Visualizing PostgreSQL Storage Internals

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PgUs

Why should you care?

This is not academic knowledge

Table bloat

VACUUM

Performance

Concurrency

DELETEs and UPDATEs

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The toolkit

The pg-storage-visualizer

github.com/boringSQL/pg-storage-visualizer

pageinspect
pgstattuple

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Act I

Why does a simple UPDATE create a whole new row?

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Tuple vs Row

Row is a logical concept (SQL)

Tuple is the physical concept

1:N (over time)

PostgreSQL does not care about your rows

It cares about 8KB blocks.

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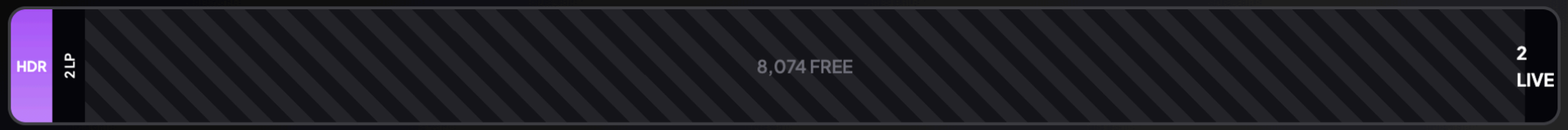
```
SHOW block_size;

block_size
------------
 8192
```

Heap Page 0 Table: demo

Page 1 → ×

8KB Heap Page (8,192 bytes)

1% Full



Live Tuples	Dead Tuples	Free Space	Line Pointers
2	0	7.9 KB	2

Heap Tuples

● 2 live

lp=1 LP_NORMAL (0,1)

xmin (insert)	xmax (delete)
406999	–

ctid (next version) (0,1)

Size 43 bytes

COMMITTED

lp=2 LP_NORMAL (0,2)

xmin (insert)	xmax (delete)
406999	–

ctid (next version) (0,2)

Size 43 bytes

COMMITTED

Page Header Line Pointers Data

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Every row carries 23 bytes of overhead

HeapTupleHeaderData struct

Field	Size	What it does
t_xmin	4B	Transaction that **created** this row
t_xmax	4B	Transaction that **deleted/updated** this row
t_ctid	6B	Physical location (self-pointer, or forward link)
t_infomask	2B	16 hint bits (XMIN_COMMITTED, HAS_NULL, ...)
t_infomask2	2B	Number of columns + HOT flags
t_hoff	1B	Offset to actual data
null bitmap	var	1 bit per column (if any NULLs)

t_xmin + t_xmax = the MVCC fingerprint

Eight bytes to rule them all, and in PostgreSQL bind them

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An UPDATE is a DELETE + INSERT

```
Before UPDATE:
  Row v1: xmin=100, xmax=0, ctid=(0,1)    <- visible

After UPDATE:
  Row v1: xmin=100, xmax=200, ctid=(0,2)  <- dead, "deleted" by tx 200
  Row v2: xmin=200, xmax=0,   ctid=(0,2)  <- new version, created by tx 200
```

Act II

Why does a 2GB table use 20GB on disk?

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Dead tuples don't clean themselves up

One UPDATE = one corpse.
A million UPDATEs = ?

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Enter VACUUM

The cleanup crew

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Why your 2GB table is 20GB

Reusable ≠ returned

Dead space is marked reusable (Free Space Map)

OS only gets space back from **empty pages at the tail**

REPACK is the only option

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Act III

Why does VACUUM seem to do nothing?

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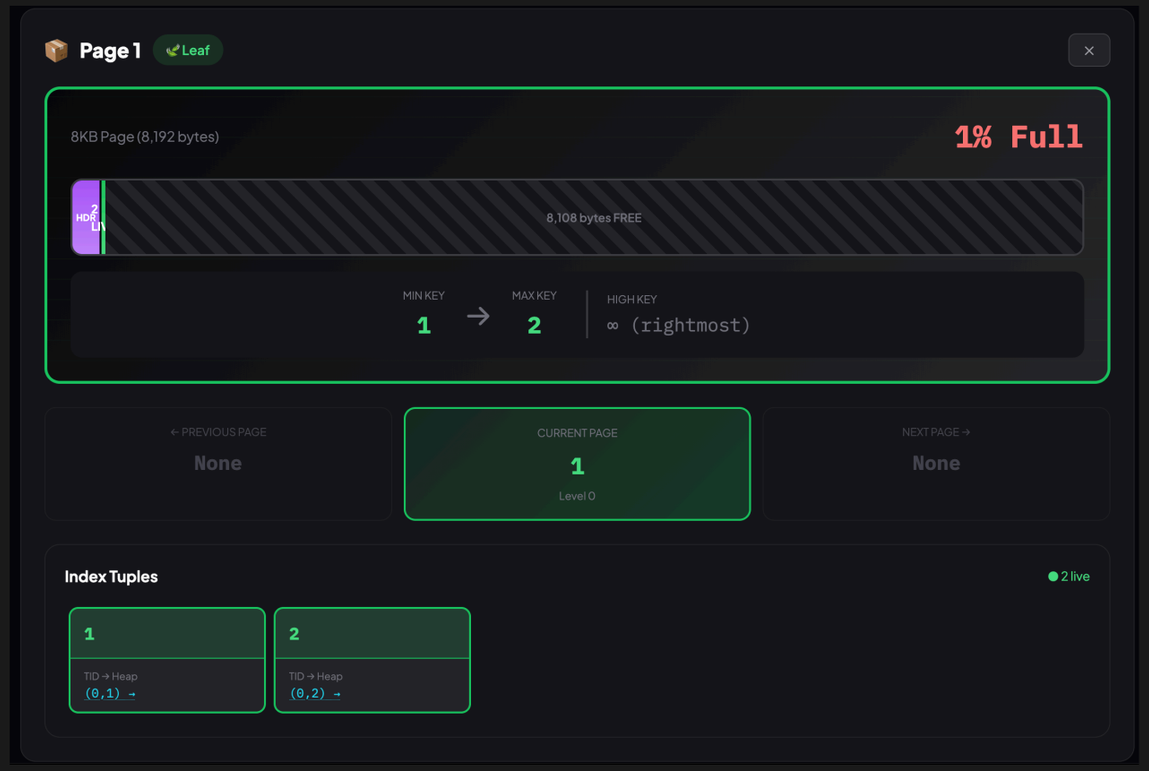
Heap Page vs B-tree Page

Same 8KB skeleton, different cargo

	Heap Page	B-tree Page
Page header	24B, identical	24B, identical
Line pointers	point to heap tuples	point to index tuples
Stored data	full row (tuple)	key + ctid
Special space	**empty**	**sibling + level pointers**
MVCC	xmin / xmax per tuple	none — lives in the heap



Key difference: special space at the bottom holds B-tree navigation pointers (left page, right page, tree level).

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What's in an index tuple?

Simpler version of a heap tuple

The **indexed column value** (the key)

A **ctid** pointing back to the heap row: `(page, line_pointer)`

No xmin/xmax **-- indexes don't do MVCC directly**

Indexes point to ALL versions of a row. Dead or alive.

> *Index entries have no xmin/xmax — visibility lives in the heap*

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Not every UPDATE bloats the index

The one the index never hears about

...with room left on the heap page

→ a **HOT** update (Heap-Only Tuple)

The index gets **no new entry**. None. WIN!

Don't just throw indexes left and right.

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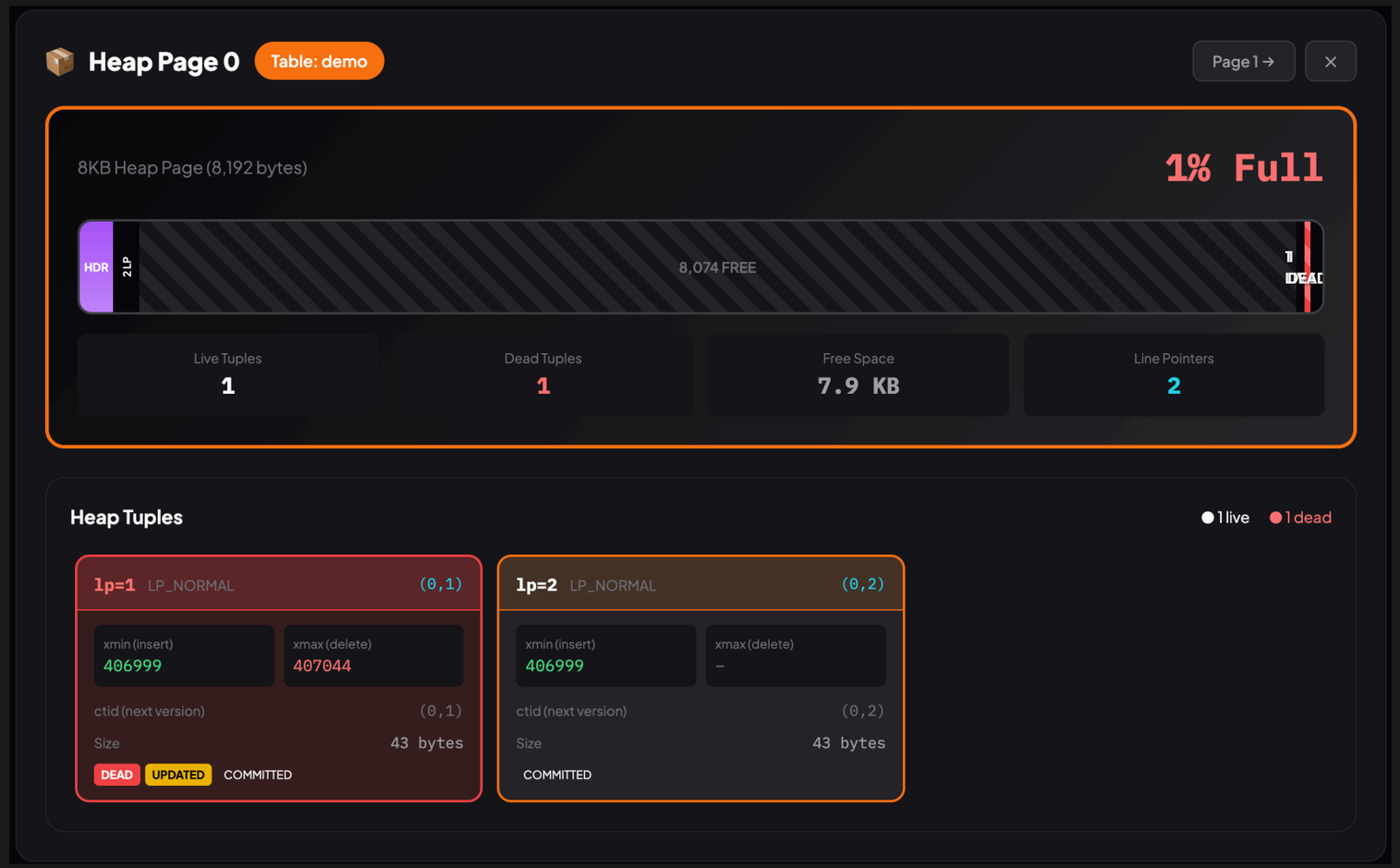

Heap Page

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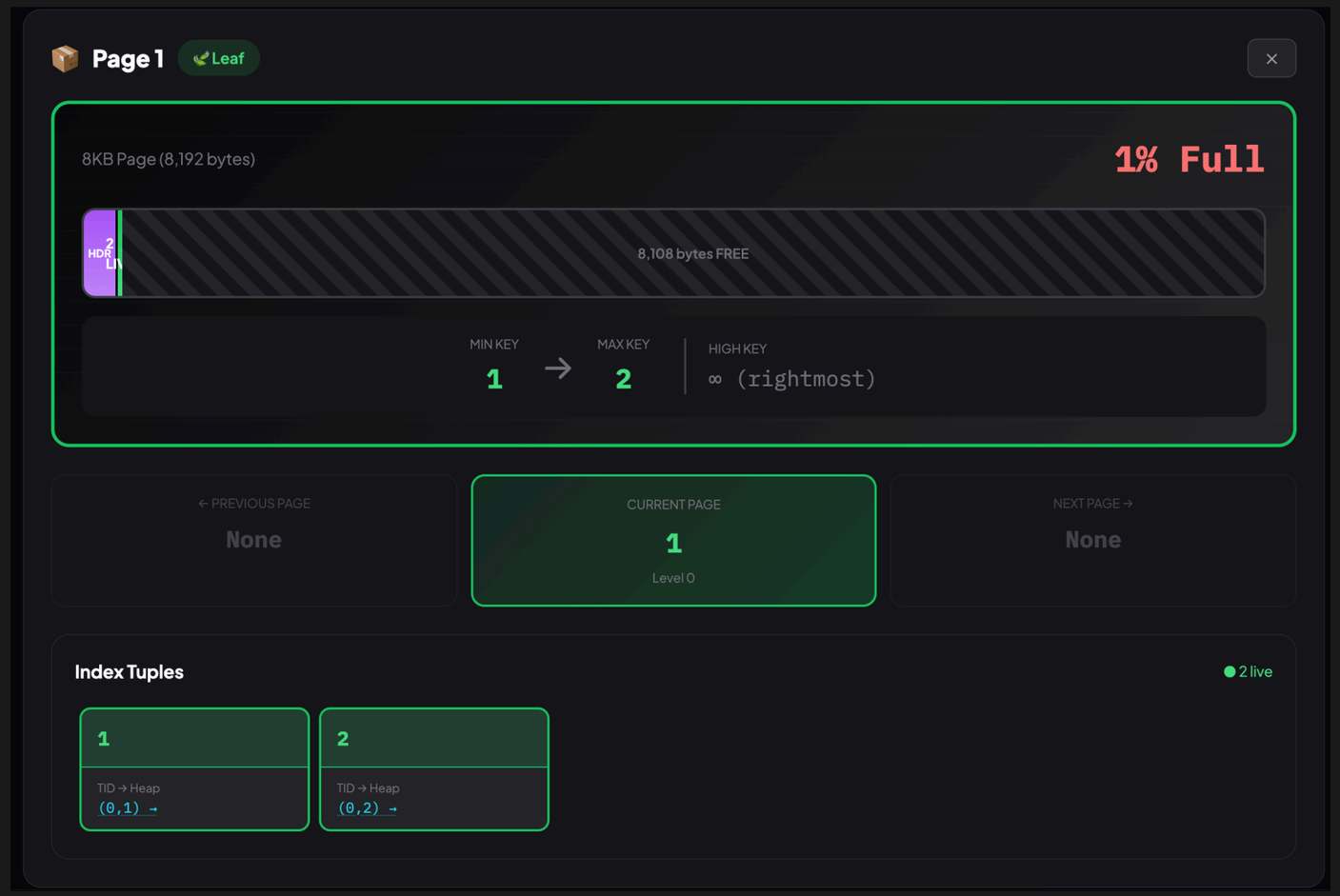

B-Tree Page

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VACUUM

The False hope for indexes

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Why VACUUM can't compact B-tree indexes

1. B-tree pages are **linked in order** (left-right sibling pointers)
2. Removing a page from the middle means **relinking siblings**
3. Other transactions might be **mid-scan** through those pages
4. PostgreSQL takes the safe path: **leave the page, mark it reusable**

REINDEX

The real fix

```
REINDEX INDEX demo_pkey;

SELECT * FROM pgstatindex('demo_pkey');
```

How to stay "clean"

For table it's simple

```
ALTER TABLE demo SET (
    autovacuum_vacuum_scale_factor = 0.01,
    autovacuum_analyze_scale_factor = 0.01
);
```

For index "it depends"

```
SELECT
    schemaname || '.' || indexrelname as index,
    pg_size_pretty(pg_relation_size(indexrelid)) as size,
    idx_scan as scans,
    idx_tup_read as tuples_read,
    idx_tup_fetch as tuples_fetched
FROM pg_stat_user_indexes
ORDER BY pg_relation_size(indexrelid) DESC;
```

Red flags

Index size >> table size

`avg_leaf_density` below 50%

Large `empty_pages` or `deleted_pages` counts

Index size keeps growing despite stable row count

Problem	Fix	Downtime?
Index bloat	`REINDEX CONCURRENTLY`	No (PG 12+)
Index bloat (older PG)	`CREATE INDEX CONCURRENTLY` + swap	No
Index bloat (urgent)	`REINDEX`	**Yes** (exclusive lock)
Heap bloat	`VACUUM FULL` or `pg_repack`	Depends
Prevent bloat	Tune autovacuum per table	No

What VACUUM does vs. what it doesn't

	Heap	B-tree Index
Remove dead tuples	**Yes**	**Yes** (entries)
Reclaim space within page	**Yes**	**Yes**
Return pages to OS	Only trailing pages	**No**
Compact/defragment	Page-level pruning	**No**
Rebuild structure	No	**No**

VACUUM is necessary but not sufficient for indexes.

github.com/boringSQL/pg-storage-visualizer

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https://boringsql.com/visualizers/

https://github.com/boringSQL/

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DEMO TIME

Easiest way to fail live

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Feedback appreciated

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