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Dissecting PostgreSQL Data Corruption

PostgreSQL 18 made one very important change – data block checksums are now enabled by default for new clusters at cluster initialization time. I already wrote about it in my previous article. I also mentioned that there are still many existing PostgreSQL installations without data checksums enabled, because this was the default in previous versions. In those installations, data corruption can sometimes cause mysterious errors and prevent normal operational functioning. In this post, I want to dissect common PostgreSQL data corruption modes, to show how to diagnose them, and sketch how to recover from them.

Corruption in PostgreSQL relations without data checksums surfaces as low-level errors like "invalid page in block xxx", transaction ID errors, TOAST chunk inconsistencies, or even backend crashes. Unfortunately, some backup strategies can mask the corruption. If the cluster does not use checksums, then tools like *pg_basebackup*, which copy data files as they are, cannot perform any validation of data, so corrupted pages can quietly end up in a base backup. If checksums are enabled, *pg_basebackup* verifies them by default unless *–no-verify-checksums* is used. In practice, these low-level errors often become visible only when we directly access the corrupted data. Some data is rarely touched, which means corruption often surfaces only during an attempt to run *pg_dump* — because pg_dump must read all data.

Typical errors include:

```
-- invalid page in a table:
pg_dump: error: query failed: ERROR: invalid page in block 0 of relation base/16384/66427
pg_dump: error: query was: SELECT last_value, is_called FROM public.test_table_bytea_id_seq

-- damaged system columns in a tuple:
pg_dump: error: Dumping the contents of table "test_table_bytea" failed: PQgetResult() failed.
pg_dump: error: Error message from server: ERROR: could not access status of transaction 3353862211
DETAIL: Could not open file "pg_xact/0C7E": No such file or directory.
pg_dump: error: The command was: COPY public.test_table_bytea (id, id2, id3, description, data) TO stdout;

-- damaged sequence:
pg_dump: error: query to get data of sequence "test_table_bytea_id2_seq" returned 0 rows (expected 1)

-- memory segmentation fault during pg_dump:
pg_dump: error: Dumping the contents of table "test_table_bytea" failed: PQgetCopyData() failed.
pg_dump: error: Error message from server: server closed the connection unexpectedly
This probably means the server terminated abnormally
before or while processing the request.
pg_dump: error: The command was: COPY public.test_table_bytea (id, id2, id3, description, data) TO stdout;
```

Note: in such cases, unfortunately *pg_dump* exits on the first error and does not continue. But we can use a simple script which, in a loop, reads table names from the database and dumps each table separately into a separate file, with redirection of error messages into a table-specific log file. This way we both back up tables which are still intact and find all corrupted objects.

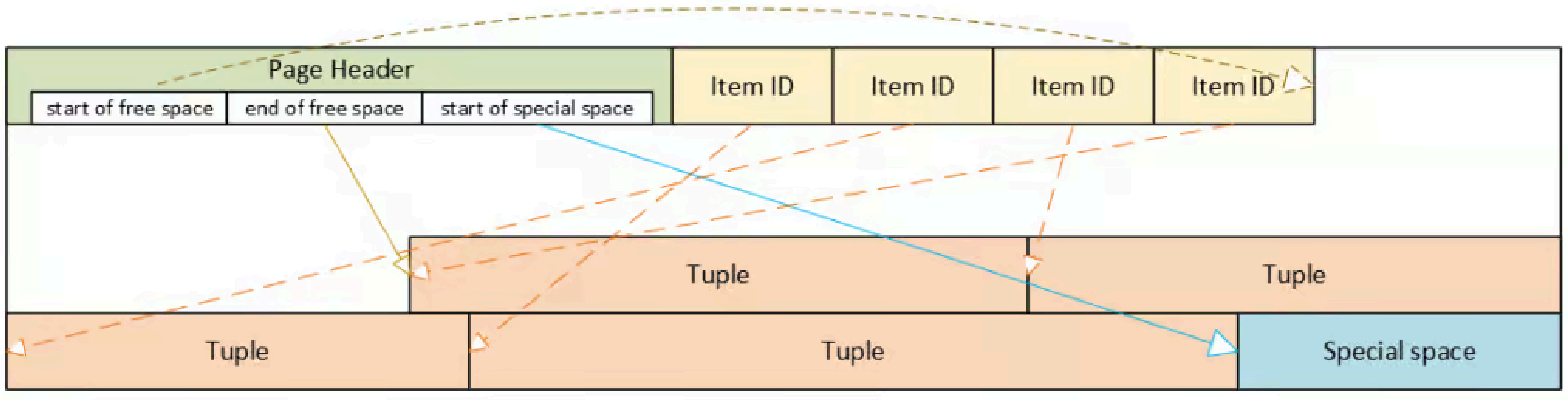
Understanding errors

The fastest way to make sense of those symptoms is to map them back to which part of an 8 KB heap page is damaged. To be able to test it, I created a “corruption simulator” Python script which can surgically damage specific parts of a data block. Using it we can test common corruption modes. We will see how to diagnose each with *pageinspect*, look if *amcheck* can help in these cases, and show how to surgically unblock queries with *pg_surgery* when a single tuple makes an entire table unreadable.

PostgreSQL heap table format

PostgreSQL stores heap table data in fixed-size blocks (typically 8 KB). Each block is laid out as:

- Header: metadata for block management and integrity
- Item ID (tuple pointer) array: entries pointing to tuples (offset + length + flags)
- Free space
- Tuples: actual row data, each with its own tuple header (system columns)
- Special space: reserved for index-specific or other relation-specific data – heap tables do not use it



Corrupted page header: the whole block becomes inaccessible

The page header contains the layout pointers for the page. The most important fields, which we can also see via *pageinspect* are:

- *pd_flags*: header flag bits
- *pd_lower*: offset to the start of free space
- *pd_upper*: offset to the end of free space
- *pd_special*: offset to the start of special space
- plus *lsn, checksum, pagesize, version, prune_xid*

The block header occupies the first 24 bytes of each data block. Corruption in the header makes the entire block inaccessible, typically with an error like:

```
ERROR: invalid page in block 285 of relation base/16384/29724
```

This is the only class of corruption error that can be skipped by enabling *zero_damaged_pages = on* when the cluster does not use data block checksums. With *zero_damaged_pages = on*, blocks with corrupted headers are “zeroed” in memory and skipped, which literally means the whole content of the block is replaced with zeros. AUTOVACUUM removes zeroed pages, but cannot zero out unscanned pages.

Where the error comes from in PostgreSQL source code

Of course the question is, how PostgreSQL diagnoses this problem without data block checksums. To answer it, we can check code in branches *REL_17_STABLE* / *REL_18_STABLE*. The error message: “invalid page in block xx of relation xxx” originates from the *src/backend/catalog/storage.c* file, in the *RelationCopyStorage* function. There, PostgreSQL calls *PageIsVerifiedExtended* (or *PageIsVerified* in 18) to validate the page before copying it. If the function returns *false*, the error is raised. Here is the part of the code which performs this test:

```
/*
* The following checks don't prove the header is correct, only that
* it looks sane enough to allow into the buffer pool. Later usage of
* the block can still reveal problems, which is why we offer the
* checksum option.
*/

if ((p->pd_flags & ~PD_VALID_FLAG_BITS) == 0 &&
    p->pd_lower <= p->pd_upper &&
    p->pd_upper <= p->pd_special &&
    p->pd_special <= BLCKSZ &&
    p->pd_special == MAXALIGN(p->pd_special))
    header_sane = true;

if (header_sane && !checksum_failure)
    return true;
```

The comment gives us very important information – the check cannot prove that the header is correct, only that it “looks sane enough”. This immediately shows how important checksums are for data corruption diagnostics. Without checksums, PostgreSQL must check if values in the page header have expected “sane” ranges. Here is what a healthy page header looks like:

```
SELECT * FROM page_header(get_raw_page('pg_toast.pg_toast_32840', 100));

     lsn    | checksum | flags | lower | upper | special | pagesize | version | prune_xid
------------+----------+-------+-------+-------+---------+----------+---------+-----------
 0/2B2FCD68 |        0 |     4 |    40 |    64 |    8192 |     8192 |       4 |         0
```

Here we can see the values which are tested in PostgreSQL code, to check if the header “looks sane enough”. Flag bits have valid values 0x0001, 0x0002, 0x0004 and their combinations, i.e. a maximum of 0x0007. Any higher value is taken as an indication of corruption.
If the header is tested as corrupted, we cannot diagnose anything using SQL. With *zero_damaged_pages = off* any attempt to read this page ends with an error similar to the example shown above. If we set *zero_damaged_pages = on* then on the first attempt to read this page everything is replaced with all zeroes, including the header:

```
SELECT * from page_header(get_raw_page('pg_toast.pg_toast_28740', 578));
WARNING: invalid page in block 578 of relation base/16384/28751; zeroing out page

 lsn | checksum | flags | lower | upper | special | pagesize | version | prune_xid
-----+----------+-------+-------+-------+---------+----------+---------+-----------
 0/0 |        0 |     0 |     0 |     0 |       0 |        0 |       0 |         0
```

Corrupted Item IDs array: offsets and lengths become nonsense

The Item IDs array contains 4-byte pointers to tuples – offset + length + flags. If this array is corrupted, tuples cannot be safely located/read, because offset and length now contain random values. Frequently bigger than the data page size –

bigger than 8192. Typical errors caused by this problem are:

- ERROR: invalid memory alloc request size 18446744073709551594
- DEBUG: server process (PID 76) was terminated by signal 11: Segmentation fault

Here is what a healthy data page looks like:

```
SELECT lp, lp_off, lp_flags, lp_len, t_xmin, t_xmax, t_field3, t_ctid, t_infomask2, t_infomask, t_hoff, t_bits,
t_oid, substr(t_data::text,1,50) as t_data
FROM heap_page_items(get_raw_page('public.test_table', 7));

 lp | lp_off | lp_flags | lp_len | t_xmin | t_xmax | t_field3 | t_ctid | t_infomask2 | t_infomask | t_hoff | t_bits
| t_oid | t_data
----+--------+----------+--------+--------+--------+----------+--------+-------------+------------+--------+-------
-+-------+----------------------------------------------------
  1 |   7936 |        1 |    252 |  29475 |      0 |        0 |  (7,1) |           5 |       2310 |     24 |
|       | \x01010000010100000101000018030000486f742073656520
  2 |   7696 |        1 |    236 |  29476 |      0 |        0 |  (7,2) |           5 |       2310 |     24 |
|       | \x020100000201000002010000d802000043756c747572616c
  3 |   7504 |        1 |    189 |  29477 |      0 |        0 |  (7,3) |           5 |       2310 |     24 |
|       | \x03010000030100000301000001c020000446f6f7220726563
  4 |   7368 |        1 |    132 |  29478 |      0 |        0 |  (7,4) |           5 |       2310 |     24 |
|       | \x040100000401000004010000 9d4d6f76656d656e74207374
```

Here we can nicely see the Item IDs array – offsets and lengths. The first tuple is stored at the very end of the data block, therefore it has the biggest offset. Each subsequent tuple is stored closer and closer to the beginning of the page, so offsets are getting smaller. We can also see lengths of tuples, they are all different, because they contain a variable-length text value. We can also see tuples and their system columns, but we will look at them later.

Now, when we damage the Item IDs array and diagnose how it looks like – output is shortened because all other columns are empty as well. Due to the damaged Item IDs array, we cannot properly read tuples. Here we can immediately see the problem – offsets and lengths contain random values, the majority of them exceeding 8192, i.e. pointing well beyond data page boundaries:

```
 lp | lp_off | lp_flags | lp_len | t_xmin | t_xmax
----+--------+----------+--------+--------+--------
  1 |  19543 |        1 |  16226 |        |
  2 |   5585 |        2 |   3798 |        |
  3 |  25664 |        3 |  15332 |        |
  4 |  10285 |        2 |  17420 |        |
```

Because PostgreSQL is, most of the time, remarkably stable and corruption is rare, the code which interprets the content of the data page does not perform any additional checks of key values beyond what we have already seen in the test of the page header. Therefore, these damaged offsets and lengths are used as they are, in many cases exceeding the 8kB variable containing the data page, which causes the errors mentioned above.
Note about the *amcheck* extension – although this extension can be useful in other cases, when we try to use it in this situation, we get strangely formulated messages which do not clearly indicate the problem:

```
SELECT * FROM verify_heapam('test_table', FALSE, FALSE, 'none', 7, 7);

 blkno | offnum | attnum | msg
-------+--------+--------+---------------------------------------------------------------------------
     7 |      1 |        | line pointer to page offset 19543 is not maximally aligned
     7 |      2 |        | line pointer redirection to item at offset 5585 exceeds maximum offset 4
     7 |      4 |        | line pointer redirection to item at offset 10285 exceeds maximum offset 4
```

Corrupted tuples: system columns can break scans

Tuple corruption leads to random values in columns, but the most critical part is the tuple header (system columns). Columns *xmin*, *xmax* and *hint bits* are especially critical. Random content in these columns causes errors like these examples:

- 58P01 – could not access status of transaction 3047172894
- XX000 – MultiXactId 1074710815 has not been created yet — apparent wraparound
- WARNING: Concurrent insert in progress within table “test_table”

These errors can raise concerns about the overall status of the PostgreSQL cluster. But there is nothing wrong with the actual transactions; these error messages are entirely caused by damaged system columns in tuples because PostgreSQL tries to interpret values as they are. We can see it clearly when we examine tuples using *pageinspect*:

```
 lp | lp_off | lp_flags | lp_len |   t_xmin    |   t_xmax    |  t_field3  |       t_ctid        | t_infomask2 |
t_infomask | t_hoff | t_bits | t_oid
----+--------+----------+--------+------------+------------+------------+--------------------+-------------+-------
-----+--------+--------+-------
  1 |   6160 |        1 |   2032 | 1491852297 |  287039843 |  491133876 | (3637106980,61186) |       50867 |
46441 |    124 |        |
  2 |   4128 |        1 |   2032 | 3846288155 | 3344221045 | 2002219688 | (2496224126,65391) |       34913 |
32266 |     82 |        |
  3 |   2096 |        1 |   2032 | 1209990178 | 1861759146 | 2010821376 | (426538995,32644)  |       23049 |
2764 |    215 |        |
```

As we can see, all system columns in tuples contain completely ridiculous values. No wonder PostgreSQL fails with strange errors when it tries to interpret them as they are. If the table contains toasted values and the TOAST table is damaged, we can see additional errors caused again by damaged tuples:

- XX000 – unexpected chunk number -556107646 (expected 20) for toast value 29611 in pg_toast_29580
- XX000 – found toasted toast chunk for toast value 29707 in pg_toast_29580

Dealing with corrupted tuples using pg_surgery

Even a single corrupted tuple can prevent selects from the entire table. Corruption in *xmin*, *xmax* and *hint bits* will cause a query to fail because the MVCC mechanism will be unable to determine visibility of these damaged tuples. Without data block checksums, we cannot easily zero out such damaged pages, since their header already passed the “sanity” test. We would have to do salvaging row-by-row using a PL/pgSQL script. But if a table is huge and the count of damaged tuples is small, this will be highly impractical.

In such a case, we should think about using the *pg_surgery* extension to freeze or remove corrupted tuples. But first, the correct identification of damaged tuples is critical, and second, the extension exists since PostgreSQL 14, it is not available in older versions. Its functions require *ctid*, but we must construct a proper value based on page number and ordinal number of the tuple in the page, we cannot use a damaged *ctid* from tuple header as shown above.

Freeze vs kill

Frozen tuples are visible to all transactions and stop blocking reads. But they still contain corrupted data: queries will return garbage. Therefore, just freezing corrupted tuples will most likely not help us, and we must kill damaged tuples. But freezing them first might be helpful for making sure we are targeting the proper tuples. Freezing simply means that function *heap_force_freeze* (with the proper *ctid*) will replace *t_xmin* with value *2* (frozen tuple), *t_xmax* with *0* and will repair *t_ctid*.

But all other values will stay as they are, i.e. still damaged. Using the *pageinspect* extension as shown above will confirm we work with a proper tuple. After this check, we can kill damaged tuples using the *heap_force_kill* function with the same parameters. This function will rewrite the pointer in the Item ID array for this specific tuple and mark it as dead.

Warning — functions in *pg_surgery* are considered unsafe by definition, so use them with caution. You can call them from SQL like any other function, but they are not MVCC-transactional operations. Their actions are irreversible – ROLLBACK cannot "undo" a freeze or kill, because these functions directly modify a heap page in shared buffers and WAL-log the change. Therefore, we should first test them on a copy of that specific table (if possible) or on some test table. Killing the tuple can also cause inconsistency in indexes, because the tuple does not exist anymore, but it could be referenced in some index. They write changes into the WAL log; therefore, the change will be replicated to standbys.

Summary

Without a proper backup, damaged data cannot be repaired. It can only be removed. But even this can be quite painful if the cluster does not use data page checksums. We can only either kill corrupted tuples or salvage readable data row-by-row. Real-life examples have repeatedly shown that the majority of companies can live with some data loss – but they need to resume normal operations as soon as possible. Therefore, in very specific situations – like having only a few corrupted tuples in a table with the size of dozens or hundreds of gigabytes – "surgery on tuples" could be the only way to resume normal operations without time consuming salvage of records. This again shows the importance of checksums.

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