

Egor Rogov

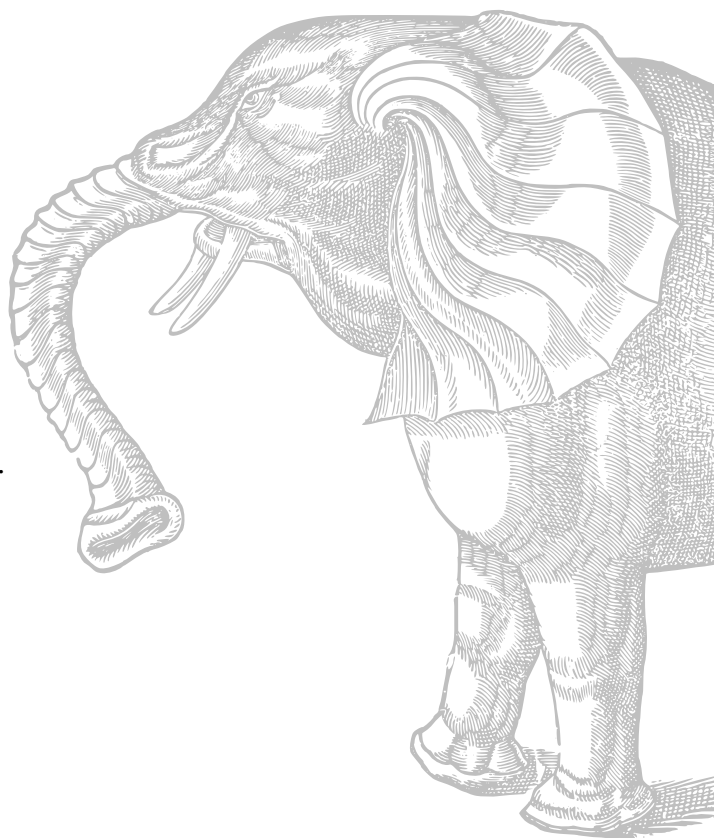
PostgreSQL 14 Internals

These are Parts I–III of the book.
The other parts will follow soon:

IV. Query Execution

V. Index Types

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The elephant on the cover is a fragment of an illustration from Edward Topsell's *The History of Four-footed Beasts and Serpents*, published in London in 1658

PostgreSQL 14 Internals

by Egor Rogov

Translated from Russian by Liudmila Mantrova

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About This Book

Books are not made to be believed, but to be subjected to inquiry.

— Umberto Eco, *The Name of the Rose*

For Whom Is This Book?

This book is for those who will not settle for a black-box approach when working with a database. If you are eager to learn, prefer not to take expert advice for granted, and would like to figure out everything yourself, follow along.

I assume that the reader has already tried using PostgreSQL and has at least some general understanding of how it works. Entry-level users may find the text a bit difficult. For example, I will not tell anything about how to install the server, enter `psql` commands, or set configuration parameters.

I hope that the book will also be useful for those who are familiar with another database system, but switch over to PostgreSQL and would like to understand how they differ. A book like this would have saved me a lot of time several years ago. And that's exactly why I finally wrote it.

What This Book Will Not Provide

This book is not a collection of recipes. You cannot find ready-made solutions for every occasion, but if you understand inner mechanisms of a complex system, you will be able to analyze and critically evaluate other people's experience and come to your own conclusions. For this reason, I explain such details that may at first seem to be of no practical use.

But this book is not a tutorial either. While delving deeply into some fields (in which I am more interested myself), it may say nothing at all about the other.

By no means is this book a reference. I tried to be precise, but I did not aim at replacing documentation, so I could easily leave out some details that I considered insignificant. In any unclear situation read the documentation.

This book will not teach you how to develop the PostgreSQL core. I do not expect any knowledge of the C language, as this book is mainly intended for database administrators and application developers. But I do provide multiple references to the source code, which can give you as many details as you like, and even more.

What This Book Does Provide

In the introductory chapter, I briefly touch upon the main database concepts that will serve as the foundation for all the further narration. I do not expect you to get much new information from this chapter but still include it to complete the big picture. Besides, this overview can be found useful by those who are migrating from other database systems.

Part I is devoted to questions of data consistency and isolation. I first cover them from the user's perspective (you will learn which isolation levels are available and what are the implications) and then dwell on their internals. For this purpose, I have to explain implementation details of multiversion concurrency control and snapshot isolation, paying special attention to cleanup of outdated row versions.

Part II describes buffer cache and WAL, which is used to restore data consistency after a failure.

Part III goes into details about the structure and usage of various types of locks: lightweight locks for RAM, heavyweight locks for relations, and row-level locks.

Part IV explains how the server plans and executes SQL queries. I will tell you which data access methods are available, which join methods can be used, and how the collected statistics are applied.

Part V extends the discussion of indexes from the already covered B-trees to other access methods. I will explain some general principles of extensibility that define the boundaries between the core of the indexing system, index access methods, and data types (which will bring us to the concept of operator classes), and then elaborate on each of the available methods.

PostgreSQL includes multiple “introspective” extensions, which are not used in routine work, but give us an opportunity to peek into the server’s internal behavior. This book uses quite a few of them. Apart from letting us explore the server internals, these extensions can also facilitate troubleshooting in complex usage scenarios.

Conventions

I tried to write this book in a way that would allow reading it page by page, from start to finish. But it is hardly possible to uncover all the truth at once, so I had to get back to one and the same topic several times. Writing that “it will be considered later” over and over again would inevitably make the text much longer, that’s why in such cases I simply put the page number in the margin to refer you to further discussion. A similar number pointing backwards will take you to the page where something has been already said on the subject. p. 13

Both the text and all the code examples in this book apply to PostgreSQL 14. Next to some paragraphs, you can see a version number in the page margin. It means that the provided information is relevant starting from the indicated PostgreSQL version, while all the previous versions either did not have the described feature at all, or used a different implementation. Such notes can be useful for those who have not upgraded their systems to the latest release yet. v. 14

I also use the margins to show the default values of the discussed parameters. The names of both regular and storage parameters are printed in italics: *work_mem*. 4MB

In footnotes, I provide multiple links to various sources of information. There are several of them, but first and foremost, I list the PostgreSQL documentation,¹ which is a wellspring of knowledge. Being an essential part of the project, it is always kept up-to-date by PostgreSQL developers themselves. However, the primary reference is definitely the source code.² It is amazing how many answers you can find by simply reading comments and browsing through README files, even if you do not know C. Sometimes I also refer to commitfest entries:³ you can always trace the

¹ [postgresql.org/docs/14/index.html](https://www.postgresql.org/docs/14/index.html)

² git.postgresql.org/gitweb/?p=postgresql.git;a=summary

³ commitfest.postgresql.org

history of all changes and understand the logic of decisions taken by developers if you read the related discussions in the `psql-hackers` mailing list, but it requires digging through piles of emails.

Side notes that can lead the discussion astray (which I could not help but include into the book) are printed like this, so they can be easily skipped.

Naturally, the book contains multiple code examples, mainly in SQL. The code is provided with the prompt `=>`; the server response follows if necessary:

```
=> SELECT now();
               now
-----
2022-09-19 14:50:52.347483+03
(1 row)
```

If you carefully repeat all the provided commands in PostgreSQL 14, you should get exactly the same results (down to transaction IDs and other inessential details). Anyway, all the code examples in this book have been generated by the script containing exactly these commands.

When it is required to illustrate concurrent execution of several transactions, the code run in another session is indented and marked off by a vertical line.

```
| => SHOW server_version;
|      server_version
| -----
|      14.4
| (1 row)
```

To try out such commands (which is useful for self-study, just like any experimentation), it is convenient to open two `psql` terminals.

The names of commands and various database objects (such as tables and columns, functions, or extensions) are highlighted in the text using a sans-serif font: `UPDATE`, `pg_class`.

If a utility is called from the operating system, it is shown with a prompt that ends with `$`:

```
postgres$ whoami  
postgres
```

I use Linux, but without any technicalities; having some basic understanding of this operating system will be enough.

Acknowledgments

It is impossible to write a book alone, and now I have an excellent opportunity to thank good people.

I am very grateful to Pavel Luzanov who found the right moment and offered me to start doing something really worthwhile.

I am obliged to Postgres Professional for the opportunity to work on this book beyond my free time. But there are actual people behind the company, so I would like to express my gratitude to Oleg Bartunov for sharing ideas and infinite energy, and to Ivan Panchenko for thorough support and \LaTeX .

I would like to thank my colleagues from the education team for the creative atmosphere and discussions that shaped the scope and format of our training courses, which also got reflected in the book. Special thanks to Pavel Tolmachev for his meticulous review of the drafts.

Many chapters of this book were first published as articles in the Habr blog,¹ and I am grateful to the readers for their comments and feedback. It showed the importance of this work, highlighted some gaps in my knowledge, and helped me improve the text.

I would also like to thank Liudmila Mantrova who has put much effort into polishing this book's language. If you do not stumble over every other sentence, the credit goes to her. Besides, Liudmila took the trouble to translate this book into English, for which I am very grateful too.

¹ habr.com/en/company/postgrespro/blog

About This Book

I do not provide any names, but each function or feature mentioned in this book has required years of work done by particular people. I admire PostgreSQL developers, and I am very glad to have the honor of calling many of them my colleagues.

1

Introduction

1.1 Data Organization

Databases

PostgreSQL is a program that belongs to the class of database management systems. When this program is running, we call it a PostgreSQL *server*, or *instance*.

Data managed by PostgreSQL is stored in databases.¹ A single PostgreSQL instance can serve several databases at a time; together they are called a *database cluster*.

To be able to use the cluster, you must first *initialize*² (create) it. The directory that contains all the files related to the cluster is usually called `PGDATA`, after the name of the environment variable pointing to this directory.

Installations from pre-built packages can add their own “abstraction layers” over the regular PostgreSQL mechanism by explicitly setting all the parameters required by utilities. In this case, the database server runs as an operating system service, and you may never come across the `PGDATA` variable directly. But the term itself is well-established, so I am going to use it.

After cluster initialization, `PGDATA` contains three identical databases:

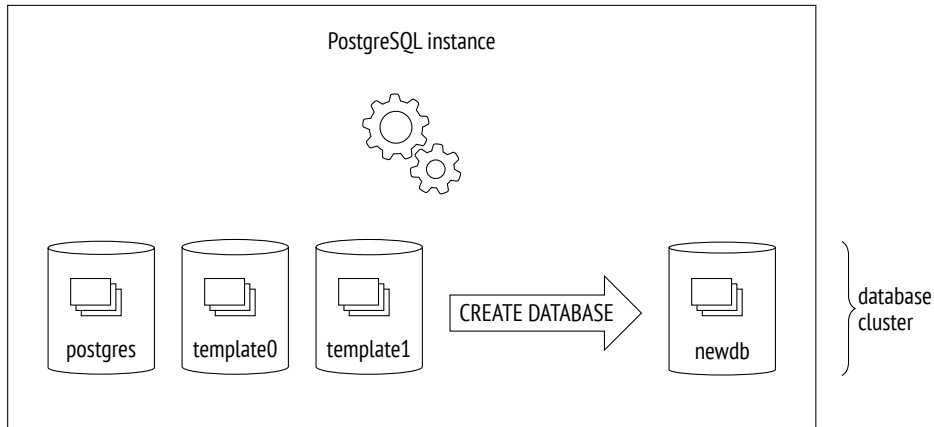
template0 is used for cases like restoring data from a logical backup or creating a database with a different encoding; it must never be modified.

template1 serves as a template for all the other databases that a user can create in the cluster.

¹ [postgresql.org/docs/14/managing-databases.html](https://www.postgresql.org/docs/14/managing-databases.html)

² [postgresql.org/docs/14/app-initdb.html](https://www.postgresql.org/docs/14/app-initdb.html)

postgres is a regular database that you can use at your discretion.



System Catalog

Metadata of all cluster objects (such as tables, indexes, data types, or functions) is stored in tables that belong to the *system catalog*.¹ Each database has its own set of tables (and views) that describe the objects of this database. Several system catalog tables are common to the whole cluster; they do not belong to any particular database (technically, a dummy database with a zero ID is used), but can be accessed from all of them.

The system catalog can be viewed using regular SQL queries, while all modifications in it are performed by DDL commands. The psql client also offers a whole range of commands that display the contents of the system catalog.

Names of all system catalog tables begin with `pg_`, like in `pg_database`. Column names start with a three-letter prefix that usually corresponds to the table name, like in `datname`.

In all system catalog tables, the column declared as the primary key is called `oid` (object identifier); its type, which is also called `oid`, is a 32-bit integer.

¹ [postgresql.org/docs/14/catalogs.html](https://www.postgresql.org/docs/14/catalogs.html)

The implementation of oid object identifiers is virtually the same as that of sequences, but it appeared in PostgreSQL much earlier. What makes it special is that the generated unique IDs issued by a common counter are used in different tables of the system catalog. When an assigned ID exceeds the maximum value, the counter is reset. To ensure that all values in a particular table are unique, the next issued oid is checked by the unique index; if it is already used in this table, the counter is incremented, and the check is repeated.¹

Schemas

*Schemas*² are namespaces that store all objects of a database. Apart from user schemas, PostgreSQL offers several predefined ones:

public is the default schema for user objects unless other settings are specified.

pg_catalog is used for system catalog tables.

information_schema provides an alternative view for the system catalog as defined by the SQL standard.

pg_toast is used for objects related to TOAST.

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pg_temp comprises temporary tables. Although different users create temporary tables in different schemas called `pg_temp_N`, everyone refers to their objects using the `pg_temp` alias.

Each schema is confined to a particular database, and all database objects belong to this or that schema.

If the schema is not specified explicitly when an object is accessed, PostgreSQL selects the first suitable schema from the *search path*. The search path is based on the value of the *search_path* parameter, which is implicitly extended with `pg_catalog` and (if necessary) `pg_temp` schemas. It means that different schemas can contain objects with the same names.

¹ `backend/catalog/catalog.c, GetNewOidWithIndex function`

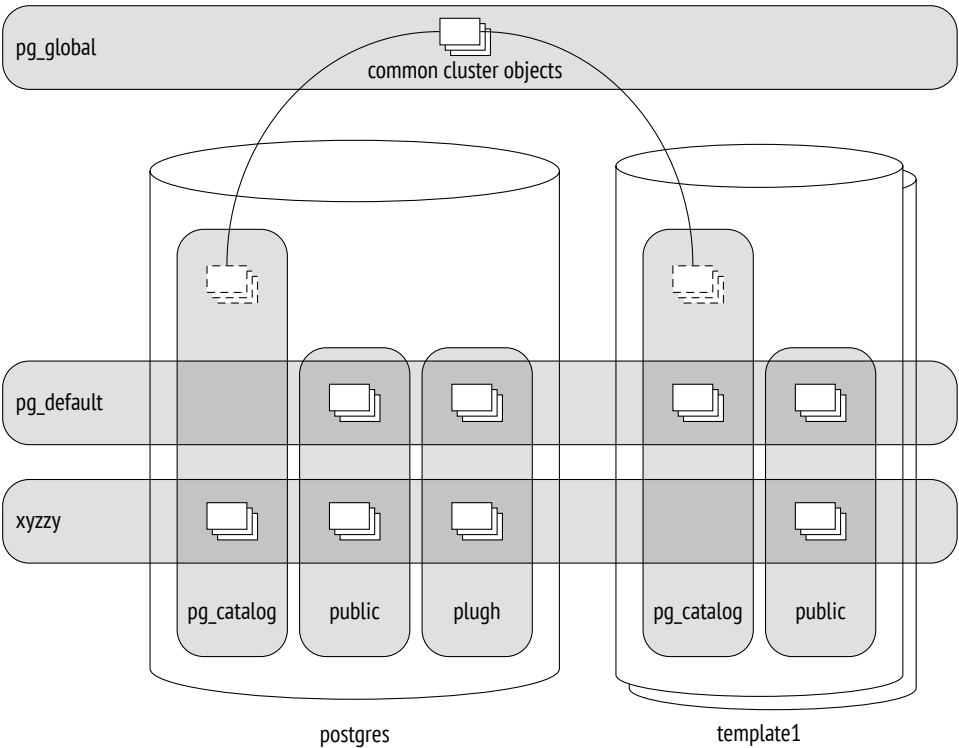
² [postgresql.org/docs/14/ddl-schemas.html](https://www.postgresql.org/docs/14/ddl-schemas.html)

Tablespaces

Unlike databases and schemas, which determine logical distribution of objects, *tablespaces* define physical data layout. A tablespace is virtually a directory in a file system. You can distribute your data between tablespaces in such a way that archive data is stored on slow disks, while the data that is being actively updated goes to fast disks.

One and the same tablespace can be used by different databases, and each database can store data in several tablespaces. It means that logical structure and physical data layout do not depend on each other.

Each database has the so-called *default tablespace*. All database objects are created in this tablespace unless another location is specified. System catalog objects related to this database are also stored there.



During cluster initialization, two tablespaces are created:

pg_default is located in the `PGDATA/base` directory; it is used as the default tablespace unless another tablespace is explicitly selected for this purpose.

pg_global is located in the `PGDATA/global` directory; it stores system catalog objects that are common to the whole cluster.

When creating a custom tablespace, you can specify any directory; PostgreSQL will create a symbolic link to this location in the `PGDATA/pg_tblspc` directory. In fact, all paths used by PostgreSQL are relative to the `PGDATA` directory, which allows you to move it to a different location (provided that you have stopped the server, of course).

The illustration on the previous page puts together databases, schemas, and tablespaces. Here the `postgres` database uses tablespace `xyzzzy` as the default one, whereas the `template1` database uses `pg_default`. Various database objects are shown at the intersections of tablespaces and schemas.

Relations

For all of their differences, *tables* and *indexes*—the most important database objects—have one thing in common: they consist of rows. This point is quite self-evident when we think of tables, but it is equally true for B-tree nodes, which contain indexed values and references to other nodes or table rows.

Some other objects also have the same structure; for example, *sequences* (virtually one-row tables) and *materialized views* (which can be thought of as tables that “keep” the corresponding queries). Besides, there are regular *views*, which do not store any data but otherwise are very similar to tables.

In PostgreSQL, all these objects are referred to by the generic term *relation*.

In my opinion, it is not a happy term because it confuses database tables with “genuine” relations defined in the relational theory. Here we can feel the academic legacy of the project and the inclination of its founder, Michael Stonebraker, to see everything as a relation. In one of his works, he even introduced the concept of an “ordered relation” to denote a table in which the order of rows is defined by an index.

The system catalog table for relations was originally called `pg_relation`, but following the object orientation trend, it was soon renamed to `pg_class`, which we are now used to. Its columns still have the `REL` prefix though.

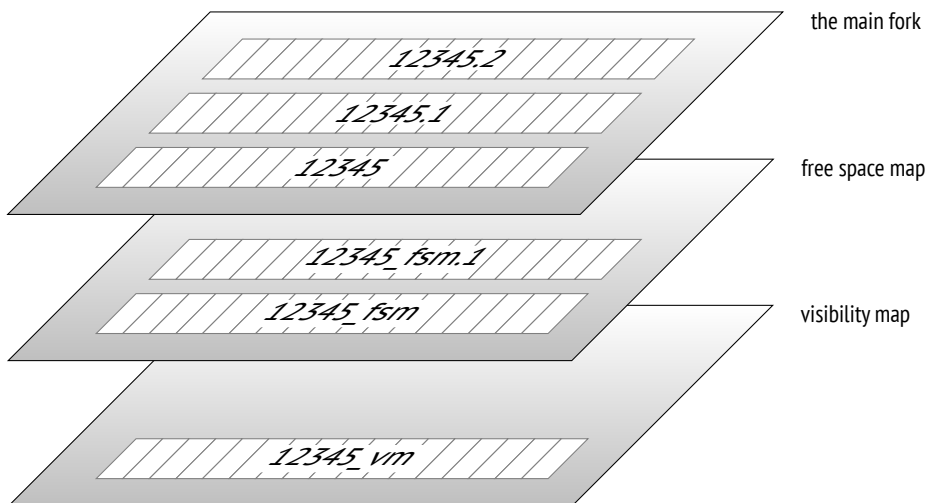
Files and Forks

All information associated with a relation is stored in several different *forks*,¹ each containing data of a particular type.

At first, a fork is represented by a single *file*. Its filename consists of a numeric ID (oid), which can be extended by a suffix that corresponds to the fork's type.

The file grows over time, and when its size reaches 1 GB, another file of this fork is created (such files are sometimes called *segments*). The sequence number of the segment is added to the end of its filename.

The file size limit of 1 GB was historically established to support various file systems that could not handle large files. You can change this limit when building PostgreSQL (`./configure --with-segsize`).



¹ [postgresql.org/docs/14/storage-file-layout.html](https://www.postgresql.org/docs/14/storage-file-layout.html)

Thus, a single relation is represented on disk by several files. Even a small table without indexes will have at least three files, by the number of mandatory forks.

Each tablespace directory (except for `pg_global`) contains separate subdirectories for particular databases. All files of the objects belonging to the same tablespace and database are located in the same subdirectory. You must take it into account because too many files in a single directory may not be handled well by file systems.

There are several standard types of forks.

The main fork represents actual data: table rows or index rows. This fork is available for any relations (except for views, which contain no data).

Files of the main fork are named by their numeric IDs, which are stored as `relfilenode` values in the `pg_class` table.

Let's take a look at the path to a file that belongs to a table created in the `pg_default` tablespace:

```
=> CREATE UNLOGGED TABLE t(
    a integer,
    b numeric,
    c text,
    d json
);
=> INSERT INTO t VALUES (1, 2.0, 'foo', '{}');
=> SELECT pg_relation_filepath('t');
pg_relation_filepath
-----
base/16384/16385
(1 row)
```

The base directory corresponds to the `pg_default` tablespace, the next subdirectory is used for the database, and it is here that we find the file we are looking for:

```
=> SELECT oid FROM pg_database WHERE datname = 'internals';
oid
-----
16384
(1 row)
```

```
=> SELECT relfilenode FROM pg_class WHERE relname = 't';
      relfilenode
-----
           16385
(1 row)
```

Here is the corresponding file in the file system:

```
=> SELECT size
FROM pg_stat_file('/usr/local/pgsql/data/base/16384/16385');
      size
-----
       8192
(1 row)
```

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The initialization fork¹ is available only for unlogged tables (created with the `UNLOGGED` clause) and their indexes. Such objects are the same as regular ones, except that any actions performed on them are not written into the write-ahead log. It makes these operations considerably faster, but you will not be able to restore consistent data in case of a failure. Therefore, PostgreSQL simply deletes all forks of such objects during recovery and overwrites the main fork with the initialization fork, thus creating a dummy file.

The `t` table is created as unlogged, so the initialization fork is present. It has the same name as the main fork, but with the `_init` suffix:

```
=> SELECT size
FROM pg_stat_file('/usr/local/pgsql/data/base/16384/16385_init');
      size
-----
         0
(1 row)
```

The free space map² keeps track of available space within pages. Its volume changes all the time, growing after vacuuming and getting smaller when new row versions appear. The free space map is used to quickly find a page that can accommodate new data being inserted.

¹ postgresql.org/docs/14/storage-init.html

² postgresql.org/docs/14/storage-fsm.html
[backend/storage/freespace/README](http://postgresql.org/docs/14/backup-restore/freespace/README)

All files related to the free space map have the `_fsm` suffix. Initially, no such files are created; they appear only when necessary. The easiest way to get them is to vacuum a table:

p. 121

```
=> VACUUM t;
=> SELECT size
FROM pg_stat_file('/usr/local/pgsql/data/base/16384/16385_fsm');
size
-----
24576
(1 row)
```

To speed up search, the free space map is organized as a tree; it takes at least three pages (hence its file size for an almost empty table).

The free space map is provided for both tables and indexes. But since an index row cannot be added into an arbitrary page (for example, B-trees define the place of insertion by the sort order), PostgreSQL tracks only those pages that have been fully emptied and can be reused in the index structure.

The visibility map¹ can quickly show whether a page needs to be vacuumed or frozen. For this purpose, it provides two bits for each table page.

The first bit is set for pages that contain only up-to-date row versions. Vacuum skips such pages because there is nothing to clean up. Besides, when a transaction tries to read a row from such a page, there is no point in checking its visibility, so an index-only scan can be used.

p. 120

The second bit is set for pages that contain only frozen row versions. I will use the term *freeze map* to refer to this part of the fork.

v. 9.6

p. 139

Visibility map files have the `_vm` suffix. They are usually the smallest ones:

```
=> SELECT size
FROM pg_stat_file('/usr/local/pgsql/data/base/16384/16385_vm');
size
-----
8192
(1 row)
```

The visibility map is provided for tables, but not for indexes.

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¹ [postgresql.org/docs/14/storage-vm.html](https://www.postgresql.org/docs/14/storage-vm.html)

Pages

p. 66 To facilitate I/O, all files are logically split into *pages* (or *blocks*), which represent the minimum amount of data that can be read or written. Consequently, many internal PostgreSQL algorithms are tuned for page processing.

The page size is usually 8 kB. It can be configured to some extent (up to 32 kB), but only at build time (`./configure --with-blocksize`), and nobody usually does it. Once built and launched, the instance can work only with pages of the same size; it is impossible to create tablespaces that support different page sizes.

p. 165 Regardless of the fork they belong to, all the files are handled by the server in roughly the same way. Pages are first moved to the buffer cache (where they can be read and updated by processes) and then flushed back to disk as required.

TOAST

Each row must fit a single page: there is no way to continue a row on the next page. To store long rows, PostgreSQL uses a special mechanism called TOAST¹ (The Oversized Attributes Storage Technique).

TOAST implies several strategies. You can move long attribute values into a separate service table, having sliced them into smaller “toasts.” Another option is to compress a long value in such a way that the row fits the page. Or you can do both: first compress the value, and then slice and move it.

If the main table contains potentially long attributes, a separate TOAST table is created for it right away, one for all the attributes. For example, if a table has a column of the numeric or text type, a TOAST table will be created even if this column will never store any long values.

For indexes, the TOAST mechanism can offer only compression; moving long attributes into a separate table is not supported. It limits the size of the keys that can be indexed (the actual implementation depends on a particular operator class).

¹ [postgresql.org/docs/14/storage-toast.html](https://www.postgresql.org/docs/14/storage-toast.html)
`include/access/heaptoast.h`

By default, the TOAST strategy is selected based on the data type of a column. The easiest way to review the used strategies is to run the `\d+` command in `psql`, but I will query the system catalog to get an uncluttered output:

```
=> SELECT attname, atttypid::regtype,
       CASE attstorage
         WHEN 'p' THEN 'plain'
         WHEN 'e' THEN 'external'
         WHEN 'm' THEN 'main'
         WHEN 'x' THEN 'extended'
       END AS storage
FROM pg_attribute
WHERE attrelid = 't'::regclass AND attnum > 0;
```

attname	atttypid	storage
a	integer	plain
b	numeric	main
c	text	extended
d	json	extended

(4 rows)

PostgreSQL supports the following strategies:

plain means that TOAST is not used (this strategy is applied to data types that are known to be “short,” such as the integer type).

extended allows both compressing attributes and storing them in a separate TOAST table.

external implies that long attributes are stored in the TOAST table in an uncompressed state.

main requires long attributes to be compressed first; they will be moved to the TOAST table only if compression did not help.

In general terms, the algorithm looks as follows.¹ PostgreSQL aims at having at least four rows in a page. So if the size of the row exceeds one fourth of the page, excluding the header (for a standard-size page it is about 2000 bytes), we must apply the TOAST mechanism to some of the values. Following the workflow described below, we stop as soon as the row length does not exceed the threshold anymore:

¹ backend/access/heap/heapttoast.c

1. First of all, we go through attributes with external and extended strategies, starting from the longest ones. Extended attributes get compressed, and if the resulting value (on its own, without taking other attributes into account) exceeds one fourth of the page, it is moved to the TOAST table right away. External attributes are handled in the same way, except that the compression stage is skipped.
2. If the row still does not fit the page after the first pass, we move the remaining attributes that use external or extended strategies into the TOAST table, one by one.
3. If it did not help either, we try to compress the attributes that use the main strategy, keeping them in the table page.
4. If the row is still not short enough, the main attributes are moved into the TOAST table.

v. 11 The threshold value is 2000 bytes, but it can be redefined at the table level using the `toast_tuple_target` storage parameter.

It may sometimes be useful to change the default strategy for some of the columns. If it is known in advance that the data in a particular column cannot be compressed (for example, the column stores JPEG images), you can set the external strategy for this column; it allows you to avoid futile attempts to compress the data. The strategy can be changed as follows:

```
=> ALTER TABLE t ALTER COLUMN d SET STORAGE external;
```

If we repeat the query, we will get the following result:

attname	atttypid	storage
a	integer	plain
b	numeric	main
c	text	extended
d	json	external

(4 rows)

TOAST tables reside in a separate schema called `pg_toast`; it is not included into the search path, so TOAST tables are usually hidden. For temporary tables, `pg_toast_temp_N` schemas are used, by analogy with `pg_temp_N`.

Let's take a look at the inner mechanics of the process. Suppose table `t` contains three potentially long attributes; it means that there must be a corresponding TOAST table. Here it is:

```
=> SELECT relnamespace::regnamespace, relname
FROM pg_class
WHERE oid = (
    SELECT reltoastrelid
    FROM pg_class WHERE relname = 't'
);
 relnamespace |      relname
-----+-----
 pg_toast      | pg_toast_16385
(1 row)
```

```
=> \d+ pg_toast.pg_toast_16385
TOAST table "pg_toast.pg_toast_16385"
  Column   | Type   | Storage
-----+-----+-----
 chunk_id  | oid    | plain
 chunk_seq | integer| plain
 chunk_data| bytea  | plain
Owning table: "public.t"
Indexes:
    "pg_toast_16385_index" PRIMARY KEY, btree (chunk_id, chunk_seq)
Access method: heap
```

It is only logical that the resulting chunks of the toasted row use the plain strategy: there is no second-level TOAST.

Apart from the TOAST table itself, PostgreSQL creates the corresponding index in the same schema. This index is *always* used to access TOAST chunks. The name of the index is displayed in the output, but you can also view it by running the following query:

```
=> SELECT indexrelid::regclass FROM pg_index
WHERE indrelid = (
    SELECT oid
    FROM pg_class WHERE relname = 'pg_toast_16385'
);
      indexrelid
-----
 pg_toast.pg_toast_16385_index
(1 row)
```

```
=> \d pg_toast.pg_toast_16385_index
Unlogged index "pg_toast.pg_toast_16385_index"
  Column   | Type   | Key? | Definition
-----+-----+-----+-----
 chunk_id  | oid    | yes  | chunk_id
 chunk_seq | integer| yes  | chunk_seq
primary key, btree, for table "pg_toast.pg_toast_16385"
```

Thus, a TOAST table increases the minimum number of fork files used by the table up to eight: three for the main table, three for the TOAST table, and two for the TOAST index.

Column `c` uses the extended strategy, so its values will be compressed:

```
=> UPDATE t SET c = repeat('A',5000);
=> SELECT * FROM pg_toast.pg_toast_16385;
 chunk_id | chunk_seq | chunk_data
-----+-----+-----
(0 rows)
```

The TOAST table is empty: repeated symbols have been compressed by the LZ algorithm, so the value fits the table page.

And now let's construct this value of random symbols:

```
=> UPDATE t SET c = (
  SELECT string_agg( chr(trunc(65+random()*26)::integer), '')
  FROM generate_series(1,5000)
)
RETURNING left(c,10) || '...' || right(c,10);
      ?column?
-----
KRAZUZAWGE...UVRXRWJJPYB
(1 row)
UPDATE 1
```

This sequence cannot be compressed, so it gets into the TOAST table:

```
=> SELECT chunk_id,
 chunk_seq,
 length(chunk_data),
 left(encode(chunk_data,'escape')::text, 10) || '...' ||
 right(encode(chunk_data,'escape')::text, 10)
FROM pg_toast.pg_toast_16385;
```

chunk_id	chunk_seq	length	?column?
16390	0	1996	KRAZUZAWGE...OSREMITVWR
16390	1	1996	IIIAAPCKUF...GBPMOOTBID
16390	2	1008	XTDOFJVSOS...UVRXRWJPYB

(3 rows)

We can see that the characters are sliced into chunks. The chunk size is selected in such a way that the page of the TOAST table can accommodate four rows. This value varies a little from version to version depending on the size of the page header.

When a long attribute is accessed, PostgreSQL automatically restores the original value and returns it to the client; it all happens seamlessly for the application. If long attributes do not participate in the query, the TOAST table will not be read at all. It is one of the reasons why you should avoid using the asterisk in production solutions.

If the client queries one of the first chunks of a long value, PostgreSQL will read the required chunks only, even if the value has been compressed. v. 13

Nevertheless, data compression and slicing require a lot of resources; the same goes for restoring the original values. That's why it is not a good idea to keep bulky data in PostgreSQL, especially if this data is being actively used and does not require transactional logic (like scanned accounting documents). A potentially better alternative is to store such data in the file system, keeping in the database only the names of the corresponding files. But then the database system cannot guarantee data consistency.

1.2 Processes and Memory

A PostgreSQL server instance consists of several interacting processes.

The first process launched at the server start is `postgres`, which is traditionally called `postmaster`. It spawns all the other processes (Unix-like systems use the `fork` system call for this purpose) and supervises them: if any process fails, `postmaster` restarts it (or the whole server if there is a risk that the shared data has been damaged).

Because of its simplicity, the process model has been used in PostgreSQL from the very beginning, and ever since there have been unending discussions about switching over to threads.

The current model has several drawbacks: static shared memory allocation does not allow resizing structures like buffer cache on the fly; parallel algorithms are hard to implement and less efficient than they could be; sessions are tightly bound to processes. Using threads sounds promising, even though it involves some challenges related to isolation, OS compatibility, and resource management. However, their implementation would require a radical code overhaul and years of work, so conservative views prevail for now: no such changes are expected in the near future.

Server operation is maintained by background processes. Here are the main ones:

startup restores the system after a failure.

p. 123 **autovacuum** removes stale data from tables and indexes.

p. 206 **wal writer** writes WAL entries to disk.

p. 192 **checkpointer** executes checkpoints.

p. 198 **writer** flushes dirty pages to disk.

stats collector collects usage statistics for the instance.

wal sender sends WAL entries to a replica.

wal receiver gets WAL entries on a replica.

Some of these processes are terminated once the task is complete, others run in the background all the time, and some can be switched off.

Each process is managed by configuration parameters, sometimes by dozens of them. To set up the server in a comprehensive manner, you have to be aware of its inner workings. But general considerations will only help you select more or less adequate initial values; later on, these settings have to be fine-tuned based on monitoring data.

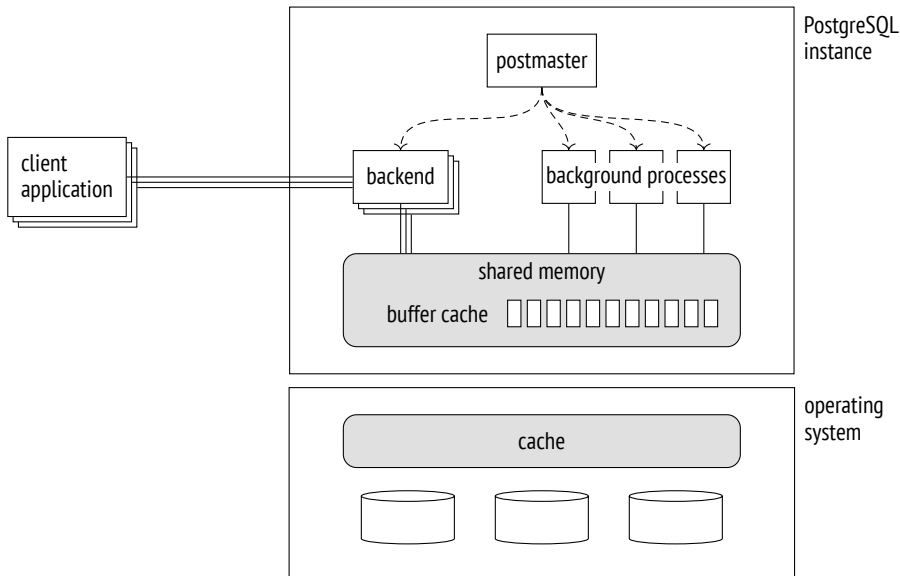
To enable process interaction, postmaster allocates *shared memory*, which is available to all the processes.

p. 165 Since disks (especially HDD, but SSD too) are much slower than RAM, PostgreSQL uses caching: some part of the shared RAM is reserved for recently read pages, in hope that they will be needed more than once and the overhead of repeated disk

access will be reduced. Modified data is also flushed to disk after some delay, not immediately.

Buffer cache takes the greater part of the shared memory, which also contains other buffers used by the server to speed up disk access.

The operating system has its own cache too. PostgreSQL (almost) never bypasses the operating system mechanisms to use direct I/O, so it results in double caching.



In case of a failure (such as a power outage or an operating system crash), the data kept in RAM is lost, including that of the buffer cache. The files that remain on disk have their pages written at different points in time. To be able to restore data consistency, PostgreSQL maintains the *write-ahead log* (WAL) during its operation, which makes it possible to repeat lost operations when necessary. p. 185

1.3 Clients and the Client-Server Protocol

Another task of the postmaster process is to listen for incoming connections. Once a new client appears, postmaster spawns a separate *backend process*.¹ The client

¹ backend/tcop/postgres.c, PostgresMain function

establishes a connection and starts a *session* with this backend. The session continues until the client disconnects or the connection is lost.

The server has to spawn a separate backend for each client. If many clients are trying to connect, it can turn out to be a problem.

- Each process needs RAM to cache catalog tables, prepared statements, intermediate query results, and other data. The more connections are open, the more memory is required.
- If connections are short and frequent (a client performs a small query and disconnects), the cost of establishing a connection, spawning a new process, and performing pointless local caching is unreasonably high.
- The more processes are started, the more time is required to scan their list, and this operation is performed very often. As a result, performance may decline as the number of clients grows.

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This problem can be resolved by *connection pooling*, which limits the number of spawned backends. PostgreSQL has no such built-in functionality, so we have to rely on third-party solutions: pooling managers integrated into the application server or external tools (such as PgBouncer¹ or Odyssey²). This approach usually means that each server backend can execute transactions of different clients, one after another. It imposes some restrictions on application development since it is only allowed to use resources that are local to a transaction, not to the whole session.

To understand each other, a client and a server must use one and the same interfacing protocol.³ It is usually based on the standard libpq library, but there are also other custom implementations.

Speaking in the most general terms, the protocol allows clients to connect to the server and execute SQL queries.

A connection is always established to a particular database on behalf of a particular role, or user. Although the server supports a database cluster, it is required to establish a separate connection to each database that you would like to use in your

¹ pgbouncer.org

² github.com/yandex/odyssey

³ postgresql.org/docs/14/protocol.html

application. At this point, *authentication* is performed: the backend process verifies the user's identity (for example, by asking for the password) and checks whether this user has the right to connect to the server and to the specified database.

SQL queries are passed to the backend process as text strings. The process parses the text, optimizes the query, executes it, and returns the result to the client.

Part I

Isolation and MVCC

2

Isolation

2.1 Consistency

The key feature of relational databases is their ability to ensure data *consistency*, that is, data *correctness*.

It is a known fact that at the database level it is possible to create *integrity constraints*, such as NOT NULL or UNIQUE. The database system ensures that these constraints are never broken, so data integrity is never compromised.

If all the required constraints could be formulated at the database level, consistency would be guaranteed. But some conditions are too complex for that, for example, they touch upon several tables at once. And even if a constraint can be defined in the database, but for some reason it is not, it does not mean that this constraint may be violated.

Thus, data consistency is stricter than integrity, but the database system has no idea what “consistency” actually means. If an application breaks it without breaking the integrity, there is no way for the database system to find out. Consequently, it is the application that must lay down the criteria for data consistency, and we have to believe that it is written correctly and will never have any errors.

But if the application always executes only correct sequences of operators, where does the database system come into play?

First of all, a correct sequence of operators can temporarily break data consistency, and—strange as it may seem—it is perfectly normal.

A hackneyed but clear example is a transfer of funds from one account to another. A consistency rule may sound as follows: *a money transfer must never change the total*

balance of the affected accounts. It is quite difficult (although possible) to formulate this rule as an integrity constraint in SQL, so let's assume that it is defined at the application level and remains opaque to the database system. A transfer consists of two operations: the first one draws some money from one of the accounts, whereas the second one adds this sum to another account. The first operation breaks data consistency, whereas the second one restores it.

If the first operation succeeds, but the second one does not (because of some failure), data consistency will be broken. Such situations are unacceptable, but it takes a great deal of effort to detect and address them at the application level. Luckily it is not required—the problem can be completely solved by the database system itself if it knows that these two operations constitute an indivisible whole, that is, a *transaction*.

But there is also a more subtle aspect here. Being absolutely correct on their own, transactions can start operating incorrectly when run in parallel. That's because operations belonging to different transactions often get intermixed. There would be no such issues if the database system first completed all operations of one transaction and then moved on to the next one, but performance of sequential execution would be implausibly low.

A truly simultaneous execution of transactions can only be achieved on systems with suitable hardware: a multi-core processor, a disk array, and so on. But the same reasoning is also true for a server that executes commands sequentially in the time-sharing mode. For generalization purposes, both these situations are sometimes referred to as *concurrent execution*.

Correct transactions that behave incorrectly when run together result in concurrency *anomalies*, or *phenomena*.

Here is a simple example. To get consistent data from the database, the application must not see any changes made by other uncommitted transactions, at the very minimum. Otherwise (if some transactions are rolled back), it would see the database state that has never existed. Such an anomaly is called a *dirty read*. There are also many other anomalies, which are more complex.

When running transactions concurrently, the database must guarantee that the result of such execution will be the same as the outcome of one of the possible se-

quential executions. In other words, it must *isolate* transactions from one another, thus taking care of any possible anomalies.

To sum it up, a transaction is a set of operations that takes the database from one correct state to another correct state (*consistency*), provided that it is executed in full (*atomicity*) and without being affected by other transactions (*isolation*). This definition combines the requirements implied by the first three letters of the ACID acronym. They are so intertwined that it makes sense to discuss them together. In fact, the durability requirement is hardly possible to split off either: after a crash, the system may still contain some changes made by uncommitted transactions, and you have to do something about it to restore data consistency. p. 185

Thus, the database system helps the application maintain data consistency by taking transaction boundaries into account, even though it has no idea about the implied consistency rules.

Unfortunately, full isolation is hard to implement and can negatively affect performance. Most real-life systems use weaker isolation levels, which prevent some anomalies, but not all of them. It means that the job of maintaining data consistency partially falls on the application. And that's exactly why it is very important to understand which isolation level is used in the system, what is guaranteed at this level and what is not, and how to ensure that your code will be correct in such conditions.

2.2 Isolation Levels and Anomalies Defined by the SQL Standard

The SQL standard specifies four isolation levels.¹ These levels are defined by the list of anomalies that may or may not occur during concurrent transaction execution. So when talking about isolation levels, we have to start with anomalies.

We should bear in mind that the standard is a theoretical construct: it affects the practice, but the practice still diverges from it in lots of ways. That's why all ex-

¹ [postgresql.org/docs/14/transaction-iso.html](https://www.postgresql.org/docs/14/transaction-iso.html)

amples here are rather hypothetical. Dealing with transactions on bank accounts, these examples are quite self-explanatory, but I have to admit that they have nothing to do with real banking operations.

It is interesting that the actual database theory also diverges from the standard: it was developed after the standard had been adopted, and the practice was already well ahead.

Lost Update

The *lost update* anomaly occurs when two transactions read one and the same table row, then one of the transactions updates this row, and finally the other transaction updates the same row without taking into account any changes made by the first transaction.

Suppose that two transactions are going to increase the balance of one and the same account by \$100. The first transaction reads the current value (\$1,000), then the second transaction reads the same value. The first transaction increases the balance (making it \$1,100) and writes the new value into the database. The second transaction does the same: it gets \$1,100 after increasing the balance and writes this value. As a result, the customer loses \$100.

Lost updates are forbidden by the standard at all isolation levels.

Dirty Reads and Read Uncommitted

The *dirty read* anomaly occurs when a transaction reads uncommitted changes made by another transaction.

For example, the first transaction transfers \$100 to an empty account but does not commit this change. Another transaction reads the account state (which has been updated but not committed) and allows the customer to withdraw the money—even though the first transaction gets interrupted and its changes are rolled back, so the account is empty.

The standard allows dirty reads at the Read Uncommitted level.

Non-Repeatable Reads and Read Committed

The *non-repeatable read* anomaly occurs when a transaction reads one and the same row twice, whereas another transaction updates (or deletes) this row between these reads and commits the change. As a result, the first transaction gets different results.

For example, suppose there is a consistency rule that *forbids having a negative balance in bank accounts*. The first transaction is going to reduce the account balance by \$100. It checks the current value, gets \$1,000, and decides that this operation is possible. At the same time, another transaction withdraws all the money from this account and commits the changes. If the first transaction checked the balance again at this point, it would get \$0 (but the decision to withdraw the money is already taken, and this operation causes an overdraft).

The standard allows non-repeatable reads at the Read Uncommitted and Read Committed levels.

Phantom Reads and Repeatable Read

The *phantom read* anomaly occurs when one and the same transaction executes two identical queries returning a set of rows that satisfy a particular condition, while another transaction adds some other rows satisfying this condition and commits the changes in the time interval between these queries. As a result, the first transaction gets two different sets of rows.

For example, suppose there is a consistency rule that *forbids a customer to have more than three accounts*. The first transaction is going to open a new account, so it checks how many accounts are currently available (let's say there are two of them) and decides that this operation is possible. At this very moment, the second transaction also opens a new account for this client and commits the changes. If the first transaction double-checked the number of open accounts, it would get three (but it is already opening another account, and the client ends up having four of them).

The standard allows phantom reads at the Read Uncommitted, Read Committed, and Repeatable Read isolation levels.

No Anomalies and Serializable

The standard also defines the Serializable level, which does not allow any anomalies. It is not the same as the ban on lost updates and dirty, non-repeatable, and phantom reads. In fact, there is a much higher number of known anomalies than the standard specifies, and an unknown number of still unknown ones.

The Serializable level must prevent *any* anomalies. It means that the application developer does not have to take isolation into account. If transactions execute correct operator sequences when run on their own, concurrent execution cannot break data consistency either.

To illustrate this idea, I will use a well-known table provided in the standard; the last column is added here for clarity:

	lost update	dirty read	non-repeatable read	phantom read	other anomalies
Read Uncommitted	—	yes	yes	yes	yes
Read Committed	—	—	yes	yes	yes
Repeatable Read	—	—	—	yes	yes
Serializable	—	—	—	—	—

Why These Anomalies?

Of all the possible anomalies, why does the standard mentions only some, and why exactly these ones?

No one seems to know it for sure. But it is not unlikely that other anomalies were simply not considered when the first versions of the standard were adopted, as theory was far behind practice at that time.

Besides, it was assumed that isolation had to be based on locks. The widely used *two-phase locking protocol* (2PL) requires transactions to lock the affected rows during execution and release the locks upon completion. In simplistic terms, the more locks a transaction acquires, the better it is isolated from other transactions. And consequently, the worse is the system performance, as transactions start queuing to get access to the same rows instead of running concurrently.

I believe that to a great extent the difference between the standard isolation levels is defined by the number of locks required for their implementation.

If the rows to be updated are locked for writes but not for reads, we get the Read Uncommitted isolation level, which allows reading data before it is committed.

If the rows to be updated are locked for both reads and writes, we get the Read Committed level: it is forbidden to read uncommitted data, but a query can return different values if it is run more than once (non-repeatable reads).

Locking the rows to be read and to be updated for all operations gives us the Repeatable Read level: a repeated query will return the same result.

However, the Serializable level poses a problem: it is impossible to lock a row that does not exist yet. It leaves an opportunity for phantom reads to occur: a transaction can add a row that satisfies the condition of the previous query, and this row will appear in the next query result.

Thus, regular locks cannot provide full isolation: to achieve it, we have to lock conditions (predicates) rather than rows. Such *predicate* locks were introduced as early as 1976 when System R was being developed; however, their practical applicability is limited to simple conditions for which it is clear whether two different predicates may conflict. As far as I know, predicate locks in their intended form have never been implemented in any system. p. 264

2.3 Isolation Levels in PostgreSQL

Over time, lock-based protocols for transaction management got replaced with the *Snapshot Isolation* (SI) protocol. The idea behind this approach is that each transaction accesses a consistent snapshot of data as it appeared at a particular point in time. The snapshot includes all the current changes committed before the snapshot was taken.

Snapshot isolation minimizes the number of required locks. In fact, a row will be locked only by concurrent update attempts. In all other cases, operations can be executed concurrently: writes never lock reads, and reads never lock anything. p. 235

PostgreSQL uses a *multiversion* flavor of the SI protocol. Multiversion concurrency control implies that at any moment the database system can contain several versions of one and the same row, so PostgreSQL can include an appropriate version into the snapshot rather than abort transactions that attempt to read stale data.

Based on snapshots, PostgreSQL isolation differs from the requirements specified in the standard—in fact, it is even stricter. Dirty reads are forbidden by design. Technically, you can specify the Read Uncommitted level, but its behavior will be the same as that of Read Committed, so I am not going to mention this level anymore. Repeatable Read allows neither non-repeatable nor phantom reads (even though it does not guarantee full isolation). But *in some cases*, there is a risk of losing changes at the Read Committed level.

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	lost updates	dirty reads	non-repeatable reads	phantom reads	other anomalies
Read Committed	yes	—	yes	yes	yes
Repeatable Read	—	—	—	—	yes
Serializable	—	—	—	—	—

p. 88 Before exploring the internal mechanisms of isolation, let’s discuss each of the three isolation levels from the user’s perspective.

For this purpose, we are going to create the accounts table; Alice and Bob will have \$1,000 each, but Bob will have two accounts:

```
=> CREATE TABLE accounts(  
  id integer PRIMARY KEY GENERATED BY DEFAULT AS IDENTITY,  
  client text,  
  amount numeric  
);  
=> INSERT INTO accounts VALUES  
  (1, 'alice', 1000.00), (2, 'bob', 100.00), (3, 'bob', 900.00);
```

Read Committed

No dirty reads. It is easy to check that reading dirty data is not allowed. Let’s start a transaction. By default, it uses the Read Committed¹ isolation level:

¹ [postgresql.org/docs/14/transaction-iso.html#XACT-READ-COMMITTED](https://www.postgresql.org/docs/14/transaction-iso.html#XACT-READ-COMMITTED)

```
=> BEGIN;
=> SHOW transaction_isolation;
transaction_isolation
-----
read committed
(1 row)
```

To be more exact, the default level is set by the following parameter, which can be changed as required:

```
=> SHOW default_transaction_isolation;
default_transaction_isolation
-----
read committed
(1 row)
```

The opened transaction withdraws some funds from the customer account but does not commit these changes yet. It will see its own changes though, as it is always allowed:

```
=> UPDATE accounts SET amount = amount - 200 WHERE id = 1;
=> SELECT * FROM accounts WHERE client = 'alice';
 id | client | amount
-----+-----+-----
  1 | alice  | 800.00
(1 row)
```

In the second session, we start another transaction that will also run at the Read Committed level:

```
=> BEGIN;
=> SELECT * FROM accounts WHERE client = 'alice';
 id | client | amount
-----+-----+-----
  1 | alice  | 1000.00
(1 row)
```

Predictably, the second transaction does not see any uncommitted changes—dirty reads are forbidden.

Non-repeatable reads. Now let the first transaction commit the changes. Then the second transaction will repeat the same query:

```
=> COMMIT;
```

```
=> SELECT * FROM accounts WHERE client = 'alice';
   id | client | amount
-----+-----+-----
    1 | alice  | 800.00
(1 row)
=> COMMIT;
```

The query receives an updated version of the data—and it is exactly what is understood by the *non-repeatable read* anomaly, which is allowed at the Read Committed level.

A practical insight: in a transaction, you must not take any decisions based on the data read by the previous operator, as everything can change in between. Here is an example whose variations appear in the application code so often that it can be considered a classic anti-pattern:

```
IF (SELECT amount FROM accounts WHERE id = 1) >= 1000 THEN
  UPDATE accounts SET amount = amount - 1000 WHERE id = 1;
END IF;
```

During the time that passes between the check and the update, other transactions can freely change the state of the account, so such a “check” is absolutely useless. For better understanding, you can imagine that random operators of other transactions are “wedged” between the operators of the current transaction. For example, like this:

```
IF (SELECT amount FROM accounts WHERE id = 1) >= 1000 THEN
  UPDATE accounts SET amount = amount - 200 WHERE id = 1;
  COMMIT;

  UPDATE accounts SET amount = amount - 1000 WHERE id = 1;
END IF;
```


If everything goes wrong as soon as the operators are rearranged, then the code is incorrect. Do not delude yourself that you will never get into this trouble: anything that can go wrong will go wrong. Such errors are very hard to reproduce, and consequently, fixing them is a real challenge.

How can you correct this code? There are several options:

- Replace procedural code with declarative one.

For example, in this particular case it is easy to turn an IF statement into a CHECK constraint:

```
ALTER TABLE accounts
ADD CHECK amount >= 0;
```

Now you do not need any checks in the code: it is enough to simply run the command and handle the exception that will be raised if an integrity constraint violation is attempted.

- Use a single SQL operator.

Data consistency can be compromised if a transaction gets committed within the time gap between operators of another transaction, thus changing data visibility. If there is only one operator, there are no such gaps.

PostgreSQL has enough capabilities to solve complex tasks with a single SQL statement. In particular, it offers common table expressions (CTE) that can contain operators like INSERT, UPDATE, DELETE, as well as the INSERT ON CONFLICT operator that implements the following logic: insert the row if it does not exist, otherwise perform an update.

- Apply explicit locks.

The last resort is to manually set an exclusive lock on all the required rows (SELECT FOR UPDATE) or even on the whole table (LOCK TABLE). This approach always works, but it nullifies all the advantages of MVCC: some operations that could be executed concurrently will run sequentially. p. 235
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Read skew. However, it is not all that simple. The PostgreSQL implementation allows other, less known anomalies, which are not regulated by the standard.

Suppose the first transaction has started a money transfer between Bob's accounts:

```
=> BEGIN;
=> UPDATE accounts SET amount = amount - 100 WHERE id = 2;
```

Meanwhile, the other transaction starts looping through all Bob's accounts to calculate their total balance. It begins with the first account (seeing its previous state, of course):

```
=> BEGIN;
=> SELECT amount FROM accounts WHERE id = 2;
      amount
-----
    100.00
(1 row)
```

At this moment, the first transaction completes successfully:

```
=> UPDATE accounts SET amount = amount + 100 WHERE id = 3;
=> COMMIT;
```

The second transaction reads the state of the second account (and sees the already updated value):

```
=> SELECT amount FROM accounts WHERE id = 3;
      amount
-----
    1000.00
(1 row)
=> COMMIT;
```

As a result, the second transaction gets \$1,100 because it has read incorrect data. Such an anomaly is called *read skew*.

How can you avoid this anomaly at the Read Committed level? The answer is obvious: use a single operator. For example, like this:

```
SELECT sum(amount) FROM accounts WHERE client = 'bob';
```

I have been stating so far that data visibility can change only between operators, but is it really so? What if the query is running for a long time? Can it see different parts of data in different states in this case?

Let's check it out. A convenient way to do it is to add a delay to an operator by calling the `pg_sleep` function. Then the first row will be read at once, but the second row will have to wait for two seconds:

```
=> SELECT amount, pg_sleep(2) -- two seconds
FROM accounts WHERE client = 'bob';
```

While this statement is being executed, let's start another transaction to transfer the money back:

```
=> BEGIN;
=> UPDATE accounts SET amount = amount + 100 WHERE id = 2;
=> UPDATE accounts SET amount = amount - 100 WHERE id = 3;
=> COMMIT;
```

The result shows that the operator has seen all the data in the state that corresponds to the beginning of its execution, which is certainly correct:

```
amount | pg_sleep
-----+-----
      0.00 |
    1000.00 |
(2 rows)
```

But it is not all that simple either. If the query contains a function that is declared `VOLATILE`, and this function executes another query, then the data seen by this nested query will not be consistent with the result of the main query.

Let's check the balance in Bob's accounts using the following function:

```
=> CREATE FUNCTION get_amount(id integer) RETURNS numeric
AS $$
  SELECT amount FROM accounts a WHERE a.id = get_amount.id;
$$ VOLATILE LANGUAGE sql;
=> SELECT get_amount(id), pg_sleep(2)
FROM accounts WHERE client = 'bob';
```

We will transfer the money between the accounts once again while our delayed query is being executed:

```
=> BEGIN;
=> UPDATE accounts SET amount = amount + 100 WHERE id = 2;
=> UPDATE accounts SET amount = amount - 100 WHERE id = 3;
=> COMMIT;
```

In this case, we are going to get inconsistent data—\$100 has been lost:

```
get_amount | pg_sleep
-----+-----
      100.00 |
      800.00 |
(2 rows)
```

I would like to emphasize that this effect is possible only at the Read Committed isolation level, and only if the function is `VOLATILE`. The trouble is that PostgreSQL uses exactly this isolation level and this volatility category by default. So we have to admit that the trap is set in a very cunning way.

Read skew instead of lost updates. The read skew anomaly can also occur within a single operator during an update—even though in a somewhat unexpected way.

Let's see what happens if two transactions try to modify one and the same row. Bob currently has a total of \$1,000 in two accounts:

```
=> SELECT * FROM accounts WHERE client = 'bob';
 id | client | amount
----+-----+-----
   2 | bob    | 200.00
   3 | bob    | 800.00
(2 rows)
```

Start a transaction that will reduce Bob's balance:

```
=> BEGIN;
=> UPDATE accounts SET amount = amount - 100 WHERE id = 3;
```

At the same time, the other transaction will be calculating the interest for all customer accounts with the total balance of \$1,000 or more:

```
=> UPDATE accounts SET amount = amount * 1.01
WHERE client IN (
  SELECT client
  FROM accounts
  GROUP BY client
  HAVING sum(amount) >= 1000
);
```

The UPDATE operator execution virtually consists of two stages. First, the rows to be updated are selected based on the provided condition. Since the first transaction is not committed yet, the second transaction cannot see its result, so the selection of rows picked for interest accrual is not affected. Thus, Bob's accounts satisfy the condition, and his balance must be increased by \$10 once the UPDATE operation completes.

At the second stage, the selected rows are updated one by one. The second transaction has to wait because the row with id = 3 is locked: it is being updated by the first transaction.

Meanwhile, the first transaction commits its changes:

```
=> COMMIT;
=> SELECT * FROM accounts WHERE client = 'bob';
 id | client | amount
----+-----+-----
  2 | bob   | 202.0000
  3 | bob   | 707.0000
(2 rows)
```

On the one hand, the UPDATE command must not see any changes made by the first transaction. But on the other hand, it must not lose any committed changes.

Once the lock is released, the UPDATE operator *re-reads* the row to be updated (but only this row!). As a result, Bob gets \$9 of interest, based on the total of \$900. But if he had \$900, his accounts should not have been included into the query results in the first place. p. 245

Thus, our transaction has returned incorrect data: different rows have been read from different snapshots. Instead of a lost update, we observe the read skew anomaly again.

Lost updates. However, the trick of re-reading the locked row will not help against lost updates if the data is modified by different SQL operators.

p. 42 Here is an example that we have already seen. The application reads and registers (outside of the database) the current balance of Alice's account:

```
=> BEGIN;
=> SELECT amount FROM accounts WHERE id = 1;
      amount
-----
      800.00
(1 row)
```

Meanwhile, the other transaction does the same:

```
=> BEGIN;
=> SELECT amount FROM accounts WHERE id = 1;
      amount
-----
      800.00
(1 row)
```

The first transaction increases the previously registered value by \$100 and commits this change:

```
=> UPDATE accounts SET amount = 800.00 + 100 WHERE id = 1
RETURNING amount;
      amount
-----
      900.00
(1 row)
UPDATE 1
=> COMMIT;
```

The second transaction does the same:

```
=> UPDATE accounts SET amount = 800.00 + 100 WHERE id = 1
RETURNING amount;
      amount
-----
      900.00
(1 row)
UPDATE 1
```

```
| => COMMIT;
```

Unfortunately, Alice has lost \$100. The database system does not know that the registered value of \$800 is somehow related to `accounts.amount`, so it cannot prevent the lost update anomaly. At the Read Committed isolation level, this code is incorrect.

Repeatable Read

No non-repeatable and phantom reads. As its name suggests, the Repeatable Read¹ isolation level must guarantee repeatable reading. Let's check it and make sure that phantom reads cannot occur either. For this purpose, we are going to start a transaction that will revert Bob's accounts to their previous state and create a new account for Charlie:

```
=> BEGIN;

=> UPDATE accounts SET amount = 200.00 WHERE id = 2;
=> UPDATE accounts SET amount = 800.00 WHERE id = 3;
=> INSERT INTO accounts VALUES
    (4, 'charlie', 100.00);

=> SELECT * FROM accounts ORDER BY id;
 id | client | amount
-----+-----+-----
  1 | alice  | 900.00
  2 | bob    | 200.00
  3 | bob    | 800.00
  4 | charlie | 100.00
(4 rows)
```

In the second session, let's start another transaction, with the Repeatable Read level explicitly specified in the `BEGIN` command (the level of the first transaction is not important):

```
| => BEGIN ISOLATION LEVEL REPEATABLE READ;
| => SELECT * FROM accounts ORDER BY id;
```

¹ [postgresql.org/docs/14/transaction-iso.html#XACT-REPEATABLE-READ](https://www.postgresql.org/docs/14/transaction-iso.html#XACT-REPEATABLE-READ)

id	client	amount
1	alice	900.00
2	bob	202.0000
3	bob	707.0000

(3 rows)

Now the first transaction commits its changes, and the second transaction repeats the same query:

=> **COMMIT;**

```
=> SELECT * FROM accounts ORDER BY id;
```

id	client	amount
1	alice	900.00
2	bob	202.0000
3	bob	707.0000

(3 rows)

```
=> COMMIT;
```

The second transaction still sees the same data as before: neither new rows nor row updates are visible. At this isolation level, you do not have to worry that something will change between operators.

p. 52 **Serialization failures instead of lost updates.** As we have already seen, if two transactions update one and the same row at the Read Committed level, it can cause the read skew anomaly: the waiting transaction has to re-read the locked row, so it sees the state of this row at a different point in time as compared to other rows.

Such an anomaly is not allowed at the Repeatable Read isolation level, and if it does happen, the transaction can only be aborted with a serialization failure. Let's check it out by repeating the scenario with interest accrual:

```
=> SELECT * FROM accounts WHERE client = 'bob';
```

id	client	amount
2	bob	200.00
3	bob	800.00

(2 rows)

```
=> BEGIN;
```



```
=> UPDATE accounts SET amount = amount - 100.00 WHERE id = 3;
```

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> UPDATE accounts SET amount = amount * 1.01
WHERE client IN (
  SELECT client
  FROM accounts
  GROUP BY client
  HAVING sum(amount) >= 1000
);
```

```
=> COMMIT;
```

```
ERROR: could not serialize access due to concurrent update
=> ROLLBACK;
```

The data remains consistent:

```
=> SELECT * FROM accounts WHERE client = 'bob';
 id | client | amount
-----+-----+-----
  2 | bob    | 200.00
  3 | bob    | 700.00
(2 rows)
```

The same error will be raised by any concurrent row updates, even if they affect different columns.

We will also get this error if we try to update the balance based on the previously stored value:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> SELECT amount FROM accounts WHERE id = 1;
 amount
-----
 900.00
(1 row)
```

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
```

```
=> SELECT amount FROM accounts WHERE id = 1;
      amount
-----
      900.00
(1 row)
```

```
=> UPDATE accounts SET amount = 900.00 + 100.00 WHERE id = 1
RETURNING amount;
      amount
-----
      1000.00
(1 row)
UPDATE 1
=> COMMIT;
```

```
=> UPDATE accounts SET amount = 900.00 + 100.00 WHERE id = 1
RETURNING amount;
ERROR:  could not serialize access due to concurrent update
=> ROLLBACK;
```

A practical insight: if your application is using the Repeatable Read isolation level for write transactions, it must be ready to retry transactions that have been completed with a serialization failure. For read-only transactions, such an outcome is impossible.

Write skew. As we have seen, the PostgreSQL implementation of the Repeatable Read isolation level prevents all the anomalies described in the standard. But not all possible ones: no one knows how many of them exist. However, one important fact is proved for sure: snapshot isolation does not prevent *only two* anomalies, no matter how many other anomalies are out there.

The first one is *write skew*.

Let's define the following consistency rule: *it is allowed to have a negative balance in some of the customer's accounts as long as the total balance is non-negative*.

The first transaction gets the total balance of Bob's accounts:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
```

```
=> SELECT sum(amount) FROM accounts WHERE client = 'bob';
```

sum
900.00

(1 row)

The second transaction gets the same sum:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> SELECT sum(amount) FROM accounts WHERE client = 'bob';
```

sum
900.00

(1 row)

The first transaction fairly assumes that it can debit one of the accounts by \$600:

```
=> UPDATE accounts SET amount = amount - 600.00 WHERE id = 2;
```

The second transaction comes to the same conclusion, but debits the other account:

```
=> UPDATE accounts SET amount = amount - 600.00 WHERE id = 3;
=> COMMIT;
```

```
=> COMMIT;
=> SELECT * FROM accounts WHERE client = 'bob';
```

id	client	amount
2	bob	-400.00
3	bob	100.00

(2 rows)

Bob's total balance is now negative, although both transactions would have been correct if run separately.

Read-only transaction anomaly. The *read-only transaction* anomaly is the second and the last one allowed at the Repeatable Read isolation level. To observe this anomaly, we have to run three transactions: two of them are going to update the data, while the third one will be read-only.

But first let's restore Bob's balance:

```
=> UPDATE accounts SET amount = 900.00 WHERE id = 2;
=> SELECT * FROM accounts WHERE client = 'bob';
  id | client | amount
-----+-----+-----
   3 | bob    | 100.00
   2 | bob    | 900.00
(2 rows)
```

The first transaction calculates the interest to be accrued on Bob's total balance and adds this sum to one of his accounts:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ; -- 1
=> UPDATE accounts SET amount = amount + (
    SELECT sum(amount) FROM accounts WHERE client = 'bob'
) * 0.01
WHERE id = 2;
```

Then the second transaction withdraws some money from Bob's other account and commits this change:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ; -- 2
=> UPDATE accounts SET amount = amount - 100.00 WHERE id = 3;
=> COMMIT;
```

If the first transaction gets committed at this point, there will be no anomalies: we could assume that the first transaction is committed before the second one (but not vice versa—the first transaction had seen the state of account with id = 3 before any updates were made by the second transaction).

But let's imagine that at this very moment we start a read-only transaction to query an account that is not affected by the first two transactions:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ; -- 3
=> SELECT * FROM accounts WHERE client = 'alice';
  id | client | amount
-----+-----+-----
   1 | alice  | 1000.00
(1 row)
```

And only now will the first transaction get committed:

```
=> COMMIT;
```

Which state should the third transaction see at this point? Having started, it could see the changes made by the second transaction (which had already been committed), but not by the first one (which had not been committed yet). But as we have already established, the second transaction should be treated as if it were started after the first one. Any state seen by the third transaction will be inconsistent—this is exactly what is meant by the read-only transaction anomaly:

```
=> SELECT * FROM accounts WHERE client = 'bob';
 id | client | amount
-----+-----+-----
  2 | bob   | 900.00
  3 | bob   |   0.00
(2 rows)
=> COMMIT;
```

Serializable

The Serializable¹ isolation level prevents all possible anomalies. This level is virtually built on top of snapshot isolation. Those anomalies that do not occur at the Repeatable Read isolation level (such as dirty, non-repeatable, or phantom reads) cannot occur at the Serializable level either. And those two anomalies that do occur (write skew and read-only transaction anomalies) get detected in a special way to abort the transaction, causing an already familiar serialization failure.

No anomalies. Let's make sure that our write skew scenario will eventually end with a serialization failure: p. 58

```
=> BEGIN ISOLATION LEVEL SERIALIZABLE;
=> SELECT sum(amount) FROM accounts WHERE client = 'bob';
 sum
-----
910.0000
(1 row)
```

¹ [postgresql.org/docs/14/transaction-iso.html#XACT-SERIALIZABLE](https://www.postgresql.org/docs/14/transaction-iso.html#XACT-SERIALIZABLE)

```
=> BEGIN ISOLATION LEVEL SERIALIZABLE;
=> SELECT sum(amount) FROM accounts WHERE client = 'bob';
      sum
-----
 910.0000
(1 row)
```

```
=> UPDATE accounts SET amount = amount - 600.00 WHERE id = 2;
```

```
=> UPDATE accounts SET amount = amount - 600.00 WHERE id = 3;
=> COMMIT;
COMMIT
```

```
=> COMMIT;
```

```
ERROR: could not serialize access due to read/write dependencies
among transactions
DETAIL: Reason code: Canceled on identification as a pivot, during
commit attempt.
HINT: The transaction might succeed if retried.
```

The scenario with the read-only transaction anomaly will lead to the same error.

Deferring a read-only transaction. To avoid situations when a read-only transaction can cause an anomaly that compromises data consistency, PostgreSQL offers an interesting solution: this transaction can be deferred until its execution becomes safe. It is the only case when a `SELECT` statement can be blocked by row updates.

We are going to check it out by repeating the scenario that demonstrated the read-only transaction anomaly:

```
=> UPDATE accounts SET amount = 900.00 WHERE id = 2;
=> UPDATE accounts SET amount = 100.00 WHERE id = 3;
=> SELECT * FROM accounts WHERE client = 'bob' ORDER BY id;
 id | client | amount
-----+-----+-----
  2 | bob    | 900.00
  3 | bob    | 100.00
(2 rows)
=> BEGIN ISOLATION LEVEL SERIALIZABLE; -- 1
```

```
=> UPDATE accounts SET amount = amount + (
    SELECT sum(amount) FROM accounts WHERE client = 'bob'
) * 0.01
WHERE id = 2;
```

```
=> BEGIN ISOLATION LEVEL SERIALIZABLE; -- 2
=> UPDATE accounts SET amount = amount - 100.00 WHERE id = 3;
=> COMMIT;
```

Let's explicitly declare the third transaction as READ ONLY and DEFERRABLE:

```
=> BEGIN ISOLATION LEVEL SERIALIZABLE READ ONLY DEFERRABLE; -- 3
=> SELECT * FROM accounts WHERE client = 'alice';
```

An attempt to run the query blocks the transaction—otherwise, it would have caused an anomaly.

And only when the first transaction is committed, the third one can continue its execution:

```
=> COMMIT;
```

```
id | client | amount
----+-----+-----
  1 | alice  | 1000.00
(1 row)
=> SELECT * FROM accounts WHERE client = 'bob';
id | client | amount
----+-----+-----
  2 | bob    | 910.0000
  3 | bob    |      0.00
(2 rows)
=> COMMIT;
```

Thus, if an application uses the Serializable isolation level, it must be ready to retry transactions that have ended with a serialization failure. (The Repeatable Read level requires the same approach unless the application is limited to read-only transactions.)

The Serializable isolation level brings ease of programming, but the price you pay is the overhead incurred by anomaly detection and forced termination of a certain

fraction of transactions. You can lower this impact by explicitly using the `READ ONLY` clause when declaring read-only transactions. But the main question is, of course, how big the fraction of aborted transactions is—since these transactions will have to be retried. It would have been not so bad if PostgreSQL aborted only those transactions that result in data conflicts and are really incompatible. But such an approach would inevitably be too resource-intensive, as it would involve tracking operations on each row.

p. 264 The current implementation allows false positives: PostgreSQL can abort some absolutely safe transactions that are simply out of luck. Their “luck” depends on many factors, such as the presence of appropriate indexes or the amount of RAM available, so the actual behavior is hard to predict in advance.

If you use the `Serializable` level, it must be observed by all transactions of the application. When combined with other levels, `Serializable` behaves as `Repeatable Read` without any notice. So if you decide to use the `Serializable` level, it makes sense to modify the `default_transaction_isolation` parameter value accordingly—even though someone can still overwrite it by explicitly setting a different level.

v. 12 There are also other restrictions; for example, queries run at the `Serializable` level cannot be executed on replicas. And although the functionality of this level is constantly being improved, the current limitations and overhead make it less attractive.

2.4 Which Isolation Level to Use?

`Read Committed` is the default isolation level in PostgreSQL, and apparently it is this level that is used in the vast majority of applications. This level can be convenient because it allows aborting transactions only in case of a failure; it does not abort any transactions to preserve data consistency. In other words, serialization failures cannot occur, so you do not have to take care of transaction retries.

The downside of this level is a large number of possible anomalies, which have been discussed in detail above. A developer has to keep them in mind all the time and write the code in a way that prevents their occurrence. If it is impossible to define all the needed actions in a single SQL statement, then you have to resort to explicit locking. The toughest part is that the code is hard to test for errors

related to data inconsistency; such errors can appear in unpredictable and barely reproducible ways, so they are very hard to fix too.

The Repeatable Read isolation level eliminates some of the inconsistency problems, but alas, not all of them. Therefore, you must not only remember about the remaining anomalies, but also modify the application to correctly handle serialization failures, which is certainly inconvenient. However, for read-only transactions this level is a perfect complement to the Read Committed level; it can be very useful for cases like building reports that involve multiple SQL queries.

And finally, the Serializable isolation level allows you not to worry about data consistency at all, which simplifies writing the code to a great extent. The only thing required from the application is the ability to retry any transaction that is aborted with a serialization failure. However, the number of aborted transactions and associated overhead can significantly reduce system throughput. You should also keep in mind that the Serializable level is not supported on replicas and cannot be combined with other isolation levels.

3

Pages and Tuples

3.1 Page Structure

Each page has a certain inner layout that usually consists of the following parts:¹

- page header
- an array of item pointers
- free space
- items (row versions)
- special space

Page Header

p. 116 The page *header* is located in the lowest addresses and has a fixed size. It stores various information about the page, such as its checksum and the sizes of all the other parts of the page.

These sizes can be easily displayed using the `pageinspect` extension.² Let's take a look at the first page of the table (page numbering is zero-based):

¹ postgresql.org/docs/14/storage-page-layout.html
`include/storage/bufpage.h`

² postgresql.org/docs/14/pageinspect.html

```
=> CREATE EXTENSION pageinspect;
=> SELECT lower, upper, special, pagesize
FROM page_header(get_raw_page('accounts',0));
 lower | upper | special | pagesize
-----+-----+-----+-----
    152 | 6904 |    8192 |    8192
(1 row)
```

0	header
24	an array of item pointers
lower	free space
upper	items
special	special space
pagesize	

Special Space

The *special space* is located in the opposite part of the page, taking its highest addresses. It is used by some indexes to store auxiliary information; in other indexes and table pages this space is zero-sized.

In general, the layout of index pages is quite diverse; their content largely depends on a particular index type. Even one and the same index can have different kinds of pages: for example, B-trees have a metadata page of a special structure (page zero) and regular pages that are very similar to table pages.

Tuples

Rows contain the actual data stored in the database, together with some additional information. They are located just before the special space.

In the case of tables, we have to deal with *row versions* rather than rows because multiversion concurrency control implies having several versions of one and the same row. Indexes do not use this MVCC mechanism; instead, they have to reference all the available row versions, falling back on visibility rules to select the appropriate ones.

Both table row versions and index entries are often referred to as *tuples*. This term is borrowed from the relational theory—it is yet another legacy of PostgreSQL’s academic past.

Item Pointers

The *array of pointers* to tuples serves as the page’s table of contents. It is located right after the header.

p. 23 Index entries have to refer to particular heap tuples somehow. PostgreSQL employs six-byte *tuple identifiers* (TIDs) for this purpose. Each TID consists of the page number of the main fork and a reference to a particular row version located in this page.

In theory, tuples could be referred to by their offset from the start of the page. But then it would be impossible to move tuples within pages without breaking these references, which in turn would lead to page fragmentation and other unpleasant consequences.

For this reason, PostgreSQL uses indirect addressing: a tuple identifier refers to the corresponding pointer number, and this pointer specifies the current offset of the tuple. If the tuple is moved within the page, its TID still remains the same; it is enough to modify the pointer, which is also located in this page.

Each pointer takes exactly four bytes and contains the following data:

- tuple offset from the start of the page
- tuple length
- several bits defining the tuple status

Free Space

Pages can have some *free space* left between pointers and tuples (which is reflected in the free space map). There is no page fragmentation: all the free space available is always aggregated into one chunk.¹ p. 24

3.2 Row Version Layout

Each row version contains a header followed by actual data. The header consists of multiple fields, including the following:

xmin, xmax represent transaction IDs; they are used to differentiate between this and other versions of one and the same row.

infomask provides a set of information bits that define version properties.

ctid is a pointer to the next updated version of the same row.

null bitmap is an array of bits marking the columns that can contain NULL values.

As a result, the header turns out quite big: it requires at least 23 bytes for each tuple, and this value is often exceeded because of the null bitmap and the mandatory padding used for data alignment. In a “narrow” table, the size of various metadata can easily beat the size of the actual data stored.

Data layout on disk fully coincides with data representation in RAM. The page along with its tuples is read into the buffer cache as is, without any transformations. That’s why data files are incompatible between different platforms.²

One of the sources of incompatibility is the byte order. For example, the x86 architecture is little-endian, z/Architecture is big-endian, and ARM has configurable byte order.

Another reason is data alignment by machine word boundaries, which is required by many architectures. For example, in a 32-bit x86 system, integer numbers (the integer type, takes four bytes) are aligned by the boundary of four-byte words,

¹ backend/storage/page/bufpage.c, PageRepairFragmentation function

² include/access/htup_details.h

just like double-precision floating-point numbers (the double precision type, eight bytes). But in a 64-bit system, double values are aligned by the boundary of eight-byte words.

Data alignment makes the size of a tuple dependent on the order of fields in the table. This effect is usually negligible, but in some cases it can lead to a significant size increase. Here is an example:

```
=> CREATE TABLE padding(  
    b1 boolean,  
    i1 integer,  
    b2 boolean,  
    i2 integer  
);  
=> INSERT INTO padding VALUES (true,1,false,2);  
=> SELECT lp_len FROM heap_page_items(get_raw_page('padding', 0));  
lp_len  
-----  
      40  
(1 row)
```

I have used the `heap_page_items` function of the `pageinspect` extension to display some details about pointers and tuples.

In PostgreSQL, tables are often referred to as *heap*. This is yet another obscure term that hints at the similarity between space allocation for tuples and dynamic memory allocation. Some analogy can certainly be seen, but tables are managed by completely different algorithms. We can interpret this term in the sense that “everything is piled up into a heap,” by contrast with ordered indexes.

The size of the row is 40 bytes. Its header takes 24 bytes, a column of the integer type takes 4 bytes, and boolean columns take 1 byte each. It makes 34 bytes, and 6 bytes are wasted on four-byte alignment of integer columns.

If we rebuild the table, the space will be used more efficiently:

```
=> DROP TABLE padding;  
=> CREATE TABLE padding(  
    i1 integer,  
    i2 integer,  
    b1 boolean,  
    b2 boolean  
);
```

```
=> INSERT INTO padding VALUES (1,2,true,false);
=> SELECT lp_len FROM heap_page_items(get_raw_page('padding', 0));
   lp_len
-----
        34
(1 row)
```

Another possible micro-optimization is to start the table with the fixed-length columns that cannot contain NULL values. Access to such columns will be more efficient because it is possible to cache their offset within the tuple.¹

3.3 Operations on Tuples

To identify different versions of one and the same row, PostgreSQL marks each of them with two values: xmin and xmax. These values define “validity time” of each row version, but instead of the actual time, they rely on ever-increasing transaction IDs.

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When a row is created, its xmin value is set to the transaction ID of the INSERT command.

When a row is deleted, the xmax value of its current version is set to the transaction ID of the DELETE command.

With a certain degree of abstraction, the UPDATE command can be regarded as two separate operations: DELETE and INSERT. First, the xmax value of the current row version is set to the transaction ID of the UPDATE command. Then a new version of this row is created; its xmin value will be the same as the xmax value of the previous version.

Now let’s get down to some low-level details of different operations on tuples.²

For these experiments, we will need a two-column table with an index created on one of the columns:

¹ backend/access/common/heaptuple.c, heap_deform_tuple function

² backend/access/transam/README

```
=> CREATE TABLE t(  
    id integer GENERATED ALWAYS AS IDENTITY,  
    s text  
);  
=> CREATE INDEX ON t(s);
```

Insert

Start a transaction and insert one row:

```
=> BEGIN;  
=> INSERT INTO t(s) VALUES ('F00');
```

Here is the current transaction ID:

```
=> -- txid_current() before v.13  
SELECT pg_current_xact_id();  
pg_current_xact_id  
-----  
776  
(1 row)
```

To denote the concept of a transaction, PostgreSQL uses the term xact, which can be found both in SQL function names and in the source code. Consequently, a transaction ID can be called xact ID, TXID, or simply XID. We are going to come across these abbreviations over and over again.

Let's take a look at the page contents. The `heap_page_items` function can give us all the required information, but it shows the data “as is,” so the output format is a bit hard to comprehend:

```
=> SELECT *  
FROM heap_page_items(get_raw_page('t',0)) \gx  
-[ RECORD 1 ]-----  
lp          | 1  
lp_off      | 8160  
lp_flags    | 1  
lp_len      | 32  
t_xmin      | 776  
t_xmax      | 0  
t_field3    | 0  
t_ctid      | (0,1)
```



```

t_infomask2 | 2
t_infomask  | 2050
t_hoff      | 24
t_bits      |
t_oid       |
t_data      | \x0100000009464f4f

```

To make it more readable, we can leave out some information and expand a few columns:

```

=> SELECT '(0,||lp||)' AS ctid,
       CASE lp_flags
         WHEN 0 THEN 'unused'
         WHEN 1 THEN 'normal'
         WHEN 2 THEN 'redirect to '||lp_off
         WHEN 3 THEN 'dead'
       END AS state,
       t_xmin as xmin,
       t_xmax as xmax,
       (t_infomask & 256) > 0 AS xmin_committed,
       (t_infomask & 512) > 0 AS xmin_aborted,
       (t_infomask & 1024) > 0 AS xmax_committed,
       (t_infomask & 2048) > 0 AS xmax_aborted
FROM heap_page_items(get_raw_page('t',0)) \gx

```

```

-[ RECORD 1 ]--+-----
ctid          | (0,1)
state         | normal
xmin          | 776
xmax          | 0
xmin_committed | f
xmin_aborted   | f
xmax_committed | f
xmax_aborted   | t

```

This is what has been done here:

- The lp pointer is converted to the standard format of a tuple ID: (page number, pointer number).
- The lp_flags state is spelled out. Here it is set to the normal value, which means that it really points to a tuple.
- Of all the information bits, we have singled out just two pairs so far. The xmin_committed and xmin_aborted bits show whether the xmin transaction is

committed or aborted. The `xmax_committed` and `xmax_aborted` bits give similar information about the `xmax` transaction.

- v. 13 The `pageinspect` extension provides the `heap_tuple_infomask_flags` function that explains all the information bits, but I am going to retrieve only those that are required at the moment, showing them in a more concise form.

Let's get back to our experiment. The `INSERT` command has added pointer 1 to the heap page; it refers to the first tuple, which is currently the only one.

The `xmin` field of the tuple is set to the current transaction ID. This transaction is still active, so the `xmin_committed` and `xmin_aborted` bits are not set yet.

The `xmax` field contains 0, which is a dummy number showing that this tuple has not been deleted and represents the current version of the row. Transactions will ignore this number because the `xmax_aborted` bit is set.

It may seem strange that the bit corresponding to an aborted transaction is set for the transaction that has not happened yet. But there is no difference between such transactions from the isolation standpoint: an aborted transaction leaves no trace, hence it has never existed.

We will use this query more than once, so I am going to wrap it into a function. And while being at it, I will also make the output more concise by hiding the information bit columns and displaying the status of transactions together with their IDs.

```
=> CREATE FUNCTION heap_page(relname text, pageno integer)
RETURNS TABLE(ctid tid, state text, xmin text, xmax text)
AS $$
SELECT (pageno,lp)::text::tid AS ctid,
       CASE lp_flags
         WHEN 0 THEN 'unused'
         WHEN 1 THEN 'normal'
         WHEN 2 THEN 'redirect to '||lp_off
         WHEN 3 THEN 'dead'
       END AS state,
       t_xmin || CASE
         WHEN (t_infomask & 256) > 0 THEN ' c'
         WHEN (t_infomask & 512) > 0 THEN ' a'
         ELSE ''
       END AS xmin,
       t_xmax || CASE
```

```

        WHEN (t_infomask & 1024) > 0 THEN ' c'
        WHEN (t_infomask & 2048) > 0 THEN ' a'
        ELSE ''
    END AS xmax
FROM heap_page_items(get_raw_page(relname, pageno))
ORDER BY lp;
$$ LANGUAGE sql;

```

Now it is much clearer what is happening in the tuple header:

```

=> SELECT * FROM heap_page('t',0);
   ctid  | state  | xmin | xmax
-----+-----+-----+-----
 (0,1) | normal | 776  | 0 a
(1 row)

```

You can get similar but less detailed information from the table itself by querying the xmin and xmax pseudocolumns:

```

=> SELECT xmin, xmax, * FROM t;
   xmin | xmax | id | s
-----+-----+-----+-----
    776 |    0 |  1 | F00
(1 row)

```

Commit

Once a transaction has been completed successfully, its status has to be stored somehow—it must be registered that the transaction is *committed*. For this purpose, PostgreSQL employs a special CLOG (commit log) structure.¹ It is stored as files in the PGDATA/pg_xact directory rather than as a system catalog table.

Previously, these files were located in PGDATA/pg_clog, but in version 10 this directory got renamed:² it was not uncommon for database administrators unfamiliar with PostgreSQL to delete it in search of free disk space, thinking that a “log” is something unnecessary.

¹ include/access/clog.h

backend/access/transam/clog.c

² commitfest.postgresql.org/13/750

p. 149 CLOG is split into several files solely for convenience. These files are accessed page by page via buffers in the server's shared memory.¹

Just like a tuple header, CLOG contains two bits for each transaction: committed and aborted.

Once committed, a transaction is marked in CLOG with the committed bit. When any other transaction accesses a heap page, it has to answer the question: has the xmin transaction already finished?

- If not, then the created tuple must not be visible.

To check whether the transaction is still active, PostgreSQL uses yet another structure located in the shared memory of the instance; it is called ProcArray. This structure contains the list of all the active processes, with the corresponding current (active) transaction specified for each process.

- If yes, was it committed or aborted? In the latter case, the corresponding tuple cannot be visible either.

It is this check that requires CLOG. But even though the most recent CLOG pages are stored in memory buffers, it is still expensive to perform this check every time. Once determined, the transaction status is written into the tuple header—more specifically, into xmin_committed and xmin_aborted information bits, which are also called *hint bits*. If one of these bits is set, then the xmin transaction status is considered to be already known, and the next transaction will have to access neither CLOG nor ProcArray.

Why aren't these bits set by the transaction that performs row insertion? The problem is that it is not known yet at that time whether this transaction will complete successfully. And when it is committed, it is already unclear which tuples and pages have been changed. If a transaction affects many pages, it may be too expensive to track them. Besides, some of these pages may be not in the cache anymore; reading them again to simply update the hint bits would seriously slow down the commit.

¹ backend/access/transam/clog.c

The flip side of this cost reduction is that any transaction (even a read-only `SELECT` command) can start setting hint bits, thus leaving a trail of dirtied pages in the buffer cache.

Finally, let's commit the transaction started with the `INSERT` statement:

```
=> COMMIT;
```

Nothing has changed in the page (but we know that the transaction status has already been written into CLOG):

```
=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
 (0,1) | normal | 776  | 0 a
(1 row)
```

Now the first transaction that accesses the page (in a “standard” way, without using `pageinspect`) has to determine the status of the `xmin` transaction and update the hint bits:

```
=> SELECT * FROM t;
 id | s
----+---
  1 | F00
(1 row)

=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
 (0,1) | normal | 776 c | 0 a
(1 row)
```

Delete

When a row is deleted, the `xmax` field of its current version is set to the transaction ID that performs the deletion, and the `xmax_aborted` bit is unset.

p. 235 While this transaction is active, the xmax value serves as a row lock. If another transaction is going to update or delete this row, it will have to wait until the xmax transaction is complete.

Let's delete a row:

```
=> BEGIN;
=> DELETE FROM t;
=> SELECT pg_current_xact_id();
       pg_current_xact_id
-----
                777
(1 row)
```

The transaction ID has already been written into the xmax field, but the information bits have not been set yet:

```
=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
 (0,1) | normal | 776 c | 777
(1 row)
```

Abort

The mechanism of aborting a transaction is similar to that of commit and happens just as fast, but instead of committed it sets the aborted bit in CLOG. Although the corresponding command is called ROLLBACK, no actual data rollback is happening: all the changes made by the aborted transaction in data pages remain in place.

```
=> ROLLBACK;
=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
 (0,1) | normal | 776 c | 777
(1 row)
```

When the page is accessed, the transaction status is checked, and the tuple receives the `xmax_aborted` hint bit. The `xmax` number itself still remains in the page, but no one is going to pay attention to it anymore:

```
=> SELECT * FROM t;
 id | s
----+-----
  1 | F00
(1 row)
```

```
=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
(0,1) | normal | 776 c | 777 a
(1 row)
```

Update

An update is performed in such a way as if the current tuple is deleted, and then a new one is inserted:

```
=> BEGIN;
```

```
=> UPDATE t SET s = 'BAR';
```

```
=> SELECT pg_current_xact_id();
 pg_current_xact_id
-----
                  778
(1 row)
```

The query returns a single row (its new version):

```
=> SELECT * FROM t;
 id | s
----+-----
  1 | BAR
(1 row)
```

But the page keeps both versions:

```
=> SELECT * FROM heap_page('t',0);
```

ctid	state	xmin	xmax
(0,1)	normal	776 c	778
(0,2)	normal	778	0 a

```
(2 rows)
```

The xmax field of the previously deleted version contains the current transaction ID. This value is written on top of the old one because the previous transaction was aborted. The xmax_aborted bit is unset since the status of the current transaction is still unknown.

To complete this experiment, let's commit the transaction.

```
=> COMMIT;
```

3.4 Indexes

Regardless of their type, indexes do not use row versioning; each row is represented by exactly one tuple. In other words, index row headers do not contain xmin and xmax fields. Index entries point to all the versions of the corresponding table row. To figure out which row version is visible, transactions have to access the table (unless the required page appears in the visibility map).

For convenience, let's create a simple function that will use pageinspect to display all the index entries in the page (B-tree index pages store them as a flat list):

```
=> CREATE FUNCTION index_page(relname text, pageno integer)
RETURNS TABLE(itemoffset smallint, htid tid)
AS $$
SELECT itemoffset,
       htid -- ctid before v.13
FROM bt_page_items(relname,pageno);
$$ LANGUAGE sql;
```

The page references both heap tuples, the current and the previous one:


```
=> SELECT * FROM index_page('t_s_idx',1);
 itemoffset | htid
-----+-----
          1 | (0,2)
          2 | (0,1)
(2 rows)
```

Since `BAR < FOO`, the pointer to the second tuple comes first in the index.

3.5 TOAST

A TOAST table is virtually a regular table, and it has its own versioning that does not depend on row versions of the main table. However, rows of TOAST tables are handled in such a way that they are never updated; they can be either added or deleted, so their versioning is somewhat artificial. p. 26

Each data modification results in creation of a new tuple in the main table. But if an update does not affect any long values stored in TOAST, the new tuple will reference an existing toasted value. Only when a long value gets updated will PostgreSQL create both a new tuple in the main table and new “toasts.”

3.6 Virtual Transactions

To consume transaction IDs sparingly, PostgreSQL offers a special optimization.

If a transaction is read-only, it does not affect row visibility in any way. That’s why such a transaction is given a *virtual xid*¹ at first, which consists of the backend process ID and a sequential number. Assigning a virtual xid does not require any synchronization between different processes, so it happens very fast. At this point, the transaction has no real ID yet: p. 227

```
=> BEGIN;
```

¹ backend/access/transam/xact.c

```
=> -- txid_current_if_assigned() before v.13
SELECT pg_current_xact_id_if_assigned();
pg_current_xact_id_if_assigned
-----
```

(1 row)

At different points in time, the system can contain some virtual XIDs that have already been used. And it is perfectly normal: virtual XIDs exist only in RAM, and only while the corresponding transactions are active; they are never written into data pages and never get to disk.

Once the transaction starts modifying data, it receives an actual unique ID:

```
=> UPDATE accounts
SET amount = amount - 1.00;

=> SELECT pg_current_xact_id_if_assigned();
pg_current_xact_id_if_assigned
-----
```

780

(1 row)

```
=> COMMIT;
```

3.7 Subtransactions

Savepoints

SQL supports *savepoints*, which enable canceling some of the operations within a transaction without aborting this transaction as a whole. But such a scenario does not fit the course of action described above: the status of a transaction applies to all its operations, and no physical data rollback is performed.

To implement this functionality, a transaction containing a savepoint is split into several *subtransactions*,¹ so their status can be managed separately.

¹ backend/access/transam/subtrans.c

Subtransactions have their own IDs (which are bigger than the ID of the main transaction). The status of a subtransaction is written into CLOG in the usual manner; however, committed subtransactions receive both the committed and the aborted bits at once. The final decision depends on the status of the main transaction: if it is aborted, all its subtransactions will be considered aborted too.

The information about subtransactions is stored under the `PGDATA/pg_subtrans` directory. File access is arranged via buffers that are located in the instance's shared memory and have the same structure as CLOG buffers.¹

Do not confuse subtransactions with autonomous ones. Unlike subtransactions, the latter do not depend on each other in any way. Vanilla PostgreSQL does not support autonomous transactions, and it is probably for the best: they are required in very rare cases, but their availability in other database systems often provokes misuse, which can cause a lot of trouble.

Let's truncate the table, start a new transaction, and insert a row:

```
=> TRUNCATE TABLE t;
=> BEGIN;
=> INSERT INTO t(s) VALUES ('F00');
=> SELECT pg_current_xact_id();
       pg_current_xact_id
-----
                782
(1 row)
```

Now create a savepoint and insert another row:

```
=> SAVEPOINT sp;
=> INSERT INTO t(s) VALUES ('XYZ');
=> SELECT pg_current_xact_id();
       pg_current_xact_id
-----
                782
(1 row)
```

Note that the `pg_current_xact_id` function returns the ID of the main transaction, not that of a subtransaction.

¹ `backend/access/transam/slru.c`

```
=> SELECT *
FROM heap_page('t',0) p
LEFT JOIN t ON p.ctid = t.ctid;
 ctid | state | xmin | xmax | id | s
-----+-----+-----+-----+-----+-----
(0,1) | normal | 782 | 0 a | 2 | F00
(0,2) | normal | 783 | 0 a | 3 | XYZ
(2 rows)
```

Let's roll back to the savepoint and insert the third row:

```
=> ROLLBACK TO sp;

=> INSERT INTO t(s) VALUES ('BAR');
=> SELECT *
FROM heap_page('t',0) p
LEFT JOIN t ON p.ctid = t.ctid;
 ctid | state | xmin | xmax | id | s
-----+-----+-----+-----+-----+-----
(0,1) | normal | 782 | 0 a | 2 | F00
(0,2) | normal | 783 | 0 a |  | 
(0,3) | normal | 784 | 0 a | 4 | BAR
(3 rows)
```

The page still contains the row added by the aborted subtransaction.

Commit the changes:

```
=> COMMIT;

=> SELECT * FROM t;
 id | s
----+----
 2 | F00
 4 | BAR
(2 rows)

=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
(0,1) | normal | 782 c | 0 a
(0,2) | normal | 783 a | 0 a
(0,3) | normal | 784 c | 0 a
(3 rows)
```

Now we can clearly see that each subtransaction has its own status.

SQL does not allow using subtransactions directly, that is, you cannot start a new transaction before completing the current one:

```
=> BEGIN;
BEGIN
=> BEGIN;
WARNING:  there is already a transaction in progress
BEGIN
=> COMMIT;
COMMIT
=> COMMIT;
WARNING:  there is no transaction in progress
COMMIT
```

Subtransactions are employed implicitly: to implement savepoints, handle exceptions in PL/pgSQL, and in some other, more exotic cases.

Errors and Atomicity

What happens if an error occurs during execution of a statement?

```
=> BEGIN;
=> SELECT * FROM t;
  id | s
----+-----
   2 | FOO
   4 | BAR
(2 rows)
=> UPDATE t SET s = repeat('X', 1/(id-4));
ERROR:  division by zero
```

After a failure, the whole transaction is considered aborted and cannot perform any further operations:

```
=> SELECT * FROM t;
ERROR:  current transaction is aborted, commands ignored until end
of transaction block
```

And even if you try to commit the changes, PostgreSQL will report that the transaction is rolled back:

```
=> COMMIT;
ROLLBACK
```

Why is it forbidden to continue transaction execution after a failure? Since the already executed operations are never rolled back, we would get access to some changes made before the error—it would break the atomicity of the statement, and hence that of the transaction itself.

For example, in our experiment the operator has managed to update one of the two rows before the failure:

```
=> SELECT * FROM heap_page('t',0);
 ctid | state | xmin | xmax
-----+-----+-----+-----
 (0,1) | normal | 782 c | 785
 (0,2) | normal | 783 a | 0 a
 (0,3) | normal | 784 c | 0 a
 (0,4) | normal | 785   | 0 a
(4 rows)
```

On a side note, psql provides a special mode that allows you to continue a transaction after a failure as if the erroneous statement were rolled back:

```
=> \set ON_ERROR_ROLLBACK on

=> BEGIN;

=> UPDATE t SET s = repeat('X', 1/(id-4));
ERROR:  division by zero

=> SELECT * FROM t;
 id | s
----+---
  2 | FOO
  4 | BAR
(2 rows)

=> COMMIT;
COMMIT
```

As you can guess, `psql` simply adds an implicit savepoint before each command when run in this mode; in case of a failure, a rollback is initiated. This mode is not used by default because issuing savepoints (even if they are not rolled back to) incurs significant overhead.



Snapshots

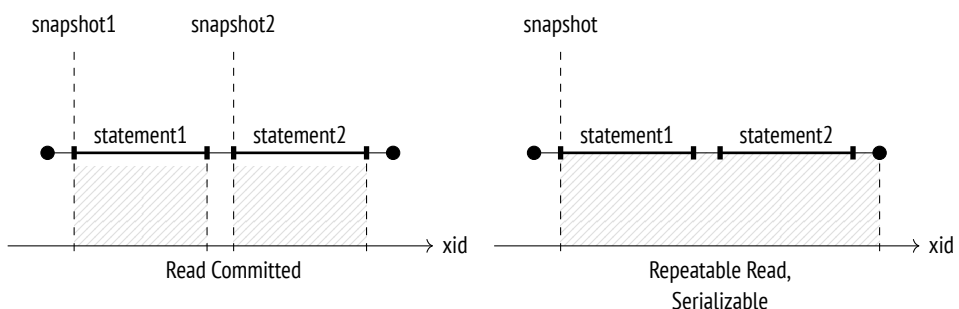
4.1 What is a Snapshot?

p. 45 A data page can contain several versions of one and the same row, although each transaction must see only one of them at the most. Together, visible versions of all the different rows constitute a *snapshot*. A snapshot includes only the current data committed by the time it was taken, thus providing a consistent (in the ACID sense) view of the data for this particular moment.

To ensure isolation, each transaction uses its own snapshot. It means that different transactions can see different snapshots taken at different points in time, which are nevertheless consistent.

At the Read Committed isolation level, a snapshot is taken at the beginning of each statement, and it remains active only for the duration of this statement.

At the Repeatable Read and Serializable levels, a snapshot is taken at the beginning of the first statement of a transaction, and it remains active until the whole transaction is complete.



4.2 Row Version Visibility

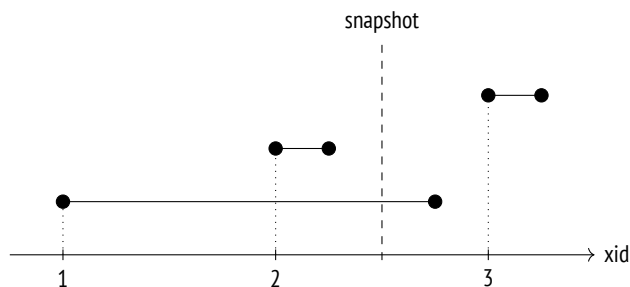
A snapshot is not a physical copy of all the required tuples. Instead, it is defined by several numbers, while tuple visibility is determined by certain rules.

Tuple visibility is defined by $xmin$ and $xmax$ fields of the tuple header (that is, IDs of transactions that perform insertion and deletion) and the corresponding hint bits. Since $xmin$ – $xmax$ intervals do not intersect, each row is represented in any snapshot by only one of its versions.

The exact visibility rules are quite complex,¹ as they take into account a variety of different scenarios and corner cases. Very roughly, we can describe them as follows: a tuple is visible in a snapshot that includes $xmin$ transaction changes but excludes $xmax$ transaction changes (in other words, the tuple has already appeared and has not been deleted yet).

In their turn, transaction changes are visible in a snapshot if this transaction was committed before the snapshot creation. As an exception, transactions can see their own uncommitted changes. If a transaction is aborted, its changes will not be visible in any snapshot.

Let's take a look at a simple example. In this illustration line segments represent transactions (from their start time till commit time):



Here visibility rules are applied to transactions as follows:

- Transaction 2 was committed before the snapshot creation, so its changes are visible.

¹ `backend/access/heap/heapam_visibility.c`

- Transaction 1 was active at the time of the snapshot creation, so its changes are not visible.
- Transaction 3 was started after the snapshot creation, so its changes are not visible either (it makes no difference whether this transaction is completed or not).

4.3 Snapshot Structure

Unfortunately, the previous illustration has nothing to do with the way PostgreSQL actually sees this picture.¹ The problem is that the system does not know when transactions got committed. It is only known when they were started (this moment is defined by the transaction ID), while their completion is not registered anywhere.

off Commit times can be tracked² if you enable the *track_commit_timestamp* parameter, but they do not participate in visibility checks in any way (although it can still be useful to track them for other purposes, for example, to apply in external replication solutions).

p. 185 Besides, PostgreSQL always logs commit and rollback times in the corresponding WAL entries, but this information is used only for point-in-time recovery.

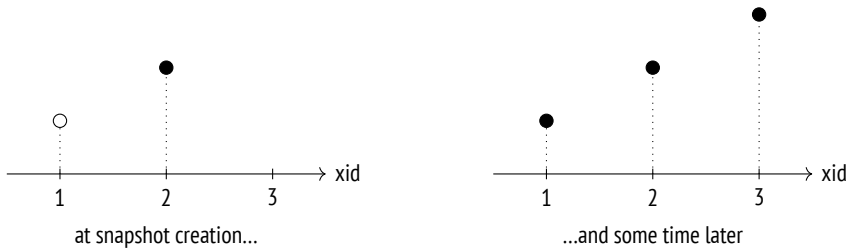
It is only the *current* status of a transaction that we can learn. This information is available in the server's shared memory: the *ProcArray* structure contains the list of all the active sessions and their transactions. Once a transaction is complete, it is impossible to find out whether it was active at the time of the snapshot creation.

So to create a snapshot, it is not enough to register the moment when it was taken: it is also necessary to collect the status of all the transactions at that moment. Otherwise, later it will be impossible to understand which tuples must be visible in the snapshot, and which must be excluded.

Take a look at the information available to the system when the snapshot was taken and some time afterwards (the white circle denotes an active transaction, whereas the black circles stand for completed ones):

¹ `include/utils/snapshot.h`
`backend/utils/time/snapmgr.c`

² `backend/access/transam/commit_ts.c`



Suppose we did not know that at the time the snapshot was taken the first transaction was still being executed and the third transaction had not started yet. Then it would seem that they were just like the second transaction (which was committed at that time), and it would be impossible to filter them out.

For this reason, PostgreSQL cannot create a snapshot that shows a consistent state of data at some arbitrary point in the past, even if all the required tuples are present in heap pages. Consequently, it is impossible to implement retrospective queries (which are sometimes also called temporal or flashback queries).

Intriguingly, such functionality was declared as one of the objectives of Postgres and was implemented at the very start, but it was removed from the database system when the project support was passed on to the community.¹

Thus, a snapshot consists of several values saved at the time of its creation:²

xmin is the snapshot's lower boundary, which is represented by the ID of the oldest active transaction.

All the transactions with smaller IDs are either committed (so their changes are included into the snapshot) or aborted (so their changes are ignored). p. 139

xmax is the snapshot's upper boundary, which is represented by the value that exceeds the ID of the latest committed transaction by one. The upper boundary defines the moment when the snapshot was taken.

All the transactions whose IDs are equal to or greater than xmax are either still running or do not exist, so their changes cannot be visible.

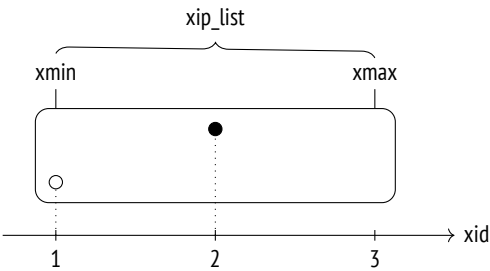
xip_list is the list of IDs of all the active transactions except for virtual ones, which do not affect visibility in any way. p. 81

¹ Joseph M. Hellerstein, Looking Back at Postgres. <https://arxiv.org/pdf/1901.01973.pdf>

² backend/storage/ipc/proccarray.c, GetSnapshotData function

Snapshots also include several other parameters, but we will ignore them for now.

In a graphical form, a snapshot can be represented as a rectangle that comprises transactions from xmin to xmax:



To understand how visibility rules are defined by the snapshot, we are going to reproduce the above scenario on the accounts table.

```
=> TRUNCATE TABLE accounts;
```

The first transaction inserts the first row into the table and remains open:

```
=> BEGIN;
=> INSERT INTO accounts VALUES (1, 'alice', 1000.00);
=> SELECT pg_current_xact_id();
pg_current_xact_id
-----
790
(1 row)
```

The second transaction inserts the second row and commits this change immediately:

```
=> BEGIN;
=> INSERT INTO accounts VALUES (2, 'bob', 100.00);
=> SELECT pg_current_xact_id();
pg_current_xact_id
-----
791
(1 row)
=> COMMIT;
```

At this point, let's create a new snapshot in another session. We could simply run any query for this purpose, but we will use a special function to take a look at this snapshot right away:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> -- txid_current_snapshot() before v.13
SELECT pg_current_snapshot();
       pg_current_snapshot
-----
790:792:790
(1 row)
```

This function displays the following snapshot components, separated by colons: xmin, xmax, and xip_list (the list of active transactions; in this particular case it consists of a single item).

Once the snapshot is taken, commit the first transaction:

```
=> COMMIT;
```

The third transaction is started after the snapshot creation. It modifies the second row, so a new tuple appears:

```
=> BEGIN;
=> UPDATE accounts SET amount = amount + 100 WHERE id = 2;
=> SELECT pg_current_xact_id();
       pg_current_xact_id
-----
                          792
(1 row)
=> COMMIT;
```

Our snapshot sees only one tuple:

```
=> SELECT ctid, * FROM accounts;
 ctid | id | client | amount
-----+-----+-----+-----
(0,2) |  2 | bob    | 100.00
(1 row)
```

But the table contains three of them:

```
||      => SELECT * FROM heap_page('accounts',0);  
||  
||      ctid | state | xmin | xmax  
||      -----+-----+-----+-----  
||      (0,1) | normal | 790 c | 0 a  
||      (0,2) | normal | 791 c | 792 c  
||      (0,3) | normal | 792 c | 0 a  
||      (3 rows)
```

So how does PostgreSQL choose which versions to show? By the above rules, changes are included into a snapshot only if they are made by committed transactions that satisfy the following criteria:

- If $xid < xmin$, changes are shown unconditionally (like in the case of the transaction that created the accounts table).
- If $xmin \leq xid < xmax$, changes are shown only if the corresponding transaction IDs are not in `xip_list`.

The first row (0,1) is invisible because it is inserted by a transaction that appears in `xip_list` (even though this transaction falls into the snapshot range).

The latest version of the second row (0,3) is invisible because the corresponding transaction ID is above the upper boundary of the snapshot.

But the first version of the second row (0,2) is visible: row insertion was performed by a transaction that falls into the snapshot range and does not appear in `xip_list` (the insertion is visible), while row deletion was performed by a transaction whose ID is above the upper boundary of the snapshot (the deletion is invisible).

```
||      => COMMIT;
```

4.4 Visibility of Transactions' Own Changes

Things get a bit more complicated when it comes to defining visibility rules for transactions' own changes: in some cases, only part of such changes must be visible. For example, a cursor that was opened at a particular point in time must not see any changes that happened later, regardless of the isolation level.

To address such situations, tuple headers provide a special field (displayed as `cmin` and `cmax` pseudocolumns) that shows the sequence number of the operation within the transaction. The `cmin` column identifies insertion, while `cmax` is used for deletion operations. To save space, these values are stored in a single field of the tuple header rather than in two different ones. It is assumed that one and the same row almost never gets both inserted and deleted within a single transaction. (If it does happen, PostgreSQL writes a special combo identifier into this field, and the actual `cmin` and `cmax` values are stored by the backend in this case.¹)

As an illustration, let's start a transaction and insert a row into the table:

```
=> BEGIN;
=> INSERT INTO accounts VALUES (3, 'charlie', 100.00);
=> SELECT pg_current_xact_id();
       pg_current_xact_id
-----
                793
(1 row)
```

Open a cursor to run the query that returns the number of rows in this table:

```
=> DECLARE c CURSOR FOR SELECT count(*) FROM accounts;
```

Insert one more row:

```
=> INSERT INTO accounts VALUES (4, 'charlie', 200.00);
```

Now extend the output by another column to display the `cmin` value for the rows inserted by our transaction (it makes no sense for other rows):

```
=> SELECT xmin, CASE WHEN xmin = 793 THEN cmin END cmin, *
FROM accounts;
 xmin | cmin | id | client  | amount
-----+-----+---+-----+-----
  790 |      |  1 | alice   | 1000.00
  792 |      |  2 | bob     |  200.00
  793 |    0 |  3 | charlie |  100.00
  793 |    1 |  4 | charlie |  200.00
(4 rows)
```

¹ backend/utils/time/combocid.c

The cursor query gets only three rows; the row inserted when the cursor was already open does not make it into the snapshot because the `cmin < 1` condition is not satisfied:

```
=> FETCH c;
```

```
count
-----
      3
(1 row)
```

Naturally, this `cmin` number is also stored in the snapshot, but it is impossible to display it using any SQL means.

4.5 Transaction Horizon

As mentioned earlier, the lower boundary of the snapshot is represented by `xmin`, which is the ID of the oldest transaction that was active at the moment of the snapshot creation. This value is very important because it defines the *horizon* of the transaction that uses this snapshot.

If a transaction has no active snapshot (for example, at the Read Committed isolation level between statement execution), its horizon is defined by its own ID if it is assigned.

All the transactions that are beyond the horizon (those with `xid < xmin`) are guaranteed to be committed. It means that a transaction can see only the current row versions beyond its horizon.

As you can guess, this term is inspired by the concept of *event horizon* in physics.

PostgreSQL tracks the current horizons of all its processes; transactions can see their own horizons in the `pg_stat_activity` table:

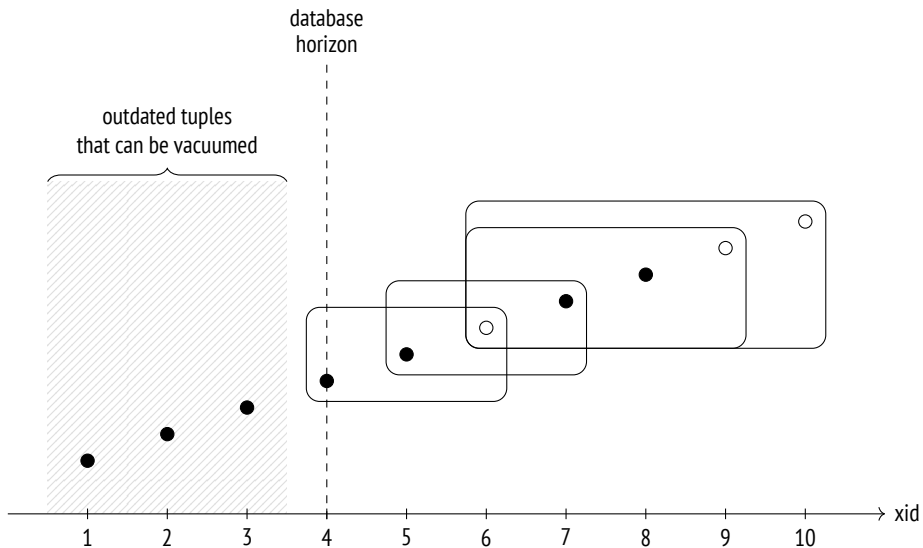
```
=> BEGIN;
```

```
=> SELECT backend_xmin FROM pg_stat_activity
WHERE pid = pg_backend_pid();
```

```
backend_xmin
-----
          793
(1 row)
```


Virtual transactions have no real IDs, but they still use snapshots just like regular transactions, so they have their own horizons. The only exception is virtual transactions without an active snapshot: the concept of the horizon makes no sense for them, and they are fully “transparent” to the system when it comes to snapshots and visibility (even though `pg_stat_activity.backend_xmin` may still contain an `xmin` of an old snapshot).

We can also define the *database horizon* in a similar manner. For this purpose, we should take the horizons of all the transactions in this database and select the most remote one, which has the oldest `xmin`.¹ Beyond this horizon, outdated heap tuples will never be visible to any transaction in this database. *Such tuples can be safely cleaned up by vacuum*—this is exactly why the concept of the horizon is so important from a practical standpoint.



Let's draw some conclusions:

- If a transaction (no matter whether it is real or virtual) at the Repeatable Read or Serializable isolation level is running for a long time, it thereby holds the database horizon and defers vacuuming.

¹ `backend/storage/ipc/proccarray.c`, `ComputeXidHorizons` function

- A real transaction at the Read Committed isolation level holds the database horizon in the same way, even if it is not executing any operators (being in the “idle in transaction” state).
- A virtual transaction at the Read Committed isolation level holds the horizon only while executing operators.

There is only one horizon for the whole database, so if it is being held by a transaction, it is impossible to vacuum any data within this horizon—even if this data has not been accessed by this transaction.

Cluster-wide tables of the system catalog have a separate horizon that takes into account all transactions in all databases. Temporary tables, on the contrary, do not have to pay attention to any transactions except those that are being executed by the current process.

Let’s get back to our current experiment. The active transaction of the first session still holds the database horizon; we can see it by incrementing the transaction counter:

```
=> SELECT pg_current_xact_id();
      pg_current_xact_id
      -----
                794
(1 row)
```

```
=> SELECT backend_xmin FROM pg_stat_activity
WHERE pid = pg_backend_pid();
      backend_xmin
      -----
                793
(1 row)
```

And only when this transaction is complete, the horizon moves forward, and out-dated tuples can be vacuumed:

```
=> COMMIT;
=> SELECT backend_xmin FROM pg_stat_activity
WHERE pid = pg_backend_pid();
      backend_xmin
      -----
                795
(1 row)
```

In a perfect world, you should avoid combining long transactions with frequent updates (that spawn new row versions), as it will lead to table and index bloating. p. 159

4.6 System Catalog Snapshots

Although the system catalog consists of regular tables, they cannot be accessed via a snapshot used by a transaction or an operator. The snapshot must be “fresh” enough to include all the latest changes, otherwise transactions could see outdated definitions of table columns or miss newly added integrity constraints.

Here is a simple example:

```
=> BEGIN TRANSACTION ISOLATION LEVEL REPEATABLE READ;

=> SELECT 1; -- a snapshot for the transaction is taken

| => ALTER TABLE accounts
|     ALTER amount SET NOT NULL;

=> INSERT INTO accounts(client, amount)
    VALUES ('alice', NULL);
ERROR: null value in column "amount" of relation "accounts"
violates not-null constraint
DETAIL: Failing row contains (1, alice, null).

=> ROLLBACK;
```

The integrity constraint that appeared after the snapshot creation was visible to the `INSERT` command. It may seem that such behavior breaks isolation, but if the inserting transaction had accessed the `accounts` table, the `ALTER TABLE` command would have been blocked until this transaction completion. p. 228

In general, the server behaves as if a separate snapshot is created for each system catalog query. But the implementation is, of course, much more complex¹ since frequent snapshot creation would negatively affect performance; besides, many system catalog objects get cached, and it must also be taken into account.

¹ backend/utils/time/snapmgr.c, GetCatalogSnapshot function

4.7 Exporting Snapshots

In some situations, concurrent transactions must see one and the same snapshot by all means. For example, if the `pg_dump` utility is run in the parallel mode, all its processes must see the same database state to produce a consistent backup.

We cannot assume that snapshots will be identical simply because transactions were started “simultaneously.” To ensure that all the transactions see the same data, we must employ the snapshot export mechanism.

The `pg_export_snapshot` function returns a snapshot ID, which can be passed to another transaction (outside of the database system):

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> SELECT count(*) FROM accounts;
count
-----
      4
(1 row)
```

```
=> SELECT pg_export_snapshot();
pg_export_snapshot
-----
00000004-0000006E-1
(1 row)
```

Before executing the first statement, the other transaction can import the snapshot by running the `SET TRANSACTION SNAPSHOT` command. The isolation level must be set to Repeatable Read or Serializable because operators use their own snapshots at the Read Committed level:

```
=> DELETE FROM accounts;
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> SET TRANSACTION SNAPSHOT '00000004-0000006E-1';
```

Now the second transaction is going to use the snapshot of the first transaction, and consequently, it will see four rows (instead of zero):

```

=> SELECT count(*) FROM accounts;
      count
-----
         4
(1 row)

```

Clearly, the second transaction will not see any changes made by the first transaction after the snapshot export (and vice versa): regular visibility rules still apply.

The exported snapshot's lifetime is the same as that of the exporting transaction.

```

=> COMMIT;

```

```

=> COMMIT;

```

5

Page Pruning and HOT Updates

5.1 Page Pruning

While a heap page is being read or updated, PostgreSQL can perform some quick page cleanup, or *pruning*.¹ It happens in the following cases:

- The previous `UPDATE` operation did not find enough space to place a new tuple into the same page. This event is reflected in the page header.
- The heap page contains more data than allowed by the *fillfactor* storage parameter.

An `INSERT` operation can add a new row into the page only if this page is filled for less than *fillfactor* percent. The rest of the space is kept for `UPDATE` operations (no such space is reserved by default).

p. 97 Page pruning removes the tuples that cannot be visible in any snapshot anymore (that is, that are beyond the database horizon). It never goes beyond a single heap page, but in return it is performed very fast. Pointers to pruned tuples remain in place since they may be referenced from an index—which is already a different page.

For the same reason, neither the visibility map nor the free space map is refreshed (so the recovered space is set aside for updates, not for insertions).

p. 76 Since a page can be pruned during reads, any `SELECT` statement can cause page modifications. This is yet another such case in addition to deferred setting of information bits.

¹ `backend/access/heap/pruneheap.c`, `heap_page_prune_opt` function

Let's take a look at how page pruning actually works. We are going to create a two-column table and build an index on each of the columns:

```
=> CREATE TABLE hot(id integer, s char(2000)) WITH (fillfactor = 75);
=> CREATE INDEX hot_id ON hot(id);
=> CREATE INDEX hot_s ON hot(s);
```

If the *s* column contains only Latin letters, each heap tuple will have a fixed size of 2004 bytes, plus 24 bytes of the header. The *fillfactor* storage parameter is set to 75 %. It means that the page has enough free space for four tuples, but we can insert only three.

Let's insert a new row and update it several times:

```
=> INSERT INTO hot VALUES (1, 'A');
=> UPDATE hot SET s = 'B';
=> UPDATE hot SET s = 'C';
=> UPDATE hot SET s = 'D';
```

Now the page contains four tuples:

```
=> SELECT * FROM heap_page('hot',0);
 ctid  | state  | xmin  | xmax
-----+-----+-----+-----
(0,1)  | normal | 801 c | 802 c
(0,2)  | normal | 802 c | 803 c
(0,3)  | normal | 803 c | 804
(0,4)  | normal | 804   | 0 a
(4 rows)
```

Expectedly, we have just exceeded the *fillfactor* threshold. You can tell it by the difference between the pagesize and upper values—it is bigger than 75 % of the page size, which is 6144 bytes: p. 66

```
=> SELECT upper, pagesize FROM page_header(get_raw_page('hot',0));
 upper | pagesize
-----+-----
    64 |    8192
(1 row)
```

The next page access triggers page pruning that removes all the outdated tuples. Then a new tuple (0,5) is added into the freed space:

```
=> UPDATE hot SET s = 'E';
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax
(0,1)	dead		
(0,2)	dead		
(0,3)	dead		
(0,4)	normal	804 c	805
(0,5)	normal	805	0 a

(5 rows)

The remaining heap tuples are physically moved towards the highest addresses so that all the free space is aggregated into a single continuous chunk. The tuple pointers are also modified accordingly. As a result, there is no free space fragmentation in the page.

The pointers to the pruned tuples cannot be removed yet because they are still referenced from the indexes; PostgreSQL changes their status from normal to dead. Let's take a look at the first page of the hot_s index (the zero page is used for meta-data):

```
=> SELECT * FROM index_page('hot_s',1);
```

itemoffset	htid
1	(0,1)
2	(0,2)
3	(0,3)
4	(0,4)
5	(0,5)

(5 rows)

We can see the same picture in the other index too:

```
=> SELECT * FROM index_page('hot_id',1);
```

itemoffset	htid
1	(0,1)
2	(0,2)
3	(0,3)
4	(0,4)
5	(0,5)

(5 rows)

An index scan can return (0,1), (0,2), and (0,3) as tuple identifiers. The server tries to read the corresponding heap tuple but sees that the pointer has the dead status; it means that this tuple does not exist anymore and should be ignored. And while being at it, the server also changes the pointer status in the index page to avoid repeated heap page access.¹

Let's extend the function displaying index pages so that it also shows whether the pointer is dead: v. 13

```
=> DROP FUNCTION index_page(text, integer);

=> CREATE FUNCTION index_page(relname text, pageno integer)
RETURNS TABLE(itemoffset smallint, htid tid, dead boolean)
AS $$
SELECT itemoffset,
        htid,
        dead -- starting from v.13
FROM bt_page_items(relname,pageno);
$$ LANGUAGE sql;
```

```
=> SELECT * FROM index_page('hot_id',1);
```

itemoffset	htid	dead
1	(0,1)	f
2	(0,2)	f
3	(0,3)	f
4	(0,4)	f
5	(0,5)	f

(5 rows)

All the pointers in the index page are active so far. But as soon as the first index scan occurs, their status changes:

```
=> EXPLAIN (analyze, costs off, timing off, summary off)
```

```
SELECT * FROM hot WHERE id = 1;
```

QUERY PLAN

```
-----
Index Scan using hot_id on hot (actual rows=1 loops=1)
```

```
Index Cond: (id = 1)
```

(2 rows)

¹ backend/access/index/indexam.c, index_fetch_heap function

```
=> SELECT * FROM index_page('hot_id',1);
 itemoffset | htid | dead
-----+-----+-----
          1 | (0,1) | t
          2 | (0,2) | t
          3 | (0,3) | t
          4 | (0,4) | t
          5 | (0,5) | f
(5 rows)
```

Although the heap tuple referenced by the fourth pointer is still unpruned and has the normal status, it is already beyond the database horizon. That’s why this pointer is also marked as dead in the index.

5.2 HOT Updates

It would be very inefficient to keep references to all heap tuples in an index.

To begin with, each row modification triggers updates of *all* the indexes created on the table: once a new heap tuple appears, each index must include a reference to this tuple, even if the modified fields are not indexed.

Furthermore, indexes accumulate references to historic heap tuples, so they have to be pruned together with these tuples.

Things get worse as you create more indexes on a table.

But if the updated column is not a part of *any* index, there is no point in creating another index entry that contains the same key value. To avoid such redundancies, PostgreSQL provides an optimization called *Heap-Only Tuple updates*.¹

If such an update is performed, an index page contains only one entry for each row. This entry points to the very first row version; all the subsequent versions located in the same page are bound into a chain by ctid pointers in the tuple headers.

Row versions that are not referenced from any index are tagged with the Heap-Only Tuple bit. If a version is included into the HOT chain, it is tagged with the Heap Hot Updated bit.

¹ backend/access/heap/README.HOT

If an index scan accesses a heap page and finds a row version marked as Heap Hot Updated, it means that the scan should continue, so it goes further along the chain of HOT updates. Obviously, all the fetched row versions are checked for visibility before the result is returned to the client.

To take a look at how HOT updates are performed, let's delete one of the indexes and truncate the table.

```
=> DROP INDEX hot_s;
=> TRUNCATE TABLE hot;
```

For convenience, we will redefine the heap_page function so that its output includes three more fields: ctid and the two bits related to HOT updates:

```
=> DROP FUNCTION heap_page(text, integer);
=> CREATE FUNCTION heap_page(relname text, pageno integer)
RETURNS TABLE(
    ctid tid, state text,
    xmin text, xmax text,
    hhu text, hot text, t_ctid tid
) AS $$
SELECT (pageno,lp)::text::tid AS ctid,
       CASE lp_flags
         WHEN 0 THEN 'unused'
         WHEN 1 THEN 'normal'
         WHEN 2 THEN 'redirect to '||lp_off
         WHEN 3 THEN 'dead'
       END AS state,
       t_xmin || CASE
         WHEN (t_infomask & 256) > 0 THEN ' c'
         WHEN (t_infomask & 512) > 0 THEN ' a'
         ELSE ''
       END AS xmin,
       t_xmax || CASE
         WHEN (t_infomask & 1024) > 0 THEN ' c'
         WHEN (t_infomask & 2048) > 0 THEN ' a'
         ELSE ''
       END AS xmax,
       CASE WHEN (t_infomask2 & 16384) > 0 THEN 't' END AS hhu,
       CASE WHEN (t_infomask2 & 32768) > 0 THEN 't' END AS hot,
       t_ctid
FROM heap_page_items(get_raw_page(relname,pageno))
ORDER BY lp;
$$ LANGUAGE sql;
```

Let's repeat the insert and update operations:

```
=> INSERT INTO hot VALUES (1, 'A');
```

```
=> UPDATE hot SET s = 'B';
```

The page now contains a chain of HOT updates:

- The Heap Hot Updated bit shows that the executor should follow the CTID chain.
- The Heap Only Tuple bit indicates that this tuple is not referenced from any indexes.

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	normal	812 c	813	t		(0,2)
(0,2)	normal	813	0 a		t	(0,2)

(2 rows)

As we make further updates, the chain will grow—but only within the page limits:

```
=> UPDATE hot SET s = 'C';
```

```
=> UPDATE hot SET s = 'D';
```

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	normal	812 c	813 c	t		(0,2)
(0,2)	normal	813 c	814 c	t	t	(0,3)
(0,3)	normal	814 c	815	t	t	(0,4)
(0,4)	normal	815	0 a		t	(0,4)

(4 rows)

The index still contains only one reference, which points to the head of this chain:

```
=> SELECT * FROM index_page('hot_id',1);
```

itemoffset	htid	dead
1	(0,1)	f

(1 row)

A HOT update is possible if the modified fields are not a part of *any* index. Otherwise, some of the indexes would contain a reference to a heap tuple that appears in the middle of the chain, which contradicts the idea of this optimization. Since a HOT chain can grow only within a single page, traversing the whole chain never requires access to other pages and thus does not hamper performance.

5.3 Page Pruning for HOT Updates

A special case of page pruning—which is nevertheless important—is pruning of HOT update chains.

In the example above, the *fillfactor* threshold is already exceeded, so the next update should trigger page pruning. But this time the page contains a chain of HOT updates. The head of this chain must always remain in its place since it is referenced from the index, but other pointers can be released because they are sure to have no external references.


To avoid moving the head, PostgreSQL uses dual addressing: the pointer referenced from the index (which is (0,1) in this case) receives the redirect status since it points to the tuple that currently starts the chain:

```
=> UPDATE hot SET s = 'E';
```

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	redirect to 4					
(0,2)	normal	816	0 a		t	(0,2)
(0,3)	unused					
(0,4)	normal	815 c	816	t	t	(0,2)

(4 rows)



The tuples (0,1), (0,2), and (0,3) have been pruned; the head pointer 1 remains for redirection purposes, while pointers 2 and 3 have been deallocated (received the unused status) since they are guaranteed to have no references from indexes. The new tuple is written into the freed space as tuple (0,2).

Let's perform some more updates:

```
=> UPDATE hot SET s = 'F';
```

```
=> UPDATE hot SET s = 'G';
```

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	redirect to 4					
(0,2)	normal	816 c	817 c	t	t	(0,3)
(0,3)	normal	817 c	818	t	t	(0,5)
(0,4)	normal	815 c	816 c	t	t	(0,2)
(0,5)	normal	818	0 a		t	(0,5)

(5 rows)

The next update is going to trigger page pruning:

```
=> UPDATE hot SET s = 'H';
```

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	redirect to 5					
(0,2)	normal	819	0 a		t	(0,2)
(0,3)	unused					
(0,4)	unused					
(0,5)	normal	818 c	819	t	t	(0,2)

(5 rows)

Again, some of the tuples are pruned, and the pointer to the head of the chain is shifted accordingly.

If unindexed columns are modified frequently, it makes sense to reduce the *fillfactor* value, thus reserving some space in the page for updates. Obviously, you have to keep in mind that the lower the *fillfactor* value is, the more free space is left in the page, so the physical size of the table grows.

5.4 HOT Chain Splits

If the page has no more space to accommodate a new tuple, the chain will be cut off. PostgreSQL will have to add a separate index entry to refer to the tuple located in another page.

To observe this situation, let's start a concurrent transaction with a snapshot that blocks page pruning:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;
=> SELECT 1;
```

Now we are going to perform some updates in the first session:

```
=> UPDATE hot SET s = 'I';
```

```
=> UPDATE hot SET s = 'J';
```

```
=> UPDATE hot SET s = 'K';
```

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	redirect to 2					
(0,2)	normal	819 c	820 c	t	t	(0,3)
(0,3)	normal	820 c	821 c	t	t	(0,4)
(0,4)	normal	821 c	822	t	t	(0,5)
(0,5)	normal	822	0 a		t	(0,5)

(5 rows)

When the next update happens, this page will not be able to accommodate another tuple, and page pruning will not manage to free any space:

```
=> UPDATE hot SET s = 'L';
```

```
=> COMMIT; -- the snapshot is not required anymore
```

```
=> SELECT * FROM heap_page('hot',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	redirect to 2					
(0,2)	normal	819 c	820 c	t	t	(0,3)
(0,3)	normal	820 c	821 c	t	t	(0,4)
(0,4)	normal	821 c	822 c	t	t	(0,5)
(0,5)	normal	822 c	823		t	(1,1)

(5 rows)

Tuple (0,5) contains the (1,1) reference that goes to page 1:

```
=> SELECT * FROM heap_page('hot',1);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(1,1)	normal	823	0 a			(1,1)

(1 row)

However, this reference is not used: the Heap Hot Updated bit is not set for tuple (0,5). As for tuple (1,1), it can be accessed from the index that now has two entries. Each of them points to the head of their own HOT chain:

```
=> SELECT * FROM index_page('hot_id',1);
```

itemoffset	htid	dead
1	(0,1)	f
2	(1,1)	f

(2 rows)

5.5 Page Pruning for Indexes

I have declared that page pruning is confined to a single heap page and does not affect indexes. However, indexes have their own pruning,¹ which also cleans up a single page—an index one in this case.

Index pruning happens when an insertion into a B-tree is about to split the page into two, as the original page does not have enough space anymore. The problem is that even if some index entries are deleted later, two separate index pages will not

¹ [postgresql.org/docs/14/btree-implementation.html#BTREE-DELETION](https://www.postgresql.org/docs/14/btree-implementation.html#BTREE-DELETION)

be merged into one. It leads to index bloating, and once bloated, the index cannot shrink even if a large part of the data is deleted. But if pruning can remove some of the tuples, a page split may be deferred.

There are two types of tuples that can be pruned from an index.

First of all, PostgreSQL prunes those tuples that have been tagged as dead.¹ As I have already said, PostgreSQL sets such a tag during an index scan if it detects an index entry pointing to a tuple that is not visible in any snapshot anymore or simply does not exist.

If no tuples are known to be dead, PostgreSQL checks those index entries that reference different versions of one and the same table row.² Because of MVCC, update operations may generate a large number of row versions, and many of them are soon likely to disappear behind the database horizon. HOT updates cushion this effect, but they are not always applicable: if the column to update is a part of an index, the corresponding references are propagated to all the indexes. Before splitting the page, it makes sense to search for the rows that are not tagged as dead yet but can already be pruned. To achieve this, PostgreSQL has to check visibility of heap tuples. Such checks require table access, so they are performed only for “promising” index tuples, which have been created as copies of the existing ones for MVCC purposes. It is cheaper to perform such a check than to allow an extra page split. v. 14

¹ backend/access/nbtree/README, Simple deletion section

² backend/access/nbtree/README, Bottom-Up deletion section
include/access/tableam.h

6

Vacuum and Autovacuum

6.1 Vacuum

Page pruning happens very fast, but it frees only part of the space that can be potentially reclaimed. Operating within a single heap page, it does not touch upon indexes (or vice versa, it cleans up an index page without affecting the table).

Routine vacuuming,¹ which is the main vacuuming procedure, is performed by the `VACUUM` command.² It processes the whole table and eliminates both outdated heap tuples and all the corresponding index entries.

Vacuuming is performed in parallel with other processes in the database system. While being vacuumed, tables and indexes can be used in the usual manner, both for read and write operations (but concurrent execution of such commands as `CREATE INDEX`, `ALTER TABLE`, and some others is not allowed).

p. 228

p. 25 To avoid scanning extra pages, PostgreSQL uses a visibility map. Pages tracked in this map are skipped since they are sure to contain only the current tuples, so a page will only be vacuumed if it does not appear in this map. If all the tuples remaining in a page after vacuuming are beyond the database horizon, the visibility map is refreshed to include this page.

The free space map also gets updated to reflect the space that has been cleared.

Let's create a table with an index on it:

¹ postgresql.org/docs/14/routine-vacuuming.html

² postgresql.org/docs/14/sql-vacuum.html
[backend/commands/vacuum.c](https://postgresql.org/docs/14/commands/vacuum.c)

```
=> CREATE TABLE vac(
    id integer,
    s char(100)
)
WITH (autovacuum_enabled = off);

=> CREATE INDEX vac_s ON vac(s);
```

The *autovacuum_enabled* storage parameter turns off autovacuum; we are doing it here solely for the purpose of experimentation to precisely control vacuuming start time.

Let's insert a row and make a couple of updates:

```
=> INSERT INTO vac(id,s) VALUES (1, 'A');

=> UPDATE vac SET s = 'B';

=> UPDATE vac SET s = 'C';
```

Now the table contains three tuples:

```
=> SELECT * FROM heap_page('vac',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	normal	826 c	827 c			(0,2)
(0,2)	normal	827 c	828			(0,3)
(0,3)	normal	828	0 a			(0,3)

(3 rows)

Each tuple is referenced from the index:

```
=> SELECT * FROM index_page('vac_s',1);
```

itemoffset	htid	dead
1	(0,1)	f
2	(0,2)	f
3	(0,3)	f

(3 rows)

Vacuuming has removed all the dead tuples, leaving only the current one:

```
=> VACUUM vac;
```

```
=> SELECT * FROM heap_page('vac',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	unused					
(0,2)	unused					
(0,3)	normal	828 c	0 a			(0,3)

(3 rows)

In the case of page pruning, the first two pointers would be considered dead, but here they have the unused status since no index entries are referring to them now:

```
=> SELECT * FROM index_page('vac_s',1);
```

itemoffset	htid	dead
1	(0,3)	f

(1 row)

Pointers with the unused status are treated as free and can be reused by new row versions.

Now the heap page appears in the visibility map; we can check it using the `pg_visibility` extension:

```
=> CREATE EXTENSION pg_visibility;
=> SELECT all_visible
FROM pg_visibility_map('vac',0);
```

all_visible
t

(1 row)

The page header has also received an attribute showing that all its tuples are visible in all snapshots:

```
=> SELECT flags & 4 > 0 AS all_visible
FROM page_header(get_raw_page('vac',0));
```

all_visible
t

(1 row)

6.2 Database Horizon Revisited

Vacuuming detects dead tuples based on the database horizon. This concept is so fundamental that it makes sense to get back to it once again.

Let's restart our experiment from the very beginning:

```
=> TRUNCATE vac;
=> INSERT INTO vac(id,s) VALUES (1,'A');
=> UPDATE vac SET s = 'B';
```

But this time, before updating the row, we are going to open another transaction that will hold the database horizon (it can be almost any transaction, except for a virtual one executed at the Read Committed isolation level). For example, this transaction can modify some rows in *another* table. p. 97

```
=> BEGIN;
=> UPDATE accounts SET amount = 0;
```

```
=> UPDATE vac SET s = 'C';
```

Now our table contains three tuples, and the index contains three references. Let's vacuum the table and see what changes:

```
=> VACUUM vac;
=> SELECT * FROM heap_page('vac',0);
```

ctid	state	xmin	xmax	hhu	hot	t_ctid
(0,1)	unused					
(0,2)	normal	833 c	835 c			(0,3)
(0,3)	normal	835 c	0 a			(0,3)

```
(3 rows)
=> SELECT * FROM index_page('vac_s',1);
```

itemoffset	htid	dead
1	(0,2)	f
2	(0,3)	f

```
(2 rows)
```

While the previous run left only one tuple in the page, now we have two of them: `VACUUM` has decided that version (0,2) cannot be removed yet. The reason is the database horizon, which is defined by an unfinished transaction in this case:

```
=> SELECT backend_xmin FROM pg_stat_activity
WHERE pid = pg_backend_pid();
 backend_xmin
-----
          834
(1 row)
```

We can use the `VERBOSE` clause when calling `VACUUM` to observe what is going on:

```
=> VACUUM VERBOSE vac;
INFO:  vacuuming "public.vac"
INFO:  table "vac": found 0 removable, 2 nonremovable row versions
in 1 out of 1 pages
DETAIL:  1 dead row versions cannot be removed yet, oldest xmin: 834
Skipped 0 pages due to buffer pins, 0 frozen pages.
CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s.
VACUUM
```

The output shows the following information:

- `VACUUM` has detected no tuples that can be removed (0 REMOVABLE).
- Two tuples must not be removed (2 NONREMOVABLE).
- One of the nonremovable tuples is dead (1 DEAD), the other is in use.
- The current horizon respected by `VACUUM` (OLDEST XMIN) is the horizon of the active transaction.

Once the active transaction completes, the database horizon moves forward, and vacuuming can continue:

```
=> COMMIT;
```

```
=> VACUUM VERBOSE vac;
INFO: vacuuming "public.vac"
INFO: scanned index "vac_s" to remove 1 row versions
DETAIL: CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s
INFO: table "vac": removed 1 dead item identifiers in 1 pages
DETAIL: CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s
INFO: index "vac_s" now contains 1 row versions in 2 pages
DETAIL: 1 index row versions were removed.
0 index pages were newly deleted.
0 index pages are currently deleted, of which 0 are currently
reusable.
CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s.
INFO: table "vac": found 1 removable, 1 nonremovable row versions
in 1 out of 1 pages
DETAIL: 0 dead row versions cannot be removed yet, oldest xmin: 836
Skipped 0 pages due to buffer pins, 0 frozen pages.
CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s.
VACUUM
```

VACUUM has detected and removed a dead tuple beyond the new database horizon.

Now the page contains no outdated row versions; the only version remaining is the current one:

```
=> SELECT * FROM heap_page('vac',0);
 ctid | state | xmin | xmax | hhu | hot | t_ctid
-----+-----+-----+-----+-----+-----+-----
(0,1) | unused |      |      |     |    |
(0,2) | unused |      |      |     |    |
(0,3) | normal | 835 c | 0 a  |     |    | (0,3)
(3 rows)
```

The index also contains only one entry:

```
=> SELECT * FROM index_page('vac_s',1);
 itemoffset | htid | dead
-----+-----+-----
          1 | (0,3) | f
(1 row)
```

6.3 Vacuum Phases

The mechanism of vacuuming seems quite simple, but this impression is misleading. After all, both tables and indexes have to be processed concurrently, without blocking other processes. To enable such operation, vacuuming of each table is carried out in several phases.¹

It all starts with scanning a table in search of dead tuples; if found, they are first removed from indexes and then from the table itself. If too many dead tuples have to be vacuumed in one go, this process is repeated. Eventually, heap truncation may be performed.

Heap Scan

In the first phase, a *heap scan* is performed.² The scanning process takes the visibility map into account: all pages tracked in this map are skipped because they are sure to contain no outdated tuples. If a tuple is beyond the horizon and is not required anymore, its ID is added to a special tid array. Such tuples cannot be removed yet because they may still be referenced from indexes.

64MB The tid array resides in the local memory of the `VACUUM` process; the size of the allocated memory chunk is defined by the `maintenance_work_mem` parameter. The whole chunk is allocated at once rather than on demand. However, the allocated memory never exceeds the volume required in the worst-case scenario, so if the table is small, vacuuming may use less memory than specified in this parameter.

Index Vacuuming

The first phase can have two outcomes: either the table is scanned in full, or the memory allocated for the tid array is filled up before this operation completes. In any case, *index vacuuming* begins.³ In this phase, *each* of the indexes created on

¹ `backend/access/heap/vacuumlazy.c`, `heap_vacuum_rel` function

² `backend/access/heap/vacuumlazy.c`, `lazy_scan_heap` function

³ `backend/access/heap/vacuumlazy.c`, `lazy_vacuum_all_indexes` function

the table is *fully scanned* to find all the entries that refer to the tuples registered in the tid array. These entries are removed from index pages.

An index can help you quickly get to a heap tuple by its index key, but there is no way to quickly find an index entry by the corresponding tuple ID. This functionality is currently being implemented for B-trees,¹ but this work is not completed yet.

If there are several indexes bigger than the *min_parallel_index_scan_size* value, they can be vacuumed by background workers running in parallel. Unless the level of parallelism is explicitly defined by the *parallel N* clause, *VACUUM* launches one worker per suitable index (within the general limits imposed on the number of background workers).² One index cannot be processed by several workers. 512kB v. 13

During the index vacuuming phase, PostgreSQL updates the free space map and calculates statistics on vacuuming. However, this phase is skipped if rows are only inserted (and are neither deleted nor updated) because the table contains no dead tuples in this case. Then an index scan will be forced only once at the very end, as part of a separate phase of *index cleanup*.³

The index vacuuming phase leaves no references to outdated heap tuples in indexes, but the tuples themselves are still present in the table. It is perfectly normal: index scans cannot find any dead tuples, while sequential scans of the table rely on visibility rules to filter them out.

Heap Vacuuming

Then the *heap vacuuming* phase begins.⁴ The table is scanned again to remove the tuples registered in the tid array and free the corresponding pointers. Now that all the related index references have been removed, it can be done safely.

The space recovered by *VACUUM* is reflected in the free space map, while the pages that now contain only the current tuples visible in all snapshots are tagged in the visibility map.

¹ commitfest.postgresql.org/21/1802

² postgresql.org/docs/14/bgworker.html

³ `backend/access/heap/vacuumlazy.c`, `lazy_cleanup_all_indexes` function
`backend/access/nbtree/nbtree.c`, `btvacuumcleanup` function

⁴ `backend/access/heap/vacuumlazy.c`, `lazy_vacuum_heap` function

If the table was not read in full during the heap scan phase, the tid array is cleared, and the heap scan is resumed from where it left off last time.

Heap Truncation

Vacuumed heap pages contain some free space; occasionally, you may be lucky to clear the whole page. If you get several empty pages at the end of the file, vacuuming can “bite off” this tail and return the reclaimed space to the operating system. It happens during *heap truncation*,¹ which is the final vacuum phase.

p. 228 Heap truncation requires a short exclusive lock on the table. To avoid holding other processes for too long, attempts to acquire a lock do not exceed five seconds.

Since the table has to be locked, truncation is only performed if the empty tail takes at least $\frac{1}{16}$ of the table or has reached the length of 1,000 pages. These thresholds are hardcoded and cannot be configured.

v. 12 If, despite all these precautions, table locks still cause any issues, truncation can be disabled altogether using the *vacuum_truncate* and *toast.vacuum_truncate* storage parameters.

6.4 Analysis

When talking about vacuuming, we have to mention yet another task that is closely related to it, even though there is no formal connection between them. It is *analysis*,² or gathering statistical information for the query planner. The collected statistics include the number of rows (*pg_class.reltuples*) and pages (*pg_class.relpages*) in relations, data distribution within columns, and some other information.

You can run the analysis manually using the *ANALYZE* command,³ or combine it with vacuuming by calling *VACUUM ANALYZE*. However, these two tasks are still performed sequentially, so there is no difference in terms of performance.

¹ *backend/access/heap/vacuumlazy.c*, *lazy_truncate_heap* function

² [postgresql.org/docs/14/routine-vacuuming.html#VACUUM-FOR-STATISTICS](https://www.postgresql.org/docs/14/routine-vacuuming.html#VACUUM-FOR-STATISTICS)

³ *backend/commands/analyze.c*

Historically, `VACUUM ANALYZE` appeared first, in version 6.1, while a separate `ANALYZE` command was not implemented until version 7.2. In earlier versions, statistics were collected by a TCL script.

Automatic vacuum and analysis are set up in a similar way, so it makes sense to discuss them together.

6.5 Automatic Vacuum and Analysis

Unless the database horizon is held up for a long time, routine vacuuming should cope with its work. But how often do we need to call the `VACUUM` command?

If a frequently updated table is vacuumed too seldom, it will grow bigger than desired. Besides, it may accumulate too many changes, and then the next `VACUUM` run will have to make several passes over the indexes.

If the table is vacuumed too often, the server will be busy with maintenance instead of useful work.

Furthermore, typical workloads may change over time, so having a fixed vacuuming schedule will not help anyway: the more often the table is updated, the more often it has to be vacuumed.

This problem is solved by *autovacuum*,¹ which launches vacuum and analysis processes based on the intensity of table updates.

About the Autovacuum Mechanism

When autovacuum is enabled (*autovacuum* configuration parameter is on), the autovacuum launcher process is always running in the system. This process defines the autovacuum schedule and maintains the list of “active” databases based on usage statistics. Such statistics are collected if the *track_counts* parameter is enabled. Do not switch off these parameters, otherwise autovacuum will not work.

¹ [postgresql.org/docs/14/routine-vacuuming.html#AUTOVACUUM](https://www.postgresql.org/docs/14/routine-vacuuming.html#AUTOVACUUM)

- 1min Once in *autovacuum_naptime*, the autovacuum launcher starts an autovacuum worker¹ for each active database in the list (these workers are spawned by postmaster, as usual). Consequently, if there are N active databases in the cluster, N workers are spawned within the *autovacuum_naptime* interval. But the total number of autovacuum workers running in parallel cannot exceed the threshold defined by the *autovacuum_max_workers* parameter.

Autovacuum workers are very similar to regular background workers, but they appeared much earlier than this general mechanism of task management. It was decided to leave the autovacuum implementation unchanged, so autovacuum workers do not use *max_worker_processes* slots.

Once started, the background worker connects to the specified database and builds two lists:

- the list of all tables, materialized views, and TOAST tables to be vacuumed
- the list of all tables and materialized views to be analyzed (TOAST tables are not analyzed because they are always accessed via an index)

Then the selected objects are vacuumed or analyzed one by one (or undergo both operations), and once the job is complete, the worker is terminated.

Automatic vacuuming works similar to the manual one initiated by the `VACUUM` command, but there are some nuances:

- Manual vacuuming accumulates tuple IDs in a memory chunk of the *maintenance_work_mem* size. However, using the same limit for autovacuum is undesirable, as it can result in excessive memory consumption: there may be several autovacuum workers running in parallel, and each of them will get *maintenance_work_mem* of memory at once. Instead, PostgreSQL provides a separate memory limit for autovacuum processes, which is defined by the *autovacuum_work_mem* parameter.
- 1 By default, the *autovacuum_work_mem* parameter falls back on the regular *maintenance_work_mem* limit, so if the *autovacuum_max_workers* value is high, you may have to adjust the *autovacuum_work_mem* value accordingly.

¹ backend/postmaster/autovacuum.c

- Concurrent processing of several indexes created on one table can be performed only by manual vacuuming; using autovacuum for this purpose would result in a large number of parallel processes, so it is not allowed.

If a worker fails to complete all the scheduled tasks within the *autovacuum_naptime* interval, the autovacuum launcher spawns another worker to be run in parallel in that database. The second worker will build its own lists of objects to be vacuumed and analyzed and will start processing them. There is no parallelism at the table level; only *different* tables can be processed concurrently.

Which Tables Need to be Vacuumed?

You can disable autovacuum at the table level—although it is hard to imagine why it could be necessary. There are two storage parameters provided for this purpose, one for regular tables and the other for TOAST tables:

- *autovacuum_enabled*
- *toast.autovacuum_enabled*

In usual circumstances, autovacuum is triggered either by accumulation of dead tuples or by insertion of new rows. p. 145

Dead tuple accumulation. Dead tuples are constantly being counted by the statistics collector; their current number is shown in the system catalog table called *pg_stat_all_tables*.

It is assumed that dead tuples have to be vacuumed if they exceed the threshold defined by the following two parameters:

- *autovacuum_vacuum_threshold*, which specifies the number of dead tuples (an absolute value) 50
- *autovacuum_vacuum_scale_factor*, which sets the fraction of dead tuples in a table 0.2

Vacuuming is required if the following condition is satisfied:

$$\text{pg_stat_all_tables.n_dead_tup} > \\ \text{autovacuum_vacuum_threshold} + \\ \text{autovacuum_vacuum_scale_factor} \times \text{pg_class.reltuples}$$

The main parameter here is of course *autovacuum_vacuum_scale_factor*: its value is important for large tables (and it is large tables that are likely to cause the majority of issues). The default value of 20 % seems too big and may have to be significantly reduced.

For different tables, optimal parameter values may vary: they largely depend on the table size and workload type. It makes sense to set more or less adequate initial values and then override them for particular tables using storage parameters:

- *autovacuum_vacuum_threshold* and *toast.autovacuum_vacuum_threshold*
- *autovacuum_vacuum_scale_factor* and *toast.autovacuum_vacuum_scale_factor*

v. 13 **Row insertions.** If rows are only inserted and are neither deleted nor updated, the table contains no dead tuples. But such tables should also be vacuumed to freeze
p. 139 heap tuples in advance and update the visibility map (thus enabling index-only scans).

A table will be vacuumed if the number of rows inserted since the previous vacuuming exceeds the threshold defined by another similar pair of parameters:

- 1000 • *autovacuum_vacuum_insert_threshold*
- 0.2 • *autovacuum_vacuum_insert_scale_factor*

The formula is as follows:

$$\text{pg_stat_all_tables.n_ins_since_vacuum} > \\ \text{autovacuum_vacuum_insert_threshold} + \\ \text{autovacuum_vacuum_insert_scale_factor} \times \text{pg_class.reltuples}$$

Like in the previous example, you can override these values at the table level using storage parameters:

- *autovacuum_vacuum_insert_threshold* and its TOAST counterpart
- *autovacuum_vacuum_insert_scale_factor* and its TOAST counterpart

Which Tables Need to Be Analyzed?

Automatic analysis needs to process only modified rows, so the calculations are a bit simpler than those for autovacuum.

It is assumed that a table has to be analyzed if the number of rows modified since the previous analysis exceeds the threshold defined by the following two configuration parameters:

- *autovacuum_analyze_threshold* 50
- *autovacuum_analyze_scale_factor* 0.1

Autoanalysis is triggered if the following condition is met:

$$\text{pg_stat_all_tables.n_mod_since_analyze} > \text{autovacuum_analyze_threshold} + \text{autovacuum_analyze_scale_factor} \times \text{pg_class.reltuples}$$

To override autoanalysis settings for particular tables, you can use the same-name storage parameters:

- *autovacuum_analyze_threshold*
- *autovacuum_analyze_scale_factor*

Since TOAST tables are not analyzed, they have no corresponding parameters.

Autovacuum in Action

To formalize everything said in this section, let's create two views that show which tables currently need to be vacuumed and analyzed.¹ The function used in these views returns the current value of the passed parameter, taking into account that this value can be redefined at the table level:

```
=> CREATE FUNCTION p(param text, c pg_class) RETURNS float
AS $$
    SELECT coalesce(
        -- use storage parameter if set
        (SELECT option_value
         FROM pg_options_to_table(c.reloptions)
         WHERE option_name = CASE
             -- for TOAST tables the parameter name is different
             WHEN c.relkind = 't' THEN 'toast.' ELSE ''
            END || param
        ),
        -- else take the configuration parameter value
        current_setting(param)
    )::float;
$$ LANGUAGE sql;
```

This is how a vacuum-related view can look like:

```
=> CREATE VIEW need_vacuum AS
WITH c AS (
    SELECT c.oid,
           greatest(c.reltuples, 0) reltuples,
           p('autovacuum_vacuum_threshold', c) threshold,
           p('autovacuum_vacuum_scale_factor', c) scale_factor,
           p('autovacuum_vacuum_insert_threshold', c) ins_threshold,
           p('autovacuum_vacuum_insert_scale_factor', c) ins_scale_factor
    FROM pg_class c
    WHERE c.relkind IN ('r','m','t')
)
SELECT st.schemaname || '.' || st.relname AS tablename,
       st.n_dead_tup AS dead_tup,
       c.threshold + c.scale_factor * c.reltuples AS max_dead_tup,
       st.n_ins_since_vacuum AS ins_tup,
       c.ins_threshold + c.ins_scale_factor * c.reltuples AS max_ins_tup,
       st.last_autovacuum
FROM pg_stat_all_tables st
JOIN c ON c.oid = st.relid;
```

¹ backend/postmaster/autovacuum.c, relation_needs_vacanalyze function

The `max_dead_tup` column shows the number of dead tuples that will trigger autovacuum, whereas the `max_ins_tup` column shows the threshold value related to insertion.

Here is a similar view for analysis:

```
=> CREATE VIEW need_analyze AS
WITH c AS (
    SELECT c.oid,
           greatest(c.reltuples, 0) reltuples,
           p('autovacuum_analyze_threshold', c) threshold,
           p('autovacuum_analyze_scale_factor', c) scale_factor
    FROM pg_class c
    WHERE c.relkind IN ('r','m')
)
SELECT st.schemaname || '.' || st.relname AS tablename,
       st.n_mod_since_analyze AS mod_tup,
       c.threshold + c.scale_factor * c.reltuples AS max_mod_tup,
       st.last_autoanalyze
FROM pg_stat_all_tables st
JOIN c ON c.oid = st.relid;
```

The `max_mod_tup` column shows the threshold value for autoanalysis.

To speed up the experiment, we will be starting autovacuum every second:

```
=> ALTER SYSTEM SET autovacuum_naptime = '1s';
=> SELECT pg_reload_conf();
```

Let's truncate the `vac` table and then insert 1,000 rows. Note that autovacuum is turned off at the table level.

```
=> TRUNCATE TABLE vac;
=> INSERT INTO vac(id,s)
    SELECT id, 'A' FROM generate_series(1,1000) id;
```

Here is what our vacuum-related view will show:

```
=> SELECT * FROM need_vacuum WHERE tablename = 'public.vac' \gx
-[ RECORD 1 ]-----+-----
tablename      | public.vac
dead_tup       | 0
max_dead_tup   | 50
ins_tup        | 1000
max_ins_tup    | 1000
last_autovacuum |
```

The actual threshold value is `max_dead_tup = 50`, although the formula listed above suggests that it should be $50 + 0.2 \times 1000 = 250$. The thing is that statistics on this table are not available yet since the `INSERT` command does not update it:

```
=> SELECT reltuples FROM pg_class WHERE relname = 'vac';
      reltuples
-----
             -1
(1 row)
```

- v. 14 The `pg_class.reltuples` value is set to `-1`; this special constant is used instead of zero to differentiate between a table without any statistics and a really empty table that has already been analyzed. For the purpose of calculation, the negative value is taken as zero, which gives us $50 + 0.2 \times 0 = 50$.

The value of `max_ins_tup = 1000` differs from the projected value of 1,200 for the same reason.

Let's have a look at the analysis view:

```
=> SELECT * FROM need_analyze WHERE tablename = 'public.vac' \gx
-[ RECORD 1 ]-----+-----
tablename          | public.vac
mod_tup             | 1006
max_mod_tup         | 50
last_autoanalyze    |
```

We have updated (inserted in this case) 1,000 rows; as a result, the threshold is exceeded: since the table size is unknown, it is currently set to 50. It means that autoanalysis will be triggered immediately when we turn it on:

```
=> ALTER TABLE vac SET (autovacuum_enabled = on);
```

Once the table analysis completes, the threshold is reset to an adequate value of 150 rows.

```
=> SELECT reltuples FROM pg_class WHERE relname = 'vac';
      reltuples
-----
          1000
(1 row)
```

```
=> SELECT * FROM need_analyze WHERE tablename = 'public.vac' \gx
-[ RECORD 1 ]-----+-----
tablename      | public.vac
mod_tup        | 0
max_mod_tup    | 150
last_autoanalyze | 2022-09-19 14:51:25.983319+03
```

Let's get back to autovacuum:

```
=> SELECT * FROM need_vacuum WHERE tablename = 'public.vac' \gx
-[ RECORD 1 ]-----+-----
tablename      | public.vac
dead_tup       | 0
max_dead_tup   | 250
ins_tup        | 1000
max_ins_tup    | 1200
last_autovacuum |
```

The max_dead_tup and max_ins_tup values have also been updated based on the actual table size discovered by the analysis.

Vacuuming will be started if at least one of the following conditions is met:

- More than 250 dead tuples are accumulated.
- More than 200 rows are inserted into the table.

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Let's turn off autovacuum again and update 251 rows so that the threshold value is exceeded by one:

```
=> ALTER TABLE vac SET (autovacuum_enabled = off);
=> UPDATE vac SET s = 'B' WHERE id <= 251;
=> SELECT * FROM need_vacuum WHERE tablename = 'public.vac' \gx
-[ RECORD 1 ]-----+-----
tablename      | public.vac
dead_tup       | 251
max_dead_tup   | 250
ins_tup        | 1000
max_ins_tup    | 1200
last_autovacuum |
```

Now the trigger condition is satisfied. Let's enable autovacuum; after a while, we will see that the table has been processed, and its usage statistics has been reset:

```
=> ALTER TABLE vac SET (autovacuum_enabled = on);
=> SELECT * FROM need_vacuum WHERE tablename = 'public.vac' \gx
-[ RECORD 1 ]-----+-----
tablename       | public.vac
dead_tup        | 0
max_dead_tup    | 250
ins_tup         | 0
max_ins_tup     | 1200
last_autovacuum | 2022-09-19 14:51:32.001381+03
```

6.6 Managing the Load

Operating at the page level, vacuuming does not block other processes; but nevertheless, it increases the system load and can have a noticeable impact on performance.

Vacuum Throttling

To control vacuuming intensity, PostgreSQL makes regular pauses in table processing. After completing about *vacuum_cost_limit* units of work, the process falls asleep and remains idle for the *vacuum_cost_delay* time interval.

The default zero value of *vacuum_cost_delay* means that routine vacuuming actually never sleeps, so the exact *vacuum_cost_limit* value makes no difference. It is assumed that if administrators have to resort to manual vacuuming, they are likely to expect its completion as soon as possible.

If the sleep time is set, then the process will pause each time it has spent *vacuum_cost_limit* units of work on page processing in the buffer cache. The cost of each page read is estimated at *vacuum_cost_page_hit* units if the page is found in the buffer cache, or *vacuum_cost_page_miss* units otherwise.¹ If a clean page is dirtied by vacuum, it adds another *vacuum_cost_page_dirty* units.²

¹ backend/storage/buffer/bufmgr.c, ReadBuffer_common function

² backend/storage/buffer/bufmgr.c, MarkBufferDirty function

If you keep the default value of the *vacuum_cost_limit* parameter, `VACUUM` can process up to 200 pages per cycle in the best-case scenario (if all the pages are cached, and no pages are dirtied by `VACUUM`) and only nine pages in the worst case (if all the pages are read from disk and become dirty).

Autovacuum Throttling

Throttling for autovacuum¹ is quite similar to `VACUUM` throttling. However, autovacuum can be run with a different intensity as it has its own set of parameters:

- *autovacuum_vacuum_cost_limit* -1
- *autovacuum_vacuum_cost_delay* 2ms

If any of these parameters is set to -1, it falls back on the corresponding parameter for regular `VACUUM`. Thus, the *autovacuum_vacuum_cost_limit* parameter relies on the *vacuum_cost_limit* value by default.

Prior to version 12, the default value of *autovacuum_vacuum_cost_delay* was 20 ms, and it led to very poor performance on modern hardware.

Autovacuum work units are limited to *autovacuum_vacuum_cost_limit* per cycle, and since they are shared between all the workers, the overall impact on the system remains roughly the same, regardless of their number. So if you need to speed up autovacuum, both the *autovacuum_max_workers* and *autovacuum_vacuum_cost_limit* values should be increased proportionally.

If required, you can override these settings for particular tables by setting the following storage parameters:

- *autovacuum_vacuum_cost_delay* and *toast.autovacuum_vacuum_cost_delay*
- *autovacuum_vacuum_cost_limit* and *toast.autovacuum_vacuum_cost_limit*

¹ backend/postmaster/autovacuum.c, *autovac_balance_cost* function

6.7 Monitoring

If vacuuming is monitored, you can detect situations when dead tuples cannot be removed in one go, as references to them do not fit the *maintenance_work_mem* memory chunk. In this case, all the indexes will have to be fully scanned several times. It can take a substantial amount of time for large tables, thus creating a significant load on the system. Even though queries will not be blocked, extra I/O operations can seriously limit system throughput.

Such issues can be corrected either by vacuuming the table more often (so that each run cleans up fewer tuples) or by allocating more memory.

Monitoring Vacuum

v. 9.6 When run with the `VERBOSE` clause, the `VACUUM` command performs the cleanup and displays the status report, whereas the `pg_stat_progress_vacuum` view shows the current state of the started process.

v. 13 There is also a similar view for analysis (`pg_stat_progress_analyze`), even though it is usually performed very fast and is unlikely to cause any issues.

Let's insert more rows into the table and update them all so that `VACUUM` has to run for a noticeable period of time:

```
=> TRUNCATE vac;
=> INSERT INTO vac(id,s)
    SELECT id, 'A' FROM generate_series(1,500000) id;
=> UPDATE vac SET s = 'B';
```

For the purpose of this demonstration, we will limit the amount of memory allocated for the tid array by 1 MB:

```
=> ALTER SYSTEM SET maintenance_work_mem = '1MB';
=> SELECT pg_reload_conf();
```

Launch the `VACUUM` command and query the `pg_stat_progress_vacuum` view several times while it is running:

=> **VACUUM VERBOSE** vac;

```
=> SELECT * FROM pg_stat_progress_vacuum \gx
```

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

pid	14542
datid	16391
datname	internals
relid	16479
phase	vacuuming indexes
heap_blks_total	17242
heap_blks_scanned	3009
heap_blks_vacuumed	0
index_vacuum_count	0
max_dead_tuples	174761
num_dead_tuples	174522

```
=> SELECT * FROM pg_stat_progress_vacuum \gx
```

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

pid	14542
datid	16391
datname	internals
relid	16479
phase	vacuuming indexes
heap_blks_total	17242
heap_blks_scanned	17242
heap_blks_vacuumed	6017
index_vacuum_count	2
max_dead_tuples	174761
num_dead_tuples	150956

In particular, this view shows:

- phase—the name of the current vacuum phase (I have described the main ones, but there are actually more of them¹)
- heap_blks_total—the total number of pages in a table
- heap_blks_scanned—the number of scanned pages
- heap_blks_vacuumed—the number of vacuumed pages
- index_vacuum_count—the number of index scans

¹ [postgresql.org/docs/14/progress-reporting.html#VACUUM-PHASES](https://www.postgresql.org/docs/14/progress-reporting.html#VACUUM-PHASES)

The overall vacuuming progress is defined by the ratio of `heap_blks_vacuumed` to `heap_blks_total`, but you have to keep in mind that it changes in spurts because of index scans. In fact, it is more important to pay attention to the number of vacuum cycles: if this value is greater than one, it means that the allocated memory was not enough to complete vacuuming in one go.

You can see the whole picture in the output of the `VACUUM VERBOSE` command, which has already finished by this time:

```
INFO: vacuuming "public.vac"
INFO: scanned index "vac_s" to remove 174522 row versions
DETAIL: CPU: user: 0.02 s, system: 0.00 s, elapsed: 0.05 s
INFO: table "vac": removed 174522 dead item identifiers in
3009 pages
DETAIL: CPU: user: 0.01 s, system: 0.00 s, elapsed: 0.05 s
INFO: scanned index "vac_s" to remove 174522 row versions
DETAIL: CPU: user: 0.03 s, system: 0.00 s, elapsed: 0.07 s
INFO: table "vac": removed 174522 dead item identifiers in
3009 pages
DETAIL: CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.02 s
INFO: scanned index "vac_s" to remove 150956 row versions
DETAIL: CPU: user: 0.02 s, system: 0.00 s, elapsed: 0.03 s
INFO: table "vac": removed 150956 dead item identifiers in
2603 pages
DETAIL: CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s
INFO: index "vac_s" now contains 500000 row versions in
932 pages
DETAIL: 500000 index row versions were removed.
433 index pages were newly deleted.
433 index pages are currently deleted, of which 0 are
currently reusable.
CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s.
INFO: table "vac": found 500000 removable, 500000
nonremovable row versions in 17242 out of 17242 pages
DETAIL: 0 dead row versions cannot be removed yet, oldest
xmin: 851
Skipped 0 pages due to buffer pins, 0 frozen pages.
CPU: user: 0.20 s, system: 0.01 s, elapsed: 0.47 s.
VACUUM
```

} index vacuum

} table vacuum

} index vacuum

} table vacuum

} index vacuum

} table vacuum

All in all, there have been three index scans; each scan has removed 174,522 pointers to dead tuples at the most. This value is defined by the number of tid pointers (each of them takes 6 bytes) that can fit into an array of the `maintenance_work_mem` size. The maximum size possible is shown by `pg_stat_prog-`

ress_vacuum.max_dead_tuples, but the actually used space is always a bit smaller. It guarantees that when the next page is read, all its pointers to dead tuples, no matter how many of them are located in this page, will fit into the remaining memory.

Monitoring Autovacuum

The main approach to monitoring autovacuum is to print its status information (which is similar to the output of the `VACUUM VERBOSE` command) into the server log for further analysis. If the `log_autovacuum_min_duration` parameter is set to zero, all autovacuum runs are logged: -1

```
=> ALTER SYSTEM SET log_autovacuum_min_duration = 0;
```

```
=> SELECT pg_reload_conf();
```

```
=> UPDATE vac SET s = 'C';
```

```
UPDATE 500000
```

```
postgres$ tail -n 13 /home/postgres/logfile
```

```
2022-09-19 14:51:50.730 MSK [17371] LOG: automatic vacuum of table
"internals.public.vac": index scans: 3
```

```
pages: 0 removed, 17242 remain, 0 skipped due to pins, 0
skipped frozen
```

```
tuples: 500000 removed, 500000 remain, 0 are dead but not
yet removable, oldest xmin: 853
```

```
index scan needed: 8622 pages from table (50.01% of total)
```

```
had 500000 dead item identifiers removed
```

```
index "vac_s": pages: 1428 in total, 496 newly deleted, 929
currently deleted, 433 reusable
```

```
avg read rate: 13.020 MB/s, avg write rate: 18.228 MB/s
```

```
buffer usage: 45851 hits, 5857 misses, 8200 dirtied
```

```
WAL usage: 41686 records, 14922 full page images, 97549479
bytes
```

```
system usage: CPU: user: 0.30 s, system: 0.28 s, elapsed:
3.51 s
```

```
2022-09-19 14:51:51.064 MSK [17371] LOG: automatic analyze of table
"internals.public.vac"
```

```
avg read rate: 47.743 MB/s, avg write rate: 0.023 MB/s
```

```
buffer usage: 15355 hits, 2035 misses, 1 dirtied
```

```
system usage: CPU: user: 0.09 s, system: 0.00 s, elapsed:
0.33 s
```

To track the list of tables that have to be vacuumed and analyzed, you can use the `need_vacuum` and `need_analyze` views, which we have already reviewed. If this list grows, it means that autovacuum does not cope with the load and has to be sped up by either reducing the gap (*autovacuum_vacuum_cost_delay*) or increasing the amount of work done between the gaps (*autovacuum_vacuum_cost_limit*). It is not unlikely that the degree of parallelism will also have to be increased (*autovacuum_max_workers*).

7

Freezing

7.1 Transaction ID Wraparound

In PostgreSQL, a transaction ID takes 32 bits. Four billions seems to be quite a big number, but it can be exhausted very fast if the system is being actively used. For example, for an average load of 1,000 transactions per second (excluding virtual ones), it will happen in about six weeks of continuous operation.

Once all the numbers are used up, the counter has to be reset to start the next round (this situation is called a “wraparound”). But a transaction with a smaller ID can only be considered older than another transaction with a bigger ID if the assigned numbers are always increasing. So the counter cannot simply start using the same numbers anew after being reset.

Allocating 64 bits for transaction IDs would have eliminated this problem altogether, so why doesn't PostgreSQL take advantage of it? The thing is that each tuple header has to store IDs for two transactions: xmin and xmax. The header is quite big already (at least 24 bytes if data alignment is taken into account), and adding more bits would have given another 8 bytes. p. 66

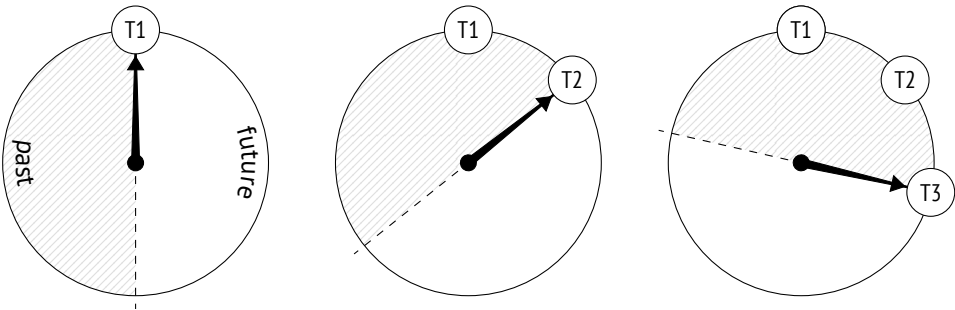
PostgreSQL does implement 64-bit transaction IDs¹ that extend a regular ID by a 32-bit epoch, but they are used only internally and never get into data pages.

To correctly handle wraparound, PostgreSQL has to compare the age of transactions (defined as the number of subsequent transactions that have appeared since the start of this transaction) rather than transaction IDs. Thus, instead of the terms *less than* and *greater than* we should use the concepts of *older* (precedes) and *younger* (follows).

¹ include/access/transam.h, FullTransactionId type

In the code, this comparison is implemented by simply using the 32-bit arithmetic: first the difference between 32-bit transaction IDs is found, and then this result is compared to zero.¹

To better visualize this idea, you can imagine a sequence of transaction IDs as a clock face. For each transaction, half of the circle in the clockwise direction will be in the future, while the other half will be in the past.



However, this visualization has an unpleasant catch. An old transaction (T1) is in the remote past as compared to more recent transactions. But sooner or later a new transaction will see it in the half of the circle related to the future. If it were really so, it would have a catastrophic impact: from now on, all newer transactions would not see the changes made by transaction T1.

7.2 Tuple Freezing and Visibility Rules

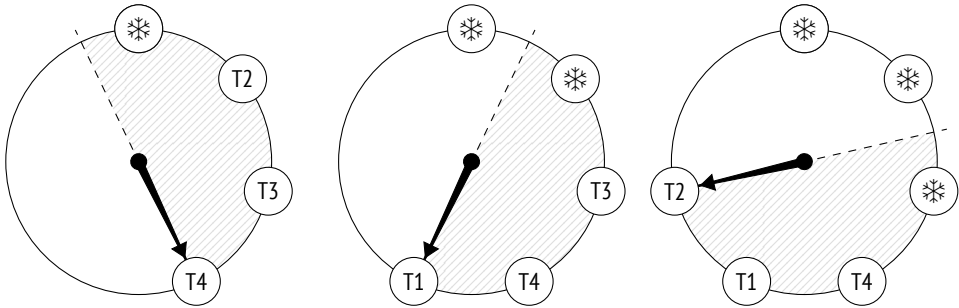
To prevent such “time travel,” vacuuming performs one more task (in addition to page cleanup):² it searches for tuples that are beyond the database horizon (so they are visible in all snapshots) and tags them in a special way, that is, *freezes* them.

For frozen tuples, visibility rules do not have to take xmin into account since such tuples are known to be visible in all snapshots, so this transaction ID can be safely reused.

¹ backend/access/transam/transam.c, TransactionIdPrecedes function

² postgresql.org/docs/14/routine-vacuuming.html#VACUUM-FOR-WRAPAROUND

You can imagine that the xmin transaction ID is replaced in frozen tuples by a hypothetical “minus infinity” (pictured as a snowflake below); it is a sign that this tuple is created by a transaction that is so far in the past that its actual ID does not matter anymore. Yet in reality xmin remains unchanged, whereas the freezing attribute is defined by a combination of two hint bits: committed and aborted.



Many sources (including the documentation) mention `FrozenTransactionId = 2`. It is the “minus infinity” that I have already referred to—this value used to replace xmin in versions prior to 9.4, but now hint bits are employed instead. As a result, the original transaction ID remains in the tuple, which is convenient for both debugging and support. Old systems can still contain the obsolete `FrozenTransactionId`, even if they have been upgraded to higher versions.

The xmax transaction ID does not participate in freezing in any way. It is only present in outdated tuples, and once such tuples stop being visible in all snapshots (which means that the xmax ID is beyond the database horizon), they will be vacuumed away.

Let’s create a new table for our experiments. The *fillfactor* parameter should be set to the lowest value so that each page can accommodate only two tuples—it will be easier to track the progress this way. We will also disable autovacuum to make sure that the table is only cleaned up on demand.

```
=> CREATE TABLE tfreeze(
    id integer,
    s char(300)
)
WITH (fillfactor = 10, autovacuum_enabled = off);
```

We are going to create yet another flavor of the function that displays heap pages using `pageinspect`. Dealing with a range of pages, it will show the values of the freezing attribute (f) and the xmin transaction age for each tuple (it will have to call the age system function—the age itself is not stored in heap pages, of course):

```
=> CREATE FUNCTION heap_page(
    relname text, pageno_from integer, pageno_to integer
)
RETURNS TABLE(
    ctid tid, state text,
    xmin text, xmin_age integer, xmax text
) AS $$
SELECT (pageno,lp)::text::tid AS ctid,
       CASE lp_flags
         WHEN 0 THEN 'unused'
         WHEN 1 THEN 'normal'
         WHEN 2 THEN 'redirect to '||lp_off
         WHEN 3 THEN 'dead'
       END AS state,
       t_xmin || CASE
         WHEN (t_infomask & 256+512) = 256+512 THEN ' f'
         WHEN (t_infomask & 256) > 0 THEN ' c'
         WHEN (t_infomask & 512) > 0 THEN ' a'
         ELSE ''
       END AS xmin,
       age(t_xmin) AS xmin_age,
       t_xmax || CASE
         WHEN (t_infomask & 1024) > 0 THEN ' c'
         WHEN (t_infomask & 2048) > 0 THEN ' a'
         ELSE ''
       END AS xmax
FROM generate_series(pageno_from, pageno_to) p(pageno),
     heap_page_items(get_raw_page(relname, pageno))
ORDER BY pageno, lp;
$$ LANGUAGE sql;
```

Now let's insert some rows into the table and run the `VACUUM` command that will immediately create the visibility map.

```
=> INSERT INTO tfreeze(id, s)
     SELECT id, 'F00'||id FROM generate_series(1,100) id;
INSERT 0 100

=> VACUUM tfreeze;
```

We are going to observe the first two heap pages using the `pg_visibility` extension. When vacuuming completes, both pages get tagged in the visibility map (`all_visible`) but not in the freeze map (`all_frozen`), as they still contain some unfrozen tuples: v. 9.6

```
=> CREATE EXTENSION pg_visibility;
=> SELECT *
FROM generate_series(0,1) g(blkno),
     pg_visibility_map('tfreeze',g.blkno)
ORDER BY g.blkno;
 blkno | all_visible | all_frozen
-----+-----+-----
      0 | t           | f
      1 | t           | f
(2 rows)
```

The `xmin_age` of the transaction that has created the rows equals 1 because it is the latest transaction performed in the system:

```
=> SELECT * FROM heap_page('tfreeze',0,1);
 ctid  | state  | xmin | xmin_age | xmax
-----+-----+-----+-----+-----
(0,1)  | normal | 856 c |         1 | 0 a
(0,2)  | normal | 856 c |         1 | 0 a
(1,1)  | normal | 856 c |         1 | 0 a
(1,2)  | normal | 856 c |         1 | 0 a
(4 rows)
```

7.3 Managing Freezing

There are four main parameters that control freezing. All of them represent transaction age and define when the following events happen:

- Freezing starts (`vacuum_freeze_min_age`).
- Aggressive freezing is performed (`vacuum_freeze_table_age`).
- Freezing is forced (`autovacuum_freeze_max_age`).
- Freezing receives priority (`vacuum_failsafe_age`).

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Minimal Freezing Age

50 million The `vacuum_freeze_min_age` parameter defines the minimal freezing age of xmin transactions. The lower its value, the higher the overhead: if a row is “hot” and is actively being changed, then freezing all its newly created versions will be a wasted effort. Setting this parameter to a relatively high value allows you to wait for a while.

To observe the freezing process, let’s reduce this parameter value to one:

```
=> ALTER SYSTEM SET vacuum_freeze_min_age = 1;
=> SELECT pg_reload_conf();
```

Now update one row in the zero page. The new row version will get into the same page because the `fillfactor` value is quite small:

```
=> UPDATE tfreeze SET s = 'BAR' WHERE id = 1;
```

The age of all transactions has been increased by one, and the heap pages now look as follows:

```
=> SELECT * FROM heap_page('tfreeze',0,1);
 ctid | state | xmin | xmin_age | xmax
-----+-----+-----+-----+-----
(0,1) | normal | 856 c |         2 | 857
(0,2) | normal | 856 c |         2 | 0 a
(0,3) | normal | 857   |         1 | 0 a
(1,1) | normal | 856 c |         2 | 0 a
(1,2) | normal | 856 c |         2 | 0 a
(5 rows)
```

At this point, the tuples that are older than `vacuum_freeze_min_age = 1` are subject to freezing. But vacuum will not process any pages tagged in the visibility map:

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```
=> SELECT * FROM generate_series(0,1) g(blkno),
      pg_visibility_map('tfreeze',g.blkno)
ORDER BY g.blkno;
 blkno | all_visible | all_frozen
-----+-----+-----
      0 | f           | f
      1 | t           | f
(2 rows)
```


The previous `UPDATE` command has removed the visibility bit of the zero page, so the tuple that has an appropriate `xmin` age in this page will be frozen. But the first page will be skipped altogether:

```
=> VACUUM tfreeze;
```

```
=> SELECT * FROM heap_page('tfreeze',0,1);
```

ctid	state	xmin	xmin_age	xmax
(0,1)	redirect to 3			
(0,2)	normal	856 f	2	0 a
(0,3)	normal	857 c	1	0 a
(1,1)	normal	856 c	2	0 a
(1,2)	normal	856 c	2	0 a

(5 rows)

Now the zero page appears in the visibility map again, and if nothing changes in it, vacuuming will not return to this page anymore:

```
=> SELECT * FROM generate_series(0,1) g(blkno),
      pg_visibility_map('tfreeze',g.blkno)
ORDER BY g.blkno;
```

blkno	all_visible	all_frozen
0	t	f
1	t	f

(2 rows)

Age for Aggressive Freezing

As we have just seen, if a page contains only the current tuples that are visible in all snapshots, vacuuming will not freeze them. To overcome this constraint, PostgreSQL provides the `vacuum_freeze_table_age` parameter. It defines the transaction age that allows vacuuming to ignore the visibility map, so any heap page can be frozen. 150 million

For each table, the system catalog keeps a transaction ID for which it is known that all the older transactions are sure to be frozen. It is stored as `relfrozenid`:

```
=> SELECT relfrozenxid, age(relfrozenxid)
FROM pg_class
WHERE relname = 'tfreeze';
 relfrozenxid | age
-----+-----
          854 |    4
(1 row)
```

It is the age of this transaction that is compared to the *vacuum_freeze_table_age* value to decide whether the time has come for aggressive freezing.

- v. 9.6 Thanks to the freeze map, there is no need to perform a full table scan during vacuuming: it is enough to check only those pages that do not appear in the map. Apart from this important optimization, the freeze map also brings fault tolerance: if vacuuming is interrupted, its next run will not have to get back to the pages that have already been processed and are tagged in the map.

PostgreSQL performs aggressive freezing of all pages in a table each time when the number of transactions in the system reaches the *vacuum_freeze_table_age* – *vacuum_freeze_min_age* limit (if the default values are used, it happens after each 100 million transactions). Thus, if the *vacuum_freeze_min_age* value is too big, it can lead to excessive freezing and increased overhead.

To freeze the whole table, let's reduce the *vacuum_freeze_table_age* value to four; then the condition for aggressive freezing will be satisfied:

```
=> ALTER SYSTEM SET vacuum_freeze_table_age = 4;

=> SELECT pg_reload_conf();
```

Run the VACUUM command:

```
=> VACUUM VERBOSE tfreeze;
INFO:  aggressively vacuuming "public.tfreeze"
INFO:  table "tfreeze": found 0 removable, 100 nonremovable row
versions in 50 out of 50 pages
DETAIL:  0 dead row versions cannot be removed yet, oldest xmin: 858
Skipped 0 pages due to buffer pins, 0 frozen pages.
CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s.
VACUUM
```

Now that the whole table has been analyzed, the `relfrozenxid` value can be advanced—heap pages are guaranteed to have no older unfrozen xmin transactions:

```
=> SELECT relfrozenxid, age(relfrozenxid)
FROM pg_class
WHERE relname = 'tfreeze';
 relfrozenxid | age
-----+-----
          857 |    1
(1 row)
```

The first page now contains only frozen tuples:

```
=> SELECT * FROM heap_page('tfreeze',0,1);
 ctid |      state      | xmin | xmin_age | xmax
-----+-----+-----+-----+-----
(0,1) | redirect to 3 |      |          |
(0,2) | normal        | 856 f |          | 2 | 0 a
(0,3) | normal        | 857 c |          | 1 | 0 a
(1,1) | normal        | 856 f |          | 2 | 0 a
(1,2) | normal        | 856 f |          | 2 | 0 a
(5 rows)
```

Besides, this page is tagged in the freeze map:

```
=> SELECT * FROM generate_series(0,1) g(blkno),
pg_visibility_map('tfreeze',g.blkno)
ORDER BY g.blkno;
 blkno | all_visible | all_frozen
-----+-----+-----
      0 | t           | f
      1 | t           | t
(2 rows)
```

Age for Forced Autovacuum

Sometimes it is not enough to configure the two parameters discussed above to timely freeze tuples. Autovacuum might be switched off, while regular `VACUUM` is not being called at all (it is a very bad idea, but technically it is possible). Besides,

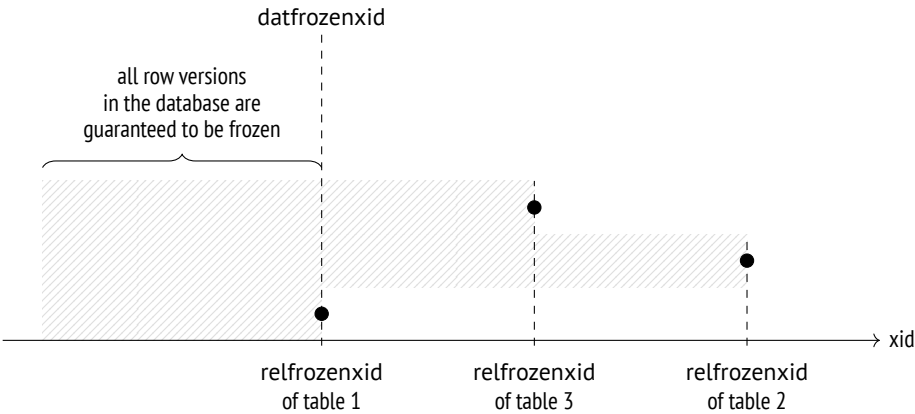
p. 123 some inactive databases (like template0) may not be vacuumed. PostgreSQL can handle such situations by *forcing* autovacuum in the aggressive mode.

200 million Autovacuum is forced¹ (even if it is switched off) when there is a risk that the age of some unfrozen transaction IDs in the database will exceed the *autovacuum_freeze_max_age* value. The decision is taken based on the age of the oldest pg_class.relfrozenxid transaction in all the tables, as all the older transactions are guaranteed to be frozen. The ID of this transaction is stored in the system catalog:

```
=> SELECT datname, datfrozenxid, age(datfrozenxid) FROM pg_database;
```

datname	datfrozenxid	age
postgres	726	132
template1	726	132
template0	726	132
internals	726	132

(4 rows)



The *autovacuum_freeze_max_age* limit is set to 2 billion transactions (a bit less than half of the circle), while the default value is 10 times smaller. It is done for good reason: a big value increases the risk of transaction ID wraparound, as PostgreSQL may fail to timely freeze all the required tuples. In this case, the server must stop immediately to prevent possible issues and will have to be restarted by an administrator.

¹ backend/access/transam/varsup.c, SetTransactionIdLimit function

The *autovacuum_freeze_max_age* value also affects the size of CLOG. There is no need to keep the status of frozen transactions, and all the transactions that precede the one with the oldest *datfrozenxid* in the cluster are sure to be frozen. Those CLOG files that are not required anymore are removed by autovacuum.¹ p. 75

Changing the *autovacuum_freeze_max_age* parameter requires a server restart. However, all the freezing settings discussed above can also be adjusted at the table level via the corresponding storage parameters. Note that the names of all these parameters start with “auto”:

- *autovacuum_freeze_min_age* and *toast.autovacuum_freeze_min_age*
- *autovacuum_freeze_table_age* and *toast.autovacuum_freeze_table_age*
- *autovacuum_freeze_max_age* and *toast.autovacuum_freeze_max_age*

Age for Failsafe Freezing

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If autovacuum is already struggling to prevent transaction ID wraparound and it is clearly a race against time, a safety switch is pulled: autovacuum will ignore the *autovacuum_vacuum_cost_delay* (*vacuum_cost_delay*) value and will stop vacuuming indexes to freeze heap tuples as soon as possible.

A failsafe freezing mode² is enabled if there is a risk that the age of an unfrozen transaction in the database will exceed the *vacuum_failsafe_age* value. It is assumed that this value must be higher than *autovacuum_freeze_max_age*. 1.6 billion

7.4 Manual Freezing

It is sometimes more convenient to manage freezing manually rather than rely on autovacuum.

¹ backend/commands/vacuum.c, *vac_truncate_clog* function

² backend/access/heap/vacuumlazy.c, *lazy_check_wraparound_failsafe* function

Freezing by Vacuum

You can initiate freezing by calling the `VACUUM` command with the `FREEZE` option. It will freeze all the heap tuples regardless of their transaction age, as if `vacuum_freeze_min_age = 0`.

- v. 12 If the purpose of such a call is to freeze heap tuples as soon as possible, it makes sense to disable index vacuuming, like it is done in the failsafe mode. You can do it either explicitly, by running the `VACUUM (freeze, index_cleanup false)` command, or via the `vacuum_index_cleanup` storage parameter. It is rather obvious that it should not be done on a regular basis since in this case `VACUUM` will not be coping well with its main task of page cleanup.

Freezing Data at the Initial Loading

The data that is not expected to change can be frozen at once, while it is being loaded into the database. It is done by running the `COPY` command with the `FREEZE` option.

- p. 228 Tuples can be frozen during the initial loading only if the resulting table has been created or truncated within the same transaction, as both these operations acquire an exclusive lock on the table. This restriction is necessary because frozen tuples are expected to be visible in all snapshots, regardless of the isolation level; otherwise, transactions would suddenly see freshly-frozen tuples right as they are being uploaded. But if the lock is acquired, other transactions will not be able to get access to this table.

Nevertheless, it is still technically possible to break isolation. Let's start a new transaction at the Repeatable Read isolation level in a separate session:

```
=> BEGIN ISOLATION LEVEL REPEATABLE READ;  
=> SELECT 1; -- the snapshot is built
```

Truncate the `tfreeze` table and insert new rows into this table within the same transaction. (If the read-only transaction had already accessed the `tfreeze` table, the `TRUNCATE` command will be blocked.)

```
=> BEGIN;
=> TRUNCATE tfreeze;
=> COPY tfreeze FROM stdin WITH FREEZE;
1 FOO
2 BAR
3 BAZ
\.
=> COMMIT;
```

Now the reading transaction sees the new data as well:

```
=> SELECT count(*) FROM tfreeze;
 count
-----
      3
(1 row)
=> COMMIT;
```

It does break isolation, but since data loading is unlikely to happen regularly, in most cases it will not cause any issues.

If you load data with freezing, the visibility map is created at once, and page headers receive the visibility attribute: v. 14
p. 116

```
=> SELECT * FROM pg_visibility_map('tfreeze',0);
 all_visible | all_frozen
-----+-----
 t           | t
(1 row)
=> SELECT flags & 4 > 0 AS all_visible
FROM page_header(get_raw_page('tfreeze',0));
 all_visible
-----
 t
(1 row)
```

Thus, if the data has been loaded with freezing, the table will not be processed by vacuum (as long as the data remains unchanged). Unfortunately, this functionality is not supported for TOAST tables yet: if an oversized value is loaded, vacuum will have to rewrite the whole TOAST table to set visibility attributes in all page headers. v. 14

8

Rebuilding Tables and Indexes

8.1 Full Vacuuming

Why is Routine Vacuuming not Enough?

Routine vacuuming can free more space than page pruning, but sometimes it may still be not enough.

If table or index files have grown in size, `VACUUM` can clean up some space within pages, but it can rarely reduce the number of pages. The reclaimed space can only be returned to the operating system if several empty pages appear at the very end of the file, which does not happen too often.

An excessive size can lead to unpleasant consequences:

- Full table (or index) scan will take longer.
- A bigger buffer cache may be required (pages are cached as a whole, so data density decreases).
- B-trees can get an extra level, which slows down index access.
- Files take up extra space on disk and in backups.

If the fraction of useful data in a file has dropped below some reasonable level, an administrator can perform *full vacuuming* by running the `VACUUM FULL` command.¹

In this case, the table and all its indexes are rebuilt from scratch, and the data is packed as densely as possible (taking the *fillfactor* parameter into account).

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¹ [postgresql.org/docs/14/routine-vacuuming.html#VACUUM-FOR-SPACE-RECOVERY](https://www.postgresql.org/docs/14/routine-vacuuming.html#VACUUM-FOR-SPACE-RECOVERY)

When full vacuuming is performed, PostgreSQL first fully rebuilds the table and then each of its indexes. While an object is being rebuilt, both old and new files have to be stored on disk,¹ so this process may require a lot of free space.

You should also keep in mind that this operation fully blocks access to the table, both for reads and writes.

Estimating Data Density

For the purpose of illustration, let's insert some rows into the table:

```
=> TRUNCATE vac;
=> INSERT INTO vac(id,s)
    SELECT id, id::text FROM generate_series(1,500000) id;
```

Storage density can be estimated using the pgstattuple extension:

```
=> CREATE EXTENSION pgstattuple;
=> SELECT * FROM pgstattuple('vac') \gx
```

[RECORD 1]	
table_len	70623232
tuple_count	500000
tuple_len	64500000
tuple_percent	91.33
dead_tuple_count	0
dead_tuple_len	0
dead_tuple_percent	0
free_space	381844
free_percent	0.54

The function reads the whole table and displays statistics on space distribution in its files. The `tuple_percent` field shows the percentage of space taken up by useful data (heap tuples). This value is inevitably less than 100% because of various metadata within pages, but in this example it is still quite high.

For indexes, the displayed information differs a bit, but the `avg_leaf_density` field has the same meaning: it shows the percentage of useful data (in B-tree leaf pages).

¹ `backend/commands/cluster.c`

```
=> SELECT * FROM pgstatindex('vac_s') \gx
-[ RECORD 1 ]-----+-----
version          | 4
tree_level       | 3
index_size       | 114302976
root_block_no   | 2825
internal_pages   | 376
leaf_pages       | 13576
empty_pages      | 0
deleted_pages    | 0
avg_leaf_density | 53.88
leaf_fragmentation | 10.59
```

The previously used pgstattuple functions read the table or index in full to get the precise statistics. For large objects, it can turn out to be too expensive, so the extension also provides another function called pgstattuple_approx, which skips the pages tracked in the visibility map to show approximate figures.

A faster but even less accurate method is to roughly estimate the ratio between the data volume and the file size using the system catalog.¹

Here are the current sizes of the table and its index:

```
=> SELECT pg_size_pretty(pg_table_size('vac')) AS table_size,
         pg_size_pretty(pg_indexes_size('vac')) AS index_size;
 table_size | index_size
-----+-----
 67 MB     | 109 MB
(1 row)
```

Now let's delete 90% of all the rows:

```
=> DELETE FROM vac WHERE id % 10 != 0;
DELETE 450000
```

Routine vacuuming does not affect the file size because there are no empty pages at the end of the file:

```
=> VACUUM vac;
```

¹ wiki.postgresql.org/wiki/Show_database_bloat

```
=> SELECT pg_size_pretty(pg_table_size('vac')) AS table_size,
          pg_size_pretty(pg_indexes_size('vac')) AS index_size;
 table_size | index_size
-----+-----
 67 MB      | 109 MB
(1 row)
```

However, data density has dropped about 10 times:

```
=> SELECT vac.tuple_percent, vac_s.avg_leaf_density
FROM pgstattuple('vac') vac, pgstatindex('vac_s') vac_s;
 tuple_percent | avg_leaf_density
-----+-----
          9.13 |             6.71
(1 row)
```

The table and the index are currently located in the following files:

```
=> SELECT pg_relation_filepath('vac') AS vac_filepath,
          pg_relation_filepath('vac_s') AS vac_s_filepath \gx
-[ RECORD 1 ]--+-+-----
vac_filepath   | base/16391/16514
vac_s_filepath | base/16391/16515
```

Let's check what we will get after `VACUUM FULL`. While the command is running, its progress can be tracked in the `pg_stat_progress_cluster` view (which is similar to the `pg_stat_progress_vacuum` view provided for `VACUUM`):

```
=> VACUUM FULL vac;
```

```
=> SELECT * FROM pg_stat_progress_cluster \gx
-[ RECORD 1 ]--+-+-----
pid           | 19492
datid         | 16391
datname       | internals
relid         | 16479
command       | VACUUM FULL
phase         | rebuilding index
cluster_index_relid | 0
heap_tuples_scanned | 50000
heap_tuples_written | 50000
heap_blks_total   | 8621
heap_blks_scanned  | 8621
index_rebuild_count | 0
```

Expectedly, `VACUUM FULL` phases¹ differ from those of routine vacuuming.

Full vacuuming has replaced old files with new ones:

```
=> SELECT pg_relation_filepath('vac') AS vac_filepath,
          pg_relation_filepath('vac_s') AS vac_s_filepath \gx
-[ RECORD 1 ]--+-+-----
vac_filepath   | base/16391/16526
vac_s_filepath | base/16391/16529
```

Both index and table sizes are much smaller now:

```
=> SELECT pg_size_pretty(pg_table_size('vac')) AS table_size,
          pg_size_pretty(pg_indexes_size('vac')) AS index_size;
 table_size | index_size
-----+-----
 6904 kB   | 6504 kB
(1 row)
```

As a result, data density has increased. For the index, it is even higher than the original one: it is more efficient to create a B-tree from scratch based on the available data than to insert entries row by row into an already existing index:

```
=> SELECT vac.tuple_percent,
          vac_s.avg_leaf_density
FROM pgstattuple('vac') vac,
     pgstatindex('vac_s') vac_s;
 tuple_percent | avg_leaf_density
-----+-----
          91.23 |             91.08
(1 row)
```

Freezing

When the table is being rebuilt, PostgreSQL freezes its tuples because this operation costs almost nothing compared to the rest of the work:

¹ [postgresql.org/docs/14/progress-reporting.html#CLUSTER-PHASES](https://www.postgresql.org/docs/14/progress-reporting.html#CLUSTER-PHASES)

```
=> SELECT * FROM heap_page('vac',0,0) LIMIT 5;
```

ctid	state	xmin	xmin_age	xmax
(0,1)	normal	861 f	5	0 a
(0,2)	normal	861 f	5	0 a
(0,3)	normal	861 f	5	0 a
(0,4)	normal	861 f	5	0 a
(0,5)	normal	861 f	5	0 a

(5 rows)

But pages are registered neither in the visibility map nor in the freeze map, and the page header does not receive the visibility attribute (as it happens when the COPY command is executed with the FREEZE option):

p. 150

```
=> SELECT * FROM pg_visibility_map('vac',0);
```

all_visible	all_frozen
f	f

(1 row)

```
=> SELECT flags & 4 > 0 all_visible
FROM page_header(get_raw_page('vac',0));
```

all_visible
f

(1 row)

The situation improves only after VACUUM is called (or autovacuum is triggered):

```
=> VACUUM vac;
```

```
=> SELECT * FROM pg_visibility_map('vac',0);
```

all_visible	all_frozen
t	t

(1 row)

```
=> SELECT flags & 4 > 0 AS all_visible
FROM page_header(get_raw_page('vac',0));
```

all_visible
t

(1 row)

It essentially means that even if all tuples in a page are beyond the database horizon, such a page will still have to be rewritten.

8.2 Other Rebuilding Methods

Alternatives to Full Vacuuming

In addition to `VACUUM FULL`, there are several other commands that can fully rebuild tables and indexes. All of them exclusively lock the table, all of them delete old data files and recreate them anew.

The `CLUSTER` command is fully analogous to `VACUUM FULL`, but it also reorders tuples in files based on one of the available indexes. In some cases, it can help the planner use index scans more efficiently. But you should bear in mind that clusterization is not supported: all further table updates will be breaking the physical order of tuples.

Programmatically, `VACUUM FULL` is simply a special instance of the `CLUSTER` command that does not require tuple reordering.¹

The `REINDEX` command rebuilds one or more indexes.² In fact, `VACUUM FULL` and `CLUSTER` use this command under the hood when rebuilding indexes.

p. 77 The `TRUNCATE` command³ deletes all table rows; it is a logical equivalent of `DELETE` run without the `WHERE` clause. But while `DELETE` simply marks heap tuples as deleted (so they still have to be vacuumed), `TRUNCATE` creates a new empty file, which is usually faster.

Reducing Downtime during Rebuilding

p. 228 `VACUUM FULL` is not meant to be run regularly, as it exclusively locks the table (even for queries) for the whole duration of its operation. This is usually not an option for highly available systems.

¹ backend/commands/cluster.c

² backend/commands/indexcmds.c

³ backend/commands/tablecmds.c, `ExecuteTruncate` function

There are several extensions (such as `pg_repack`¹) that can rebuild tables and indexes with almost zero downtime. An exclusive lock is still required, but only at the beginning and at the end of this process, and only for a short time. It is achieved by a more complex implementation: all the changes made on the original table while it is being rebuilt are saved by a trigger and then applied to the new table. To complete the operation, the utility replaces one table with the other in the system catalog.

An unconventional solution is offered by the `pgcompacttable` utility.² It performs multiple fake row updates (that do not change any data) so that current row versions gradually move towards the start of the file.

Between these update series, vacuuming removes outdated tuples and truncates the file little by little. This approach takes much more time and resources, but it requires no extra space for rebuilding the table and does not lead to load spikes. Short-time exclusive locks are still acquired while the table is being truncated, but vacuuming handles them rather smoothly. *p. 122*

8.3 Preventive Measures

Read-Only Queries

One of the reasons for file bloating is executing long-running transactions that hold the database horizon alongside intensive data updates. *p. 97*

As such, long-running (read-only) transactions do not cause any issues. So a common approach is to split the load between different systems: keep fast OLTP queries on the primary server and direct all OLAP transactions to a replica. Although it makes the solution more expensive and complicated, such measures may turn out to be indispensable.

In some cases, long transactions are the result of application or driver bugs rather than a necessity. If an issue cannot be resolved in a civilized way, the administrator can resort to the following two parameters:

¹ github.com/reorg/pg_repack

² github.com/dataegret/pgcompacttable

- v. 9.6 • The *old_snapshot_threshold* parameter defines the maximum lifetime of a snapshot. Once this time is up, the server has the right to remove outdated tuples; if a long-running transaction still requires them, it will get an error (“snapshot too old”).
- v. 9.6 • The *idle_in_transaction_session_timeout* parameter limits the lifetime of an idle transaction. The transaction is aborted upon reaching this threshold.

Data Updates

Another reason for bloating is simultaneous modification of a large number of tuples. If all table rows get updated, the number of tuples can double, and vacuuming will not have enough time to interfere. Page pruning can reduce this problem, but not resolve it entirely.

Let’s extend the output with another column to keep track of the processed rows:

```
=> ALTER TABLE vac ADD processed boolean DEFAULT false;
=> SELECT pg_size_pretty(pg_table_size('vac'));
pg_size_pretty
-----
6936 kB
(1 row)
```

Once all the rows are updated, the table gets almost two times bigger:

```
=> UPDATE vac SET processed = true;
UPDATE 50000
=> SELECT pg_size_pretty(pg_table_size('vac'));
pg_size_pretty
-----
14 MB
(1 row)
```

To address this situation, you can reduce the number of changes performed by a single transaction, spreading them out over time; then vacuuming can delete outdated tuples and free some space for new ones within the already existing pages. Assuming that each row update can be committed separately, we can use the following query that selects a batch of rows of the specified size as a template:


```

SELECT ID
FROM table
WHERE filtering the already processed rows
LIMIT batch size
FOR UPDATE SKIP LOCKED

```

This code snippet selects and immediately locks a set of rows that does not exceed the specified size. The rows that are already locked by other transactions are skipped: they will get into another batch next time. It is a rather flexible and convenient solution that allows you to easily change the batch size and restart the operation in case of a failure. Let's unset the processed attribute and perform full vacuuming to restore the original size of the table: p. 251

```

=> UPDATE vac SET processed = false;
=> VACUUM FULL vac;

```

Once the first batch is updated, the table size grows a bit:

```

=> WITH batch AS (
    SELECT id FROM vac WHERE NOT processed LIMIT 1000
    FOR UPDATE SKIP LOCKED
)
UPDATE vac SET processed = true
WHERE id IN (SELECT id FROM batch);
UPDATE 1000
=> SELECT pg_size_pretty(pg_table_size('vac'));
    pg_size_pretty
-----
    7064 kB
(1 row)

```

But from now on, the size remains almost the same because new tuples replace the removed ones:

```

=> VACUUM vac;
=> WITH batch AS (
    SELECT id FROM vac WHERE NOT processed LIMIT 1000
    FOR UPDATE SKIP LOCKED
)
UPDATE vac SET processed = true
WHERE id IN (SELECT id FROM batch);
UPDATE 1000

```

```
=> SELECT pg_size_pretty(pg_table_size('vac'));  
      pg_size_pretty  
-----  
      7072 kB  
(1 row)
```

Part II

Buffer cache and WAL

9

Buffer Cache

9.1 Caching

In modern computing systems, caching is omnipresent—both at the hardware and at the software level. The processor alone can have up to three or four levels of cache. RAID controllers and disks add their own cache too.

Caching is used to even out performance difference between fast and slow types of memory. Fast memory is expensive and has smaller volume, while slow memory is bigger and cheaper. Therefore, fast memory cannot accommodate *all* the data stored in slow memory. But in most cases only a *small* portion of data is being actively used at each particular moment, so allocating some fast memory for *cache* to keep hot data can significantly reduce the overhead incurred by slow memory access.

In PostgreSQL, buffer cache¹ holds relation pages, thus balancing access times to disks (milliseconds) and RAM (nanoseconds).

The operating system has its own cache that serves the same purpose. For this reason, database systems are usually designed to avoid double caching: the data stored on disk is usually queried directly, bypassing the OS cache. But PostgreSQL uses a different approach: it reads and writes all data via buffered file operations.

Double caching can be avoided if you apply direct I/O. It will reduce the overhead, as PostgreSQL will use direct memory access (DMA) instead of copying buffered pages into the OS address space; besides, you will gain immediate control over physical writes on disk. However, direct I/O does not support data prefetching enabled by bufferization, so you have to implement it separately via asynchronous I/O, which requires massive code

¹ [backend/storage/buffer/README](#)

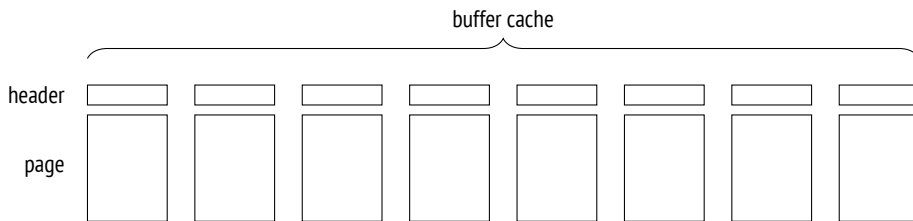
modifications in PostgreSQL core, as well as handling os incompatibilities when it comes to direct and asynchronous i/o support. But once the asynchronous communication is set up, you can enjoy additional benefits of no-wait disk access.

The PostgreSQL community has already started this major effort,¹ but it will take a long time for the actual results to appear.

9.2 Buffer Cache Design

Buffer cache is located in the server's shared memory and is accessible to all the processes. It takes the major part of the shared memory and is surely one of the most important and complex data structures in PostgreSQL. Understanding how cache works is important in its own right, but even more so as many other structures (such as subtransactions, CLOG transaction status, and WAL entries) use a similar caching mechanism, albeit a simpler one.

The name of this cache is inspired by its inner structure, as it consists of an array of *buffers*. Each buffer reserves a memory chunk that can accommodate a single data page together with its header.²



A header contains some information about the buffer and the page in it, such as:

- physical location of the page (file ID, fork, and block number in the fork)
- the attribute showing that the data in the page has been modified and sooner or later has to be written back to disk (such a page is called *dirty*)
- buffer usage count
- pin count (or reference count)

¹ www.postgresql.org/message-id/flat/20210223100344.llw5an2aklengrmn%40alap3.anarazel.de

² `include/storage/buf_internals.h`

To get access to a relation's data page, a process requests it from the buffer manager¹ and receives the ID of the buffer that contains this page. Then it reads the cached data and modifies it right in the cache if needed. While the page is in use, its buffer is *pinned*. Pins forbid eviction of the cached page and can be applied together with other locks. Each pin increments the usage count as well. p. 271

As long as the page is cached, its usage does not incur any file operations.

We can explore the buffer cache using the `pg_buffercache` extension:

```
=> CREATE EXTENSION pg_buffercache;
```

Let's create a table and insert a row:

```
=> CREATE TABLE cacheme(
    id integer
) WITH (autovacuum_enabled = off);
=> INSERT INTO cacheme VALUES (1);
```

Now the buffer cache contains a heap page with the newly inserted row. You can see it for yourself by selecting all the buffers related to a particular table. We will need such a query again, so let's wrap it into a function:

```
=> CREATE FUNCTION buffercache(rel regclass)
RETURNS TABLE(
    bufferid integer, relfork text, relblk bigint,
    isdirty boolean, usagecount smallint, pins integer
) AS $$
SELECT bufferid,
    CASE relforknumber
        WHEN 0 THEN 'main'
        WHEN 1 THEN 'fsm'
        WHEN 2 THEN 'vm'
    END,
    relblocknumber,
    isdirty,
    usagecount,
    pinning_backends
FROM pg_buffercache
WHERE relfilenode = pg_relation_filenode(rel)
ORDER BY relforknumber, relblocknumber;
$$ LANGUAGE sql;
```

¹ backend/storage/buffer/bufmgr.c

```
=> SELECT * FROM buffercache('cacheme');
bufferid | relfork | relblk | isdirty | usagecount | pins
-----+-----+-----+-----+-----+-----
      268 | main   |      0 | t       |          1 |    0
(1 row)
```

The page is dirty: it has been modified, but is not written to disk yet. Its usage count is set to one.

9.3 Cache Hits

When the buffer manager has to read a page,¹ it first checks the buffer cache.

All buffer IDs are stored in a hash table,² which is used to speed up their search.

Many modern programming languages include hash tables as one of the basic data types. Hash tables are often called associative arrays, and indeed, from the user's perspective they do look like an array; however, their index (a *hash key*) can be of any data type, for example, a text string rather than an integer.

While the range of possible key values can be quite large, hash tables never contain that many different values at a time. The idea of hashing is to convert a key value into an integer number using a *hash function*. This number (or some of its bits) is used as an index of a regular array. The elements of this array are called *hash table buckets*.

A good hash function distributes hash keys between buckets more or less uniformly, but it can still assign the same number to different keys, thus placing them into the same bucket; it is called a *collision*. For this reason, values are stored in buckets together with hash keys; to access a hashed value by its key, PostgreSQL has to check all the keys in the bucket.

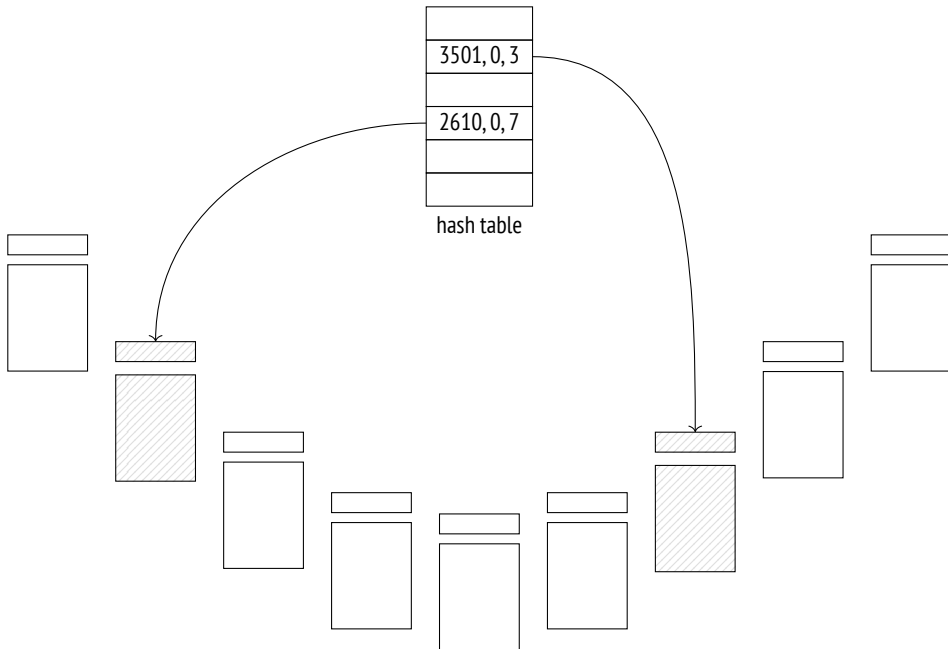
There are multiple implementations of hash tables; of all the possible options, the buffer cache uses the extendible table that resolves hash collisions by chaining.³

A hash key consists of the ID of the relation file, the type of the fork, and the ID of the page within this fork's file. Thus, knowing the page, PostgreSQL can quickly find the buffer containing this page or make sure that the page is not currently cached.

¹ backend/storage/buffer/bufmgr.c, ReadBuffer_common function

² backend/storage/buffer/buf_table.c

³ backend/utils/hash/dynahash.c



The buffer cache implementation has long been criticized for relying on a hash table: this structure is of no use when it comes to finding all the buffers taken by pages of a particular relation, which is required to remove pages from cache when running `DROP` and `TRUNCATE` commands or truncating a table during vacuuming.¹ Yet no one has suggested an adequate alternative so far.

If the hash table contains the required buffer ID, the buffer manager pins this buffer and returns its ID to the process. Then this process can start using the cached page without incurring any I/O traffic.

To pin a buffer, PostgreSQL has to increment the pin counter in its header; a buffer can be pinned by several processes at a time. While its pin counter is greater than zero, the buffer is assumed to be in use, and no radical changes in its contents are allowed. For example, a new tuple can appear (it will be invisible following the visibility rules), but the page itself cannot be replaced.

When run with the `analyze` and `buffers` options, the `EXPLAIN` command executes the displayed query plan and shows the number of used buffers:

¹ backend/storage/buffer/bufmgr.c, DropRelFileNodeBuffers function

=> **EXPLAIN** (analyze, buffers, costs off, timing off, summary off)

SELECT * FROM cacheme;

QUERY PLAN

Seq Scan on cacheme (actual rows=1 loops=1)

Buffers: shared hit=1

Planning:

Buffers: shared hit=12 read=7

(4 rows)

Here hit=1 means that the only page that had to be read was found in the cache.

Buffer pinning increases the usage count by one:

=> **SELECT * FROM** buffercache('cacheme');

bufferid	relfork	relblk	isdirty	usagecount	pins
268	main	0	t	2	0

(1 row)

To observe pinning in action during query execution, let's open a cursor—it will hold the buffer pin, as it has to provide quick access to the next row in the result set:

=> **BEGIN**;

=> **DECLARE c CURSOR FOR SELECT * FROM** cacheme;

=> **FETCH c**;

id

1

(1 row)

=> **SELECT * FROM** buffercache('cacheme');

bufferid	relfork	relblk	isdirty	usagecount	pins
268	main	0	t	3	1

(1 row)

If a process cannot use a pinned buffer, it usually skips it and simply chooses another one. We can see it during table vacuuming:

```
=> VACUUM VERBOSE cacheme;
INFO: vacuuming "public.cacheme"
INFO: table "cacheme": found 0 removable, 0 nonremovable row
versions in 1 out of 1 pages
DETAIL: 0 dead row versions cannot be removed yet, oldest xmin:
878
Skipped 1 page due to buffer pins, 0 frozen pages.
CPU: user: 0.00 s, system: 0.00 s, elapsed: 0.00 s.
VACUUM
```

The page was skipped because its tuples could not be physically removed from the pinned buffer.

But if it is exactly this buffer that is required, the process joins the queue and waits for exclusive access to this buffer. An example of such an operation is vacuuming with freezing.¹

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Once the cursor closes or moves on to another page, the buffer gets unpinned. In this example, it happens at the end of the transaction:

```
=> COMMIT;
=> SELECT * FROM buffercache('cacheme');
 bufferid | relfork | relblk | isdirty | usagecount | pins
-----+-----+-----+-----+-----+-----
      268 | main   |      0 | t       |          3 | 0
      310 | vm     |      0 | f       |          2 | 0
(2 rows)
```

Page modifications are protected by the same pinning mechanism. For example, let's insert another row into the table (it will get into the same page):

```
=> INSERT INTO cacheme VALUES (2);
=> SELECT * FROM buffercache('cacheme');
 bufferid | relfork | relblk | isdirty | usagecount | pins
-----+-----+-----+-----+-----+-----
      268 | main   |      0 | t       |          4 | 0
      310 | vm     |      0 | f       |          2 | 0
(2 rows)
```

¹ backend/storage/buffer/bufmgr.c, LockBufferForCleanup function

PostgreSQL does not perform any immediate writes to disk: a page remains dirty in the buffer cache for a while, providing some performance gains for both reads and writes.

9.4 Cache Misses

If the hash table has no entry related to the queried page, it means that this page is not cached. In this case, a new buffer is assigned (and immediately pinned), the page is read into this buffer, and the hash table references are modified accordingly.

Let's restart the instance to clear its buffer cache:

```
postgres$ pg_ctl restart -l /home/postgres/logfile
```

An attempt to read a page will result in a cache miss, and the page will be loaded into a new buffer:

```
=> EXPLAIN (analyze, buffers, costs off, timing off, summary off)
    SELECT * FROM cacheme;
               QUERY PLAN
-----
Seq Scan on cacheme (actual rows=2 loops=1)
  Buffers: shared read=1 dirtied=1
Planning:
  Buffers: shared hit=15 read=7
(4 rows)
```

Instead of hit, the plan now shows the read status, which denotes a cache miss.

p. 76 Besides, this page has become dirty, as the query has modified some hint bits.

A buffer cache query shows that the usage count for the newly added page is set to one:

```
=> SELECT * FROM buffercache('cacheme');
 bufferid | relfork | relblk | isdirty | usagecount | pins
-----+-----+-----+-----+-----+-----
      98 | main   |      0 | t       |          1 |    0
(1 row)
```

The `pg_statio_all_tables` view contains the complete statistics on buffer cache usage by tables:

```
=> SELECT heap_blks_read, heap_blks_hit
FROM pg_statio_all_tables
WHERE relname = 'cacheme';
```

	heap_blks_read	heap_blks_hit
(1 row)	2	5

PostgreSQL provides similar views for indexes and sequences. They can also display statistics on I/O operations, but only if *track_io_timing* is enabled. off

Buffer Search and Eviction

Choosing a buffer for a page is not so trivial.¹ There are two possible scenarios:

1. Right after the server start all the buffers are empty and are bound into a list.

While some buffers are still free, the next page read from disk will occupy the first buffer, and it will be removed from the list.

A buffer can return to the list² only if its page disappears, without being replaced by another page. It can happen if you call `DROP` or `TRUNCATE` commands, or if the table is truncated during vacuuming.

2. Sooner or later no free buffers will be left (since the size of the database is usually bigger than the memory chunk allocated for cache). Then the buffer manager will have to select one of the buffers that is already in use and evict the cached page from this buffer. It is performed using the clock sweep algorithm, which is well illustrated by the clock metaphor. Pointing to one of the buffers, the clock hand starts going around the buffer cache and reduces the usage count for each cached page by one as it passes. The first unpinning buffer with the zero count found by the clock hand will be cleared.

¹ backend/storage/buffer/freelist.c, StrategyGetBuffer function

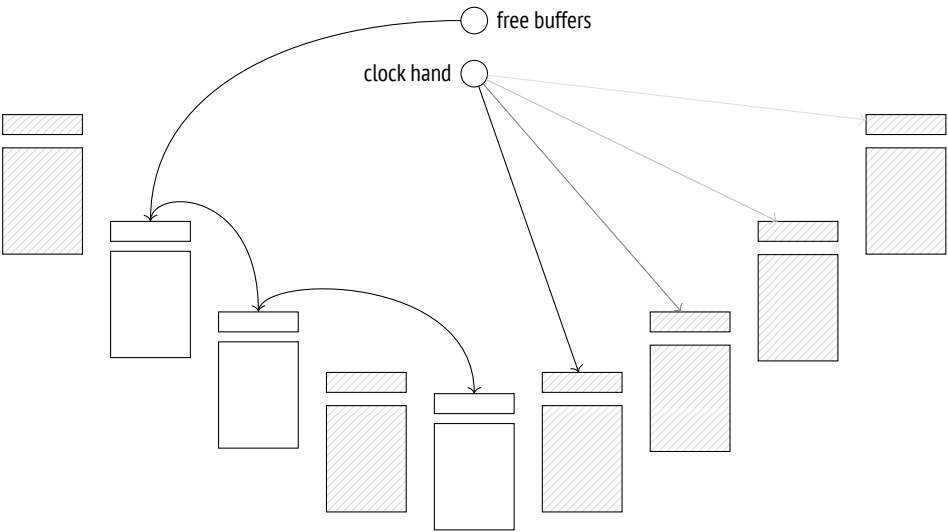
² backend/storage/buffer/freelist.c, StrategyFreeBuffer function

Thus, the usage count is incremented each time the buffer is accessed (that is, pinned), and reduced when the buffer manager is searching for pages to evict. As a result, the least recently used pages are evicted first, while those that have been accessed more often will remain in the cache longer.

As you can guess, if all the buffers have a non-zero usage count, the clock hand has to complete more than one full circle before any of them finally reaches the zero value. To avoid running multiple laps, PostgreSQL limits the usage count by 5.

Once the buffer to evict is found, the reference to the page that is still in this buffer must be removed from the hash table.

p. 198 But if this buffer is dirty, that is, it contains some modified data, the old page cannot be simply thrown away—the buffer manager has to write it to disk first.



Then the buffer manager reads a new page into the found buffer—no matter if it had to be cleared or was still free. It uses buffered I/O for this purpose, so the page will be read from disk only if the operating system cannot find it in its own cache.

Those database systems that use direct I/O and do not depend on the OS cache differentiate between logical reads (from RAM, that is, from the buffer cache) and physical reads (from

disk). From the standpoint of PostgreSQL, a page can be either read from the buffer cache or requested from the operating system, but there is no way to tell whether it was found in RAM or read from disk in the latter case.

The hash table is updated to refer to the new page, and the buffer gets pinned. Its usage count is incremented and is now set to one, which gives this buffer some time to increase this value while the clock hand is traversing the buffer cache.

9.5 Bulk Eviction

If bulk reads or writes are performed, there is a risk that one-time data can quickly oust useful pages from the buffer cache.

As a precaution, bulk operations use rather small *buffer rings*, and eviction is performed within their boundaries, without affecting other buffers.

Alongside the “buffer ring,” the code also uses the term “ring buffer”. However, this synonym is rather ambiguous because the ring buffer itself consists of several buffers (that belong to the buffer cache). The term “buffer ring” is more accurate in this respect.

A buffer ring of a particular size consists of an array of buffers that are used one after another. At first, the buffer ring is empty, and individual buffers join it one by one, after being selected from the buffer cache in the usual manner. Then eviction comes into play, but only within the ring limits.¹

Buffers added into a ring are not excluded from the buffer cache and can still be used by other operations. So if the buffer to be reused turns out to be pinned, or its usage count is higher than one, it will be simply detached from the ring and replaced by another buffer.

PostgreSQL supports three eviction strategies.

Bulk reads strategy is used for sequential scans of large tables if their size exceeds $\frac{1}{4}$ of the buffer cache. The ring buffer takes 256 kB (32 standard pages).

¹ backend/storage/buffer/freelist.c, GetBufferFromRing function

This strategy does not allow writing dirty pages to disk to free a buffer; instead, the buffer is excluded from the ring and replaced by another one. As a result, reading does not have to wait for writing to complete, so it is performed faster.

If it turns out that the table is already being scanned, the process that starts another scan joins the existing buffer ring and gets access to the currently available data, without incurring extra I/O operations.¹ When the first process completes the scan, the second one gets back to the skipped part of the table.

Bulk writes strategy is applied by `COPY FROM`, `CREATE TABLE AS SELECT`, and `CREATE MATERIALIZED VIEW` commands, as well as by those `ALTER TABLE` flavors that cause table rewrites. The allocated ring is quite big, its default size being 16 MB (2048 standard pages), but it never exceeds $\frac{1}{8}$ of the total size of the buffer cache.

Vacuuming strategy is used by the process of vacuuming when it performs a full table scan without taking the visibility map into account. The ring buffer is assigned 256 kB of RAM (32 standard pages).

Buffer rings do not always prevent undesired eviction. If `UPDATE` or `DELETE` commands affect a lot of rows, the performed table scan applies the bulk reads strategy, but since the pages are constantly being modified, buffer rings virtually become useless.

p. 26 Another example worth mentioning is storing oversized data in `TOAST` tables. In spite of a potentially large volume of data that has to be read, toasted values are always accessed via an index, so they bypass buffer rings.

Let's take a closer look at the bulk reads strategy. For simplicity, we will create a table in such a way that an inserted row takes the whole page. By default, the buffer cache size is 16,384 pages, 8 kB each. So the table must take more than 4096 pages for the scan to use a buffer ring.

```
=> CREATE TABLE big(  
    id integer PRIMARY KEY GENERATED ALWAYS AS IDENTITY,  
    s char(1000)  
) WITH (fillfactor = 10);
```

¹ backend/access/common/syncscan.c


```
=> INSERT INTO big(s)
    SELECT 'F00' FROM generate_series(1,4096+1);
```

Let's analyze the table:

```
=> ANALYZE big;
=> SELECT relname, relfilenode, relpages
FROM pg_class
WHERE relname IN ('big', 'big_pkey');
 relname | relfilenode | relpages
-----+-----+-----
big      |      16546 |      4097
big_pkey |      16551 |         14
(2 rows)
```

Restart the server to clear the cache, as now it contains some heap pages that have been read during analysis.

```
postgres$ pg_ctl restart -l /home/postgres/logfile
```

Once the server is restarted, let's read the whole table:

```
=> EXPLAIN (analyze, costs off, timing off, summary off, summary off)
SELECT id FROM big;
               QUERY PLAN
-----
Seq Scan on big (actual rows=4097 loops=1)
(1 row)
```

Heap pages take only 32 buffers, which make up the buffer ring for this operation:

```
=> SELECT count(*)
FROM pg_buffercache
WHERE relfilenode = pg_relation_filenode('big'::regclass);
 count
-----
     32
(1 row)
```

But in the case of an index scan the buffer ring is not used:

```
=> EXPLAIN (analyze, costs off, timing off, summary off, summary off)
SELECT * FROM big ORDER BY id;
```

QUERY PLAN

```
-----
Index Scan using big_pkey on big (actual rows=4097 loops=1)
(1 row)
```

As a result, the buffer cache ends up containing the whole table and the whole index:

```
=> SELECT relfilenode, count(*)
FROM pg_buffercache
WHERE relfilenode IN (
    pg_relation_filenode('big'),
    pg_relation_filenode('big_pkey')
)
GROUP BY relfilenode;
 relfilenode | count
-----+-----
        16546 |   4097
        16551 |     14
(2 rows)
```

9.6 Choosing the Buffer Cache Size

128MB The size of the buffer cache is defined by the *shared_buffers* parameter. Its default value is known to be low, so it makes sense to increase it right after the PostgreSQL installation. You will have to reload the server in this case because shared memory is allocated for cache at the server start.

But how can we determine an appropriate value?

Even a very large database has a limited set of hot data that is being used simultaneously. In the perfect world, it is this set that must fit the buffer cache (with some space being reserved for one-time data). If the cache size is smaller, the actively used pages will be evicting each other all the time, thus leading to excessive I/O operations. But thoughtless increase of the cache size is not a good idea either: RAM is a scarce resource, and besides, larger cache incurs higher maintenance costs.

The optimal buffer cache size differs from system to system: it depends on things like the total size of the available memory, data profiles, and workload types. Unfortunately, there is no magic value or formula to suit everyone equally well.

You should also keep in mind that a cache miss in PostgreSQL does not necessarily trigger a physical I/O operation. If the buffer cache is quite small, the OS cache uses the remaining free memory and can smooth things out to some extent. But unlike the database, the operating system knows nothing about the read data, so it applies a different eviction strategy.

A typical recommendation is to start with $\frac{1}{4}$ of RAM and then adjust this setting as required.

The best approach is experimentation: you can increase or decrease the cache size and compare the system performance. Naturally, it requires having a test system that is fully analogous to the production one, and you must be able to reproduce typical workloads.

You can also run some analysis using the `pg_buffercache` extension. For example, explore buffer distribution depending on their usage:

```
=> SELECT usagecount, count(*)
FROM pg_buffercache
GROUP BY usagecount
ORDER BY usagecount;
```

usagecount	count
1	4128
2	50
3	4
4	4
5	73
	12125

(6 rows)

NULL usage count values correspond to free buffers. They are quite expected in this case because the server was restarted and remained idle most of the time. The majority of the used buffers contain pages of the system catalog tables read by the backend to fill its system catalog cache and to perform queries.

We can check what fraction of each relation is cached, and whether this data is hot (a page is considered hot here if its usage count is bigger than one):

```
=> SELECT c.relname,
       count(*) blocks,
       round( 100.0 * 8192 * count(*) /
             pg_table_size(c.oid) ) AS "% of rel",
       round( 100.0 * 8192 * count(*) FILTER (WHERE b.usagecount > 1) /
             pg_table_size(c.oid) ) AS "% hot"
FROM pg_buffercache b
     JOIN pg_class c ON pg_relation_filenode(c.oid) = b.relfilenode
WHERE b.reldatabase IN (
    0, -- cluster-wide objects
    (SELECT oid FROM pg_database WHERE datname = current_database())
)
AND b.usagecount IS NOT NULL
GROUP BY c.relname, c.oid
ORDER BY 2 DESC
LIMIT 10;
```

relname	blocks	% of rel	% hot
big	4097	100	1
pg_attribute	30	48	47
big_pkey	14	100	0
pg_proc	13	12	6
pg_operator	11	61	50
pg_class	10	59	59
pg_proc_oid_index	9	82	45
pg_attribute_relid_attnum_index	8	73	64
pg_proc_proname_args_nsp_index	6	18	6
pg_amproc	5	56	56

(10 rows)

This example shows that the big table and its index are fully cached, but their pages are not being actively used.

Analyzing data from different angles, you can gain some useful insights. However, make sure to follow these simple rules when running `pg_buffercache` queries:

- Repeat such queries several times since the returned figures will vary to some extent.
- Do not run such queries non-stop because the `pg_buffercache` extension locks the viewed buffers, even if only briefly.

9.7 Cache Warming

After a server restart, the cache requires some time to warm up, that is, to accumulate the actively used data. It may be helpful to cache certain tables right away, and the `pg_prewarm` extension serves exactly this purpose:

```
=> CREATE EXTENSION pg_prewarm;
```

Apart from loading tables into the buffer cache (or into the OS cache only), this extension can write the current cache state to disk and then restore it after the server restart. To enable this functionality, you have to add this extension's library to `shared_preload_libraries` and restart the server: v. 11

```
=> ALTER SYSTEM SET shared_preload_libraries = 'pg_prewarm';
```

```
postgres$ pg_ctl restart -l /home/postgres/logfile
```

If the `pg_prewarm.autoprewarm` setting has not changed, a process called `autoprewarm leader` will be started automatically after the server is reloaded; once in `pg_prewarm.autoprewarm_interval` seconds, this process will flush the list of cached pages to disk (using one of the `max_parallel_processes` slots). on
300s

```
postgres$ ps -o pid,command \
--ppid `head -n 1 /usr/local/pgsql/data/postmaster.pid` | \
grep prewarm
23129 postgres: autoprewarm leader
```

Now that the server has been restarted, the big table is not cached anymore:

```
=> SELECT count(*)
FROM pg_buffercache
WHERE relfilenode = pg_relation_filenode('big'::regclass);
 count
-----
      0
(1 row)
```

If you have well-grounded assumptions that the whole table is going to be actively used and disk access will make response times unacceptably high, you can load this table into the buffer cache in advance:

```
=> SELECT pg_prewarm('big');
      pg_prewarm
-----
          4097
(1 row)

=> SELECT count(*)
FROM pg_buffercache
WHERE relfilenode = pg_relation_filenode('big'::regclass);
      count
-----
          4097
(1 row)
```

The list of pages is dumped into the `PGDATA/autoprewarm.blocks` file. You can wait until the autoprewarm leader completes for the first time, but we will initiate the dump manually:

```
=> SELECT autoprewarm_dump_now();
      autoprewarm_dump_now
-----
                4224
(1 row)
```

The number of flushed pages is bigger than 4097 because all the used buffers are taken into account. The file is written in a text format; it contains the IDs of the database, tablespace, and file, as well as the fork and segment numbers:

```
postgres$ head -n 10 /usr/local/pgsql/data/autoprewarm.blocks
<<4224>>
0,1664,1262,0,0
0,1664,1260,0,0
16391,1663,1259,0,0
16391,1663,1259,0,1
16391,1663,1259,0,2
16391,1663,1259,0,3
16391,1663,1249,0,0
16391,1663,1249,0,1
16391,1663,1249,0,2
```

Let's restart the server again.

```
postgres$ pg_ctl restart -l /home/postgres/logfile
```

The table appears in the cache right away:

```
=> SELECT count(*)
FROM pg_buffercache
WHERE relfilenode = pg_relation_filenode('big'::regclass);
 count
-----
    4097
(1 row)
```

It is again the autoprewarm leader that does all the preliminary work: it reads the file, sorts the pages by databases, reorders them (so that disk reads happen sequentially if possible), and then passes them to the autoprewarm worker for processing.

9.8 Local Cache

Temporary tables do not follow the workflow described above. Since temporary data is visible to a single process only, there is no point in loading it into the shared buffer cache. Therefore, temporary data uses the local cache of the process that owns the table.¹

In general, local buffer cache works similar to the shared one:

- Page search is performed via a hash table.
- Eviction follows the standard algorithm (except that buffer rings are not used).
- Pages can be pinned to avoid eviction.

However, local cache implementation is much simpler because it has to handle neither locks on memory structures (buffers can be accessed by a single process only) nor fault tolerance (temporary data exists till the end of the session at the most). p. 271
p. 185

¹ backend/storage/buffer/localbuf.c

Since only few sessions typically use temporary tables, local cache memory is assigned on demand. The maximum size of the local cache available to a session is limited by the *temp_buffers* parameter.

Despite a similar name, the *temp_file_limit* parameter has nothing to do with temporary tables; it is related to files that may be created during query execution to temporarily store intermediate data.

In the EXPLAIN command output, all calls to the local buffer cache are tagged as local instead of shared:

```
=> CREATE TEMPORARY TABLE tmp AS SELECT 1;
=> EXPLAIN (analyze, buffers, costs off, timing off, summary off)
    SELECT * FROM tmp;
          QUERY PLAN
-----
Seq Scan on tmp (actual rows=1 loops=1)
  Buffers: local hit=1
Planning:
  Buffers: shared hit=12 read=7
(4 rows)
```


10

Write-Ahead Log

10.1 Logging

In case of a failure, such as a power outage, an OS error, or a database server crash, all the contents of RAM will be lost; only the data written to disk will persist. To start the server after a failure, you have to restore data consistency. If the disk itself has been damaged, the same issue has to be resolved by backup recovery.

In theory, you could maintain data consistency on disk at all times. But in practice it means that the server has to constantly write random pages to disk (even though sequential writing is cheaper), and the order of such writes must guarantee that consistency is not compromised at any particular moment (which is hard to achieve, especially if you deal with complex index structures).

Just like the majority of database systems, PostgreSQL uses a different approach.

While the server is running, some of the current data is available only in RAM, its writing to permanent storage being deferred. Therefore, the data stored on disk is always inconsistent during server operation, as pages are never flushed all at once. But each change that happens in RAM (such as a page update performed in the buffer cache) is *logged*: PostgreSQL creates a log entry that contains all the essential information required to repeat this operation if the need arises.¹

A log entry related to a page modification must be written to disk *ahead* of the modified page itself. Hence the name of the log: *write-ahead log*, or WAL. This requirement guarantees that in case of a failure PostgreSQL can read WAL entries from disk and *replay* them to repeat the already completed operations whose results were still in RAM and did not make it to disk before the crash.

¹ [postgresql.org/docs/14/wal-intro.html](https://www.postgresql.org/docs/14/wal-intro.html)

Keeping a write-ahead log is usually more efficient than writing random pages to disk. WAL entries constitute a continuous stream of data, which can be handled even by HDDs. Besides, WAL entries are often smaller than the page size.

It is required to log all operations that can potentially break data consistency in case of a failure. In particular, the following actions are recorded in WAL:

- page modifications performed in the buffer cache—since writes are deferred
- transaction commits and rollbacks—since the status change happens in CLOG buffers and does not make it to disk right away
- file operations (like creation and deletion of files and directories when tables get added or removed)—since such operations must be in sync with data changes

The following actions are not logged:

- operations on `UNLOGGED` tables
- operations on temporary tables—since their lifetime is anyway limited by the session that spawns them

Prior to PostgreSQL 10, hash indexes were not logged either. Their only purpose was to match hash functions to different data types.

Apart from crash recovery, WAL can also be used for point-in-time recovery from a backup and replication.

10.2 WAL Structure

Logical Structure

Speaking about its logical structure, we can describe WAL¹ as a stream of log entries of variable length. Each entry contains some *data* about a particular operation

¹ [postgresql.org/docs/14/wal-internals.html](https://www.postgresql.org/docs/14/wal-internals.html)
[backend/access/transam/README](#)

preceded by a standard *header*.¹ Among other things, the header provides the following information:

- transaction ID related to the entry
- the resource manager that interprets the entry²
- the checksum to detect data corruption
- entry length
- a reference to the previous WAL entry

WAL is usually read in the forward direction, but some utilities like `pg_rewind` may scan it backwards.

WAL data itself can have different formats and meaning. For example, it can be a page fragment that has to replace some part of the page at the specified offset. The corresponding resource manager must know how to interpret and replay a particular entry. There are separate managers for tables, various index types, transaction status, and other entities.

WAL files take up special buffers in the server's shared memory. The size of the cache used by WAL is defined by the `wal_buffers` parameter. By default, this size is chosen automatically as $\frac{1}{32}$ of the total buffer cache size. -1

WAL cache is quite similar to buffer cache, but it usually operates in the ring buffer mode: new entries are added to its head, while older entries are saved to disk starting at the tail. If WAL cache is too small, disk synchronization will be performed more often than necessary.

Under low load, the insert position (the buffer's head) is almost always the same as the position of the entries that have already been saved to disk (the buffer's tail):

```
=> SELECT pg_current_wal_lsn(), pg_current_wal_insert_lsn();
 pg_current_wal_lsn | pg_current_wal_insert_lsn
-----+-----
 0/3E807B58        | 0/3E807B58
(1 row)
```

¹ `include/access/xlogrecord.h`

² `include/access/rmgrlist.h`

Prior to PostgreSQL 10, all function names contained the xLOG acronym instead of WAL.

To refer to a particular entry, PostgreSQL uses a special data type: `pg_lsn` (log sequence number, LSN). It represents a 64-bit offset in bytes from the start of the WAL to an entry. An LSN is displayed as two 32-bit numbers in the hexadecimal notation separated by a slash.

Let's create a table:

```
=> CREATE TABLE wal(id integer);
=> INSERT INTO wal VALUES (1);
```

Start a transaction and note the LSN of the WAL insert position:

```
=> BEGIN;
=> SELECT pg_current_wal_insert_lsn();
   pg_current_wal_insert_lsn
-----
0/3E820AC8
(1 row)
```

Now run some arbitrary command, for example, update a row:

```
=> UPDATE wal SET id = id + 1;
```

The page modification is performed in the buffer cache in RAM. This change is logged in a WAL page, also in RAM. As a result, the insert LSN is advanced:

```
=> SELECT pg_current_wal_insert_lsn();
   pg_current_wal_insert_lsn
-----
0/3E820B10
(1 row)
```

To ensure that the modified data page is flushed to disk strictly after the corresponding WAL entry, the page header stores the LSN of the latest WAL entry related to this page. You can view this LSN using `pageinspect`:

```
=> SELECT lsn FROM page_header(get_raw_page('wal',0));
   lsn
-----
0/3E820B10
(1 row)
```

There is only one WAL for the whole database cluster, and new entries constantly get appended to it. For this reason, the LSN stored in the page may turn out to be smaller than the one returned by the `pg_current_wal_insert_lsn` function some time ago. But if nothing has happened in the system, these numbers will be the same.

Now let's commit the transaction:

```
=> COMMIT;
```

The commit operation is also logged, and the insert LSN changes again:

```
=> SELECT pg_current_wal_insert_lsn();
       pg_current_wal_insert_lsn
-----
0/3E820B38
(1 row)
```

A commit updates transaction status in CLOG pages, which are kept in their own cache.¹ The CLOG cache usually takes 128 pages in the shared memory.² To make sure that a CLOG page is not flushed to disk before the corresponding WAL entry, the LSN of the latest WAL entry has to be tracked for CLOG pages too. But this information is stored in RAM, not in the page itself. p. 75

At some point WAL entries will make it to disk; then it will be possible to evict CLOG and data pages from the cache. If they had to be evicted earlier, it would have been discovered, and WAL entries would have been forced to disk first.³ p. 206

If you know two LSN positions, you can calculate the size of WAL entries between them (in bytes) by simply subtracting one position from the other. You just have to cast them to the `pg_lsn` type:

```
=> SELECT '0/3E820B38'::pg_lsn - '0/3E820AC8'::pg_lsn;
       ?column?
-----
112
(1 row)
```

¹ `backend/access/transam/slru.c`

² `backend/access/transam/clog.c`, `CLOGShmemBuffers` function

³ `backend/storage/buffer/bufmgr.c`, `FlushBuffer` function

In this particular case, WAL entries related to `UPDATE` and `COMMIT` operations took about a hundred of bytes.

You can use the same approach to estimate the volume of WAL entries generated by a particular workload per unit of time. This information will be required for the checkpoint setup.

Physical Structure

On disk, the WAL is stored in the `PGDATA/pg_wal` directory as separate files, or segments. Their size is shown by the read-only `wal_segment_size` parameter.

- 16MB
- v. 11
- For high-load systems, it makes sense to increase the segment size since it may reduce the overhead, but this setting can be modified only during cluster initialization (`initdb --wal-segsize`).

WAL entries get into the current file until it runs out of space; then PostgreSQL starts a new file.

We can learn in which file a particular entry is located, and at what offset from the start of the file:

```
=> SELECT file_name, upper(to_hex(file_offset)) file_offset
FROM pg_walfile_name_offset('0/3E820AC8');

      file_name      | file_offset
-----+-----
000000001000000000000003E | 820AC8
      {
      timeline          log sequence number
```

The name of the file consists of two parts. The highest eight hexadecimal digits define the *timeline* used for recovery from a backup, while the rest represent the highest LSN bits (the lowest LSN bits are shown in the `file_offset` field).

- v. 10
- To view the current WAL files, you can call the following function:

```
=> SELECT *
FROM pg_ls_waldir()
WHERE name = '000000010000000000000003E';
```

name	size	modification
00000001000000000000003E	16777216	2022-09-19 14:52:22+03

(1 row)

Now let's take a look at the headers of the newly created WAL entries using the `pg_waldump` utility, which can filter WAL entries both by the LSN range (like in this example) and by a particular transaction ID.

The `pg_waldump` utility should be started on behalf of the postgres OS user, as it needs access to WAL files on disk.

```
postgres$ /usr/local/pgsql/bin/pg_waldump \
-p /usr/local/pgsql/data/pg_wal -s 0/3E820AC8 -e 0/3E820B38#
rmgr: Heap len (rec/tot): 69/ 69, tx: 887, lsn:
0/3E820AC8, prev 0/3E820AA0, desc: HOT_UPDATE off 1 xmax 887 flags
0x40 ; new off 2 xmax 0, blkref #0: rel 1663/16391/16562 blk 0
rmgr: Transaction len (rec/tot): 34/ 34, tx: 887, lsn:
0/3E820B10, prev 0/3E820AC8, desc: COMMIT 2022-09-19 14:52:22.552253
MSK
```

Here we can see the headers of two entries.

The first one is the `HOT_UPDATE` operation handled by the Heap resource manager. *p. 106*
The `blkref` field shows the filename and the page ID of the updated heap page:

```
=> SELECT pg_relation_filepath('wal');
pg_relation_filepath
-----
base/16391/16562
(1 row)
```

The second entry is the `COMMIT` operation supervised by the Transaction resource manager.

10.3 Checkpoint

To restore data consistency after a failure (that is, to perform recovery), PostgreSQL has to replay the WAL in the forward direction and apply the entries that represent lost changes to the corresponding pages. To find out what has been lost, the LSN

of the page stored on disk is compared to the LSN of the WAL entry. But at which point should we start the recovery? If we start too late, the pages written to disk before this point will fail to receive all the changes, which will lead to irreversible data corruption. Starting from the very beginning is unrealistic: it is impossible to store such a potentially huge volume of data, and neither is it possible to accept such a long recovery time. We need a *checkpoint* that is gradually moving forward, thus making it safe to start the recovery from this point and remove all the previous WAL entries.

The most straightforward way to create a checkpoint is to periodically suspend all system operations and force all dirty pages to disk. This approach is of course unacceptable, as the system will hang for an indefinite but quite significant time.

For this reason, the checkpoint is spread out over time, virtually constituting an interval. Checkpoint execution is performed by a special background process called *checkpointer*.¹

Checkpoint start. The *checkpointer* process flushes to disk everything that can be written instantaneously: CLOG transaction status, subtransactions' metadata, and a few other structures.

Checkpoint execution. Most of the checkpoint execution time is spent on flushing dirty pages to disk.²

First, a special tag is set in the headers of all the buffers that were dirty at the checkpoint start. It happens very fast since no I/O operations are involved.

Then *checkpointer* traverses all the buffers and writes the tagged ones to disk. Their pages are not evicted from the cache: they are simply written down, so usage and pin counts can be ignored.

- v. 9.6 Pages are processed in the order of their IDs to avoid random writing if possible. For better load balancing, PostgreSQL alternates between different tablespaces (as they may be located on different physical devices).

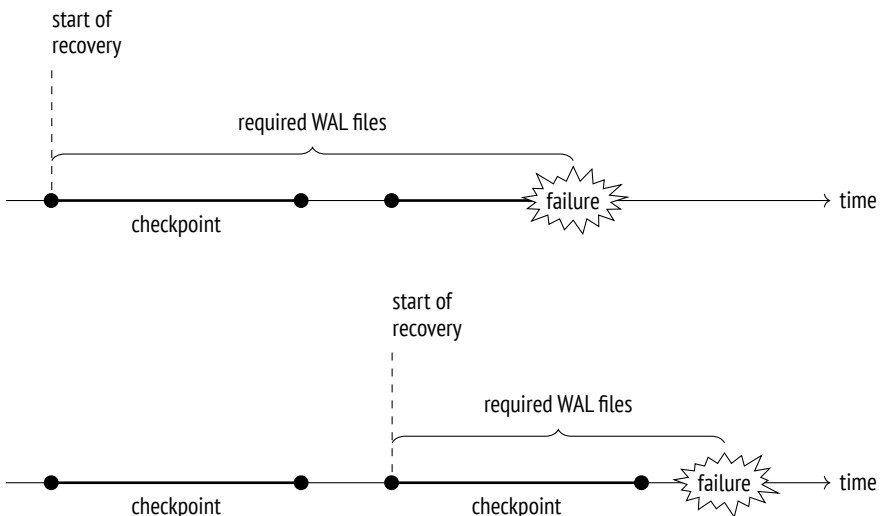
¹ backend/postmaster/checkpointer.c
backend/access/transam/xlog.c, CreateCheckPoint function

² backend/storage/buffer/bufmgr.c, BufferSync function

Backends can also write tagged buffers to disk—if they get to them first. In any case, buffer tags are removed at this stage, so for the purpose of the checkpoint each buffer will be written only once.

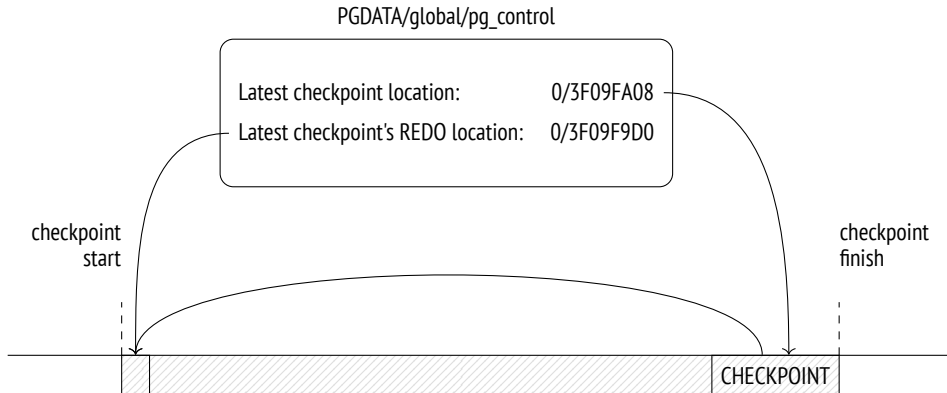
Naturally, pages can still be modified in the buffer cache while the checkpoint is in progress. But since new dirty buffers are not tagged, checkpointer will ignore them.

Checkpoint completion. When all the buffers that were dirty *at the start* of the checkpoint are written to disk, the checkpoint is considered *complete*. From now on (but not earlier!), the *start* of the checkpoint will be used as a new starting point of recovery. All the WAL entries written before this point are not required anymore.



Finally, checkpointer creates a WAL entry that corresponds to the checkpoint completion, specifying the checkpoint's start LSN. Since the checkpoint logs nothing when it starts, this LSN can belong to a WAL entry of any type.

The `PGDATA/global/pg_control` file also gets updated to refer to the latest completed checkpoint. (Until this process is over, `pg_control` keeps the previous checkpoint.)



To figure out once and for all what points where, let's take a look at a simple example. We will make several cached pages dirty:

```
=> UPDATE big SET s = 'F00';
=> SELECT count(*) FROM pg_buffercache WHERE isdirty;
 count
-----
    4119
(1 row)
```

Note the current WAL position:

```
=> SELECT pg_current_wal_insert_lsn();
 pg_current_wal_insert_lsn
-----
 0/3F09F9D0
(1 row)
```

Now let's complete the checkpoint manually. All the dirty pages will be flushed to disk; since nothing happens in the system, new dirty pages will not appear:

```
=> CHECKPOINT;
=> SELECT count(*) FROM pg_buffercache WHERE isdirty;
 count
-----
      0
(1 row)
```

Let's see how the checkpoint is reflected in the WAL:

```
=> SELECT pg_current_wal_insert_lsn();
       pg_current_wal_insert_lsn
-----
0/3F09FA80
(1 row)
```

```
postgres$ /usr/local/pgsql/bin/pg_waldump \
-p /usr/local/pgsql/data/pg_wal -s 0/3F09F9D0 -e 0/3F09FA80
rmgr: Standby      len (rec/tot):   50/   50, tx:         0, lsn:
0/3F09F9D0, prev 0/3F09F9A8, desc: RUNNING_XACTS nextXid 889
latestCompletedXid 888 oldestRunningXid 889
-----
rmgr: XLOG         len (rec/tot):  114/  114, tx:         0, lsn:
0/3F09FA08, prev 0/3F09F9D0, desc: CHECKPOINT_ONLINE redo
0/3F09F9D0; tli 1; prev tli 1; fpw true; xid 0:889; oid 24754; multi
1; offset 0; oldest xid 726 in DB 1; oldest multi 1 in DB 1;
oldest/newest commit timestamp xid: 0/0; oldest running xid 889;
online
```

The latest WAL entry is related to the checkpoint completion (CHECKPOINT_ONLINE). The start LSN of this checkpoint is specified after the word redo; this position corresponds to the latest inserted WAL entry at the time of the checkpoint start.

The same information can also be found in the pg_control file:

```
postgres$ /usr/local/pgsql/bin/pg_controldata \
-D /usr/local/pgsql/data | egrep 'Latest.*location'
Latest checkpoint location:          0/3F09FA08
Latest checkpoint's REDO location:   0/3F09F9D0
```

10.4 Recovery

The first process launched at the server start is postmaster. In its turn, postmaster spawns the startup process,¹ which takes care of data recovery in case of a failure.

To determine whether recovery is needed, the startup process reads the pg_control file and checks the cluster status. The pg_controldata utility enables us to view the content of this file:

¹ backend/postmaster/startup.c
backend/access/transam/xlog.c, StartupXLOG function

```
postgres$ /usr/local/pgsql/bin/pg_controldata \  
-D /usr/local/pgsql/data | grep state  
Database cluster state:                in production
```

A properly stopped server has the “shut down” status; the “in production” status of a non-running server indicates a failure. In this case, the startup process will automatically initiate recovery from the start LSN of the latest completed checkpoint found in the same `pg_control` file.

If the `PGDATA` directory contains a `backup_label` file related to a backup, the start LSN position is taken from that file.

The startup process reads WAL entries one by one, starting from the defined position, and applies them to data pages if the LSN of the page is smaller than the LSN of the WAL entry. If the page contains a bigger LSN, WAL should not be applied; in fact, it *must not* be applied because its entries are designed to be replayed strictly sequentially.

However, some WAL entries constitute a *full page image*, or FPI. Entries of this type can be applied to any state of the page since all the page contents will be erased anyway. Such modifications are called *idempotent*. Another example of an idempotent operation is registering transaction status changes: each transaction status is defined in CLOG by certain bits that are set regardless of their previous values, so there is no need to keep the LSN of the latest change in CLOG pages.

WAL entries are applied to pages in the buffer cache, just like regular page updates during normal operation.

Files get restored from WAL in a similar manner: for example, if a WAL entry shows that the file must exist, but it is missing for some reason, it will be created anew.

Once the recovery is over, all unlogged relations are overwritten by the corresponding initialization forks.

Finally, the checkpoint is executed to secure the recovered state on disk.

The job of the startup process is now complete.

In its classic form, the recovery process consists of two phases. In the roll-forward phase, WAL entries are replayed, repeating the lost operations. In the roll-back phase, the server aborts the transactions that were not yet committed at the time of the failure.

In PostgreSQL, the second phase is not required. After the recovery, the clog will contain neither commit nor abort bits for an unfinished transaction (which technically denotes an active transaction), but since it is known for sure that the transaction is not running anymore, it will be considered aborted.¹

We can simulate a failure by forcing the server to stop in the immediate mode:

```
postgres$ pg_ctl stop -m immediate
```

Here is the new cluster state:

```
postgres$ /usr/local/pgsql/bin/pg_controldata \
-D /usr/local/pgsql/data | grep 'state'
Database cluster state:          in production
```

When we launch the server, the startup process sees that a failure has occurred and enters the recovery mode:

```
postgres$ pg_ctl start -l /home/postgres/logfile
postgres$ tail -n 6 /home/postgres/logfile
LOG:  database system was interrupted; last known up at 2022-09-19
14:52:23 MSK
LOG:  database system was not properly shut down; automatic recovery
in progress
LOG:  redo starts at 0/3F09F9D0
LOG:  invalid record length at 0/3F09FA80: wanted 24, got 0
LOG:  redo done at 0/3F09FA08 system usage: CPU: user: 0.00 s,
system: 0.00 s, elapsed: 0.00 s
LOG:  database system is ready to accept connections
```

If the server is being stopped normally, postmaster disconnects all clients and then executes the final checkpoint to flush all dirty pages to disk.

Note the current WAL position:

```
=> SELECT pg_current_wal_insert_lsn();
 pg_current_wal_insert_lsn
-----
0/3F09FAF8
(1 row)
```

¹ backend/access/heap/heapam_visibility.c, HeapTupleSatisfiesMVCC function

Now let's stop the server properly:

```
postgres$ pg_ctl stop
```

Here is the new cluster state:

```
postgres$ /usr/local/pgsql/bin/pg_controldata \
-D /usr/local/pgsql/data | grep state
Database cluster state:                shut down
```

At the end of the WAL, we can see the CHECKPOINT_SHUTDOWN entry, which denotes the final checkpoint:

```
postgres$ /usr/local/pgsql/bin/pg_waldump \
-p /usr/local/pgsql/data/pg_wal -s 0/3F09FAF8
rmgr: XLOG          len (rec/tot):   114/   114, tx:           0, lsn:
0/3F09FAF8, prev 0/3F09FA80, desc: CHECKPOINT_SHUTDOWN redo
0/3F09FAF8; tli 1; prev tli 1; fpw true; xid 0:889; oid 24754; multi
1; offset 0; oldest xid 726 in DB 1; oldest multi 1 in DB 1;
oldest/newest commit timestamp xid: 0/0; oldest running xid 0;
shutdown
-----
pg_waldump: fatal: error in WAL record at 0/3F09FAF8: invalid record
length at 0/3F09FB70: wanted 24, got 0
```

The latest pg_waldump message shows that the utility has read the WAL to the end.

Let's start the instance again:

```
postgres$ pg_ctl start -l /home/postgres/logfile
```

10.5 Background Writing

If the backend needs to evict a dirty page from a buffer, it has to write this page to disk. Such a situation is undesired because it leads to waits—it is much better to perform writing asynchronously in the background.

This job is partially handled by checkpointer, but it is still not enough.

Therefore, PostgreSQL provides another process called `bgwriter`,¹ specifically for *background writing*. It relies on the same buffer search algorithm as eviction, except for the two main differences:

- The `bgwriter` process uses its own clock hand that never lags behind that of eviction and typically overtakes it.
- As the buffers are being traversed, the usage count is not reduced.

A dirty page is flushed to disk if the buffer is not pinned and has zero usage count. Thus, `bgwriter` runs before eviction and proactively writes to disk those pages that are highly likely to be evicted soon.

It raises the odds of the buffers selected for eviction being clean.

10.6 WAL Setup

Configuring Checkpoints

The checkpoint duration (to be more exact, the duration of writing dirty buffers to disk) is defined by the `checkpoint_completion_target` parameter. Its value specifies the fraction of time between the starts of two neighboring checkpoints that is allotted to writing. Avoid setting this parameter to one: as a result, the next checkpoint may be due before the previous one is complete. No disaster will happen, as it is impossible to execute more than one checkpoint at a time, but normal operation may still be disrupted. 0.9 v. 14

When configuring other parameters, we can use the following approach. First, we define an appropriate volume of WAL files to be stored between two neighboring checkpoints. The bigger the volume, the smaller the overhead, but this value will anyway be limited by the available free space and the acceptable recovery time.

To estimate the time required to generate this volume by *normal* load, you need to note the initial insert LSN and check the difference between this and the current insert positions from time to time.

¹ `backend/postmaster/bgwriter.c`

5min
p. 214 The received figure is assumed to be a typical interval between checkpoints, so we will use it as the `checkpoint_timeout` parameter value. The default setting is likely to be too small; it is usually increased, for example, to 30 minutes.

1GB However, it is quite possible (and even probable) that the load will *sometimes* be higher, so the size of WAL files generated during this interval will be too big. In this case, the checkpoint must be executed more often. To set up such a trigger, we will limit the size of WAL files required for recovery by the `max_wal_size` parameter. When this threshold is exceeded, the server invokes an extra checkpoint.¹

v. 1.1 WAL files required for recovery contain all the entries both for the latest completed checkpoint and for the current one, which is not completed yet. So to estimate their total volume you should multiply the calculated WAL size between checkpoints by $1 + \text{checkpoint_completion_target}$.

Prior to version 11, PostgreSQL kept WAL files for two completed checkpoints, so the multiplier was $2 + \text{checkpoint_completion_target}$.

Following this approach, most checkpoints are executed on schedule, once per the `checkpoint_timeout` interval; but should the load increase, the checkpoint is triggered when WAL size exceeds the `max_wal_size` value.

The actual progress is periodically checked against the expected figures:²

The actual progress is defined by the fraction of cached pages that have already been processed.

The expected progress (by time) is defined by the fraction of time that has already elapsed, assuming that the checkpoint must be completed within the $\text{checkpoint_timeout} \times \text{checkpoint_completion_target}$ interval.

The expected progress (by size) is defined by the fraction of the already filled WAL files, their expected number being estimated based on the $\text{max_wal_size} \times \text{checkpoint_completion_target}$ value.

If dirty pages get written to disk ahead of schedule, checkpointing is paused for a while; if there is any delay by either of the parameters, it catches up as soon as

¹ `backend/access/transam/xlog.c`, `LogCheckpointNeeded` & `CalculateCheckpointSegments` functions

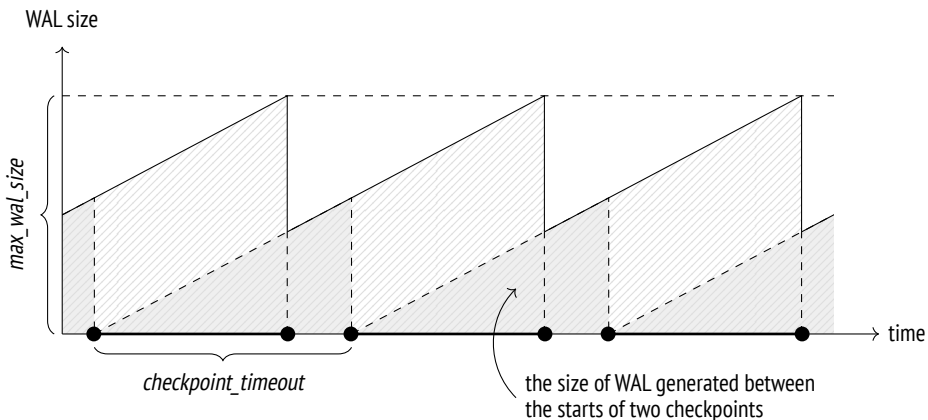
² `backend/postmaster/checkpointer.c`, `IsCheckpointOnSchedule` function

possible.¹ Since both time and data size are taken into account, PostgreSQL can manage scheduled and on-demand checkpoints using the same approach.

Once the checkpoint has been completed, WAL files that are not required for recovery anymore are deleted;² however, several files (up to *min_wal_size* in total) are kept for reuse and are simply renamed. 80MB

Such renaming reduces the overhead incurred by constant file creation and deletion, but you can turn off this feature using the *wal_recycle* parameter if you do not need it. v. 12 on

The following figure shows how the size of WAL files stored on disk changes under normal conditions.



It is important to keep in mind that the actual size of WAL files on disk may exceed the *max_wal_size* value:

- The *max_wal_size* parameter specifies the desired target value rather than a hard limit. If the load spikes, writing may lag behind the schedule.
- The server has no right to delete WAL files that are yet to be replicated or handled by continuous archiving. If enabled, this functionality must be constantly monitored, as it can easily cause a disk overflow.

¹ backend/postmaster/checkpointer.c, CheckpointWriteDelay function

² backend/access/transam/xlog.c, RemoveOldXlogFiles function

- v. 12 • You can reserve a certain amount of space for WAL files by configuring the
0MB *wal_keep_size* parameter.

Configuring Background Writing

Once checkpointer is configured, you should also set up bgwriter. Together, these processes must be able to cope with writing dirty buffers to disk before backends need to reuse them.

200ms During its operation, bgwriter makes periodic pauses, sleeping for *bgwriter_delay* units of time.

The number of pages written between two pauses depends on the average number of buffers accessed by backends since the previous run (PostgreSQL uses a moving average to level out possible spikes and avoid depending on very old data at the same time). The calculated number is then multiplied by *bgwriter_lru_multiplier*. But in any case, the number of pages written in a single run cannot exceed the *bgwriter_lru_maxpages* value.

If no dirty buffers are detected (that is, nothing happens in the system), bgwriter sleeps until one of the backends accesses a buffer. Then it wakes up and continues its regular operation.

Monitoring

Checkpoint settings can and should be tuned based on monitoring data.

30s If size-triggered checkpoints have to be performed more often than defined by the *checkpoint_warning* parameter, PostgreSQL issues a warning. This setting should be brought in line with the expected peak load.

off The *log_checkpoints* parameter enables printing checkpoint-related information into the server log. Let's turn it on:

```
=> ALTER SYSTEM SET log_checkpoints = on;  
=> SELECT pg_reload_conf();
```

Now we will modify some data and execute a checkpoint:

```
=> UPDATE big SET s = 'BAR';
=> CHECKPOINT;
```

The server log shows the number of written buffers, some statistics on WAL file changes after the checkpoint, the duration of the checkpoint, and the distance (in bytes) between the starts of two neighboring checkpoints:

```
postgres$ tail -n 2 /home/postgres/logfile
LOG:  checkpoint starting: immediate force wait
LOG:  checkpoint complete: wrote 4100 buffers (25.0%); 0 WAL file(s)
added, 0 removed, 0 recycled; write=0.049 s, sync=0.004 s,
total=0.062 s; sync files=3, longest=0.002 s, average=0.002 s;
distance=9213 kB, estimate=9213 kB
```

The most useful data that can affect your configuration decisions is statistics on background writing and checkpoint execution provided in the `pg_stat_bgwriter` view.

Prior to version 9.2, both tasks were performed by `bgwriter`; then a separate `checkpointer` process was introduced, but the common view remained unchanged.

```
=> SELECT * FROM pg_stat_bgwriter \gx
-[ RECORD 1 ]-----+-----
checkpoints_timed    | 0
checkpoints_req      | 14
checkpoint_write_time | 29168
checkpoint_sync_time | 185
buffers_checkpoint   | 14106
buffers_clean        | 12246
maxwritten_clean     | 116
buffers_backend      | 84054
buffers_backend_fsync | 0
buffers_alloc        | 84449
stats_reset          | 2022-09-19 14:50:51.861607+03
```

Among other things, this view displays the number of completed checkpoints:

- The `checkpoints_timed` field shows scheduled checkpoints (which are triggered when the `checkpoint_timeout` interval is reached).
- The `checkpoints_req` field shows on-demand checkpoints (including those triggered when the `max_wal_size` size is reached).

A large `checkpoint_req` value (as compared to `checkpoints_timed`) indicates that checkpoints are performed more often than expected.

The following statistics on the number of written pages are also very important:

- `buffers_checkpoint` pages written by checkpointer
- `buffers_backend` pages written by backends
- `buffers_clean` pages written by `bgwriter`

In a well-configured system, the `buffers_backend` value must be considerably lower than the sum of `buffers_checkpoint` and `buffers_clean`.

When setting up background writing, pay attention to the `maxwritten_clean` value: it shows how many times `bgwriter` had to stop because of exceeding the threshold defined by `bgwriter_lru_maxpages`.

The following call will drop the collected statistics:

```
=> SELECT pg_stat_reset_shared('bgwriter');
```

11

WAL Modes

11.1 Performance

While the server is running normally, WAL files are being constantly written to disk. However, these writes are sequential: there is almost no random access, so even HDDs can cope with this task. Since this type of load is very different from a typical data file access, it may be worth setting up a separate physical storage for WAL files and replacing the `PGDATA/pg_wal` catalog by a symbolic link to a directory in a mounted file system.

There are a couple of situations when WAL files have to be both written and read. The first one is the obvious case of crash recovery; the second one is stream replication. The `walsender`¹ process reads WAL entries directly from files.² So if a replica does not receive WAL entries while the required pages are still in the OS buffers of the primary server, the data has to be read from disk. But the access will still be sequential rather than random.

WAL entries can be written in one of the following modes:

- The synchronous mode forbids any further operations until a transaction commit saves all the related WAL entries to disk.
- The asynchronous mode implies instant transaction commits, with WAL entries being written to disk later in the background.

The current mode is defined by the `synchronous_commit` parameter.

on

¹ `backend/replication/walsender.c`

² `backend/access/transam/xlogreader.c`

Synchronous mode. To reliably register the fact of a commit, it is not enough to simply pass WAL entries to the operating system; you have to make sure that disk synchronization has completed successfully. Since synchronization implies actual I/O operations (which are quite slow), it is beneficial to perform it as seldom as possible.

0s
5 For this purpose, the backend that completes the transaction and writes WAL entries to disk can make a small pause as defined by the *commit_delay* parameter. However, it will only happen if there are at least *commit_siblings* active transactions in the system:¹ during this pause, some of them may finish, and the server will manage to synchronize all the WAL entries in one go. It is a lot like holding doors of an elevator for someone to rush in.

By default, there is no pause. It makes sense to modify the *commit_delay* parameter only for systems that perform a lot of short OLTP transactions.

After a potential pause, the process that completes the transaction flushes all the accumulated WAL entries to disk and performs synchronization (it is important to save the commit entry and all the previous entries related to this transaction; the rest is written just because it does not increase the cost).

From this time on, the ACID's durability requirement is guaranteed—the transaction is considered to be reliably committed.² That's why the synchronous mode is the default one.

The downside of the synchronous commit is longer latencies (the COMMIT command does not return control until the end of synchronization) and lower system throughput, especially for OLTP loads.

Asynchronous mode. To enable asynchronous commits,³ you have to turn off the *synchronous_commit* parameter.

200ms In the asynchronous mode, WAL entries are written to disk by the walwriter⁴ process, which alternates between work and sleep. The duration of pauses is defined by the *wal_writer_delay* value.

¹ backend/access/transam/xlog.c, XLogFlush function

² backend/access/transam/xlog.c, RecordTransactionCommit function

³ postgresql.org/docs/14/wal-async-commit.html

⁴ backend/postmaster/walwriter.c

Waking up from a pause, the process checks the cache for new *completely filled* WAL pages. If any such pages have appeared, the process writes them to disk, skipping the current page. Otherwise, it writes the current half-empty page since it has woken up anyway.¹

The purpose of this algorithm is to avoid flushing one and the same page several times, which brings noticeable performance gains for workloads with intensive data changes.

Although WAL cache is used as a ring buffer, walwriter stops when it reaches the last page of the cache; after a pause, the next writing cycle starts from the first page. So in the worst case walwriter needs three runs to get to a particular WAL entry: first, it will write all full pages located at the end of the cache, then it will get back to the beginning, and finally, it will handle the underfilled page containing the entry. But in most cases it takes one or two cycles.

Synchronization is performed each time the `wal_writer_flush_after` amount of 1MB data is written, and once again at the end of the writing cycle.

Asynchronous commits are faster than synchronous ones since they do not have to wait for physical writes to disk. But reliability suffers: you can lose the data committed within the $3 \times \text{wal_writer_delay}$ timeframe before a failure (which is 0.6 seconds by default).

In the real world, these two modes complement each other. In the synchronous mode, WAL entries related to a long transaction can still be written asynchronously to free WAL buffers. And vice versa, a WAL entry related to a page that is about to be evicted from the buffer cache will be immediately flushed to disk even in the asynchronous mode—otherwise, it is impossible to continue operation.

In most cases, a hard choice between performance and durability has to be made by the system designer.

The `synchronous_commit` parameter can also be set for particular transactions. If it is possible to classify all transactions at the application level as either absolutely critical (such as handling financial data) or less important, you can boost performance while risking to lose only non-critical transactions.

¹ backend/access/transam/xlog.c, XLogBackgroundFlush function

To get some idea of potential performance gains of the asynchronous commit, let's compare latency and throughput in the two modes using a `pgbench` test.¹

First, initialize the required tables:

```
postgres$ /usr/local/pgsql/bin/pgbench -i internals
```

Start a 30-second test in the synchronous mode:

```
postgres$ /usr/local/pgsql/bin/pgbench -T 30 internals
pgbench (14.4)
starting vacuum...end.
transaction type: <builtin: TPC-B (sort of)>
scaling factor: 1
query mode: simple
number of clients: 1
number of threads: 1
duration: 30 s
number of transactions actually processed: 22133
latency average = 1.355 ms
initial connection time = 1.860 ms
tps = 737.788800 (without initial connection time)
```

And now run the same test in the asynchronous mode:

```
=> ALTER SYSTEM SET synchronous_commit = off;
=> SELECT pg_reload_conf();
postgres$ /usr/local/pgsql/bin/pgbench -T 30 internals
pgbench (14.4)
starting vacuum...end.
transaction type: <builtin: TPC-B (sort of)>
scaling factor: 1
query mode: simple
number of clients: 1
number of threads: 1
duration: 30 s
number of transactions actually processed: 71925
latency average = 0.417 ms
initial connection time = 2.091 ms
tps = 2397.630831 (without initial connection time)
```

¹ [postgresql.org/docs/14/pgbench.html](https://www.postgresql.org/docs/14/pgbench.html)

In the asynchronous mode, this simple benchmark shows a significantly lower latency and higher throughput (TPS). Naturally, each particular system will have its own figures depending on the current load, but it is clear that the impact on short OLTP transactions can be quite tangible.

Let's restore the default settings:

```
=> ALTER SYSTEM RESET synchronous_commit;  
=> SELECT pg_reload_conf();
```

11.2 Fault Tolerance

It is self-evident that write-ahead logging must guarantee crash recovery under any circumstances (unless the persistent storage itself is broken). There are many factors that can affect data consistency, but I will cover only the most important ones: caching, data corruption, and non-atomic writes.¹

Caching

Before reaching a non-volatile storage (such as a hard disk), data can pass through various caches.

A disk write simply instructs the operating system to place the data into its cache (which is also prone to crashes, just like any other part of RAM). The actual writing is performed asynchronously, as defined by the settings of the I/O scheduler of the operating system.

Once the scheduler decides to flush the accumulated data, this data is moved to the cache of a storage device (like an HDD). Storage devices can also defer writing, for example, to group of adjacent pages together. A RAID controller adds one more caching level between the disk and the operating system.

Unless special measures are taken, the moment when the data is reliably stored on disk remains unknown. It is usually not so important because we have the WAL,

¹ [postgresql.org/docs/14/wal-reliability.html](https://www.postgresql.org/docs/14/wal-reliability.html)

but WAL entries themselves must be reliably saved on disk right away.¹ It is equally true for the asynchronous mode—otherwise, it is impossible to guarantee that WAL entries get to disk ahead of the modified data.

The checkpoint process must also save the data in a reliable way, ensuring that dirty pages make it to disk from the OS cache. Besides, it has to synchronize all the file operations that have been performed by other processes (such as page writes or file deletions): when the checkpoint completes, the results of all these actions must be already saved on disk.²

There are also some other situations that demand fail-safe writing, such as executing unlogged operations at the minimal WAL level.

Operating systems provide various means to guarantee immediate writing of data into a non-volatile storage. All of them boil down to the following two main approaches: either a separate synchronization command is called after writing (such as `fsync` or `fdatasync`), or the requirement to perform synchronization (or even direct writing that bypasses OS cache) is specified when the file is being opened or written into.

The `pg_test_fsync` utility can help you determine the best way to synchronize the WAL depending on your OS and file system; the preferred method can be specified in the `wal_sync_method` parameter. For other operations, an appropriate synchronization method is selected automatically and cannot be configured.³

A subtle aspect here is that in each particular case the most suitable method depends on the hardware. For example, if you use a controller with a backup battery, you can take advantage of its cache, as the battery will protect the data in case of a power outage.

on You should keep in mind that the asynchronous commit and lack of synchronization are two totally different stories. Turning off synchronization (by the `fsync` parameter) boosts system performance, yet any failure will lead to fatal data loss. The asynchronous mode guarantees crash recovery up to a consistent state, but some of the latest data updates may be missing.

¹ `backend/access/transam/xlog.c`, `issue_xlog_fsync` function

² `backend/storage/sync/sync.c`

³ `backend/storage/file/fd.c`, `pg_fsync` function

Data Corruption

Technical equipment is imperfect, and data can get damaged both in memory and on disk, or while it is being transferred via interface cables. Such errors are usually handled at the hardware level, yet some can escape.

To catch issues in good time, PostgreSQL always protects WAL entries by checksums.

Checksums can be calculated for data pages as well.¹ It is done either during cluster initialization or by running the `pg_checksums`² utility when the server is stopped.³ v. 12

In production systems, checksums must always be enabled, despite some (minor) calculation and verification overhead. It raises the chance of timely corruption discovery, even though some corner cases still remain:

- Checksum verification is performed only when the page is accessed, so data corruption can go unnoticed for a long time, up to the point when it gets into all backups and leaves no source of correct data.
- A zeroed page is considered correct, so if the file system zeroes out a page by mistake, this issue will not be discovered.
- Checksums are calculated only for the main fork of relations; other forks and files (such as transaction status in CLOG) remain unprotected.

Let's take a look at the read-only `data_checksums` parameter to make sure that checksums are enabled:

```
=> SHOW data_checksums;
data_checksums
-----
on
(1 row)
```

Now stop the server and zero out several bytes in the zero page of the main fork of the table:

¹ [backend/storage/page/README](#)

² [postgresql.org/docs/14/app-pgchecksums.html](#)

³ [commitfest.postgresql.org/27/2260](#)

```
=> SELECT pg_relation_filepath('wal');
pg_relation_filepath
-----
base/16391/16562
(1 row)
postgres$ pg_ctl stop
postgres$ dd if=/dev/zero of=/usr/local/pgsql/data/base/16391/16562 \
oflag=dsync conv=notrunc bs=1 count=8
8+0 records in
8+0 records out
8 bytes copied, 0,00765127 s, 1,0 kB/s
```

Start the server again:

```
postgres$ pg_ctl start -l /home/postgres/logfile
```

In fact, we could have left the server running—it is enough to write the page to disk and evict it from cache (otherwise, the server will continue using its cached version). But such a workflow is harder to reproduce.

Now let's attempt to read the table:

```
=> SELECT * FROM wal LIMIT 1;
WARNING: page verification failed, calculated checksum 24386 but
expected 33119
ERROR: invalid page in block 0 of relation base/16391/16562
```

If the data cannot be restored from a backup, it makes sense to at least try to read the damaged page (risking to get garbled output). For this purpose, you have to enable the *ignore_checksum_failure* parameter:

```
=> SET ignore_checksum_failure = on;
=> SELECT * FROM wal LIMIT 1;
WARNING: page verification failed, calculated checksum 24386 but
expected 33119
id
----
2
(1 row)
```

Everything went fine in this case because we have damaged a non-critical part of the page header (the LSN of the latest WAL entry), not the data itself.

Non-Atomic Writes

A database page usually takes 8 kB, but at the low level writing is performed by blocks, which are often smaller (typically 512 bytes or 4 kB). Thus, if a failure occurs, a page may be written only partially. It makes no sense to apply regular WAL entries to such a page during recovery.

To avoid partial writes, PostgreSQL saves a full page image (FPI) in the WAL when this page is modified for the first time after the checkpoint start. This behavior is controlled by the *full_page_writes* parameter, but turning it off can lead to fatal data corruption. p. 196
on

If the recovery process comes across an FPI in the WAL, it will unconditionally write it to disk (without checking its LSN); just like any WAL entry, FPIs are protected by checksums, so their damage cannot go unnoticed. Regular WAL entries will then be applied to this state, which is guaranteed to be correct.

There is no separate WAL entry type for setting hint bits: this operation is considered non-critical because any query that accesses a page will set the required bits anew. However, any hint bit change will affect the page's checksum. So if checksums are enabled (or if the *wal_log_hints* parameter is on), hint bit modifications are logged as FPIs.¹ p. 76
off

Even though the logging mechanism excludes empty space from an FPI,² the size of the generated WAL files still significantly increases. The situation can be greatly improved if you enable FPI compression via the *wal_compression* parameter. off

Let's run a simple experiment using the *pgbench* utility. We will perform a checkpoint and immediately start a benchmark test with a hard-set number of transactions:

```
=> CHECKPOINT;
=> SELECT pg_current_wal_insert_lsn();
       pg_current_wal_insert_lsn
-----
0/43A58068
(1 row)
```

¹ backend/storage/buffer/bufmgr.c, MarkBufferDirtyHint function

² backend/access/transam/xloginsert.c, XLogRecordAssemble function

```
postgres$ /usr/local/pgsql/bin/pgbench -t 20000 internals
=> SELECT pg_current_wal_insert_lsn();
pg_current_wal_insert_lsn
-----
0/450F0628
(1 row)
```

Here is the size of the generated WAL entries:

```
=> SELECT pg_size_pretty('0/450F0628'::pg_lsn - '0/43A58068'::pg_lsn);
pg_size_pretty
-----
23 MB
(1 row)
```

In this example, FPIs take more than half of the total WAL size. You can see it for yourself in the collected statistics that show the number of WAL entries (N), the size of regular entries (Record size), and the FPI size for each resource type (Type):

```
postgres$ /usr/local/pgsql/bin/pg_waldump --stats \
-p /usr/local/pgsql/data/pg_wal -s 0/43A58068 -e 0/450F0628
```

Type	N	(%)	Record size	(%)	FPI size	(%)
XLLOG	1848 (1,51)		90552 (1,14)		14860928 (96,72)	
Transaction	20001 (16,37)		680114 (8,53)		0 (0,00)	
Storage	1 (0,00)		42 (0,00)		0 (0,00)	
CLOG	1 (0,00)		30 (0,00)		0 (0,00)	
Standby	2 (0,00)		96 (0,00)		0 (0,00)	
Heap2	20221 (16,55)		1282112 (16,08)		16384 (0,11)	
Heap	80047 (65,52)		5917982 (74,22)		273392 (1,78)	
Btree	49 (0,04)		2844 (0,04)		213480 (1,39)	
Total	122170		7973772 [34,17%]		15364184 [65,83%]	

This ratio will be smaller if data pages get modified between checkpoints several times. It is yet another reason to perform checkpoints less often.

We will repeat the same experiment to see if compression can help.

```
=> ALTER SYSTEM SET wal_compression = on;
=> SELECT pg_reload_conf();
=> CHECKPOINT;
```

```
=> SELECT pg_current_wal_insert_lsn();
pg_current_wal_insert_lsn
-----
0/450F06D8
(1 row)

postgres$ /usr/local/pgsql/bin/pgbench -t 20000 internals
=> SELECT pg_current_wal_insert_lsn();
pg_current_wal_insert_lsn
-----
0/45B94888
(1 row)
```

Here is the WAL size with compression enabled:

```
=> SELECT pg_size_pretty('0/45B94888'::pg_lsn - '0/450F06D8'::pg_lsn);
pg_size_pretty
-----
11 MB
(1 row)

postgres$ /usr/local/pgsql/bin/pg_waldump --stats \
-p /usr/local/pgsql/data/pg_wal -s 0/450F06D8 -e 0/45B94888
```

Type	N	(%)	Record size	(%)	FPI size	(%)
----	-	---	-----	---	-----	---
XLOG	1836	(1,50)	93636	(1,17)	2820704	(98,05)
Transaction	20001	(16,38)	680114	(8,53)	0	(0,00)
Storage	1	(0,00)	42	(0,00)	0	(0,00)
CLOG	1	(0,00)	30	(0,00)	0	(0,00)
Standby	3	(0,00)	150	(0,00)	0	(0,00)
Heap2	20220	(16,56)	1285090	(16,12)	244	(0,01)
Heap	80013	(65,54)	5911850	(74,16)	37188	(1,29)
Btree	15	(0,01)	906	(0,01)	18568	(0,65)
	-----		-----		-----	
Total	122090		7971818	[73,48%]	2876704	[26,52%]

To sum it up, when there is a large number of FPIs caused by enabled checksums or *full_page_writes* (that is, almost always), it makes sense to use compression despite some additional CPU overhead.

11.3 WAL Levels

The main objective of write-ahead logging is to enable crash recovery. But if you extend the scope of logged information, a WAL can be used for other purposes too.

PostgreSQL provides minimal, replica, and logical logging levels. Each level includes everything that is logged on the previous one and adds some more information.

replica The level in use is defined by the *wal_level* parameter; its modification requires a server restart.

Minimal

The minimal level guarantees only crash recovery. To save space, the operations on relations that have been created or truncated within the current transaction are not logged if they incur insertion of large volumes of data (like in the case of `CREATE TABLE AS SELECT` and `CREATE INDEX` commands).¹ Instead of being logged, all the required data is immediately flushed to disk, and system catalog changes become visible right after the transaction commit.

If such an operation is interrupted by a failure, the data that has already made it to disk remains invisible and does not affect consistency. If a failure occurs when the operation is complete, all the data required for applying the subsequent WAL entries is already saved to disk.

v. 13 The volume of data that has to be written into a newly created relation for this
2MB optimization to take effect is defined by the *wal_skip_threshold* parameter.

Let's see what gets logged at the minimal level.

v. 10 By default, a higher replica level is used, which supports data replication. If you
10 choose the minimal level, you also have to set the allowed number of walsender processes to zero in the *max_wal_senders* parameter:

```
=> ALTER SYSTEM SET wal_level = minimal;  
=> ALTER SYSTEM SET max_wal_senders = 0;
```

The server has to be restarted for these changes to take effect:

```
postgres$ pg_ctl restart -l /home/postgres/logfile
```

Note the current WAL position:

```
=> SELECT pg_current_wal_insert_lsn();
```

¹ `include/utils/rel.h`, `RelationNeedsWAL` macro


```
pg_current_wal_insert_lsn
-----
0/45B96B70
(1 row)
```

Truncate the table and keep inserting new rows within the same transaction until the *wal_skip_threshold* is exceeded:

```
=> BEGIN;
=> TRUNCATE TABLE wal;
=> INSERT INTO wal
    SELECT id FROM generate_series(1,100000) id;
=> COMMIT;
=> SELECT pg_current_wal_insert_lsn();
pg_current_wal_insert_lsn
-----
0/45B96D18
(1 row)
```

Instead of creating a new table, I run the TRUNCATE command as it generates fewer WAL entries.

Let's examine the generated WAL using the already familiar pg_waldump utility.

```
postgres$ /usr/local/pgsql/bin/pg_waldump \
-p /usr/local/pgsql/data/pg_wal -s 0/45B96B70 -e 0/45B96D18#
rmgr: Storage len (rec/tot): 42/ 42, tx: 0, lsn:
0/45B96B70, prev 0/45B96B38, desc: CREATE base/16391/24784
rmgr: Heap len (rec/tot): 123/ 123, tx: 134966, lsn:
0/45B96BA0, prev 0/45B96B70, desc: UPDATE off 45 xmax 134966 flags
0x60 ; new off 48 xmax 0, blkref #0: rel 1663/16391/1259 blk 0
rmgr: Btree len (rec/tot): 64/ 64, tx: 134966, lsn:
0/45B96C20, prev 0/45B96BA0, desc: INSERT_LEAF off 176, blkref #0:
rel 1663/16391/2662 blk 2
rmgr: Btree len (rec/tot): 64/ 64, tx: 134966, lsn:
0/45B96C60, prev 0/45B96C20, desc: INSERT_LEAF off 147, blkref #0:
rel 1663/16391/2663 blk 2
rmgr: Btree len (rec/tot): 64/ 64, tx: 134966, lsn:
0/45B96CA0, prev 0/45B96C60, desc: INSERT_LEAF off 254, blkref #0:
rel 1663/16391/3455 blk 4
rmgr: Transaction len (rec/tot): 54/ 54, tx: 134966, lsn:
0/45B96CE0, prev 0/45B96CA0, desc: COMMIT 2022-09-19 14:54:24.911435
MSK; rels: base/16391/24783
```

p. 158 The first entry logs creation of a new file for the relation (since `TRUNCATE` virtually rewrites the table).

The next four entries are associated with system catalog operations. They reflect the changes in the `pg_class` table and its three indexes.

Finally, there is a commit-related entry. Data insertion is not logged.

Replica

During crash recovery, WAL entries are replayed to restore the data on disk up to a consistent state. Backup recovery works in a similar way, but it can also restore the database state up to the specified recovery target point using a WAL archive. The number of archived WAL entries can be quite high (for example, they can span several days), so the recovery period will include multiple checkpoints. Therefore, the minimal WAL level is not enough: it is impossible to repeat an operation if it is unlogged. For backup recovery, WAL files must include *all* the operations.

The same is true for replication: unlogged commands will not be sent to a replica and will not be replayed on it.

p. 228 Things get even more complicated if a replica is used for executing queries. First of all, it needs to have the information on exclusive locks acquired on the primary server since they may conflict with queries on the replica. Second, it must be able to capture snapshots, which requires the information on active transactions. When p. 88 we deal with a replica, both local transactions and those running on the primary server have to be taken into account.

The only way to send this data to a replica is to periodically write it into WAL files.¹ It is done by the `bgwriter`² process, once in 15 seconds (the interval is hard-coded).

The ability to perform data recovery from a backup and use physical replication is guaranteed at the replica level.

¹ `backend/storage/ipc/standby, LogStandbySnapshot` function

² `backend/postmaster/bgwriter.c`

The replica level is used by default, so we can simply reset the parameters configured above and restart the server:

```
=> ALTER SYSTEM RESET wal_level;
=> ALTER SYSTEM RESET max_wal_senders;

postgres$ pg_ctl restart -l /home/postgres/logfile
```

Let's repeat the same workflow as before (but now we will insert only one row to get a neater output):

```
=> SELECT pg_current_wal_insert_lsn();
pg_current_wal_insert_lsn
-----
0/461B8330
(1 row)

=> BEGIN;
=> TRUNCATE TABLE wal;
=> INSERT INTO wal VALUES (42);
=> COMMIT;

=> SELECT pg_current_wal_insert_lsn();
pg_current_wal_insert_lsn
-----
0/461B85F0
(1 row)
```

Check out the generated WAL entries.

Apart from what we have seen at the minimal level, we have also got the following entries:

- replication-related entries of the Standby resource manager: `RUNNING_XACTS` (active transactions) and `LOCK`
- the entry that logs the `INSERT+INIT` operation, which initializes a new page and inserts a new row into this page

```

postgres$ /usr/local/pgsql/bin/pg_waldump \
-p /usr/local/pgsql/data/pg_wal -s 0/461B8330 -e 0/461B85F0
rmgr: Standby      len (rec/tot):   42/   42, tx:      134968, lsn:
0/461B8330, prev 0/461B82B8, desc: LOCK  xid 134968 db 16391 rel 16562
rmgr: Storage      len (rec/tot):   42/   42, tx:      134968, lsn:
0/461B8360, prev 0/461B8330, desc: CREATE base/16391/24786
rmgr: Heap         len (rec/tot):  123/  123, tx:      134968, lsn:
0/461B8390, prev 0/461B8360, desc: UPDATE off 49 xmax 134968 flags
0x60 ; new off 50 xmax 0, blkref #0: rel 1663/16391/1259 blk 0
rmgr: Btree        len (rec/tot):   64/   64, tx:      134968, lsn:
0/461B8410, prev 0/461B8390, desc: INSERT_LEAF off 178, blkref #0:
rel 1663/16391/2662 blk 2
rmgr: Btree        len (rec/tot):   64/   64, tx:      134968, lsn:
0/461B8450, prev 0/461B8410, desc: INSERT_LEAF off 149, blkref #0:
rel 1663/16391/2663 blk 2
rmgr: Btree        len (rec/tot):   64/   64, tx:      134968, lsn:
0/461B8490, prev 0/461B8450, desc: INSERT_LEAF off 256, blkref #0:
rel 1663/16391/3455 blk 4
rmgr: Heap         len (rec/tot):   59/   59, tx:      134968, lsn:
0/461B84D0, prev 0/461B8490, desc: INSERT+INIT off 1 flags 0x00,
blkref #0: rel 1663/16391/24786 blk 0
rmgr: Standby      len (rec/tot):   42/   42, tx:      0, lsn:
0/461B8510, prev 0/461B84D0, desc: LOCK  xid 134968 db 16391 rel 16562
rmgr: Standby      len (rec/tot):   54/   54, tx:      0, lsn:
0/461B8540, prev 0/461B8510, desc: RUNNING_XACTS nextXid 134969
latestCompletedXid 134967 oldestRunningXid 134968; 1 xacts: 134968
rmgr: Transaction len (rec/tot):  114/  114, tx:      134968, lsn:
0/461B8578, prev 0/461B8540, desc: COMMIT 2022-09-19 14:54:40.912861
MSK; rels: base/16391/24785; inval msgs: catcache 51 catcache 50
relcache 16562

```

Logical

Last but not least, the logical level enables logical decoding and logical replication. It has to be activated on the publishing server.

If we take a look at WAL entries, we will see that this level is almost the same as replica: it adds the entries related to replication sources and some arbitrary logical entries that may be generated by applications. For the most part, logical decoding depends on the information about active transactions (`RUNNING_XACTS`) because it requires capturing a snapshot to track system catalog changes.

Part III

Locks

12

Relation-Level Locks

12.1 About Locks

Locks control concurrent access to shared resources.

Concurrent access implies that several processes try to get one and the same resource at the same time. It makes no difference whether these processes are executed in parallel (if the hardware permits) or sequentially in the time-sharing mode. If there is no concurrent access, there is no need to acquire locks (for example, shared buffer cache requires locking, while local cache can do without it).

Before accessing a resource, the process must *acquire* a lock on it; when the operation is complete, this lock must be *released* for the resource to become available to other processes. If locks are managed by the database system, the established order of operations is maintained automatically; if locks are controlled by the application, the protocol must be enforced by the application itself.

At a low level, a lock is simply a chunk of shared memory that defines the lock status (whether it is acquired or not); it can also provide some additional information, such as the process number or acquisition time.

As you can guess, a shared memory segment is a resource in its own right. Concurrent access to such resources is regulated by synchronization primitives (such as semaphores or mutexes) provided by the operating system. They guarantee strictly consecutive execution of the code that accesses a shared resource. At the lowest level, these primitives are based on atomic CPU instructions (such as test-and-set or compare-and-swap).

In general, we can use locks to protect any resource as long as it can be unambiguously identified and assigned a particular lock address.

For example, we can lock a database object, such as a table (identified by oid in the system catalog), a data page (identified by a filename and a position within this file), a row version (identified by a page and an offset within this page). We can also lock a memory structure, such as a hash table or a buffer (identified by an assigned ID). We can even lock an abstract resource that has no physical representation.

But it is not always possible to acquire a lock at once: a resource can be already locked by someone else. Then the process either joins the queue (if it is allowed for this particular lock type) or tries again some time later. Either way, it has to wait for the lock to be released.

I would like to single out two factors that can greatly affect locking efficiency.

Granularity, or the “grain size” of a lock. Granularity is important if resources form a hierarchy.

For example, a table consists of pages, which, in their turn, consist of tuples. All these objects can be protected by locks. Table-level locks are coarse-grained; they forbid concurrent access even if the processes need to get to different pages or rows.

Row-level locks are fine-grained, so they do not have this drawback; however, the number of locks grows. To avoid using too much memory for lock-related metadata, PostgreSQL can apply various methods, one of them being *lock escalation*: if the number of fine-grained locks exceeds a certain threshold, they are replaced by a single lock of coarser granularity.

A set of modes in which a lock can be acquired.

As a rule, only two modes are applied. The *exclusive* mode is incompatible with all the other modes, including itself. The *shared* mode allows a resource to be locked by several processes at a time. The shared mode can be used for reading, while the exclusive mode is applied for writing.

In general, there may be other modes too. Names of modes are unimportant, it is their compatibility matrix that matters.

Finer granularity and support for multiple compatible modes give more opportunities for concurrent execution.

All locks can be classified by their duration.

Long-term locks are acquired for a potentially long time (in most cases, till the end of the transaction); they typically protect such resources as relations and rows. These locks are usually managed by PostgreSQL automatically, but a user still has some control over this process.

Long-term locks offer multiple modes that enable various concurrent operations on data. They usually have extensive infrastructure (including such features as wait queues, deadlock detection, and instrumentation) since its maintenance is anyway much cheaper than operations on protected data.

Short-term locks are acquired for fractions of a second and rarely last longer than several CPU instructions; they usually protect data structures in the shared memory. PostgreSQL manages such locks in a fully automated way.

Short-term locks typically offer very few modes and only basic infrastructure, which may have no instrumentation at all.

PostgreSQL supports various types of locks.¹ *Heavyweight locks* (which are acquired on relations and other objects) and *row-level locks* are considered long-term. Short-term locks comprise various *locks on memory structures*. Besides, there is also a distinct group of *predicate locks*, which, despite their name, are not locks at all.

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p. 270
p. 264

12.2 Heavyweight Locks

Heavyweight locks are long-term ones. Acquired at the *object* level, they are mainly used for relations, but can also be applied to some other types of objects. Heavyweight locks typically protect objects from concurrent updates or forbid their usage during restructuring, but they can address other needs too. Such a vague definition is deliberate: locks of this type are used for all kinds of purposes. The only thing they have in common is their internal structure.

Unless explicitly specified otherwise, the term *lock* usually implies a heavyweight lock.

¹ backend/storage/lmgr/README

64 Heavyweight locks are located in the server's shared memory¹ and can be displayed
100 in the `pg_locks` view. Their total number is limited by the `max_locks_per_transaction`
value multiplied by `max_connections`.

All transactions use a common pool of locks, so one transaction can acquire more than `max_locks_per_transaction` locks. What really matters is that the total number of locks in the system does not exceed the defined limit. Since the pool is initialized when the server is launched, changing any of these two parameters will require a server restart.

If a resource is already locked in an incompatible mode, the process trying to acquire another lock joins the queue. Waiting processes do not waste CPU time: they fall asleep until the lock is released and the operating system wakes them up.

p. 252 Two transactions can find themselves in a *deadlock* if the first transaction is unable to continue its operation until it gets a resource locked by the other transaction, which, in its turn, needs a resource locked by the first transaction. This case is rather simple; a deadlock can also involve more than two transactions. Since deadlocks cause infinite waits, PostgreSQL detects them automatically and aborts one of the affected transactions to ensure that normal operation can continue.

Different types of heavyweight locks serve different purposes, protect different resources, and support different modes, so we will consider them separately.

The following list provides the names of lock types as they appear in the `locktype` column of the `pg_locks` view:

p. 227 **transactionid** and **virtualxid** — a lock on a transaction ID

p. 228 **relation** — a relation-level lock

p. 241 **tuple** — a lock acquired on a tuple

p. 259 **object** — a lock on an object that is not a relation

p. 261 **extend** — a relation extension lock

p. 261 **page** — a page-level lock used by some index types

p. 262 **advisory** — an advisory lock

¹ backend/storage/lmgr/lock.c

Almost all heavyweight locks are acquired automatically as needed and are released automatically when the corresponding transaction completes. There are some exceptions though: for example, a relation-level lock can be set explicitly, while advisory locks are always managed by users.

12.3 Locks on Transaction IDs

Each transaction always holds an exclusive lock on its own ID (both virtual and real, *p. 81* if available).

PostgreSQL offers two locking modes for this purpose, exclusive and shared. Their compatibility matrix is very simple: the shared mode is compatible with itself, while the exclusive mode cannot be combined with any mode.

	Shared	Exclusive
Shared		×
Exclusive	×	×

To track completion of a particular transaction, a process can request a lock on this transaction's ID, in any mode. Since the transaction itself is already holding an exclusive lock on its own ID, another lock is impossible to acquire. The process requesting this lock joins the queue and falls asleep. Once the transaction completes, the lock is released, and the queued process wakes up. Clearly, it will not manage to acquire the lock because the corresponding resource has already disappeared, but this lock is not what is actually needed anyway.

Let's start a transaction in a separate session and get the process ID (PID) of the backend:

```
=> BEGIN;
=> SELECT pg_backend_pid();
       pg_backend_pid
-----
          28991
(1 row)
```

The started transaction holds an exclusive lock on its own virtual ID:

```
=> SELECT locktype, virtualxid, mode, granted
FROM pg_locks WHERE pid = 28991;
```

locktype	virtualxid	mode	granted
virtualxid	5/2	ExclusiveLock	t

(1 row)

Here locktype is the type of the lock, virtualxid is the virtual transaction ID (which identifies the locked resource), and mode is the locking mode (exclusive in this case). The granted flag shows whether the requested lock has been acquired.

Once the transaction gets a real ID, the corresponding lock is added to this list:

```
=> SELECT pg_current_xact_id();
```

pg_current_xact_id
134971

(1 row)

```
=> SELECT locktype, virtualxid, transactionid AS xid, mode, granted
FROM pg_locks WHERE pid = 28991;
```

locktype	virtualxid	xid	mode	granted
virtualxid	5/2		ExclusiveLock	t
transactionid		134971	ExclusiveLock	t

(2 rows)

Now this transaction holds exclusive locks on both its IDs.

12.4 Relation-Level Locks

PostgreSQL provides as many as eight modes in which a relation (a table, an index, or any other object) can be locked.¹ Such a variety allows you to maximize the number of concurrent commands that can be run on a relation.

The next page shows the compatibility matrix extended with examples of commands that require the corresponding locking modes. There is no point in memorizing all these modes or trying to find the logic behind their naming, but it is

¹ [postgresql.org/docs/14/explicit-locking#LOCKING-TABLES.html](https://www.postgresql.org/docs/14/explicit-locking#LOCKING-TABLES.html)

definitely useful to look through this data, draw some general conclusions, and refer to this table as required.

	AS	RS	RE	SUE	S	SRE	E	AE	
Access Share								×	SELECT
Row Share							×	×	SELECT FOR UPDATE/SHARE
Row Exclusive					×	×	×	×	INSERT, UPDATE, DELETE
Share Update Exclusive				×	×	×	×	×	VACUUM, CREATE INDEX CONCURRENTLY
Share			×	×		×	×	×	CREATE INDEX
Share Row Exclusive			×	×	×	×	×	×	CREATE TRIGGER
Exclusive		×	×	×	×	×	×	×	REFRESH MAT.VIEW CONCURRENTLY
Access Exclusive	×	×	×	×	×	×	×	×	DROP, TRUNCATE, VACUUM FULL, LOCK TABLE, REFRESH MAT.VIEW

The Access Share mode is the weakest one; it can be used with any other mode except Access Exclusive, which is incompatible with all the modes. Thus, a `SELECT` command can be run in parallel with almost any operation, but it does not let you drop a table that is being queried.

The first four modes allow concurrent heap modifications, while the other four do not. For example, the `CREATE INDEX` command uses the Share mode, which is compatible with itself (so you can create several indexes on a table concurrently) and with the modes used by read-only operations. As a result, `SELECT` commands can run in parallel, while `INSERT`, `UPDATE`, and `DELETE` commands will be blocked.

Conversely, unfinished transactions that modify heap data block the `CREATE INDEX` command. Instead, you can call `CREATE INDEX CONCURRENTLY`, which uses a weaker Share Update Exclusive mode: it takes longer to create an index (and this operation can even fail), but in return, concurrent data updates are allowed.

The `ALTER TABLE` command has multiple flavors that use different locking modes (Share Update Exclusive, Share Row Exclusive, Access Exclusive). All of them are described in the documentation.¹

¹ [postgresql.org/docs/14/sql-altertable.html](https://www.postgresql.org/docs/14/sql-altertable.html)

Examples in this part of the book rely on the accounts table again:

```
=> TRUNCATE accounts;
=> INSERT INTO accounts(id, client, amount)
VALUES
  (1, 'alice', 100.00),
  (2, 'bob', 200.00),
  (3, 'charlie', 300.00);
```

We will have to access the `pg_locks` table more than once, so let's create a view that shows all IDs in a single column, thus making the output more concise:

```
=> CREATE VIEW locks AS
SELECT pid,
       locktype,
       CASE locktype
         WHEN 'relation' THEN relation::regclass::text
         WHEN 'transactionid' THEN transactionid::text
         WHEN 'virtualxid' THEN virtualxid
       END AS lockid,
       mode,
       granted
FROM pg_locks
ORDER BY 1, 2, 3;
```

The transaction that is still running in the first session updates a row. This operation locks the accounts table and all its indexes, which results in two new locks of the relation type acquired in the Row Exclusive mode:

```
| => UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
```

```
=> SELECT locktype, lockid, mode, granted
FROM locks WHERE pid = 28991;
```

locktype	lockid	mode	granted
relation	accounts	RowExclusiveLock	t
relation	accounts_pkey	RowExclusiveLock	t
transactionid	134971	ExclusiveLock	t
virtualxid	5/2	ExclusiveLock	t

(4 rows)

12.5 Wait Queue

Heavyweight locks form a fair wait queue.¹ A process joins the queue if it attempts to acquire a lock that is incompatible either with the current lock or with the locks requested by other processes already in the queue.

While the first session is working on an update, let's try to create an index on this table in another session:

```
=> SELECT pg_backend_pid();
pg_backend_pid
-----
        29470
(1 row)

=> CREATE INDEX ON accounts(client);
```

The command hangs, waiting for the resource to be released. The transaction tries to lock the table in the Share mode but cannot do it:

```
=> SELECT locktype, lockid, mode, granted
FROM locks WHERE pid = 29470;
```

locktype	lockid	mode	granted
relation	accounts	ShareLock	f
virtualxid	6/3	ExclusiveLock	t

(2 rows)

Now let the third session start the `VACUUM FULL` command. It will also join the queue because it requires the Access Exclusive mode, which conflicts with all the other modes:

```
=> SELECT pg_backend_pid();
pg_backend_pid
-----
        29673
(1 row)

=> VACUUM FULL accounts;
```

¹ backend/storage/lmgr/lock.c, LockAcquire function

```
=> SELECT locktype, lockid, mode, granted
FROM locks WHERE pid = 29673;
```

locktype	lockid	mode	granted
relation	accounts	AccessExclusiveLock	f
transactionid	134975	ExclusiveLock	t
virtualxid	7/4	ExclusiveLock	t

(3 rows)

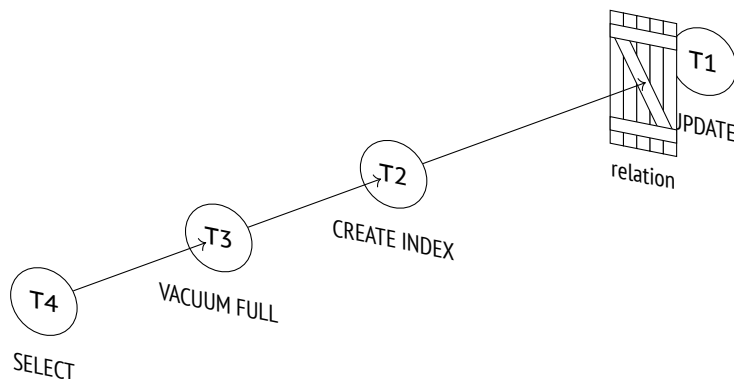
All the subsequent contenders will now have to join the queue, regardless of their locking mode. Even simple `SELECT` queries will honestly follow `VACUUM FULL`, although they are compatible with the Row Exclusive lock held by the first session performing an update.

```
=> SELECT pg_backend_pid();
pg_backend_pid
-----
          29883
(1 row)
=> SELECT * FROM accounts;
```

```
=> SELECT locktype, lockid, mode, granted
FROM locks WHERE pid = 29883;
```

locktype	lockid	mode	granted
relation	accounts	AccessShareLock	f
virtualxid	8/3	ExclusiveLock	t

(2 rows)



The `pg_blocking_pids` function gives a high-level overview of all waits. It shows the IDs of all processes queued before the specified one that are already holding or would like to acquire an incompatible lock: v. 9.6

```
=> SELECT pid,
        pg_blocking_pids(pid),
        wait_event_type,
        state,
        left(query,50) AS query
FROM pg_stat_activity
WHERE pid IN (28991,29470,29673,29883) \gx
```

pid	pg_blocking_pids	wait_event_type	state	query
28991	{}	Client	idle in transaction	UPDATE accounts SET amount = amount + 100.00 WHERE
29470	{28991}	Lock	active	CREATE INDEX ON accounts(client);
29673	{28991,29470}	Lock	active	VACUUM FULL accounts;
29883	{29673}	Lock	active	SELECT * FROM accounts;

To get more details, you can review the information provided in the `pg_locks` table.¹

Once the transaction is completed (either committed or aborted), all its locks are released.² The first process in the queue gets the requested lock and wakes up.

¹ wiki.postgresql.org/wiki/Lock_dependency_information

² `backend/storage/lmgr/lock.c`, `LockReleaseAll` & `LockRelease` functions

Here the transaction commit in the first session leads to sequential execution of all the queued processes:

```
| => ROLLBACK;  
| ROLLBACK
```

```
|| CREATE INDEX
```

```
||| VACUUM
```

```
|||| id | client | amount  
|----+-----+-----  
| 1 | alice  | 100.00  
| 2 | bob    | 200.00  
| 3 | charlie| 300.00  
| (3 rows)
```

13

Row-Level Locks

13.1 Lock Design

Thanks to snapshot isolation, heap tuples do not have to be locked for reading. However, two write transactions must not be allowed to modify one and the same row at the same time. Rows must be locked in this case, but heavyweight locks are not a very good choice for this purpose: each of them takes space in the server's shared memory (hundreds of bytes, not to mention all the supporting infrastructure), and PostgreSQL internal mechanisms are not designed to handle a huge number of concurrent heavyweight locks.

Some database systems solve this problem by lock escalation: if row-level locks are too many, they are replaced by a single lock of finer granularity (for example, by a page-level or table-level lock). It simplifies the implementation, but can greatly limit system throughput.

In PostgreSQL, the information on whether a particular row is locked is kept only in the header of its current heap tuple. Row-level locks are virtually attributes in heap pages rather than actual locks, and they are not reflected in RAM in any way.

A row is typically locked when it is being updated or deleted. In both cases, the current version of the row is marked as deleted. The attribute used for this purpose is the current transaction's ID specified in the `xmax` field, and it is the same ID (combined with additional hint bits) that indicates that the row is locked. If a transaction wants to modify a row but sees an active transaction ID in the `xmax` field of its current version, it has to wait for this transaction to complete. Once it is over, all the locks are released, and the waiting transaction can proceed. *p. 77*

This mechanism allows locking as many rows as required at no extra cost.

The downside of this solution is that other processes cannot form a queue, as RAM contains no information about such locks. Therefore, heavyweight locks are still required: a process waiting for a row to be released requests a lock on the ID of the transaction currently busy with this row. Once the transaction completes, the row becomes available again. Thus, the number of heavyweight locks is proportional to the number of concurrent processes rather than rows being modified.

13.2 Row-Level Locking Modes

Row-level locks support four modes.¹ Two of them implement exclusive locks that can be acquired by only one transaction at a time, while the other two provide shared locks that can be held by several transactions simultaneously.

Here is the compatibility matrix of these modes:

	Key Share	Share	No Key Update	Update
Key Share				×
Share			×	×
No Key Update		×	×	×
Update	×	×	×	×

Exclusive Modes

The Update mode allows modifying any tuple fields and even deleting the whole tuple, while the No Key Update mode permits only those changes that do not involve any fields related to unique indexes (in other words, foreign keys must not be affected).

The UPDATE command automatically chooses the weakest locking mode possible; keys usually remain unchanged, so rows are typically locked in the No Key Update mode.

¹ [postgresql.org/docs/14/explicit-locking#LOCKING-ROWS.html](https://www.postgresql.org/docs/14/explicit-locking#LOCKING-ROWS.html)

Let's create a function that uses `pageinspect` to display some tuple metadata that we are interested in, namely the `xmax` field and several hint bits:

```
=> CREATE FUNCTION row_locks(relname text, pageno integer)
RETURNS TABLE(
    ctid tid, xmax text,
    lock_only text, is_multi text,
    keys_upd text, keyshr text,
    shr text
)
AS $$
SELECT (pageno,lp)::text::tid,
    t_xmax,
    CASE WHEN t_infomask & 128 = 128 THEN 't' END,
    CASE WHEN t_infomask & 4096 = 4096 THEN 't' END,
    CASE WHEN t_infomask2 & 8192 = 8192 THEN 't' END,
    CASE WHEN t_infomask & 16 = 16 THEN 't' END,
    CASE WHEN t_infomask & 16+64 = 16+64 THEN 't' END
FROM heap_page_items(get_raw_page(relname,pageno))
ORDER BY lp;
$$ LANGUAGE sql;
```

Now start a transaction on the `accounts` table to update the balance of the first account (the key remains the same) and the ID of the second account (the key gets updated):

```
=> BEGIN;
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
=> UPDATE accounts SET id = 20 WHERE id = 2;
```

The page now contains the following metadata:

```
=> SELECT * FROM row_locks('accounts',0) LIMIT 2;
```

ctid	xmax	lock_only	is_multi	keys_upd	keyshr	shr
(0,1)	134980					
(0,2)	134980			t		

(2 rows)

The locking mode is defined by the `keys_updated` hint bit.

```
=> ROLLBACK;
```

The `SELECT FOR` command uses the same `xmax` field as a locking attribute, but in this case the `xmax_lock_only` hint bit must also be set. This bit indicates that the tuple is locked but not deleted, which means that it is still current:

```
=> BEGIN;
=> SELECT * FROM accounts WHERE id = 1 FOR NO KEY UPDATE;
=> SELECT * FROM accounts WHERE id = 2 FOR UPDATE;
=> SELECT * FROM row_locks('accounts',0) LIMIT 2;
 ctid | xmax | lock_only | is_multi | keys_upd | keyshr | shr
-----+-----+-----+-----+-----+-----+-----
(0,1) | 134981 | t         |          |          |        | 
(0,2) | 134981 | t         |          | t        |        | 
(2 rows)
=> ROLLBACK;
```

Shared Modes

The Share mode can be applied when a row needs to be read, but its modification by another transaction must be forbidden. The Key Share mode allows updating any tuple fields except key attributes.

Of all the shared modes, the PostgreSQL core uses only Key Share, which is applied when foreign keys are being checked. Since it is compatible with the No Key Update exclusive mode, foreign key checks do not interfere with concurrent updates of non-key attributes. As for applications, they can use any shared modes they like.

Let me stress once again that simple `SELECT` commands never use row-level locks.

```
=> BEGIN;
=> SELECT * FROM accounts WHERE id = 1 FOR KEY SHARE;
=> SELECT * FROM accounts WHERE id = 2 FOR SHARE;
```

Here is what we see in the heap tuples:

```
=> SELECT * FROM row_locks('accounts',0) LIMIT 2;
 ctid | xmax | lock_only | is_multi | keys_upd | keyshr | shr
-----+-----+-----+-----+-----+-----+-----
(0,1) | 134982 | t         |          |          | t      | 
(0,2) | 134982 | t         |          |          | t      | t
(2 rows)
```

The `xmax_keyshr_lock` bit is set for both operations, but you can recognize the Share mode by other hint bits.¹

13.3 Multitransactions

As we have seen, the locking attribute is represented by the `xmax` field, which is set to the ID of the transaction that has acquired the lock. So how is this attribute set for a shared lock held by several transactions at a time?

When dealing with shared locks, PostgreSQL applies so-called *multitransactions* (multixacts).² A multitransaction is a group of transactions that is assigned a separate ID. Detailed information on group members and their locking modes is stored in files under the `PGDATA/pg_multixact` directory. For faster access, locked pages are cached in the shared memory of the server;³ all changes are logged to ensure fault tolerance.

Multixact IDs have the same 32-bit length as regular transaction IDs, but they are issued independently. It means that transactions and multitransactions can potentially have the same IDs. To differentiate between the two, PostgreSQL uses an additional hint bit: `xmax_is_multi`.

Let's add one more exclusive lock acquired by another transaction (Key Share and No Key Update modes are compatible):

```
=> BEGIN;
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
```

```
=> SELECT * FROM row_locks('accounts',0) LIMIT 2;
```

ctid	xmax	lock_only	is_multi	keys_upd	keyshr	shr
(0,1)	1		t			
(0,2)	134982	t			t	t

(2 rows)

¹ `include/access/htup_details.h`

² `backend/access/transam/multixact.c`

³ `backend/access/transam/slru.c`

The `xmax_is_multi` bit shows that the first row uses a multitransaction ID instead of a regular one.

Without going into further implementation details, let's display the information on all the possible row-level locks using the `pgrowlocks` extension:

```
=> CREATE EXTENSION pgrowlocks;
=> SELECT * FROM pgrowlocks('accounts') \gx
-[ RECORD 1 ]-----
locked_row | (0,1)
locker     | 1
multi      | t
xids       | {134982,134983}
modes      | {"Key Share","No Key Update"}
pids       | {30434,30734}
-[ RECORD 2 ]-----
locked_row | (0,2)
locker     | 134982
multi      | f
xids       | {134982}
modes      | {"For Share"}
pids       | {30434}
```

It looks a lot like querying the `pg_locks` view, but the `pgrowlocks` function has to access heap pages, as RAM contains no information on row-level locks.

```
=> COMMIT;
```

```
| => ROLLBACK;
```

p. 139 Since multixact IDs are 32-bit, they are subject to wraparound because of counter limits, just like regular transaction IDs. Therefore, PostgreSQL has to process multixact IDs in a way similar to freezing: old multixact IDs are replaced with new ones (or with a regular transaction ID if only one transaction is holding the lock by that time).¹

But while regular transaction IDs are frozen only in the `xmin` field (as a non-empty `xmax` indicates that the tuple is outdated and will soon be removed), it is the `xmax` field that has to be frozen for multitransactions: the current row version may be repeatedly locked by new transactions in a shared mode.

¹ `backend/access/heap/heapam.c`, `FreezeMultiXactId` function

Freezing of multitransactions can be managed by server parameters, which are similar to those provided for regular freezing: `vacuum_multixact_freeze_min_age`, `vacuum_multixact_freeze_table_age`, `autovacuum_multixact_freeze_max_age`, as well as `vacuum_multixact_failsafe_age`.

V. 14

13.4 Wait Queue

Exclusive Modes

Since a row-level lock is just an attribute, the queue is arranged in a not-so-trivial way. When a transaction is about to modify a row, it has to follow these steps:¹

- 1 If the `xmax` field and the hint bits indicate that the row is locked in an incompatible mode, acquire an exclusive heavyweight lock on the tuple that is being modified.
- 2 If necessary, wait until all the incompatible locks are released by requesting a lock on the ID of the `xmax` transaction (or several transactions if `xmax` contains a mutixact ID).
- 3 Write its own ID into `xmax` in the tuple header and set the required hint bits.
- 4 Release the tuple lock if it was acquired in the first step.

A *tuple* lock is yet another kind of heavyweight locks, which has the tuple type (not to be confused with a regular row-level lock).

It may seem that steps 1 and 4 are redundant and it is enough to simply wait until all the locking transactions are over. However, if several transactions are trying to update one and the same row, all of them will be waiting on the transaction currently processing this row. Once it completes, they will find themselves in a race condition for the right to lock the row, and some “unlucky” transactions may have to wait for an indefinitely long time. Such a situation is called *resource starvation*.

A tuple lock identifies the first transaction in the queue and guarantees that it will be the next one to get the lock.

¹ `backend/access/heap/README.tuplock`

But you can see it for yourself. Since PostgreSQL acquires many different locks during its operation, and each of them is reflected in a separate row in the `pg_locks` table, I am going to create yet another view on top of `pg_locks`. It will show this information in a more concise form, keeping only those locks that we are currently interested in (the ones related to the accounts table and to the transaction itself, except for any locks on virtual IDs):

```
=> CREATE VIEW locks_accounts AS
SELECT pid,
       locktype,
       CASE locktype
         WHEN 'relation' THEN relation::regclass::text
         WHEN 'transactionid' THEN transactionid::text
         WHEN 'tuple' THEN relation::regclass||'('||page||','||tuple||')'
       END AS lockid,
       mode,
       granted
FROM pg_locks
WHERE locktype in ('relation','transactionid','tuple')
      AND (locktype != 'relation' OR relation = 'accounts'::regclass)
ORDER BY 1, 2, 3;
```

Let's start the first transaction and update a row:

```
=> BEGIN;
=> SELECT txid_current(), pg_backend_pid();
      txid_current | pg_backend_pid
-----+-----
      134985 |           30734
(1 row)
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
```

The transaction has completed all the four steps of the workflow and is now holding a lock on the table:

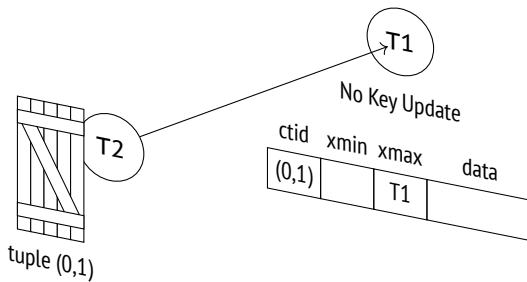
```
=> SELECT * FROM locks_accounts WHERE pid = 30734;
 pid | locktype | lockid | mode | granted
-----+-----+-----+-----+-----
 30734 | relation | accounts | RowExclusiveLock | t
 30734 | transactionid | 134985 | ExclusiveLock | t
(2 rows)
```

Start the second transaction and try to update the same row. The transaction will hang, waiting on a lock:

```

=> BEGIN;
=> SELECT txid_current(), pg_backend_pid();
      txid_current | pg_backend_pid
      -----+-----
            134986 |             30805
(1 row)
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;

```



The second transaction only gets as far as the second step. For this reason, apart from locking the table and its own ID, it adds two more locks, which are also reflected in the pg_locks view: the tuple lock acquired at the first step and the lock of the ID of the second transaction requested at the second step:

```

=> SELECT * FROM locks_accounts WHERE pid = 30805;

```

pid	locktype	lockid	mode	granted
30805	relation	accounts	RowExclusiveLock	t
30805	transactionid	134985	ShareLock	f
30805	transactionid	134986	ExclusiveLock	t
30805	tuple	accounts(0,1)	ExclusiveLock	t

(4 rows)

The third transaction will get stuck on the first step. It will try to acquire a lock on the tuple and will stop at this point:

```

=> BEGIN;
=> SELECT txid_current(), pg_backend_pid();
      txid_current | pg_backend_pid
      -----+-----
            134987 |             30876
(1 row)
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;

```

```
=> SELECT * FROM locks_accounts WHERE pid = 30876;
```

pid	locktype	lockid	mode	granted
30876	relation	accounts	RowExclusiveLock	t
30876	transactionid	134987	ExclusiveLock	t
30876	tuple	accounts(0,1)	ExclusiveLock	f

(3 rows)

The fourth and all the subsequent transactions trying to update this row will not differ from the third transaction in this respect: all of them will be waiting on the same tuple lock.

```
=> BEGIN;
```

```
=> SELECT txid_current(), pg_backend_pid();
```

txid_current	pg_backend_pid
134988	30947

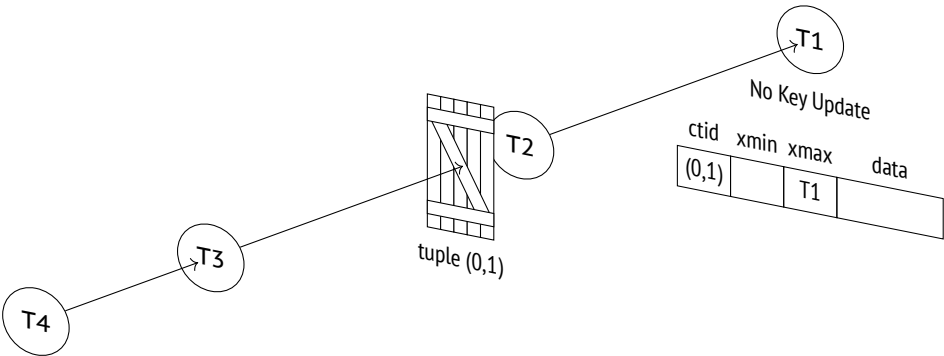
(1 row)

```
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
```

```
=> SELECT * FROM locks_accounts WHERE pid = 30876;
```

pid	locktype	lockid	mode	granted
30876	relation	accounts	RowExclusiveLock	t
30876	transactionid	134987	ExclusiveLock	t
30876	tuple	accounts(0,1)	ExclusiveLock	f

(3 rows)



To get the full picture of the current waits, you can extend the `pg_stat_activity` view with the information on locking processes:

```
=> SELECT pid,
        wait_event_type,
        wait_event,
        pg_blocking_pids(pid)
FROM pg_stat_activity
WHERE pid IN (30734,30805,30876,30947);
```

pid	wait_event_type	wait_event	pg_blocking_pids
30734	Client	ClientRead	{}
30805	Lock	transactionid	{30734}
30876	Lock	tuple	{30805}
30947	Lock	tuple	{30805,30876}

(4 rows)

If the first transaction is aborted, everything will work as expected: all the subsequent transactions will move one step further without jumping the queue.

And yet it is more likely that the first transaction will be committed. At the Repeatable Read or Serializable isolation levels, it would result in a serialization failure, so the second transaction would have to be aborted¹ (and all the subsequent transactions in the queue would get aborted too). But at the Read Committed isolation level the modified row will be re-read, and its update will be retried.

So, the first transaction is committed:

```
| => COMMIT;
```

The second transaction wakes up and successfully completes the third and the fourth steps of the workflow:

```
|| UPDATE 1
```

```
=> SELECT * FROM locks_accounts WHERE pid = 30805;
```

pid	locktype	lockid	mode	granted
30805	relation	accounts	RowExclusiveLock	t
30805	transactionid	134986	ExclusiveLock	t

(2 rows)

As soon as the second transaction releases the tuple lock, the third one also wakes up, but it sees that the xmax field of the new tuple contains a different ID already.

¹ backend/executor/nodeModifyTable.c, ExecUpdate function

At this point, the above workflow is over. At the Read Committed isolation level, one more attempt to lock the row is performed,¹ but it does not follow the outlined steps. The third transaction is now waiting for the second one to complete without trying to acquire a tuple lock:

```
=> SELECT * FROM locks_accounts WHERE pid = 30876;
```

pid	locktype	lockid	mode	granted
30876	relation	accounts	RowExclusiveLock	t
30876	transactionid	134986	ShareLock	f
30876	transactionid	134987	ExclusiveLock	t

(3 rows)

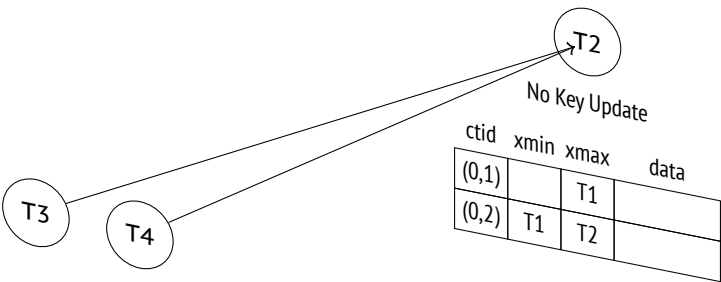
The fourth transaction does the same:

```
=> SELECT * FROM locks_accounts WHERE pid = 30947;
```

pid	locktype	lockid	mode	granted
30947	relation	accounts	RowExclusiveLock	t
30947	transactionid	134986	ShareLock	f
30947	transactionid	134988	ExclusiveLock	t

(3 rows)

Now both the third and the fourth transactions are waiting for the second one to complete, risking to get into a race condition. The queue has virtually fallen apart.



If other transactions had joined the queue while it still existed, all of them would have been dragged into this race.

¹ backend/access/heap/heapam_handler.c, heapam_tuple_lock function

Conclusion: it is not a good idea to update one and the same table row in multiple concurrent processes. Under high load, this hotspot can quickly turn into a bottleneck that causes performance issues.

Let's commit all the started transactions.

```
||      => COMMIT;
```

```
|||     UPDATE 1  
|||     => COMMIT;
```

```
|||     UPDATE 1  
|||     => COMMIT;
```

Shared Modes

PostgreSQL acquires shared locks only for referential integrity checks. Using them in a high-load application can lead to resource starvation, and a two-level locking model cannot prevent such an outcome.

Let's recall the steps a transaction should take to lock a row:

- 1 If the xmax field and hint bits indicate that the row is locked in the *exclusive* mode, acquire an exclusive heavyweight tuple lock.
- 2 If required, wait for all the *incompatible* locks to be released by requesting a lock on the ID of the xmax transaction (or several transactions if xmax contains a multixact ID).
- 3 Write its own ID into xmax in the tuple header and set the required hint bits.
- 4 Release the tuple lock if it was acquired in the first step.

The first two steps imply that if the locking modes are *compatible*, the transaction will *jump the queue*.

Let's repeat our experiment from the very beginning.

```
=> TRUNCATE accounts;
```

```
=> INSERT INTO accounts(id, client, amount)
VALUES
(1, 'alice', 100.00),
(2, 'bob', 200.00),
(3, 'charlie', 300.00);
```

Start the first transaction:

```
=> BEGIN;
=> SELECT txid_current(), pg_backend_pid();
   txid_current | pg_backend_pid
-----+-----
      134991 |           30734
(1 row)
```

The row is now locked in a shared mode:

```
=> SELECT * FROM accounts WHERE id = 1 FOR SHARE;
```

The second transaction tries to update the same row, but it is not allowed: Share and No Key Update modes are incompatible:

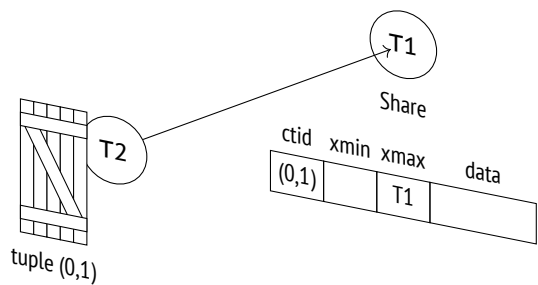
```
=> BEGIN;
=> SELECT txid_current(), pg_backend_pid();
   txid_current | pg_backend_pid
-----+-----
      134992 |           30805
(1 row)
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
```

Waiting for the first transaction to complete, the second transaction is holding the tuple lock, just like in the previous example:

```
=> SELECT * FROM locks_accounts WHERE pid = 30805;
```

pid	locktype	lockid	mode	granted
30805	relation	accounts	RowExclusiveLock	t
30805	transactionid	134991	ShareLock	f
30805	transactionid	134992	ExclusiveLock	t
30805	tuple	accounts(0,1)	ExclusiveLock	t

(4 rows)

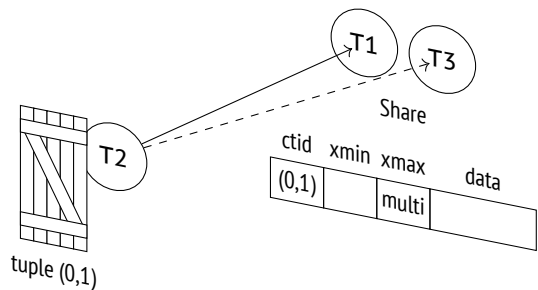


Now let the third transaction lock the row in a shared mode. Such a lock is compatible with the already acquired lock, so this transaction jumps the queue:

```
=> BEGIN;
=> SELECT txid_current(), pg_backend_pid();
       txid_current | pg_backend_pid
-----+-----
       134993      |          30876
(1 row)
=> SELECT * FROM accounts WHERE id = 1 FOR SHARE;
```

We have got two transactions locking the same row:

```
=> SELECT * FROM pgrowlocks('accounts') \gx
-[ RECORD 1 ]-----
locked_row | (0,1)
locker     | 2
multi      | t
xids       | {134991,134993}
modes      | {Share,Share}
pids       | {30734,30876}
```



If the first transaction completes at this point, the second one will wake up to see that the row is still locked and will get back to the queue—but this time it will find itself behind the third transaction:

```
|      => COMMIT;
```



```
=> SELECT * FROM locks_accounts WHERE pid = 30805;
```

pid	locktype	lockid	mode	granted
30805	relation	accounts	RowExclusiveLock	t
30805	transactionid	134992	ExclusiveLock	t
30805	transactionid	134993	ShareLock	f
30805	tuple	accounts(0,1)	ExclusiveLock	t

(4 rows)

And only when the third transaction completes will the second one be able to perform an update (unless other shared locks appear within this time interval).

```
|||      => COMMIT;
```



```
||      UPDATE 1
||      => COMMIT;
```

Foreign key checks are unlikely to cause any issues, as key attributes usually remain unchanged and Key Share can be used together with No Key Update. But in most cases, you should avoid shared row-level locks in applications.

13.5 No-Wait Locks

SQL commands usually wait for the requested resources to be freed. But sometimes it makes sense to cancel the operation if the lock cannot be acquired immediately. For this purpose, commands like `SELECT`, `LOCK`, and `ALTER` offer the `NOWAIT` clause.

Let's lock a row:

```
=> BEGIN;
```

```
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 1;
```

The command with the `NOWAIT` clause immediately completes with an error if the requested resource is locked:

```
=> SELECT * FROM accounts
    FOR UPDATE NOWAIT;
ERROR:  could not obtain lock on row in relation "accounts"
```

Such an error can be captured and handled by the application code.

The `UPDATE` and `DELETE` commands do not have the `NOWAIT` clause. Instead, you can try to lock the row using the `SELECT FOR UPDATE NOWAIT` command and then update or delete it if the attempt is successful.

In some rare cases, it may be convenient to skip the already locked rows and start processing the available ones right away. This is exactly what `SELECT FOR` does when run with the `SKIP LOCKED` clause:

```
=> SELECT * FROM accounts
    ORDER BY id
    FOR UPDATE SKIP LOCKED
    LIMIT 1;
   id | client | amount
-----+-----+-----
    2 | bob    | 200.00
(1 row)
```

In this example, the first (already locked) row was skipped, and the query locked and returned the second row.

This approach enables us to process rows in batches or set up parallel processing of event queues. However, avoid inventing other use cases for this command—most tasks can be addressed using much simpler methods. p. 160

Last but not least, you can avoid long waits by setting a timeout:

```
=> SET lock_timeout = '1s';
=> ALTER TABLE accounts DROP COLUMN amount;
ERROR:  canceling statement due to lock timeout
```

The command completes with an error because it has failed to acquire a lock within one second. A timeout can be set not only at the session level, but also at lower levels, for example, for a particular transaction.

This method prevents long waits during table processing when the command requiring an exclusive lock is executed under load. If an error occurs, this command can be retried after a while.

While *statement_timeout* limits the total time of operator execution, the *lock_timeout* parameter defines the maximum time that can be spent waiting on a lock.

=> **ROLLBACK;**

13.6 Deadlocks

A transaction may sometimes require a resource that is currently being used by another transaction, which, in its turn, may be waiting on a resource locked by the third transaction, and so on. Such transactions get queued using heavyweight locks.

But occasionally a transaction already in the queue may need yet another resource, so it has to join the same queue again and wait for this resource to be released. A *deadlock*¹ occurs: the queue now has a circular dependency that cannot resolve on its own.

For better visualization, let's draw a wait-for graph. Its nodes represent active processes, while the edges shown as arrows point from the processes waiting on locks to the processes holding these locks. If the graph has a *cycle*, that is, a node can reach itself following the arrows, it means that a deadlock has occurred.

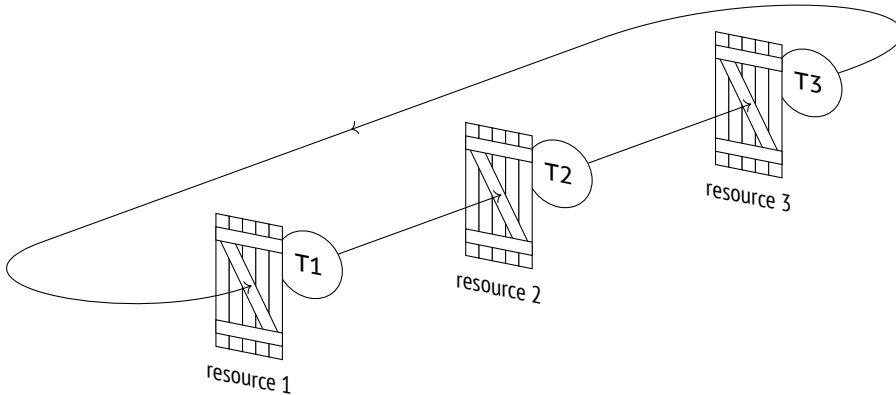
The illustrations here show transactions rather than processes. This substitution is usually acceptable because one transaction is executed by one process, and locks can only be acquired within a transaction. But in general, it is more correct to talk about processes, as some locks may not be released right away when the transaction is complete.

If a deadlock has occurred, and none of its participants has set a timeout, transactions will be waiting on each other forever. That's why the lock manager² performs automatic deadlock detection.

However, this check requires some effort, which should not be wasted each time a lock is requested (after all, deadlocks do not happen too often). So if the process

¹ [postgresql.org/docs/14/explicit-locking#LOCKING-DEADLOCKS.html](https://www.postgresql.org/docs/14/explicit-locking#LOCKING-DEADLOCKS.html)

² [backend/storage/lmgr/README](#)



makes an unsuccessful attempt to acquire a lock and falls asleep after joining the queue, PostgreSQL automatically sets a timeout as defined by the *deadlock_timeout* parameter.¹ If the resource becomes available earlier—great, then the extra cost of the check will be avoided. But if the wait continues after the *deadlock_timeout* units of time, the waiting process wakes up and initiates the check.² 1s

This check effectively consists in building a wait-for graph and searching it for cycles.³ To “freeze” the current state of the graph, PostgreSQL stops any processing of heavyweight locks for the whole duration of the check.

If no deadlocks are detected, the process falls asleep again; sooner or later its turn will come.

If a deadlock is detected, one of the transactions will be forced to terminate, thus releasing its locks and enabling other transactions to continue their execution. In most cases, it is the transaction initiating the check that gets interrupted, but if the cycle includes an autovacuum process that is not currently freezing tuples to prevent wraparound, the server terminates autovacuum as having lower priority.

Deadlocks usually indicate bad application design. To discover such situations, you have two things to watch out for: the server log will contain the corresponding messages, and the deadlocks value in the *pg_stat_database* table will be increasing.

¹ backend/storage/lmgr/proc.c, ProcSleep function

² backend/storage/lmgr/proc.c, CheckDeadLock function

³ backend/storage/lmgr/deadlock.c

Deadlocks by Row Updates

Although deadlocks are ultimately caused by heavyweight locks, it is mostly row-level locks acquired in different order that lead to them.

Suppose a transaction is going to transfer \$100 between two accounts. It starts by drawing this sum from the first account:

```
=> BEGIN;  
=> UPDATE accounts SET amount = amount - 100.00 WHERE id = 1;  
UPDATE 1
```

At the same time, another transaction is going to transfer \$10 from the second account to the first one. It begins by drawing this sum from the second account:

```
=> BEGIN;  
=> UPDATE accounts SET amount = amount - 10.00 WHERE id = 2;  
UPDATE 1
```

Now the first transaction attempts to increase the amount in the second account but sees that the corresponding row is locked:

```
=> UPDATE accounts SET amount = amount + 100.00 WHERE id = 2;
```

Then the second transaction tries to update the first account but also gets locked:

```
=> UPDATE accounts SET amount = amount + 10.00 WHERE id = 1;
```

This circular wait will never resolve on its own. Unable to obtain the resource within one second, the first transaction initiates a deadlock check and gets aborted by the server:

```
ERROR: deadlock detected  
DETAIL: Process 30434 waits for ShareLock on transaction 134999;  
blocked by process 30734.  
Process 30734 waits for ShareLock on transaction 134998; blocked by  
process 30434.  
HINT: See server log for query details.  
CONTEXT: while updating tuple (0,2) in relation "accounts"
```

Now the second transaction can continue. It wakes up and performs an update:

```
| UPDATE 1
```

Let's complete the transactions.

```
| => ROLLBACK;
```

```
=> ROLLBACK;
```

The right way to perform such operations is to lock resources in the same order. For example, in this particular case the accounts could have been locked in ascending order based on their numbers.

Deadlocks Between Two UPDATE Statements

In some cases deadlocks seem impossible, and yet they do occur.

We usually assume that SQL commands are atomic, but is it really so? Let's take a closer look at UPDATE: this command locks rows as they are being updated rather than all at once, and it does not happen simultaneously. So if one UPDATE command modifies several rows in one order while the other is doing the same in a different order, a deadlock can occur.

Let's reproduce this scenario. First, we are going to build an index on the amount column, in descending order:

```
=> CREATE INDEX ON accounts(amount DESC);
```

To be able to observe the process, we can write a function that slows things down:

```
=> CREATE FUNCTION inc_slow(n numeric)
RETURNS numeric
AS $$
    SELECT pg_sleep(1);
    SELECT n + 100.00;
$$ LANGUAGE sql;
```

The first UPDATE command is going to update all the tuples. The execution plan relies on a sequential scan of the whole table.

```
=> EXPLAIN (costs off)
UPDATE accounts SET amount = inc_slow(amount);
      QUERY PLAN
-----
Update on accounts
-> Seq Scan on accounts
(2 rows)
```

To make sure that the heap page stores the rows in ascending order based on the amount column, we have to truncate the table and insert the rows anew:

```
=> TRUNCATE accounts;
=> INSERT INTO accounts(id, client, amount)
VALUES
  (1,'alice',100.00),
  (2,'bob',200.00),
  (3,'charlie',300.00);
=> ANALYZE accounts;
=> SELECT ctid, * FROM accounts;
 ctid | id | client | amount
-----+-----+-----+-----
(0,1) | 1 | alice  | 100.00
(0,2) | 2 | bob    | 200.00
(0,3) | 3 | charlie| 300.00
(3 rows)
```

p. 175 The sequential scan will update the rows in the same order (it is not always true for large tables though).

Let's start the update:

```
| => UPDATE accounts SET amount = inc_slow(amount);
```

Meanwhile, we are going to forbid sequential scans in another session:

```
|| => SET enable_seqscan = off;
```

As a result, the planner chooses an index scan for the next UPDATE command.

```
|| => EXPLAIN (costs off)
|| UPDATE accounts SET amount = inc_slow(amount)
|| WHERE amount > 100.00;
```



```
ERROR: deadlock detected
DETAIL: Process 30805 waits for ShareLock on transaction 135005;
blocked by process 30734.
Process 30734 waits for ShareLock on transaction 135006; blocked by
process 30805.
HINT: See server log for query details.
CONTEXT: while updating tuple (0,2) in relation "accounts"
```

And the other completes its execution:

```
| UPDATE 3
```

Although such situations seem impossible, they do occur in high-load systems when batch row updates are performed.

14

Miscellaneous Locks

14.1 Non-Object Locks

To lock a resource that is not considered a *relation*, PostgreSQL uses heavyweight locks of the object type.¹ You can lock almost anything that is stored in the system catalog: tablespaces, subscriptions, schemas, roles, policies, enumerated data types, and so on.

Let's start a transaction that creates a table:

```
=> BEGIN;
=> CREATE TABLE example(n integer);
```

Now take a look at non-relation locks in the `pg_locks` table:

```
=> SELECT database,
(
    SELECT datname FROM pg_database WHERE oid = database
) AS dbname,
classid,
(
    SELECT relname FROM pg_class WHERE oid = classid
) AS classname,
objid,
mode,
granted
FROM pg_locks
WHERE locktype = 'object'
AND pid = pg_backend_pid() \gx
```

¹ backend/storage/lmgr/lmgr.c, LockDatabaseObject & LockSharedObject functions

```
-[ RECORD 1 ]-----  
database    | 16391  
dbname      | internals  
classid     | 2615  
classname   | pg_namespace  
objid       | 2200  
mode        | AccessShareLock  
granted     | t
```

The locked resource is defined here by three values:

database — the oid of the database that contains the object being locked (or zero if this object is common to the whole cluster)

classid — the oid listed in `pg_class` that corresponds to the name of the system catalog table defining the type of the resource

objid — the oid listed in the system catalog table referenced by `classid`

The database value points to the `internals` database; it is the database to which the current session is connected. The `classid` column points to the `pg_namespace` table, which lists schemas.

Now we can decipher the `objid`:

```
=> SELECT nsname FROM pg_namespace WHERE oid = 2200;  
nsname  
-----  
public  
(1 row)
```

Thus, PostgreSQL has locked the `public` schema to make sure that no one can delete it while the transaction is still running.

Similarly, object deletion requires exclusive locks on both the object itself and all the resources it depends on.¹

```
=> ROLLBACK;
```

¹ `backend/catalog/dependency.c`, `performDeletion` function

14.2 Relation Extension Locks

As the number of tuples in a relation grows, PostgreSQL inserts new tuples into free space in the already available pages whenever possible. But it is clear that at some point it will have to add new pages, that is, to *extend the relation*. In terms of the physical layout, new pages get added to the end of the corresponding file (which, in turn, can lead to creation of a new file).

For new pages to be added by only one process at a time, this operation is protected by a special heavyweight lock of the extend type.¹ Such a lock is also used by index vacuuming to forbid adding new pages during an index scan.

Relation extension locks behave a bit differently from what we have seen so far:

- They are released as soon as the extension is created, without waiting for the transaction to complete.
- They cannot cause a deadlock, so they are not included into the wait-for graph.

However, a deadlock check will still be performed if the procedure of extending a relation is taking longer than *deadlock_timeout*. It is not a typical situation, but it can happen if a large number of processes perform multiple insertions concurrently. In this case, the check can be called multiple times, virtually paralyzing normal system operation.

To minimize this risk, heap files are extended by several pages at once (in proportion to the number of processes awaiting the lock, but not more than 512 pages per operation).² An exception to this rule is B-tree index files, which are extended by one page at a time.³ v. 9.6

14.3 Page Locks

A page-level heavyweight lock of the page type⁴ is applied only by GIN indexes, and only in the following case.

¹ backend/storage/lmgr/lmgr.c, LockRelationForExtension function

² backend/access/heap/hio.c, RelationAddExtraBlocks function

³ backend/access/nbtree/nbtpage.c, _bt_getbuf function

⁴ backend/storage/lmgr/lmgr.c, LockPage function

GIN indexes can speed up search of elements in compound values, such as words in text documents. They can be roughly described as B-trees that store separate words rather than the whole documents. When a new document is added, the index has to be thoroughly updated to include each word that appears in this document.

on To improve performance, GIN indexes allow deferred insertion, which can be enabled using the *fastupdate* storage parameter. New words are first quickly added into an unordered *pending list*, and after a while all the accumulated entries are moved into the main index structure. Since different documents are likely to contain duplicate words, this approach proves to be quite cost-effective.

To avoid concurrent transfer of words by several processes, the index metapage is locked in the exclusive mode until all the words are moved from the pending list to the main index. This lock does not interfere with regular index usage.

Just like relation extension locks, page locks are released immediately when the task is complete, without waiting for the end of the transaction, so they never cause deadlocks.

14.4 Advisory Locks

Unlike other heavyweight locks (such as relation locks), *advisory locks*¹ are never acquired automatically: they are controlled by the application developer. These locks are convenient to use if the application requires dedicated locking logic for some particular purposes.

Suppose we need to lock a resource that does not correspond to any database object (which we could lock using `SELECT FOR` or `LOCK TABLE` commands). In this case, the resource needs to be assigned a numeric ID. If the resource has a unique name, the easiest way to do it is to generate a hash code for this name:

```
=> SELECT hashtext('resource1');
      hashtext
      -----
      991601810
(1 row)
```

¹ [postgresql.org/docs/14/explicit-locking#ADVISORY-LOCKS.html](https://www.postgresql.org/docs/14/explicit-locking#ADVISORY-LOCKS.html)

PostgreSQL provides a whole class of functions for managing advisory locks.¹ Their names begin with the `pg_advisory` prefix and can contain the following words that hint at the function purpose:

lock — acquire a lock

try — acquire a lock if it can be done without waits

unlock — release the lock

share — use a shared locking mode (by default, the exclusive mode is used)

xact — acquire a lock till the end of the transaction (by default, the lock is held till the end of the session)

Let's acquire an exclusive lock until the end of the session:

```
=> BEGIN;
=> SELECT pg_advisory_lock(hashtext('resource1'));
=> SELECT locktype, objid, mode, granted
FROM pg_locks WHERE locktype = 'advisory' AND pid = pg_backend_pid();
```

locktype	objid	mode	granted
advisory	991601810	ExclusiveLock	t

(1 row)

For advisory locks to actually work, other processes must also observe the established order when accessing the resource; it must be guaranteed by the application.

The acquired lock will be held even after the transaction is complete:

```
=> COMMIT;
=> SELECT locktype, objid, mode, granted
FROM pg_locks WHERE locktype = 'advisory' AND pid = pg_backend_pid();
```

locktype	objid	mode	granted
advisory	991601810	ExclusiveLock	t

(1 row)

Once the operation on the resource is over, the lock has to be explicitly released:

```
=> SELECT pg_advisory_unlock(hashtext('resource1'));
```

¹ [postgresql.org/docs/14/functions-admin#FUNCTIONS-ADVISORY-LOCKS.html](https://www.postgresql.org/docs/14/functions-admin#FUNCTIONS-ADVISORY-LOCKS.html)

14.5 Predicate Locks

The term *predicate lock* appeared as early as the first attempts to implement full isolation based on locks.¹ The problem confronted at that time was that locking all the rows to be read and updated still could not guarantee full isolation. Indeed, if *new* rows that satisfy the filter condition get inserted into the table, they will

p. 43 become *phantoms*.

For this reason, it was suggested to lock conditions (predicates) rather than rows. If you run a query with the $a > 10$ predicate, locking this predicate will not allow adding new rows into the table if they satisfy this condition, so phantoms will be avoided. The trouble is that if a query with a different predicate appears, such as $a < 20$, you have to find out whether these predicates overlap. In theory, this problem is algorithmically unsolvable; in practice, it can be solved only for a very simple class of predicates (like in this example).

In PostgreSQL, the Serializable isolation level is implemented in a different way: it uses the Serializable Snapshot Isolation (SSI) protocol.² The term *predicate lock* still remains, but its sense has radically changed. In fact, such “locks” do not lock anything: they are used to track data dependencies between different transactions.

p. 58 It is proved that snapshot isolation at the Repeatable Read level allows no anomalies except for the *write skew* and the *read-only transaction anomaly*. These two anomalies result in certain patterns in the data dependence graph that can be discovered at a relatively low cost.

The problem is that we must differentiate between two types of dependencies:

- The first transaction reads a row that is later updated by the second transaction (RW dependency).
- The first transaction modifies a row that is later read by the second transaction (WR dependency).

¹ K. P. Eswaran, J. N. Gray, R. A. Lorie, I. L. Traiger. The notions of consistency and predicate locks in a database system

² backend/storage/lmgr/README-SSI
backend/storage/lmgr/predicate.c

WR dependencies can be detected using regular locks, but rw dependencies have to be tracked via predicate locks. Such tracking is turned on automatically at the Serializable isolation level, and that's exactly why it is important to use this level for *all* transactions (or at least all the interconnected ones). If any transaction is running at a different level, it will not set (or check) predicate locks, so the Serializable level will be downgraded to Repeatable Read.

I would like to stress once again that despite their name, predicate locks do not lock anything. Instead, a transaction is checked for “dangerous” dependencies when it is about to be committed, and if PostgreSQL suspects an anomaly, this transaction will be aborted.

Let's create a table with an index that will span several pages (it can be achieved by using a low *fillfactor* value):

```
=> CREATE TABLE pred(n numeric, s text);
=> INSERT INTO pred(n) SELECT n FROM generate_series(1,10000) n;
=> CREATE INDEX ON pred(n) WITH (fillfactor = 10);
=> ANALYZE pred;
```

If the query performs a sequential scan, a predicate lock is acquired on the whole table (even if some of the rows do not satisfy the provided filter conditions).

```
=> SELECT pg_backend_pid();
pg_backend_pid
-----
          34763
(1 row)
=> BEGIN ISOLATION LEVEL SERIALIZABLE;
=> EXPLAIN (analyze, costs off, timing off, summary off)
    SELECT * FROM pred WHERE n > 100;
               QUERY PLAN
-----
Seq Scan on pred (actual rows=9900 loops=1)
  Filter: (n > '100'::numeric)
  Rows Removed by Filter: 100
(3 rows)
```

Although predicate locks have their own infrastructure, the `pg_locks` view displays them together with heavyweight locks. All predicate locks are always acquired in the `SIRead` mode, which stands for `Serializable Isolation Read`:

```
=> SELECT relation::regclass, locktype, page, tuple
FROM pg_locks WHERE mode = 'SIReadLock' AND pid = 34763
ORDER BY 1, 2, 3, 4;
```

relation	locktype	page	tuple
pred	relation		

(1 row)

```
=> ROLLBACK;
```

You should bear in mind that predicate locks may be held longer than the transaction duration, as they are used to track dependencies *between* transactions. But anyway, they are managed automatically.

If the query performs an index scan, the situation improves. For a B-tree index, it is enough to set a predicate lock on the read heap tuples and on the scanned leaf pages of the index. It will “lock” the whole range that has been read, not only the exact values.

```
=> BEGIN ISOLATION LEVEL SERIALIZABLE;
=> EXPLAIN (analyze, costs off, timing off, summary off)
    SELECT * FROM pred WHERE n BETWEEN 1000 AND 1001;
```

QUERY PLAN

```
-----
Index Scan using pred_n_idx on pred (actual rows=2 loops=1)
  Index Cond: ((n >= '1000'::numeric) AND (n <= '1001'::numeric))
(2 rows)
```

```
=> SELECT relation::regclass, locktype, page, tuple
FROM pg_locks WHERE mode = 'SIReadLock' AND pid = 34763
ORDER BY 1, 2, 3, 4;
```

relation	locktype	page	tuple
pred	tuple	4	96
pred	tuple	4	97
pred_n_idx	page	28	

(3 rows)

The number of leaf pages corresponding to the already scanned tuples can change: for example, an index page can be split when new rows get inserted into the table. However, PostgreSQL takes it into account and locks newly appeared pages too:

```
=> INSERT INTO pred
      SELECT 1000+(n/1000.0) FROM generate_series(1,999) n;
=> SELECT relation::regclass, locktype, page, tuple
FROM pg_locks WHERE mode = 'SIReadLock' AND pid = 34763
ORDER BY 1, 2, 3, 4;
```

relation	locktype	page	tuple
pred	tuple	4	96
pred	tuple	4	97
pred_n_idx	page	28	
pred_n_idx	page	266	
pred_n_idx	page	267	
pred_n_idx	page	268	
pred_n_idx	page	269	

(7 rows)

Each read tuple is locked separately, and there may be quite a few of such tuples. Predicate locks use their own pool allocated at the server start. The total number of predicate locks is limited by the *max_pred_locks_per_transaction* value multiplied by *max_connections* (despite the parameter names, predicate locks are not being counted per separate transactions). 64 100

Here we get the same problem as with row-level locks, but it is solved in a different way: *lock escalation* is applied.¹

As soon as the number of tuple locks related to one page exceeds the value of the *max_pred_locks_per_page* parameter, they are replaced by a single page-level lock. v. 10 2

```
=> EXPLAIN (analyze, costs off, timing off, summary off)
      SELECT * FROM pred WHERE n BETWEEN 1000 AND 1002;
               QUERY PLAN
-----
Index Scan using pred_n_idx on pred (actual rows=3 loops=1)
  Index Cond: ((n >= '1000'::numeric) AND (n <= '1002'::numeric))
(2 rows)
```

¹ backend/storage/lmgr/predicate.c, PredicateLockAcquire function

Instead of three locks of the tuple type we now have one lock of the page type:

```
=> SELECT relation::regclass, locktype, page, tuple
FROM pg_locks WHERE mode = 'SIReadLock' AND pid = 34763
ORDER BY 1, 2, 3, 4;
```

relation	locktype	page	tuple
pred	page	4	
pred_n_idx	page	28	
pred_n_idx	page	266	
pred_n_idx	page	267	
pred_n_idx	page	268	
pred_n_idx	page	269	

(6 rows)

```
=> ROLLBACK;
```

- v. 10 Escalation of page-level locks follows the same principle. If the number of such
-2 locks for a particular relation exceeds the *max_pred_locks_per_relation* value, they
64 get replaced by a single relation-level lock. (If this parameter is set to a negative
value, the threshold is calculated as *max_pred_locks_per_transaction* divided by the
absolute value of *max_pred_locks_per_relation*; thus, the default threshold is 32).

Lock escalation is sure to lead to multiple false-positive serialization errors, which negatively affects system throughput. So you have to find an appropriate balance between performance and spending the available RAM on locks.

Predicate locks support the following index types:

- B-trees
- v. 11 • hash indexes, GiST, and GIN

If an index scan is performed, but the index does not support predicate locks, the whole index will be locked. It is only to be expected that the number of transactions aborted for no good reason will also increase in this case.

For more efficient operation at the Serializable level, it makes sense to explicitly declare read-only transactions as such using the `READ ONLY` clause. If the lock manager sees that a read-only transaction will not conflict with other transactions,¹ it

¹ backend/storage/lmgr/predicate.c, `SxactIsROSafe` macro


can release the already set predicate locks and refrain from acquiring new ones. And if such a transaction is also declared `DEFERRABLE`, the read-only transaction anomaly will be avoided too. *p. 62*

15

Locks on Memory Structures

15.1 Spinlocks

To protect data structures in shared memory, PostgreSQL uses several types of lighter and less expensive locks rather than regular heavyweight ones.

The simplest locks are  *spinlocks*. They are usually acquired for a very short time interval (no longer than several CPU cycles) to protect particular memory cells from concurrent updates.

Spinlocks are based on atomic CPU instructions, such as compare-and-swap.¹ They only support the exclusive locking mode. If the required resource is already locked, the process busy-waits, repeating the command (it “spins” in the loop, hence the name). If the lock cannot be acquired within the specified time interval, the process pauses for a while and then starts another loop.

This strategy makes sense if the probability of a conflict is estimated as very low, so after an unsuccessful attempt the lock is likely to be acquired within several instructions.

Spinlocks have neither deadlock detection nor instrumentation. From the practical standpoint, we should simply know about their existence; the whole responsibility for their correct implementation lies with PostgreSQL developers.

¹ backend/storage/lmgr/s_lock.c

15.2 Lightweight Locks

Next, there are so-called **6** *lightweight locks*, or *lwlocks*.¹ Acquired for the time needed to process a data structure (for example, a hash table or a list of pointers), lightweight locks are typically short; however, they can take longer when used to protect I/O operations.

Lightweight locks support two modes: exclusive (for data modification) and shared (for read-only operations). There is no queue as such: if several processes are waiting on a lock, one of them will get access to the resource in a more or less random fashion. In high-load systems with multiple concurrent processes, it can lead to some unpleasant effects.

Deadlock checks are not provided; we have to trust PostgreSQL developers that lightweight locks are implemented correctly. However, these locks do have instrumentation, so, unlike spinlocks, they can be observed.

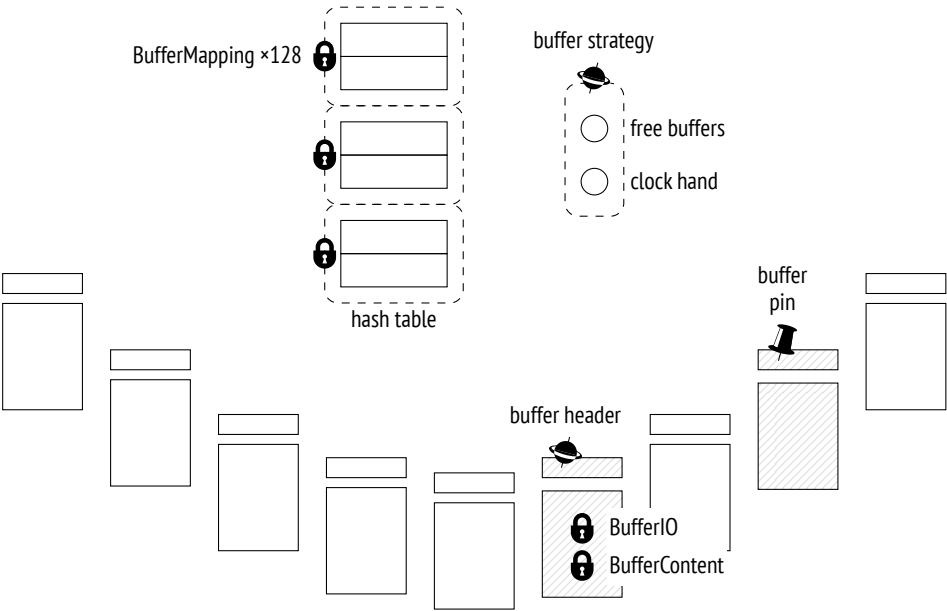
15.3 Examples

To get some idea of how and where spinlocks and lightweight locks can be used, let's take a look at two shared memory structures: buffer cache and WAL buffers. I will name only some of the locks; the full picture is too complex and is likely to interest only PostgreSQL core developers.

Buffer Cache


To access a hash table used to locate a particular buffer in the cache, the process must acquire a **6** BufferMapping lightweight lock either in the shared mode for reading or in the exclusive mode if any modifications are expected. p. 165



¹ backend/storage/lmgr/lwlock.c



The hash table is accessed very frequently, so this lock often becomes a bottleneck. To maximize granularity, it is structured as a *tranche* of 128 individual lightweight locks, each protecting a separate part of the hash table.¹


A hash table lock was converted into a tranche of 16 locks as early as 2006, in PostgreSQL 8.2; ten years later, when version 9.5 was released, the size of the tranche was increased to 128, but it may still be not enough for modern multi-core systems.


To get access to the buffer header, the process acquires a  buffer header spinlock² (the name is arbitrary, as spinlocks have no user-visible names). Some operations, such as incrementing the usage counter, do not require explicit locks and can be performed using atomic CPU instructions.

To read a page in a buffer, the process acquires a  BufferContent lock in the header of this buffer.³ It is usually held only while tuple pointers are being read; later on, the protection provided by  buffer pinning will be enough. If the buffer content has to be modified, the BufferContent lock must be acquired in the exclusive mode.

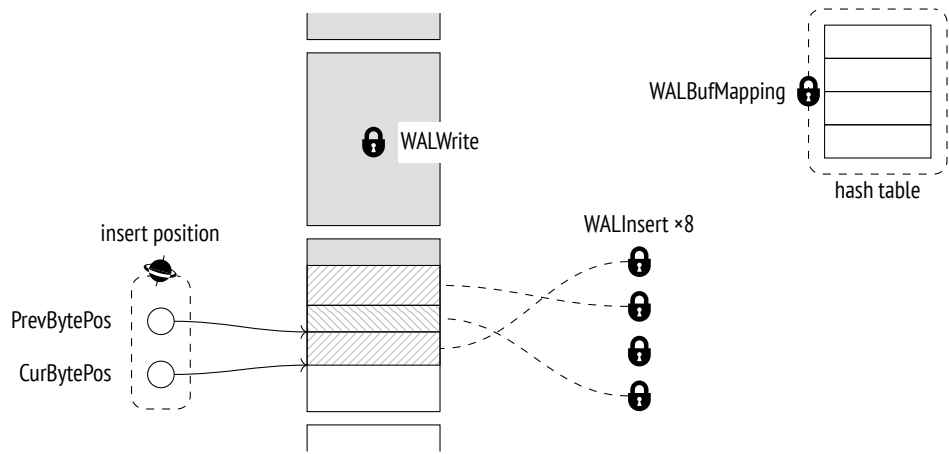
p. 167


¹ backend/storage/buffer/bufmgr.c
include/storage/buf_internals.h, BufMappingPartitionLock function
² backend/storage/buffer/bufmgr.c, LockBufHdr function
³ include/storage/buf_internals.h


When a buffer is read from disk (or written to disk), PostgreSQL also acquires a  BufferIO lock in the buffer header; it is virtually an attribute used as a lock rather than an actual lock.¹ It signals other processes requesting access to this page that they have to wait until the I/O operation is complete.


The pointer to free buffers and the clock hand of the eviction mechanism are protected by a single common  buffer strategy spinlock.²

WAL Buffers



WAL cache also uses a hash table to map pages to buffers. Unlike the buffer cache hash table, it is protected by a single  WALBufMapping lightweight lock because WAL cache is smaller (it usually takes $\frac{1}{32}$ of the buffer cache size) and buffer access is more ordered.³

Writing of WAL pages to disk is protected by a  WALWrite lightweight lock, which ensures that this operation is performed by one process at a time.

To create a WAL entry, the process first reserves some space within the WAL page and then fills it with data. Space reservation is strictly ordered; the process must acquire an  insert position spinlock that protects the insertion pointer.⁴ But

¹ backend/storage/buffer/bufmgr.c, StartBufferIO function
² backend/storage/buffer/freelist.c
³ backend/access/transam/xlog.c, AdvanceXLogInsertBuffer function
⁴ backend/access/transam/xlog.c, ReserveXLogInsertLocation function

once the space is reserved, it can be filled by several concurrent processes. For this purpose, each process must acquire *any* of the eight lightweight locks constituting the **6** WALInsert tranche.¹

15.4 Monitoring Waits

Without doubt, locks are indispensable for correct PostgreSQL operation, but they can lead to undesirable waits. It is useful to track such waits to understand their origin.

off The easiest way to get an overview of long-term locks is to turn the *log_lock_waits*
1s parameter on; it enables extensive logging of all the locks that cause a transaction
p. 252 to wait for more than *deadlock_timeout*. This data is displayed when a deadlock
check completes, hence the parameter name.

v. 9.6 However, the *pg_stat_activity* view provides much more useful and complete in-
formation. Whenever a process—either a system process or a backend—cannot
proceed with its task because it is waiting for something, this wait is reflected in
the *wait_event_type* and *wait_event* fields, which show the type and name of the
wait, respectively.

All waits can be classified as follows.²

Waits on various locks constitute quite a large group:

Lock — heavyweight locks

LWLock — lightweight locks

BufferPin — pinned buffers

But processes can be waiting for other events too:

IO — input/output, when it is required to read or write some data

¹ backend/access/transam/xlog.c, WALInsertLockAcquire function

² postgresql.org/docs/14/monitoring-stats#WAIT-EVENT-TABLE.html

Client — data sent by the client (psql spends most of the time in this state)

IPC — data sent by another process

Extension — a specific event registered by an extension

Sometimes a process simply does not perform any useful work. Such waits are usually “normal,” meaning that they do not indicate any issues. This group comprises the following waits:

Activity — background processes in their main cycle

Timeout — timer

Locks of each wait type are further classified by wait names. For example, waits on lightweight locks get the name of the lock or the corresponding tranche.¹

You should bear in mind that the `pg_stat_activity` view displays only those waits that are handled in the source code in an appropriate way.² Unless the name of the wait appears in this view, the process is not in the state of wait of any known type. Such time should be considered *unaccounted for*; it does not necessarily mean that the process is not waiting on anything—we simply do not know what is happening at the moment.

```
=> SELECT backend_type, wait_event_type AS event_type, wait_event
FROM pg_stat_activity;
```

backend_type	event_type	wait_event
logical replication launcher	Activity	LogicalLauncherMain
autovacuum launcher	Activity	AutoVacuumMain
client backend		
background writer	Activity	BgWriterMain
checkpointer	Activity	CheckpointerMain
walwriter	Activity	WalWriterMain

(6 rows)

Here all the background processes were idle when the view was sampled, while the client backend was busy executing the query and was not waiting on anything.

¹ [postgresql.org/docs/14/monitoring-stats#WAIT-EVENT-LWLOCK-TABLE.html](https://www.postgresql.org/docs/14/monitoring-stats#WAIT-EVENT-LWLOCK-TABLE.html)

² `include/utills/wait_event.h`

15.5 Sampling

Unfortunately, the `pg_stat_activity` view shows only the *current* information on waits; statistics are not accumulated. The only way to collect wait data over time is to *sample* the view at regular intervals.

We have to take into account the stochastic nature of sampling. The shorter the wait as compared to the sampling interval, the lower the chance to detect this wait. Thus, longer sampling intervals require more samples to reflect the actual state of things (but as you increase the sampling rate, the overhead also rises). For the same reason, sampling is virtually useless for analyzing short-lived sessions.

PostgreSQL provides no built-in tools for sampling; however, we can still try it out using the `pg_wait_sampling`¹ extension. We just have to specify its library in the `shared_preload_libraries` parameter and restart the server:

```
=> ALTER SYSTEM SET shared_preload_libraries = 'pg_wait_sampling';
postgres$ pg_ctl restart -l /home/postgres/logfile
```

Now let's install the extension into the database:

```
=> CREATE EXTENSION pg_wait_sampling;
```

This extension can display the history of waits, which is saved in its ring buffer. However, it is much more interesting to get the waiting profile—the accumulated statistics for the whole duration of the session.

For example, let's take a look at the waits during benchmarking. We have to start the `pgbench` utility and determine its process ID while it is running:

```
postgres$ /usr/local/pgsql/bin/pgbench -T 60 internals
=> SELECT pid FROM pg_stat_activity
WHERE application_name = 'pgbench';
 pid
-----
 36380
(1 row)
```

Once the test is complete, the waits profile will look as follows:

¹ github.com/postgrespro/pg_wait_sampling

```
=> SELECT pid, event_type, event, count
FROM pg_wait_sampling_profile WHERE pid = 36380
ORDER BY count DESC LIMIT 4;
```

pid	event_type	event	count
36380	IO	WALSync	4067
36380	IO	WALWrite	98
36380	Client	ClientRead	26
36380	IO	DataFileRead	4

(4 rows)

By default (set by the `pg_wait_sampling.profile_period` parameter) samples are taken 10ms 100 times per second. So to estimate the duration of waits in seconds, you have to divide the count value by 100.

In this particular case, most of the waits are related to flushing WAL entries to disk. v. 12 It is a good illustration of the unaccounted-for wait time: the WALSync event was not instrumented until PostgreSQL 12; for lower versions, a waits profile would not contain the first row, although the wait itself would still be there.

And here is how the profile will look like if we artificially slow down the file system for each I/O operation to take 0.1 seconds (I use `slowfs`¹ for this purpose) :

```
postgres$ /usr/local/pgsql/bin/pgbench -T 60 internals
```

```
=> SELECT pid FROM pg_stat_activity
WHERE application_name = 'pgbench';
```

```
pid
-----
36759
(1 row)
```

```
=> SELECT pid, event_type, event, count
FROM pg_wait_sampling_profile WHERE pid = 36759
ORDER BY count DESC LIMIT 4;
```

pid	event_type	event	count
36759	IO	WALWrite	3586
36759	LWLock	WALWrite	1842
36759	IO	WALSync	31
36759	IO	DataFileExtend	19

(4 rows)

¹ github.com/nirs/slowfs

Now I/O operations are the slowest ones—mainly those that are related to writing WAL files to disk in the synchronous mode. Since WAL writing is protected by a WALWrite lightweight lock, the corresponding row also appears in the profile.

Clearly, the same lock is acquired in the previous example too, but since the wait is shorter than the sampling interval, it either is sampled very few times or does not make it into the profile at all. It illustrates once again that to analyze short waits you have to sample them for quite a long time.

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