# Managing Your Tuple Graveyard

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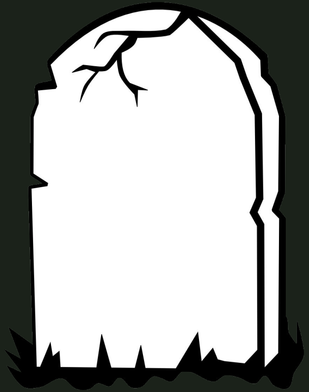
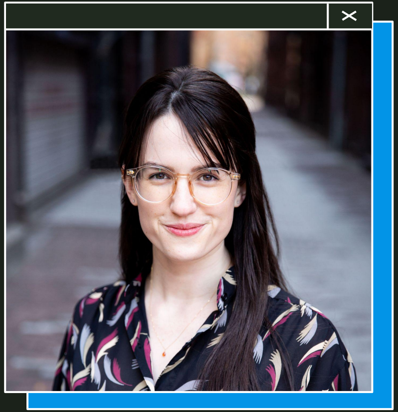


- Senior Software Engineer, Brex
  - “The credit card for startups”, expense management software
  - Previously: Data Engineer, Backend Engineer
- Tech Lead, Data Storage Team
  - Postgres infrastructure
  - Query optimization
  - & more!



**Chelsea Dole**

# 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:

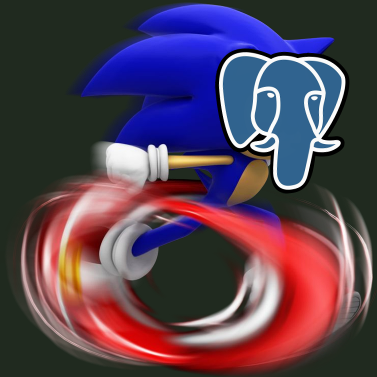
1. Transaction isolation
2. Fast performance

## 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

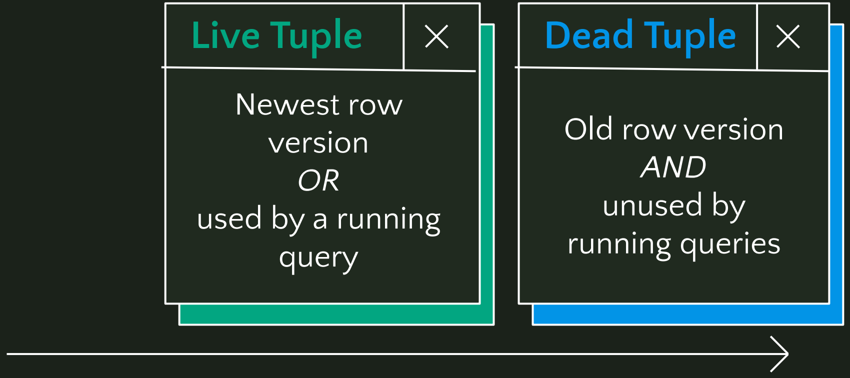
# MVCC’s approach

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

**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`

**TUPLE COUNT: 2**

**CURRENT TXID: 605**

# Example – `UPDATE`

| 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 freeze/wraparound

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

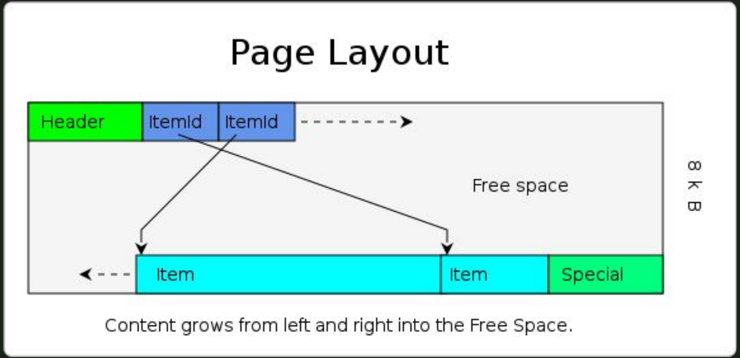
- ➔ Vacuum: "frees up space for reuse"
- ➔ Without explicit intervention*, Postgres disk usage only increases
  - ◆ Pages are only created, not deleted
  - ◆ Vacuum deletes tuples, not pages
- ➔ Exceptions:
  - ◆ Page truncation, but VERY rare

**Page**

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

- ⭐ Heap tuples
- Page header data
- Line pointers

Page Layout



Content grows from left and right into the Free Space.

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* (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**
    1. Bloat is caused by pages becoming saturated with dead tuples, generated by updates and deletes
    2. Example:
        1. User activity resulting in cascading updates/deletes
        2. Scheduled batch jobs editing massive amounts of data

2. **Badly-tuned autovacuum configuration**
    1. 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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| … | … | … | {...} | … |

## ML Feature Store

- ➔ 100s/1000s features/user
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- ➔ Default autovacuum configs

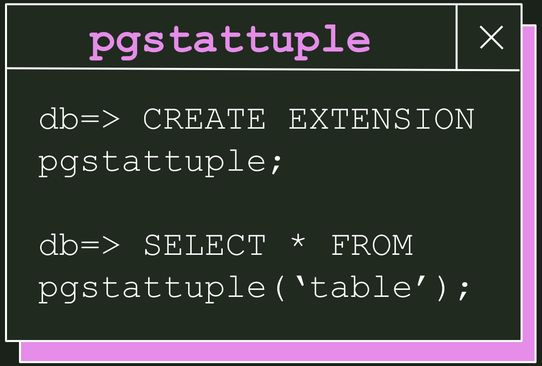
# 3.

# Quantifying, Mitigating, & Avoiding Bloat

# Quantifying table bloat

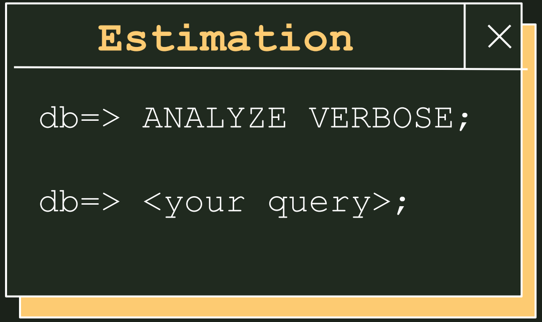
1. `pgstattuple`
   1. Postgres contrib module created specifically for quantifying table bloat
   2. Precise return value, but can be very expensive. Slow-running, high resource usage
   3. `O(n)` runtime based on table size

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



```
db=> CREATE EXTENSION
pgstattuple;

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



```
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 length (bytes)

# of total live tuples

% of total tuples which are live

% of total tuples which are dead

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

-[ RECORD 1 ]------+---------
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table length (bytes)

# of total live tuples

% of total tuples which are live

% 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
```

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

```
db=> ANALYZE VERBOSE;

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

```
-[ RECORD 1 ]---+---------------------
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```

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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# **Interpreting results:**
## 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?

# Data Access Patterns

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    - What is your process for enforcing this?

# 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?

My rule of thumb: 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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