A Tour of PostgreSQL's On-Disk Storage

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About Me

- Architect for Data Engineering at Braintree Payments (PayPal)
- Contributor to Postgres versions 12+, including patches like:
  - Incremental sort (Postgres 13)
  - `ScalarArrayOpExpr` (`[NOT] IN, = ANY/ALL`) planner optimization and query execution improvements

Agenda

1. How to find data on disk
2. Heap table storage
3. BTree index storage
4. Data modeling implications

Relations: What and Where

Relations

What do they include?

- Tables
  - Note: We'll only discuss Heap tables.
  - Sequences
- Views
- Indexes

Relations

Where can we find them?

- As with all Postgres objects; start with catalog tables.
- `pg_catalog.pg_class` contains tables, indexes, sequences, views, etc.
  - `relfilenode` points us to the on-disk file (if non-zero); must also consider `reltablespace` if using tablespaces.

https://www.postgresql.org/docs/current/catalogs.html
https://www.postgresql.org/docs/current/catalog-pg-class.html

Relations

Where can we find them?

```
my_db=# select oid, relname, relfilenode from pg_class where relname = 'foo';
  oid  | relname | relfilenode
-------+---------+-------------
 16393 | foo     |       16393
```

Relations

Where can we find them?

```
my_db=# vacuum full foo;
VACUUM

my_db=# select oid, relname, relfilenode from pg_class where relname = 'foo';
  oid  | relname | relfilenode
-------+---------+-------------
 16393 | foo     |       16396
```

Relations

Where can we find them?

```
[dev]jcoleman-postgres:~/postgresql-test-data% ls

PG_VERSION      pg_hba.conf     pg_replslot/    pg_subtrans/
postgresql.auto.conf
base/           pg_ident.conf   pg_serial/      pg_tblspc/      postgresql.conf
global/         pg_logical/     pg_snapshots/   pg_twophase/    postmaster.opts
pg_commit_ts/   pg_multixact/   pg_stat/        pg_wal/         postmaster.pid
pg_dynshmem/    pg_notify/      pg_stat_tmp/    pg_xact/
```

Relations

Where can we find them?

```
[dev]jcoleman-postgres:~/postgresql-test-data% cd base
[dev]jcoleman-postgres:~/postgresql-test-data/base% ls

1/  16392/  4/  5/
```

- We previously found `relfilenode = 16396`; why isn't that here?

```
my_db=# select oid, datname from pg_database;
  oid   |  datname
--------+-----------
      5 | postgres
      1 | template1
      4 | template0
  16392 | my_db
```

Relations

Where can we find them?

```
[dev]jcoleman-postgres:~/postgresql-test-data/base/16392% ls
112         2336        2616_fsm  2685        3079_fsm  3576        4156
...
2187        2615        2681      2841        3541_vm   4152        PG_VERSION
2224        2615_fsm    2682      2995        3542      4153        pg_filenode.map
2228        2615_vm     2683      2996        3574      4154        pg_internal.init
2328        2616        2684      3079        3575      4155

[dev]jcoleman-postgres:~/postgresql-test-data/base/16392% ls -lah 16396*
-rw------- 1 admin admin 0 Sep 25 15:34 16396
```

Relations

Where can we find them?

```
my_db=# SHOW data_directory;
          data_directory
--------------------------------
 /home/admin/postgresql-test-data


my_db=# SELECT pg_relation_filepath('foo');
 pg_relation_filepath
----------------------
 base/16392/16396
```

Relations

What happens when we insert lots of data?

```
my_db=# create table bar(pk bigserial primary key, i int, some_fk bigint,
  other_fk bigint, t text, created_at timestamp default ‘now()',
  updated_at timestamp default 'now()');
CREATE TABLE

my_db=# insert into bar(i, some_fk, other_fk, t) select s.n, s.n % 10,
  s.n % 100, md5(s.n::text) from generate_series(1, 13_000_000) s(n);
INSERT 0 13000000

my_db=# select pg_size_pretty(pg_relation_size('bar'));
 pg_size_pretty
————————
 1451 MB
```

Relations

What happens when we insert lots of data?

```
my_db=# SELECT pg_relation_filepath('bar');
 pg_relation_filepath
----------------------
 base/16392/16400

[dev]jcoleman-postgres:~/postgresql-test-data/base/16392% ls -lah 16400*
-rw------- 1 admin admin 1.0G Sep 25 17:33 16400
-rw------- 1 admin admin 427M Sep 25 17:41 16400.1
-rw------- 1 admin admin 384K Sep 25 17:41 16400_fsm
-rw------- 1 admin admin  48K Sep 25 17:41 16400_vm
```

- Relation segment size is configurable at compile time with **RELSEG_SIZE**, but cluster must also be initialized to match the running binaries.

Heap Pages

Pages

Size

- Each relation segment file is divided into 8 KB pages.
  - Similarly to relation segment size, this can be configured at compilation time (`BLCKSZ`) and must match the cluster's storage.
  - Always the same on all relations.

Pages

Layout (Tables)

- `ItemIdData` is an array that grows front-to-back.
  - Each id is a pointer (offset, size) to an item in the Items array.
- Items is an array that grows back-to-front.
  - An “item” may be a tuple (on a heap table relation) or an index entry.

https://www.postgresql.org/docs/current/storage-page-layout.html

Pages

PageHeaderData

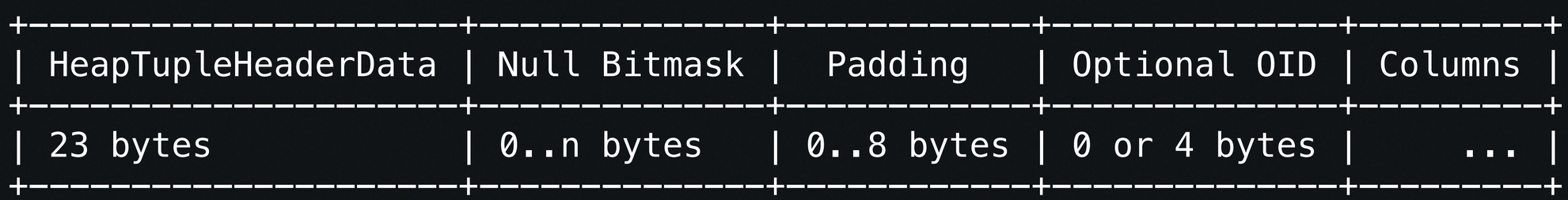
pd_lsn	pd_checksum	pd_flags	pd_lower	pd_upper	pg_special	pd_pagesize_version	pd_prune_xid
8 bytes	2 bytes	2 bytes	2 bytes	2 bytes	2 bytes	2 bytes	4 bytes

- `pd_lsn`: first byte of WAL that was written after this page was last changed
- `pd_flags`: hints about free space; flag denoting if all items are globally visible
- `pd_lower/pd_upper`: offsets to free space on the page
- `pd_prune_xid`: max XID of any unpruned tuples on the page

https://www.postgresql.org/docs/current/storage-page-layout.html

Heap Tuples

Heap Tuple Layout



- Column data must start on a multiple of MAXALIGN (usually 4 or 8 bytes)
  - Virtually all systems will have at least one byte for the null bitmask (first 8 nulls are free!)
  - Assume at least 24 bytes of overhead per tuple.
- Each column value may also have type-dependent alignment requirements.

https://www.postgresql.org/docs/current/storage-page-layout.html

Heap Tuples

HeapTupleHeaderData

t_xmin	t_xmax	t_cid/t_xvac	t_ctid	t_infomask2	t_infomask	t_hoff
4 bytes	4 bytes	4 bytes	6 bytes	2 bytes	2 bytes	1 byte

- `t_xmin` / `t_xmax`: Implement MVCC visibility.
- `t_ctid`: can link to other tuples within the same page to implement HOT update chains.
- `t_hoff`: offset to column data.

https://www.postgresql.org/docs/current/storage-page-layout.html

Heap Tuples

- Each tuple must fit within a single page (excluding TOAST data).
- Variable length fields (e.g., `text`, `bytea`, `jsonb`) stored with 1 or 4 bytes of overhead inline.
- TOAST (The Oversized-Attribute Storage Technique)
  - Max size of 1 GB per value
  - 18 byte pointer stored inline; storage is moved outside of the page.

https://www.postgresql.org/docs/current/storage-page-layout.html
https://www.postgresql.org/docs/current/limits.html
https://www.postgresql.org/docs/current/storage-toast.html

Tooling

pageinspect

- The pageinspect extension is included in the contrib package that ships (depending on your distribution) with PostgreSQL.
- Provides functions that allow low-level inspection of database pages.
  - Unfortunately the reads still go through standard buffer validation, and so you can’t read pages with an invalid checksum.

pageinspect

Raw pages

```
my_db=# select get_raw_page('bar', 1);

                                get_raw_page
------------------------------------------------------------------------
\x00000000a00fe401000004003001600100200420000000000909fe000209fe000b09ee
000409ee000d09de000609de000f09ce000809ce000109ce000a09be000309be000c09a
e000509ae000e099e0007099e0000099e0009098e0002098e000b097e0004097e000d09
6e0006096e000f095e0008095e0001095e000a094e0003094e000c093e0005093e000e0
92e0007092e0000092e0009091e0002091e000b090e0004090e000d08fe000608fe000f
08ee000808ee000108ee000a08de000308de000c08ce000508ce000e08be000708be000
008be000908ae000208ae000b089e0004089e000d088e0006088e000f087e0008087e00
01...
```

pageinspect

Page headers

```
my_db=# select * from page_header(get_raw_page('bar', 1));
-[ RECORD 1 ]---------
lsn       | 0/1E40FA0
checksum  | 0
flags     | 4
lower     | 304
upper     | 352
special   | 8192
pagesize  | 8192
version   | 4
prune_xid | 0
```

pageinspect

Page headers (after deleting a tuple)

```
my_db=# select * from page_header(get_raw_page('bar', 1));
-[ RECORD 1 ]---------
lsn       | 0/A861DD50
checksum  | 0
flags     | 0
lower     | 304
upper     | 352
special   | 8192
pagesize  | 8192
version   | 4
prune_xid | 758
```

pageinspect

Page headers (after vacuuming)s

```
my_db=# select * from page_header(get_raw_page('bar', 1));
-[ RECORD 1 ]---------
lsn       | 0/A861FF20
checksum  | 0
flags     | 0
lower     | 304
upper     | 464
special   | 8192
pagesize  | 8192
version   | 4
prune_xid | 0
```

pageinspect

Heap items

```
my_db=# select * from heap_page_items(get_raw_page('bar', 5));

-[ RECORD 70 ]-------------------------------------------------------------------
lp          | 70
lp_off      | 352
lp_flags    | 1
lp_len      | 112
t_xmin      | 749
t_xmax      | 0
t_field3    | 0
t_ctid      | (5,70)
t_infomask2 | 7
t_infomask  | 2306
t_hoff      | 24
t_bits      |
t_oid       |
t_data      | \xa401000000000000a401000000000000000000000000014000000000000043623666303437...
```

pageinspect

Heap items with attributes

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar', 1), 'bar'::regclass);

-[ RECORD 70 ]-------------------------------------------------------------------
lp          | 70
lp_off      | 352
lp_flags    | 1
lp_len      | 112
t_xmin      | 749
t_xmax      | 0
t_field3    | 0
t_ctid      | (1,70)
t_infomask2 | 7
t_infomask  | 2306
t_hoff      | 24
t_bits      |
t_oid       |
t_attrs     | {“\\x8c00000000000000”,"\\x8c000000","\\x0000000000000000","\\x2800000000000000",
              "\\x43313338353937346564353930346134333836313666663762646233663734333 9”,
              "\\x2ccb6e2630a90200","\\x2ccb6e2630a90200"}
```

pageinspect

Heap page items with flags

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar', 1), 'bar'::regclass),
           lateral heap_tuple_infomask_flags(t_infomask, t_infomask2);

-[ RECORD 70 ]-------------------------------------------------------------------
lp             | 70
lp_off         | 352
lp_flags       | 1
lp_len         | 112
t_xmin         | 749
t_xmax         | 0
t_field3       | 0
t_ctid         | (1,70)
t_infomask2    | 7
t_infomask     | 2306
t_hoff         | 24
t_bits         |
t_oid          |
t_attrs        | {...}
raw_flags      | {HEAP_HASVARWIDTH,HEAP_XMIN_COMMITTED,HEAP_XMAX_INVALID}
combined_flags | {}
```

pageinspect

Heap page items with flags (after deleting a tuple)

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar', 1), 'bar'::regclass),
           lateral heap_tuple_infomask_flags(t_infomask, t_infomask2);

-[ RECORD 70 ]---------------------------------------------------------------------
lp             | 70
lp_off         | 352
lp_flags       | 1
lp_len         | 112
t_xmin         | 749
t_xmax         | 758
t_field3       | 0
t_ctid         | (1,70)
t_infomask2    | 8199
t_infomask     | 258
t_hoff         | 24
t_bits         |
t_oid          |
t_attrs        | {...}
raw_flags      | {HEAP_HASVARWIDTH,HEAP_XMIN_COMMITTED,HEAP_KEYS_UPDATED}
combined_flags | {}
```

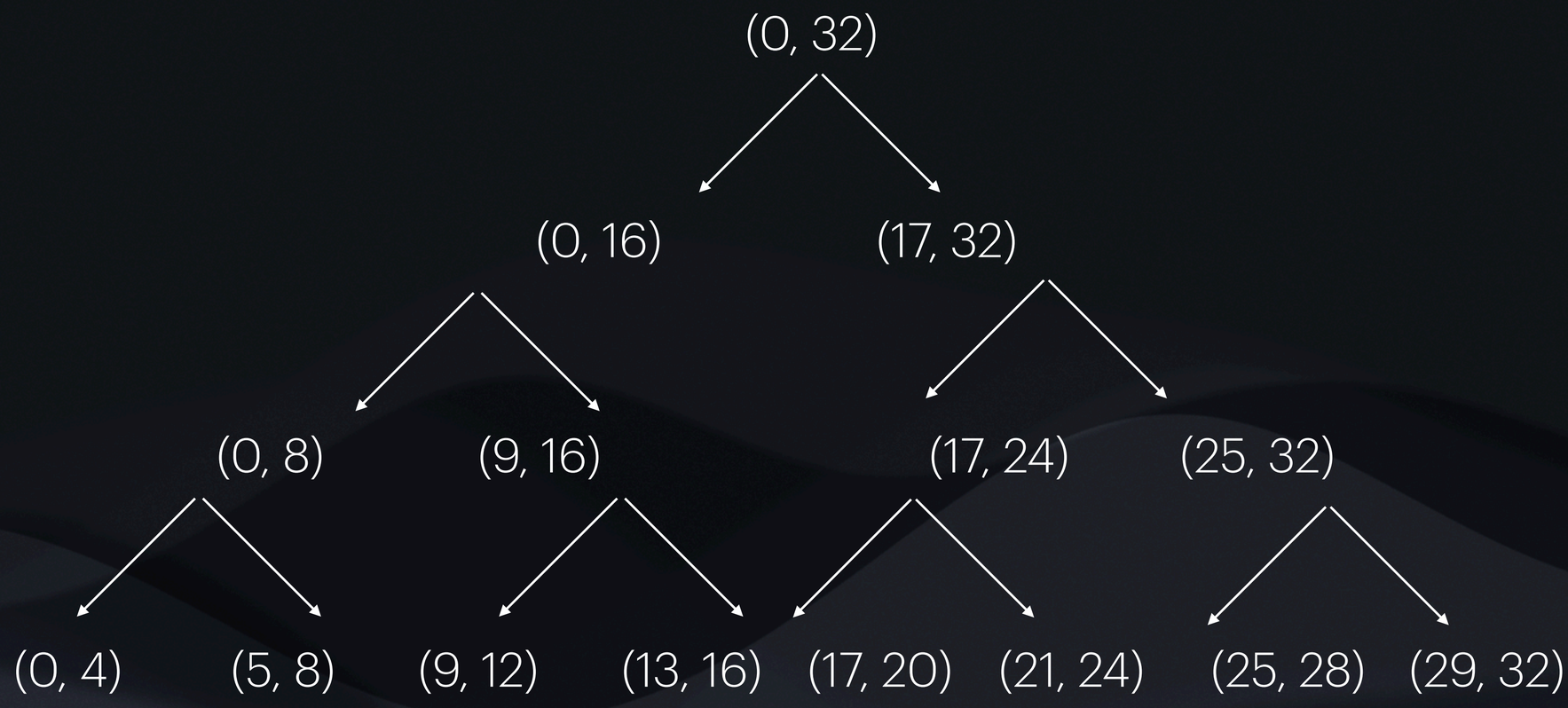
Heap Trade-offs

- MVCC implementation treats updates as inserts.
  - Simplifies MVCC as all visible tuple versions are physically present in the same heap.
  - Requires vacuuming dead tuples.
  - Updating a single attribute means copying the whole tuple.
- Bloat!
  - The per-page items array can end up with holes that are too small to hold a new tuple.

BTrees

BTrees

Not a binary tree, per se



and so on...

BTrees

Nodes and Pages

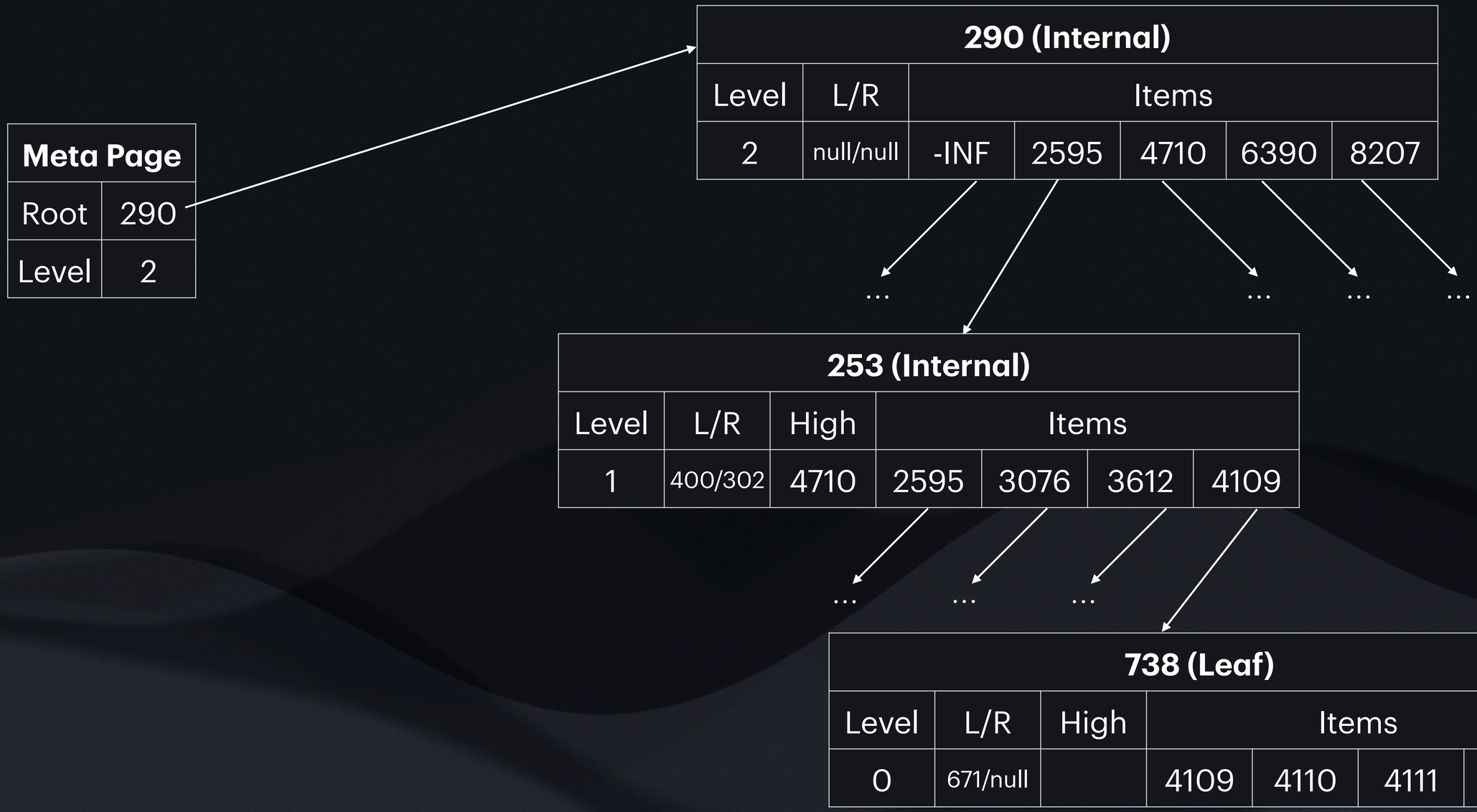
- Can store just the low key at each fork or the tree (rather than the full range).
- Each node in the tree is a whole page (i.e., 8 KB).
- Each level in the tree is a doubly-linked list (i.e., each page has left and right pointers).
- Two types of nodes:
  - Internal: contain tuples pointing to the next level of the tree.
  - Leaf: contain tuples pointing to rows in the table.

BTrees

Design choices

- PostgreSQL indexes are always indirect
  - Index entries contain a pointer to a physical row rather than a logical row.
  - Clustering on an index rarely makes sense.
- Multi-column indexes store the full index key at each tree level (as opposed to e.g. nested trees).

BTrees


Meta Page
Root 290
Level 2
290 (Internal)
Level L/R Items
2 null/null -INF 2595 4710 6390 8207
253 (Internal)
Level L/R High Items
1 400/302 4710 2595 3076 3612 4109
738 (Leaf)
Level L/R High Items
0 671/null 4109 4110 4111 4112

BTrees

Tooling

```
my_db=# insert into bar2(i)
        select case
               when n % 5 < 3 then round(n * random())
               else n % 1_000_000
               end
        from generate_series(1, 10_000_000) s(n);
INSERT 0 10000000

my_db=# create index index_bar2_on_i on bar2(i);
CREATE INDEX
```

BTrees

Tooling

```
my_db=# select * from bt_metap('index_bar2_on_i');
-[ RECORD 1 ]-------------+-------
magic                     | 340322          #define BTREE_MAGIC 0x053162
version                   | 4
root                      | 290
level                     | 2
fastroot                  | 290
fastlevel                 | 2
last_cleanup_num_delpages | 0
last_cleanup_num_tuples   | -1
allequalimage             | t
```

BTrees

Tooling

```
my_db=# select * from bt_page_items('index_bar2_on_i', 290);
 itemoffset |   ctid    | itemlen | nulls | vars |          data           | dead | htid | tids
------------+-----------+---------+-------+------+-------------------------+------+------+------
          1 | (3,0)     |       8 | f     | f    |                         |      |      |
          2 | (289,1)   |      16 | f     | f    | ee 72 00 00 00 00 00 00 |      |      |
          3 | (575,1)   |      16 | f     | f    | 9e ef 00 00 00 00 00 00 |      |      |
          4 | (860,1)   |      16 | f     | f    | b0 70 01 00 00 00 00 00 |      |      |
          5 | (1145,1)  |      16 | f     | f    | d6 f4 01 00 00 00 00 00 |      |      |
          6 | (1430,1)  |      16 | f     | f    | d6 7b 02 00 00 00 00 00 |      |      |
          7 | (1715,1)  |      16 | f     | f    | 0b 05 03 00 00 00 00 00 |      |      |
          8 | (2000,1)  |      16 | f     | f    | 76 90 03 00 00 00 00 00 |      |      |
          9 | (2285,1)  |      16 | f     | f    | 66 1d 04 00 00 00 00 00 |      |      |
         10 | (2570,1)  |      16 | f     | f    | 40 ac 04 00 00 00 00 00 |      |      |
         11 | (2855,1)  |      16 | f     | f    | 36 3c 05 00 00 00 00 00 |      |      |
...
```

Note:
ee 72 00 00 = 29,422
36 3c 05 00 = 343,094

BTrees

Tooling

```
my_db=# select * from bt_page_items('index_bar2_on_i', 575);
 itemoffset |  ctid   | itemlen | nulls | vars |          data           | dead | htid | tids
------------+---------+---------+-------+------+-------------------------+------+------+------
          1 | (857,1) |      16 | f     | f    | b0 70 01 00 00 00 00 00 |      |      |
          2 | (572,0) |       8 | f     | f    |                         |      |      |
          3 | (573,1) |      16 | f     | f    | 10 f0 00 00 00 00 00 00 |      |      |
          4 | (574,1) |      16 | f     | f    | 82 f0 00 00 00 00 00 00 |      |      |
          5 | (576,1) |      16 | f     | f    | f6 f0 00 00 00 00 00 00 |      |      |
          6 | (577,1) |      16 | f     | f    | 66 f1 00 00 00 00 00 00 |      |      |
          7 | (578,1) |      16 | f     | f    | dd f1 00 00 00 00 00 00 |      |      |
          8 | (579,1) |      16 | f     | f    | 4d f2 00 00 00 00 00 00 |      |      |
          9 | (580,1) |      16 | f     | f    | c4 f2 00 00 00 00 00 00 |      |      |
         10 | (581,1) |      16 | f     | f    | 39 f3 00 00 00 00 00 00 |      |      |
         11 | (582,1) |      16 | f     | f    | ac f3 00 00 00 00 00 00 |      |      |
...

Note:
b0 70 01 00 = 94,384
10 f0 00 00 = 61,456
ac f3 00 00 = 62,380
```

BTrees

Tooling

```
my_db=# select * from bt_page_items('index_bar2_on_i', 579);
 itemoffset |    ctid     | itemlen | nulls | vars |   data       | dead |    htid     |   tids
------------+-------------+---------+-------+------+--------------+------+-------------+-----------------
          1 | (16,1)      |      16 | f     | f    | c4 f2 00 ... |      |             |
          2 | (16,8204)   |      88 | f     | f    | 4d f2 00 ... | f    | (274,105)   | {“(274,105)”,”(382,84)",...}
          3 | (16,8196)   |      40 | f     | f    | 4e f2 00 ... | f    | (358,157)   | {“(358,157)”,”(7194,188)",...}
          4 | (16,8197)   |      48 | f     | f    | 4f f2 00 ... | f    | (731,189)   | {“(731,189)”,”(2704,96)",...}
          5 | (14571,114) |      16 | f     | f    | 50 f2 00 ... | f    | (14571,114) |
          6 | (16,8204)   |      88 | f     | f    | 51 f2 00 ... | f    | (274,109)   | {“(274,109)”,”(1506,109)",...}
          7 | (16,8205)   |      96 | f     | f    | 52 f2 00 ... | f    | (274,110)   | {“(274,110)”,”(448,162)",...}
          8 | (16,8194)   |      32 | f     | f    | 53 f2 00 ... | f    | (811,105)   | {"(811,105)","(1498,169)"}
          9 | (16,8197)   |      48 | f     | f    | 54 f2 00 ... | f    | (798,3)     | {“(798,3)”,”(1602,129)",...}
         10 | (16,8194)   |      32 | f     | f    | 55 f2 00 ... | f    | (365,182)   | {"(365,182)","(1764,147)"}
         11 | (16,8202)   |      80 | f     | f    | 56 f2 00 ... | f    | (274,114)   | {“(274,114)”,”(4699,64)",...}
...
```

Note:
c4 f2 00 00 = 62,148
4d f2 00 00 = 62,029
56 f2 00 00 = 62,038

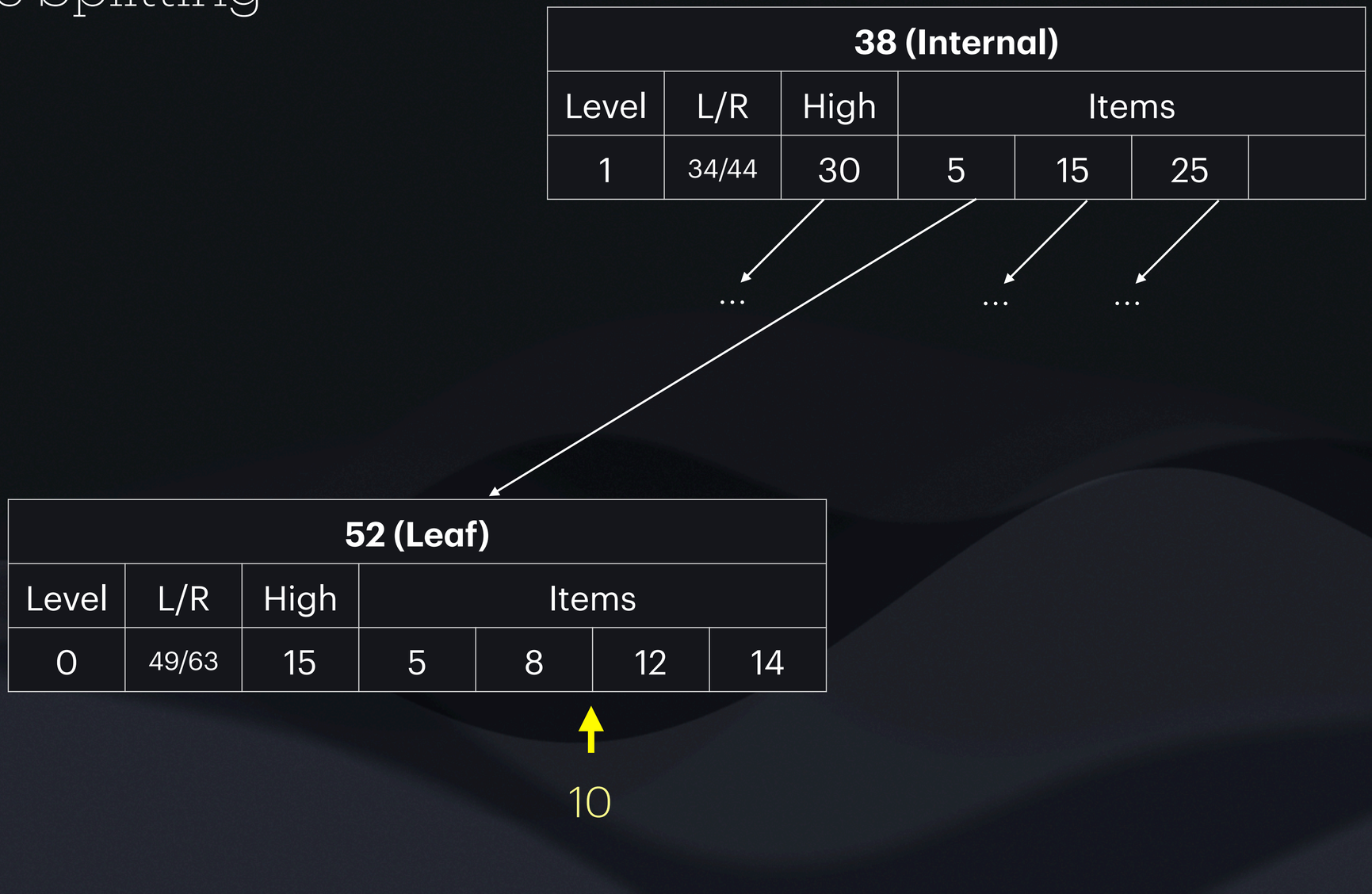
BTrees

Tooling

```
my_db=# select * from bar2 where ctid in ('(274,114)', '(4699,64)');
   pk    |   i
---------+-------
   62038 | 62038
 1062038 | 62038
```

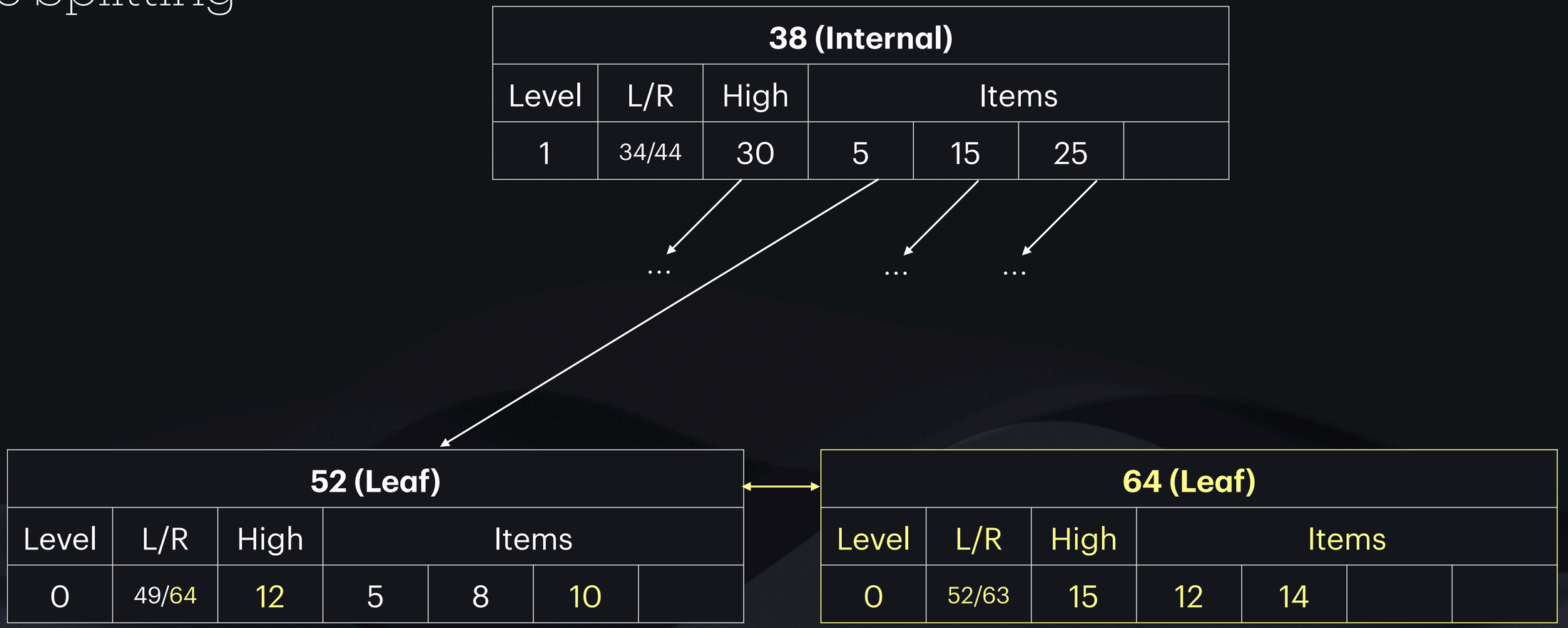
BTrees

Page Splitting



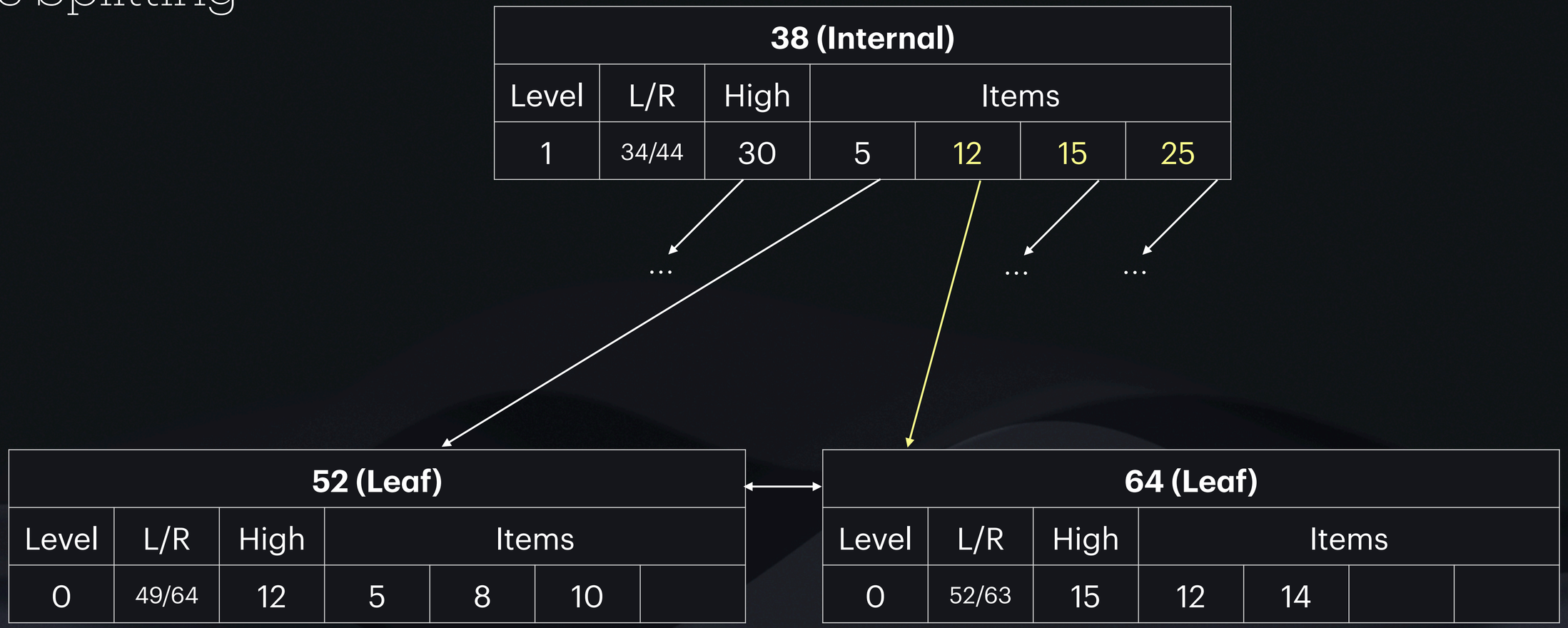
BTrees

Page Splitting



BTrees

Page Splitting



BTrees

MVCC

- New versions of the same logical tuple are inserted as separate physical entries in the index.
  - Old versions must be cleaned up later (either opportunistically or when vacuuming).
    - Bloat!
    - WAL writes *can be generated by index scans*.
    - This may also require splitting a page!
    - Can encode bloat structurally in the index structure (lots of dead space).

BTrees

MVCC

- HOT (Heap Only Tuple) Updates
  - When an update 1.) doesn’t logically change the entry in an index and 2.) there’s space for the new version on the same heap page, the index update can be skipped.
  - Another place where reads can generate WAL traffic (cleaning up dead tuples).

BTrees

MVCC

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar3', 1), 'bar3'::regclass),
           lateral heap_tuple_infomask_flags(t_infomask, t_infomask2)
           where lp = 127;
-[ RECORD 1 ]--+-----------------------------------
lp             | 127
lp_off         | 4128
lp_flags       | 1
lp_len         | 28
t_xmin         | 826
t_xmax         | 0
t_field3       | 0
t_ctid         | (1,127)
t_infomask2    | 1
t_infomask     | 2304
t_hoff         | 24
t_bits         |
t_oid          |
t_attrs        | {"\\x23040000",NULL}
raw_flags      | {HEAP_XMIN_COMMITTED,HEAP_XMAX_INVALID}
combined_flags | {}
```

BTrees

MVCC

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar3', 1), 'bar3'::regclass),
           lateral heap_tuple_infomask_flags(t_infomask, t_infomask2)
           where lp = 127;
-[ RECORD 1 ]--+-----------------------------------
lp             | 127
lp_off         | 4128
lp_flags       | 1
lp_len         | 28
t_xmin         | 826
t_xmax         | 831
t_field3       | 0
t_ctid         | (1,184)
t_infomask2    | 16385
t_infomask     | 256
t_hoff         | 24
t_bits         |
t_oid          |
t_attrs        | {"\\x23040000",NULL}
raw_flags      | {HEAP_XMIN_COMMITTED,HEAP_HOT_UPDATED}
combined_flags | {}
```

BTrees

MVCC

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar3', 1), 'bar3'::regclass),
           lateral heap_tuple_infomask_flags(t_infomask, t_infomask2)
           where lp = 184;
-[ RECORD 1 ]--+-----------------------------------------
lp             | 184
lp_off         | 2304
lp_flags       | 1
lp_len         | 32
t_xmin         | 831
t_xmax         | 0
t_field3       | 0
t_ctid         | (1,184)
t_infomask2    | 32770
t_infomask     | 10240
t_hoff         | 24
t_bits         |
t_oid          |
t_attrs        | {"\\x23040000","\\x05000000"}
raw_flags      | {HEAP_XMAX_INVALID,HEAP_UPDATED,HEAP_ONLY_TUPLE}
combined_flags | {}
```

BTrees

MVCC

```
my_db=# select * from heap_page_item_attrs(get_raw_page('bar3', 1), 'bar3'::regclass),
           lateral heap_tuple_infomask_flags(t_infomask, t_infomask2)
           where lp = 127;
-[ RECORD 1 ]--+----
lp             | 127
lp_off         | 184
lp_flags       | 2
lp_len         | 0
t_xmin         |
t_xmax         |
t_field3       |
t_ctid         |
t_infomask2    |
t_infomask     |
t_hoff         |
t_bits         |
t_oid          |
t_attrs        |
raw_flags      |
combined_flags |
```

```
#define LP_REDIRECT 2 /* HOT redirect (should have lp_len=0) */
```

Wrapping it all up

Data Modeling Implications

Storage size

- Lots of small tuples have (relatively) high storage cost.
- Sparse columns are (relatively) cheap.
- Ordering columns by alignment requirements can save measurable space.
- Append-only workloads can avoid bloat.
- Use `fillfactor` to tune HOT frequency.
- Indexes on columns you don’t query by are more expensive than you realize.

Data Modeling Implications

Performance

- Bloat can significantly impact performance.
- TOAST can be slow (don’t abuse large fields; use a file system for those images!)
- Inserts/updates of pseudo-random values in a BTree.
  - Cache locality
  - Full page writes to WAL

Additional Topics

- Buffer cache (as well as the Linux page cache)
- FSM (free space map): Optimizes finding a page with free space. See also the pg_freespace module for inspection.
- Visibility map: Separate relation fork for heap tables; tracks pages with all-visible and all-frozen rows. Optimizes vacuum and supports index-only scans.
- amcheck: Tool to verify table and index consistency
- pageinspect functions for other index types

https://www.postgresql.org/docs/current/storage-fsm.html
https://www.postgresql.org/docs/current/storage-vm.html
https://www.postgresql.org/docs/current/amcheck.html

Q/A