Managing Your Tuple Graveyard

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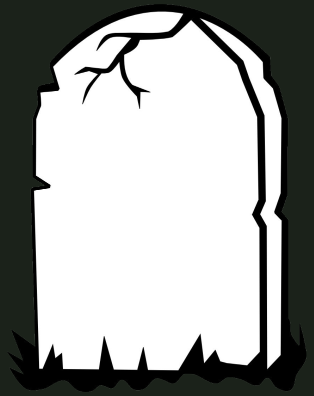
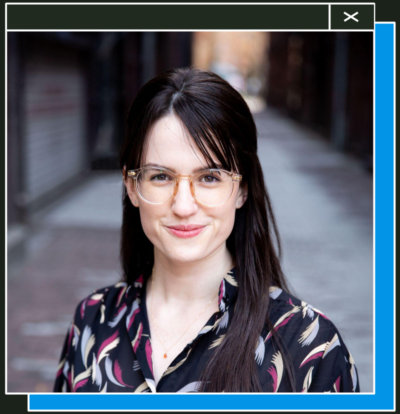


- Senior Software Engineer, Brex
    - “The credit card for startups”, expense management software
    - Previously: Data Engineer, Backend Engineer
- Tech Lead, Data Storage Team
    - Postgres infrastructure
    - Query optimization
    - & more!



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Outline

1. **Multi-Version Concurrency Control (MVCC)**
   a. What is MVCC and why does it need to exist?
   b. Vacuum, live vs dead tuples, and more
2. **Table bloat**
   a. What is it, what causes it, and how does it impact databases?
   b. Case study
3. **Quantifying, mitigating, and avoiding table bloat**
   a. `pgstattuple`, `pg_repack`, …
   b. Autovacuum configuration
4. **Designing bloat-aware data access patterns**

1. MVCC

(Multi-Version Concurrency Control)

What is MVCC?

Multi-Version Concurrency Control:

A set of rules through which Postgres provides two important (yet seemingly contradictory) features:

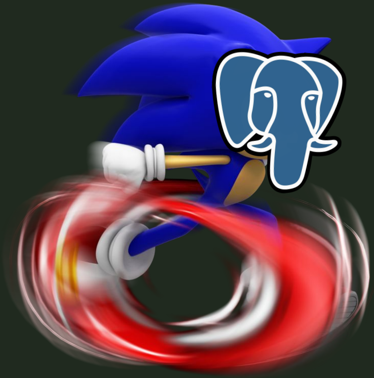
1. Transaction isolation
2. Fast performance

Transaction Isolation

- The "I" in **ACID**
  - *Atomic, Consistent, Isolated, Durable*
- Data within a transaction represents table state at transaction start

Fast Performance

- Writes don't block reads
- Reads don't block writes



Why are these goals contradictory?

TLDR; locks ensure transaction isolation, but lead to cascading locks/waits (and therefore bad performance)

- **EX: Basic Locking**
  - Most straightforward way to ensure transaction isolation
  - Not compatible with performance concurrent operations

MVCC's approach

- “Row versioning” via tuples
- All DML operations create new tuple(s) or update tuple metadata only
  - `INSERT`, `UPDATE`, `DELETE`, `MERGE`

Tuple

A physical, immutable “row” stored on disk.

A "row" is a logical construct consisting of `1 to n` tuples under the hood, representing the data over time.

Live Tuple

Newest row version
OR
used by a running query

Dead Tuple

Old row version
AND
unused by running queries

MVCC's approach

- Transaction snapshots
- Tuple visibility
  - `xmin` - TXID which inserted the tuple
  - `xmax` - TXID which updated/deleted the tuple
  - `xip_list` – TXIDs of active transactions
- TXID: assigned at transaction start

Snapshot

A data structure created on a per-transaction basis.

Uses `xmin`, `xmax`, and `xip_list` to determine which tuples are visible for the transaction.

Example

xmin	xmax	id	first_name	city	updated_at
594		1	chelsea	seattle	2015-03-26T10:58:51
594		2	stephen	nashville	2021-07-23T21:11:48
594		3	selena	bellingham	2018-01-04T07:33:21
594		4	tommy	toronto	1998-09-17T04:03:02
594		5	adam	chicago	2017-04-15T10:07:52

TUPLE COUNT: 1

CURRENT TXID: 600

Example – INSERT

xmin	xmax	id	first_name	city	updated_at
594		1	chelsea	seattle	2015-03-26T10:58:51
594		2	stephen	nashville	2021-07-23T21:11:48
594		3	selena	bellingham	2018-01-04T07:33:21
594		4	tommy	toronto	1998-09-17T04:03:02
594		5	adam	chicago	2017-04-15T10:07:52
600		6	john	new york	2002-03-13T11:15:14

1. INSERT new tuple
   a. xmin = current txid

Example – UPDATE

TUPLE COUNT: 2

CURRENT TXID: 605

xmin	xmax	id	first_name	city	updated_at
594		1	chelsea	seattle	2015-03-26T10:58:51
594		2	stephen	nashville	2021-07-23T21:11:48
594		3	selena	bellingham	2018-01-04T07:33:21
594		4	tommy	toronto	1998-09-17T04:03:02
594		5	adam	chicago	2017-04-15T10:07:52
600	605	6	john	new york	2002-03-13T11:15:14
605		6	john	seattle	2023-03-10T14:07:52

1. Soft DELETE existing tuple
   a. `xmax = current txid`
2. INSERT new tuple with updated values
   a. `xmin = current txid`

TUPLE COUNT: 2

CURRENT TXID: 609

Example – DELETE

xmin	xmax	id	first_name	city	updated_at
594		1	chelsea	seattle	2015-03-26T10:58:51
594		2	stephen	nashville	2021-07-23T21:11:48
594		3	selena	bellingham	2018-01-04T07:33:21
594		4	tommy	toronto	1998-09-17T04:03:02
594		5	adam	chicago	2017-04-15T10:07:52
600	605	6	john	new york	2002-03-13T11:15:14
605	609	6	john	seattle	2023-03-10T14:07:52

1. Soft DELETE existing tuple
   a. xmax = current txid

So… infinitely increasing row count forever?

Vacuum

1. ⭐ Deletes dead tuples from Postgres pages, freeing up the space for reuse
2. Updates Postgres internal statistics via `ANALYZE`, improving query planner's effectiveness
3. Updates the "visibility map", which helps vacuum and Index-Only Scan performance
4. Frees up TXIDs for reuse to avoid TXID exhaustion

TUPLE COUNT: 0

CURRENT TXID: 609

Example – VACUUM

xmin	xmax	id	first_name	city	updated_at
594		1	chelsea	seattle	2015-03-26T10:58:51
594		2	stephen	nashville	2021-07-23T21:11:48
594		3	selena	bellingham	2018-01-04T07:33:21
594		4	tommy	toronto	1998-09-17T04:03:02
594		5	adam	chicago	2017-04-15T10:07:52

1. VACUUM
   hard-deletes dead tuples, freeing up page space for reuse

Example – INSERT + SELECT

xmin	xmax	id	first_name	city	updated_at
594		1	chelsea	seattle	2015-03-26T10:58:51
594		2	stephen	nashville	2021-07-23T21:11:48
594		3	selena	bellingham	2018-01-04T07:33:21
594		4	tommy	toronto	1998-09-17T04:03:02
594		5	adam	chicago	2017-04-15T10:07:52
611		89	olivia	new york	2023-04-10T17:19:37

SELECT Snapshot X

xmin: 611+

xip_list: [611]

1. **TXID=611:** INSERT INTO <table> VALUES (x, y, z);
2. SELECT * FROM <table>;

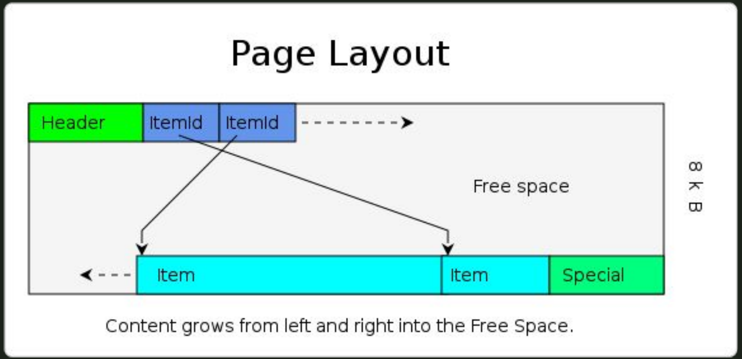
Postgres disk usage

- ➔ Vacuum: "frees up space for reuse"
- ➔ Without explicit intervention*, Postgres disk usage only increases
  - ◆ Pages are only created, not deleted
  - ◆ Vacuum deletes tuples, not pages
- ➔ Exceptions:
  - ◆ Page truncation, but VERY rare

Page

The smallest unit of disk space, 8kB in size by default. Stores:

- ⭐ Heap tuples
- Page header data
- Line pointers



* (we'll get to this later)

2. Table Bloat

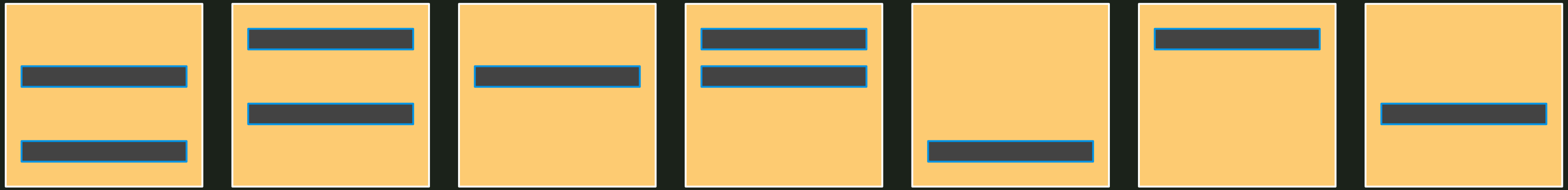
Table Bloat

Less-than-optimal "page density"

(number of live tuples per page vs how many could hypothetically fit)

Example

vs



Why is bloat often problematic?

- With dead tuples occupying what should be allocate-able disk space for new tuples, Postgres continues to create new pages
  - Unnecessarily increases disk usage
- After vacuum runs and dead tuples are deleted, live tuples are stored <u>sparsely</u> over many pages
  - More I/O usage during scans (more pages per scan)

Why is bloat often problematic?

Things are problematic… when they create problems 🤯🧠

- Problems:
  - Bad read latency
  - High (expensive?) disk usage
  - High (expensive?) IOPS
- Bloat == the root cause of other problems, not necessarily a problem in itself

How does bloat occur?

1. **`UPDATE/DELETE`-heavy workloads**
   a. Bloat is caused by pages becoming saturated with dead tuples, generated by updates and deletes
   b. Example:
      i. User activity resulting in cascading updates/deletes
      ii. Scheduled batch jobs editing massive amounts of data

2. **Badly-tuned autovacuum configuration**
   a. Overly conservative (or older default) autovacuum configurations paired with high `UPDATE/DELETE` workload mean autovacuum can't catch up

Example Case Study

id	feature_name (varchar)	user_id (bigint)	value (JSONB)	…
1	last_login	61466	{...}	…
2	likes_cats	9953217	true	…
3	owns_house	33644221	false	…
4	svd_vector	37995002	[...]	…
…	…	…	{...}	…

ML Feature Store

- ➔ 100s/1000s features/user
- ➔ Table size: 300GB
- ➔ All writes = upserts
- ➔ Burst-based, high volume write traffic triggered by user activity
- ➔ Feature deprecation → cron-based job to remove old values
- ➔ Default autovacuum configs

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id	feature_name (varchar)	user_id (bigint)	value (JSONB)	…
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…	…	…	{...}	…

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3. Quantifying, Mitigating, & Avoiding Bloat

Quantifying table bloat

1. `pgstattuple`
   a. Postgres contrib module created specifically for quantifying table bloat
   b. Precise return value, but can be very expensive. Slow-running, high resource usage
   c. `O(n)` runtime based on table size

2. Estimation queries
   a. Open-source estimation queries leveraging `pg_class.reltuples`
   b. Run `ANALYZE` first
   c. `O(1)` runtime, but results are only estimates

pgstattuple

```
db=> CREATE EXTENSION
pgstattuple;

db=> SELECT * FROM
pgstattuple('table');
```

Estimation

```
db=> ANALYZE VERBOSE;

db=> <your query>;
```

```
db=> SELECT * FROM pgstattuple('table_name');
-[ RECORD 1 ]------+---------
table_len          | 81584128
tuple_count        | 108963
tuple_len          | 73811880
tuple_percent      | 90.47
dead_tuple_count   | 2517
dead_tuple_len     | 2006536
dead_tuple_percent | 2.46
free_space         | 5017928
free_percent       | 6.15
```

- table_len ← table length (bytes)
- tuple_count ← # of total live tuples
- tuple_percent ← % of total tuples which are live
- dead_tuple_percent ← % of total tuples which are dead

```
db=> SELECT * FROM pgstattuple('table_name');

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table_len: table length (bytes)

tuple_count: # of total live tuples

tuple_percent: % of total tuples which are live

dead_tuple_percent: % of total tuples which are dead

```
db=> ANALYZE VERBOSE;

db=> <really long bloat estimation query>;
```

```
-[ RECORD 1 ]---+--------------------
real_size        | 81723392
bloat_size       | 7700480
bloat_pct        | 9.422614274258219
```

- real_size: estimated table length (bytes)
- bloat_size: estimated size of bloat (bytes)
- bloat_pct: estimated % of real_size used by bloat

https://github.com/ioguix/pgsql-bloat-estimation/tree/master

```
db=> ANALYZE VERBOSE;

db=> <really long bloat estimation query>;


-[ RECORD 1 ]---+--------------------
real_size       | 81723392
bloat_size      | 7700480
bloat_pct       | 9.42261427425821 9
```

estimated table length (bytes)

estimated size of bloat (bytes)

estimated % of real_size used by bloat

https://github.com/ioguix/pgsql-bloat-estimation/tree/master

Comparing methods

- ➔ % dead tuple count (pgstattuple) vs % dead disk space (estimation)
- ➔ Not directly comparable
  - ◆ Tuple size varies wildly
  - ◆ Page-level opportunistic pruning leaves 4-byte “tombstones”
  - ◆ 1KB “dead page space”: 250 4-byte tombstones, or 10 100-byte tuples?
- ➔ More info: Bloat in PostgreSQL: A Taxonomy (Peter Geoghegan)

Interpreting results:
How much bloat is “too much”?

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How much bloat is "too much"?

1. **Very Small (<= 1GB):**
   a. Up to ~70% bloat is acceptable
   b. This is high and not ideal, but at this table size, bloat has an imperceptible impact on performance.
2. **Small – Medium (~1–30GB):**
   a. Up to ~25% dead tuples is acceptable
3. **Large (~30–100GB):**
   a. Up to ~20% dead tuples is acceptable
4. **Very Large (~100GB+):**
   a. Up to ~18% dead tuples is acceptable

Dealing with bloated tables

1. Configure autovacuum to be more aggressive
2. Repack or rebuild tables

1. Configure autovacuum aggressively

- `autovacuum_vacuum_scale_factor`
  - Default: 0.2 (20% of table size)
  - "At least x% of the table must have changed since last vacuum for autovacuum to run"
  - Smaller → more frequent triggering of vacuums
  - EX: `autovacuum_vacuum_scale_factor = 0.01`
    - 1% of table size

- `autovacuum_vacuum_threshold`
  - Default: 50
  - Can be used to set raw value for vacuum trigger:
    - `autovacuum_vacuum_scale_factor = 0`
    - `autovacuum_vacuum_threshold = 200000`

Typically tune per-table via `ALTER TABLE`, not server-wide

1. Configure autovacuum aggressively

- `autovacuum_vacuum_cost_delay`
  - Default: 2ms (20ms PG11 and before)
  - Cost delay/wait time used in autovacuum operations
  - If using modern hardware, 2ms should be used regardless of PG version

- `autovacuum_max_workers`
  - Default: 3 (server-wide)
  - If you have many tables (1000s+) on your database server
  - Check `pg_stat_progress_vacuum` to see how many vacuums are currently running. Increase +1 if always at max.

2. Repack or rebuild tables

`VACUUM FULL`

Rewrites table and all indexes into a new disk file with no extra space

- ➔ Lock: `ACCESS EXCLUSIVE` (blocks reads & writes)
- ➔ "Wasted space" returned to the operating system.
- ➔ Not recommended due to extremely heavy lock

2. Repack or rebuild tables

`pg_repack` (+ `pg_squeeze`, etc)

Duplicates the bloated table, copies over incoming data via triggers – then `ALTER`s the table names to switch them, dropping the old table

- Lock: `ACCESS SHARE`
- Requires 2x current table size in disk, significant CPU/RAM
- Occasionally flaky
  - Failure scenario: incomplete tables in `pg_repack` schema must be manually `DROP`-ped. No data loss, downtime.
- Overall recommended for use!

pg_repack (+ pg_squeeze, etc)

pg_repack

```
db=> CREATE EXTENSION pg_repack;

$ /usr/…/pg_repack -h <HOST> -U <USER>
-d <DATABASE> -t <SCHEMA>.<TABLE>
```

- ➔ External binary, less invasive
- ➔ Supported in most managed Postgres services (EX: AWS RDS)

pg_squeeze

```
db=> CREATE EXTENSION pg_squeeze;
db=> SELECT squeeze.squeeze_table(...);
```

- ➔ Operates entirely within the database, no external binary
- ➔ Background worker to schedule rewrites

4. Designing bloat-aware data access patterns

Data Access Patterns

- How, when, and for what purpose are you writing & reading data?
  - What % of transactions are reads, vs insert/update/deletes?
- Roughly what % data growth do you expect to occur annually?
- What sort of access will you/won’t you support?
  - What is your process for enforcing this?

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If your app is `UPDATE/DELETE` heavy...

Can you redesign your data access patterns to have fewer updates/deletes?

- EX: User actions trigger a "burst" of updates on a single row.
  - Can you update each row once instead of `n` times?

- EX: You're updating the same row (`last_seen`) 5x/second.
  - Can you have an append-only log style table with just inserts, index on `(user_id, inserted_at)`, and query for the most recent row?

If you have regular large `DELETE` jobs…

- ➔ Is your dataset compatible with partitioning, meaning you can replace `DELETE` with `DETACH PARTITION`/`pg_partman`?
  - ◆ Range or hash partitioning
  - ◆ Always able to provide partition key for user queries?
- ➔ Are you making sure to always use a reasonable batch size in your `DELETE`s, rather than just running in one huge transaction?
- ➔ Instead of 1 large weekly `DELETE` job, can you run 7 smaller daily `DELETE` jobs, and configure autovacuum to trigger per job?

Are you reinventing any wheels?

<u>My rule of thumb:</u> using Postgres for things outside of Postgres' intended OLTP purpose is fine (often via community-supported extensions) up to a certain scale.

- Full Text Search (FTS)
  - 25GB data → Postgres
  - 100GB data → Elasticsearch
- Key/Value Store
  - 50GB K/V table, 80% traffic == reads → Postgres
  - 120GB K/V table, 80% traffic == writes → Redis

Thank you!

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