PostgreSQL Mistakes
and How to Avoid Them

Jimmy Angelakos

MEAP

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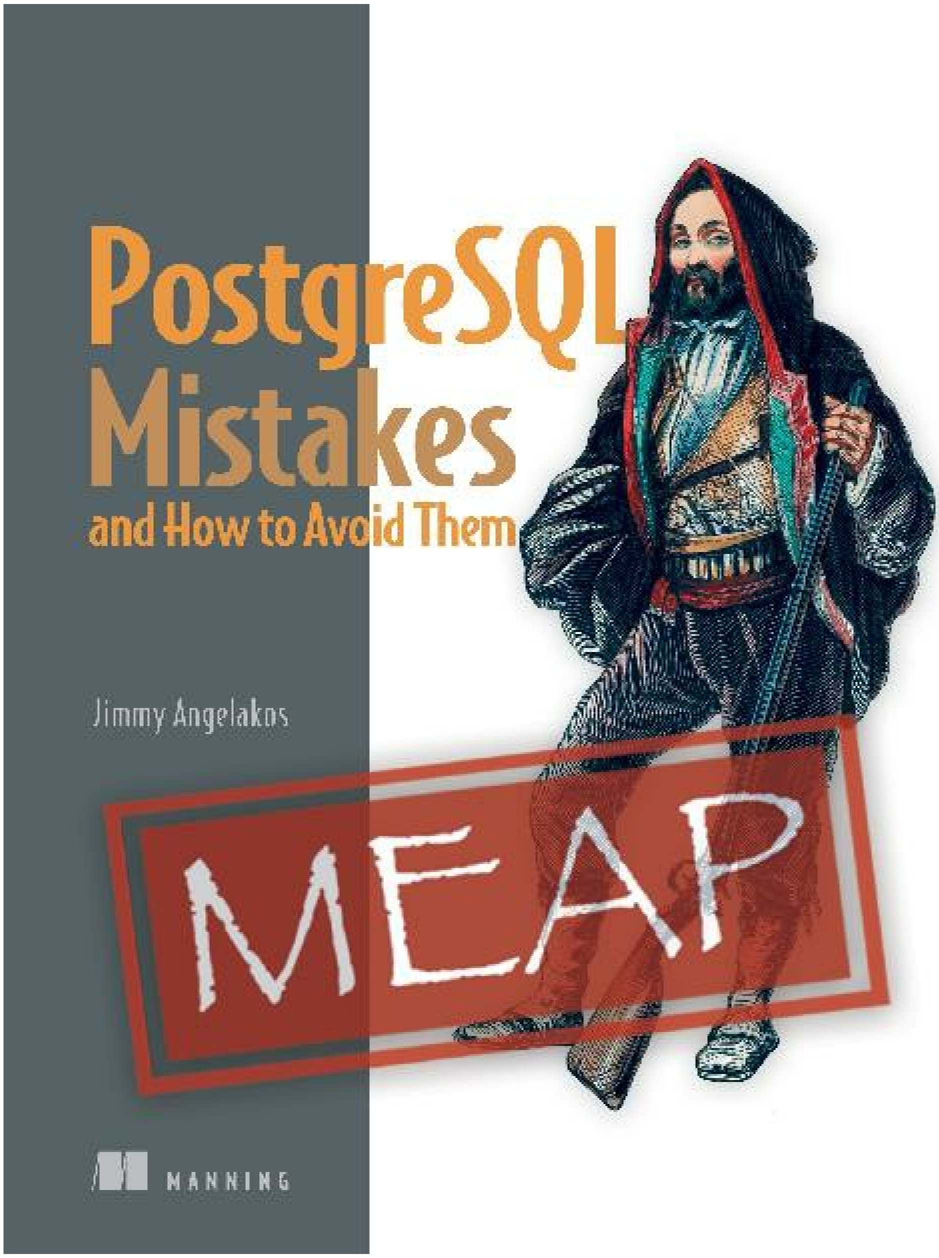
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Welcome

Thank you for purchasing the MEAP for *PostgreSQL Mistakes and How to Avoid Them*!

PostgreSQL is really booming right now and seeing a rapidly expanding user base. According to the Stack Overflow 2023 Developer Survey, it's now the most admired and desired database among developers and professional developers. This is the right time to get important content out there for this crowd of newcomers to Postgres but also cover aspects of this database that are not well-known or overlooked.

Through more than 15 years of experience with PostgreSQL and having worked for two of the foremost Postgres database companies, I saw a lot of mistakes being made "in the field" and started speaking about them at conferences. As searching for "things not to do" is not common, and the advice out there is scattered across disparate blog and forum posts, it made sense to gather the most important PostgreSQL mistakes in a book.

The book's approach to the topic is to give you a story or narrative to help understand the setting and context of a problem to be solved. Then, uncover how potential solutions can turn into mistakes, and finally explain why this is wrong in PostgreSQL, and give workarounds and recommendations. Code snippets, sample application code, mind maps and diagrams, and comparative figures and tables are used throughout this book to illustrate the points being made.

Many books tell you what to do without providing the context of why – wherever relevant, I spend a couple of lines explaining the reasons, ranging from simple math, to standards compliance, to Postgres internals. By sharing these stories with your peers and spreading knowledge of these pitfalls, we can make everyone's PostgreSQL experience more productive and enjoyable.

MEAP is a great way to get the book's content out there as soon as possible without waiting for the final publication date. I will be very happy to receive your feedback in the liveBook’s Discussion Forum, and hopefully your comments will lead to an even better finished book!

– Jimmy Angelakos

In this book

1 Introduction

In this chapter

- Learning about PostgreSQL
- Identifying and talking about PostgreSQL mistakes
- Categorizing PostgreSQL mistakes
- Using this book to learn

Welcome to *PostgreSQL Mistakes and How to Avoid Them*! Presumably, you got your hands on this book to learn more about PostgreSQL, and that is indeed the book's purpose. However, it's not a tutorial book in the traditional sense, nor is it an administration guide - there are good books already on those subjects. This book makes it a point that mistakes do happen, and that they are a good learning opportunity. In this chapter, we will see why PostgreSQL is important right now, how this book examines PostgreSQL-related mistakes and why this is a worthwhile endeavor.

1.1 Why learning about PostgreSQL matters

As we mentioned before, PostgreSQL (a.k.a. Postgres) is a disruptive technology that has started unseating giant database vendors from their thrones. It is a robust and reliable feature-rich database, very extensible, and gaining more enterprise features with each new release. It has found wide acceptance in the database community but also in commercial circles, with hundreds of vendors now offering code contributions, professional support, enhanced capabilities versions and even hosted, cloud, or Database-as-a-Service (DBaaS) Postgres offerings.

Very importantly, the PostgreSQL Project is a prime example of community-led and community-driven free software, and this is expressed in the PostgreSQL License. This is particularly significant with most every other database vendor adhering to proprietary software and with both established and emerging database efforts switching to non-open-source compliant licenses in an attempt to chase profitability by restricting the ways others can make money with their product. On the other hand, you can freely profit from PostgreSQL by selling support, hosting, training or services, and even basing your own open source or proprietary product on it with no nasty legal surprises hiding around the corner. The lack of vendor lock-in combined with the ability to be able to base your business entirely on Postgres with no licensing restrictions is a powerful differentiator that makes Postgres shine bright in the database field.

This license won’t change: as Jonathan Katz of the Core Team pointed out in March 2024, "The PostgreSQL Project began as a collaborative open source effort and is set up to prevent a single entity to take control. This carries through in the project’s ethos almost 30 years later, and is even codified throughout the project policies".

PostgreSQL’s power and extensibility have helped it find use cases in a very wide array of industries and applications. Notably, there are huge banking, credit and retail systems putting it to use in Online Transaction Processing (OLTP) scenarios, but also taking advantage of its advanced querying and reporting capabilities to perform large-scale business analytics, including Online Analytical Processing (OLAP). Extensions such as PostGIS for Geographic Information Systems (GIS), Citus columnar stores, TimescaleDB for time series data, and pgvector for vector search added lots of specialized functionality to further expand its user base. There are hotel chains, film studios, shipping firms, insurance companies, state organizations, health institutions and space agencies using one form of Postgres or another, and the list goes on. For these uses, robustness, scalability and reliability are of paramount importance. Of course, this ecosystem is completed by several large and small vendors, consultants and contractors who enable all these applications with their expertise.

1.2 Why talking about PostgreSQL mistakes matters

In line with PostgreSQL becoming more popular and seeing more use cases every day, we see a multitude of users either trying to apply practices they’ve learned from using other Database Management Systems (DBMSs) or misunderstanding Postgres features. This can be in the form of repeating something that you know works on another database system, or using a feature without a full understanding of its documentation. For example, PostgreSQL supports complex data types like arrays, whereas you would have to insert multiple rows with repeated data in other databases. Sometimes it’s just a case of using the wrong tool for the job, for example, the wrong function or data type. It can even be the case that a choice that you have made made works right now, but will stop working in the future for various reasons, such as a table becoming much larger.

These factors and more often lead to mistakes which can be costly, if they happen on a production system. It’s better to be aware and to catch them early, as these mistakes can also be time-consuming to rectify and may involve a high degree of difficulty or risk, such as changing something on a live system that is in use.

It is important to spread awareness of potential mistakes and pitfalls in order to:

- Save person-hours that will be spent dealing with their consequences
- Protect the stored data
- Future-proof database designs
- Fight anti-patterns detrimental to design and performance
- Embrace standard solutions instead of reinventing the wheel
- Build awareness of database best practices elsewhere in your team or organization
- Get the most out of PostgreSQL

And finally:

- Protect the reputation of your favorite database! Too often have we seen blog posts or articles decrying PostgreSQL because the author didn’t understand the technology, then tried to do something in an unorthodox way, failed, and came to the mistaken conclusion that Postgres was an inadequate platform.

1.3 What you will learn

PostgreSQL Mistakes and How to Avoid Them will hopefully help you:

- Educate yourself about potential PostgreSQL pitfalls relevant to various aspects of PostgreSQL configuration, administration, and operation.
- Learn how to avoid aforementioned pitfalls before their consequences manifest themselves, or how to employ workarounds to correct them.
- Gain a wider understanding of fundamental database operating principles and best practices to be applied.
- Better understand the differences and nuances that distinguish PostgreSQL from other databases.
- Understand the impact of enforcing best practices on PostgreSQL usage and performance.

What it will help you do — or do better — in your everyday life on the job:

- Save time and effort by recognizing best practices and associated usage patterns.
- Be proactive in addressing potential problems before they become damaging.
- Shield yourself against accidental or intentional misuse of the database by others by taking preventive measures.
- Educate your peers by sharing this knowledge and make everyone’s experience with PostgreSQL more productive and enjoyable.

1.4 Typical kinds of PostgreSQL mistakes

Let’s examine some of the different ways that you can inadvertently find yourself doing something in PostgreSQL that turns out to be a mistake.

1.4.1 Coming with expectations from other databases

Many newcomers to Postgres find themselves confused and frustrated when taking their first steps with the database. This may be due to a number of reasons:

One possible reason is that other databases frequently require a lengthy and complicated installation wizard where you have to make important (and often irreversible) decisions before you can start using the database. With Postgres, many users are stunned by the unexpected realization that, in most cases, once you've installed it, you're able to use the database server straight away. No frills, connect your database client to the server and you can get busy exploring the possibilities. However, with this comes a risk — out of the box, Postgres is configured with some "sensible defaults". How sensible this default configuration is really depends on what you intend to use the database for. The default configuration is almost certainly not suitable for most production usage scenarios.

Another possible source of confusion is that most DBMSs have their own way of doing things, often diverging from the SQL Standard (the international standard for Structured Query Language — currently ISO/IEC 9075:2023) for historical, business or implementation reasons. PostgreSQL has its way of doing things as well, and it is generally recognized that it is the most SQL Standard-compliant database currently available. This means that sometimes people come to expect what they're used to from previous exposure to other database systems. Such an expectation is that creating a database `USER` will create a `SCHEMA` with the same name, with implied ownership of its objects by the same user. Where some databases will silently auto-convert between types, such as being able to insert ones and zeros into a `BOOLEAN` column, PostgreSQL will tell you that this is an error. It then would make sense that users would be surprised by the fact that none of these things work in Postgres.

1.4.2 Misunderstanding PostgreSQL

Postgres *is* a general-purpose database. Regardless, that doesn't mean it's suitable for every single use imaginable. We have witnessed people attempting to use it:

- As an embedded database
- As a distributed database with home-brew replication
- As a log server
- As bulk video storage for films

- For in-memory use cases better suited to Redis
- As a graph database (guilty!)

Yes, it can do all these things to an extent. But you should always be aware of available solutions for the particular niche you are trying to inhabit, and weigh the pros and cons of using a generic database solution versus something specialized.

1.4.3 Misunderstanding the documentation

PostgreSQL is very richly documented, and this is enforced in the governance of the project. It is well established that no patch gets accepted without the submission of accompanying documentation — if you build or change something, you must document it. All of this documentation material is available on the Web at: https://postgresql.org/docs/ .

Often, this official documentation is presented in a very technical or academic way (in line with the PostgreSQL Project’s origins). For laypersons used to tutorial-style walkthroughs or notes including more practical applications, this may be hard to follow. As a consequence, it is possible to misunderstand the nature of a feature or the correct way to utilize it.

It may also be possible to miss important side notes, or to lack the context that more advanced users may have gained through experience. Sometimes, parts of the documentation feel incomplete because insights, terms or details that are essential for understanding have to be located elsewhere in the documentation. Finally, you need to make sure you are reading the specific documentation for the version of PostgreSQL you are using to avoid confusion and misunderstandings.

1.4.4 Using relics from the SQL Standard

In short, I would call this "just because it’s in the official SQL Standard doesn’t mean you have to use it". There are many holdovers in the standard that either are relevant to an older era, seemed like a good idea at the time, or are forgotten by nearly everyone. Some are poorly defined implementation-wise and work differently in every database system. Some SQL features have been retained for backward compatibility purposes, or the reasons why they are not to be preferred — or used at all — are broadly understood. A good example of this is the `TIME WITH TIME ZONE` type, explained in Chapter 3.

1.4.5 Not following best practices

Best practices for the design, development, administration and maintenance of IT systems have been established through decades of observation and industry experience. Many systems have commonalities that lend themselves to similar best practices and it makes sense to apply these to database systems as well. In particular, databases are complex systems that have numerous correctness, performance and security considerations, and Postgres is no exception to the rule.

Failing to follow best practices when you are designing your application's database schema, planning for usage patterns or concurrency, implementing high availability and disaster recovery solutions, and establishing security policies can lead to serious problems. It is a surefire way to trip yourself up somewhere down the road.

1.5 How this book works

As we already mentioned, most if not all of the mistakes and ideas in this book have come through observation of PostgreSQL installations and their users' behavior in the field, either first-hand or through documented stories shared by others in the industry or community who were kind enough to do so.

A story, or narrative, is key to comprehending the setting and context of a theoretical or practical problem. It sets the stage for understanding the mindset of whoever is attempting to solve it and sheds light on their decision-making process. From there, we can get into the general use case and the specific issue at hand. We will see the formation of the resolution attempt and the chain of events that leads to the mistake. We will then dive deeper into why this is a mistake, its causes, and its potential consequences down the line. Finally, we will discuss the correct solution and how to implement it.

All of this discussion is supplemented, where needed, with actual samples of database schema and data, SQL or PL/pgSQL code for both erroneous solutions and the right way to do things, and finally expected output in both cases.

At the time of writing, the current release is PostgreSQL 17, so that’s the version we are going to use in this book. Of course, the vast majority of the book’s content will be applicable to older recent versions of Postgres as well. Where there are differences, they will be pointed out.

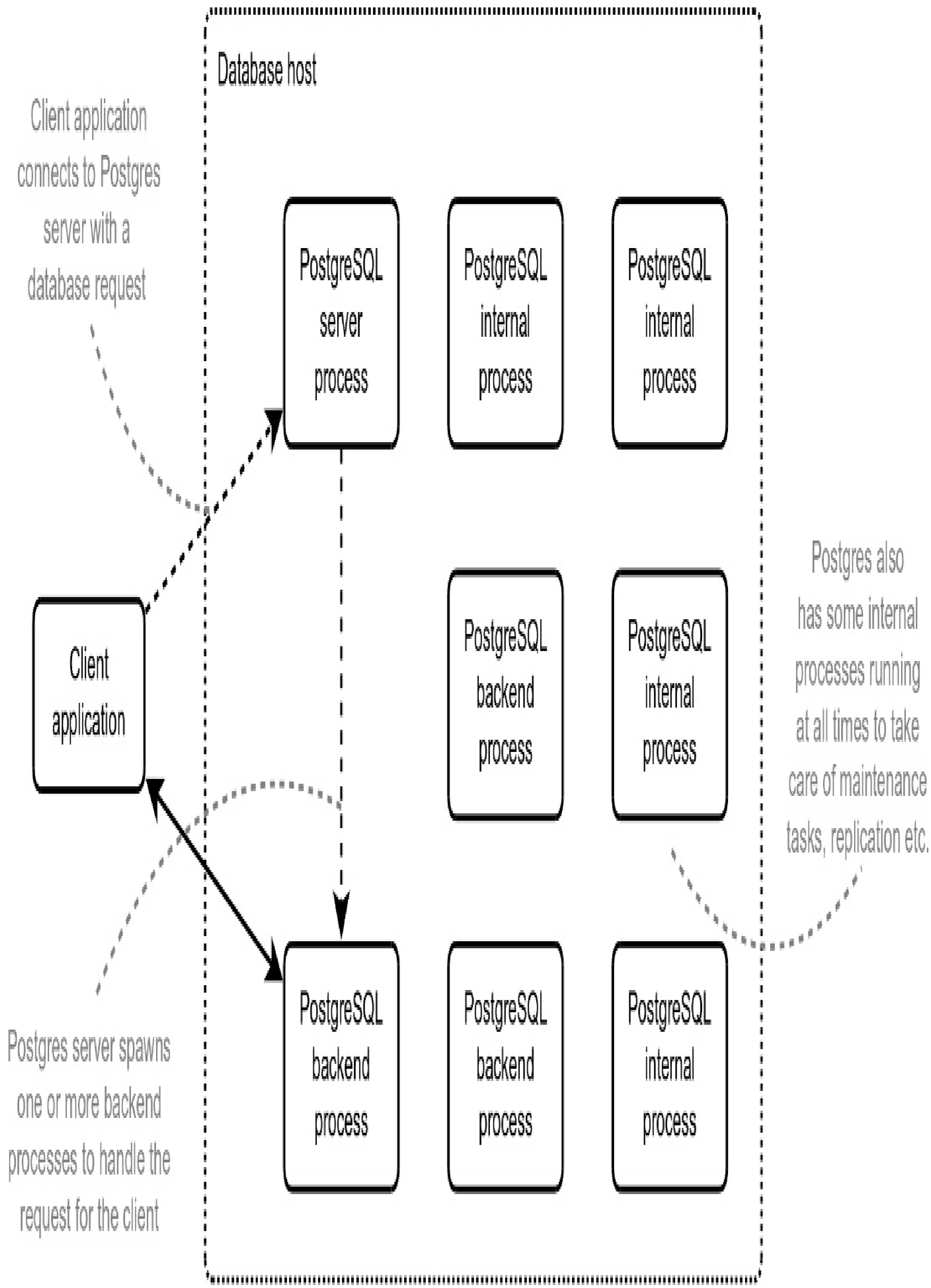
Tip

PL/pgSQL is an easy procedural language for PostgreSQL that can be used to create functions, procedures, and triggers. It adds control structures to the SQL language, can use all user-defined types, functions and operators, and can perform complex computations.

1.5.1 Mental models

Something useful to always keep in mind is that PostgreSQL is a client-server and multi-process database management system. This means that any client application connects to the database server (or Postgres server) running inside a single host to run queries and retrieve data. This connection is handled by one or more Postgres backend processes running inside the server. There are also other internal Postgres processes, that may not directly interact with the client. The multi-process design allows parallelization and utilization of all available CPUs, but behaves in some ways that are different to multi-threaded database systems. This is what this model looks like:

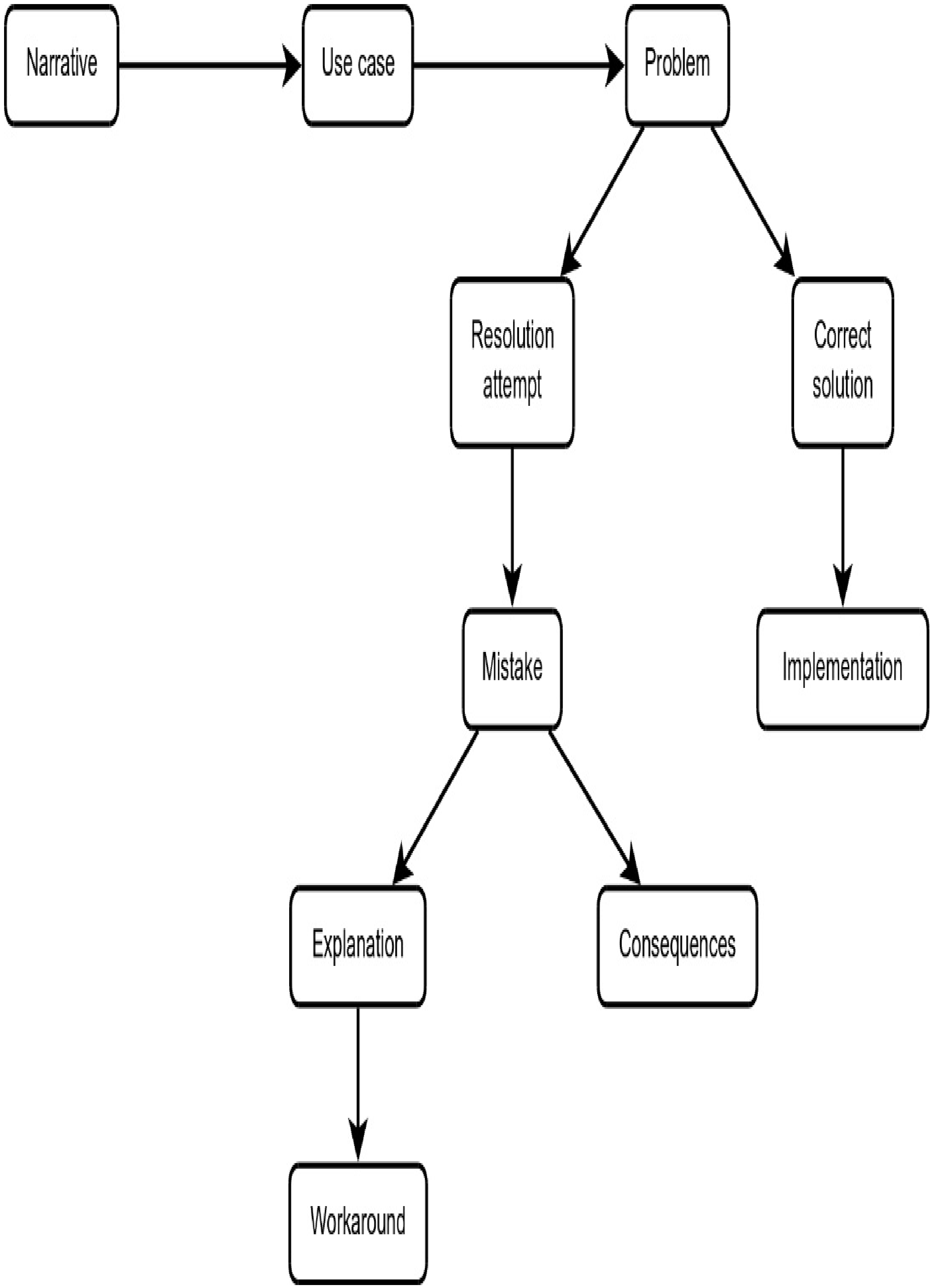
Figure 1.1 How the PostgreSQL client-server architecture works



Database host
Client application connects to Postgres server with a database request
PostgreSQL server process
PostgreSQL internal process
PostgreSQL internal process
Client application
PostgreSQL backend process
PostgreSQL internal process
Postgres also has some internal processes running at all times to take care of maintenance tasks, replication etc.
PostgreSQL backend process
PostgreSQL backend process
PostgreSQL internal process
Postgres server spawns one or more backend processes to handle the request for the client

This book works as follows: We start with a narrative which provides context for our use case. We see the problem and the resolution attempt that leads to a mistake. Then we see why this is wrong, its consequences and potential workarounds. Finally, the correct solution and how to implement it. Something like this:

Figure 1.2 How "PostgreSQL Mistakes and How to Avoid Them" works


Narrative
Use case
Problem
Resolution attempt
Correct solution
Mistake
Implementation
Explanation
Consequences
Workaround

1.5.2 Example mistake

Let’s now look at a possible mistake, to help illustrate briefly how this book walks through the narrative, problem, and resolution steps.

Side note

This example isn’t particularly thrilling, and may not even apply exclusively to Postgres, but it shows how this book treats issues according to the mental model presented above.

Let’s assume that you have a table with hundreds of thousands of customer support tickets such as the one in this (simplistic) model:

```
CREATE TABLE support.tickets (id int, content text, status smalli
```

For our sample data, we will assume that a ticket’s `status = 10` means "open", and `status = 20` means "closed". Let’s insert a few hundred thousand rows of closed tickets:

```
INSERT INTO support.tickets
SELECT id, 'case description text', 20
FROM generate_series(1, 499750) AS id;
```

And now let’s insert a few hundred rows of recent, still-open tickets:

```
INSERT INTO support.tickets
SELECT id, 'case description text', 10
FROM generate_series(499751, 500000) AS id;
```

For the sake of simplicity, we will assume that parallelization is not possible, so let’s disable it via:

```
SET max_parallel_workers_per_gather = 0;
```

We will be tracking query duration by enabling timing in `psql`:

```
\timing
Timing is on.
```

Let’s now say that, for your customer support application, only the open tickets are relevant. You therefore want to count how many of those open tickets you have because you are interested only in them. Let’s try the following:

Listing 1.1 Trying to solve the problem

```
SELECT count(*)
FROM support.tickets
WHERE status = 10;
```

Indeed this open ticket count returns the correct result. But it is slow:

```
 count
-------
   250
(1 row)

Time: 110.036 ms
```

Let’s see why it is slow by running `EXPLAIN`, which shows us how PostgreSQL will execute the query (the *query plan*):

```
EXPLAIN SELECT count(*)
FROM support.tickets
WHERE status = 10;
                           QUERY PLAN
----------------------------------------------------------------
 Aggregate  (cost=9927.28..9927.29 rows=1 width=8)
   ->  Seq Scan on tickets  (cost=0.00..9927.28 rows=1 width=0)
         Filter: (status = 10)
(3 rows)
```

This tells us that in order to run the `Aggregate count()`, PostgreSQL is planning to use a `Seq Scan` on the table `tickets` and then `Filter` the results by `status = 10`.

Sequential scans (also known as full table scans) are slow. So, you think, I’ll create an index. Indexes make everything faster, right?

```
CREATE INDEX ON support.tickets(status);
CREATE INDEX
Time: 732.403 ms
```

Now that the index has been created, we try again:

```
SELECT count(*)
FROM support.tickets
WHERE status = 10;
 count
-------
   250
(1 row)

Time: 3.715 ms
```

That's much better. `EXPLAIN` will confirm why it is much faster now - an `Index Only Scan` is being used:

```
                                QUERY PLAN
-----------------------------------------------------------------
 Aggregate  (cost=4.44..4.45 rows=1 width=8)
   ->  Index Only Scan using tickets_status_idx on tickets
 (cost=0.42..4.44 rows=1 width=0)
         Index Cond: (status = 10)
(3 rows)
```

However, this index is quite big:

Listing 1.2 Why doesn't this work?

```
\x
\di+ support.tickets*
List of relations
-[ RECORD 1 ]-+-------------
Schema        | support
Name          | tickets_status_idx
Type          | index
Owner         | frogge
Table         | tickets
Persistence   | permanent
Access method | btree
Size          | 3408 kB
Description   |
```

Imagine hundreds of millions of tickets in your customer support history, but only around the latest 250 are ever open at the same time.

Large indexes, of course, take up more disk space. But they are also slower because there's more data to traverse, and they slow down write operations because they need to get updated with every `INSERT` or `UPDATE`.

In our case, we only care about the comparatively few open tickets. So we can save on the index size by using what's known as a *partial index*, and add only the rows that we are interested in, the ones `WHERE status = 10`.

We now drop the previous index and create a new partial index:

Listing 1.3 Correct solution

```
DROP INDEX support.tickets_status_idx;
CREATE INDEX ON support.tickets(status)
WHERE status = 10;
```

Look at how much smaller this index is! It makes sense, since we're only indexing around **0.05%** of the total rows, right?

```
\di+ support.tickets*
List of relations
-[ RECORD 1 ]-+-------------
Schema        | support
Name          | tickets_status_idx
Type          | index
Owner         | frogge
Table         | tickets
Persistence   | permanent
Access method | btree
Size          | 16 kB
Description   |
```

This is what the execution time looks like now, after having reduced the index size by a factor of more than 200:

```
SELECT count(*)
FROM support.tickets
WHERE status = 10;
 count
-------
   250
(1 row)
```

```
Time: 0.762 ms
```

And this is what `EXPLAIN` shows now:

```
                               QUERY PLAN
-----------------------------------------------------------------
 Aggregate  (cost=4.16..4.17 rows=1 width=8)
   ->  Index Only Scan using tickets_status_idx on tickets
 (cost=0.14..4.16 rows=1 width=0)
(2 rows)
```

The operation is still an `Index Only Scan`, but of a much smaller index, so it takes far less time to execute.

So we have seen that just plopping an index on a column technically works, but is not the optimal solution when you consider things such as large data volumes and performance requirements.

1.6 Sample database: Frogge Emporium

Every database book needs a sample database schema, and why go with something that's been floating around the Web for decades?

Here's **Frogge Emporium**, which, as a self-respecting retail chain, will certainly have processes, files, records, archives and datasets relevant to its business. These can, of course, be represented as relational tables. Some of the tables that its database will have are:

- `branches` with
- `stock`,
- `customers`,
- `suppliers`,
- `products`, lots and lots of
- `orders`,
- `payments` with
- `payment_types`

and more.

Please see Appendix A for the full database schema.

Note

The test data generation script in Appendix A creates data using the current date and works its way back one year. As a result, your generated test data will reflect the date when you run the script, which means it won't exactly match the output shown in the examples in this book. This is by design to ensure that the script remains dynamic and useful for testing in any time period.

1.7 Summary

- PostgreSQL is a powerful, free and standards-compliant database that is disrupting the industry and gaining in popularity every day.
- It's important to learn about Postgres mistakes (and from those mistakes) to save time and effort and safeguard your data.
- Raising awareness of potential issues benefits everyone.
- You need to understand how Postgres works and in what ways it is different from other DBMSs in order to avoid making mistakes, especially if you are coming from another system — not all databases are created equal.
- PostgreSQL has a client-server multi-process architecture and this forms important context for the rest of this book.
- Following best practices and examining the documentation carefully will guide you to the correct technical solution for your problem.
- This book uses a use case narrative, accompanied by code, to demonstrate how you can make a mistake and prevent or recover from it.

2 Bad SQL usage

In this chapter

- Avoiding SQL pitfalls
- Exercising due care with your query results
- Improving performance of complex queries
- Checking your queries for correctness

Let's begin our journey into the land of PostgreSQL mistakes with what most relational database users are familiar with: Structured Query Language (SQL). In this chapter, we examine some bad SQL habits that can lead to bad query performance or, even worse, getting wrong query results. Postgres is very particular about the way it wants queries to be written and in most cases follows a strict interpretation of the SQL Standard. This means that you need to be careful about the way you construct those queries, and always check that you are actually getting exactly the results you want.

2.1 Using NOT IN to exclude

It's often that we need to specify a condition with a negative expression. No, that doesn't mean that we are trying to be unpleasant! It's simply that sometimes, to define a query, instead of specifying what we want in our results, we specify what we don't want in our results—the inverse of the desired condition.

Lingo: "Predicate"

A predicate is simply a conditional expression that resolves to a boolean value: either `TRUE` or `FALSE`. A good example of a predicate is the content of our `WHERE` clause.

Negative predicates are expressed with the `NOT` keyword and they can be used to invert any SQL expression, including those based around `IN`:

Listing 2.1 Example queries with `IN / NOT IN`

```
SELECT * FROM (VALUES ('Harper', 'salesperson'),
                      ('Parker', 'driver'),
                      ('Riley', 'electrician'),
                      ('Skyler', 'manager'))
              AS t(first_name, job_title)
WHERE job_title IN ('salesperson', 'driver', 'electrician');
 first_name |  job_title
------------+-------------
 Harper     | salesperson
 Parker     | driver
 Riley      | electrician
(3 rows)


SELECT * FROM (VALUES ('Harper', 'salesperson'),
                      ('Parker', 'driver'),
                      ('Riley', 'electrician'),
                      ('Skyler', 'manager'))
              AS t(first_name, job_title)
WHERE job_title NOT IN ('manager');
 first_name |  job_title
------------+-------------
 Harper     | salesperson
 Parker     | driver
 Riley      | electrician
(3 rows)
```

We see that specifying `NOT IN` can save a bit of typing and make queries simpler to read, especially if you are only looking to exclude a small number of values.

Now let's assume Frogge Emporium wants to do exactly that. Their problem is that they want to run a promotion, and they need to find all the email addresses of customers from states where they do not have a supplier so that they can send promotional items from the central warehouse.

This is what the table `customer_contact_details` looks like:

Table 2.1 Sample row from `customer_contact_details`

id	email	street_address	city	state	country	p

100	jordan.barber@example.com		Albany	NY	United States of America

And table `suppliers` looks like this:

Table 2.2 Sample row from `suppliers`

id	company_name	state	country	phone_no	email
1	Omni Consumer Products	MI	United States of America		ocp@example.com

Therefore they come up with this query:

```
SELECT email
FROM erp.customer_contact_details
WHERE state NOT IN (SELECT state
                    FROM erp.suppliers);
```

They select all emails from `customer_contact_details` where the customer's state is not contained in the list of states from all suppliers. However, when they run it, this happens:

```
 email
-------
(0 rows)
```

Why do they get zero results when there are certainly customers in states that do not have suppliers?

Let's say Frogge Emporium knows that they don't have suppliers in Kansas. Here's an SQL query that checks for at least one customer in a state without suppliers:

```
SELECT email
FROM erp.customer_contact_details
WHERE state = 'KS'
LIMIT 1;
          email
-------------------------
 river.smith@example.com
(1 row)
```

What is happening here is a consequence of how SQL treats `NULL` in predicates. In our example, not all suppliers are in a US state, so we have some suppliers with `NULL` in the field `state`. Let's check for at least one supplier that is not in a US state:

```
SELECT *
FROM erp.suppliers
WHERE state IS NULL;
 id | company_name | state | country | phone_no |        email
----+--------------+-------+---------+----------+-----------------
  2 | Yoyodyne     |       | Japan   |          | yoyodyne@example
(1 row)
```

Column `state` for this supplier is `NULL`. This causes the subquery `SELECT state FROM erp.suppliers` to return at least one `NULL` value.

What is probably unexpected is that the predicate `state NOT IN (SELECT state FROM erp.suppliers)` can never return `TRUE` if there is even one `NULL` present. The expression evaluates to "unknown" if the subquery returns any null values, effectively negating the predicate and leading to an empty result set.

Why is that? Let's look at the logic of queries using `NOT IN`, considering both cases: with and without `NULL` values.

No `NULL`s:

```
SELECT email, state
FROM erp.customer_contact_details
WHERE state NOT IN ('Fake state')
LIMIT 1;
           email           | state
---------------------------+-------
 jordan.barber@example.com | NY
```

```
(1 row)
```

With `NULL`s:

```
SELECT email, state
FROM erp.customer_contact_details
WHERE state NOT IN ('Fake state', null)
LIMIT 1;
 email | state
-------+-------
(0 rows)
```

This is the same as writing `NOT (state IN ('Fake state'))` so basically `NOT (FALSE)`, therefore `TRUE`.

Adding a `NULL` makes the predicate unknown, because `NOT (state IN ('Fake state', null))` evaluates to `NOT (NULL)`, which is the same as `NULL`, and so cannot be `TRUE`.

We must remember that SQL is a query language and not a high-level programming language like Python where the equivalent `1 not in [2, None]` is `True`.

2.1.1 Performance implications

Postgres cannot optimize queries using `NOT IN (SELECT … )` well. Specifically, it can't automatically convert such expressions into an anti-join in the query plan, and chooses a hashed Subplan or plain Subplan. This produces an inferior execution strategy as the hashed subplan works fast but is only chosen for small result sets, while the plain subplan is very slow. This means that this query execution plan may offer decent performance on a small scale, but can slow down by whole orders of magnitude if you cross a size threshold.

The PostgreSQL documentation on using `EXPLAIN` has some more information on query plans: https://www.postgresql.org/docs/current/using-explain.html

Lingo: "Anti-join"

Assuming we have tables `a` and `b`, an anti-join is a query for only the rows from `a` that result in no rows being returned from a correlated subquery on `b`. It comes from relational algebra, and the operation is usually expressed with the predicate `NOT EXISTS` in PostgreSQL: https://www.postgresql.org/docs/current/functions-subquery.html#FUNCTIONS-SUBQUERY-EXISTS

2.1.2 Alternative

It is obvious that in most cases `NOT IN (SELECT …)`, which can counter-intuitively end up being `NULL`, would not be what you want. A way of writing this query that can yield more predictable results would be the following alternative which uses `NOT EXISTS`:

```
SELECT ccd.email
FROM erp.customer_contact_details ccd
WHERE NOT EXISTS (SELECT FROM erp.suppliers s
                  WHERE ccd.state = s.state)
AND ccd.state IS NOT NULL;
           email
---------------------------
 river.smith@example.com
 drew.anderson@example.com
(2 rows)
```

This finally gives the correct results. It should also be faster to execute, as the query planner this time chooses an anti-join. Here is what the `NOT EXISTS` query plan looks like:

```
EXPLAIN SELECT ccd.email
FROM erp.customer_contact_details ccd
WHERE NOT EXISTS (SELECT FROM erp.suppliers s
                  WHERE ccd.state = s.state)
AND ccd.state IS NOT NULL;
                                 QUERY PLAN
-----------------------------------------------------------------
 Hash Anti Join  (cost=19.45..319.48 rows=2 width=25)
   Hash Cond: (ccd.state = s.state)
   ->  Seq Scan on customer_contact_details ccd  (cost=0.00..300.
 width=28)
         Filter: (state IS NOT NULL)
   ->  Hash  (cost=14.20..14.20 rows=420 width=32)
         ->  Seq Scan on suppliers s  (cost=0.00..14.20 rows=420
```

```
(6 rows)
```

The following alternative query explicitly demonstrates the anti-join mechanism and allows you to better visualize how rows are getting excluded based on the lack of matches:

```
SELECT ccd.email
FROM erp.customer_contact_details ccd
LEFT JOIN erp.suppliers s USING (state)
WHERE s.state IS NULL;
```

We can see that there are compelling reasons to not use the `NOT IN` syntax. However, if you are positive that your subquery cannot return any nulls, or if you are providing a list of constant values (such as in Listing 2.1), then it should be safe to use.

Negative predicates can be an efficient way to exclude data but their usage requires careful consideration of `NULL` values.

2.2 Selecting ranges with BETWEEN

`BETWEEN` is a convenient SQL feature that allows you to specify a range of values in relative shorthand, such as this example that selects customers with `id` from 1 to 100:

Listing 2.2 Example query with `BETWEEN`

```
SELECT *
FROM erp.customers
WHERE id BETWEEN 1 AND 100;
 id  | first_name  | middle_name  | last_name  | marketing_consent
-----+------------+-------------+-----------+-------------------
   1 | River      | J           | Smith     | t
   2 | Drew       |             | Anderson  | t
                            ...
 100 | Jordan     | A           | Barber    | t
(100 rows)
```

Frogge Emporium have decided they need a query that runs early every morning to calculate the total amount of payments that they received during the previous day. They set out to write this query as follows:

```
WITH t(today) AS (SELECT CURRENT_DATE::timestamptz)
SELECT sum(amount)
FROM erp.payments, t
WHERE tstamp BETWEEN t.today - INTERVAL '1 day' AND t.today;
```

This retrieves the current date and casts it to a timestamp, which gives us the start of the current day at midnight. Then we sum up all payment amounts from payments that happened between midnight yesterday and midnight today. Running the query yields:

```
    sum
------------
 5179739.95
(1 row)
```

So everything's fine, right? Well, not exactly.

We've forgotten that `BETWEEN` is inclusive of both ends of the range, the upper and lower bound. That's easy to spot because, if you remember from Listing 2.2, we got both `1` and `100` in what was returned, this is also called a closed interval.

What does that mean for our results? Let's select yesterday's last payment:

```
WITH t(today) AS (SELECT CURRENT_DATE::timestamptz)
SELECT max(tstamp)
FROM erp.payments, t
WHERE tstamp BETWEEN t.today - INTERVAL '1 day' AND t.today;
          max
------------------------
 2024-05-27 00:00:00+01
(1 row)
```

And now let's select today's first payment:

```
WITH t(today) AS (SELECT CURRENT_DATE::timestamptz)
SELECT min(tstamp)
FROM erp.payments, t
WHERE tstamp BETWEEN t.today AND t.today + interval '1 day';
          min
------------------------
 2024-05-27 00:00:00+01
```

```
(1 row)
```

Notice something? It's the same timestamp. So if payments occur exactly at midnight then you'll count them twice, which is bad when you're dealing with money.

Essentially this is the same query as:

```
WITH t(today) AS (SELECT CURRENT_DATE::timestamptz)
SELECT sum(amount)
FROM erp.payments, t
WHERE tstamp >= t.today - INTERVAL '1 day'
AND tstamp <= t.today;
```

Whenever we want to select rows for specific consecutive ranges, we need to make sure that we don't include overlapping data at the ends of the range. A safer way to write this is to exclude the upper bound with an explicit range definition like the following (note the lack of an equals sign in the expression `AND tstamp < t.today`):

```
WITH t(today) AS (SELECT CURRENT_DATE::timestamptz)
SELECT sum(amount), count(amount)
FROM erp.payments, t
WHERE tstamp >= t.today - INTERVAL '1 day'
AND tstamp < t.today;
    sum     | count
------------+-------
 5179680.00 | 86400
(1 row)
```

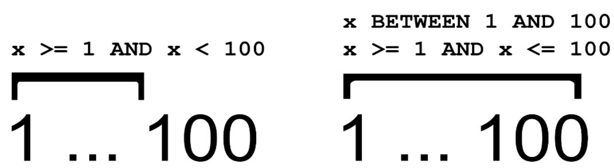
Let's verify the difference by examining the total payment amounts and number of rows:

```
WITH t(today) AS (SELECT CURRENT_DATE::timestamptz)
SELECT sum(amount), count(amount)
FROM erp.payments, t
WHERE tstamp BETWEEN t.today - INTERVAL '1 day' AND t.today;
    sum     | count
------------+-------
 5179739.95 | 86401
(1 row)
```

It may cost you a few more keystrokes, but defining ranges explicitly is cleaner and easier to read at a glance. The more complicated your queries become, the more you'll appreciate clarity and understandability.

So remember, `BETWEEN` is shorthand for "greater than or equals `AND` less than or equals":

Figure 2.1 BETWEEN is inclusive



2.3 Not using CTEs

Common Table Expressions (CTEs), or `WITH`-syntax, are useful bits of syntactic sugar that allow you to tidy up your query code. If you have complex queries, CTEs can make them more readable by breaking up the SQL into smaller, more digestible pieces. Compared to subqueries, CTEs can save you some repetition because you can reference them multiple times within the same query.

Let's look at an example of a complicated query which is not very readable. Frogge Emporium needs to compile a list of customer email addresses who have already been notified that they have an unpaid invoice for purchased services (i.e. not purchased items).

This is what the query initially looks like:

Listing 2.3 Non-CTE query example

```
SELECT DISTINCT email
FROM erp.customer_contact_details ccd
JOIN erp.invoices i ON i.customer = ccd.id
JOIN erp.order_groups og ON i.order_group = og.id
JOIN erp.sent_emails se ON se.invoice = i.id
JOIN erp.orders o ON o.order_group = og.id
WHERE ccd.id IN (
    SELECT customer
    FROM erp.invoices
    WHERE paid = false
)
AND i.order_group IN (
    SELECT order_group
    FROM erp.invoices
    WHERE paid = false
)
AND se.email_type = 'Invoice reminder'
AND o.item IS NULL;
```

It's functional but not great to read, because of its convoluted structure with multiple joins, filters and subqueries. Running it with `EXPLAIN ANALYZE` to see how it fares when it comes to efficiency, we get the following long output:

Figure 2.2 Non-CTE query plan

```
                                                                                                    QUERY PLAN
---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
 Unique  (cost=17472.51..17472.66 rows=1 width=25) (actual time=42.934..49.193 rows=8 loops=1)
   ->  Nested Loop  (cost=17472.51..17472.66 rows=1 width=25) (actual time=42.933..49.190 rows=8 loops=1)
         ->  Gather Merge  (cost=17472.09..17472.21 rows=1 width=49) (actual time=42.925..49.168 rows=8 loops=1)
               Workers Planned: 1
               Workers Launched: 1
               ->  Sort  (cost=16472.08..16472.09 rows=1 width=49) (actual time=40.868..40.872 rows=4 loops=2)
                     Sort Key: ccd.email
                     Sort Method: quicksort  Memory: 25kB
                     Worker 0:  Sort Method: quicksort  Memory: 25kB
                     ->  Parallel Hash Semi Join  (cost=12648.82..16472.07 rows=1 width=49) (actual time=40.736..40.844 rows=4 loops=2)
                           Hash Cond: (i.customer = invoices.customer)
                           ->  Nested Loop  (cost=8576.55..12399.79 rows=1 width=65) (actual time=32.546..32.653 rows=4 loops=2)
                                 ->  Parallel Hash Join  (cost=8576.26..12399.49 rows=1 width=32) (actual time=32.527..32.623 rows=4 loops=2)
                                       Hash Cond: (o.order_group = i.order_group)
                                       ->  Parallel Seq Scan on orders o  (cost=0.00..3820.59 rows=701 width=8) (actual time=6.956..7.012 rows=675 loops=2)
                                             Filter: (item IS NULL)
                                             Rows Removed by Filter: 124325
                                       ->  Parallel Hash  (cost=8576.21..8576.21 rows=4 width=24) (actual time=25.525..25.527 rows=675 loops=2)
                                             Buckets: 2048 (originally 1024)  Batches: 1 (originally 1)  Memory Usage: 152kB
                                             ->  Hash Join  (cost=4116.03..8576.21 rows=4 width=24) (actual time=25.018..25.299 rows=675 loops=2)
                                                   Hash Cond: (i.id = se.invoice)
                                                   ->  Parallel Hash Semi Join  (cost=4072.28..8529.52 rows=775 width=32) (actual time=24.725..24.872 rows=675 loops=2)
                                                         Hash Cond: (i.order_group = invoices_1.order_group)
                                                         ->  Parallel Seq Scan on invoices i  (cost=0.00..4062.59 rows=147059 width=24) (actual time=0.003..6.724 rows=125000 loops=2)
                                                         ->  Parallel Hash  (cost=4062.59..4062.59 rows=775 width=8) (actual time=7.198..7.198 rows=675 loops=2)
                                                               Buckets: 2048  Batches: 1  Memory Usage: 80kB
                                                               ->  Parallel Seq Scan on invoices invoices_1  (cost=0.00..4062.59 rows=775 width=8) (actual time=6.983..7.055 rows=675 loops=2)
                                                                     Filter: (NOT paid)
                                                                     Rows Removed by Filter: 124325
                                                   ->  Hash  (cost=26.88..26.88 rows=1350 width=8) (actual time=0.281..0.281 rows=1350 loops=2)
                                                         Buckets: 2048  Batches: 1  Memory Usage: 69kB
                                                         ->  Seq Scan on sent_emails se  (cost=0.00..26.88 rows=1350 width=8) (actual time=0.008..0.147 rows=1350 loops=2)
                                                               Filter: (type = 'Invoice reminder'::email_type)
                                 ->  Index Scan using customer_contact_details_pkey on customer_contact_details ccd  (cost=0.29..0.31 rows=1 width=33) (actual time=0.006..0.006 rows=1 loops=8)
                                       Index Cond: (id = i.customer)
                           ->  Parallel Hash  (cost=4062.59..4062.59 rows=775 width=8) (actual time=7.940..7.941 rows=675 loops=2)
                                 Buckets: 2048  Batches: 1  Memory Usage: 80kB
                                 ->  Parallel Seq Scan on invoices  (cost=0.00..4062.59 rows=775 width=8) (actual time=7.729..7.795 rows=675 loops=2)
                                       Filter: (NOT paid)
                                       Rows Removed by Filter: 124325
         ->  Index Only Scan using order_groups_pkey on order_groups og  (cost=0.42..0.45 rows=1 width=8) (actual time=0.002..0.002 rows=1 loops=8)
               Index Cond: (id = i.order_group)
               Heap Fetches: 0
 Planning Time: 2.229 ms
 Execution Time: 49.244 ms
(45 rows)
```

The planning and execution times are not that good, because that's the nature of complicated queries. They're not only harder for us to understand but also harder for Postgres's query planner to optimize.

Let us rewrite the query to return the same result, but with CTEs to see how they can help. Here, we use CTE `unp` to get the unpaid invoices, and CTE `ni` to get service orders ("no items"):

Listing 2.4 CTE query example

```
WITH
unp AS (
    SELECT id, customer c, order_group AS og
    FROM erp.invoices
    WHERE paid = false
),
ni AS (
    SELECT og.id
    FROM erp.order_groups og
    JOIN erp.orders o ON o.order_group = og.id
    WHERE o.item IS NULL
)
SELECT DISTINCT email
FROM erp.customer_contact_details ccd
JOIN unp ON unp.c = ccd.id
JOIN ni ON ni.id = unp.og
JOIN erp.sent_emails se ON se.invoice = unp.id
AND se.email_type = 'Invoice reminder';
```

Hopefully, the new query makes it a bit clearer that table `invoices` provides `customer` and `order_group` data only for unpaid invoices, while table `order_groups` isolates service orders by selecting rows with `NULL` item values. We then join up our CTEs with table `sent_emails` and filter on invoice reminder emails.

`EXPLAIN ANALYZE` of the new query yields the following plan:

Figure 2.3 CTE query plan

```
                                                  QUERY PLAN
----------------------------------------------------------------------------------------------------------------
 Unique  (cost=8933.91..8936.10 rows=1 width=25) (actual time=18.037..23.136 rows=8 loops=1)
   ->  Nested Loop  (cost=8933.91..8936.10 rows=1 width=25) (actual time=18.036..23.133 rows=8 loops=1)
         Join Filter: (og.id = o.order_group)
         ->  Gather Merge  (cost=8933.49..8933.68 rows=1 width=41) (actual time=18.029..23.111 rows=8 loops=1)
               Workers Planned: 1
               Workers Launched: 1
               ->  Sort  (cost=7933.48..7933.48 rows=1 width=41) (actual time=16.100..16.102 rows=4 loops=2)
                     Sort Key: ccd.email
                     Sort Method: quicksort  Memory: 25kB
                     Worker 0:  Sort Method: quicksort  Memory: 25kB
                     ->  Nested Loop  (cost=4109.62..7933.47 rows=1 width=41) (actual time=15.967..16.078 rows=4 loops=2)
                           ->  Parallel Hash Join  (cost=4109.33..7932.56 rows=1 width=24) (actual time=15.949..16.051 rows=4 loops=2)
                                 Hash Cond: (o.order_group = invoices.order_group)
                                 ->  Parallel Seq Scan on orders o  (cost=0.00..3820.59 rows=701 width=8) (actual time=7.729..7.787 rows=675 loops=2)
                                       Filter: (item IS NULL)
                                       Rows Removed by Filter: 124325
                                 ->  Parallel Hash  (cost=4109.28..4109.28 rows=4 width=16) (actual time=7.960..7.961 rows=675 loops=2)
                                       Buckets: 1024  Batches: 1  Memory Usage: 104kB
                                       ->  Hash Join  (cost=43.75..4109.28 rows=4 width=16) (actual time=7.655..7.813 rows=675 loops=2)
                                             Hash Cond: (invoices.id = se.invoice)
                                             ->  Parallel Seq Scan on invoices  (cost=0.00..4062.59 rows=775 width=24) (actual time=7.366..7.428 rows=675 loops=2)
                                                   Filter: (NOT paid)
                                                   Rows Removed by Filter: 124325
                                             ->  Hash  (cost=26.88..26.88 rows=1350 width=8) (actual time=0.201..0.201 rows=1350 loops=2)
                                                   Buckets: 2048  Batches: 1  Memory Usage: 69kB
                                                   ->  Seq Scan on sent_emails se  (cost=0.00..26.88 rows=1350 width=8) (actual time=0.007..0.146 rows=1350 loops=2)
                                                         Filter: (type = 'Invoice reminder'::email_type)
                           ->  Index Scan using customer_contact_details_pkey on customer_contact_details ccd  (cost=0.29..0.90 rows=1 width=33) (actual time=0.006..0.006 rows=1 loops=8)
                                 Index Cond: (id = invoices.customer)
         ->  Index Only Scan using order_groups_pkey on order_groups og  (cost=0.42..2.48 rows=1 width=8) (actual time=0.002..0.002 rows=1 loops=8)
               Index Cond: (id = invoices.order_group)
               Heap Fetches: 0
 Planning Time: 0.471 ms
 Execution Time: 23.168 ms
(34 rows)
```

That is a much simpler plan, and also planning and execution of the query were faster too.

Lingo: "Selectivity"

Selectivity is the measure of how many rows we expect our query to retrieve for the given predicate. So, "low selectivity" would be a relatively small number of rows to scan and filter. In this context high selectivity probably has the opposite meaning of what "being highly selective" means in daily usage.

What has happened here is that the optimizer has determined that there is a faster way to retrieve this data by reordering things. By applying filters with low selectivity early on we weed out most of the data that we don't need to go over.

The fact that we have now placed the CTEs first doesn't mean they will get executed first. PostgreSQL has effectively *inlined* the CTEs, or merged them into the main query's execution plan, to find an optimal order of execution based on the statistics of table contents that it keeps. Also, we are replacing `IN` operations with more optimized `JOIN`s.

Note

Another benefit of CTEs is that they will get evaluated just once, regardless of how many times they are referenced in the larger query or other CTEs.

Sometimes, when we know very well what our tables contain, and the selectivity of each (sub)query, we can craft targeted CTEs. For example, if we know that a really expensive query or function returns a few things that are reused lots of times, and are important for determining the selectivity of the rest of the query, we can specify for the CTE to be `MATERIALIZED` so that we can force its evaluation early.

Finally, CTEs are generally easier to run standalone than a correlated subquery, which can aid in optimization and troubleshooting, and they also allow us to run recursive SQL queries.

Note

Take care not to choose names for your CTEs that clash with the names of your existing objects, such as tables or views, because inside the query your CTE name will override the object name and be used instead. This can lead to wrong results and confusion. You should also avoid choosing names already in use by SQL functions, etc.

2.4 Using uppercase identifiers

By default, PostgreSQL ignores case and always turns every identifier you input into lowercase. So if you're coming from a certain database background that likes to put everything `IN_UPPERCASE`, it may make sense for you to carry this habit over into your daily Postgres usage.

However, this can end up causing problems and broken code. Postgres preserves case only when you double quote it, and double-quoted identifiers, also known as *delimited identifiers*, **are** case sensitive. So if you're being inconsistent with your quoting, that can lead to errors. A very plausible way this can happen is if you sometimes forget to double quote identifiers when creating queries by hand, but the ORM you're using always double quotes everything. Let's look at an example:

The DBA creates some tables:

```
SET search_path = erp, "$user", public;
CREATE TABLE Customers (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    first_name text,
    middle_name text,
    last_name text,
    marketing_consent boolean DEFAULT false
);

CREATE TABLE "Invoices" (
    "Invoice ID" bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    "Amount" numeric NOT NULL,
    "Customer" bigint NOT NULL REFERENCES Customers(id),
    "Paid" boolean NOT NULL DEFAULT false
);
```

This has resulted in the creation of two tables:

- One is called `customers` (case-insensitive)
- The other is called `"Invoices"` (case-sensitive)

If we attempt to use these tables the following will happen:

```
TABLE Customers;
 id | first_name | middle_name | last_name | marketing_consent
----+------------+-------------+-----------+-------------------
(0 rows)
```

This works fine. The table name has effectively been turned to lowercase, the same as every other Postgres identifier:

```
\d customers
                            Table "erp.customers"
      Column       |  Type   | Collation | Nullable |        Defa
-------------------+---------+-----------+----------+------------
 id                | bigint  |           | not null | generated a
                   |         |           |          |  identity
 first_name        | text    |           |          |
 middle_name       | text    |           |          |
 last_name         | text    |           |          |
 marketing_consent | boolean |           |          | false
Indexes:
    "customers_pkey" PRIMARY KEY, btree (id)
```

Let's look at the other table:

```
TABLE Invoices;
ERROR:  relation "invoices" does not exist
LINE 1: TABLE Invoices;
              ^
```

This doesn't work fine.

Note

The SQL command `TABLE table_name` can be used as shorthand for `SELECT * FROM table_name`.

The same is also true for column names:

```
CREATE TABLE "Invoices" (
    "Invoice ID" bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    "Amount" numeric NOT NULL,
    "Customer" bigint NOT NULL REFERENCES Customers(id),
    "Paid" boolean NOT NULL DEFAULT false
);
```

Here we have created all mixed-case column names, which become case-sensitive because they were quoted.

```
SELECT count(Customer)
FROM "Invoices";
ERROR:  column "customer" does not exist
LINE 1: SELECT count(Customer)
                     ^
HINT:  Perhaps you meant to reference the column "Invoices.Custome
```

Forgetting to use the column identifier with double quotes results in an error.

We can see that using case in identifiers creates a usability issue, in the sense that once you've done it, you have to always use the quoted names from that point onwards:

```
SELECT count("Customer")
FROM "Invoices";
 count
-------
     1
                                                            (1 row)
```

It is best practice if you don't quote identifiers. However, if the reason why you're using quoted identifiers is for better alignment with your coworkers—for instance, if they want reports where the columns are named like `"Entry Date"` or `"Reconciliation Amount"`—you can satisfy them by simply using column aliases in your queries used to generate their reports. You don't have to put their fancy reporting names in your database, and they'll be none the wiser!

```
SELECT reconc_amt AS "Reconciliation Amount", entry_date AS "Entry
FROM financials
WHERE entry_date = '2023-02-02';
```

Yields:

```
 Reconciliation Amount | Entry Date
-----------------------+------------
                235.11 | 2023-02-02
(1 row)
```

2.5 Dividing INTEGERs

We have decided that we want to find out how many orders we have received that are for physical stock items versus orders for services. Therefore we write this query to select from table `orders`:

```
WITH
i AS (
    SELECT count(*) c
    FROM erp.orders
    WHERE item IS NOT NULL
),
s AS (
    SELECT count(*) c
    FROM erp.orders
    WHERE service IS NOT NULL
)
SELECT
    i.c AS "Item orders",
    s.c AS "Service orders",
    i.c + s.c AS "Total",
    i.c / (i.c + s.c) * 100 AS "Item order %",
    s.c / (i.c + s.c) * 100 AS "Service order %"
    FROM i, s;
```

Which gives us:

```
 Item orders | Service orders | Total  | Item order % | Service or
-------------+----------------+--------+--------------+-----------
      248650 |           1350 | 250000 |            0 |
(1 row)
```

Wait, that can't be right. Look at the last two columns, the math doesn't check out, we do have orders.

What has happened here is that we divided two integers, an operation that could give you a fractional result if performed by hand, but works out differently in SQL.

The PostgreSQL documentation tells us the following about the division operator `/`:

> for integral types (`int` and `bigint`), division truncates the result towards zero‚Äâ‚Äî‚Äâhttps://www.postgresql.org/docs/current/functions-math.html#FUNCTIONS-MATH-OP-TABLE

This can give you wildly inaccurate numeric results where you least expect them.

What we need to do is cast to a type that can be divided without this consequence, such as a `float` or a `double precision` floating-point number:

```
SELECT
    10 / 4 AS "int division",
    pg_typeof(10 / 4) AS "-> output type",
    10::double precision / 4 AS "double division",
    pg_typeof(10::double precision / 4) AS "-> output type";

 int division | -> output type | double division |  -> output typ
--------------+----------------+-----------------+---------------
            2 | integer        |             2.5 | double precisi
(1 row)
```

But, you say, we only converted one of the integers into double and it worked. What happens silently here is that Postgres automatically casts the integer into a compatible type in order to divide it with a `double precision` number.

Note

In PostgreSQL, you can `CAST` between types with the `::` shorthand. `pg_typeof()` is the function that we can use to find out the Postgres data type of the value that is passed to it.

Armed with this knowledge, we now write our query as:

```
WITH
i AS (
    SELECT count(*)::float c
    FROM erp.orders
```

```
    WHERE item IS NOT NULL
),
s AS (
    SELECT count(*)::float c
    FROM erp.orders
    WHERE service IS NOT NULL
)
SELECT
    i.c AS "Item orders",
    s.c AS "Service orders",
    i.c + s.c AS "Total",
    round((i.c / (i.c + s.c) * 100)::numeric, 1) AS "Item order %
    round((s.c / (i.c + s.c) * 100)::numeric, 1) AS "Service orde
FROM i, s;
```

We get the correct result, with some casts and rounding applied as well:

```
 Item orders | Service orders | Total  | Item order % | Service or
-------------+----------------+--------+--------------+-----------
      248650 |           1350 | 250000 |         99.5 |
(1 row)
```

Another somewhat related and potentially painful mistake is when you allow division by zero to happen—something mathematics frowns upon, and computers definitely don't like. You should generally never have application code that allows this type of input to reach the database query, but if you do, this is what is going to happen:

```
WITH zero AS (SELECT count(*) FROM erp.customers WHERE 1=2)
SELECT 10 / zero.count
FROM zero;
ERROR:  division by zero
```

Note

Here `WHERE 1=2` is an impossible condition that cannot be met so the subquery's `count()` of zero rows returns `0`.

What you can do now is make the result undefined (in other words `NULL`) if you encounter a zero—as in our first column here—or you may decide to replace the `0` with another value known to be safe—such as `1` in our second column:

```
WITH zero AS (SELECT count(*) FROM erp.customers WHERE 1=2)
SELECT
    10 / NULLIF(zero.count, 0) AS nullified,
    10 / COALESCE(NULLIF(zero.count, 0), 1) AS replaced
FROM zero;
 nullified | replaced
-----------+----------
           |       10
(1 row)
```

Note

`NULLIF` returns null if the first argument equals the second, and `COALESCE` returns the first non-null argument.

2.6 COUNTing NULL values

Something you need to be aware of when you're trying to count values or rows is whether the column you're using for the `count()` aggregate is nullable or not.

Here Frogge are trying to count the number of orders placed since the beginning of the year. Their query looks like this:

```
SELECT count(item)
FROM erp.orders
WHERE placed_at > date_trunc('year', CURRENT_DATE);
```

and when they run it, they get the following result:

```
 count
--------
 198908
(1 row)
```

However, some orders were not for physical items but for services. Those orders don't have an item attached so their column `item` is `NULL`.

```
SELECT id, status, placed_at, item, service
FROM erp.orders
WHERE service IS NOT NULL
LIMIT 1;
```

```
   id   | status |       placed_at        | item | service
--------+--------+------------------------+------+---------
 168521 | Placed | 2024-05-26 08:55:21+01 |      |      21
(1 row)
```

Let's check how many orders they really have in total by counting rows instead of items:

```
SELECT count(*)
FROM erp.orders
WHERE placed_at > date_trunc('year', CURRENT_DATE);
 count
--------
 200000
                                                               (1 row)
```

This is because `count()` ignores `NULL` values (you can't count something that isn't there), and we were counting using the nullable `item` column. In this case, you need to count the entire row to get the correct result you want.

This also has an interesting side effect: you can use it to your advantage to count what your percentage of orders for services are (knowing that item orders will have a `NULL service`), like this:

```
SELECT round(count(service)::numeric
    / count(*)::numeric * 100, 1) AS "Service orders %"
FROM erp.orders
WHERE placed_at > date_trunc('year', CURRENT_DATE);
 Service orders %
------------------
              0.5
(1 row)
```

2.7 Querying indexed columns with expressions

When you have an index on a column, it makes certain types of queries extremely fast. However, when you query the same indexed column using an expression, such as passing it through a function or casting it so that the data type doesn't match the index's data type, it can cause Postgres to not use the index at all.

This is a serious performance issue—you are effectively paying the price for having an index (such as more disk space usage, slower writes to the table, etc. without benefiting from the index.

Let's see an example with our `payments` table which holds Frogge Emporium's timestamped payment data. If we select payments from a specific timestamp, we get an efficient and pretty much instant response:

```
EXPLAIN (ANALYZE, FORMAT YAML)
SELECT * FROM erp.payments
WHERE tstamp = '2023-10-18 03:40:34.000';
                                 QUERY PLAN
------------------------------------------------------------------
 - Plan:
     Node Type: "Index Scan"
     Parallel Aware: false
     Async Capable: false
     Scan Direction: "Forward"
     Index Name: "payments_tstamp_idx"
     Relation Name: "payments"
     Alias: "payments"
     Startup Cost: 0.42
     Total Cost: 8.46
     Plan Rows: 2
     Plan Width: 31
     Actual Startup Time: 0.010
     Actual Total Time: 0.011
     Actual Rows: 0
     Actual Loops: 1
     Index Cond: "(tstamp = '2023-10-18 03:40:34+01'::timestamp w
 zone)"
     Rows Removed by Index Recheck: 0
   Planning Time: 0.051
   Triggers:
   Execution Time: 0.022
(1 row)
```

This caused an `Index Scan`, which was very fast.

Now let's assume Frogge wants to make the query such that they don't have to specify the timestamp in millisecond accuracy as above. They decide to use the function `date_trunc()` to reduce the accuracy down to the level of seconds. This query will return payments that took place during a specific second:

```
EXPLAIN (ANALYZE, FORMAT YAML)
SELECT * FROM erp.payments
WHERE date_trunc('s', tstamp) = '2023-10-18 03:40:34';
                                 QUERY PLAN
-----------------------------------------------------------------
 - Plan:
     Node Type: "Seq Scan"
     Parallel Aware: false
     Async Capable: false
     Relation Name: "payments"
     Alias: "payments"
     Startup Cost: 0.00
     Total Cost: 5589.00
     Plan Rows: 1250
     Plan Width: 31
     Actual Startup Time: 1.900
     Actual Total Time: 35.880
     Actual Rows: 1
     Actual Loops: 1
     Filter: "(date_trunc('s'::text, tstamp) = '2023-10-18 03:40:
 ::timestamp with time zone)"
     Rows Removed by Filter: 249999
   Planning Time: 0.038
   Triggers:
   Execution Time: 35.892
(1 row)
```

What happened here? We can see that this query did not use the index and instead performed a full table scan, which was orders of magnitude slower.

The reason behind this is that the column is indexed against direct queries for the timestamp values stored. Changing the predicate makes it no longer match the index, and so that is not used.

One possible workaround is to move the transformation to the other side of the predicate comparison operator, like this:

```
EXPLAIN (ANALYZE, FORMAT YAML)
SELECT * FROM erp.payments
WHERE tstamp >= '2023-10-18 03:40:34'::timestamptz
AND tstamp < '2023-10-18 03:40:34'::timestamptz + INTERVAL '1 s';
                                 QUERY PLAN
-----------------------------------------------------------------
 - Plan:
     Node Type: "Index Scan"
```

```
      Parallel Aware: false
      Async Capable: false
      Scan Direction: "Forward"
      Index Name: "payments_tstamp_idx"
      Relation Name: "payments"
      Alias: "payments"
      Startup Cost: 0.42
      Total Cost: 8.44
      Plan Rows: 1
      Plan Width: 31
      Actual Startup Time: 0.014
      Actual Total Time: 0.015
      Actual Rows: 1
      Actual Loops: 1
      Index Cond: "((tstamp >= '2023-10-18 03:40:34+01'::timestamp
 zone) AND (tstamp < ('2023-10-18 03:40:34+01'::timestamp with ti
  + '00:00:01'::interval)))"
      Rows Removed by Index Recheck: 0
    Planning Time: 0.058
    Triggers:
    Execution Time: 0.023
(1 row)
```

We now see that this query uses the index and benefits from full performance again because we have moved the function from the column to the value to be compared.

Also remember one of PostgreSQL's awesome features: indexes on expressions. If we know that we will always be querying this column using `date_trunc`, for example, to find all payments that took place during that minute, we can use an expression index to include the function and speed up those queries.

```
CREATE INDEX ON erp.payments(date_trunc('m', tstamp AT TIME ZONE '
```

Which can then be queried as follows:

```
SELECT * FROM erp.payments
WHERE date_trunc('m', tstamp AT TIME ZONE 'UTC+1')
    = '2023-10-18 03:40' AT TIME ZONE 'UTC+1';
```

Beware: This will create a *lossy* index which will not apply to queries that do not use the same functions and casts that it was created with!

When a query applies a function or transformation to an indexed column, the database has to evaluate the function for each row individually. This prevents it from leveraging the index to locate matching values, as the transformed data does not align with the indexed data. Consequently, the database has to do extra work to process more rows.

2.8 Upserting NULLs in a composite unique key

`UPSERT`, short for ‚ÄúUPDATE` or `INSERT‚Äù, is the operation of entering data into a table where you want to ensure that it's either updated if it already exists or inserted if it doesn't. To apply this logic, you need to use a `UNIQUE` constraint or index. In PostgreSQL, upserts can be performed using `INSERT… ON CONFLICT…` or with the newer `MERGE` syntax.

To go hand-in-hand with a revamp of the inventory management front-end, Frogge Emporium tasks a developer with developing an upsert query for the following proposed `inventory` table to keep their stock levels accurate:

```
CREATE TABLE erp.inventory (
    product_id int NOT NULL,
    warehouse_id int,
    area text,
    quantity int NOT NULL,
    updated_at timestamptz NOT NULL DEFAULT now()
);
CREATE UNIQUE INDEX ON erp.inventory (product_id, warehouse_id, a
```

The unique index created for the stock tracking is the combination of product, warehouse and area. The idea is that each product can exist in multiple warehouses, and be in different areas within that warehouse. We can see that the table allows null in the `area` column because some products may just be in the common stock area instead of a specific location like in the freezer.

The upsert query the developer came up with to test the concept leveraged the `ON CONFLICT DO` syntax and looked like this:

```
INSERT INTO erp.inventory (product_id, warehouse_id, area, quanti
VALUES (99999, 1, 'freezer', 10)
ON CONFLICT (product_id, warehouse_id, area) DO UPDATE
    SET quantity = EXCLUDED.quantity;
```

Which returned:

```
INSERT 0 1
```

So far so good. Now let's try updating the quantity of `product_id` 99999 in `warehouse_id` 1 to 20 with this upsert:

```
INSERT INTO erp.inventory (product_id, warehouse_id, area, quantit
    updated_at)
VALUES (99999, 1, 'freezer', 20, now())
ON CONFLICT (product_id, warehouse_id, area) DO UPDATE
    SET quantity = EXCLUDED.quantity;
```

This returns:

```
INSERT 0 1
```

Let's check the inventory:

```
TABLE erp.inventory;
 product_id | warehouse_id |  area   | quantity |        updated_
------------+--------------+---------+----------+----------------
      99999 |            1 | freezer |       20 | 2024-10-28 21:0
            |              |         |          |.8+00
```

Okay, that seems to have updated the value, marking a successful upsert.

Let's put a quantity of this product in the common stock area of that warehouse:

```
INSERT INTO erp.inventory (product_id, warehouse_id, area, quantit
VALUES (99999, 1, null, 5)
ON CONFLICT (product_id, warehouse_id, area) DO UPDATE
    SET quantity = EXCLUDED.quantity;
```

Which produces:

```
TABLE erp.inventory;
 product_id | warehouse_id | area | quantity |         updated_a
------------+--------------+------+----------+-------------------
      99999 |            1 | free.|       20 | 2024-10-28 21:04:2
            |              |.zer  |          |.0
      99999 |            1 |      |        5 | 2024-10-28 21:05:1
            |              |      |          |.0
```

Let's update this quantity to 7 now:

```
INSERT INTO erp.inventory (product_id, warehouse_id, area, quantit
    updated_at)
VALUES (99999, 1, null, 7, now())
ON CONFLICT (product_id, warehouse_id, area) DO UPDATE
    SET quantity = EXCLUDED.quantity;
```

Let's check:

```
TABLE erp.inventory;
 product_id | warehouse_id | area | quantity |         updated_a
------------+--------------+------+----------+-------------------
      99999 |            1 | free.|       20 | 2024-10-28 21:04:2
            |              |.zer  |          |.0
      99999 |            1 |      |        5 | 2024-10-28 21:05:1
            |              |      |          |.0
      99999 |            1 |      |        7 | 2024-10-28 21:07:5
            |              |      |          |.0
```

Oops. What's happening here? If a product with the same id, warehouse_id, and area already exists, its quantity is updated; otherwise, a new row is inserted. However, we stumbled upon a critical issue that arises when NULL values are involved.

The problem stems from how PostgreSQL handles `NULL` values in a composite unique key. In SQL, a `NULL` value signifies the lack of a value or "unknown". This means PostgreSQL (or any database, for that matter cannot compare `NULL` values for equality. Therefore, the two rows with `NULL` in the `area` column are treated as distinct, even though they look like they should represent the same record in the database. This leads to the unexpected creation of multiple rows with `NULL` in the `area` field instead of updating the existing tuple.

Up until PostgreSQL 14, this issue created a real conundrum because the behavior of `ON CONFLICT` when `NULL` values were involved was unpredictable‚Äâ‚Äî‚Äâin some cases, it would insert new rows and in others it would't. This could lead to application bugs and data integrity problems.

From version 15 onward, PostgreSQL allows you to address this issue by explicitly defining the conflict resolution behavior of `ON CONFLICT` with unique constraints containing `NULL` fields. All you have to do is add the `NULLS NOT DISTINCT` clause when creating the index. This changes the legacy default behavior of treating `NULL` values as distinct and enables proper upserts in this scenario.

Let's illustrate by deleting the bad row and recreating the index with the new option:

```
DELETE FROM erp.inventory WHERE quantity = 7;
DROP INDEX erp.inventory_product_id_warehouse_id_area_idx;
CREATE UNIQUE INDEX ON erp.inventory (product_id, warehouse_id, ar
NULLS NOT DISTINCT;
```

Upserting now works:

```
INSERT INTO erp.inventory (product_id, warehouse_id, area, quantit
    updated_at)
VALUES (99999, 1, null, 7, now())
ON CONFLICT (product_id, warehouse_id, area) DO UPDATE
    SET quantity = EXCLUDED.quantity;
TABLE inventory;
 product_id | warehouse_id | area | quantity |          updated_a
------------+--------------+------+----------+-------------------
      99999 |            1 | free.|       20 | 2024-10-28 21:04:2
            |              |.zer  |          |.0
      99999 |            1 |      |        7 | 2024-10-28 21:22:0
            |              |      |          |.0
```

With this index, the upsert behavior now ensures that rows with `NULL` in the `area` column are considered duplicates if they match all other columns in the unique constraint. The database will then properly update existing rows instead of inserting new ones.

Although newer PostgreSQL releases offer this workaround, relying on `NULL` in composite unique constraints is probably not a good practice. You may be better off switching `NULL` with a meaningful value (e.g. `'common_area'`) or restructuring the table's schema.

2.9 Selecting and fetching all the data

In general, you should not `SELECT` more columns than you need to perform your query. Moreover, you should not fetch large amounts of data from the database to the client side, and then perform operations such as sorting and filtering outside of the database. Try to minimize the amount of data selected and fetched at every level, and that will have a positive impact on the performance of your queries.

Our developer wants to get the primary key of all tickets with `status = 10`, but proceeds to `SELECT *` instead of `SELECT id` because they know that they can just discard the columns they don't need in the application code. Let's write some sample code to see if fetching all the results can really make a difference in performance.

Let's do some prep work to get a clean Python environment running:

```
virtualenv ve
. ve/bin/activate
pip install psycopg
```

Now let's code both use cases, `SELECT` every column from the table versus just the one we want.

Listing 2.5 fetch.py: Fetch all the columns

```
import psycopg, datetime

with psycopg.connect("dbname=frogge user=frogge") as conn:
    with conn.cursor(row_factory=psycopg.rows.dict_row) as cur:
        t1 = datetime.datetime.now()
        cur.execute('''SELECT *
                       FROM support.tickets
                       WHERE status = 10''')
        res = cur.fetchall()
        tkts = []
        for row in res:
            tkts += row['id'],
        t2 = datetime.datetime.now()
        print(f'"SELECT *"  took {t2-t1} seconds.')
    with conn.cursor(row_factory=psycopg.rows.dict_row) as cur:
        t3 = datetime.datetime.now()
        cur.execute('''SELECT id
                       FROM support.tickets
```

```
                    WHERE status = 10''')
        res = cur.fetchall()
        tkts = []
        for row in res:
            tkts += row['id'],
        t4 = datetime.datetime.now()
        print(f'"SELECT id" took {t4-t3} seconds.')
```

Running the above code produces:

```
$ python3 fetch.py
"SELECT *"  took 0:00:00.244571 seconds.
"SELECT id" took 0:00:00.093342 seconds.
```

From this, we can learn that selecting and fetching data that we then discard incurs a performance penalty because of the overhead, both on the database side and on the application side, because more data gets transferred, marshaled into memory, etc. Also remember that this is just on our development machine, over slower network connections it may make for an even bigger difference in performance.

Even worse, our developer can make the mistake of fetching the entire table "to avoid the hassle of writing SQL queries", because they're a good developer and they know how to filter data efficiently on the application side. Believe me, this is something that has actually been seen "in the wild".

Listing 2.6 fetch2.py: Fetch all the rows

```
import psycopg, datetime

with psycopg.connect("dbname=frogge user=frogge") as conn:
    with conn.cursor(row_factory=psycopg.rows.dict_row) as cur:
        t1 = datetime.datetime.now()
        cur.execute('''SELECT *
                    FROM support.tickets''')
        res = cur.fetchmany(10000)
        while (res):
            tkts = []
            for row in res:
                if row['status'] == 10:
                    tkts += row['id'],
            res = cur.fetchmany(10000)
        t2 = datetime.datetime.now()
```

```
        print(f'"SELECT *" with no predicate took {t2-t1} seconds
```

Let's run it:

```
$ python3 fetch2.py
"SELECT *" with no predicate took 0:06:41.919264 seconds.
```

This run time is disastrous,Äâ,Äî,Äâgranted, this is an egregious example with a very large table and the developer forgoing index use.

In real life, code like this usually results in the developer or end user complaining to the IT manager that "PostgreSQL is slow", and leads to orders of unnecessary top-tier hardware needed to speed up the bad query.

Use the database for what it's good at: Data retrieval! PostgreSQL has had almost 30 years of query optimizations to benefit from.

Causing Index Scans vs. Index-Only Scans

If you are only selecting a column that is indexed, the operation will result in a fast Index-Only Scan. Adding more columns to the selection will cause the database to perform an Index Scan which will also read from the table and not just the index, and this can be much slower. Keeping this in mind can be especially useful when writing subqueries or CTEs that need to select the minimum amount of data and be as optimized as possible.

2.10 Not taking advantage of checkers/linters/AI

2.10.1 Code checkers/linters

Every developer worth their salt knows that having a second pair of eyes (or more) on your code is valuable because you can get additional insights or identify errors that escaped your scrutiny. Unfortunately, it's not always easy or feasible to find one or more people and show them your SQL query for feedback.

However, there are second opinions that you can get for free because there's software that can look at your code and comment. Even if you think that mechanical eyes are worse than human eyes, at the very least you lose nothing by passing your code through a checker or linter.

SQLFluff

SQLFluff is an SQL linter and code formatter that also supports Postgres. Here is an example of how it can be used to catch syntax and formatting errors, retrieved from the SQLFluff repository:

```
$ pip install sqlfluff
```

This installed our tool. We'll now create a query and save it to a file:

```
$ echo "  SELECT a  +  b FROM tbl;  " > test.sql
```

And now let's lint that query:

```
$ sqlfluff lint test.sql --dialect ansi
== [test.sql] FAIL
L:   1 | P:   1 | LT01 | Expected only single space before 'SELECT' keyword.
                       | Found '  '. [layout.spacing]
L:   1 | P:   1 | LT02 | First line should not be indented.
                       | [layout.indent]
L:   1 | P:   1 | LT13 | Files must not begin with newlines or whitespace.
                       | [layout.start_of_file]
L:   1 | P:  11 | LT01 | Expected only single space before binary operator '+'.
                       | Found '  '. [layout.spacing]
L:   1 | P:  14 | LT01 | Expected only single space before naked identifier.
                       | Found '  '. [layout.spacing]
L:   1 | P:  27 | LT01 | Unnecessary trailing whitespace at end of file.
                       | [layout.spacing]
L:   1 | P:  27 | LT12 | Files must end with a single trailing newline.
                       | [layout.end_of_file]
All Finished 📜 🎉!
```

3 Improper data type usage

In this chapter

- Avoiding using the wrong data type
- Time zone / Daylight Savings shenanigans
- Data types that should be avoided altogether

PostgreSQL is very rich in data types and probably supports more than most databases. It even goes a step further, and lets you define your own data types with their own indexes, functions and operations! We will now take a look at some popular data types and how their use or misuse can lead to consequential mistakes.

3.1 TIMESTAMP (WITHOUT TIME ZONE)

Speaking of data types, let’s begin with those used for storing date and time. Timestamps are a really popular type that’s used to store both at the same time. If you type in `TIMESTAMP`, PostgreSQL will by default assume that you want `TIMESTAMP WITHOUT TIME ZONE` because that is a behavior required by the SQL Standard.

Our friends at Frogge Emporium have decided to use `TIMESTAMP` to hold when a customer service ticket was opened and when it was closed. Because of the way their customer service system works, it stores the time a ticket was opened at the local time of the customer’s location.

Let’s take for example this ticket, opened by a customer on the US West Coast on October 28th, 2023 at 16:00 Pacific Daylight Time (8 hours behind Universal Time Coordinate or UTC-8) and closed by a Customer Service agent (who was in the UK) on October 29th, 2023 at 09:00 Greenwich Mean Time (GMT or UTC+0):

```
-[ RECORD 1 ]-------------------------------------------------
id         | 132591
```

```
content   | Kindly close our account, as we don't need it anymore
status    | 20
opened_at | 2023-10-28 16:00:00
closed_at | 2023-10-29 09:00:00
```

If we try to calculate the duration of how long it took to close the ticket, e.g. for quality assurance purposes, we will get the following:

```
SELECT pg_typeof(closed_at - opened_at), closed_at - opened_at
FROM support.tickets
WHERE id = 132591;
```

Result is:

```
 pg_typeof | ?column?
-----------+----------
 interval  | 17:00:00
(1 row)
```

17 hours? This is obviously wrong, as from the perspective of the customer, the ticket would have been closed on October 29th, 2023 at 02:00 Pacific Daylight Time (UTC-8), which is only 10 hours.

Why did we get this result? `TIMESTAMP WITHOUT TIME ZONE`, also known as a *naive* timestamp, does not store time zone information. This means that performing arithmetic (such as our subtraction here) between timestamps entered at different timezones is meaningless because it will give the wrong results.

Let’s now assume that this has been taken into account, and the application developers have agreed with the database administrator to only store times in the `Europe/London` time zone regardless of the application user’s location. This way, calculations can be performed because everything is in the same time zone.

Therefore our entry would become:

```
-[ RECORD 1 ]----------------------------------------------------
id        | 132591
content   | Kindly close our account, as we don't need it anymore
status    | 20
opened_at | 2023-10-29 00:00:00
```

```
closed_at | 2023-10-29 09:00:00
```

The time the ticket was open was:

```
 pg_typeof | ?column?
-----------+----------
 interval  | 09:00:00
(1 row)
```

Oops! What happened here is that in London, Daylight Savings Time (DST) or summer time ended at 2:00 AM on October 29th, and the clocks were turned back by one hour. So on the 29th, we effectively had 1:00 AM British Summer Time (BST, UTC+1) followed by 1:00 AM GMT (UTC+0).

Even if we get around the Daylight Savings problem by using UTC everywhere, it's still wrong to use `TIMESTAMP` to store because the database doesn't know it's storing UTC and it will be unable to convert between timezones to produce the correct calculations.

The simplest way to solve this problem is to just use `TIMESTAMPTZ` or `TIMESTAMP WITH TIME ZONE` as the data type. This way we can enter timestamps at any time zone, and the database takes care of all conversions for us when time calculations are needed. Now our table and data would look as follows.

Inserting the data properly:

```
INSERT INTO support.tickets (content, status, opened_at, closed_a
('Kindly close our account, as we don''t need it anymore. Thank y
 '10',
 '2023-10-28 16:00 PDT',
 '2023-10-29 09:00 GMT');
```

Note

Notice that in the query above, we can insert an apostrophe without conflict with the single quotes delimiting the string, by doubling it: `''`.

Seen from a database client in the `Europe/London` time zone, this record is:

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

```
id        | 1
content   | Kindly close our account, as we don't need it anymore
status    | 10
opened_at | 2023-10-29 00:00:00+01
closed_at | 2023-10-29 09:00:00+00
```

The duration calculation yields the correct result:

```
 pg_typeof | ?column?
-----------+----------
 interval  | 10:00:00
(1 row)
```

What we can learn from this is that `TIMESTAMP WITH TIME ZONE` stores a moment in time, which makes time arithmetic meaningful because you can know how much time elapsed between two moments. By contrast, `TIMESTAMP WITHOUT TIME ZONE` is more like you have taken a photo showing a calendar and a watch, capturing the time and date with no additional context.

What's also great about `TIMESTAMPTZ` is that while it displays in the client's time zone, you can ask PostgreSQL to display it at a specific time zone according to what you need:

```
SELECT opened_at AT TIME ZONE 'PDT' AS "Ticket opened",
       closed_at AT TIME ZONE 'PDT' AS "Ticket closed"
FROM support.tickets;
```

Outputs:

```
    Ticket opened    |    Ticket closed
---------------------+---------------------
 2023-10-28 16:00:00 | 2023-10-29 02:00:00
```

Also, you're not using any extra storage space, both `TIMESTAMP` types are 8 bytes in length. With its compact storage, you can use `TIMESTAMPTZ` as a natural primary key for time series data — do you really need a *surrogate* (artificial) key when it can be used to identify tickets uniquely? As an added bonus, it also partitions and indexes wonderfully, so you can use it as a practical partition key and use it to craft really efficient queries.

To summarize, `TIMESTAMPTZ` is the preferred data type for recording a specific moment in time. The naive `TIMESTAMP` is of no use for time math, and has no performance or storage advantage over the time zone-aware type.

3.2 TIME WITH TIME ZONE

For some data, it is sufficient to only capture the time without the date. So it's easy to assume that `TIME WITH TIME ZONE` or `TIMETZ` is a good choice for the data field, after all, we saw previously that omitting the time zone can cause problems sometimes.

Let's assume that Frogge Emporium has a table storing the energy usage of each of their branches, measured by a smart meter. The smart meter marks the time of each reading and the data ingested from it is stored in a `TIMETZ` column. For branch 41, we have the following consecutive readings:

```
 branch_id |    reading_time    | reading | unit
-----------+--------------------+---------+------
        41 | 01:17:27.612383+01 | 54921.8 | kWh
        41 | 01:17:21.356247+00 | 54988.0 | kWh
```

The first and second times we recorded sit across the DST boundary. We know that they are about 1 hour apart, but let's see what happens if we try to subtract them to find the interval between them:

```
SELECT '01:17:27.612383+01'::timetz - '01:17:21.356247+00'::timet
```

Results in:

```
ERROR:  operator does not exist: time with time zone - time with
LINE 1: select '01:17:27.612383+01'::timetz - '01:17:21.356247+00
                                            ^
HINT:  No operator matches the given name and argument types. You
 need to add explicit type casts.
```

Okay, so we notice that the offset stored can vary with Daylight Savings and that we cannot perform time math with this type. From this, we can understand that `TIMETZ` has questionable usefulness. If we use the (naive) `TIME` data type instead, we will run into the same issues performing calculations across DST boundaries as we have just seen with naive `TIMESTAMP`. The fact of the matter is that, in the real world, time zones have little meaning without dates to provide the necessary context.

In short, TIMETZ is included in PostgreSQL just for SQL Standard compliance. As it also takes up 8 bytes of storage space, there's really no reason to ever use it, and it's recommended to use TIMESTAMPTZ instead.

3.3 CURRENT_TIME

All right, CURRENT_TIME is not exactly a data type, but it all ties nicely together with the previous section about TIME WITH TIME ZONE.

current_time is a time function that returns the current time of day as the data type TIME WITH TIME ZONE:

```
SELECT CURRENT_TIME, pg_typeof(CURRENT_TIME);
```

Returns:

```
    current_time    |      pg_typeof
--------------------+---------------------
 20:46:27.094953+00 | time with time zone
```

If you decide to use CURRENT_TIME, you will face the same problems that using TIMETZ incurs. It's a cleaner solution to use a timestamp which represents that specific moment in time. If you don't need the date part afterward, you can just discard it either with EXTRACT() or date_part(), or programmatically on your application's side. The space used for storage of the field will be the same anyway.

In order to use the correct date/time construct, you need to be aware of what each function returns:

Table 3.1 PostgreSQL time functions and return types

Function	Return Type	Sample output
CURRENT_TIMESTAMP or now()	timestamp with time zone	2023-11-20 21:03:34.349275+00

CURRENT_DATE	date	2023-11-20
CURRENT_TIME	time with time zone	21:03:34.349275+00
LOCALTIMESTAMP	timestamp without time zone	2023-11-20 21:03:34.349275
LOCALTIME	time without time zone	21:03:34.349275

`CURRENT_TIME` and the data type it returns, `TIMETZ`, are just not very useful and you should probably use something else that will better match your use case from the above table.

You can find more information on date/time functions in the PostgreSQL documentation at: https://www.postgresql.org/docs/current/functions-datetime.html

3.4 CHAR(n)

Let's now discuss PostgreSQL character types, or what you use to store strings of text inside the database, beginning with `CHAR(n)` or `CHARACTER(n)`. This is a fixed-length, blank-padded textual type — this means that it is always of length *n* as declared and that if the string is less than *n* characters long, the rest of the field is padded with blank characters. You should generally avoid using `CHARACTER(n)`, and it will become apparent in the next few paragraphs why.

Note

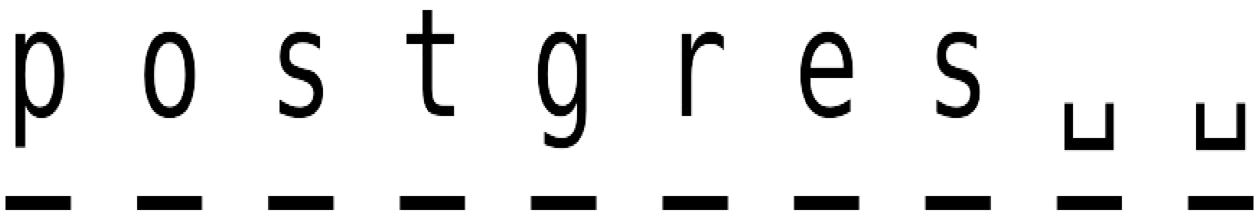
Because it's a **b**lank **p**added **char**acter type of length ***n***, it is also known as type `BPCHAR(n)`. This was previously only used as an internal type designation, but it is now documented, starting with PostgreSQL 16.

This is what the string `'postgres'` looks like inside a `CHAR` of length 10:

```
SELECT 'postgres'::CHAR(10);
   bpchar
------------
 postgres
(1 row)
```

To make what we’re looking at a bit clearer, this is what’s really happening (where blanks are represented by ␣):

Figure 3.1 String padding with CHAR(10)



Because `'postgres'` is 8 characters long, 2 blank characters are added at the end in order to pad out the field to length 10. These padding spaces are ignored — or treated as *semantically not significant* — when comparing strings like so:

```
SELECT 'postgres'::CHAR(10) = 'postgres'::CHAR(20);
 ?column?
----------
 t
(1 row)
```

But beware: Padding is not ignored when performing pattern matching with `LIKE` and regular expressions (regex)!

```
SELECT 'postgres'::CHAR(10) LIKE '%ostgres';
 ?column?
----------
 f
(1 row)
```

`LIKE` does not match "a string ending in `ostgres`" because our `CHAR(10)` value ends in two blank characters.

Similarly, regular expression matching "string ending in `ostgres` " will fail:

```
SELECT 'postgres'::CHAR(10) ~ '.*ostgres$';
 ?column?
----------
 f
(1 row)
```

We see that the same is true for POSIX regular expressions using the ~ regex match operator.

Another annoyance is that if you cast a string that is longer than *n* to a `CHAR(`*n*`)`, then it will be truncated with no warning or error raised, as this is a behavior required by the SQL Standard!

```
SELECT 'I heart PostgreSQL'::CHAR(10);
   bpchar
------------
 I heart Po
(1 row)
```

Even if you need to enforce that the length of a string in a column is exactly *n* characters, using CHAR(*n*) is not the proper way to do that, as it will happily accept shorter strings.

What’s even worse with this data type is that internally in PostgreSQL it’s actually not even stored as a fixed-width field. As, depending on the character encoding, characters may need more than one byte to store, the stored string is represented as a variable-length value on disk. This means that you can simply end up wasting disk space storing irrelevant blank spaces, because these are explicitly stored.

The performance implication is that when you use `CHAR(`*n*`)`, your server spends extra computation time stripping spaces in order to perform string operations and comparisons.

Finally, indexes created for `CHAR(`*n*`)` columns may not work for queries with a `TEXT` parameter passed to the database from a PostgreSQL connector or driver (similarly to what we have seen in Chapter 2, section "Querying indexed columns with expressions").

The bottom line here is: for almost every use case, you should just go ahead and use `TEXT`, the variable unlimited length textual data type (confusingly, also known as `VARCHAR` with no limit specification). `TEXT` gives you more flexibility by not restricting you further down the line, and can give a performance advantage over fixed-length `CHAR` types.

3.5 VARCHAR(n)

`CHARACTER VARYING(`*n*`)` or `VARCHAR(`*n*`)` is a variable-length field for textual data with a length limit, so you can store any string up to that length. This means that inserting longer strings will result in an error:

```
CREATE TEMP TABLE test1 (col VARCHAR(5));
CREATE TABLE

INSERT INTO test1 VALUES ('12345678');
ERROR:  value too long for type character varying(5)
```

Weirdly, if the extra characters beyond *n* are spaces, the string will be truncated silently to length *n* with no error reported, and this is something that the SQL Standard dictates:

```
INSERT INTO test1 VALUES ('1234    ');
INSERT 0 1
TABLE test1;
  col
-------
 1234
```

We see that the string inserted was `'1234 '`, 5 characters, ending in a space. These behaviors are shared with `CHAR(`*n*`)`. Similarly, however, if a longer value is cast to `VARCHAR(`*n*`)`, it’s truncated without warning or error:

```
SELECT 'Just use TEXT'::VARCHAR(10);
  varchar
------------
 Just use T
(1 row)
```

In contrast, `VARCHAR(`*n*`)` doesn’t store any blank padding at the end of the string, so the issues of waste of storage space and string comparisons that we saw with `CHAR(n)` are avoided.

However, you are again getting absolutely no benefit by enforcing a length limit, as the storage on disk is identical to `TEXT`. Even worse, just when you think you have everything sorted out, with your table `suppliers` and its column `company_name VARCHAR(50)`, along comes this supplier, and they're annoyed that they don't see their full company name when they log into your portal.

```
SELECT length('Peterson''s and Sons and Friends Bits & Parts Limi
 length
--------
     52
(1 row)
```

Instead of having to resize your column with `ALTER TABLE` and deal with all the locking needed by the `DDL`, never mind the fact that shrinking down to a smaller limit is impossible, using `VARCHAR(n)` is more trouble than it's worth.

If you positively want to restrict the length of the field, let's say for compliance reasons, just enforce a `CHECK` constraint, which you can then change easily. `CHECK` integrity constraints specify requirements for the value that can be stored in a column, like so:

```
DROP TABLE test1;
DROP TABLE

CREATE TEMP TABLE test1 (col TEXT CHECK(length(col)<=5));
CREATE TABLE

INSERT INTO test1 VALUES ('12345678');
ERROR:  new row for relation "test1" violates check constraint
 "test1_col_check"
DETAIL:  Failing row contains (12345678).
```

Alternately, you can use `CREATE DOMAIN` over the `TEXT` data type to enforce constraints. Domains are data types with constraints already specified that are useful for not repeating your `CHECK` definitions.

Again, the bottom line here is don't use the `VARCHAR(n)` type: it can end up restricting you in a way that is difficult or tedious to circumvent, and it has no performance advantage over the unrestricted kind, so you should just use `TEXT`.

Note

More information on character types in PostgreSQL — be sure to check the tip about performance: https://www.postgresql.org/docs/current/datatype-character.html#DATATYPE-CHARACTER

Type BPCHAR

Also documented since PostgreSQL 16, the type `BPCHAR` with no length specification is for storing variable unlimited length blank-trimmed strings. Like `VARCHAR`, `BPCHAR` also accepts strings of any length, but trailing spaces are semantically not significant. Beware that this means it has significantly different behavior to `VARCHAR`.

Let's illustrate the difference between `BPCHAR` and `VARCHAR` in how they treat trailing whitespace:

```
CREATE TEMP TABLE trailing_ws (v VARCHAR, b BPCHAR);
CREATE TABLE

INSERT INTO trailing_ws VALUES ('vvv   ', 'bbb   ');
INSERT 0 1

SELECT v, ('vvv' = v), b, ('bbb' = b) FROM trailing_ws;
   v    | ?column? |   b    | ?column?
--------+----------+--------+----------
 vvv    | f        | bbb    | t
(1 row)
```

From this, we can see that `BPCHAR` ignores the trailing spaces and treats `'bbb   '` with 3 trailing spaces the same as `'bbb'` whereas `VARCHAR` thinks the strings `'vvv   '` and `'vvv'` differ.

3.6 MONEY

Frogge Emporium wants to store payment amounts for the `payments` they receive so, naturally, for this they are considering to use the data type `MONEY`.

It can store a currency amount with some specific fractional precision set by the database. They create the following table:

```
CREATE TABLE erp.payments (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    tstamp timestamp with time zone NOT NULL,
    amount money NOT NULL,
    invoice bigint NOT NULL
);
```

Inserting a sample payment:

```
INSERT INTO erp.payments (tstamp, amount, invoice)
VALUES (now(), 99.99, 0);
INSERT 0 1

TABLE erp.payments;
 id |            tstamp             | amount | invoice
----+-------------------------------+--------+---------
  1 | 2023-11-20 21:25:12.501561+00 | £99.99 |       0
(1 row)
```

Let's unpack what happened here: in the writer's sample database, PostgreSQL's locale setting `LC_MONETARY` has inherited the system default of `en_GB`, which selects the British Pound (GBP). So the database has assumed we inserted `£99.99` in that currency. This is a bad initial sign, `MONEY` doesn't actually store the currency type, but goes with whatever is configured on your server.

Notwithstanding that, what happens if we want to retroactively apply a 25% discount on all of the customer's payments as a token of appreciation? Calculating that should be simple. After all, we know that the discount equals:

```
SELECT 99.99 * 0.25;
 ?column?
----------
  24.9975
(1 row)
```

So let's apply this to the value stored in our table:

```
SELECT amount * 0.25
```

```
FROM erp.payments
WHERE id = 1;
 ?column?
----------
   £25.00
(1 row)
```

Er, oops. `MONEY` cannot handle fractions of a penny or a cent, or any other denomination, so you will end up losing money, which is unacceptable for most intents and purposes. From this, it is clear that `MONEY` will not have the required accuracy for currency conversions either, where rounding is not an option.

It turns out that `MONEY` is, counter-intuitively, a rubbish type for storing monetary data.

Suitably, the `MONEY` data type is happy to accept garbage input:

```
SELECT ',123,456,,7,8.1,0,9'::MONEY;
     money
----------------
 £12,345,678.11
(1 row)
```

Accepting invalid input into a monetary data type is astoundingly bad. Is this really a data type you want to utilize inside your database? The reality is that, for these reasons, the PostgreSQL core developers have tried to deprecate `MONEY` multiple times, and every time it's been done, there have been persistent requests to bring back the type because some people had existing databases using it, and did not want to change them to migrate to a more sensible type.

Note

Beware that you should not use any floating point number types, such as `real` or `double precision` for handling money because those have the potential for rounding errors. By definition, these are inexact numeric types and the approximations of numbers that they offer are not suitable for storing exact amounts, such as currency.

The proposed solution is to just use `NUMERIC` instead of `MONEY`, and it's also a very good idea to store the currency associated with the monetary value in another adjacent column on the table.

Tip

There is no difference between `NUMERIC` and `DECIMAL` in PostgreSQL.

3.7 SERIAL

`SERIAL` is a PostgreSQL extension, that is, a non SQL standard way to ask the database to create an auto-incrementing integer field. The same applies for its bigger brother `BIGSERIAL`, which auto-increments a `BIGINT`. It used to be a useful shorthand, but today it is actually more trouble than it's worth. To elaborate, let's see how it works by creating a table with a `SERIAL` primary key:

```
CREATE TEMP TABLE transactions (
    id SERIAL PRIMARY KEY,
    amount numeric NOT NULL);
CREATE TABLE

\d transactions
                       Table "pg_temp_4.transactions"
 Column |  Type   | Collation | Nullable |             Default
--------+---------+-----------+----------+-----------------------
 id     | integer |           | not null | nextval('transactions_
        |         |           |          | regclass)
 amount | numeric |           | not null |
Indexes:
    "transactions_pkey" PRIMARY KEY, btree (id)
```

As expected, it automatically created a sequence `transactions_id_seq` to generate values for the `id` column.

Now let's give permission to another user to use this table:

```
CREATE USER jimmy;
CREATE ROLE

GRANT ALL ON TABLE transactions TO jimmy;
```

```
GRANT
```

Let’s see if `jimmy` can insert into this table by switching roles:

```
SET ROLE jimmy;
SET

INSERT INTO transactions (amount) VALUES (10.00);
ERROR:  permission denied for sequence transactions_id_seq
```

Other users cannot insert into the table even if we have granted them this privilege because they don’t have permission to use the automatically created sequence. This is a major shortcoming - permissions for sequences created via the use of `SERIAL` need to be managed separately from the actual table.

More worryingly, if you use `CREATE TABLE … LIKE` to create a similar table, the new table will use the same sequence!

```
CREATE TEMP TABLE new_tx (LIKE transactions INCLUDING ALL);
CREATE TABLE

\d new_tx
                          Table "pg_temp_4.new_tx"
 Column |  Type   | Collation | Nullable |             Default
--------+---------+-----------+----------+------------------------
 id     | integer |           | not null | nextval('transactions_
        |         |           |          |.egclass)
 amount | numeric |           | not null |
Indexes:
    "new_tx_pkey" PRIMARY KEY, btree (id)
```

This is unexpected, and is probably not what you want. It also has the consequence that you can’t drop the original table because the sequence the new table uses depends on it.

In order to avoid these issues you can use identity columns instead of the serial types, like this:

```
DROP TABLE new_tx;
DROP TABLE

CREATE TEMP TABLE new_tx (
    id int GENERATED BY DEFAULT AS IDENTITY PRIMARY KEY,
```

```
    amount numeric not null
);
CREATE TABLE

\d new_tx
                          Table "pg_temp_4.new_tx"
 Column |  Type   | Collation | Nullable |             Default
--------+---------+-----------+----------+----------------------
 id     | integer |           | not null | generated by default a
 amount | numeric |           | not null |
Indexes:
    "new_tx_pkey" PRIMARY KEY, btree (id)
```

With an identity column, you don’t need to know the name of the sequence in order to manipulate it:

```
ALTER TABLE new_tx ALTER COLUMN id RESTART WITH 1000;
ALTER TABLE

INSERT INTO new_tx (amount) VALUES (10.00);
INSERT 0 1

TABLE new_tx;
  id  | amount
------+--------
 1000 |  10.00
(1 row)
```

If you use the `CREATE TABLE … LIKE` construct with a table that has identity columns, the new table will get its own new sequences, so you won’t face any issues.

As a final word, if your application needs to generate a serial sequence of identifiers with no gaps, e.g. for receipt numbers, as required in some localities, it is better to generate the sequence on the application side in order to guarantee correctness. After all, PostgreSQL sequences will generate new numbers even for transactions that are not committed and then rolled back, which means that you’ll then have to find the actual last identifier in the table, and reset the sequence to serve the next number.

3.8 XML

Let us begin by acknowledging the fact that PostgreSQL does offer the option of using the data type `XML`, however ill-advised that may be, and many of the same arguments against using XML outside of the database also apply here.

Starting with the issues independent of the database, XML as a document format offers the worst of both worlds: it is basically as, or less efficient than a flat text file, and can sometimes be just barely human readable, just a cut above a binary data file.

Some more practical reasons to avoid using XML:

- It mandates having a single root element, which means that things like concatenation of XML content require specific parsing and become much harder.
- It uses the concept of namespaces and introduces the additional problem of namespace collision handling.
- As a text-based format, it can allow inconsistencies in the textual representation of numeric data. One good example is including numbers that were entered at different locales, where there’s a good chance that things like the decimal divider rules and separator will be different.
- It simultaneously supports multiple different ways of escaping characters, and the rules on escaping differ whether you’re inside text, an attribute, a comment, CDATA, etc.
- The likelihood that you will receive badly formed XML and be forced to parse it anyway. The probability of someone editing XML by hand may be higher than someone editing JSON data, which is usually used for serializing/deserializing application objects through conversion library functions.
- All of the above don’t even get into why XML is a bad choice for your application, because of the memory allocation nightmares that are involved in parsing it, which mean you need to examine the advantages and disadvantages of DOM versus SAX/streaming parsers, etc.

Additionally, on the database side, and specifically in PostgreSQL:

- The DOCTYPE Document Type Declaration (DTD) is problematic as it requires an external or inline DTD definition (that will be entirely irrelevant to your database). PostgreSQL does not validate input values against it, and has no support for other XML schema languages such as XML Schema.

- Character encoding, as specified in the XML declaration, may actually be different to the character set that the XML text was saved in. Complicating matters even more, you may have different character encodings on the client and server side, as well as on the XML data side. By default, PostgreSQL converts all character data passed between client and server in both directions, so this will include the string representations of values in your XML, and it may render the XML encoding declaration invalid. This makes it your responsibility to ensure that all three encodings and the XML declaration are aligned.
- The same goes for the language identification attribute `xml:lang`, it is simply irrelevant inside a PostgreSQL database.
- There are no applicable comparison operators for the `XML` type, as a well-known and trusted comparison algorithm for XML data does not exist, even outside of Postgres. provide comparison operators. This means that you cannot retrieve rows by comparing an `XML` column against a search value. So the main option you're left with is converting everything to `TEXT` and comparing strings, which is less than ideal.
- `XML` is queryable using XPath 1.0, but this is a moot point, as the type is not indexable. Compare and contrast to `JSONB`, which is very well indexable using the `GIN` and `GIST` index types.
- It is very verbose, which makes for a lot of redundant bytes and consequently a waste of storage space.
- In PostgreSQL, it offers no advantages over the much more compact notation of the same data as JSON. Consider this fragment, which doesn't even include the basic overhead and declarations needed to be considered an XML document:

```
SELECT
'<property>
    <key>color</key>
    <value>00000</value>
</property>'::XML,
pg_column_size(
'<property>
    <key>color</key>
    <value>00000</value>
```

```
</property>'::XML
);

           xml            | pg_column_size
--------------------------+----------------
 <property>              +|             72
     <key>color</key>    +|
     <value>00000</value>+|
 </property>              |
(1 row)
```

compare this to a more stripped down way to represent essentially the same data:

```
SELECT
'{"color":0}'::JSON,
pg_column_size(
'{"color":0}'::JSON
);

    json     | pg_column_size
-------------+----------------
 {"color":0} |             15
(1 row)
```

Note

`pg_column_size()` is the function we use to measure the space in bytes used to store any individual data value.

In conclusion, XML is error-prone, inefficient and slow. Don’t use `XML` for any heavy lifting, especially inside your Postgres database. You will be much better off using `JSON`, or even better, `JSONB` for your structured data needs. You can find more on JSONB inside the PostgreSQL Documentation: https://www.postgresql.org/docs/current/datatype-json.html

3.9 Summary

- There is no benefit to using `TIMESTAMP (WITHOUT TIME ZONE)`, as it can lead to time calculation errors due to lack of time zone and DST context. `TIMESTAMP WITH TIME ZONE` is the proper data type for recording timestamps as specific moments in time.

- `TIMETZ` and `CURRENT_TIME` have questionable usefulness because time zones have no meaning without the context of dates. Again, it is preferable to use `TIMESTAMPTZ` even if we don't need to display the date part of the timestamp.
- `MONEY` doesn't store which currency, it suffers from a limited and flawed implementation, and should be avoided in favor of using `NUMERIC` or other number formats that can accurately store exact values, potentially in conjunction with storing the currency as a separate column.
- The two serial types `SERIAL` and `BIGSERIAL` have been effectively superseded by identity columns, which have more predictable behavior when it comes to role ownership and use of sequences, and clarity regarding which table the sequence belongs to.
- You don't save storage space by using the limited character types `CHAR(`*n*`)` and `VARCHAR(`*n*`)`, and the whitespace stored with `CHAR(`*n*`)` can be detrimental to performance. Additionally, you run the risk of running into SQL quirks and painting yourself in a corner with maximum lengths — `TEXT` is the better choice.
- `XML` is a terrible choice for document storage, unless you're just copying immutable XML data inside the database — if you intend to query/manipulate the data, you should use `JSON(B)`.

4 Table and index mistakes

In this chapter

- Table inheritance: an unusual feature
- Why partitioning is important and how to get it right
- Using the right type of key and index for your tables

Some PostgreSQL particularities give it additional flexibility compared to other Relational Database Management Systems (RDBMSs) and can enable powerful and expressive database designs. However, these same features also have the potential to become pitfalls when coming to Postgres with preconceptions from other systems or if the documentation is misunderstood.

4.1 Table inheritance

At the time of writing, PostgreSQL describes itself as a "powerful, open source object-relational database system" and this may throw some people off, as it seems to be a description from another era in computing. It may well be an outdated reference to object-oriented programming (OOP) which, as some of you may remember, used to be all the rage in past years. The PostgreSQL project was very keen on showing support for OOP and one of the advanced features that were particularly relevant to OOP was table inheritance.

Simply put, table inheritance lets you create tables that inherit columns from other tables — the same way that object classes might inherit variables and methods from their parent classes. Using it is as simple as `CREATE TABLE (…) INHERITS …`.

For example, if we think of a meeting as a kind of event, then we can create a table `meetings` that includes the attributes of table `events`:

Listing 4.1 Table inheritance

```
CREATE SCHEMA calendar;
SET search_path = calendar, "$user", public;

CREATE TABLE events (
    id int PRIMARY KEY,
    scheduled_time timestamptz,
    status smallint
);
CREATE TABLE

CREATE TABLE meetings (
    invited_emails text[],
    confirmed_emails text[],
    location text
) INHERITS (events);
CREATE TABLE

\d events
                          Table "calendar.events"
     Column     |           Type           | Collation | Nullable
----------------+--------------------------+-----------+---------
 id             | integer                  |           |
 scheduled_time | timestamp with time zone |           |
 status         | smallint                 |           |
Number of child tables: 1 (Use \d+ to list them.)

\d meetings
                         Table "calendar.meetings"
      Column      |          Type           | Collation | Nullable
------------------+-------------------------+-----------+---------
 id               | integer                 |           |
 scheduled_time   | timestamp with time zo.|           |
                  |.ne                      |           |
 status           | smallint                |           |
 invited_emails   | text[]                  |           |
 confirmed_emails | text[]                  |           |
 location         | text                    |           |
Inherits: events
```

So we see that the relationship between the tables has been established and is being reported by PostgreSQL. Let’s see what we can do now — what happens if we insert a meeting?

```
INSERT INTO meetings (id, scheduled_time, status, invited_emails,
    location)
VALUES (1981, '2024-02-01 09:00', 10,
```

```
    ARRAY['kerry.moss@example.com', 'morgan.avenal@example.com'],
    'https://webmeetings.example.com/pas/ok/1981');
INSERT 0 1

TABLE meetings;
-[ RECORD 1 ]----+-----------------------------------------------------
id               | 1981
scheduled_time   | 2024-02-01 09:00:00+00
status           | 10
invited_emails   | {kerry.moss@example.com,morgan.avenal@example.
confirmed_emails |
location         | https://webmeetings.example.com/pas/ok/1981

TABLE events;
-[ RECORD 1 ]--+-----------------------
id             | 1981
scheduled_time | 2024-02-01 09:00:00+00
status         | 10
```

So we see that inserting a meeting also generates a row in events with the corresponding inherited fields filled in. I guess that’s pretty neat, and it must have seemed like a good idea before Object-Relational Mapping tools (ORMs) started appearing.

Before PostgreSQL 10, table inheritance was also used to implement partitioning by defining the relationships between the parent table and the (child) partition tables. However, since PostgreSQL 10, when declarative table partitioning was introduced, there has been practically no reason to use the much more complicated inheritance path for partitioning tables.

Let’s see what happens if we decide that this table will grow to be too large, so we try to create a partitioned version, and attach the current table as the first partition:

```
CREATE TABLE events_partitioned (
    id int,
    scheduled_time timestamptz,
    status smallint
) PARTITION BY RANGE (scheduled_time);
CREATE TABLE

ALTER TABLE events_partitioned ATTACH PARTITION events
FOR VALUES FROM ('2000-01-01') TO ('2025-01-01');
ERROR:  cannot attach inheritance parent as partition
```

Whoopsie! Inheritance is fundamentally incompatible with declarative partitioning. You cannot inherit from a partitioned table and you cannot add inheritance to a partitioned table. So what can you do now that you’re stuck with table inheritance? You would need to find some way to undo it.

Fortunately, it isn’t all that complicated: you can simply replace the relationship defined by table inheritance with foreign key relationships. You shouldn’t really have second thoughts about this because, by forfeiting table inheritance, you won’t be missing out on any important functionality anyway.

All you need to do is to create a new table to hold the data, and add the foreign key column. Let’s do this for the `meetings` table:

```
CREATE TABLE new_meetings (LIKE meetings);
CREATE TABLE

ALTER TABLE new_meetings ADD event_id int;
ALTER TABLE
```

Then, you copy the data from the old table into the new one (which may take a long time):

```
INSERT INTO new_meetings
SELECT *, id FROM meetings;
INSERT 0 520628
```

Following that, you can create all required constraints, indexes, triggers, etc. for `new_meetings`.

There is a dirty hack you can resort to if your table is huge and you are performing this on a live system. It involves creating the foreign key constraint but not validating it immediately. This would of course presuppose that you trust the data that’s inside your tables — namely that the data in the foreign key column is valid (which it probably will be, being an exact copy of the original table). However, actions such as this are generally not recommended, as they involve touching the PostgreSQL catalog.

Note

Modifying the PostgreSQL catalog is something that should be avoided because, unless you know exactly what you’re doing, you can make a change that causes data corruption or the database to become unusable.

Having stated the risk, here is what you can do:

```
ALTER TABLE new_meetings ADD
CONSTRAINT event_id_fk FOREIGN KEY (event_id)
REFERENCES events (id) NOT VALID;
UPDATE pg_constraint SET convalidated = true WHERE conname = 'eve
```

If this is a live system, you should also probably create triggers to replicate the changes that are coming into `meetings` to `new_meetings` too. Also, triggers to replicate changes to `events` as `meetings` changes — it’s easy as now we have the foreign key.

Finally, you perform all the DDL at once inside a single code block:

```
DO $$
BEGIN
    ALTER TABLE meetings RENAME TO old_meetings;
    ALTER TABLE new_meetings RENAME TO meetings;
    DROP TABLE old_meetings;
    COMMIT;
END $$ LANGUAGE plpgsql;
```

That’s it; you’re now free of table inheritance and can do things such as experimenting with partitioning (which, fortuitously, is discussed in the very next section in this book).

4.2 Neglecting table partitioning

We previously mentioned table partitioning, but what is it all about? In a relational database context, it’s simply the division of a table into distinct independent tables. Also known as *horizontal partitioning*, it makes it so that rows that are different in some particular respect end up in different tables. Having heard a decade of complaints by users of databases made by other vendors that PostgreSQL didn’t support partitioning, I have always been stunned to discover how few people are aware of partitioning in Postgres. PostgreSQL 10 introduced *declarative partitioning* (the ability to do it via `CREATE TABLE`) in 2017, and there had been less elegant ways of implementing partitioning since at least PostgreSQL 8.1, released way back in 2005! PostgreSQL has continued to improve partitioning features in later versions, such as adding foreign key support in version 12, and enhancing performance for partitioned tables.

Now we come to the question of when leaving your tables unpartitioned turns out to be a mistake. Frogge Emporium has a large `payments` table, and let's assume it doesn't make sense for them to index it because they are receiving a very large volume of data and they don't want to slow down insert performance. This is what searching for a payment looks like:

```
SELECT count(*) FROM erp.payments;
   count
-----------
 150001000
(1 row)

SET jit=off; SET max_parallel_workers_per_gather=0;
SET
SET

EXPLAIN (ANALYZE, BUFFERS)
    SELECT * FROM erp.payments WHERE tstamp='2022-03-09 22:58:20.

                                 QUERY PLAN
------------------------------------------------------------------
 Seq Scan on payments  (cost=0.00..3026445.20 rows=1 width=31) (a
 time=38723.267..62110.334 rows=1 loops=1)
   Filter: (tstamp = '2022-03-09 22:58:20.431946+00'::timestamp w
 zone)
   Rows Removed by Filter: 150000999
   Buffers: shared hit=812 read=1151157
 Planning Time: 0.115 ms
 Execution Time: 62110.373 ms
(6 rows)
```

Wow! It takes a full minute to find a row in this table and what's even worse is that we appear to have read 1151157 buffers or 9 whole GB of data from the disk. Similarly, if we want to delete the oldest month of data, which happens to be September 2021:

```
\timing
Timing is on.
```

```
DELETE FROM erp.payments WHERE tstamp < '2021-10-01';
DELETE 1209894
Time: 65914.030 ms (01:05.914)
```

That's quite bad, for an OLTP database that has performance requirements. Partitioning the table can help with this workload because it can split it into smaller tables that perform better in our use case and are easier to maintain.

PostgreSQL declarative partitioning is, simply put, specifying for your table:

- A partitioning method
- A partition key, which can be one or more columns or expressions
- Partition boundaries

And it's done simply with DDL. Let's create an empty partitioned version of the `payments` table, like this:

```
CREATE TABLE erp.payments_p (
    id bigint GENERATED ALWAYS AS IDENTITY,
    tstamp timestamp with time zone NOT NULL,
    amount numeric NOT NULL,
    invoice bigint NOT NULL
) PARTITION BY RANGE (tstamp);
CREATE TABLE
```

An additional reason to partition your tables is that PostgreSQL does have some hard size limits when it comes to tables. Admittedly, they are hard to reach but not impossible given the ever-increasing amounts of data people are handling today.

Postgres supports an unlimited data size, which is great news. It also supports having 1.4 billion tables per database, regardless of how bad an idea that would be. However, a very real limitation is the maximum table size, which for the default block size of 8192 bytes is 32 terabytes. The maximum number of rows per table limitation is less clear: as many rows as can fit in 4.2 billion blocks.

Here's where dimensioning comes in — it's important to plan ahead so that you don't get stuck with an unmanageably large table a few months or years down the line. You should get your calculator out and take into account your system’s data ingestion rate, both in terms of number of rows getting created but also in terms of data size in bytes. Something else to factor in are projected increases, which may even be outside of the IT system, such as Frogge Emporium having 25 retail locations which are projected to grow to 200 over the next four years. Finally, you need to take into account your data retention requirements, such as e.g. the law mandating you keep 10 years' worth of records around.

The capacity planning exercise you perform will inform your choice of partitioning method and key. For instance let’s say you determine that from each device from a sensor network of 1000, you receive 1440 measurements per day. Then you can extrapolate this number to see how many measurements you ingest per year. Obviously, you need to keep checking that this estimate remains valid and be prepared to revise accordingly.

Frogge Emporium has determined that the most meaningful partition size for them is one month. They can use `tstamp` as the partition key, and divide the table by `RANGE` partitioning, which is suitable for ranges of time, identifiers, etc. Therefore they write a script to create monthly partitions for the table we just created:

```
DO $$
BEGIN
  FOR i IN 0..28
  LOOP
    EXECUTE format('CREATE TABLE erp.%s PARTITION OF erp.payments
        FOR VALUES FROM (''%s'') TO (''%s'')',
        'payments_p_' ||
        extract('year' FROM date_trunc('month', now()) -
            (i * INTERVAL '1 month')) || '_' ||
        extract('month' FROM date_trunc('month', now()) -
            (i * INTERVAL '1 month')),
        date_trunc('month', now()) - (i * INTERVAL '1 month'),
        date_trunc('month', now()) + ((1 - i) * INTERVAL '1 month
  END LOOP;
END;
$$;
DO
```

The script’s loop starts 28 months before the current month and creates each month’s partition like so:

```
CREATE TABLE erp.payments_p_<year>_<month>
PARTITION OF erp.payments_p
FOR VALUES FROM (<first day of month>) TO (<last day of month>);
```

The resulting partition structure looks like this:

```
payments_p
├── payments_p_2021_1
├── payments_p_2021_2
├── payments_p_2021_3
├── ...
├── payments_p_2022_1
├── payments_p_2022_2
└── ...
```

We copy the data from the unpartitioned table into our new tables (this takes a long time):

```
INSERT INTO erp.payments_p (tstamp, amount, invoice)
    SELECT tstamp, amount, invoice FROM erp.payments;
INSERT 0 150001000
```

Now let's see how long it takes to find the same row in the partitioned table:

```
EXPLAIN (ANALYZE, BUFFERS)
    SELECT * FROM erp.payments_p
    WHERE tstamp='2022-03-09 22:58:20.431946+00';

                                 QUERY PLAN
-----------------------------------------------------------------
 Seq Scan on payments_p_2022_3 payments_p  (cost=0.00..111450.00
 width=32) (actual time=1780.649..2535.625 rows=1 loops=1)
   Filter: (tstamp = '2022-03-09 22:58:20.431946+00'::timestamp w
 zone)
   Rows Removed by Filter: 5349599
   Buffers: shared read=44580
 Planning:
   Buffers: shared hit=20 dirtied=2
 Planning Time: 0.406 ms
 Execution Time: 2535.658 ms
(8 rows)
```

At only 2.5 seconds, it's 24.5 times faster than the unpartitioned table. Because PostgreSQL does what is known as *partition pruning* — or not searching in partitions that cannot possibly contain the row we're looking for

— it only needed to check partition `payments_p_2022_3` and to read just 44580 buffers or 348 MB from the disk. Partition pruning is enabled by our inclusion of the partition key as a predicate to our query, therefore letting the internal query planner know which rows we are **not** looking for.

Let’s see how much faster it is to drop a month’s partition than to delete that month’s data:

```
\timing
Timing is on.

DROP TABLE erp.payments_p_2021_9;
DROP TABLE
Time: 43.113 ms
```

This is simply stunning performance which makes data management and maintenance a lot easier.

Note

You can find more details on selecting a partitioning method and key in the official PostgreSQL documentation at: https://www.postgresql.org/docs/current/ddl-partitioning.html

Partitioning can help with:

- Performance, because you have sequential and index scans of smaller amounts of data due to partition pruning.
- Maintenance, because you can `DROP TABLE` to delete old data and because `VACUUM` of multiple smaller tables can parallelize and complete quicker than one very long running operation for one huge table.
- Disk size limitations, because you can put partitions on different *tablespaces* (which in PostgreSQL can live on different filesystems or disks). This also means you can put different partitions on slower and cheaper disks, and also that you can decide whether to create indexes on some of them or not.
- Circumventing a pitfall of extremely large tables: they are split into 1 GB files and PostgreSQL loops through some code that’s the same for each 1 GB segment, so it would execute that 32000 times for a 32 TB

table.

However, you need to be aware that choosing the wrong partitioning method, partition key or partition sizing may actually lead to performance degradation. For example, you should favor keys with sufficient cardinality to distribute the data evenly across your partitions. Additionally, if your queries don’t include the partition key in the `WHERE` clause they will not leverage partition pruning and this can lead to worse execution plans.

Using a poorly selected partitioning strategy and key may lead to having too many partitions with just a few rows in each. If the partitioning key doesn’t group the data effectively, you may incur higher overheads with excessive partition scans, which will lead to increased I/O and, consequently, slower queries.

To summarize, partitioning with due diligence can make your tables easier to manage, help you get around PostgreSQL limitations when you’re dealing with big data, and give you a significant performance boost for your queries.

4.3 Partitioning by multiple keys

In the PostgreSQL documentation’s `CREATE TABLE` partitioning section, you can easily find the syntax for partitioning by multiple keys. Sometimes it makes sense to partition a table by multiple columns, to have better granularity or a larger number of partitions more finely tuned to the data.

Frogge wants to partition their energy usage table both by month and branch so that the data in each table will be more specific. Let’s try partitioning by multiple keys:

```
CREATE TABLE erp.energy_usage (
    branch_id integer NOT NULL,
    reading_time timestamptz DEFAULT CURRENT_TIMESTAMP,
    reading numeric NOT NULL,
    unit varchar DEFAULT 'kWh' NOT NULL
)
PARTITION BY RANGE (reading_time, branch_id);
CREATE TABLE
```

Now that the base table is created, let's create a partition for January 2024 and branch IDs 1-10:

```
CREATE TABLE erp.energy_usage_2024_01_01to10
PARTITION OF erp.energy_usage
FOR VALUES FROM ('2024-01-01', 1) TO ('2024-02-01', 10);
CREATE TABLE
```

That went well. Now let's create the next partition for the same month, for data from branches 11-20:

```
CREATE TABLE erp.energy_usage_2024_01_11to20
PARTITION OF erp.energy_usage
FOR VALUES FROM ('2024-01-01', 11) TO ('2024-02-01', 20);
ERROR:  partition "energy_usage_2024_01_11to20" would overlap par
 "energy_usage_2024_01_01to10"
LINE 3: FOR VALUES FROM ('2024-01-01', 11) TO ('2024-02-01', 20);
```

We got an error! We can see that PostgreSQL states that effectively a `reading_time` value such as `'2024-02-01 10:00:00'` can only exist inside the first partition, regardless of `branch_id`!

Why is this? Taking a closer look at what we were trying to do reveals that what we did was to define partition boundaries on two keys. This simply restricts the values for each key that can go into each partition. Be careful! This is not partitioning on multiple levels.

What we actually need for our use case (having one partition per month for a specific set of branches) is called *sub-partitioning*. Sub-partitioning is, simply put, partitioning the partitions. Since each partition is a separate table, it can be a partitioned table itself.

Caution

Partitioning by multiple keys is not the same as multi-level partitioning.

Let's see the right way to do this. We create the base table with `reading_time` as the partition key:

```
CREATE TABLE erp.energy_usage (
    branch_id integer NOT NULL,
```

```
    reading_time timestamptz DEFAULT CURRENT_TIMESTAMP,
    reading numeric NOT NULL,
    unit varchar DEFAULT 'kWh' NOT NULL
)
PARTITION BY RANGE (reading_time);
CREATE TABLE
```

Then we create partitions for each month, and afterward, we partition those monthly partitions by `branch_id`:

```
CREATE TABLE erp.energy_usage_2024_01
PARTITION OF erp.energy_usage
FOR VALUES FROM ('2024-01-01') TO ('2024-02-01')
PARTITION BY RANGE (branch_id);
CREATE TABLE

CREATE TABLE erp.energy_usage_2024_01_01to10
PARTITION OF erp.energy_usage_2024_01
FOR VALUES FROM (1) TO (10);
CREATE TABLE

CREATE TABLE erp.energy_usage_2024_01_11to20
PARTITION OF erp.energy_usage_2024_01
FOR VALUES FROM (11) TO (20);
CREATE TABLE
```

And so on. Our schema now looks lovely!

```
\dt erp*
                         List of relations
 Schema |            Name             |       Type        | Owner
--------+-----------------------------+-------------------+------
 erp    | energy_usage                | partitioned table | frogg
 erp    | energy_usage_2024_01        | partitioned table | frogg
 erp    | energy_usage_2024_01_01to10 | table             | frogg
 erp    | energy_usage_2024_01_11to20 | table             | frogg
(4 rows)
```

And `\d+ erp.energy_usage_2024_01` for January 2024's partitioned table reports this:

```
Partition of: erp.energy_usage FOR VALUES FROM ('2024-01-01 00:00
 ('2024-02-01 00:00:00+00')
Partition constraint: ((reading_time IS NOT NULL) AND (reading_ti
 '2024-01-01 00:00:00+00'::timestamp with time zone) AND (reading
```

```
 '2024-02-01 00:00:00+00'::timestamp with time zone))
Partition key: RANGE (branch_id)
Partitions: erp.energy_usage_2024_01_01to10 FOR VALUES FROM (1) T
            erp.energy_usage_2024_01_11to20 FOR VALUES FROM (11)
```

So, if we continue down this path, our partitioning will start looking like this:

```
energy_usage
├── energy_usage_2024_01
│   ├── energy_usage_2024_01_01to10
│   └── energy_usage_2024_01_11to20
├── energy_usage_2024_02
│   ├── energy_usage_2024_02_01to10
│   └── energy_usage_2024_02_11to20
├── energy_usage_2024_03
│   └── ...
└── ...
```

Partitioning by multiple columns certainly has its usefulness, like for example keeping scientific data separate and allowing rapid access via partition pruning (provided `WHERE` clauses for both columns are specified in the query). What's easy to miss in the documentation is this part:

"For example, given `PARTITION BY RANGE (x,y)`, a partition bound `FROM (1, 2) TO (3, 4)` allows `x=1` with any `y>=2`, `x=2` with any non-null `y`, and `x=3` with any `y<4`."

In most cases, sub-partitioning may be more practically useful to you than this syntax, so it's good to be aware.

4.4 Using the wrong index type

There is a wide variety of indexes offered by PostgreSQL, alongside the incredibly powerful capability to be able to write your own index types. Each built-in index type uses its own algorithm that is suitable for specific uses. Namely, improving query performance for specific types of queries on certain types of data.

The default index type is B-Tree, and again it's surprising to find out how many people think it's the only index type in PostgreSQL. The B-Tree index can speed up queries with equality or ordering comparisons, and can also offer some querying capabilities with the `LIKE` operator for pattern matching and ~ operator for regular expressions.

Let's see what we can do with the default index type for a dataset such as ArXiv's Open Access research metadata, which has entries for 2.4 million articles, complete with titles, authors, categories, abstracts, etc.

Note

You can create a Kaggle account to download the dataset at: https://www.kaggle.com/datasets/Cornell-University/arxiv/

After unzipping the 4.2 GB JSON dataset, we run the following to escape backslashes and make Postgres happier with our JSON file:

```
sed -i 's/\\/\\\\/g' 'arxiv-metadata-oai-snapshot.json'
```

We then copy it into our database table called `arxiv`, with everything inside a `jsonb` column called `data`:

```
CREATE TABLE test.arxiv (data jsonb);
CREATE TABLE

\copy test.arxiv FROM 'arxiv-metadata-oai-snapshot.json'
COPY 2417693
```

We can access the elements of each entry, such as the title, like this:

```
SELECT data ->> 'title' FROM test.arxiv TABLESAMPLE BERNOULLI (0.
                           ?column?
---------------------------------------------------------------
 Modeling of hydrogen and hydroxyl group migration on graphene
(1 row)
```

We can now create an index to speed up searching through those titles by indexing only the title element from the entire JSON document. We'd rather use case-insensitive search, so let's turn everything into lower case, and specify that we need the index for `text_pattern_ops`:

```
CREATE INDEX ON test.arxiv (lower(data->>'title') text_pattern_op
```

```
CREATE INDEX

ANALYZE test.arxiv;
ANALYZE
```

Now that the index is created, we can search for articles with titles beginning for example with "Modeling of hydrogen". Remember to always use the expression that was previously used in the index creation in the `WHERE` clause for querying:

```
EXPLAIN ANALYZE
    SELECT data->'doi'
    FROM test.arxiv
    WHERE lower(data->>'title') LIKE 'modeling of hydrogen%';
                                 QUERY PLAN
-----------------------------------------------------------------
 Index Scan using arxiv_lower_idx on arxiv  (cost=0.56..9.19 rows
 width=32) (actual time=0.085..0.085 rows=1 loops=1)
   Index Cond: ((lower((data ->> 'title'::text)) ~>=~
 'modeling of hydrogen'::text) AND (lower((data ->> 'title'::text
 'modeling of hydrogeo'::text))
   Filter: (lower((data ->> 'title'::text)) ~~ 'modeling of
 hydrogen%'::text)
 Planning Time: 0.755 ms
 Execution Time: 0.134 ms
(5 rows)
```

That wasn’t too bad; let’s try filtering by titles **containing** "modeling of hydrogen" (notice the query pattern change to `'%modeling of hydrogen%'`):

```
SET jit=off; SET max_parallel_workers_per_gather=0;
SET
SET

EXPLAIN ANALYZE
    SELECT data->'doi'
    FROM test.arxiv
    WHERE lower(data->>'title') LIKE '%modeling of hydrogen%';
                                 QUERY PLAN
-----------------------------------------------------------------
 Seq Scan on arxiv  (cost=0.00..488032.26 rows=242 width=32) (act
 time=539.217..8624.051 rows=5 loops=1)
   Filter: (lower((data ->> 'title'::text)) ~~ '%modeling of
 hydrogen%'::text)
   Rows Removed by Filter: 2417688
```

```
 Planning Time: 0.084 ms
 Execution Time: 8624.065 ms
(5 rows)
```

That was much, much worse. The index wasn't used at all, because B-Tree indexes are only good for equality and sorting searches, even with the `text_pattern_ops` specifier (did you notice that PostgreSQL was looking for index keys in between `'modeling of hydrogen%'` and `'modeling of hydrogeo%'` in the previous query's plan?).

So the default index type is no good for searching for substrings that are not at the beginning (or end) of the value, and that makes it pretty much unsuitable for full-text search. But even if it magically was capable of that, we'd run into this issue if we tried, for example, to index the abstract instead of the title:

```
CREATE INDEX ON test.arxiv (lower(data->>'abstract') text_pattern
ERROR:  index row size 2728 exceeds btree version 4 maximum 2704
 "arxiv_lower_idx1"
DETAIL:  Index row references tuple (213838,4) in relation "arxiv
HINT:  Values larger than 1/3 of a buffer page cannot be indexed.
Consider a function index of an MD5 hash of the value, or use ful
 indexing.
```

You can't really index values that long. This makes B-Tree unsuitable for indexing documents, in most cases. But it's actually quite cool of Postgres to tell us what we're probably doing wrong here!

Let's also notice the size of the B-Tree index:

```
\di+ test.arxiv*
List of relations
-[ RECORD 1 ]-+----------------
Schema        | test
Name          | arxiv_lower_idx
Type          | index
Owner         | frogge
Table         | arxiv
Persistence   | permanent
Access method | btree
Size          | 239 MB
Description   |
```

The proper index to use here is PostgreSQL's Generalized Inverted Index (GIN) which works very well for full-text search with the `tsvector` data type. Creating the index on titles looks like this:

```
DROP INDEX test.arxiv_lower_idx;
DROP INDEX

CREATE INDEX ON test.arxiv
    USING gin (to_tsvector('english', data->>'title'));
CREATE INDEX
```

And querying reveals how much better the GIN index is for this sort of thing:

```
EXPLAIN ANALYZE
    SELECT data->'doi'
    FROM test.arxiv
    WHERE to_tsvector('english', data->>'title')
    @@ plainto_tsquery('english', 'modeling of hydrogen');
                                 QUERY PLAN
-----------------------------------------------------------------
 Bitmap Heap Scan on arxiv  (cost=38.89..292.85 rows=60 width=32)
 time=1.829..4.949 rows=236 loops=1)
   Recheck Cond: (to_tsvector('english'::regconfig, (data ->>
 'title'::text)) @@ '''model'' & ''hydrogen'''::tsquery)
   Heap Blocks: exact=236
   ->  Bitmap Index Scan on arxiv_to_tsvector_idx  (cost=0.00..38
 rows=60 width=0) (actual time=1.783..1.783 rows=236 loops=1)
         Index Cond: (to_tsvector('english'::regconfig, (data ->>
 'title'::text)) @@ '''model'' & ''hydrogen'''::tsquery)
 Planning Time: 3.455 ms
 Execution Time: 4.989 ms
(7 rows)
```

That's awesome performance for millions of documents. We should expect performance to be comparable for the abstracts, or we could concatenate both elements and index them together.

What's even better is the index size, which is smaller than B-Tree:

```
\di+ test.arxiv*
List of relations
-[ RECORD 1 ]-+---------------------
Schema        | test
Name          | arxiv_to_tsvector_idx
Type          | index
```

```
Owner         | frogge
Table         | arxiv
Persistence   | permanent
Access method | gin
Size          | 100 MB
Description   |
```

However, GIN can be used improperly too. Separately from full-text search, you can use GIN to index entire JSON documents to speed up access to the elements contained within. It's easy to assume that this one big index covers every use case:

```
DROP INDEX test.arxiv_to_tsvector_idx ;
DROP INDEX

CREATE INDEX ON test.arxiv USING gin (data);
CREATE INDEX

\di+ test.arxiv*
List of relations
-[ RECORD 1 ]-+---------------
Schema        | test
Name          | arxiv_data_idx
Type          | index
Owner         | frogge
Table         | arxiv
Persistence   | permanent
Access method | gin
Size          | 1680 MB
Description   |
```

Let's use the index to search for specific article Digital Object Identifiers (DOIs):

```
EXPLAIN ANALYZE
    SELECT *
    FROM test.arxiv
    WHERE data @> '{"doi": "10.1039/c0cp01009j"}';
                                 QUERY PLAN
------------------------------------------------------------------
 Bitmap Heap Scan on arxiv  (cost=56.90..1011.01 rows=242 width=1
 (actual time=0.127..0.127 rows=1 loops=1)
   Recheck Cond: (data @> '{"doi": "10.1039/c0cp01009j"}'::jsonb)
   Heap Blocks: exact=1
   ->  Bitmap Index Scan on arxiv_data_idx  (cost=0.00..56.84 row
```

```
 width=0) (actual time=0.116..0.116 rows=1 loops=1)
         Index Cond: (data @> '{"doi": "10.1039/c0cp01009j"}'::js
 Planning Time: 2.345 ms
 Execution Time: 0.159 ms
(7 rows)
```

That’s awesome performance. But if we’re only ever looking for DOIs is it really the right choice? Let’s compare:

```
DROP INDEX test.arxiv_data_idx ;
DROP INDEX

CREATE INDEX ON test.arxiv((data->>'doi'));
CREATE INDEX

\di+ test.arxiv*
List of relations
-[ RECORD 1 ]-+----------------
Schema        | test
Name          | arxiv_expr_idx
Type          | index
Owner         | frogge
Table         | arxiv
Persistence   | permanent
Access method | btree
Size          | 61 MB
Description   |
```

That’s tiny! Let’s find our DOI:

```
EXPLAIN ANALYZE
    SELECT * FROM test.arxiv
    WHERE data->>'doi' = '10.1039/c0cp01009j';
                                 QUERY PLAN
-----------------------------------------------------------------
 Bitmap Heap Scan on arxiv  (cost=254.11..42289.79 rows=12088 wid
 (actual time=0.043..0.044 rows=1 loops=1)
   Recheck Cond: ((data ->> 'doi'::text) = '10.1039/c0cp01009j'::
   Heap Blocks: exact=1
   ->  Bitmap Index Scan on arxiv_expr_idx  (cost=0.00..251.09 ro
 width=0) (actual time=0.034..0.034 rows=1 loops=1)
         Index Cond: ((data ->> 'doi'::text) = '10.1039/c0cp01009
 Planning Time: 0.554 ms
 Execution Time: 0.076 ms
(7 rows)
```

Look at that speed, B-Tree is awesome when it comes to comparing identifiers. Remember this, and use the right index for the right queries depending on each index type's strengths.

You can also look up in the PostgreSQL documentation when using a *lossy* index, such as a Generalized Search Tree (GiST), would be beneficial in place of GIN — for instance, when you have a huge dataset but query times aren't critical. GiST indexes come in handy for Postgres range types, such as `daterange`. Along the same lines, you can use a lossy Block Range Index (BRIN), which is orders of magnitudes smaller than a B-Tree, for searching in ranges of values such as timestamps, if it is sufficient for what you are planning to query. As updating indexes is slow, especially complicated index types such as GIN, remember to only index what you need, and for whatever level of performance you deem to be acceptable.

More information on these index types and their usage can be found here:

- https://www.postgresql.org/docs/current/textsearch-indexes.html
- https://www.postgresql.org/docs/current/brin.html

4.5 Summary

- If you discovered table inheritance and you think you need it, you're probably wrong. Implement the parent-child relationships with foreign keys and triggers if needed.
- You can leverage table partitioning to make management and maintenance of large tables easier, and speed up the queries hitting those tables.
- Take care when sub-partitioning because partitioning by multiple keys is not the same thing. Unfortunately, it is not obvious from the documentation what the multiple key partitioning syntax does, when best to use it, and what its implications are.
- Each index type offered in PostgreSQL has its strengths and weaknesses. By adapting your indexing plan to the type of data you have and type of queries you need to run, you can optimize performance and storage space. When you get it right, your queries can run orders of magnitude faster.

5 Improper feature usage

In this chapter

- What choosing the `SQL_ASCII` encoding entails
- Creating rules, and the associated pitfalls
- Misusing NoSQL features for SQL queries
- Improvising distributed/multi-master systems can lead to problems

The rich feature set of PostgreSQL is what makes it such a powerful tool for data processing. Far from being a traditional Relational Database Management System (RDBMS), additional features such as NoSQL capabilities, logical replication, foreign data wrappers and rules give you the flexibility to design a wide variety of database-oriented systems (and to make mistakes with those designs)!

5.1 Selecting SQL_ASCII as the encoding

Since the dawn of computing, character encoding, or the numeric representation of text characters, has used various encoding schemes for mapping characters to numeric values for storage. With the use of computers expanding around the globe, the need to create more (and almost always incompatible) *code pages* or *character sets* for use with different languages' written characters became a hot topic.

Encoding / code page / character set

A *character set* is simply a grouping of characters and symbols, such as the ones necessary to properly represent a language and locale combination. It is also known as a *code page* in some legacy environments. The term *encoding* refers to how this character set is represented internally as one or more bytes per character. So for instance we have the very large Unicode character set, also known as the Universal Coded Character Set (UCS), which can be represented in a binary form by the UTF-8 encoding.

PostgreSQL supports lots of character sets or text encodings, mostly for reasons of compatibility with legacy data already using those encodings. These are also known as server-side encodings, and you can have a global default selected for the entire PostgreSQL server which is set at initialization time and, at the same time, individual databases each having their own encoding. Depending on the encoding, one or multiple bytes per character can be used.

If the locale is not set, as can sometimes be the case on badly configured cloud compute instances, Postgres will default to `SQL_ASCII`. Your databases will then look something like this:

```
\l
List of databases
-[ RECORD 1 ]-----+---------------------
Name              | frogge
Owner             | frogge
Encoding          | SQL_ASCII
Locale Provider   | libc
Collate           | C
Ctype             | C
ICU Locale        |
ICU Rules         |
Access privileges |
-[ RECORD 2 ]-----+---------------------
Name              | postgres
Owner             | postgres
Encoding          | SQL_ASCII
Locale Provider   | libc
Collate           | C
Ctype             | C
ICU Locale        |
ICU Rules         |
Access privileges |
...
```

Our friends at Frogge Emporium want to store ticket content text in the `tickets` table but their customer base can use multiple languages. So, they decide to stay with database encoding `SQL_ASCII`, which seems to accept characters from any character set that the customer may use without complaining.

In the PostgreSQL documentation, we can see under "24.3.1. PostgreSQL

Character Sets" the following:

Table 5.1 PostgreSQL Character Sets

Name	Description	Language	Server?	ICU?	Bytes/ Char	Aliases
`SQL_ASCII`	unspecified (see text)	*any*	Yes	No	1	

And under "24.3.4. Available Character Set Conversions" we find:

Table 5.2 Available Character Set Conversions

Server Character Set	Available Client Character Sets
`SQL_ASCII`	*any (no conversion will be performed)*

Let's see what happens when we accept writes from any client encoding into our `SQL_ASCII` database. In the following snippet, we'll generate text input in 3 different encodings application-side, and then insert it straight into our database.

Listing 5.1 sql_ascii_in.py: Insert multi-language text into SQL_ASCII database

```
import psycopg

english_text = ("Good evening, I would like to return my last ord
                + "please.").encode('iso-8859-1')
greek_text = ("Καλησπέρα, θα ήθελα να επιστρέψω την τελευταία μου
              + "παρακαλώ.").encode('windows-1253')
japanese_text = ("こんばんは、前回の注文を返品したいのですがお願いします。"
                ).encode('shift_jis')

with psycopg.connect("dbname=frogge user=frogge") as conn:
    with conn.cursor() as cur:
```

```
        cur.execute('''INSERT INTO support.tickets (content, stat
                       VALUES (%s, 20), (%s, 20), (%s, 20)''',
                       (english_text, greek_text, japanese_text))
```

Okay, that seemed to work. Let’s see what we put inside our database now:

```
SELECT id, content FROM support.tickets;
 id |                               content
----+-----------------------------------------------------------------
  1 | \x476f6f64206576656e696e672c204920776f756c64206c696b6520746
    |.5726e206d79206c617374206f7264657220706c656173652e
  2 | \xcae1ebe7f3f0ddf1e12c20e8e120dee8e5ebe120ede120e5f0e9f3f4f
    |.4e7ed20f4e5ebe5f5f4e1dfe120eceff520f0e1f1e1e3e3e5ebdfe120f0
    |.ebfe2e
  3 | \x82b182f182ce82f182cd8141914f89f182cc928d95b682f095d495698
    |.282cc82c582b782aa82a88ae882a282b582dc82b78142
(3 rows)
```

Wait, this is slightly confusing. What are all these crazy hexadecimal values? Ah! We did mention that text encoding is all about the numeric representation of textual characters, so it makes sense. These must be our strings' numeric representations in the encodings that we specified.

Let’s read them from the application now! As these are now sequences of bytes representing text, let’s retrieve them as such and cast to `bytea`, and then print them as UTF-8 text.

Listing 5.2 sql_ascii_out.py: Read multi-language text from SQL_ASCII database

```
import psycopg

with psycopg.connect("dbname=frogge user=frogge") as conn:
    with conn.cursor(row_factory=psycopg.rows.dict_row) as cur:
        cur.execute('''SELECT id, content::bytea FROM support.tic
        res = cur.fetchall()
        for row in res:
            print(row['id'], row['content'].decode('UTF-8'))
```

Running the above produces:

```
1 Good evening, I would like to return my last order please.
Traceback (most recent call last):
  File "/home/myuser/sql_ascii_out.py", line 8, in <module>
    print(row['id'], row['content'].decode('UTF-8'))
```

```
                     ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
UnicodeDecodeError: 'utf-8' codec can't decode byte 0xca in posit
 invalid continuation byte
```

Whoops! What happened here? We can see that the first row decoded to UTF-8 fine, but the next one failed. Well, actually, they would all have failed, if it wasn’t for the happy accident that the first 128 characters in UTF-8 are the same as those in ASCII. Let’s rewind and understand what happened here:

When we choose the `SQL_ASCII` "encoding" in PostgreSQL, the database interprets byte values 0–127 as ASCII, and simply ignores byte values 128–255, not interpreting them as anything. These are the values that were inventively used by the erstwhile creators of the early computer character sets that we mentioned previously (for single-byte sets — multi-byte code pages, e.g. for Asian alphabets, are a whole other mess). The fact that these bytes are uninterpreted characters means that no conversion to other encodings will be performed, as stated in the official documentation (remember what’s in parentheses in Table 5.2?).

This means that in Postgres `SQL_ASCII` is not so much an encoding, but rather a lack thereof, and it behaves significantly differently from all other supported encodings. Input data is not validated, and encoding conversion is not possible. Using the `SQL_ASCII` setting with non-ASCII data from other languages means that it allowed us to "mix and match" encoded data with no way to decode it, and has now left us with the conundrum of needing to figure out which encoding each value is in, which is practically impossible unless you manually examine the table data row by row.

Tip

In case it’s not clear yet, just use UTF-8 for everything.

The UTF-8 encoding of the Unicode standard has practically eclipsed everything else in the modern world, and with good reason — in most cases, it has allowed us to finally stop worrying about text encodings for multilingual data. There are still many legacy applications out there using traditional code pages, but for anything new, there is really no reason to use anything besides UTF-8. And for the application side, you need to make sure your application input is UTF-8 or at the very least, for legacy applications, that UTF-8 data is sent to the database.

It is unfortunate that, in the absence of a locale configuration, PostgreSQL defaults to using `SQL_ASCII`, and if you happen to be using the Latin alphabet for your text, that will appear to work mostly fine — until you try to do any conversions. However, if your system's locale settings are configured properly, PostgreSQL will use `UTF8` for your locale.

So what happens if you do have a legacy database and you're stuck with `SQL_ASCII`? If you know the most likely encoding for your data, you can probably migrate it to `UTF8`. Extracting the data and converting it to UTF-8 is not so hard:

```
SELECT id,
    convert_from(convert(content::bytea, 'ISO-8859-1', 'UTF8'), '
FROM support.tickets
WHERE id = 1;
 id |                        convert_from
----+-----------------------------------------------------------
  1 | Good evening, I would like to return my last order please.
```

This is good, it means you can now obtain UTF-8 strings for your text which you can export. The encoding of a database cannot be changed, so you will need to create a new one for the migration. Even in a misconfigured system, you can still create a `UTF8` database:

```
CREATE DATABASE frogge_new ENCODING UTF8 LC_COLLATE 'en_US.UTF-8'
LC_CTYPE 'en_US.UTF-8' TEMPLATE template0;
CREATE DATABASE
\x\l frogge*
Expanded display is on.
List of databases
-[ RECORD 1 ]-----+------------
Name              | frogge
Owner             | frogge
Encoding          | SQL_ASCII
Locale Provider   | libc
Collate           | C
Ctype             | C
ICU Locale        |
ICU Rules         |
```

```
Access privileges |
-[ RECORD 2 ]-----+------------
Name              | frogge_new
Owner             | frogge
Encoding          | UTF8
Locale Provider   | libc
Collate           | en_US.UTF-8
Ctype             | en_US.UTF-8
ICU Locale        |
ICU Rules         |
Access privileges |
```

When we create our schema in the new database, Unicode strings work as expected:

```
INSERT INTO support.tickets (content, status) VALUES
('Good evening, I would like to return my last order please.', 20
('Καλησπέρα, θα ήθελα να επιστρέψω την τελευταία μου παραγγελία π
('こんばんは、前回の注文を返品したいのですがお願いします。', 20);
INSERT 0 3
SELECT id, content FROM support.tickets;
 id |                              content
----+-----------------------------------------------------------------
  1 | Good evening, I would like to return my last order please.
  2 | Καλησπέρα, θα ήθελα να επιστρέψω την τελευταία μου παραγγελ
    |.ώ.
  3 | こんばんは、前回の注文を返品したいのですがお願いします。
(3 rows)
```

Client encoding

So we mentioned that these are server-side encodings. PostgreSQL also lets you select a client encoding (e.g. with `SET client_encoding`), and it performs any character set conversion between server and client automatically for you (if the combination of encodings is supported — see documentation at https://www.postgresql.org/docs/current/multibyte.html#MULTIBYTE-CONVERSIONS-SUPPORTED). By implication, this allows you to use Postgres with legacy applications that use specific encodings or don’t speak Unicode.

However, you need to make sure that you write to the server using the proper encoding — for example, our script in Listing 5.1 will not work with a UTF-8 database without first encoding the strings to be inserted in UTF-8.

To recap, `SQL_ASCII` is not a database encoding, and it behaves differently from other PostgreSQL character sets. It doesn't do encoding conversion or validation, and you can end up storing a mixture of encodings with no way to recover the original strings. Unless you are interfacing with a legacy system, and you know exactly which character set that system uses, your safest bet is to always use `UTF8`. Make sure you are always aware of the selected character encoding when creating a database. If you're migrating your database, convert your strings to `UTF8`. Finally, pay close attention to your collations which can affect character classification and sort order.

Note

You can find a lot of information on collation support in PostgreSQL here: https://www.postgresql.org/docs/current/collation.html

5.2 CREATE RULE

PostgreSQL offers a powerful *rule* system that allows you to rewrite and modify the execution of queries. This is a Postgres extension of the SQL Standard for defining actions such as "when we `UPDATE` table *a*, also `INSERT` into table *b*" or "when we `SELECT` from table *x*, instead SELECT from table *y*".

Note

The rules system is exclusive to PostgreSQL. It is not related to `CREATE RULE` in other databases.

Frogge Emporium has a problem with people manually inserting orders instead of using the sales administration user interface because no stock check is made. They have decided to address this by putting in place a rule that logs manual insertions and records who did it, which row was affected, and when:

```
CREATE OR REPLACE RULE log_order_insertions AS
    ON INSERT TO erp.order_groups
```

```
    DO ALSO
        INSERT INTO audit.audit_log (what, who, id, tstamp)
        VALUES ('Manual order insertion',
            CURRENT_ROLE::text, NEW.id, clock_timestamp());
```

Let’s test the rule by inserting a row into `order_groups`, and selecting that row immediately.

```
\x
Expanded display is on.
INSERT INTO erp.order_groups (status, placed_at, updated_at, cust
    VALUES ('Placed', clock_timestamp(), clock_timestamp(), 135);
SELECT * FROM erp.order_groups ORDER BY placed_at DESC FETCH FIRS
INSERT 0 1
-[ RECORD 1 ]----------------------------
id         | 500001
status     | Placed
placed_at  | 2024-06-04 21:21:57.542003+01
updated_at | 2024-06-04 21:21:57.542003+01
customer   | 135
```

We see that we’ve inserted the row with id `500001`. Let’s see what we logged in the `audit_log` table:

```
TABLE audit.audit_log;
-[ RECORD 1 ]------------------------
what   | Manual order insertion
who    | frogge
id     | 500002
tstamp | 2024-06-04 21:21:57.52818+01
```

What?! We’ve logged that id `500002` was inserted and that is incorrect, as we know we inserted the row with id `500001`.

What happened here is that, under the covers, when we ran the `INSERT` query which automatically selected `nextval()` from the sequence `order_groups_id_seq` giving values to `id`, the rule rewrote it and it effectively became two queries:

```
INSERT INTO erp.order_groups (id, status, placed_at, updated_at,
    VALUES (nextval('erp.order_groups_id_seq'), 'Placed', clock_t
        clock_timestamp(), 135);
INSERT INTO audit.audit_log (what, who, id, tstamp)
    VALUES ('Manual order insertion',
```

```
        CURRENT_ROLE::text, nextval('erp.order_groups_id_seq'),
        clock_timestamp());
```

So we can see that the rule did not work the way we expected because it changed our SQL with an unintended side effect — incrementing the `order_groups_id_seq` sequence. A hint pointing this out would have been the different timestamp we saw in `audit_log`'s `tstamp`. We can learn two things from this: how side effects like this could have been destructive if, for instance, subsequent queries in the rule used `DELETE`, and also that using `VOLATILE` functions with rules can be tricky because they may be executed multiple times. What we should have done here is use a `TRIGGER`, because trigger behavior is well-understood and predictable.

Note

PostgreSQL functions are labeled with the volatility classifications `VOLATILE`, `STABLE`, or `IMMUTABLE`. `VOLATILE` functions can do anything, including modifying the database, whereas `STABLE` and `IMMUTABLE` functions can't modify the database. At the same time, `STABLE` functions must return the same results for the same arguments for all rows within a single statement. `IMMUTABLE` ones must always return the same results for the same arguments. Declaring the correct volatility category is crucial for improving performance via the Postgres optimizer.

Let's see another troubling aspect of `RULE` usage. We assume Frogge wants to prevent orders that are more than one year old from ever being updated again. The following rule is written:

```
CREATE OR REPLACE RULE dont_update_old_orders AS
    ON UPDATE TO erp.order_groups
        WHERE old.updated_at < now() - INTERVAL '1 year'
    DO INSTEAD NOTHING;
```

Let's find one that's older than a year:

```
SELECT *
FROM erp.order_groups
TABLESAMPLE BERNOULLI (10)
WHERE updated_at < now() - INTERVAL '1 year';
-[ RECORD 1 ]-----------------------------
```

```
id         | 651
status     | Fulfilled
placed_at  | 2023-01-23 15:36:48.270475+00
updated_at | 2023-01-23 15:36:48.270475+00
customer   | 88
```

All right, let’s carefully check if the rule will prevent us from running the following:

```
BEGIN;
BEGIN

UPDATE erp.order_groups SET status = 'Cancelled'
WHERE updated_at < '2024-01-01';
UPDATE 24067
```

Oops! Not really what we expected. Let’s undo:

```
ROLLBACK;
ROLLBACK
```

It’s very important to understand that `RULE`s don’t prevent the query from running. We saw that the query did execute fine, and affected all rows older than `'2024-01-01'` but not older than a year. It **did** execute the query but with the added condition `WHERE updated_at < now() - INTERVAL '1 year'` coming from the rule:

```
                                 QUERY PLAN
-----------------------------------------------------------------
 Update on order_groups  (cost=0.00..1.05 rows=0 width=0)
   ->  Seq Scan on order_groups  (cost=0.00..1.05 rows=1 width=10
         Filter: ((updated_at < '2024-01-01 00:00:00+00'::timesta
 time zone) AND ((updated_at < (now() - '1 year'::interval)) IS N
 TRUE))
```

Therefore it updated the 24067 rows in the table that were updated before 2024 began, but not updated during the past year.

There are other rule pitfalls as well, for example, nothing prevents you from creating circular rules:

- Rule 1: on insert to *x*, instead insert into *y*
- Rule 2: on insert to *y*, instead insert into *x*

Admittedly, `RULE`s are necessary in one case: making `VIEW`s writable. You can create rules that define `ON INSERT`, `ON UPDATE` or `ON DELETE` actions for views that in actuality get performed on the constituent tables behind the view.

By far the biggest problem with the rule system is that it's complicated to understand, and therefore ripe for making mistakes. Rules don't apply conditional logic, but they are just an SQL rewriter for modifying queries and adding additional actions.

The bottom line is: Don't use rules! In most cases, they won't do what you expect them to and what you should be using instead are triggers. Rules should be regarded as internal implementation components of the Postgres `VIEW` system, and best left untouched by users.

5.3 Relational JSON

The addition of the `json` and `jsonb` document store types to PostgreSQL unlocked a whole range of NoSQL capabilities, with the ability to combine relational and schemaless data.

Nowadays, with Javascript-based languages being ubiquitous, it's only natural for developers to gravitate towards using JSON, as it's the native data format they're intimately familiar with. However, PostgreSQL's strength of being able to combine SQL and NoSQL can turn into a detriment if these are mixed in improper ways.

A famous relational database anti-pattern is known as Entity-Attribute-Value or EAV. Also known as "open schema", it allows efficient storage of datasets with sparse attributes (i.e. not every entity or object having the same attributes, even if they are of the same object type) or sparse values (lots of nulls). It's easy to see the parallels with NoSQL here. However, in the RDBMS world, EAV is considered an anti-pattern because it requires you to write more difficult queries to retrieve the data, and often the complexity of those queries makes it easy to get them wrong or write them in a way that performs badly.

The usefulness of JSON storage for similar purposes, such as the ingestion of large amounts of data where we cannot foresee the attributes or whether they're populated, is undeniable. Nevertheless, it's easy for people to get carried away and start using JSON even for data that fits the relational pattern quite well. A good indicator of that is when you start considering the use of SQL `JOIN`s for retrieval of your JSON stored data — NoSQL / "schemaless" was meant to eliminate the need for joins!

I like to call this anti-pattern *Relational JSON*. Let's see some examples — our user has created the following tables to store customer accounts and sales data, where everything in the row is inside a JSON field to allow maximum flexibility:

```
CREATE TABLE test.accounts (
    json_account jsonb NOT NULL
);

CREATE TABLE test.sales (
    json_sale jsonb NOT NULL
);
```

The data held on customers that goes into `accounts.json_account` looks like this:

```
{
    "id": 52101,
    "name": "Freddie",
    "balance": 1500.37,
    "migrated_account": {
        "system": "legacy",
        "migrated_on": "2023-12-20"
    }
}

{
    "id": 8101,
    "name": "Emory Trenneman",
    "opened_on": "March 12, 2019",
    "balance": 2530.00
}
```

And the records of sales in `sales.json_sale` look something like this:

```
{
```

```
    "id": 133045,
    "account_id": 565,
    "timestamp": "2024-01-30 12:54:10",
    "point_of_sale": 311,
    "amount": 35.99
}

{
    "id": 133046,
    "amount": 2138,
    "account_id": 8101,
    "timestamp": "2024-01-30 12:55:46+0 UTC",
    "point_of_sale": 2
}
```

Some things may be already apparent if you have experience with databases, such as the fact that the database can’t enforce referential integrity or even ensure that values are of the correct type or within allowable ranges. All this will now need to be handled by the application.

Our user wants to find out the names of customers, not migrated from the legacy system, who have placed an order exceeding 10000 and who have an account balance less than 20000. Therefore a query is formulated:

```
SELECT a.json_account ->> 'name' AS "Name"
FROM test.accounts a
JOIN test.sales s
    ON (s.json_sale ->> 'account_id')::int = (a.json_account ->>
WHERE (a.json_account ->> 'balance')::numeric < 20000
AND (s.json_sale ->> 'amount')::numeric > 10000
AND (NOT a.json_account['migrated_account'] ->> 'system' = 'legac
    OR a.json_account -> 'migrated_account' IS NULL);
```

That is one ugly, barely legible query. Does it run? Yes, it runs. But remember, in the previous section Improper Index Usage, we saw how choosing the wrong index type may be functional, but at the same time constitute a waste of disk space or relative loss of performance. For this use case, we will practically have to index the entire contents of the tables with large GIN or GIST indexes. Even then, the index wouldn’t help with this query because it would turn into a `Merge Join` with `Materialize` and `Sorts` of `Seq Scans`.

So even if you go and create a GIN index and use the proper `jsonb` operators to take advantage of it — as follows — you can speed up the query somewhat but it will still be a nested loop instead of a proper relational join using the index:

```
SELECT a.json_account ->> 'name' AS "Name"
FROM test.accounts a
JOIN test.sales s
    ON (s.json_sale -> 'account_id') @> (a.json_account -> 'id')
WHERE (a.json_account -> 'balance')::numeric < 20000
AND (s.json_sale ->> 'amount')::numeric > 10000
AND (NOT a.json_account ->
    'migrated_account' @> '{"system": "legacy"}'::jsonb OR NOT
    a.json_account ? 'migrated_account');
```

So really your alternative would be to create expression-based indexes on JSON keys that each row may or may not have. If you're going to go to that trouble anyway, why not store everything in relational form and avoid the hassle of writing complex, hard-to-read queries? Use `json(b)` for what it's good at, such as replacing EAV, or as a second storage format for retrieving the whole object, and don't shoehorn relational-type data and queries into it.

5.4 Putting UUIDs everywhere

An interesting, and often abused, data type in PostgreSQL is UUID (elsewhere known as GUID), which gives you a sequence of 32 hex digits for use as a 128-bit identifier. The variety of UUID that is supported natively in PostgreSQL is UUIDv4 and it gives you values such as `9b287b2a-276d-4ba0-bcc7-b917246169a0`.

Without giving it much thought, the `uuid` data type looks like it's the ideal type to use for worry-free identifiers. It gives you an infinitesimally small probability of having duplicates, and a huge range of values is available for use. It is also opaque and harder to guess than a sequence of integers, being non-serially generated, so it's popular for security-via-obscurity uses.

For reference, let's examine some PostgreSQL data type sizes:

Table 5.3 PostgreSQL data type sizes

Data type	Size in bytes
`boolean`	1
`int`	4
`bigint`	8
`timestamptz`	8
`double precision`	8
`uuid`	16
`text`	1 + string bytes (+4 if > 127 bytes)

Let’s create a table with `uuid` identifiers and then index them as the primary key:

```
\timing
Timing is on.

CREATE TABLE test.tab (id uuid, content text);
CREATE
Time: 11.737 ms

INSERT INTO test.tab
    SELECT gen_random_uuid(), 'test' FROM generate_series(1,10000
INSERT 0 100000000
Time: 387838.234 ms (06:27.838)

ALTER TABLE test.tab ADD PRIMARY KEY (id);
ALTER TABLE
```

```
Time: 75875.825 ms (01:15.876)
```

That took as long as it took, now to find out our key and index size:

```
\x
Expanded display is on.

SELECT pg_column_size(id) FROM test.tab LIMIT 1;
-[ RECORD 1 ]--+---
pg_column_size | 16

Time: 2.492 ms

\di+ test.tab_pkey
List of relations
-[ RECORD 1 ]-+-----------
Schema        | test
Name          | tab_pkey
Type          | index
Owner         | frogge
Table         | tab
Persistence   | permanent
Access method | btree
Size          | 3008 MB
Description   |
```

All right, now that we have a baseline established, let's drop the table and try again with `bigint` serial identifiers.

```
CREATE TABLE test.tab (id bigint, content text);
CREATE TABLE
Time: 5.902 ms

INSERT INTO test.tab SELECT generate_series(1,100000000), 'test';
INSERT 0 100000000
Time: 83137.075 ms (01:23.137)

ALTER TABLE test.tab ADD PRIMARY KEY (id);
ALTER TABLE
Time: 38123.742 ms (00:38.124)
```

That was noticeably faster. Let's check key and index sizes:

```
SELECT pg_column_size(id) FROM test.tab LIMIT 1;
-[ RECORD 1 ]--+--
pg_column_size | 8
```

```
Time: 1.195 ms

\di+ test.tab_pkey
List of relations
-[ RECORD 1 ]-+----------
Schema        | test
Name          | tab_pkey
Type          | index
Owner         | frogge
Table         | tab
Persistence   | permanent
Access method | btree
Size          | 2142 MB
Description   |
```

Let’s put this up on a table for an easy comparison.

Table 5.4 Differences between UUIDs and serial big integers

	bigint	uuid	Difference
`INSERT`	01:23	06:28	367% slower
`CREATE INDEX`	00:38	01:16	100% slower
Index size	2142 MB	3008 MB	40% bigger

These results were to be expected, of course, as UUIDv4 is at the same time larger than a big integer and it requires generating the next value randomly (something computers are not very good at). Using lots of UUIDs in your table can also push your other data columns to spill over into the *TOAST* table and make everything somewhat less efficient. If the system you’re building requires serious performance optimization, these are certainly some things to consider.

Lingo: TOAST

The Oversized-Attribute Storage Technique (TOAST) is PostgreSQL's solution for storing large values inside columns when the page size is just 8 kB and individual rows cannot spill over into the next pages. It supports in-line compression of the values, but also storing them out-of-line (in a different, associated table). You can read a much more detailed description of TOAST at: https://www.postgresql.org/docs/current/storage-toast.html

Most of the time, you don't even need such a big identifier range, as the number of rows you will store will be many orders of magnitude smaller than the available space of UUIDs. Even a PostgreSQL big integer, with 18 quintillion (and change) available values, might offer too big a range for what you're trying to do.

Don't immediately reach out to UUID as a good identifier choice, there are compromises to be made that may be significant for your application.

What is a good case for UUIDs? Possibly as a conflict-free and fast way to generate identifiers for `INSERTs` from multiple nodes of a distributed system (because there needs to be no coordination regarding the identifiers among the nodes). But there are still disadvantages to this approach, such as that sorting keys such as sequence numbers, timestamps and node identifiers are not encoded in the UUID. What would probably be better solutions for this usage are Snowflake ID or UUIDv7 (at the time of writing, coming soon to Postgres).

Tip

Snowflake IDs and UUIDv7s encode within them precise timestamps, and are sortable by time. Additionally, Snowflakes encode a machine-specific ID and local sequence number, enabling greater collision detection and control for distributed systems.

5.5 Homemade multi-master replication

For as long as I can remember, people in IT have been asking me: "Can I write to the same filesystem, but on multiple drives?", "Can I write to the same database, but on multiple servers?", etc. — which means that essentially they want shared storage, but also high availability for that same storage. When I explain that they can't have both without compromises, they then complain that they don't want to take the performance hit of waiting for locking or consistency. It's a fundamental problem that's sadly not well understood: You can only have two out of the following three: consistency, availability and partition tolerance, and one out of consistency or low latency.

CAP / PACELC theorems

In 1998, Eric Brewer stated that distributed systems can only provide two out of the following three guarantees simultaneously: **C**onsistency (that reads get the most recent data or error out), **A**vailability (every request gets a response without the guarantee that it's the most recent data), network **P**artition tolerance (continued operation despite messages being dropped or delayed). This was formally proven and is now known as the **CAP** theorem.

By extension, in 2010, Daniel Abadi took things a step further and stated that if you have a network **P**artition, you have to choose either **A**vailability or **C**onsistency, **E**lse, the choice is between **L**atency and loss of **C**onsistency. This is much more relevant for our discussion about databases, and specifically PostgreSQL, as we expect them to be online most of the time. It is known as **PACELC** and, as a theorem, it has also received formal proof.

The understanding that we can gain from these theorems is that there are unavoidable trade-offs to be made when constructing distributed systems.

PostgreSQL replication is a shared-nothing architecture, in keeping with the requirement to provide redundancy and high availability. Therefore currently the only sane way to have a multi-master database cluster is to establish replication connections between multiple independent database instances running on different nodes.

PostgreSQL offers a wonderful feature in logical replication, and there is also an extension out there called pglogical that gives you some additional features over native logical replication. So, our friends at Frogge Emporium thought, why not use unidirectional logical replication in both directions, in order to make it bidirectional, or multi-master? It's easy enough to set this up going in both directions by reading the manual, and we won't go into too many details here (especially as I don't particularly want you to be using it) — but let's look at what happens next.

The first problem has to do with the concept of *replication origins*, or which database or node the transaction that's being replicated originated from. Remember that Postgres replication is just WAL getting streamed from one node to the other. If you don't filter out other nodes when you set up the logical replication publications and subscriptions, you will attempt to replicate your own transactions that the other nodes received and sent back to you. Inevitably, this will cause messages to ping-pong across your cluster with the eventual result of this feedback loop being your disks filling up with extraneous WAL.

Note

The Write-Ahead Log (WAL) is PostgreSQL's transaction log, used to ensure data integrity. More information on WAL can be found here: https://www.postgresql.org/docs/current/wal-intro.html

Once that is dealt with via the `origin=NONE` or `forward_origins='{}'` options for native logical replication or pglogical respectively, we can see that our hack appears to work. Let's set up a bi-directional multi-master replication between hosts `alpha` and `beta`, previously configured to allow connectivity between them, and populate a table with sample data.

Tip

To set up logical replication, you need to configure things such as `wal_level=logical`, `listen_addresses`, and Host-Based Authentication (HBA) as per https://www.postgresql.org/docs/current/logical-replication.html

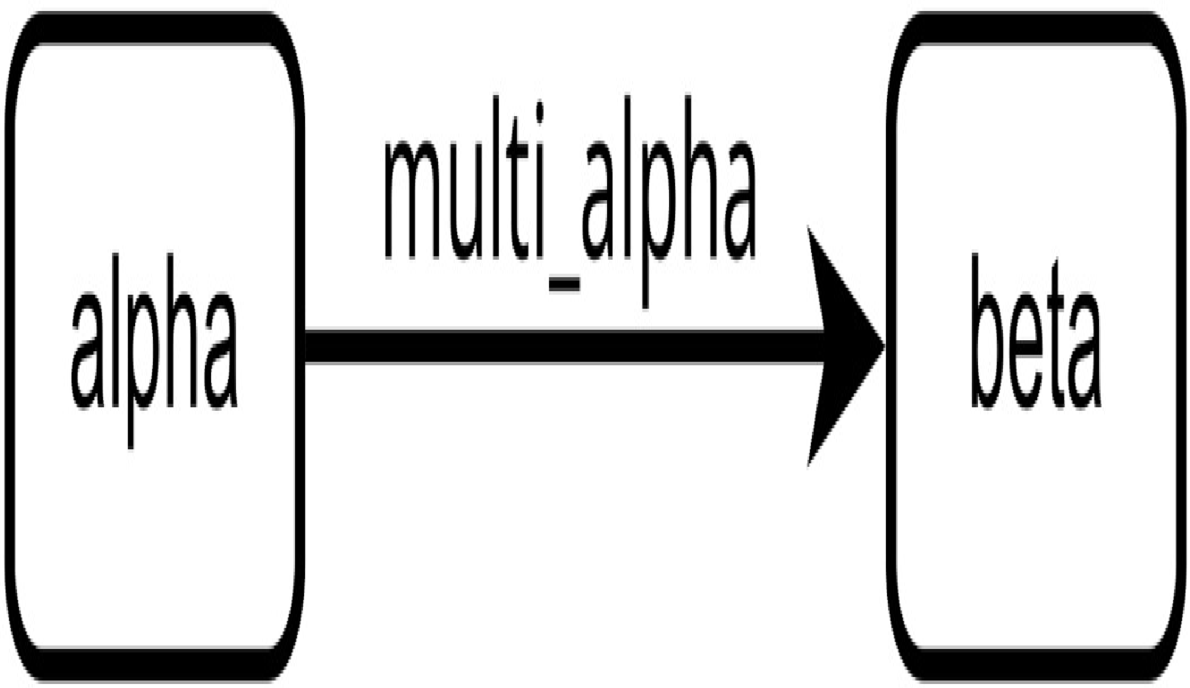
From host `alpha`, we create our publication and table:

```
CREATE PUBLICATION multi_alpha FOR ALL TABLES;
CREATE PUBLICATION

CREATE TABLE support.tickets (
    id integer PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
```

```
    content text,
    status smallint,
    opened_at timestamptz DEFAULT CURRENT_TIMESTAMP NOT NULL,
    closed_at timestamptz
);
CREATE TABLE

INSERT INTO support.tickets (content) VALUES ('first'), ('second'
INSERT 0 2

SELECT id, content FROM support.tickets;
 id | content
----+---------
  1 | first
  2 | second
(2 rows)
```

Great, that’s what we expect to see.

Figure 5.1 Unidirectional logical replication

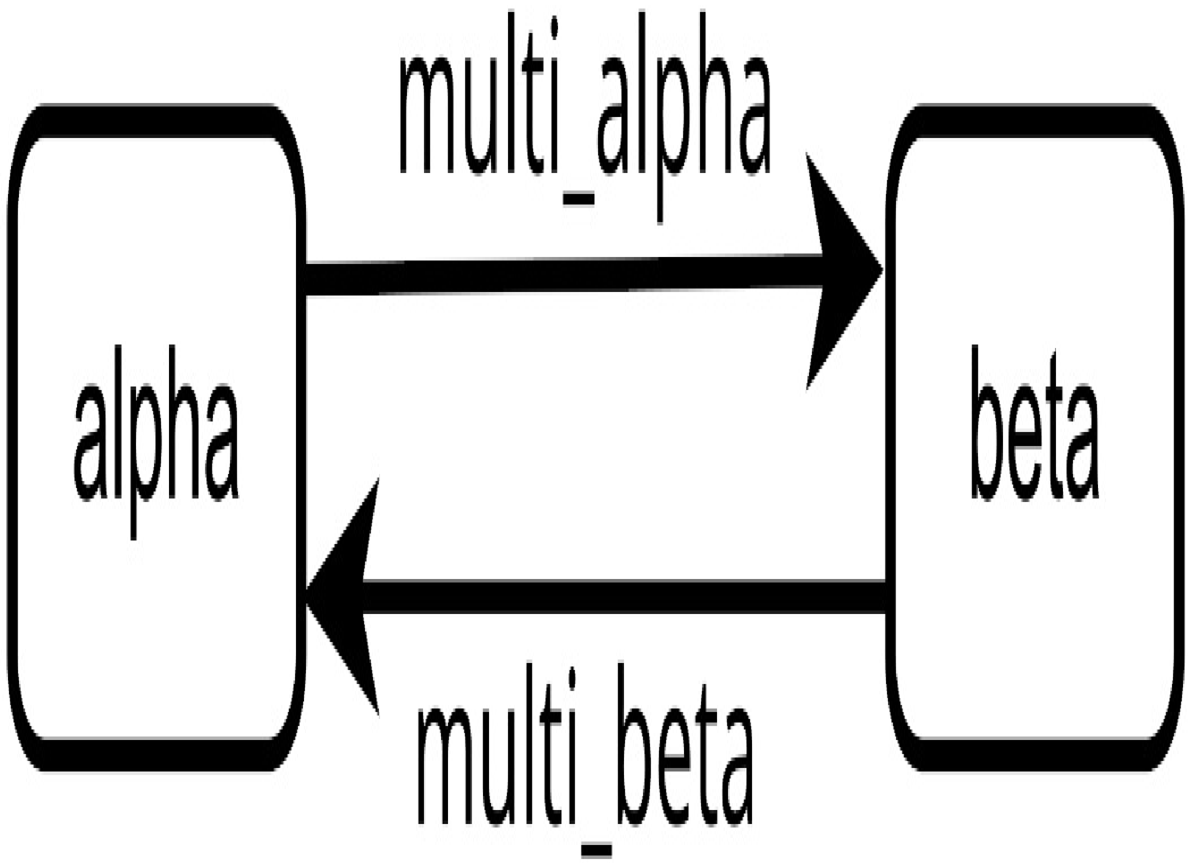


Now let’s go to host `beta`, create the same schema, subscribe to `alpha` and create a publication too:

```
CREATE TABLE support.tickets (
    id integer PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    content text,
    status smallint,
    opened_at timestamptz DEFAULT CURRENT_TIMESTAMP NOT NULL,
    closed_at timestamptz
);
CREATE TABLE

CREATE SUBSCRIPTION multi_alpha
    CONNECTION 'host=alpha dbname=frogge'
    PUBLICATION multi_alpha
    WITH (origin=NONE);
NOTICE:  created replication slot "multi_alpha" on publisher
CREATE SUBSCRIPTION

SELECT id, content FROM support.tickets;
 id | content
----+---------
  1 | first
  2 | second
(2 rows)

CREATE PUBLICATION multi_beta FOR ALL TABLES;
CREATE PUBLICATION
```

This is the arrangement we’ve set up now:

Figure 5.2 Logical replication in both directions



Nice, so all we need to do now is subscribe `alpha` to `beta` and we have bidirectional replication. On `alpha`:

```
CREATE SUBSCRIPTION multi_beta
    CONNECTION 'host=beta dbname=frogge'
    PUBLICATION multi_beta
    WITH (origin=NONE);
WARNING:  subscription "multi_beta" requested copy_data with orig
 but might copy data that had a different origin
DETAIL:  The subscription being created subscribes to a publicati
 ("multi_beta") that contains tables that are written to by other
 subscriptions.
HINT:  Verify that initial data copied from the publisher tables
```

```
 come from other origins.
NOTICE:  created replication slot "multi_beta" on publisher
CREATE SUBSCRIPTION
```

Err… all right? It’s warning us that because we set our subscription to ignore other origins, it doesn’t really know for sure that the rows we are copying originated on `beta`. Let’s insert a row here on `alpha`:

```
INSERT INTO support.tickets (content) VALUES ('third');
INSERT 0 1

SELECT id, content FROM support.tickets;
 id | content
----+---------
  1 | first
  2 | second
  3 | third
(3 rows)
```

And let’s check that it arrived on `beta`:

```
SELECT id, content FROM support.tickets;
 id | content
----+---------
  1 | first
  2 | second
  3 | third
(3 rows)
```

We now have bi-directional logical replication established and we can write to both nodes, so let’s also insert a row on `beta`.

```
INSERT INTO support.tickets (content) VALUES ('fourth');
ERROR:  duplicate key value violates unique constraint "tickets_p
DETAIL:  Key (id)=(1) already exists.
```

Oops. What happened here? It looks like `beta` tried to insert a row but the sequence generating the primary key was still at `1`, and we already had that key in the table because it was inserted by node `alpha`. For logical replication, you generally need a primary key or other unique constraint, and these tend to get values from sequences. You need to make sure that no node re-uses sequence numbers from another node because, as we just saw, that creates a data conflict.

Sequence synchronization is a complicated problem, you have to either keep the whole cluster in sync with every write (which is going to be disastrous for performance) or pre-allocate ranges to each node, which is a large administrative burden to manage manually. How do you divide the ranges, what happens when those ranges run out, and how do you deal with new nodes added?

Let's see what happens when we try something different, which you are bound to do in the real world: change the schema of the database.

Still on `beta`, we change the name of column `opened_at` to `logged_at`:

```
ALTER TABLE support.tickets RENAME opened_at TO logged_at;
ALTER TABLE
```

Meanwhile, some unaware user on `alpha` inserts a row:

```
INSERT INTO support.tickets (content) VALUES ('fourth');
INSERT 0 1

SELECT id, content, opened_at FROM support.tickets WHERE content=
 id | content |           opened_at
----+---------+-------------------------------
  4 | fourth  | 2024-02-01 19:24:09.162218+00
(1 row)
```

All right so far. Let's check on `beta`:

```
SELECT id, content, logged_at FROM support.tickets WHERE content=
 id | content | logged_at
----+---------+-----------
(0 rows)
```

The row didn't make it over. Checking the PostgreSQL log on `beta` reveals:

```
Feb  1 19:24:10 beta postgres[22139]: [2] ERROR:  logical replica
 relation "support.tickets" is missing replicated column: "opened
Feb  1 19:24:10 beta postgres[22139]: [3] CONTEXT:  processing re
 for replication origin "pg_16596" during message type "INSERT" i
 transaction 879, finished at 0/1DB9628
Feb  1 19:24:10 beta postgres[21848]: [9] LOG:  background worker
 replication worker" (PID 22139) exited with exit code 1
```

So by allowing the schema to become inconsistent, even for a short while, we not only broke data consistency across our cluster, but we also threw the PostgreSQL logical replication worker process in a crash/restart loop.

The lack of provision for consistent DDL replication is a very important blocker for rolling your own multi-master distributed Postgres cluster. Factoring in the orchestration needed to introduce schema changes increases complexity significantly, as the procedure has to be managed carefully to avoid generating conflicts and breaking replication, and it also needs to be balanced against uptime requirements.

Historically, there have been attempts to offer PostgreSQL multi-master solutions but they focused on higher levels than the actual database, such as the two replication tools originally released in 2007: Londiste, implemented in Python, and Bucardo, written in Perl (the horror!)

Practically speaking, for any enterprise usage requiring full PostgreSQL performance, you would want to go with a native PostgreSQL system performing the replication at the database level. The most advanced and proven solution is EnterpriseDB's Postgres Distributed (PGD), originally developed as 2ndQuadrant's BDR, which is at the time of writing proprietary software. A new contender is the open source Spock solution developed by pgEdge, also forked from 2ndQuadrant's pglogical code.

However, what you should do is spend some time to consider whether you actually need multi-master replication. The ability for the application to write "on any node" may sound good on paper but it usually comes with baggage that the user has not considered, with implications both on the database administration side but also from the application aspect because it needs to be multi-master aware. The only valid use cases I can think of are:

- Extreme availability — derived from the instantly available redundancy and the ability to perform minor- and major-version upgrades with no downtime
- Geo-distribution of data with minimal latency — derived from the fact that both reads and writes to the database are local to each physical location

5.6 Homemade distributed systems

A distributed system doesn't have to be multi-master. I believe that the normal clustering capabilities of PostgreSQL via streaming and logical replication qualify as being distributed systems in their own right. Therefore the CAP and PACELC theorems that we read about previously still apply.

I can assure you that attempts to write your own replication mechanism, or even worse, using external Extract/Transform/Load (ETL and ELT) systems or Change Data Capture (CDC) tools to implement replication, are not going to result in a better feature set or better performance than native PostgreSQL replication.

But even when using these reliable and performant methods you can still get into trouble. For this example, we have already configured streaming replication between the primary host `alpha` and standby host `beta`. On `alpha`, we create a table and insert some data:

```
CREATE TABLE test.accounts (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    balance numeric NOT NULL,
    updated_at timestamp with time zone DEFAULT CURRENT_TIMESTAMP
);
CREATE TABLE

INSERT INTO test.accounts (balance) VALUES (100);
TABLE test.accounts;
INSERT 0 1
 id | balance |         updated_at
----+---------+----------------------------
  1 |     100 | 2024-01-17 19:08:31.0284+00
(1 row)
```

A very common pattern, witnessed many times in the field, is for the application to read from one of the read replicas (PostgreSQL standbys) and write to the primary. We are simulating a minute's worth of replication lag between the two nodes by setting the configuration parameter `recovery_min_apply_delay` to `60000` (milliseconds) on the standby `beta`. The application now reads the account balance from the standby to charge the account, and update it on the primary (as the standby is read-only):

On the standby node `beta` we read the balance:

```
SELECT balance FROM test.accounts WHERE id=1;
 balance
---------
     100
(1 row)
```

On the primary node `alpha` we update the balance:

```
UPDATE test.accounts SET balance=90, updated_at=now() WHERE id=1;
TABLE test.accounts;
UPDATE 1
 id | balance |          updated_at
----+---------+-------------------------------
  1 |      90 | 2024-02-17 19:09:03.172174+00
(1 row)
```

Meanwhile, another part of the application tries to read the balance in order the apply the annual bonus gift to the account. On the standby `beta`:

```
SELECT balance FROM test.accounts WHERE id=1;
 balance
---------
     100
(1 row)
```

Based on the inconsistent view of the data, the application mistakenly thinks that the account balance is 100, and applies the gift of +50 to that amount on `alpha`:

```
UPDATE test.accounts SET balance=150, updated_at=now() WHERE id=1
TABLE test.accounts;
UPDATE 1
 id | balance |          updated_at
----+---------+-------------------------------
  1 |     150 | 2024-01-17 19:09:34.442339+00
(1 row)
```

The business has lost 10 monies and the customer received an unexpected gift due to a violation of the Consistency property of the **ACID** compliance requirements for databases (**A**tomicity, **C**onsistency, **I**solation, **D**urability).

If PostgreSQL is ACID compliant, what has gone wrong here? Well, the PostgreSQL database server guarantees ACID safety, but what we had here was the application trying to perform *atomic* (or indivisible) transactions across two different database nodes - a *distributed transaction*.

We can see that distributed transactions are not so simple to deal with. What is needed in this case is a transaction with two phases that applies the Two-Phase Commit (2PC) protocol using `PREPARE TRANSACTION` and its associated commands. However, prepared transactions are complicated and hard to implement on systems with latency or replication lag because they should be short-lived. Then they would have to be run exclusively on the primary, negating the benefit of having a read replica. Additionally, they cause locking of objects in the database which can cause delays in the application, and are very often left behind incomplete (e.g. when an application component crashes or is restarted and loses its state).

On the primary `alpha`:

```
TRUNCATE test.accounts;
TRUNCATE TABLE

INSERT INTO test.accounts (balance) SELECT generate_series(1,1000
INSERT 0 100000000
```

Now let’s go and run a long-running report query on the standby `beta`:

```
SELECT sum(balance) FROM test.accounts
UNION
SELECT avg(balance) FROM test.accounts;
```

Meanwhile, users keep using the database. Some data changes are made on `alpha`:

```
DELETE FROM test.accounts WHERE id BETWEEN 40000001 AND 40000020;
DELETE 20

VACUUM test.accounts;
VACUUM
```

This deleted a few accounts and cleaned up afterward with `VACUUM`. But this is what is happening now on `beta` - our query has failed:

```
SELECT sum(balance) FROM test.accounts
UNION SELECT avg(balance)
FROM test.accounts;
ERROR:  canceling statement due to conflict with recovery
DETAIL:  User query might have needed to see row versions that mu
```

Why has this happened? What we have just seen is what’s known as a *(distributed) serialization anomaly* or a violation of the ACID transaction Isolation property. Specifically, this is a type of *read-write conflict* or *unrepeatable read*, where a transaction has read the data while a second transaction overwrote some of the data before the first one got the chance to complete.

You can probably prevent this from happening in most cases by enforcing synchronous replication, but that is a horrendous trade-off and a huge sacrifice of performance that should be considered only when extreme correctness and consistency requirements trump everything else. It is self-evident that the round-trip time required for synchronicity, even with the fastest networks, will result in latency that will bottleneck database performance much sooner than network or PostgreSQL replication performance limits can be reached. The extreme in the other direction is accepting the possibility of *stale reads* or retrieving out-of-date data in a tradeoff for low latency.

These conditions apply to multi-master systems as well. The problem lies with the fact that the application-side logical "transactions" are executed spread across multiple database nodes. If the application is using one node at a time to complete the atomic operation, that’s fine because it can be handled using normal conflict management techniques. However, when the application tries to use multiple nodes within the same transaction, we need strong consistency and isolation requirements, which brings us back to PACELC.

Using read replicas to offload some of the work is fine and perfectly valid, but not within an application atomic operation that forms a distributed transaction. There is no good or easy way to avoid these types of issues without an authoritative global transaction manager. Global transaction managers necessarily form performance bottlenecks and they can become a single point of failure.

In closing, building distributed databases is no simple feat because of the limitations of the laws of physics — the industry has struggled for a long time to create solutions that balance competing priorities. Unless your use case is extremely narrow (such as one table, with defined protections and conflict management rules) you will probably not do a good job improvising a distributed solution. The effort required to implement or troubleshoot it will probably inflate the scope of your project to many times what it would be before.

5.7 Summary

- `SQL_ASCII` is not a character encoding so much as the absence of one. If you don't want to risk mixing encodings irreversibly and you enjoy the ease of automatic character set conversion, make sure you use UTF-8 for your database.
- PostgreSQL `RULE`s are not related to rules as defined in other DBMSs. `RULE`s are complicated to understand and are mainly there as Postgres internal machinery. In most cases they don't behave as the user expects them to and `TRIGGER`s are best used instead.
- Using JSON(B) values with relational access patterns makes for less efficient SQL which is harder to read and might not perform as well. It's better not to mix the SQL and NoSQL paradigms, but use each facility for what it's best at doing.
- `uuid`s take up more storage space than even `bigint`s and indexing them is less efficient. They may guarantee a range of values that you simply don't require for your use case, and an integer index might be enough to guarantee uniqueness.
- Bi-directional or multi-master replication is more complex than what appears at first sight. For practical use in a production system, there is a very long list of prerequisites, considerations and caveats. If your use case indeed justifies setting up a multi-master system, you are better off using an established multi-master solution whose developers have given thought to these issues rather than re-inventing the wheel.
- All of the above apply to homemade distributed systems as well and it is not recommended to set out building them unless your scope is very narrowly focused. You need to consider the potential for distributed serialization anomalies and the very real trade-offs laid out in the CAP

and PACELC theorems.

6 Performance bad Practices

In this chapter

- Going to production with the default PostgreSQL configuration
- Managing connection limits and life cycle
- Letting transactions go on for too long
- Turning off autovacuum may help… for a short while
- Explicit locking and its associated risks
- Having too few or too many indexes and the impact this has on performance

We know by this point in the book that PostgreSQL is a database powerhouse, a flexible database suited for many uses that can perform extremely well when you ask it nicely. And by asking it nicely we mean being aware of how it does things so that we can avoid entering code, configuration and usage patterns that lead to sub-optimal outcomes. It’s now time to start discussing some really common ways of hurting performance in Postgres. These may seem obvious to some but surprising to others, so they’re well worth exploring.

6.1 Default configuration in production

Let’s start at the top: You’ve just freshly installed PostgreSQL on your shiny new cloud compute instance, memory-optimized with 16GB of RAM, all set for database awesomeness. You decide to restore your database into this instance from the latest dump of the data you have.

Let’s generate a decent-sized database, using our old friend `pgbench` — the utility that comes with Postgres for running benchmark tests. First, we create it from the command line, as user `postgres`:

```
createdb pgbench
```

We now have an empty database to populate:

```
pgbench -i -s 1000 pgbench
dropping old tables...
NOTICE:  table "pgbench_accounts" does not exist, skipping
NOTICE:  table "pgbench_branches" does not exist, skipping
NOTICE:  table "pgbench_history" does not exist, skipping
NOTICE:  table "pgbench_tellers" does not exist, skipping
creating tables...
generating data (client-side)...
100000000 of 100000000 tuples (100%) done (elapsed 548.92 s, rema
0.00 s)
vacuuming...
creating primary keys...
done in 761.00 s (drop tables 0.00 s, create tables 0.03 s, clien
generate 549.59 s, vacuum 0.74 s, primary keys 210.64 s).
```

Note

The execution time here isn't really important, as we are just running this to have some data to dump and restore, and see how long it takes to restore.

After populating, we perform a dump:

```
pg_dump pgbench > /tmp/pgbench.dump
ls -lah /tmp/pgbench.dump
-rw-rw-r-- 1 postgres postgres 9.9G May 12 19:16 /tmp/pgbench.dum
```

And now we have our dataset in `pgbench.dump`. Let's wipe, and restore:

```
dropdb pgbench
createdb pgbench
```

This time, we want to time how long it takes to restore:

```
time psql pgbench < /tmp/pgbench.dump
SET
SET
SET
SET
SET
 set_config
------------

(1 row)

SET
```

```
SET
SET
SET
SET
SET
CREATE TABLE
ALTER TABLE
CREATE TABLE
ALTER TABLE
CREATE TABLE
ALTER TABLE
CREATE TABLE
ALTER TABLE
COPY 100000000
COPY 1000
COPY 0
COPY 10000
ALTER TABLE
ALTER TABLE
ALTER TABLE

real    44m15.279s
user    0m13.108s
sys     0m20.280s
```

Okay, that is certainly a number. Is it good? Is it bad?

Let's change some configuration settings and try again to see if we can improve upon this. In `postgresql.conf` we change some selected parameter values to:

```
shared_buffers = 3GB             #1
work_mem = 128MB                 #2
maintenance_work_mem = 512MB     #3
```

We need to restart PostgreSQL for the `shared_buffers` change to take effect. After doing that, let's see if we can make a difference:

```
dropdb pgbench
createdb pgbench
time psql pgbench < /tmp/pgbench.dump

...

real    26m17.669s
```

```
user    0m12.229s
sys     0m19.520s
```

This is a significant difference, it takes less than 60% of the time we needed with the default `postgresql.conf` values.

So isn’t the default configuration made up of the most commonly used values, or those that have empirically given the best results?

No. Unlike other bloated database systems you may be familiar with, the basic idea behind the default configuration of PostgreSQL is to have a baseline system that will "just work" in any machine (within reasonable bounds — your 486SX/25 from 1994 with 24MB RAM will be below the minimum requirements, but only just). As we can see in the documentation, the default memory allocation for things such as `shared_buffers` is only 128MB, and `work_mem` just 4MB, so you have to understand that the default configuration is geared towards simply getting up and running on just about any system no matter how small.

What we’ve just done here isn’t really "database tuning" — it’s basic due diligence when you’re testing or staging a PostgreSQL server for production usage. The new `shared_buffers` value increased the memory available to Postgres for buffers (blocks read from disk and/or used in operations), `work_mem` increased the amount of non-shared memory available to individual operations, and `maintenance_work_mem` the memory available for operations like `CREATE INDEX` or `VACUUM`.

By all means, it doesn’t mean that you have to choose some parameter values and stick with them for good, but it does mean that the default configuration will be woefully inadequate for most kinds of production workloads. Additionally, there are many more knobs to tweak than just memory settings.

When you’re performing special operations such as data loads, it may even be beneficial to forgo some of the good conventions for running PostgreSQL in production and optimize it for all-out performance at the expense of reliability or crash tolerance (because you don’t care about that during a maintenance window that you’re using to load a bunch of data into the database).

Obviously, there are other much more varied database workloads besides loading data and other factors, such as concurrency, come into play. However, as we demonstrated through this example, and as you will find in the following sections in this chapter, there are ways to adapt your system to better suit them. Just don’t trust the default configuration to be sufficient for any sort of realistic workload.

6.2 Improper memory allocation

So now we have awareness of the fact that you shouldn’t take PostgreSQL into production usage with the default settings. Specifically, in the previous section we allocated more RAM for certain uses and that helped improve performance.

Let’s run a baseline standard pgbench test for 5 minutes (300 seconds) with the database we’ve just restored to see what sort of performance figures we get.

Tip

Make sure you run benchmarks from another host, in order to avoid overloading the database server with too much work. Ideally, the host you run the tests from should be powerful enough to be able to oversaturate the database server with requests.

```
pgbench -U postgres -h test01 -c 100 -j 24 -T 300 pgbench
pgbench (17.0 (Ubuntu 17.0-1.pgdg24.04+1))
starting vacuum...end.
transaction type: <builtin: TPC-B (sort of)>
scaling factor: 1000
query mode: simple
number of clients: 100
number of threads: 24
maximum number of tries: 1
duration: 300 s
number of transactions actually processed: 323961
number of failed transactions: 0 (0.000%)
latency average = 92.347 ms
latency stddev = 60.183 ms
initial connection time = 824.391 ms
```

```
tps = 1082.342941 (without initial connection time)
```

On this system, with the configuration settings we selected before, we're getting 1082 transactions per second (TPS) with a concurrency of 100 clients. We want to give our queries the best chance of executing smoothly and successfully, so we ramp up `shared_buffers` and `work_mem` to see if this will improve our performance further:

```
shared_buffers = 12GB            #1
work_mem = 2GB                   #2
```

We restart Postgres for the change to take effect, and re-run our pgbench test:

```
pgbench -U postgres -h test01 -c 100 -j 24 -T 300 pgbench
pgbench (17.0 (Ubuntu 17.0-1.pgdg24.04+1))
starting vacuum...end.
transaction type: <builtin: TPC-B (sort of)>
scaling factor: 1000
query mode: simple
number of clients: 100
number of threads: 24
maximum number of tries: 1
duration: 300 s
number of transactions actually processed: 319069
number of failed transactions: 0 (0.000%)
latency average = 93.930 ms
latency stddev = 65.995 ms
initial connection time = 297.914 ms
tps = 1062.819169 (without initial connection time)
```

We can see that the TPS stayed roughly the same, if not a little worse. It therefore looks like we may have been tuning our parameters in the wrong direction!

Now let's find out what would happen if 1000 — ten times as many — clients hit the database with these same settings by setting `max_connections = 1000`, restarting the cluster for the change to come into effect, and simulating a heavy workload:

```
pgbench -U postgres -h test01 -c 1000 -j 24 -T 300 -P 10 pgbench
pgbench (17.0 (Ubuntu 17.0-1.pgdg24.04+1))
starting vacuum...end.
progress: 10.0 s, 147.8 tps, lat 2532.664 ms stddev 1511.880, 0 f
```

```
^C
```

After the first 10 seconds, the test hangs, and we can see that there is something wrong. We cancel with `Ctrl+C` and by looking at the system logs on the database server we find:

```
kernel: Out of memory: Killed process 15255 (postgres) total-vm:1
 anon-rss:3208kB, file-rss:5760kB, shmem-rss:0kB, UID:107 pgtable
 oom_score_adj:0
kernel: systemd-journald[436]: /dev/kmsg buffer overrun, some mes
kernel: systemd-journald[436]: Under memory pressure, flushing ca
systemd[1]: postgresql@17-main.service: A process of this unit ha
 killed by the OOM killer.
systemd[1]: postgresql@17-main.service: Failed with result 'oom-k
systemd[1]: postgresql@17-main.service: Consumed 1min 18.570s CPU
```

Warning

Running a heavy workload such as the above stress test, especially when PostgreSQL's memory allocation hasn't been properly configured, can crash your system in unpredictable ways.

This `oom-killer` is Linux's Out-of-Memory Killer, run by the Linux kernel to recover memory when the system is critically low on memory. It chooses processes to terminate based on their OOM score (found in `/proc/<PID>/oom_score`). What this means is that there is a possibility that it may not choose the fresh PostgreSQL backend process which is using lots of RAM, but some other necessary process or application on your system that happens to use a lot of memory.

But why did we run out of memory? Remember, we allocated 12GB of `shared_buffers` and 2GB of `work_mem`. This means that we potentially allocated 2GB of RAM for **each node** of the execution plan **for each** running query. Keep in mind that each of the 1000 connected sessions may run a query utilizing many nodes. It's obvious that we don't have enough available RAM to do that, and we need to be aware that things can get out of hand quickly if we have complex queries with many plan nodes and/or parallel execution.

Note

It is important to avoid the OOM killer because when a backend process gets killed PostgreSQL terminates all other active backends to avoid operating with shared memory that may have potentially been corrupted. Postgres will then go into crash recovery mode, which means that this may trigger failover to a replica or other ugliness.

You should only allocate enough `work_mem` to cover your queries' needs and no more. As with many things in this book, this is entirely dependent on the workload. If you choose a small amount of `work_mem`, more complex queries such as those involving sorting and aggregation may run out of RAM for their operations and spill over into temporary files on disk, which is many orders of magnitude slower than in-memory operation. However, we saw firsthand that choosing a `work_mem` size that is too big can jeopardize your queries because the system may run out of memory and kill their processes, or even worse, PostgreSQL itself or some other critical process. Fortunately, `work_mem` can be `SET` at the session level so we can configure the system with some sensible default and only increase `work_mem` for those queries that actually need the extra memory to run.

Similarly, there are recommendations out there that the ideal amount of `shared_buffers` is 25% of available RAM, or any number of other formulas to calculate it. You should probably not follow these blindly as the right value is again workload-dependent: OLTP usage may benefit from having a large shared memory that can fit the part of the dataset that’s in use, whereas the same large `shared_buffers` may be wasted on an OLAP workload that only visits each buffer once. You may even have mixed use which will require you to take a careful look at balancing the memory allocation. In this case, our `shared_buffers` choice is clearly excessive because it doesn’t help with our workload at all.

Warning

Be careful to always include the unit used after your value. If you don’t, the default unit used for `shared_buffers` is the buffer (8192 bytes), so you’re specifying how many buffers to allocate — therefore there’s a very big difference between 1024MB and 1024 (buffers) which is just 8 megabytes. Confusingly, in other places such as `work_mem` and `maintenance_work_mem`

Postgres uses kB as the unit, for `min_wal_size` and `max_wal_size` it uses MB, and so on.

Proper memory allocation is important and you're stuck between a rock and a hard place, because the defaults will most likely be insufficient for your workload, but bumping them up significantly may cause even worse performance and stability problems. Oftentimes, you can't avoid trial-and-error as your workload is what's going to dictate how much you need for each value. As a reminder, you should never try things out in production, but rather on staging systems with similar data and running similar workloads.

6.3 Having too many connections

It is quite common to see PostgreSQL configurations with large connection limits, such as `max_connections = 2000`. In my experience, it seems to be widely believed by developers that the more connections the database can handle, the better it will be for the application.

Let us try out an experiment to see how PostgreSQL will hold up to large numbers of connections. As we saw in the previous section, our memory allocation strategy proved dangerous, so we are now going to choose some more reasonable values for our server. By allocating a more conservative value for `shared_buffers` and especially `work_mem`, as it is relevant to the number of queries we're running, we are reducing the possibility of running out of memory. We will also change the connection limit to allow 2000 clients.

```
shared_buffers = 1GB
work_mem = 4MB
max_connections = 2000
```

After a Postgres restart, which is necessary for our changes to take effect, we bring out `pgbench` again and run a series of tests with different numbers of clients, starting with 2000:

```
pgbench -U postgres -h test01 -c 2000 -j 24 -T 300 pgbench
pgbench (17.0 (Ubuntu 17.0-1.pgdg24.04+1))
starting vacuum...end.
transaction type: <builtin: TPC-B (sort of)>
```

```
scaling factor: 1000
query mode: simple
number of clients: 2000
number of threads: 24
maximum number of tries: 1
duration: 300 s
number of transactions actually processed: 84835
number of failed transactions: 0 (0.000%)
latency average = 5535.267 ms
latency stddev = 13696.921 ms
initial connection time = 69772.527 ms
tps = 352.083626 (without initial connection time)
```

We next try 1500, 1000, 500, and so on. The results are:

Table 6.1 test results showing TPS & latency with various numbers of clients

Number of clients	TPS	Latency average
2000	352.1	5535.267 ms
1500	506.8	2869.986 ms
1000	586.1	1694.616 ms
500	628.4	794.688 ms
250	635.7	392.554 ms
125	556.9	224.411 ms
63	613.0	102.758 ms

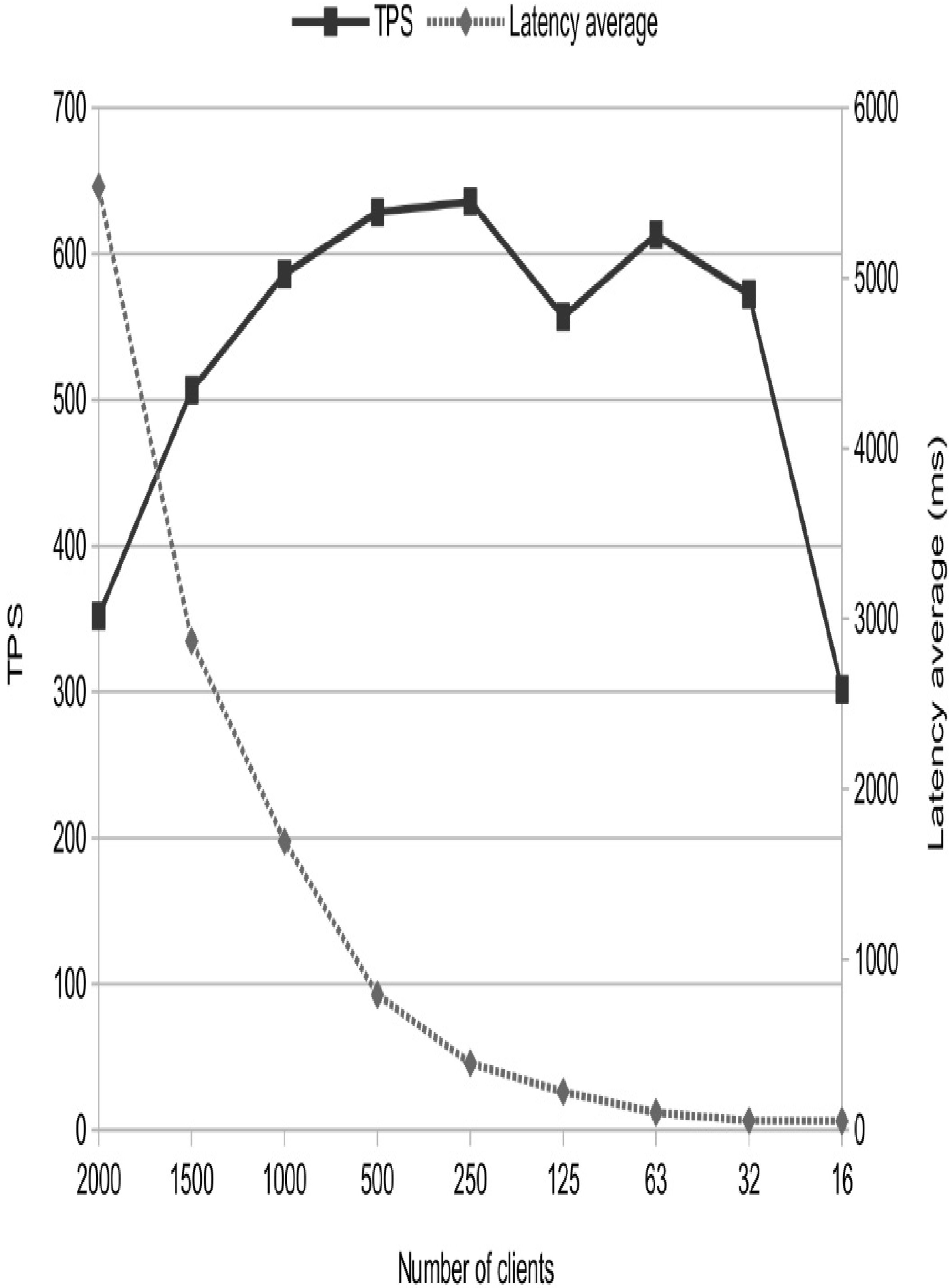
32	572.3	55.907 ms
16	301.8	53.009 ms

Let’s plot this table out onto a chart and examine the results.

Looking at the plot, we see that the TPS roughly plateaus between 1500 and 32 clients with low values at the extremes of 2000 and 16 clients.

The latency, though, shows a clear logarithmic trend, going from a very bad 5.5 seconds to stabilizing around 53 ms below 32 clients.

Figure 6.1 TPS & latency test result plot with various numbers of clients



TPS
Latency average
700
600
500
400
300
200
100
0
6000
5000
4000
3000
2000
1000
0
TPS
Latency average (ms)
2000
1500
1000
500
250
125
63
32
16
Number of clients

What does this all tell us? It tells us that we requested excessive concurrency which was too much for our modestly-sized server. When serving 2000 clients the server was struggling, which is reflected by the low TPS and high latency. Nonetheless, does it seem like it was more able to deal with the workload between 1500 and 32 clients?

Yes, at first glance it does, but the latency values tell the whole story of how overloaded the server was, with it only recovering at 32 clients and below. It was only able to sustain this TPS plateau by trading latency for higher concurrency — which, incidentally, is also how you can get around network latency because multiple connections make it less relevant for total throughput. The low TPS value at 16 clients just means that we weren't giving the server as much work as it could perform.

Multitasking aside, a computer can only do as much as it's got the resources for. If you're asking for 2000 things to be done at the same time and don't have 2000 CPU cores, you should understand that this is unreasonable. As an empirical rule of thumb, you shouldn't have more PostgreSQL connections than 4 times the number of your cores. But again: don't use my guidance as canon, because your optimal ratio is bound to be workload-specific.

Lightweight Lock contention

Accessing the same objects from multiple connections may incur many Lightweight Locks (`LWLocks` or "latches" as they are known in other database systems). Those are part of PostgreSQL's Multi-Version Concurrency Control (MVCC) mechanism and protect data in shared memory to ensure consistent reads and writes. Under high concurrency, a `LWLock` may become heavily contended, and there is no fair queuing for `LWLocks`, it's more or less random. Therefore lots of lockers can slow each other down and reduce overall query throughput. A good indication that you may have excessive concurrency is lots of `wait_event_type: LWLock` appearing in the `pg_stat_activity` monitoring view.

For PostgreSQL to have a performance headroom to better deal with increases or spikes in usage, you should trade off application-side latency for overall database server health. Instead of immediately opening as many client connections as the application requires, restrict the number of clients and make the application requests queue (hopefully not for long) for an available connection. This means that the application should be able to wait, so you may have to increase timeouts on that end.

If you cannot restrict the number of connections the application requests, a good solution is to leverage connection pooling. A connection pooler such as PgBouncer can be inserted between the application and database and implement this nicely for you. It can accept thousands of connections from the application but only allow as many clients as you specify through to PostgreSQL and make the rest wait for their turn. When you give this a try, and if you monitor database activity via `pg_stat_activity`, you may find that the real concurrency (i.e. how many things your application is actually trying to do at the same time inside the database vs. how many connections it wants to open) is much lower than what you expected. In the wild, applications with 5000 connections have been seen only running about 15-30 active tasks concurrently in the database.

Regarding excessive concurrency, remember that PostgreSQL is a multi-process system with a "process per user" model. This means that every client connects to a backend process, and all this is coordinated by the postmaster supervisor process. PostgreSQL’s inter-process communication (IPC) is via semaphores & shared memory.

This tells us that, if we have too many processes running in our system, this incurs operating system overhead and brings the risk of excessive CPU context switching. Needless to say, this is bad for server performance.

Note

Process thrashing is when you have too many processes for them to get scheduled effectively and each one gets a tiny slice of execution time, progressing very slowly as the system spends more time performing context switches than it does executing the actual processes. Additionally, the excessive memory usage caused by too many backends may cause thrashing of memory in and out of swap, and we remember that disk access is vastly slower than RAM.

To wrap up, while you may think that you are making your application run faster by parallelizing, you may actually be hampering its performance by swamping your database server with too much work. "Throttle" it, or introduce latency on the application side, to save your DB server’s performance. It sounds counter-intuitive but it doesn’t necessarily slow anything down –- your queries will execute faster on a server that’s not overloaded!

6.4 Having idle connections

Let’s now examine why you shouldn’t keep idle connections around on your PostgreSQL server.

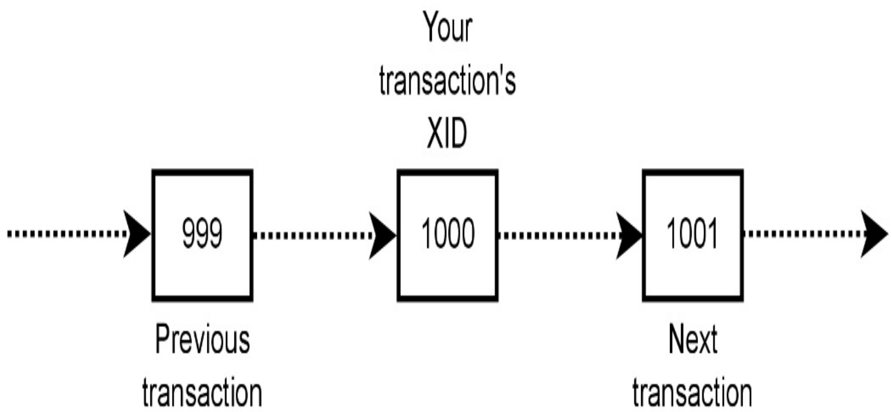
6.4.1 What is MVCC?

It’s worth our while to briefly discuss PostgreSQL’s transactions and its concurrency control at this point.

PostgreSQL uses Multi-Version Concurrency Control (MVCC) rather than locking to enable high concurrency and achieve high performance. With MVCC, reading from the database never has to wait. Writing to the DB doesn’t block reading, and reading doesn’t block writing. As you may have guessed from the name, the way the MVCC system works is that each write creates a new version of a tuple (row). We therefore have what’s called *snapshot isolation*: each transaction has a point-in-time consistent view (or snapshot) of the data. Postgres uses timestamps and transaction IDs (XIDs) to enable the activity tracking that makes enforcing these consistent views possible, that is, determine which tuples are visible from each transaction. A snapshot, which contains the earliest still-active transaction, the first as-yet-unassigned transaction, and the list of active transactions, is obtained by each transaction from the Transaction Manager. You can get a fresh snapshot via the function `pg_current_snapshot()`.

The timeline of PostgreSQL transactions looks like this:

Figure 6.2 PostgreSQL transaction timeline showing linear sequence of XIDs



From within transaction 1000, you may or may not be able to see the results of transactions 999 and 1001, depending on whether they were committed or aborted before transaction 1000 completes.

6.4.2 The issue with idle connections

It’s easy to think that idle sessions are innocuous. After all, they’re not performing any task in the database, so it should logically follow that they don’t affect the database’s performance.

It is quite common to see systems in production with thousands of idle connections, especially when language-side connection poolers are used (those offered by the programming language or framework, as opposed to intermediary or server-side). Those then keep thousands of database sessions open in order to have a pool of connections available to hand over to the application. The worst culprits are usually Java frameworks that tend to distance developers so far away from the database through abstractions that they usually have no idea how a database operates or what they should and shouldn't do.

We do know though that PostgreSQL's MVCC mechanism maintains snapshots for each and every transaction. This means that every time a transaction requests a snapshot before beginning to do its work, Postgres has to examine all open connections to compile the snapshot information. This is a consequence of having to check what each session is doing — we don't know that they're idle until we check. As veteran PostgreSQL developer Tom Lane succinctly put it in an email response to the `pgsql-performance` mailing list, this makes the [computational] cost of taking a snapshot proportional to the total number of connections.

As a result, even when your session is sitting idle doing nothing, it is consuming system resources and slowing down subsequent connections being opened, a situation that could be described as snapshot contention.

How do we end up with idle connections? It can simply be poor application design — unintentional, such as allowing many connections for no reason, or intentional, such as storing application queues or states of an application with many components or workers in a single database. Or, as we previously mentioned, it can be an attempt to maintain throughput and mitigate latency through increasing concurrency. It's also a way to deal with sudden spikes in requests (although the preferred solution would rather put a connection pooler in between the application and database).

This doesn't mean that the connections are totally unused; it is sufficient for them to remain idle most of the time (e.g. because of the application not requesting queries very often). Even so, they negatively affect the performance of those connections that are indeed active in a very real and measurable way.

Optimizations for connection handling, specifically in dealing with the process of obtaining a snapshot for a new connection, arrived in PostgreSQL 14, eliminating much of the bottleneck but not entirely. Obtaining snapshots for many incoming connections is still computationally significant, even if the situation has improved. Moreover, even if the relevant PostgreSQL internals have been optimized, you still have to remember that it's a multi-process system — every connection requires a new backend process, and the operating system overhead of having to do process accounting, scheduling, and IPC for thousands of extra processes is certainly not negligible.

As a final note, and as a deterrent, you should also consider the possibility that the application might suddenly decide to utilize thousands of those idle connections at the same time due to a spike in usage (e.g. markets opening). After all, these connections have been made available to it. Such a scenario is bound to cause a server performance meltdown.

Leveraging a transaction pooler, such as PgBouncer in Transaction Mode, can help if you find yourself in a situation where you need to open many connections that may be mostly idling. PgBouncer will just hand over the unused connections to some other transaction that needs them, thereby mitigating the system overhead. This is preferable to using `idle_session_timeout` to automatically close idle sessions, which may not be appreciated by unaware clients or applications.

6.5 Allowing long-running transactions

PostgreSQL gurus will invariably tell you to avoid having long-running transactions. But why? First of all, let's differentiate between sessions that are active and just taking a long time to complete, and those that are idle, doing nothing inside a transaction. We will start by examining the latter.

6.5.1 Idle in transaction

Simply put, a session that is `idle in transaction`, as reported by `pg_stat_activity`, is one that has begun a transaction, is not running an active query, and has not rolled back or committed the transaction. A common case is when a client opens a connection and runs `BEGIN` to start a transaction, and then lets the connection idle. Badly written applications have been known to use this access pattern. Many of us have also seen database administrators or developers initiating a connection, then leaving the client running with the connection open as they leave for the day (or for their vacation). If they happened to start a transaction before going away, their session will be left `idle in transaction`.

If you remember from our short description of MVCC, PostgreSQL determines the visibility of tuples by using transaction IDs, and this is how the Isolation property of ACID is guaranteed for compliance. If you remember, we examined ACID violations of the Isolation property in section "Homemade distributed systems" of Chapter 5.

Locks in PostgreSQL

The concept of locks in Postgres is not complicated: From a database user perspective, locks are obtained on the table level (e.g. `ACCESS SHARE`) or the row level (e.g. `FOR UPDATE`). These then either permit or prevent access to other transactions that are trying to "use" (i.e. obtain a lock on) the same thing. This is determined by way of lock types being conflicting with each other — so if someone attempts to obtain an `ACCESS EXCLUSIVE` lock on a table, that will conflict with all other types of locks so nobody can obtain a `SHARE` lock on the same table.

Now let’s explore a scenario where a client leaves a session idle in transaction:

```
 Client A
------------------------
 BEGIN;
 SELECT * FROM mytable;
 (...)
```

The `SELECT` statement completes, and returns results `(…)`. Client A leaves the connection and transaction open.

Now another client connects, and attempts to add a column to `mytable`. The table is not in use at this point, right? So the client should be able to run this DDL command.

```
 Client A                | Client B
-------------------------+-----------------------
 BEGIN;                  |
 SELECT * FROM mytable;  |
 (...)                   |
                         | ALTER TABLE mytable
                         | ADD description text;
                         | *hangs*
```

Client B's request waits forever (or at least, until Client A's transaction ends). Client A's transaction has taken the most innocuous of locks, an `ACCESS SHARE` lock, to read the table. Even though this is a lock mode that can't even block others from reading or writing to the table, it conflicts with the `ACCESS EXCLUSIVE` lock that the `ALTER TABLE ADD (COLUMN)` statement requires.

What's worse, while Client B waits its turn to obtain the lock it needs on `mytable`, any other transaction or query that needs to access `mytable` will be blocked because they have to queue behind it!

```
 Client A                | Client B               | Client C
-------------------------+------------------------+----------------
 BEGIN;                  |                        |
 SELECT * FROM mytable;  |                        |
 (...)                   |                        |
                         | ALTER TABLE mytable    |
                         | ADD description text;  |
                         | *hangs*                |
                         |                        | SELECT 1 FROM m
                         |                        | *hangs*
```

However, Client A simply ending the first transaction will unblock everything:

```
 Client A                | Client B               | Client C
-------------------------+------------------------+----------------
 BEGIN;                  |                        |
 SELECT * FROM mytable;  |                        |
 (...)                   |                        |
                         | ALTER TABLE mytable    |
                         | ADD description text;  |
                         |                        |
                         |                        | SELECT 1 FROM m
                         |                        |
 END;                    |                        |
```

```
 COMMIT                        |                              |
                               | ALTER TABLE                  |
                               |                              |  ?column?
                               |                              | ----------
                               |                              | (0 rows)
```

Note

`END` is a PostgreSQL extension to the SQL language that is equivalent to `COMMIT`.

Let’s take a brief moment to talk about **VACUUM**. MVCC gives you amazing write and rollback performance but it requires maintenance operations. Namely, VACUUM is the operation that removes "dead" tuples (old row versions) that are no longer visible by any transaction and are therefore not needed. PostgreSQL runs this automatically to perform maintenance on the database from time to time, and this is what we call autovacuum. As with everything else, it needs to use locks, and it waits to obtain them.

Worryingly, `idle in transaction` connections can prevent (auto)vacuum from running if they have modified any data or are using an isolation level such as `REPEATABLE READ` or `SERIALIZABLE`. Vacuum will also not be able to remove recently dead rows that must remain visible by this open transaction. Forgoing vacuum for some time can bring on bloat (dead rows left over inside the table) which has serious implications for performance and disk usage.

Warning

Worse, autovacuum also does other things such as "freezing" old table rows. If autovacuum is prevented from running over an extended period, this can cause transaction ID wraparound, a related failure mode that we’ll discuss in the following section.

One way to prevent connections from staying idle in transaction is designing your application properly (ha!) — another is setting a value for the configuration parameter `idle_in_transaction_session_timeout`. This will prevent sessions from sticking around in `idle in transaction` state for longer than the specified number of milliseconds, thereby preventing sessions from holding on to locks or blocking vacuum for unreasonable amounts of time. However, there is a tradeoff here: if your application needs to run processing for some time after initiating the transaction before writing back and/or closing it, the timeout needs to be sufficient to accommodate that. Moreover, your application needs to be able to tolerate these types of session timeout disconnections.

For more information on this, please read the PostgreSQL documentation: https://www.postgresql.org/docs/current/runtime-config-client.html#GUC-IDLE-IN-TRANSACTION-SESSION-TIMEOUT

6.5.2 Long-running queries in general

Many of the same points still hold true for long-running queries. Remember, even if you haven't explicitly started a transaction, each query will run within its own implicit transaction.

Each of these transactions will obtain a snapshot of the database, as previously mentioned, and hold it for as long as it is executing its statement. The same will be true for as long as a cursor is open.

Tip

When we're talking about queries with long execution times, we mean actively running ones, not queries that are slow to complete because, for example, they are blocked. `now() - query_start` under `pg_stat_activity` is the duration that you'll be looking for.

Autovacuum will skip cleanup of dead tuples if a transaction is holding a snapshot obtained before those tuples were changed or deleted. Additionally, if a query needs to obtain a lock that conflicts with it, autovacuum will voluntarily give up the lock and stop what it's doing. Obviously, if the query goes on for very long, autovacuum won't get the chance to run. All of these, again, can lead to problems with bloat and XID wraparound.

Lastly, long queries can cause query conflicts in a replication scenario. For instance, when heavy updates on the primary are changing data that is simultaneously being selected on the standby server, this can lead to the queries on the standby being cancelled. The query cancellation is due to the conflict caused by needing to apply WAL that will affect the data being selected.

Long-running transactions can also cause replication lag when synchronous or logical replication is in use, as changes are only replicated after they've been committed. This can be mitigated by using asynchronous streaming replication or enabling logical replication streaming of large in-progress transactions, respectively. You can do the former by setting `synchronous_standby_names` to an empty string in `postgresql.conf`, and the latter by enabling the `streaming` parameter when setting up your logical replication connection with `CREATE SUBSCRIPTION`.

It is relatively safe (for the database, perhaps not for the client application) to `SELECT pg_cancel_backend(<PID>);` to stop long-running queries. However, as we've already seen, terminating backends — e.g. by killing (`SIGKILL`) the PID of the backend — is very different and much more dangerous to use, as it may bring the entire server instance down into recovery mode when PostgreSQL detects that one of its backends has been killed. `pg_terminate_backend(<PID>)` is safer to use, but it is much less graceful than `pg_cancel_backend()` as it aborts the transaction and disconnects the user forcibly, which may cause problems in the application.

6.6 High transaction rate

Having the ability to process transactions at a high rate is generally desirable, but is having a sustained high transaction rate actually good for your PostgreSQL database?

6.6.1 XID wraparound

As we mentioned previously, PostgreSQL assigns an identifier (XID) to each transaction and those are used as the basis for the MVCC mechanism. We just write into the main data area (or *heap*) of the table and each tuple we write has an `xmin` (the XID that inserted it) and an `xmax` (if deleted, the XID that deleted it). Remember — updates in PostgreSQL are an insert and a delete operation.

Tip

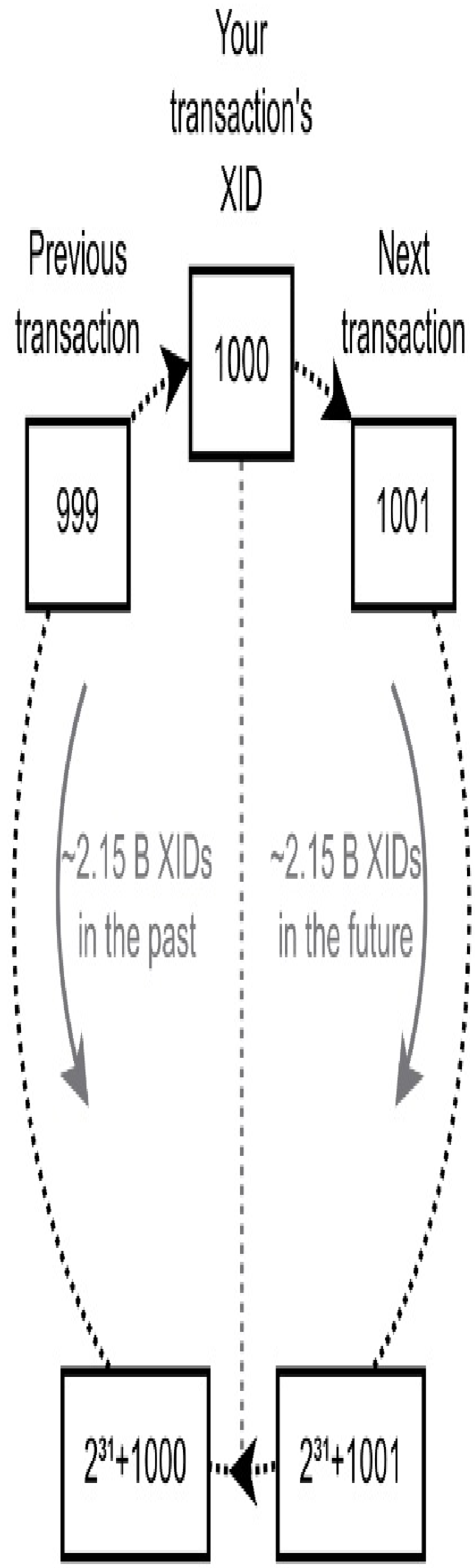
You can find out the current transaction ID via:

```
SELECT txid_current();
```

XIDs are unsigned 32-bit integers, so they have a range of approximately 4.3 billion values.

You should think of this as a circular space, with a visibility horizon: from the perspective of your transaction, there have been ~2.15 B XIDs in the past, and there are ~2.15 B XIDs in the future, like this:

Figure 6.3 Depiction of PostgreSQL's transaction IDs as a circular space


Your transaction's XID
Previous transaction
1000
Next transaction
999
1001
~2.15 B XIDs in the past
~2.15 B XIDs in the future
2^31+1000
2^31+1001

Imagine that we just zoomed out from Figure 6.2, and what appeared like a straight line was in reality a segment of a circle. When we next move to transaction 1001, there will still be the same number of billions of XIDs behind and ahead of it — as if `txid_current()` is the pointer on the Wheel of Fortune!

In the preceding section, we referred to the **XID wraparound** failure mode. This happens when you try to read a very old tuple that is more than ~2.15 billion XIDs in the past from your perspective. By looking at Figure 6.3 we can easily understand that such an XID will be in the space of future XIDs from your viewpoint, and should be invisible! This precipitates an impossible situation where we don't know if the tuple is from the past or the future, and can cause data inconsistency or loss. PostgreSQL tries to prevent XID wraparound at all costs, by running a non-interruptible anti-wraparound autovacuum that tries to rectify the situation. This can slow your system down to a crawl and is unavoidable once it starts. But how do we get to that point, and how do we prevent this from happening?

We prevent XID wraparound through a trick called *freezing*. VACUUM will go through each table, and mark very old tuples that are known to definitively be in the past with a "frozen" flag. This marks them as being "very old" and outside our current space of XIDs, therefore making the frozen tuples safe in terms of their `xmin`. In a sense, it's reclaiming previously used XIDs from tuples.

The only thing we need to care about now is ensuring that this `VACUUM FREEZE` operation happens before XID wraparound occurs, and this is what the special anti-wraparound autovacuum is doing, albeit in a rushed manner. It kicks in when PostgreSQL believes you are close to running out of XIDs (this is configurable via `autovacuum_freeze_max_age`). As we hinted in the previous section, sessions in `idle in transaction` state can hold back the XID horizon and cause freezing of old rows to be deferred.

6.6.2 Burning through lots of XIDs

It's common for users and developers to take advantage of PostgreSQL's superior `INSERT`/`UPDATE` speed and just throw tons of data into the database with little performance consequence. Each write "uses" an XID, and it’s common for heavy OLTP workloads to burn through 2 billion transactions in a short time. I have witnessed a database that went through this amount in the space of a week! This volume of activity makes it dangerously likely that our transaction burn rate will outrun autovacuum (and consequently automatic freezing), pushing us towards XID wraparound error.

So, with regard to achieving impressive transaction rates: just because you can, doesn’t mean you should.

What can you do when you find yourself having a high XID burn rate?

First, you should examine if batching can help. Does your application really need to commit everything atomically? Consider the simple fact that instituting a transaction commit batch of size 1000 will bring your application down to about 1/1000th the previous XID burn rate, solving your transaction rate issue pretty much immediately. Your application developers can also try to reorganize all those incoming rows into more efficient structures that will store the results of multiple operations.

Another thing you can try is to increase the effectiveness of autovacuum by tuning the relevant configuration parameters to make it more aggressive. This will consequently make tuple freezing more efficient.

Check out how to tune freezing in the PostgreSQL Documentation at: https://www.postgresql.org/docs/current/routine-vacuuming.html

A bit of architectural advice that is good to remember is that you don’t want to be storing too much data (that you may never use) inside your database. Many organizations tend to store every bit of data that comes across their systems in case it ever becomes useful in the future for analysis purposes or otherwise. Check with stakeholders and inform them of the risks and costs of such a course of action, and eliminate data nobody will ever look at from your ingestion flow.

An alternative for dealing with data that is useful but of a very high volume is to crunch or resample it right away and only store summaries, averages or trends — if that’s what you’re going to need in the future anyway.

6.7 Turning off autovacuum/autoanalyze

Because of the design choice to use MVCC in Postgres, VACUUM is a necessary evil. At least, some people see it as evil because it appears to be a background process that eats resources and does nothing for their workload.

As a result, when folks who think this way find out that there’s something called autovacuum running `VACUUMs` all the time inside their database, their response is to try to find a way to disable this pesky daemon. After all, it seems to be consuming system resources, often at the most inopportune times for their daily workload.

They often feel vindicated when turning it off results in performance gains, and there is a noticeable difference for their developers and end users to see.

Well, at least for a while.

To see why this is a recipe for disaster, let’s first examine what VACUUM does.

We already know that it cleans out dead tuples from our database. You can think of this as garbage collection that frees up space inside a table’s data files because those tuples are not removed from the table until a VACUUM is run on it. This cleared-out space can then be re-used by Postgres. Next, VACUUM does the same for tables' indexes by performing the corresponding cleanup. We also saw that it can freeze old table rows to prevent XID wraparound. Finally, with the command `VACUUM ANALYZE`, we run an `ANALYZE` operation after the vacuum to collect useful statistics on the table’s content which helps the query planner choose suitable plans by considering the nature of data in the table.

Now let’s see specifically how autovacuum operates. It’s all in the name really — it pops up automatically from time to time to see if tables need vacuuming or analyzing, and then performs VACUUM and/or ANALYZE on those tables. It’s a way to worry less about all of the things in the previous paragraph, as it takes care of bloat prevention, query plan optimization, and XID wraparound safety.

If it isn't already obvious, these are important functions. So important, that even when you choose to disable autovacuum in PostgreSQL's configuration, it still keeps an eye out for XID exhaustion situations, ready to intervene. The bottom line is that, the same as backups (more on that in a later chapter), maintenance operations should be automatic and not rely on manual intervention.

Any short-term performance gain from disabling autovacuum will soon be outweighed by the detrimental effect of bloat accumulation. From a performance aspect, having bloat simply means going through additional data on disk that is junk when scanning tables and indexes, slowing down queries that would otherwise perform better.

Letting bloat get out of hand can result in your tables ballooning in terms of size on disk, and this space is then non-reclaimable by simple VACUUM, which can't hand the space back to the operating system but just mark it as free inside the file for Postgres to use. To free up the disk space, you would then need to run a different command called `VACUUM FULL`, which is slow, requires even more disk space, and is highly disruptive to database operation, as it totally locks out any use of that table. This means that you should never call `VACUUM FULL` on a table that's in use unless you fully understand the implications.

Also, by overlooking the importance of gathering optimizer statistics you can run the risk of reduced query performance. The optimizer needs to know data characteristics such as cardinality, number of distinct values, and other histograms, in order to choose the best plan for executing a query.

Much of the same holds true for just leaving autovacuum with its very conservative defaults, which will be ineffective for production workloads — remember how we saw that PostgreSQL out-of-the-box defaults are too conservative for real-world usage in the first section of this chapter. Simply reducing autovacuum's potency by turning down those parameters will also have the same detrimental effects on bloat and statistics gathering.

The recommendation here, counter-intuitively, is to **increase** autovacuum's effectiveness the more write-intensive your workload becomes instead of decreasing it to balance out resource consumption. You should bite the bullet and accept that a portion of system resources will be dedicated to this MVCC maintenance operation that keeps your database running properly under the demanding conditions that you are imposing on it. For the time being — meaning until PostgreSQL gets additional storage backends — you can't avoid VACUUM.

If your server can't cope with both your workload and the autovacuum that this requires, you may need to look into scaling up your system, scaling down your workload by identifying costly queries, or adjusting your database architecture (e.g. by splitting the data, using replication, etc).

Tip

Keep in mind that you can override autovacuum settings on individual tables if the defaults are not suitable for a subset of your tables.

Autovacuum configuration parameters, including how to tune it up or down using cost-based delays and sleep time, are documented here: https://www.postgresql.org/docs/current/runtime-config-autovacuum.html

6.8 Not using EXPLAIN (ANALYZE)

You'd be surprised to find out how few people `EXPLAIN` and `EXPLAIN ANALYZE` their queries to find out how they get executed by the database. It might be because of the weird output format, that many find hard to read at first, or because they don't know what a `Recheck Cond` on a `Bitmap Heap Scan` is and where to look it up. However, judging from other DBMSs, PostgreSQL's query plans are very detailed and well-documented by comparison.

It is surprising, because in most cases where the complaint is "my query is too slow", `EXPLAIN` can help you figure out why it is taking so long to execute.

The planner/optimizer generates a multitude of possible execution plans for the query, costs them according to its internal logic, previously gathered statistics, and configuration, and finally chooses the one with the lowest cost because it will have the best chance of being the fastest to run. This is why, in the previous section, we saw how important it is to allow autovacuum/autoanalyze to gather the aforementioned planner statistics.

`EXPLAIN ANALYZE` goes a step further than showing you the chosen query plan, and tells you the actual timings of how long each component of the statement took to run.

Warning

`EXPLAIN ANALYZE` actually **runs** the SQL statement, as opposed to simple `EXPLAIN` which only plans it. This means that if your statement changes data, `EXPLAIN ANALYZE <query>;` will apply those changes! Consider putting `EXPLAIN ANALYZE` between `BEGIN` and `ROLLBACK` commands, but be aware that your `ROLLBACK` may incur the need for vacuuming (e.g. if you insert a lot of rows and then roll back).

The `auto_explain` extension allows you to automatically include execution plans for slow-running queries in the PostgreSQL log. However, be careful: running `EXPLAIN` on lots of queries can impact performance.

There are numerous examples of the use of `EXPLAIN (ANALYZE)` throughout this book, helping to demystify query performance and execution logic, to further aid us in understanding why a particular course of action is a mistake. There’s also another example in the section after next "Having no indexes"!

Supplementing the official documentation, there are numerous tutorials available online that go over the process of reading and understanding EXPLAIN output, as well as visualizers that organize query nodes and concepts in a way that some will find more user-friendly.

6.9 Locking explicitly

The lock modes that PostgreSQL provides can be used by applications to control concurrent access to table data where MVCC’s default behavior is not sufficient. By locking objects explicitly, applications can ensure data consistency, that actions won’t be executed out of order, or that application-side objects won’t get out of sync with each other.

However, locking explicitly is a bad paradigm, and should generally be avoided. These explicit locks, also known as *heavyweight locks*, can block statements' read and write access completely, leading to waits.

As we saw in the example from the section "Idle in transaction", the situation where we inadvertently locked access to a table could have proved disastrous for application performance. The statement there was waiting indefinitely for the lock it needed to be released and other statements were getting queued behind it, also waiting.

It’s easy to look at part of the issue and focus on, let’s say, synchronization of objects in the application, and explicit locks may seem like the ideal solution. In reality, it’s more likely that eventually sessions will block other sessions unless your application is exquisitely crafted — hint: it isn’t. The likely result will be longer run times for queries and increased latency or waits visible to interactive users of the application.

To be on the safe side, avoid using this kind of locking in your code. The alternative is to make clients try to obtain access to an object, and if that isn’t available, notify them immediately with an error so they can retry later. This involves making the application tolerant, so it can be allowed to fail and retry.

Luckily, there’s a PostgreSQL isolation level that does exactly that. The `SERIALIZABLE` isolation level implements *Serializable Snapshot Isolation* (SSI), which detects and prevents *anti-dependency* cycles (when a transaction writes a new version of a row while an older version is being observed by another transaction).

Anti-dependency cycle (rw-dependency)

Transaction T1 reads three rows from a table `WHERE active = true`, transaction T2 updates one of these rows with `SET active = false`, then transaction T1 tries to calculate an average value `WHERE active = true`, which only averages across the two rows. This is also known as *write skew on predicate read* or *G2 serialization anomaly*.

`SERIALIZABLE` is the strictest transaction isolation level and when a serialization failure is detected, it will throw errors such as `ERROR: could not serialize access due to read/write dependencies among transactions`. Due to the overhead of anomaly detection, it may allow for slightly reduced concurrency but the benefit is that there is nothing that can block queries, and explicit locks are not required. For some application types, serializable will be the best choice for achieving high performance.

Tip

An example of how to use SERIALIZABLE can be found in the PostgreSQL Documentation here: https://www.postgresql.org/docs/current/transaction-iso.html#XACT-SERIALIZABLE

Alternatively, you may want to handle synchronization inside your application. In this case, you can use advisory locks, a feature provided by PostgreSQL for developers to define locks that hold a meaning for the application but are not enforced by the DBMS. More information on advisory locks can be found here: https://www.postgresql.org/docs/current/explicit-locking.html#ADVISORY-LOCKS

6.10 Having no indexes

This one is kind of self-explanatory I would hope, and not 100% specific to PostgreSQL. Indexes can make a very significant difference in query performance in conjunction with predicates by offering fast scan times. The different index types on offer (B-tree, Hash, GIN, BRIN, GiST, SP-GiST and Bloom filter) cover many varied use cases, and yet we always see slow queries that could have been made blazing fast through the use of an index.

However, coming from other DBMSs, you may assume that an index will automatically be created under some conditions. In a recent real-world case, developers had trusted that because they were querying a column that was using a foreign key, PostgreSQL would have created an index on the referencing table.

Let's see what that looked like, using two tables from our Frogge Emporium database. Frogge has a table of `invoices` where the column `customer` references the table `customers`. They have a query to find how many invoices they have from a specific customer:

```
SELECT count(*)
FROM erp.invoices
JOIN erp.customers c
ON customer = c.id
WHERE first_name = 'Aiden'
AND last_name = 'Kowalski';
```

With `SET max_parallel_workers_per_gather=0;`, The `EXPLAIN ANALYZE` output for this is:

```
                                 QUERY PLAN
-----------------------------------------------------------------
 Aggregate  (cost=6054.51..6054.52 rows=1 width=8) (actual
 time=28.057..28.060 rows=1 loops=1)
   ->  Hash Join  (cost=306.01..6054.46 rows=18 width=0) (actual
 time=2.681..28.053 rows=18 loops=1)
         Hash Cond: (invoices.customer = c.id)
         ->  Seq Scan on invoices  (cost=0.00..5092.00 rows=25000
 (actual time=0.004..12.098 rows=250000 loops=1)
         ->  Hash  (cost=306.00..306.00 rows=1 width=8) (actual
 time=0.953..0.954 rows=1 loops=1)
               Buckets: 1024  Batches: 1  Memory Usage: 9kB
               ->  Seq Scan on customers c  (cost=0.00..306.00 ro
 width=8) (actual time=0.122..0.950 rows=1 loops=1)
                     Filter: ((first_name = 'Aiden'::text) AND (l
 'Kowalski'::text))
                     Rows Removed by Filter: 13999
 Planning Time: 0.139 ms
 Execution Time: 28.083 ms
(11 rows)
```

We can see that even though we are querying on a foreign key that's referencing the primary key on the `customers` table and is therefore indexed there, the `Gather` for our `count()` is performing a `Seq Scan` on table `invoices`. PostgreSQL doesn't create an index on the referencing table automatically, so none is used. However, the query still manages to complete in just 28 ms.

After `CREATE INDEX ON erp.invoices(customer);` we get this plan:

```
                                         QUERY PLAN
-----------------------------------------------------------------
 Aggregate  (cost=314.84..314.85 rows=1 width=8) (actual time=0.9
 rows=1 loops=1)
   ->  Nested Loop  (cost=0.29..314.79 rows=18 width=0) (actual
 time=0.121..0.954 rows=18 loops=1)
         ->  Seq Scan on customers c  (cost=0.00..306.00 rows=1 w
 (actual time=0.107..0.938 rows=1 loops=1)
               Filter: ((first_name = 'Aiden'::text) AND (last_na
 'Kowalski'::text))
               Rows Removed by Filter: 13999
         ->  Index Only Scan using invoices_customer_idx on invoi
 (cost=0.29..8.61 rows=18 width=8) (actual time=0.012..0.014 rows
 loops=1)
               Index Cond: (customer = c.id)
               Heap Fetches: 0
 Planning Time: 1.511 ms
 Execution Time: 1.338 ms
(10 rows)
```

This turned the `invoices` table access into an `Index Only Scan` that only takes 1.3ms in total! Big deal? We were also in the milliseconds before.

However, it made our query run 20 times faster. Imagine that this kind of query gets executed thousands of times an hour, or a minute. In this case, milliseconds that you would usually ignore can make a world of difference in total system throughput.

A few sections back, we talked about the importance of taking advantage of the `EXPLAIN` command. Here we tried it to see if an index was being used, and if the index we created helped things, by comparing execution plans before and after indexing.

If you see that you get full table scan accesses, consider the nature of that column and the `WHERE` clause you're using, and it's more than likely that you will find an index type that will speed up your SQL statement.

6.11 Having unused indexes

At the other end of the scale, just mindlessly creating indexes on every column can seriously undermine the performance of `INSERT`, `UPDATE` and `DELETE` operations. Also you can end up wasting a lot of disk space on indexes that you will never need.

In one memorable case, a table had an index on each table column, an index grouping all columns together, and also indexes for every combination of columns! Needless to say, almost none of them served a purpose.

There’s no point in repeating the `EXPLAIN` song and dance here — try it and see for yourself how much slower you can make writing to a large table by adding more indexes to its columns.

As we said in the previous section, when you have very heavy query traffic where you update a table all the time, just shaving tenths or hundreds of a millisecond off of each `UPDATE` will make for a significant throughput improvement.

Finally, an index will only be needed when you have a `WHERE` clause, and even then, only for time-critical queries. If you’re going to index something that you query only once a day and it takes a couple of seconds, it may not be worth the effort of maintaining this index. Additionally, when you’re selecting a significant portion of the table, scanning an index may be slower than actually going through the table sequentially. PostgreSQL knows this and will elect to do a `Seq Scan` instead.

You can identify unused indexes and `DROP` them by examining the view `pg_stat_all_indexes` to see which ones have `idx_scan = 0`. It means they have never been used in an index scan, so there is no reason to keep them around.

Tip

Use caution **not** to run index or constraint creation commands such as `CREATE INDEX ON invoices(customer);` more than once. Without explicitly specifying the index or constraint name, a duplicate index (with a unique, system-generated name) will be created. Duplicate indexes waste database space, slow down DML operations (`INSERT`, `UPDATE`, and `DELETE`), and increase maintenance time (such as for the aforementioned autovacuum) while providing no actual query performance benefit.

6.12 Removing indexes used elsewhere

Following the advice from the preceding section, you remove every index you find with a zero `idx_scan` value. Naturally, you feel smug because you applied some sound advice from a PostgreSQL book and as a result improved the state of your database. A few minutes later, your phone rings unexpectedly, and you pick up to find that Ashley from Accounting is livid. Their reporting queries have slowed to a crawl, and they are demanding to know what happened to the database.

How could this be possible? It turns out that Accounting is using a standby node, connected via streaming replication, for their queries as a read replica. If you had checked `pg_stat_all_indexes` on that node, you would have seen that it showed quite a large number of index scans, meaning that the index was heavily used for some queries. These kinds of statistics are instance-specific and not for the entire cluster. And of course, as there’s physical replication between the Postgres instances, when the index was dropped on the primary, it also disappeared from the standby.

When you have standby nodes, always check to see that indexes are not seeing use on any of those nodes before you decide to remove them.

6.13 Summary

- PostgreSQL’s default configuration is very conservative and in most cases will not be optimal for a real-world workload. This can mean that you are leaving your system resources underutilized and leaving potential performance gains on the table.
- You can shoot yourself in the foot by calculating memory allocation settings incorrectly. You need to take your workload into account,

including what types of queries you are running and how memory-hungry they are along with what level of client concurrency you are expecting.

- Excessive concurrency can kill your performance rather than allow more work to be performed in parallel because of the way Multi-Version Concurrency Control (MVCC) works. You need to be aware of the risks associated with opening too many sessions inside PostgreSQL, and also the nature of your workload and the limitations of your particular database host.
- Connections that are mostly or entirely idle don't come for free; they are associated with computational overhead that may affect PostgreSQL's, and your operating system's, performance in general. You should try to avoid having connections around that don't do much actual work. If you can't, you should use a connection pooler that's aware of these connection semantics, such as PgBouncer in Transaction Mode.
- Idle in transaction sessions and sessions with long-running queries can cause unexpected blocking of other queries, leading to application delays or errors. They can also postpone or altogether block autovacuum, and this can lead to performance degradation beacuse of bloat, or more serious errors.
- If you let your transaction rate get out of control, it can outrun the efforts of autovacuum to prevent XID wraparound failure and bring down your database. You can mitigate this by batching, reorganizing, and summarizing data — or even skipping the ingestion of data you aren't likely to use again.
- Autovacuum is essential for the correct operation of your database. Lowering its effectiveness or disabling it altogether to save system resources is a fallacy, because any performance gains will be undone in time by bloat accumulation, inaccurate optimizer statistics, and forced anti-wraparound prevention.
- Where there's evidence that a query is running slowly, checking its `EXPLAIN` is a quick and accurate way to identify the reasons why and help troubleshoot it.
- Locking objects explicitly can lead to read/write blocking that can make your application feel sluggish or broken. Where synchronization is needed, try to use the `SERIALIZABLE` isolation level and make your application able to retry actions.

- Indexes can make or break your queries' performance, and PostgreSQL has lots of index types. Examine your query plans and take advantage of indexing to boost performance for your `WHERE`s. Sequential scans are bad because they become linearly slower as the table grows.
- Having indexes that you don’t need can slow down your table for writing and consume valuable disk space. Identify those that aren’t in use from `pg_stat_all_indexes` and remove them.
- Be careful when dropping indexes that appear unused as this statistic is for the local node only, and those indexes may be in use on another node you are physically replicating to.

7 Administration bad practices

In this chapter

- Letting disk usage get out of hand
- Missing hints of danger by not looking at logs
- Collecting and analyzing statistics
- Upgrading is not optional

After all the exciting development and optimization topics we’ve discussed, when the time comes to take the database into production, the comparatively mundane task of administration may feel like a chore. However, how you administer the database is an integral part of PostgreSQL’s robustness and reliability. It determines the success of your Postgres deployment and can make or break critical systems. We’ll now look at some mistakes Database Administrators (DBAs) may make, either through lack of familiarity or inexperience, when managing Postgres.

7.1 Not tracking disk usage

It seems hard to believe, yet it’s still one of the top issues faced by people who support PostgreSQL installations. Inevitably one day, someone will contact them requesting their help in solving the dreaded "No space left on device" error. This section could have been named "Running out of disk space", but instead what we want to emphasize here and now is that if you aren’t tracking your disk space usage you are taking a huge risk.

Let’s take a step back and look at what happens when your PostgreSQL deployment runs out of disk space. First off, which disk are we talking about? The risks associated with space exhaustion in your operating system disk are well known. Hopefully, your PostgreSQL data directory is on a different drive or partition, and let’s assume that this is what’s run out of space.

You are likely to notice something similar to this:

```
ERROR:  could not extend file "base/12609/16048": No space left o
HINT:  Check free disk space.
```

What happens when the harrowing error above appears?

It really depends on where you keep your data files and the Write-Ahead Log and if they're on the same disk volume or not. Just filling up your data disk is not a fatal error in itself, but it can certainly prevent your application from performing its usual database activities. However, if the disk where your WAL resides runs out of space, journalling and committing data changes will no longer be possible, and this can lead to PostgreSQL going into panic and shutting down.

This is most undesirable, so people will try to prevent it at all costs. Unfortunately, knee-jerk reactions may lead to missteps that can even compound the error and make matters worse.

A lifeline many may reach for at this time is to delete some old data to free up disk space. Unfortunately, because of PostgreSQL's MVCC model, this won't yield immediate results or may even not work at all. Postgres needs to write WAL for every change to the data, so you effectively need disk space in order to delete data! If you have enough disk space to run `DELETE` or `TRUNCATE`, the dead rows left behind will still require a `VACUUM` to reclaim the space. However, even then the space won't be returned to the OS but will just be marked as free space within the table's data files. `VACUUM FULL`, which can relinquish the free space back to the OS, obtains an `ACCESS EXCLUSIVE` lock on the table while rewriting it, making the table unusable during the operation — this also qualifies as a Very Bad Thing.

Opting to resize the disk volume can also turn out to be the wrong move in production, as many cloud providers and file systems need to pause all disk operations until the volume expansion operation has been completed. This may potentially cause unexpected downtime for your database. Also, be aware that the resize operation may take a very long time, so you may be better off restoring the database to a fresh server or cloud instance with more disk space.

Another quick thought will be to look for logs to delete. This has led many an inexperienced PostgreSQL user to one of the most common ways to shoot themselves in the foot:

7.1.1 Deleting the Write-Ahead Log

In the days of yore, the PostgreSQL data directory contained directories named `pg_log`, `pg_clog`, and `pg_xlog`. If you know that `pg_log` contains logs that you want to delete, it’s easy to assume that you can also blow away those "c"-logs and those "x"-logs as well. Unfortunately `pg_clog` was the directory that contained the Commit Log, which keeps track of the state of all transactions and is an integral part of the MVCC mechanism. `pg_xlog` was the directory for the Write-Ahead Log and, by this point in the book, you should already know how important the transaction log for the database is. Effectively, removing those directories nuked the Postgres installation, making it unusable instantly, and the only remaining choice would be to rebuild the database cluster from a backup.

When the PostgreSQL project realized that this was starting to happen all too often, `pg_log` was renamed to `log` to make it somewhat unambiguous, `pg_clog` was renamed to `pg_xact` and `pg_xlog` was renamed to `pg_wal`, to stop people thinking that these are "logs" that can be removed at will. Even though these directories were intentionally renamed, still to this day people manage to delete files from inside them, which is truly one of the biggest mistakes you can make with a PostgreSQL installation.

Honestly, it seems that there’s just no way to stop people from deleting files that appear useless to them because they don’t understand their function. You could say that the only thing we can do is write books about these mistakes and hope that one day these pages will get read!

7.1.2 What can eat up your disk space?

Moving on, let’s discuss what can consume your disk space gradually or suddenly. Obviously, tables and indexes will grow over time as you add more data to them, but this can be greatly exacerbated by bloat. If dead rows aren’t removed promptly, this can cause table file size to balloon out of control, and this disk space will be lost to the filesystem until it is reclaimed. Temporary files, normally used only for the duration of an operation that doesn't fit in memory such as a large sort or hash join, can also persist on disk after an improper Postgres shutdown. These temp files will then need to be manually cleaned up.

We previously mentioned that the WAL is essential to the operation of the database — however, you may be generating and accumulating too much of it on disk. If your `max_wal_size` and `wal_keep_size` settings are not optimal, this may lead Postgres to use up more disk space than is necessary. Also, if there is replication lag or failure of a standby server using replication slots, the WAL produced will accumulate locally until the standby server can receive and consume this WAL. If this goes unnoticed (and this is more common than you may think), it can exhaust all disk space where the WAL directory resides. Finally, a failure of the `archive_command` will also lead to keeping around on disk the WAL that is supposed to get archived until it can get archived successfully.

7.1.3 What can you do?

As a mitigation strategy, you can keep your database and the WAL on separate volumes (and of course keep a very close eye on disk usage on those volumes). Moreover, *tablespaces* in PostgreSQL allow you to define the storage locations for database objects, so you are effectively free to create any table or index in any directory or volume on your filesystem. Besides the obvious performance or cost-saving optimizations you can perform with the flexibility to move things around to faster or cheaper disk storage, this allows you greater control over the disk layout of your PostgreSQL installation. Finally, you can add tablespaces at will, so you can use them temporarily until you can resolve the situation with your main disk.

Arguably the most important monitoring task of a database administrator is to ensure that the disk doesn't become full ("You Had One Job"). Now that you know how your Postgres deployment can find itself filling up its drive — and what are bad reactions to this eventuality — you are hopefully more aware of the importance of monitoring disk usage at all times. Use monitoring tools of any type, set up alerts well ahead of the panic threshold, and regularly check manually for anything that looks out of place before the alerts trigger.

Tip

Some filesystems suffer performance degradation as they fill up to capacity, so it’s important to take action before your disk is almost full.

7.2 Logging to PGDATA

You may think that letting your database run out of disk space is quite a banal error — but hey, if it wasn’t something that happens out there, it wouldn’t be in this book. In case you do think that, here’s a less obvious and insidious mistake.

By default, PostgreSQL writes its log files to the same filesystem as the database itself (we call the data directory `PGDATA` for short). This may seem like a convenient default choice, but it can also lead to trouble if logs start growing unchecked. If they consume too much disk space, they can make the database run out of room, as we saw in the previous section. If you monitor your database properly you can catch this, but what if this happens faster than the DBAs can react?

One could even argue that it can form an attack vector for a denial-of-service (DoS) attack, through the intentional generation of excessive logging to purposely fill up the disk.

Let us demonstrate, assuming that somehow the following code manages to slip past application testing and QA. The developer who works for Frogge Emporium has written a simple routine — with error checking, mind you — to calculate the total energy use from all branches for the previous day and log it to the audit log. This uses a query that calculates the totals per branch with window functions, then sums up everything and writes an entry to the audit table. The code has a built-in retry capability.

Listing 7.1 Routine to log the sum of the previous day’s energy use

```
import psycopg
from datetime import date, timedelta as td

with psycopg.connect("dbname=frogge user=frogge") as conn:
```

```
try:
    while True:
        with conn.cursor() as cur:
            try:
                # I have learned my lesson about using BETWEE
                cur.execute('''WITH
                               yesterday AS (
                                   SELECT *
                                   FROM erp.energy_use
                                   WHERE reading_time >=
                                       date_trunc('d', now())
                                       - interval '1d'
                                   AND reading_time <
                                       date_trunc('d', now())
                               perbranch AS (
                                   SELECT first_value(reading
                                       last_value(reading) OV
                                       row_number() OVER w
                                   FROM yesterday
                                   WINDOW w AS (
                                       PARTITION BY branch_id
                                       ORDER BY reading_time
                                       RANGE BETWEEN UNBOUNDE
                                       AND UNBOUNDED FOLLOWIN
                               SELECT sum(last_value - first_
                               FROM perbranch
                               WHERE row_number=1''')
                total = cur.fetchone()[0]

                cur.execute('''INSERT INTO audit.audit_log
                                   (what, who, tstamp)
                               VALUES (%s, %s, now())''',
                    (f"Energy usage for {date.today() - td(da
                     + f"{total} kWh", "Frogge Emporium"))

                conn.commit()
                break
            # If this goes wrong, something must be keeping t
            # and we can just retry
            except psycopg.errors.Error:
                conn.rollback()
finally:
    conn.close()
```

So our Frogge developer runs this, and a few seconds later the database logs are riddled with:

```
2024-09-20 12:26:19.606 BST [3055342] frogge@frogge ERROR:  relat
 "erp.energy_use" does not exist at character 148
2024-09-20 12:26:19.606 BST [3055342] frogge@frogge STATEMENT:  W
                                   yesterday AS (
                                       SELECT *
                                       FROM erp.energy_use
                                       WHERE reading_time >=
                                           date_trunc('d', now())
                                           - interval '1d'
                                       AND reading_time <
                                           date_trunc('d', now())
                                   perbranch AS (
                                       SELECT first_value(reading
                                           last_value(reading) OV
                                           row_number() OVER w
                                       FROM yesterday
                                       WINDOW w AS (
                                           PARTITION BY branch_id
                                           ORDER BY reading_time
                                           RANGE BETWEEN UNBOUNDE
                                           AND UNBOUNDED FOLLOWIN
                                   SELECT sum(last_value - first_
                                   FROM perbranch
                                   WHERE row_number=1
2024-09-20 12:26:19.606 BST [3055342] frogge@frogge ERROR:  relat
 "erp.energy_use" does not exist at character 148
2024-09-20 12:26:19.606 BST [3055342] frogge@frogge STATEMENT:  W
[...]
```

Ouch, it seems that instead of `energy_usage`, which is the proper table name, they wrote `energy_use`. In this scenario, this causes the code to run indefinitely, sending a query to the database that will always fail, because it will always try the wrong table name. Every time this occurs, the error is logged to the PostgreSQL log.

If we look at the timings, there are multiple entries during the same millisecond with this same error, which makes our code a very efficient endless loop. Unfortunately, this is particularly bad for us, as something that writes to the log so fast can rapidly fill up the disk containing the logs. If the process running this query is not interrupted, it will continue until disk space is exhausted. So if you have your database on the same disk as your logs, this can cause the database to crash, as we previously saw.

However unlikely the above scenario is, it underscores the importance of keeping the logs on a separate filesystem or partition from the main database storage. This way, you can mitigate the risk of log production eating up all the disk space from your database. As additional safety measures, you should also make sure that your installation implements log rotation and enforces size limits for your logs. If you're not using your operating system's log management and rotation facilities, you can manage the size of the logs by adjusting parameters such as `log_rotation_size`, `log_rotation_age` and `log_truncate_on_rotation`. Subsequently, you will need to find the balance point between accumulating too many logs, that consume a lot of disk space and are harder to scan through, and risking the deletion of logs with useful error history and details that you may need later.

7.3 Ignoring the logs

Many believe that database logs are something you look at only if something goes wrong. Wrong! PostgreSQL's logs are not there just for post-mortem analysis — they can inform you in near real-time of what's taking place inside your database. By ignoring them, you will be missing out on crucial insights that may help you prevent serious issues down the line.

Here are a few things you may miss if you don't examine your logs regularly:

7.3.1 Bad configuration

First off, you may catch configuration errors. For example, if you find something like this in the logs it may mean that you aren't currently replicating to a standby or taking streaming backups properly:

```
2024-09-21 13:41:10.692 BST [3214372] replicator@[unknown] FATAL:
 requested standby connections exceeds max_wal_senders (currently
```

This is probably not noticeable in the application, yet it's something that requires your immediate attention, in this case checking what actual replication connections are coming into your DB server and the `max_wal_senders` limit in the configuration.

Similarly, you may find errors in the log complaining of an insufficient number of available connections:

```
2024-09-21 13:49:39.821 BST [3219655] frogge@frogge FATAL:  remai
 connection slots are reserved for roles with the SUPERUSER attri
```

This points to the fact that either you’re not giving the application the number of connections that it legitimately needs, or that potentially the application is requesting an excessive number of connections. If you remember what we talked about in Chapter 6, this may be the time to start investigating adding a connection pooler, such as PgBouncer, to your setup.

It’s not just `FATAL` level errors that you need to worry about though, here are a few cases that aren’t errors but may reveal underlying issues, such as memory configuration problems. If you have `log_temp_files` enabled, you may notice a lot of log entries that look like this:

```
2024-09-21 13:51:15.133 BST [3226458] frogge@frogge LOG:  tempora
 path "base/pgsql_tmp/pgsql_tmp3226458.0", size 8437760
2024-09-21 13:51:15.133 BST [3226458] frogge@frogge STATEMENT:  S
 FROM erp.payments WHERE tstamp >= date_trunc('y', now()) ORDER B
 amount;
```

This may mean that your `work_mem` value is set too low, and the database is having to resort to writing temporary files on disk in order to run your queries that don’t fit in memory. As we know, this can severely affect performance because of the sheer disparity in speed and latency between memory and disk.

7.3.2 Performance issues

Slow-running queries are also something to keep an eye out for, as they may point to inefficiencies causing performance problems such as badly written SQL, missing indexes, or progressive issues such as gradual performance degradation. Setting your `log_min_duration_statement` parameter to a value like 100 milliseconds will allow you to log slow query executions similar to this:

```
2024-09-21 14:17:41.763 BST [3232957] frogge@frogge STATEMENT:  S
 FROM erp.payments WHERE tstamp >= date_trunc('y', now()) ORDER B
 amount;
```

```
2024-09-21 14:17:41.764 BST [3232957] frogge@frogge LOG:  duratio
 157.096 ms  statement: SELECT * FROM erp.payments WHERE tstamp >
 date_trunc('y', now()) ORDER BY amount;
```

As this query ran for 157 ms, it crossed our reporting threshold and was subsequently captured in the log. We discussed extensively in the previous chapter how long-running queries can seriously impact your deployment's performance and reliability.

Additionally, your workload may be causing issues to surface in the logs that may assist you in troubleshooting your database and application's performance. For example, if you find evidence in the log that checkpoints occur too frequently, this will indicate that Postgres is flushing data to disk way too often, which will hurt your performance:

```
2024-09-21 14:20:27.920 BST [3260055] LOG:  checkpoints are occur
 frequently (2 seconds apart)
2024-09-21 14:20:27.920 BST [3260055] HINT:  Consider increasing
 configuration parameter "max_wal_size".
2024-09-21 14:20:27.920 BST [3260055] LOG:  checkpoint starting:
2024-09-21 14:20:27.963 BST [3260055] LOG:  checkpoint complete:
 buffers (8.3%); 0 WAL file(s) added, 2 removed, 0 recycled; writ
 s, sync=0.019 s, total=0.201 s; sync files=2, longest=0.019 s,
average=0.010 s; distance=33073 kB, estimate=37487 kB; lsn=11/837
redo lsn=11/81A37E70
```

In this case, the `HINT` is spot on, you should probably increase `max_wal_size`, but you should also investigate the reason for the disk write spike elsewhere in your system. As previously mentioned, other workload problems such as an excessively high transaction rate can also be betrayed by the presence of anti-wraparound `VACUUM` mentions in the log.

7.3.3 Locks

Locking issues captured in the log, such as deadlock errors, can also be a telltale sign of current or impending performance problems. Instead of waiting indefinitely, Postgres will terminate one of the two conflicting queries to break the deadlock. You'll then spot something like this in the log file:

```
2024-09-21 14:40:24.541 BST [3279275] frogge@frogge ERROR:  deadl
```

```
 detected
2024-09-21 14:40:24.541 BST [3279275] frogge@frogge DETAIL:  Proc
 waits for ShareLock on transaction 3810; blocked by process 3279
Process 3279214 waits for ShareLock on transaction 3811; blocked
 3279275.
Process 3279275: UPDATE audit.audit_log SET tstamp=now() WHERE id
Process 3279214: UPDATE audit.audit_log SET tstamp=now() WHERE id
2024-09-21 14:40:24.541 BST [3279275] frogge@frogge HINT:  See se
 for query details.
2024-09-21 14:40:24.541 BST [3279275] frogge@frogge CONTEXT:  whi
 tuple (1868,57) in relation "audit_log"
2024-09-21 14:40:24.541 BST [3279275] frogge@frogge STATEMENT:  U
 audit.audit_log SET tstamp=now() WHERE id=99925;
2024-09-21 14:40:24.747 BST [3279214] frogge@frogge LOG:  duratio
 20217.150 ms  statement: UPDATE audit.audit_log SET tstamp=now()
 id=500002;
```

As no "magic bullet" PostgreSQL configuration parameter can stop deadlocks, what you can do is check your application logic to find where deadlocks are possible, so that you can potentially prevent them from occurring.

7.3.4 Corruption

One of the more serious consequences of ignoring your logs can impact your data integrity — Mentions of errors such as the one below may reveal filesystem or even hardware-related problems that may initially pass unnoticed in the application:

```
2024-09-21 14:45:11.172 BST [3281235] ERROR:  could not read bloc
 file "base/16384/2613": read only 0 of 8192 bytes
2024-09-21 14:45:11.172 BST [3281235] CONTEXT:  while reading blo
 relation base/16384/2613
2024-09-21 14:45:11.172 BST [3281235] STATEMENT:  SELECT * FROM
 audit.audit_log WHERE tstamp > '2024-09-21';
2024-09-21 14:45:11.173 BST [3281235] LOG:  invalid page in block
 relation base/16384/2613
2024-09-21 14:45:11.173 BST [3281235] HINT:  This could be a corr
 issue caused by hardware problems or a software bug. Check for h
 issues and consider running pg_checksums or other diagnostic too
```

In this case, the log may have revealed the early signs of data corruption. This can give you a heads-up which will allow you to address the issue before it can escalate into a major data loss incident.

7.3.5 Security

Scanning the logs can help you catch security incidents too: The appearance of repeated failed authentication attempts may indicate brute-force login attempts:

```
2024-09-21 14:49:34.300 BST [3306179] frogge@frogge FATAL:  passw
 authentication failed for user "frogge"
2024-09-21 14:49:34.300 BST [3306179] frogge@frogge DETAIL:  Conn
 matched file "/etc/postgresql/17/main/pg_hba.conf" line 123: "lo
 all             all                                     scram-sh
```

Moreover, things such as irregular login patterns or suspicious queries, such as SQL injection attempts or unusual interest in tables that hold sensitive data, can point to an attempted or in-progress security breach.

As the volume of logging that can be output by a database in a production environment can be very large, in some cases it’s simply not practical to review everything manually. A tool that can help out with this is a log analyzer such as pgBadger, which can summarize the data for specific periods and create nice HTML-formatted reports for us. It can capture the things we previously mentioned as well as report on resource usage, and you can configure specific thresholds or patterns that will trigger pgBadger to alert you.

Note

You can find pgBadger at: https://github.com/darold/pgbadger

Even without such a specialized tool, you can still perform due diligence and scan your log files with blazing-fast UNIX utilities such as `grep`, for example by writing something like this which scours the log for lines denoting `ERROR` or `FATAL` error conditions:

```
grep -E 'ERROR|FATAL' /var/log/postgresql/postgresql-17-main.log
```

To sum up, it is essential to actively monitor PostgreSQL logs to have a full up-to-date picture of your DB instance’s health when it comes to configuration, performance, data integrity and security, and dealing with all other sorts of unexpected events.

7.4 Not monitoring the database

One would assume that any competent person or team in charge of a PostgreSQL database will have a monitoring setup. However, it has been shown time and again that this cannot be stated enough, so here we go:

If you don’t monitor your database appropriately, things WILL go wrong, and even worse, you will get no advance warning or clue that things have gone wrong. In a database that’s used in a production environment, this should be simply unthinkable because of the risk to operations that it entails, yet you can still come across databases where basic monitoring tasks have been overlooked.

If monitoring is neglected, you may not notice that your queries are slowing down and identify and resolve the performance bottlenecks that are causing this. You need to be immediately informed about usage spikes, as these can cause slowdowns that may impact user experience and subsequently lead to reputational damage.

Similarly, you should also track PostgreSQL’s resource utilization because inefficiencies or, simply, increasing loads can lead to operating near or at the limit. This again brings the risk of degraded performance or even of your database becoming unresponsive.

Monitoring is also about detecting unusual activity, such as excessive resource usage either inadvertently or purposefully, and other things mentioned in the previous section "Ignoring the logs" that can be early warnings of security threats or malicious activity.

Finally, monitoring can alert you to the need to perform maintenance tasks such as `VACUUM` and `ANALYZE`, or can highlight that your current autovacuum settings are inadequate.

Let's talk about which things you should track to ensure that your installation is adequately monitored. PostgreSQL itself offers a wealth of information, but you need to know where to look. Most monitoring tools, even if they don't come with PostgreSQL monitoring configured out of the box, will allow you to define metrics, checks and dashboards, either through customization or via plugins. Good things to track are:

- (Naturally) disk and temporary file usage
- Table and index-related metrics from `pg_stat_user_tables` and `pg_stat_user_indexes`
- Number and total size of WAL files, from `pg_stat_wal` and with `pg_ls_waldir()`
- Connections, running queries, their duration and whether they are blocked (`pg_stat_activity`)
- Replication status, with `pg_stat_replication` and relevant WAL-related functions
- Database transaction age, from `pg_stat_database`
- Backup status

More involved things that you can monitor are:

- The detailed query statistics collected by the extension `pg_stat_statements`
- Buffer, checkpointer and background writer statistics
- Locks and waits in your server
- Lower-level I/O statistics such as those provided by the `pg_statio_*_tables` and `pg_stat_io` views (available since Postgres 16)

Some general-purpose open-source monitoring tools that people use are:

- RRDtool and Cacti
- Nagios/Icinga
- Munin Monitoring
- Zabbix
- Percona Monitoring and Management (PMM)
- Prometheus for more cloud-native settings
- PGWatch

- even pgAdmin for real-time viewing

These are all easy to find with your preferred search engine. There are also proprietary solutions like EDB’s Postgres Enterprise Manager (PEM) and SaaS offerings from DataDog and SolarWinds.

PostgreSQL’s built-in `pg_monitor` role has access to most if not all important metrics. Some tools and platforms may require access to more restricted things, such as everything that’s in `pg_stat_activity`. Before granting access, you should weigh the benefits of monitoring against the interests of your system’s security.

From dealing with performance problems and preventing resource starvation to checking for backup failures and security intrusions, it is clear that monitoring is all about effectively managing the risk to your database. Murphy’s Law ("Anything that can go wrong will go wrong") and the culture of monitoring needs to be embedded in you, your team and your organization. Don’t wait until something goes very wrong to start monitoring for that eventuality, because it may be too late.

7.5 No tracking of statistics over time

Database monitoring isn’t only about notifying you of current problems to fix. Don’t get me wrong, that’s fine, but it can only tell you so much about your database’s overall "look" over time, unless you tend to keep the data around and create reports about long periods. Most monitoring tools are focused on displaying the current state and alerting, and aren’t optimized for long-term reporting that can let you "zoom out" and give you access to the bigger picture of how your database is performing in the grand scheme of things.

If you don’t keep tabs on your PostgreSQL statistics, you may miss out on insights that can help you prepare for your database’s future growth. Having a view of performance trends, usage patterns and other metrics over time can help you perform analyses and projections to make your capacity planning and scaling decisions easier and more informed.

For example, let's say that Frogge Emporium's customer base keeps steadily expanding. Without access to historical data about how the system has responded to this gradual change, it may be hard for them to predict database architecture changes or infrastructure changes that may be necessary to deal with this growth.

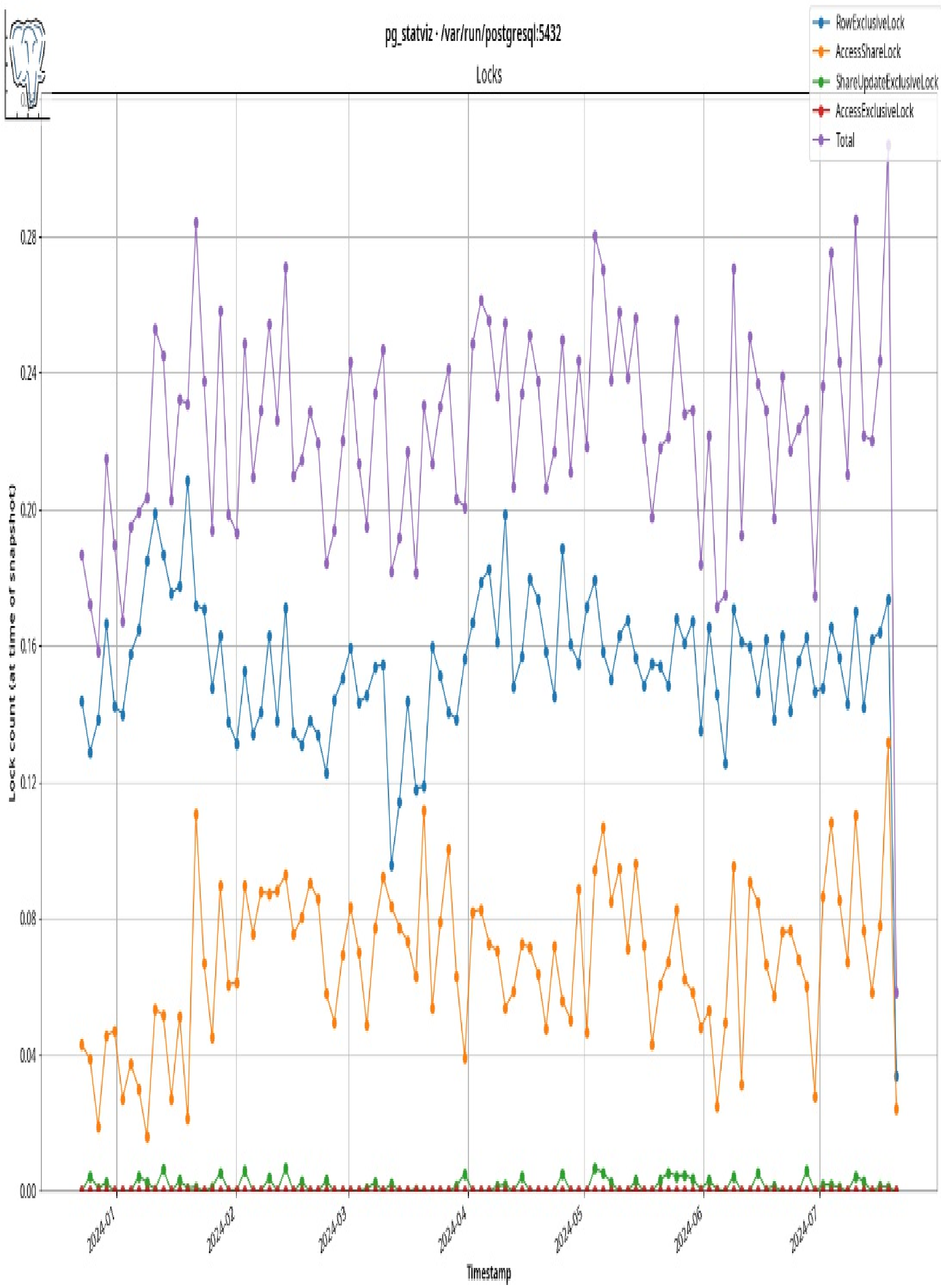
You may find a monitoring tool that allows you to track important metrics over time, but keeping around a lot of data may bring about massive storage requirements where the tool resides. In the case of proprietary tools and SaaS platforms, there are almost certainly cost factors associated with tracking many systems and accumulating lots of data from them for a long time. You may also be a fan of simplicity and use custom scripts and standard utilities for monitoring, instead of complicated tools with features you may not need.

With these in mind, I developed an extension called `pg_statviz`. It can take snapshots of important PostgreSQL cumulative and dynamic statistics so you can track their evolution over time, perform analyses and produce visualizations to aid your understanding of your server's workload. The key benefit of the extension is that it's very lightweight and does not require a module to be loaded in `shared_preload_libraries`, which means that installation doesn't even require a server restart. Secondly, it enables you to perform this analysis without the overhead of external tools or storage such as Prometheus, Logstash or Elasticsearch, or intrusive agents, such as those employed by a certain Dog of Data and others.

You can set up any job scheduler to take these periodic snapshots. With a reasonable snapshot interval of 1 minute (which is the shortest one offered by `cron`), the amount of data generated is very little, so why not keep it inside the database itself? This is exactly what `pg_statviz` does, by storing the timestamped snapshots in tables under the `pgstatviz` schema. It currently collects statistics on the background writer, checkpointer, cache hit ratio, connection count, I/O, number of tuples read/written, locks, wait events, WAL generation, transactions, configuration and others. By implementing resampling, it enables unlimited data analysis by allowing you to downsample thousands, potentially millions of snapshots down to an arbitrary number of plot points (100 by default).

The accompanying visualization utility it comes with reads from these tables and can produce graphs (output to disk as `.png` images) to let you analyze this time series data at a glance:

Figure 7.1 pg_statviz locks analysis output: This visualization displays the mean number and type of locks in the database, with snapshots taken every minute over a period of several months in 2024.



pg_statviz · /var/run/postgresql:5432
Locks
RowExclusiveLock
AccessShareLock
ShareUpdateExclusiveLock
AccessExclusiveLock
Total
Lock count (at time of snapshot)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
2024-01
2024-02
2024-03
2024-04
2024-05
2024-06
2024-07
Timestamp

You can download the `pg_statviz` extension from the PostgreSQL community repositories by installing the package `pg_statviz_extension` for Red Hat-based systems or `postgresql-statviz` for Debian-based systems. Alternatively, you can install it from *PGXN* (the PostgreSQL Extension Network). Installing it manually from source is also an option, as it requires no compilation.

You can enable the extension in the desired database by running (as a superuser):

```
CREATE EXTENSION pg_statviz;
```

As soon as the extension has been enabled, users with the appropriate privileges can immediately start taking snapshots using:

```
SELECT pgstatviz.snapshot();

NOTICE:  created pg_statviz snapshot
           snapshot
-------------------------------

 2024-06-27 11:04:58.055453+00

(1 row)
```

As mentioned previously, taking regularly scheduled snapshots is recommended and can be done with any OS or database scheduling tool, including `pg_cron`.

The visualization utility can be installed from the PostgreSQL community repos as the package `pg_statviz` for Red Hat-based systems or `pg-statviz` for Debian-based systems. It can also be downloaded from *PyPI* (the Python Package Index) as follows:

```
pip install pg_statviz
```

Its usage is as simple as:

```
pg_statviz buf --host froggeserver -d frogge -U frogge -D 2024-06
```

This will connect to host `froggeserver`'s `frogge` database as the user `frogge` and generate a visualization for the buffer statistics spanning from 23:00 on 2024-06-24 to 00:00 on 2024-06-26.

Note

The source code and documentation can be found at: https://github.com/vyruss/pg_statviz

7.6 Not upgrading Postgres

Which PostgreSQL version are YOU on? PostgreSQL's development spans over three decades and boasts both minor and major releases. **Minor** releases happen roughly quarterly, and they are the last part of your version number, i.e. 16.**4**. They fix bugs, security, and data corruption issues. They never add features or change the internal format, and the Postgres community considers not upgrading to them to be riskier than upgrading. **Major** releases are the first part in the versioning scheme, i.e. **16**.4. These bring thoroughly vetted new features, and can change the internal format of system tables and data files. As such, they don't have compatibility with the data stored by a previous major release (but you can upgrade it). In short, new major releases are what keeps Postgres moving forward. Each major version is typically supported for a period of five years, during which patches and security updates are provided.

Feature-wise, backward compatibility is almost a given. SQL is SQL, and something that was written for Postgres 9.3 will usually work with Postgres 17. The upgrade path from version to version has proven to be very reliable.

This then brings us to the burning question, why are people wary of upgrading?

First of all, the dreaded "it works fine now". You can be lulled into a false sense of stability by adhering to the tired adage "A tested and monitored system is stable". In reality, what works today may not work tomorrow if your users discover a latent bug, or if the application triggers unexpected behaviors through changing workloads or data access patterns. Also, don't forget about new security vulnerabilities that can always crop up. You should not rely solely on your own testing to ensure that the system is secure.

Closely associated is the fear of an upgrade potentially introducing problems, such as bugs, performance regressions or incompatibilities. A lack of familiarity with PostgreSQL can also be a causal factor, as DBAs may worry that they don't have sufficient knowledge to execute the upgrade without jeopardizing the system.

Finally, there are organizational reasons that may contribute to upgrade avoidance. Bureaucracy in the approval process, the need to coordinate with multiple departments, and the need for — and reluctance to schedule — downtime can all discourage upgrades.

By failing to upgrade your Postgres installation regularly, you are exposing it to significant risks. Critically, you will miss out on security-related patches. As an open-source project, PostgreSQL has the ability to issue updates to eliminate security threats, sometimes within a matter of hours — which is unheard of in proprietary software. However, if you stay on an outdated version, or even worse, one that's fallen out of support, you won't get the benefit of any of that.

The second reason why you should upgrade regularly is that bug fixes keep streaming in. Both newly introduced regressions and long-standing bugs (which can lay undetected for years) are continuously addressed. By not upgrading, you are increasing the likelihood of encountering a bug that has already been fixed in a later version.

Thirdly, you will be missing out on the newer features and performance enhancements that every new major release brings. Those that stayed on PostgreSQL 9.6 didn't get native (declarative) partitioning and logical replication. Those that stayed on version 11 didn't get `pg_checksums` or generated columns, and those that stuck with Postgres 13 didn't get throughput improvement for large numbers of connections and advanced features like the streaming of large transactions and `libpq` pipelining.

Finally, the longer you stay on an older release, the more difficult it becomes to maintain and the more complicated the upgrade path becomes.

Speaking of upgrade paths, PostgreSQL is great in that you can upgrade from one major version to another without having to upgrade to the intervening versions. However, when you do this, it is vitally important to read the release notes of every single intervening major version.

You should always read the release notes for every upgrade, even for minor version upgrades! A good reminder of why is that while release 14.4 fixed an index corruption bug, the fix required a `REINDEX` for some cases. Similarly, this release addressed a security vulnerability but the resolution could affect users of the extension `pg_trgm`.

On the subject of extensions, remember that those come with their own bug fixes and release schedules too. You should always check that the new extension version is compatible with your current PostgreSQL version.

Upgrades aren't as risky or disruptive as they are made out to be. Especially minor release upgrades involve little risk and are a good way to stay on top of the latest improvements. For major release upgrades, there are tools, such as `pg_upgrade`, that have been refined over time to the point of being considered extremely reliable (and they also have dry-run modes for sanity checking). Alternate upgrade methods, such as using logical replication for near-zero downtime upgrades, may involve more work to pull off but can also significantly reduce disruption to the deployment.

Finally, the commitment of the PostgreSQL project and its community to the reliability of the platform ensures that the upgrade path is made robust, is well-tested, and is very well documented in the accompanying release notes.

Tip

Make sure to check out the "Version and Platform Compatibility" section of the PostgreSQL Documentation for breaking changes:

https://www.postgresql.org/docs/current/runtime-config-compatible.html

7.7 Not upgrading your system

Hopefully, the benefits of keeping your PostgreSQL installation up to date are clear by now. What's slightly less obvious is that you may upgrade your Postgres regularly but leave your operating system stuck on the same release due to inertia or reluctance on the part of system administrators. It's not uncommon for production environments to stay on the same operating system major version for four or five years. Sometimes they avoid the upgrade for as long as they can get away with, only upgrading just before — or, in some cases, even just after — all support for the OS has been withdrawn. Extreme bad examples of this are Debian, Red Hat and Ubuntu's commercial offerings for support of ancient releases for up to 10 years, which is far longer than is comprehensible or reasonable.

Let us examine a real-world case where following this trend ended up affecting a production PostgreSQL deployment: A database used with the PostGIS extension for geospatial queries was exhibiting a performance slowdown which nobody could explain or account for, because it seemed to be restricted to specific values of the geospatial data being processed!

For instance, wildly inconsistent performance was observed for a PostGIS function such as `ST_DistanceSphere`, which returns the distance in meters between two points on the globe. The function seemed to be massively slower for certain pairs of data points compared to nearly identical ones, like these:

```
SELECT ST_DistanceSphere('POINT(-150 33)',
                         'POINT(-120.120120 42.488888)');
```

The above query inexplicably took more than fifty times as long to run as the one below:

```
SELECT ST_DistanceSphere('POINT(-150 33)',
                         'POINT(-120.120120 42.4888881)');
```

What's worse is that it was not possible for anyone investigating this edge case to reproduce the behavior, even when using the exact same combination of PostgreSQL and PostGIS versions. After much trial and error, someone on the team managed to trigger this condition on a test system — but only for these exact data values. This was good enough to start investigating, and profiling tools like `perf` were put to use to analyze this on a system level.

It was determined that the Postgres backend process was spending most of its time in the `libm` math library function `__mul`:

```
+   62.78%    61.29%  postgres  libm-2.23.so            [.] __mul
```

Which meant that the culprit was… a multiplication?!

`libm` is part of the broader GNU C library `glibc`, and a quick check confirmed that this behavior wasn't present on systems employing different `glibc` versions. Further investigation uncovered that some slow paths for trigonometric sine and cosine functions had been found in `glibc`. This performance problem had already been eliminated from the mathematical functions TWO years previously. However, the system in question had been using a `glibc` version that was FOUR years old.

Because a significantly outdated version was still in use, it still contained these inefficient paths and had missed out on this critical optimization. This was the cause of the hard-to-pinpoint dramatic slowdown in the geospatial math.

This underlines the importance of keeping system libraries up to date as a vital safeguard against obscure issues like this. Even when PostgreSQL and its extensions appeared to be working fine, the system library that formed the underlying dependency ended up triggering a performance bug further down the line in the software stack, making it much harder to troubleshoot.

System administrators' reluctance to update system components or Postgres itself often manifests as a misguided attempt to "maintain stability" in production environments. It is perceived that by not upgrading, the risk of introducing new bugs or downtime is reduced, as the system currently appears to be working fine. However, as shown by our example, this is a dangerous mindset because users may be exposed to lurking bugs that can manifest with new use cases or larger datasets.

Locking down dependencies for fear of potential breakages doesn't pay off, as the risk of not receiving critical bug fixes and security updates outweighs the risk of introducing a new unintended behavior which will be easy to detect and fix. Moreover, the longer updates are postponed, the more tangled the dependency chain becomes. Subsequently it becomes harder to apply all the accumulated updates, and more things have to be tested. Especially skipping minor version updates, which usually entail no functionality change or contain breaking changes, is unforgivable in a modern database environment.

7.8 Summary

- Running out of disk space can cause serious problems, so monitor your usage closely. Rash decisions like deleting what looks like logs or unnecessary files or resizing volumes can make the situation worse. Identify what’s consuming your space, and mitigate by employing multiple volumes.
- Storing PostgreSQL logs on a separate filesystem from the database helps you reduce the risk of excessive logging filling up your disk. You should also implement log rotation and enforce log size limits.
- Regularly checking PostgreSQL logs is crucial for identifying and addressing configuration issues, performance bottlenecks, data integrity concerns, and security incidents in near real-time. This can allow you to deal with problems before they escalate, and you can use pgBadger to help with the task.
- Not monitoring your PostgreSQL database can lead to undetected performance issues, security threats, and resource exhaustion that could impact its operation. By using the appropriate tools and metrics to look out for slowdowns, resource spikes, and maintenance needs, you can ensure optimal performance and mitigate risk.
- Long-term tracking of PostgreSQL statistics is important for understanding performance trends and making informed capacity planning decisions. You can use the usual monitoring tools, or the lightweight `pg_statviz` extension to capture and visualize these statistics over time without the need for heavy tooling or storage overhead.
- If you don’t upgrade Postgres regularly with minor releases, you can incur security risks or run into bugs that have been fixed. By not upgrading to the next major release you can and miss out on new features and enhancements. Upgrading is made safe and reliable by well-tested tools and thorough documentation. Don’t fear the upgrade

— fear the alternative.

- Failing to upgrade the operating system and dependency libraries as well, can lead to obscure PostgreSQL performance issues, bugs and vulnerabilities, negating the perceived stability in pursuit of which you avoided to upgrade.

8 Security bad practices

In this chapter

- Being careless with command-line password use
- Inadvertently exposing your database to outside actors
- Granting more access than necessary
- Writing and using functions insecurely

As a well-respected piece of software, PostgreSQL is renowned for taking security seriously, and its security-by-default posture. The project's Security Team is comprised of experienced contributors who assess and react to threats rapidly, through the issue of minor releases that contain the vulnerability fixes.

However, unfortunately, the majority of IT security breaches are not attributable to obscure exploits and vulnerabilities but rather more mundane reasons, such as that the system administrator hasn't changed the default credentials in the production server. When security best practices are not adhered to, there can be severe consequences like attacks leveraging privilege escalation, data breaches, and worse. What we want to address in this chapter is operator error, i.e. how sloppiness can impact Postgres security, and what you can do to prevent this.

8.1 Specifying psql -W or --password

Most PostgreSQL command line tools, like `psql`, accept the same options, such as `-h` or `--host=` for specifying the hostname of the database server to connect to or `-U`/`--username=` for the user to connect as. It's very common for users to use the `-W` or `--password` switch when connecting to specify the password for the user.

Our database administrator needs to connect to Frogge Emporium's server to perform some activities. It's something they have already done dozens of times today and are starting to find it tedious because, to connect, they've had to type in their password a lot, each time issuing this command:

```
psql -h froggeserver -U frogge -W
```

It's getting late in the day and they can feel their typing getting sloppy because of the tedium. While they're almost certain they mistyped their password, `psql` connects to the server successfully. Surprised, they think they must be a better typist than they believed they were, even when tired.

What's happened in reality, though? They had indeed entered the wrong password, yet the server let them through and accepted the connection. How can that be? Didn't they specifically ask `psql` to prompt them for a password?

This is why using the `-W` option is what we, in PostgreSQL circles, call a *footgun* or a feature that's likely to let the user shoot themselves in the foot. Using it can be misleading and detrimental to security. Why is it wrong then?

First of all, by using `--password`, you are telling whatever Postgres utility you are calling to prompt you for a password — regardless of whether one is needed by the server. To elaborate, the database server may be configured (some would say **mis**configured) to accept incoming connections without requiring a password.

As a result, our DBA is lulled into a false sense of security. Since the client is asking for a password, it's easy to assume that the server is running in password-protected mode whereas it really isn't. This means that anyone in their place could just as easily connect passwordless, and they are none the wiser because they think they are authenticating properly by entering their password.

What's more, specifying the `-W` or `--password` option is completely redundant! If PostgreSQL's authentication settings are configured to require a password to connect, the server will automatically ask for one even if you don't pass this option in the command line.

Fortunately, `-W` doesn't allow you to specify a password in the `psql` command line, as that is a significant security oversight. If you could do that, the cleartext password you typed in would be visible in the system’s processes as listed by `top` or `ps faux`. Even worse, it would be recorded in the shell’s command history. However, even though Postgres protects you against making this mistake, you should be really careful never to include cleartext passwords in connection strings in configuration or script files.

An additional issue with requiring the client to prompt for a password even when one isn’t necessary is that wrong passwords also work. Since the server doesn’t need one, it simply ignores the password sent by the client.

Finally, getting into the habit of using `-W` can result in unpleasant surprises for the user when connecting from a different workstation or client. If password-based authentication is enforced for that connection, they may be blindsided when the password they previously thought was accepted by the server no longer works. If the password wasn’t being checked by the server on their other connection, they would have thought it was correct even if it was invalid.

What’s best is to basically forget about the existence of this switch and rely on the automatic password prompt that is triggered by PostgreSQL whenever one is required. If the server is not configured to be protected with a password, this is definitely something you should be aware of.

8.2 Setting listen_addresses = '*'

Since we mentioned configuration, it’s time to look at one of the most commonly misused parameters in `postgresql.conf`, namely `listen_addresses`. It specifies the IP addresses on which the PostgreSQL server should listen for incoming connection requests. The default value for that is quite restrictive because it’s set to `localhost`. So, when our proverbial developer stops experimenting locally on their laptop and wants to try out their code on an actual database server, they find that what worked locally doesn’t let them connect over the network.

What’s the easiest way to make the server let you connect? Simple — just set `listen_addresses` to the wildcard value `"*"` which means "any address", restart the server process, and presto, you can connect. Great, right? Well, no.

The reason this scenario is not great is that this configuration change allows the database instance to accept connections coming on any of the DB server's IPs, that is, any one of its configured network interfaces.

Why is this bad? Typically, your databases will only need to be accessible from specific private networks, such as a secure intranet or a VPN connection. However, if the server has other network connections configured, such as one that is connected to the Internet, this setting will make Postgres accessible through all interfaces, including the public Internet connection. Needless to say, if your server responds to connection requests coming from a network it's not meant to listen on, this creates a larger attack surface and forms a security risk.

`listen_addresses = 'localhost'` is one of the predefined choices that are included when we are talking about PostgreSQL adopting "security by default". The configuration should default to the most secure setting possible which, in this case, is only allowing local connections on the loopback hostname and ignoring anything coming in from the network. This way, network connectivity to the database has to be explicitly enabled by the DBA.

Specifying `listen_addresses = '*'` effectively negates the default security built into the product. For a real-world example of why opting for security by default is a good idea, you should know the following:

Note

In 2020, security researchers found that a staggering **3.6 million MySQL and MariaDB servers were exposed to the Internet**.

Needless to say, you don't want your server open to potential attackers who can easily perform port scans to discover open database instances on insecure networks such as the Internet.

Instead, make sure that you are restricting `listen_addresses` to only those interfaces and networks from which clients are actually supposed to be able to connect. For instance, if Postgres should only be accessible from a private network, specify just the database server's IP on the interface connected to that network in `postgresql.conf`:

```
listen_addresses = '10.10.10.56'
```

It's also good practice to set up firewall rules that restrict access to the server instance to only trusted subnets and IPs. Many firewalls also implement logging, which can help with intrusion detection.

8.3 trust-ing in pg_hba.conf

The infamous `pg_hba.conf` is one of the most confusing and, unfortunately, feared beasts in the PostgreSQL configuration jungle. It contains the *Host-Based Authentication* (HBA) rules for the database server instance, which control who can connect, where they can connect from, what they can connect to, and how they need to authenticate for that. Its syntax is well-defined for what it's supposed to do but is sadly using a format that few will understand nowadays. This can lead to developers and administrators struggling because they have to fiddle with the entries in this file a lot to make Postgres finally accept their connections.

```
psql -h froggeserver -U frogge
Password for user frogge:
psql: error: connection to server at "froggeserver" (10.10.10.56)
 failed: FATAL:  password authentication failed for user "frogge"
```

Sometimes, out of frustration and desperation after having tried lots of combinations and seen the above message for the hundredth time, they will configure the server to just `trust` them for this connection.

This has the consequence of making the server accept their connection without the use of a password, which is frankly "fine for now", as they are finally able to connect.

Other times there is much less drama and the choice to do this turns into a learned behavior and habit for developers. To avoid dealing with passwords, `.pgpass` files, certificates, etc. they will take the easy option to allow connections with `trust` in `pg_hba.conf` to speed things along, as follows:

```
host    all     all     10.10.10.0/24   trust
```

The above entry means that **`any`** user defined in Postgres can connect to **`any`** of the cluster's databases **without a password** from the entire **network subnet `10.10.10.x`**.

"Okay, so why is this a problem?", you will say. After all, the Frogge Emporium intranet on `10.10.10.0/24` is private and only authorized persons have access to it.

What happens, though, if another device, application or piece of software on another server in this subnet is compromised? Then, as Postgres is `trust`ing all connections from that network, it will allow full access to any potential attacker with no authentication.

`pg_hba.conf` is called that for a reason. Host-Based Authentication ensures that only trusted clients from trusted hosts can connect to the server, and defines how they must authenticate to connect to specific databases.

`trust` is not an authentication method: it means "let them in with no authentication". It's dangerous and should not be used under any circumstances on machines in, or connected to, production environments as it constitutes a serious security vulnerability. Even if you use `trust` for local connections only, can you guarantee the security of every other bit of software that's running on that server?

The answer is easy: HBA `trust` should be avoided entirely. At a minimum, you should use the `scram-sha-256` password-based challenge and response authentication method to secure access to your databases, like this:

```
hostssl frogge  frogge  10.10.10.29/32  scram-sha-256
```

And while you're at it, it's not a bad idea to enforce SSL encryption and only allow access from specific users on specific hosts to specific databases, as in the above example.

"Trust" is rarely safe in any environment, let alone in production, as it bypasses essential security layers, and it can end up putting your data at risk.

8.4 Database owned by superuser

It's super common to find clusters that contain databases owned by the `postgres` user, or some other user that has been granted superuser privileges. This is not surprising, as many create those databases by simply following instructions from a post they found on StackOverflow or poor online tutorials. Alternatively, echoing a familiar theme from the two previous sections, some developer or DBA gets fed up with not being able to run all the nice DDL commands they prepared. They then end up doing everything as a superuser, including creating and owning databases. As a PostgreSQL superuser has unrestricted privileges, they can create and manage schemas, tables and all other types of database objects.

Sooner or later, someone creates a new database and makes it be owned by the superuser:

```
CREATE DATABASE frogge_next OWNER postgres;
```

Before you know it, other people are using it too, and this arrangement achieves a certain degree of permanence. Unfortunately, while you wouldn't expect to see it on production systems, it is very common to find operational databases owned by a superuser (or even worse, to find user tables and objects in production use living inside the default `postgres` database). Sometimes, you'll even find the application connecting to the database using the default `postgres` superuser account.

Let's see why this is an ill-thought-out strategy.

PostgreSQL's design is meant to encourage the application of the *Principle of Least Privilege* which advocates for granting only those permissions necessary to perform particular tasks.

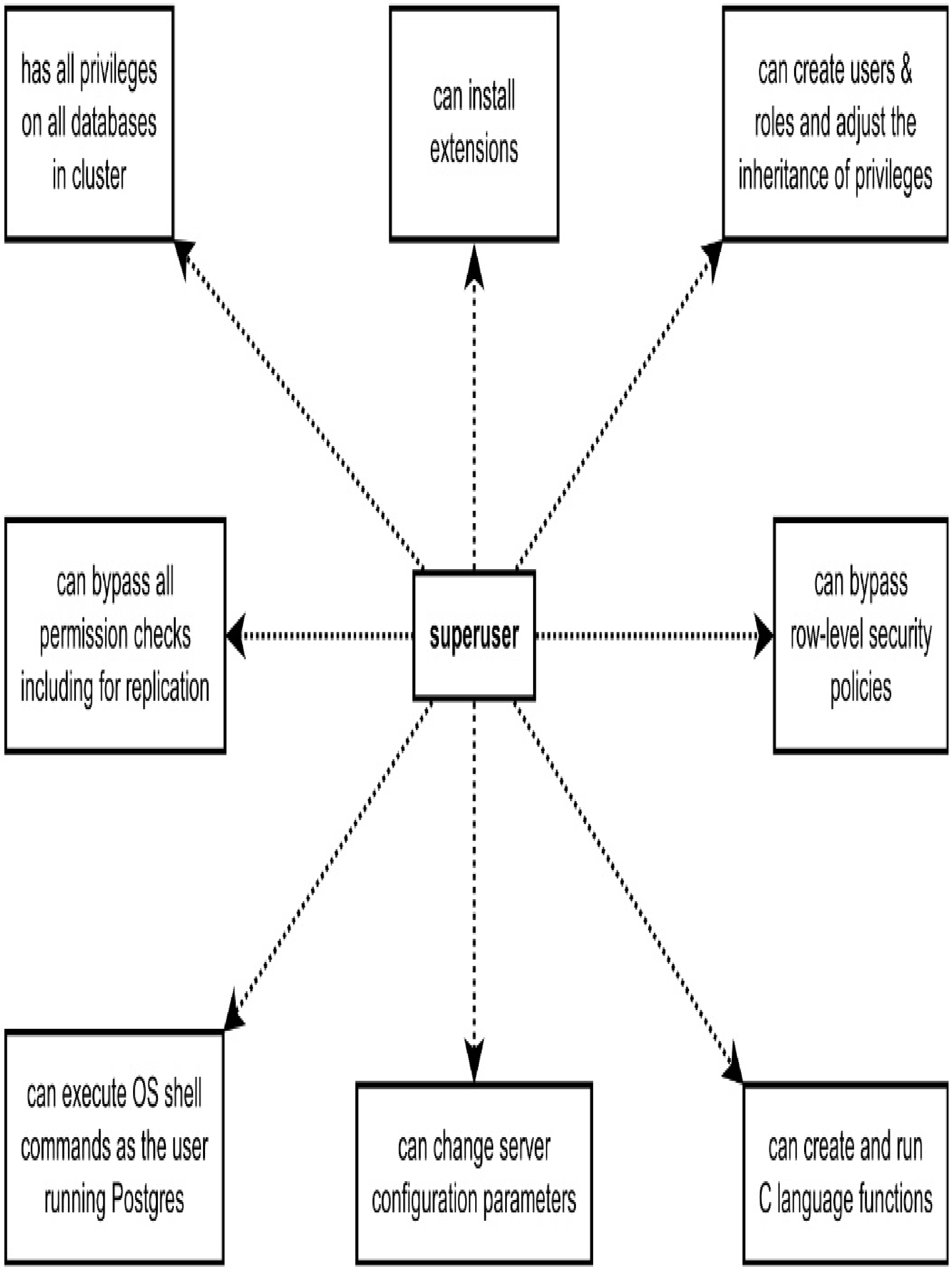
If you make the database and the objects contained within owned by a superuser, for most actions it will be necessary to access them as a superuser. Therefore, it's easy to assume that people will try to connect to this database using correspondingly privileged accounts.

The problem with this is that, in Postgres, the superuser is omnipotent and can bypass pretty much every security check. This makes using superuser accounts for regular database ownership and operations very dangerous. We can illustrate:

At some point down the road, Frogge’s new developer connects to the database with their unprivileged account `jettrodriguez`. Somehow, they manage to run a stored function called `reset_schema()`, a function that cleans out the database so a fresh copy can be restored in its place. However, it was designed by the DBA for developers to use with their unprivileged accounts in development environments only. `reset_schema` proceeds to `DROP` all tables in the current schema, and this now has disastrous consequences for the production database, as the only option is to restore the data from backup, causing significant downtime and reputational damage to Frogge.

You ask, how was this allowed to happen? The function was created by a superuser, and that superuser bestowed the rights to execute it as a superuser to anyone who uses it. As such, the function ran with superuser privileges and proceeded to wreak havoc. The unprivileged developer account DID have permission to execute functions in that database, and this function WAS visible to the account, so it was easy for disaster to strike.

Figure 8.1 A superuser, analogous to the `root` user in UNIX, can bypass all privilege checks and do more things that no other user can. It is far more dangerous than simply having all privileges on all databases.


has all privileges on all databases in cluster
can install extensions
can create users & roles and adjust the inheritance of privileges
can bypass all permission checks including for replication
superuser
can bypass row-level security policies
can execute OS shell commands as the user running Postgres
can change server configuration parameters
can create and run C language functions

As the function was created with a privileged account, allowed to run with the corresponding permissions, and provided to unprivileged users, all of the privileges pictured above became available to the unprivileged user during the execution of this function.

We'll see in the next section "Setting `SECURITY DEFINER` carelessly", how it is possible to expose yourself to malicious actions simply through improper ownership of stored functions or procedures. Even if the stored code is not supposed to be dangerous, executing a buggy procedure with superuser privileges can make the consequences much worse.

Another example: The organization has implemented Row-Level Security (RLS) policies on all their tables. A user connects with an unprivileged account that, through RLS restrictions, is not supposed to see any rows of data in those tables. The user proceeds to `SELECT` from a `VIEW` and, surprisingly, the query does return rows of data. That view is owned by a superuser and, if you remember, we said that superusers bypass most permission checks — therefore the RLS `POLICY` will not be taken into account and the view will return rows to whoever selects it.

Tip

Look up another way to protect `VIEW`s against data leaks with the `(security_barrier)` attribute in the PostgreSQL Documentation: https://www.postgresql.org/docs/current/rules-privileges.html

Therefore you need to take a step back and ask: do you really need the superuser to be involved in your database's ownership, given all the privileges a superuser has? Consider the dual risks of people connecting as a superuser to use this database and of objects having superuser privileges attached that effectively allow privilege escalation by unprivileged users. By bypassing the proper use of Postgres `ROLE`s, you are incurring the unnecessary risk of unauthorized data access and of destructive actions being performed accidentally.

Additionally, if everyone connects with the superuser account, auditing and accountability become difficult, as it's hard to track who performed what actions. Many regulatory frameworks require the enforcement of Role-Based Access Control (RBAC) and audit trails, so make sure that you use the built-in role system provided by PostgreSQL.

Most common tasks do not require superuser privileges. You should restrict the use of superuser accounts to only those administration tasks that require the added privileges and create databases and objects owned by non-privileged accounts. For every new database, you can create a dedicated database role that just has the necessary privileges to own and manage the database. Afterwards, you can `GRANT` the appropriate privileges on this database's objects to the accounts that need them.

8.5 Setting SECURITY DEFINER carelessly

In PostgreSQL, you can write code into the database backend with functions, triggers and RLS policies. As we saw, this code can be executed unintentionally, so it can become a Trojan horse of sorts.

A developer at Frogge Emporium with the username `marionjohnson` is asked by the Sales and Finance departments to create a function that returns the running total of sales income for the month, and is granted authorization to access this data. They write the function as follows:

```
CREATE OR REPLACE FUNCTION erp.current_month_sales()
RETURNS numeric AS $$
SELECT sum(amount)
FROM erp.payments
WHERE tstamp BETWEEN date_trunc('month', now()) AND now()
$$ LANGUAGE SQL SECURITY DEFINER;
```

The declaration `SECURITY INVOKER`, which is the default, means that the function will be executed with the privileges of the user that calls it. As the developer wants users from Sales and Finance to be able to execute the function, they choose to specify `SECURITY DEFINER` so that they'll be able to execute it with `marionjohnson`'s (the owner's) privileges.

It works as designed, and the departments in question are pleased, until one morning when the developer receives an angry phone call asking how everyone in the company seems to know the sales figures. You see, Frogge treated this as privileged information, and they were not expecting unauthorized employees to be able to access it. By using `SECURITY DEFINER` and not enforcing checks on who could execute this function, carte blanche was practically given to anyone who came across it.

`SECURITY DEFINER` works like the `setuid` bit in UNIX file access control. When set, it allows a file to be executed with the permissions of whoever owns the file instead of the permissions of the user executing it. It has legitimate uses for providing access to functionality that certain roles cannot perform directly themselves. For example, a trigger function that writes to the table `audit_log` — that users aren't permitted to touch — when specific actions are performed.

This is why it makes sense to keep `SECURITY DEFINER` functions as straightforward as possible to ensure that they only serve their single purpose and can't be repurposed through parameter use, side effects, or injection of logic.

Tip

Another relevant cool concept is the `LEAKPROOF` declaration in function definitions, which indicates that the function has no side effects. This means that it cannot reveal information about its arguments except through its return value. Therefore a function that throws an exception for some argument values but not for others can be considered "leaky".

To mitigate these risks, first ensure that only the roles who are supposed to can execute any functions declared as `SECURITY DEFINER`. You may do this by revoking the default execution privileges from `PUBLIC` and selectively granting the privileges to run the function, like so:

```
BEGIN;
    CREATE OR REPLACE FUNCTION erp.current_month_sales()
        ...
    REVOKE ALL ON FUNCTION erp.current_month_sales() FROM PUBLIC;
    GRANT EXECUTE ON FUNCTION erp.current_month_sales() TO sales_
    GRANT EXECUTE ON FUNCTION erp.current_month_sales() TO financ
COMMIT;
```

Wrapping everything inside the same transaction ensures nobody unauthorized can use the function before the permissions are set correctly.

Secondly, make sure that any `SECURITY DEFINER` functions are well-written, tested and reviewed, and that they validate their inputs properly. Otherwise, they may be exploited to cause data leaks or for privilege escalation purposes.

Additionally, always `SET` the `search_path` on a `SECURITY DEFINER` function to a value with a safe order (see the next section "Choosing an insecure search_path" for more details on why), like this:

```
ALTER FUNCTION erp.current_month_sales()
SET search_path = pg_catalog, erp, pg_temp;
```

Last, use `SECURITY DEFINER` only where it's strictly necessary as you may end up creating complicated permission tracking scenarios, which make managing your system's security harder.

Warning

As stated in the docs, "Functions run inside the backend server process with the operating system permissions of the database server daemon". This means that if we write a function in a programming language that permits unchecked memory access, we can write code that changes the PostgreSQL server's internal data structures. This is why languages in this category are labelled "untrusted" by Postgres, and only superusers are permitted to create functions using them.

8.6 Choosing an insecure search path

In order to save us all some typing, PostgreSQL allows us to specify unqualified object names without having to include the schema name, so we can type in the table name `customers` instead of `erp.customers`. The Schema Search Path (`search_path`) is what makes this possible, as it is the list of schema names that Postgres goes through to find the object that we're referring to.

The schemas (or schemata) are searched in their order of appearance in the `search_path`. Even if there is a table with the name `customers` in another schema that is not part of the search path, it will not match and Postgres will say that no objects with that name were found. The default looks like this:

```
SHOW search_path;
   search_path
-----------------
 "$user", public
(1 row)
```

This signifies that first, we'll look for that object in a schema with the same name as the current user. If one is not found there, we move on to the next entry, which is the `public` schema.

Unfortunately, this ordered search paired with the matching of the first item found means that you can interfere with the behavior of users' queries by accident or on purpose. To elaborate, if you have permission to create objects in a schema that is found in someone else's `search_path`, you may place your own object before the one they would normally use due to the search path order.

At the very least, this can cause confusion. For example, if a well-known function name is reused, so that `now()`, which is in fact `pg_catalog.now()`, gets overridden by `erp.now()` which gets called in its place.

At worst, someone with malicious intent could create an object in a schema that's ahead of the usual one in your search path to hijack the order in which that object name is encountered. This can trick you into accidentally reading from, or inserting into their table, or executing their code with your privileges. Because of the extensibility of PostgreSQL, this risk can extend to unexpected objects, such as operators, sequences, etc.

For instance, if you have a search path that looks like this:

```
SHOW search_path;
     search_path
----------------------
 "$user", public, erp
(1 row)
```

Someone acting in bad faith could create a function `public.current_month_sales()`, and that would be chosen over `erp.current_month_sales()`, causing you to execute their arbitrary code instead of what you were expecting to run.

This is why users nowadays don't have permission by default to create objects in the `public` schema, but BEWARE: Before PostgreSQL 14, all users had `CREATE` privileges in the schema `public`. This means that any database upgraded from PostgreSQL 14 or earlier will retain this privilege. To remove it, you can run:

```
REVOKE CREATE ON SCHEMA public FROM PUBLIC;
```

The strongest degree of protection against abuse like this can be afforded by restricting who can define objects. Users cannot access objects in a schema that doesn't belong to them unless they are granted `USAGE` privileges on that schema by the owner. They will also need `CREATE` privileges on the schema to create objects, and so on. Use roles to control which schemas each user is allowed to access and which they are allowed to `CREATE` in. In case that's not feasible, remove from the `search_path` any schemas that allow untrusted users to create stuff and make your queries refer explicitly to objects whose owners you trust.

You should also avoid overuse of the `public` schema — if you have a complicated system you should probably create separate schemas for each application component or team. If you have multiple tenants, their data can also reside in different schemas.

In general, while the `public` schema and the `search_path` offer convenience, you need to control their use carefully to avoid the risks of query hijacking and privilege escalation through object name override.

8.7 Summary

- Using `psql -W` or `--password` can be confusing and lead to lapses in security. Rely on PostgreSQL's automatic built-in password prompt mechanism instead.

- Setting `listen_addresses = '*'` can expose your database server to insecure networks, so you should only enable the trusted network interfaces that are necessary for database connectivity.
- Using the `trust` method in `pg_hba.conf` in production environments is unacceptable. You should always enforce proper authentication to your server and restrict access as much as is practical.
- Having your databases and their contents owned by a superuser can lead to security problems and accidental damage to your data. Instead, create roles that have only the relevant permissions to own and manage these databases, and grant permissions selectively to other roles.
- Declaring functions as `SECURITY DEFINER` can cause data leaks and enable privilege escalation. To reduce risk, use it sparingly and with a safe `search_path`, and prefer the combination of `SECURITY INVOKER` with explicit `GRANT`s.
- Not securing your `search_path` can let others hijack queries and escalate their privileges. Apply tight control over object creation in schemas, and reference objects owned by trusted users only in queries.

9 High availability bad practices

In this chapter

- Neglecting proper backup hygiene
- Forgoing PostgreSQL recovery features
- Being unprepared for database failure
- Using the wrong tools for the job

Another thing for which PostgreSQL has gained a reputation in the industry is its famed resilience. However, this resilience is predicated upon following best practices and using the proper tools. Dangerous situations can arise if complacency takes hold on account of "Postgres being a resilient database" and High Availability (HA) is relegated to an afterthought. Instead, HA should be central to the deployment plan of any production database cluster.

When we refer to *High Availability* in this chapter we are encompassing the techniques and methods that can keep your database accessible to its users throughout failure scenarios, from minor to catastrophic, and also allow it to recover from these failures. The goal of HA is to guarantee the minimum amount of downtime or data loss — being fully aware that the requirements and acceptable limits can differ for each organization.

Unfortunately, out there in the real world, we can find Postgres installations whose keepers neglect some (or all!) of the tenets of high availability. This may be due to misconceptions, overconfidence in hardware and software, misplaced cost-saving measures or just an outright lack of awareness of the importance of the topic. If your database suffers downtime or data loss, it will already be too late to start worrying about HA. This means that the only way to ensure that your data remains safe is to be prepared, vigilant and proactive. Now, we can take a look at how things can start to go wrong…

9.1 Not taking backups

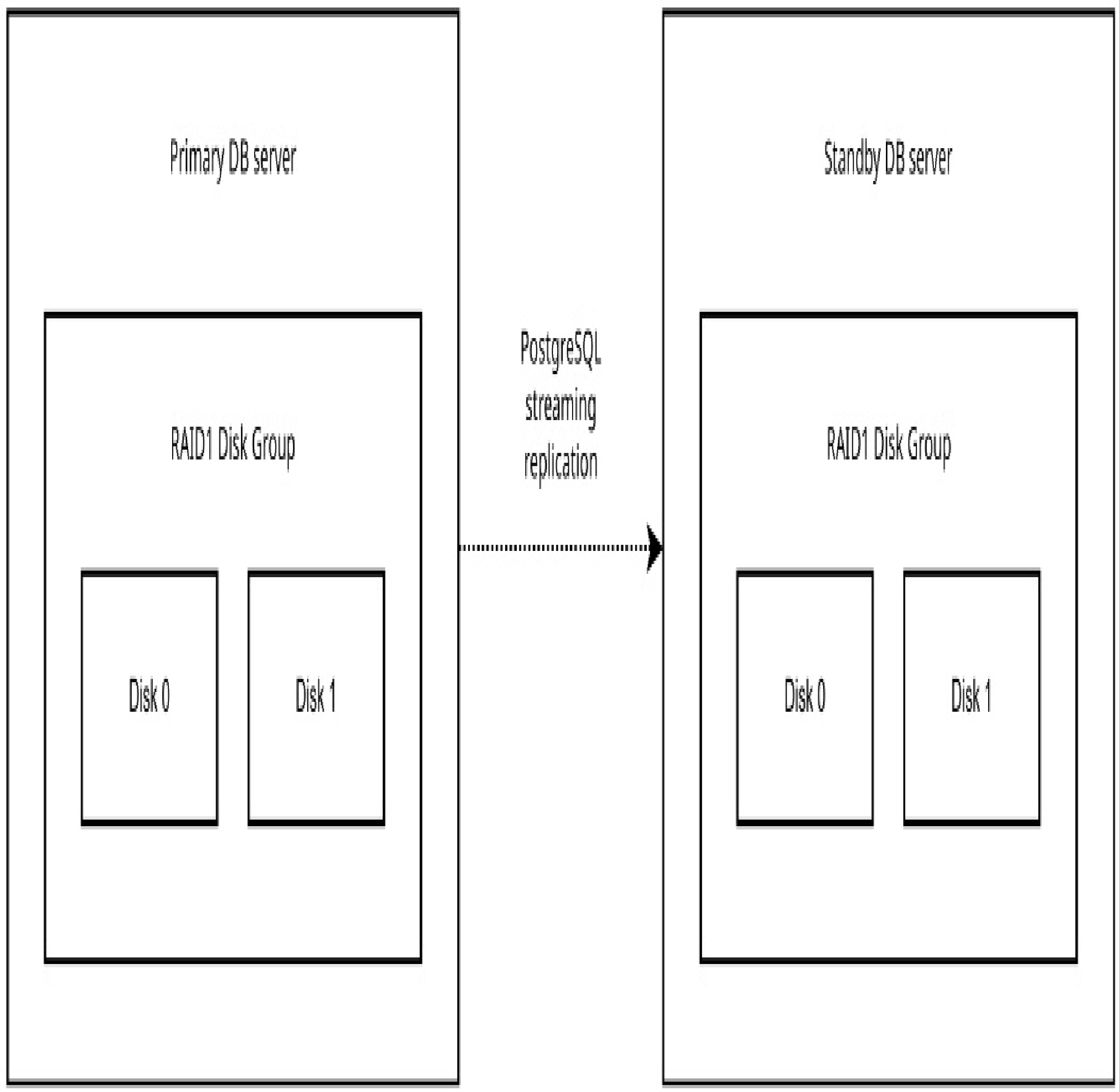
Our friendly system administrator (Not at Frogge Emporium, they have suffered enough! At some other company.) is aware of the risks associated with losing their organization's data. In order to make this outcome less likely, they have opted to go with standard solutions: the disks holding their database implement mirroring with RAID level 1 so that, even if they suffer a hard disk crash, there will be a backup drive to fall back on.

RAID

RAID or Redundant Array of Independent Disks is a storage technique that distributes the data across multiple disk devices to improve performance, achieve increased redundancy, or do both at the same time. The various disk arrangements that also specify what responsibilities each disk has in the scheme are called RAID levels. There are various levels specifying striping, mirroring and data parity arrangements, and these levels can also be combined via nesting them. In our case, RAID 1 (mirroring) stores a byte-for-byte copy of the data on other disks, and so needs a minimum of two devices.

Apart from RAID, to be extra safe, the administrator has set up a standby server with PostgreSQL streaming replication. They've got double redundancy now, so everything is rosy, right?

Figure 9.1 A PostgreSQL installation layout, demonstrating the double physical redundancy of having a standby server but also RAID1 mirrored disks in each of the servers.



Let’s see why they are not as protected as they think they are. First of all, RAID cannot protect you against filesystem corruption. If the logical file structure or data within is damaged, this corruption gets perfectly duplicated onto the redundant disks, and now you have two (or more) identical bad disks.

What if they had also enabled, through some virtualized or physical implementation, filesystem snapshots? Well, in the case of some software, snapshots may be enough to be able to restore the system to a safe state. PostgreSQL, though, is a complex system with its own write-ahead log, buffers, transaction states, segmented data files and so on. Its data integrity, as we know, depends on the WAL and data files being in a state of synchronization. It is therefore unsafe to take a file-level copy unless the snapshot is guaranteed to be atomic — i.e. a flashbulb goes off and we take an instantaneous photograph of the entire filesystem. But, even then, the result is not great because when we restore this disk snapshot and start Postgres it is just as if we had suffered a crash. So Postgres, upon startup, goes into crash recovery and proceeds to replay any committed transactions from the WAL.

You should be aware that restoring the snapshotted filesystem on top of the data directory of a running PostgreSQL instance is a recipe for disaster, because of the near-certainty of inconsistencies that will corrupt your data, so don't do that. We saw that if Postgres is stopped before restoring the filesystem it behaves as if after a crash when it starts back up, but at least any inconsistencies are taken care of. Realistically, the only safe way to take a snapshot is for the database to be shut down cleanly before taking the snapshot (or quiesced by calling `pg_backup_start()` before, and `pg_backup_stop()` after it). However, for many users, this involves an amount of downtime that they can't afford.

Warning

If the data is in multiple tablespaces then filesystem snapshots are not safe to use unless the snapshot is atomic for the sum of the filesystems in use, which is quite a tall order technically.

Moving on, let's examine why the redundancy of having a physical replica is also insufficient to protect them. Take the super simple example of the following user error taking place on the primary server:

```
DROP TABLE patient_data;
```

Some careless soul has dropped an important table in production. This immediately gets replicated to the standby server, and now the table is gone from there too. Even with superhuman speed, there is realistically no way to prevent this from propagating to the other server in time. The only way for them to get it back is to restore it from the backup that they don't have.

Even if there is no errant SQL command, replication is not a guarantee for data safety. Annoyingly, some types of corruption on the primary server (such as corruption of the WAL through a disk or memory error, or managing to run two Postgres instances on the same PGDATA) can be replicated to the standby. If the data is corrupted before it is streamed, the replica will receive the bad data.

Delayed replicas are not a solution for this class of problem. Even if you set up an 8-hour or 24-hour replication delay, what tells you that the realization that something bad has taken place won't happen 8 hours and one second after the event — or 24 hours and one millisecond, for that matter? Remember that the mistake, corruption, or malicious action may not be as immediately obvious as `DROP TABLE patient_data`.

The mistake of this organization was that, since they had RAID 1 disks, server snapshots and a redundant standby server, they felt they did not need to also take backups.

To recap, solutions at the hardware level like RAID cannot protect you against corruption occurring at any level that's above the hardware. Block-level or file-level solutions such as snapshots are also not a satisfactory backup strategy for PostgreSQL as they need to be managed and synchronized carefully in conjunction with the server process. Ideally, you need to use suitable tools to take backups that are aware of PostgreSQL's process, data file and WAL semantics so that they don't inadvertently destroy your data integrity. `pg_basebackup` is a safe backup tool that comes with Postgres for the explicit purpose of taking safe data directory snapshots — and without needing to stop the database.

Note

You can find the official documentation for `pg_basebackup` at: https://www.postgresql.org/docs/current/app-pgbasebackup.html

Finally, it is a misconception that snapshots or replication are appropriate or adequate substitutes for having proper backups, and we will see in the following section "No Point-in-Time Recovery" more reasons why this is the case. Backups give you the ability to recover your data regardless of your hardware or replication setup. Because of the high risk posed to operations, any experienced DBA should find the lack of explicit backups unforgivable.

9.2 No Point-in-Time Recovery

Our DBA has seen the light and has decided to begin backing up immediately. The time investment is seen as worthwhile, and everyone is pleased to hear that their database will be made safer. The traditional concept of a database backup involves "dumping" the data and then storing it somewhere safe, so they decide to use `pg_dump`. According to the documentation, this is "a utility for backing up a PostgreSQL database" so, as it comes with Postgres, it seems to fit the bill well.

Backups are made — `pg_dump` can only dump one database at a time so, one by one, each database in the cluster is successfully backed up. These backups are guaranteed to be consistent as `pg_dump` obtains a snapshot to extract the data, and there’s no need to interrupt database operations. A point of note though: backup consistency across two interdependent databases cannot be guaranteed while they are both running.

The `pg_dumpall` utility extends the backup scope across the cluster by essentially looping through and performing a `pg_dump` of each database. While this is convenient, and ensures that global objects common to all databases are included, the backups are still not consistent between databases.

Let’s assess where we stand now. We have safe dumps of the data that can be perfectly restored to an empty database. Great — let’s look at the problems that we mentioned in the previous section, one by one.

Are we protected against losing all our data? Yes, mostly. We can restore it at will, irrespective of what happens to our servers. The reason why it’s "mostly yes" is because we only have the data up to the point of the last backup, so while we may lose some of the most recent transactions, not all is lost. Are we safe against data corruption? Eh, again yes and no. We have a snapshot of the data, but only up to the point of the last verified safe backup. The same goes for accidental or malicious damage to the data. Even if you can pinpoint exactly when it happened, you can only roll back to the point where the last known safe backup was taken by restoring it.

This means that even if they back up their DB every day, a proverbial `DROP TABLE` executed in the afternoon would result in the loss of all data from that morning with no way to recover it. The same is true for filesystem snapshots and any full backup method, not just `pg_dump`.

This is exactly why the late great Simon Riggs introduced *Point-in-Time Recovery* (PITR) to the PostgreSQL code base some 20 years before the writing of these pages. PITR allows you to effectively roll your database back to PRECISELY the transaction you require. This means restoring to the exact point BEFORE the damage occurred because, with PITR, you are not limited to the state captured in the last full backup of the database. It can achieve this by taking advantage of the write-ahead log — after all, we do have a perfect and replayable record of each and every transaction.

To perform point-in-time recovery we leverage the combination of so-called *base backups* (produced by the Postgres utility program `pg_basebackup`) with archived WAL files. The base backups are full binary-perfect snapshot copies of the entire database cluster, not just individual databases. WAL archival is also known as *continuous backup*, because if you keep around all the WAL that's been constantly produced by Postgres since your base backup, it allows you to restore to any point in time after the base backup was taken.

All you need to do to take advantage of this is to set up WAL archiving by defining a custom `archive_command` in `postgresql.conf`, and then taking a full backup with `pg_basebackup`. Remember that base backups are snapshots in essence so it's important to note that, for PITR, you also need all the WAL generated from the moment you start the backup until it completes. Restoring is as simple as setting the `recovery_target_time` parameter to the moment you want to recover up to, and then pointing Postgres to a restored data directory. In PostgreSQL 17, a feature to facilitate backing up huge databases was introduced: incremental backups using `pg_basebackup`. These can be combined with older base backups to create full backups.

Timelines

Please read about *timelines* in the "Continuous Archiving and Point-in-Time Recovery" section of the PostgreSQL Documentation. It explains how you can travel back in time to before a transaction was committed, but also branch off into different timelines as many times as needed to pinpoint the correct moment to return to, all without overwriting or losing any data:

- https://www.postgresql.org/docs/current/continuous-archiving.html#BACKUP-TIMELINES

To return for a moment to the topic of `pg_dump`, there are other serious issues with using it as a backup tool. `pg_dump` performs *logical*, not *physical* backups. This means that it stores the description of how to recreate the database as opposed to the actual bytes of data. As a consequence, when you restore from a `pg_dump`, PostgreSQL needs to recreate on disk the binary structure of every object you are recovering. This includes indexes, which are not copied over and get recreated on-the-fly, so the restore operation can end up being quite time-consuming. Additionally, your old cluster's internal Postgres stats are lost (since this is a fresh cluster) and table statistics need to be recreated from scratch.

If you don't take advantage of point-in-time recovery, you are exposing yourself to the danger of easily avoidable data loss and possibly painstaking recreation of the missing data. PITR and continuous archival may require significant storage space because of the need to store full backups alongside any WAL generated since they were taken. Nevertheless, it is regarded as an essential feature for heavy-workload systems and enterprise usage where high reliability is critical.

9.3 Backing up manually

So, following on from the previous sections, the diligent DBA has resolved to back up the database every day, taking control of the situation personally as it's such an important process. However, it's one of the facts of life that everyone needs a day off eventually. One Monday morning comes around and the administrator isn't there to take a backup. Instead, they are basking in the warm sun at the beach on a well-deserved vacation.

Is this the mistake?

No! The diligent DBA has dutifully delegated this deed to a developer. Said developer indeed comes in on Monday morning and proceeds to take a database backup every day for the rest of the week while the DBA is away.

When the DBA comes back the following week feeling all refreshed, they take a look at the server and are horrified to discover that the developer had saved the backups of the PGDATA location `/mnt/pgdata` inside a directory called `/mnt/pgdata/backups`! Not only is this not the proper backup location but, even worse, it's on the same filesystem and physical drive as the database. Disaster was averted, but only narrowly because the organization was lucky enough to not suffer a server failure during the DBA's absence.

This should teach us two things. First of all, don't keep the backup on the same physical hardware as the database — we all know that hardware eventually fails. Some would take this further and mandate that there should always be an offsite copy of the backups, in case the whole site catches on fire or otherwise.

The second lesson here is that nobody should rely on manual processes to safeguard their data. Humans make mistakes, they get distracted or forget, they miss work, they leave on holiday or for another job. They may take the backup at a different time every day or even skip a day. Worst of all, sometimes they tend to keep all the knowledge of the backup procedure in their head so it isn't written down anywhere. I think we'll all agree that all this variability and uncertainty has no place inside an IT system.

The key to good backup hygiene is to remove the human factor and rely on automation. The ideal here is to have a non-interactive system that automatically takes regular backups of the database — and of course, this should be monitored in case it also fails for some reason. At the same time, you should take advantage of continuous WAL archiving for point-in-time recovery purposes.

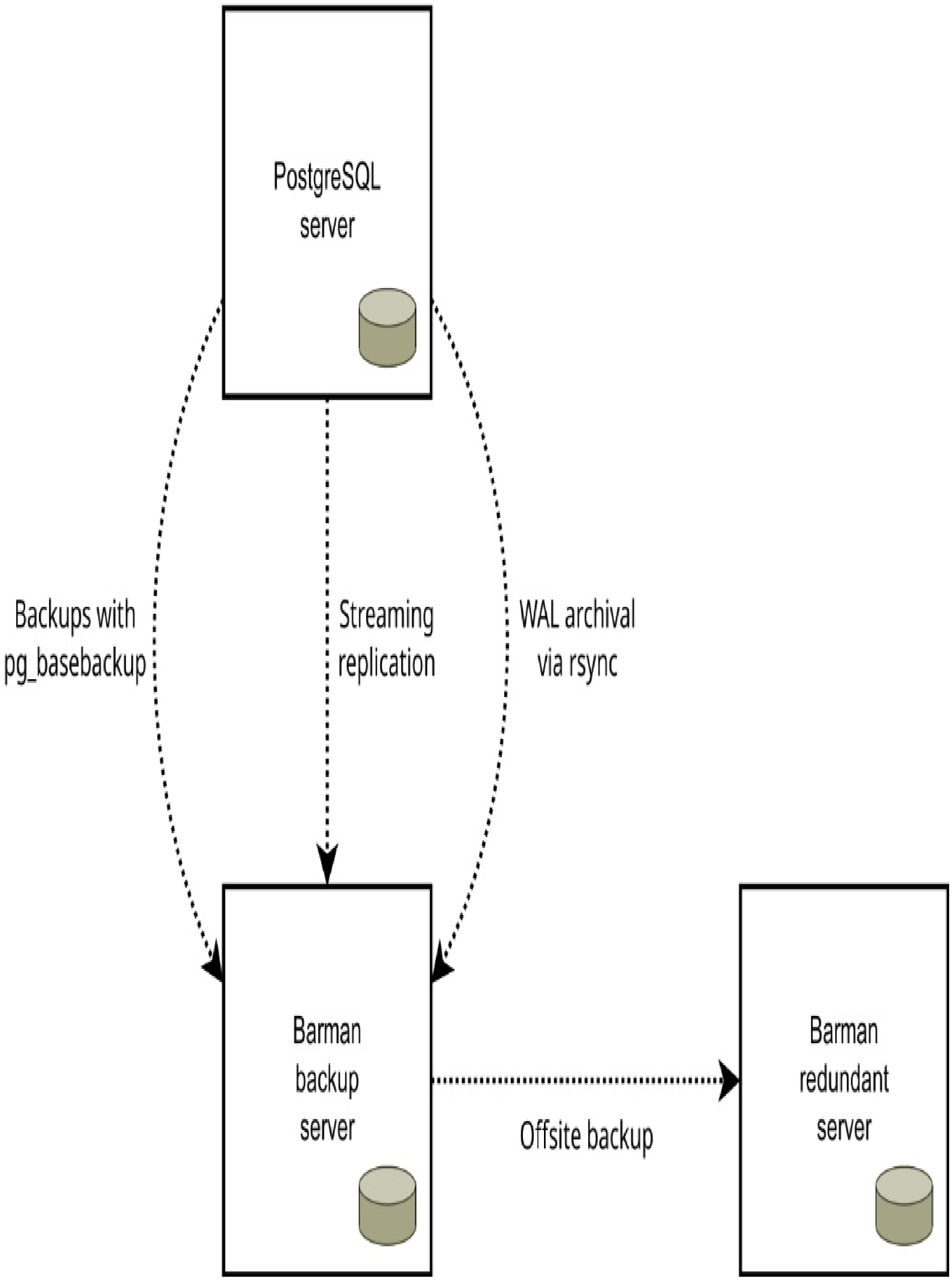
Warning

Beware that you can’t mix and match logical and physical backups — you can’t perform PITR with a `pg_dump` backup and a bunch of WAL files.

You can use any tool that comes with PostgreSQL and set up an automatic schedule for your backups using a reliable task scheduler such as `cron` which is available on any UNIX system. The two most popular dedicated open-source tools are *Barman* (Backup and Recovery Manager) and *pgBackRest* (Postgres Backup and Restore). These make PITR easy and support advanced scenarios such as complex schedules, backing up multiple servers, multiple locations for redundancy, retention policies, a choice of transfer methods, and parallelization. Setting them up is as simple as installing the packages and adding a couple of lines in their respective configuration files.

You could craft a backup architecture that looks something like this:

Figure 9.2 A sample PostgreSQL backup setup with a dedicated Barman server and geographical redundancy, showing the possible transfer paths.



PostgreSQL server
Backups with pg_basebackup
Streaming replication
WAL archival via rsync
Barman backup server
Offsite backup
Barman redundant server

So you could back up your cluster with Barman automatically using `pg_basebackup` to pull base backups and a replication connection to pull in WAL for PITR. Alternatively, Barman could set up an `archive_command` that sends the WAL using `rsync`, which allows the parallel transfer of multiple files, as a way to deal with huge WAL production.

Note

You can find these PostgreSQL backup tools and their documentation here:

- Barman: https://pgbarman.org/
- pgBackRest: https://pgbackrest.org/

Finally, besides being error-prone, manual processes don’t scale well — you can’t reasonably expect someone to perform frequent backups of dozens or hundreds of database servers, which is a realistic number for large operations these days. Now, admittedly, this mistake is not PostgreSQL-specific or even database-specific, but it happens in the industry more than you would like to think. It’s simply inexcusable to take backups manually with such an abundance of backup tools, schedulers and facilities to automate backing up in the PostgreSQL ecosystem. You can go so far as to say "A backup that is not automated is no backup at all".

9.4 Not testing backups

This one is, again, one of those that you cannot repeat enough times. There have been infamous incidents involving important names in the industry where data was lost because, even though a backup did exist, too much faith was placed in it working properly.

Let’s imagine that all the previous advice from this chapter has been adhered to, and backups are being taken from Postgres in an automated fashion, stored safely in two locations, along with all the necessary WAL to enable point-in-time recovery. The time comes for the server to blow up, and the DBA obligingly brings out the backup to restore the database. However, Murphy’s Law strikes again, and the backup doesn’t work: the restore command fails. Now, they have no database and no backup to restore one from. You could say that the situation is somewhat bad.

How can it all go so wrong? There's ample potential for failure here:

- The backup may be broken at the source, i.e. an incorrect invocation of the command producing an unusable backup.
- The backup process creates a usable backup, but the storage medium corrupts its data at some point.
- The backup succeeds, but there's something wrong with the storage location and it loses the backup after it's been placed there.

How can you be aware that something like this has happened? After all, the backup process produces no indications or hints about these eventualities.

The answer is TESTING — the only way to make 100% sure that your backups are available and working correctly is to attempt to restore them!

The stakes here are high: after all, the backup is what is supposed to save you from data loss, only for it to fail when it's needed most. If you don't want this to happen to you, it is a necessity and an absolute no-brainer to test the backups that you make. After all, commands can go wrong, software can malfunction, disks can fail, networks can go bad and so on.

You can test your PostgreSQL backups by using a testing environment to restore them. Alongside the backup itself, you'll be testing the recovery procedure too, so this forms a useful "fire drill" for you and your team in the case of an actual emergency. Here is an example of how to test the backup by restoring it to a fresh Postgres instance:

1. First, you need to copy the base backup to the testing PGDATA target directory
2. Verify the base backup's checksums with `pg_verifybackup`
3. Copy the rest of the WAL produced since the backup into the test PGDATA
4. Call `pg_waldump` on the WAL files to verify that they are parsable
5. Start Postgres from the testing PGDATA directory to recover the database and verify that it can reach a consistent state

For the ultimate peace of mind, you can go through every page in the restored database to make sure that it is correctly readable. It just involves using the `pageinspect` module to loop over every page of every relation. You read it from the disk with the `get_raw_page()` function, check its header with `page_header()` and verify its checksum with page_checksum().

Note

You can see how to use the `pageinspect` functionality at: https://www.postgresql.org/docs/current/pageinspect.html

The backup verification procedure is also a prime candidate for automation, and you should have it alert you if any errors are encountered along the way.

We will now wrap up with a true story from the field that shows how scary things can get if you don't stick to these best practices. A company that was a market leader in its field had grown organically over many years. Since the beginning, they had been using PostgreSQL for their database, which was central to their operations. It is fair to say that the company could not exist without this database as it contained critical data for the services the company provided. One fair day, their database server blew up — the hard disk malfunctioned.

They were aghast to discover that their backup was unusable and that their last usable backup was many months old, making most data irrelevant to current company operations. Ever since they were a small startup, this company had been taking backups (good) with `pg_dump` (bad because, since then, PostgreSQL had gained the features of streaming replication, base backups and point-in-time recovery, and they should have been using those). This is another reason why you shouldn't use `pg_dump` as a backup tool, even with full automation configured. If you rely on scripts written decades ago instead of using a dedicated backup utility that gets updates and fixes, you are taking a huge risk. User-created scripts can silently fail, for whatever reason — and this is exactly what happened in this case. The script the company had always been using for backing up stopped working at some point, and they were none the wiser. It may be that your ever-reliable script no longer works when it is moved into a virtualized environment or when run inside a docker container, Kubernetes pod, etc.

The only reason this was not an extinction event for the company was that they had at least one ancient backup, but it was surely a near-extinction event and a wake-up call. Fortunately, they were able to recover most filesystem contents from the broken disk but with no recognizable structure. Eventually, I painstakingly reconstructed their entire database with no data loss, but the rest of this story is long and for a different type of book.

In a callback to the previous section, you can go so far as to say "A backup that is not tested is no backup at all".

9.5 Not having redundancy

We’ll now examine the case where the backup strategy is just perfect: Frogge Emporium is using the proper PostgreSQL tools, takes regular automated backups and tests them automatically as well. They feel pretty well-protected now, and their operation is not at risk — or so they think.

What happens if the server catches on fire? They’ll have to procure a new server to restore the backup into, and that can take time. This can of course be mitigated by having a spare server around, and this is exactly what cloud computing resource providers do. Even if they’re using a hosting service provider, they’ll have to restore the whole database installation into an empty physical server or a newly created cloud instance.

Although this takes a lot less time, the downtime is still significant, and here’s when we start talking about the disaster recovery terms *RPO* (Recovery Point Objective) and *RTO* (Recovery Time Objective). RPO is how much data can we afford to lose in a theoretical disaster scenario — we’ve got that handled pretty well, with point-in-time recovery capable of restoring our data up to the last transaction that was committed in the last WAL file that we were able to save. RTO, however, is how much downtime you can afford before service is fully restored, and this is entirely dependent on our high-availability architecture.

PostgreSQL high-availability features and a bit of history

Replication has been a core part of PostgreSQL’s high availability architecture since the time of log shipping, when this was achieved with continuous archiving, by copying WAL files to the other server through the `archive_command`. Starting with PostgreSQL 8.2, this introduced the concept of *warm standby* servers that were ready to take over from the primary server at the drop of a command.

With the introduction of *streaming replication* in PostgreSQL 9.0, WAL started getting automatically streamed asynchronously to the other server. This enabled warm standby servers to have more up-to-date data than was possible by copying whole WAL files and therefore opened the door to being able to use those servers to serve data as well. The capability of connecting to a standby server to run read-only queries is known as having a *hot standby* (another Riggs feature).

PostgreSQL 9.1 allowed *synchronous replication* — by performing the streaming of WAL synchronously, standby servers were guaranteed to always be up-to-date with the primary by having exactly the same transactions committed. This eliminates any potential to lose data that hasn't been streamed to the standby because of replication lag but introduces a latency penalty (because of the roundtrip to ensure the transaction is written on both sides).

In version 9.2, the ability to *cascade* replication or stream from a standby server to another standby was added. By using a standby to relay, you can offload and reduce the number of replication connections that the primary needs to handle.

Replication slots came with Postgres 9.4, and they solved the problem of WAL being removed by the primary before it can be consumed by a standby by guaranteeing that WAL remains on disk until it can be streamed to the last standby that needs it. This, however, introduces the potential problem of accumulating WAL on disk indefinitely for an unresponsive or missing standby.

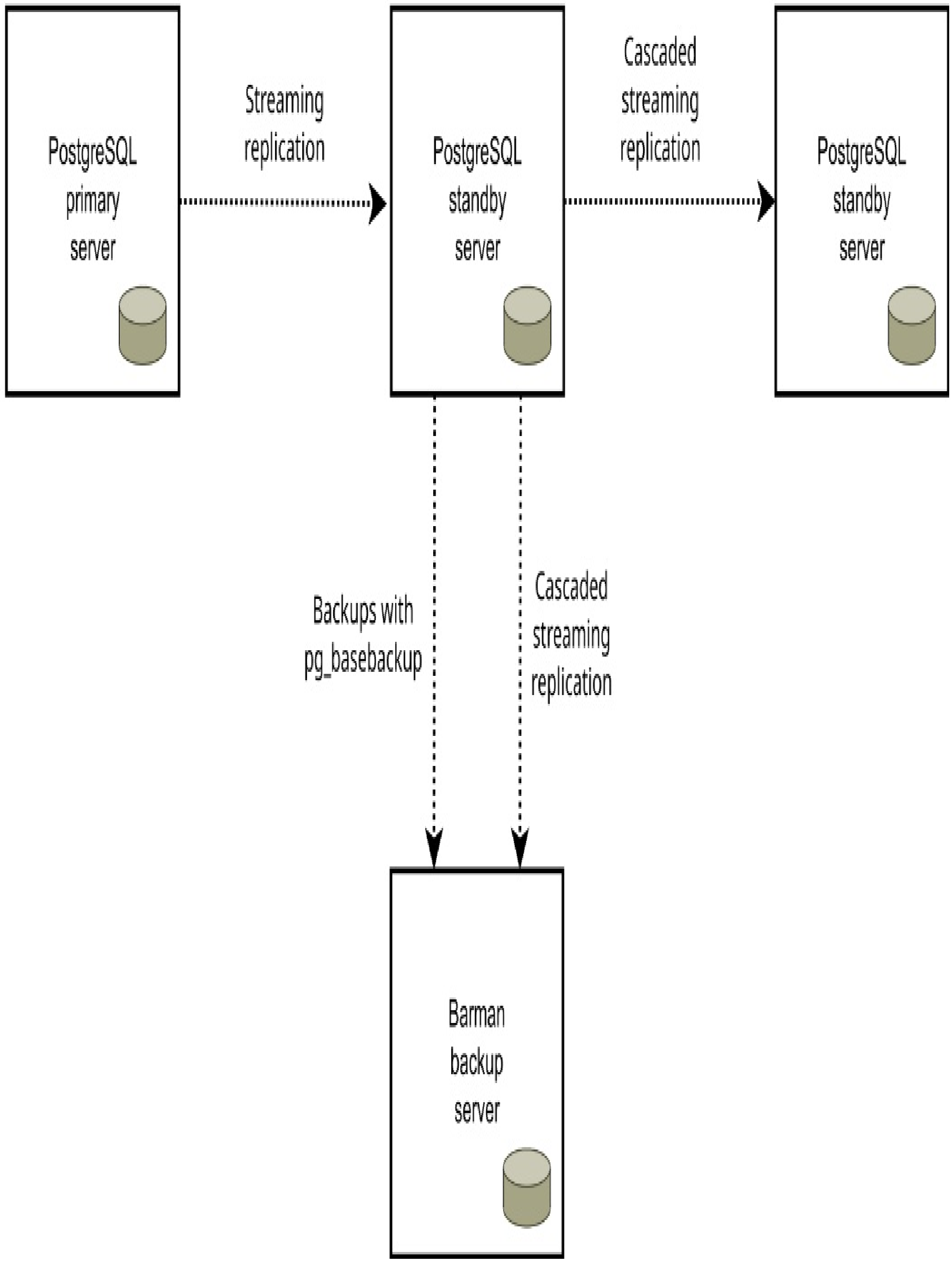
Release 9.5 introduced continuous archiving in standby, so replicas could have their own separate WAL archive. Finally, PostgreSQL 10 introduced native logical replication, but this capability's main use is not for guaranteeing high availability.

With a plethora of built-in high-availability configurations at our disposal, PostgreSQL can cater to almost every HA scenario. Restricting yourself to a single node makes no sense in a production scenario if the database is at the center of your operations. At the time of writing these words, tolerating an RTO of whole days is almost unthinkable, and most scenarios permit an RTO of minutes or seconds. For very demanding applications, there even exist solutions that allow PostgreSQL *failover* in the range of milliseconds. Remember that PostgreSQL is a single-master system, and you can’t have two primary servers for your databases at the same time. Failover is the process of *promoting* a standby to become the new primary server. We will further discuss failover mechanisms in the section that follows, "Using no HA tool".

By taking advantage of data replication to have server redundancy, your database is much less vulnerable to events such as power outages or damage to hardware or even the data center location where said hardware is hosted. Not having to wait for backups to be restored, and being able to just switch to another server and continue as normal, can make a huge difference for your organization: just imagine the amount of money a bank or trading firm can lose in seconds if their system is not available. For reference, the SWIFT banking system handles about 11.5 million international payments each day. Given an average payment size of $45,000 USD, this means nearly $6 million is transacted EVERY SECOND. Besides revenue loss, also consider the reputational harm that an organization suffers when their service is unavailable. Remember the number of times you’ve been frustrated with the social media app on your phone when it says "Sorry, something went wrong" instead of showing you wholesome pictures of cats — you’ve experienced downtime from the user perspective.

Depending on your requirements, this might be a highly-available system that you can build:

Figure 9.3 A sample PostgreSQL HA setup with a cascaded replication setup for redundancy and backup.


PostgreSQL primary server
Streaming replication
PostgreSQL standby server
Cascaded streaming replication
PostgreSQL standby server
Backups with pg_basebackup
Cascaded streaming replication
Barman backup server

In the configuration pictured above, we see that, instead of two, we have three database servers. If you don’t want to compromise your redundancy while one server is down for maintenance or because of permanent failure, you will need a second standby. To avoid putting extra replication and backup load on our primary, we have configured cascading replication from the first standby to both the second standby and the backup server.

Quick recovery from failure is something that almost everyone who uses PostgreSQL professionally needs, and providing redundancy is the best way to achieve this. Implement streaming replication and keep one or more standby nodes around — as a bonus, you can use them to offload your read traffic.

9.6 Using no HA tool

Just as with backups, your high availability setup can greatly benefit from automation. Consider the following case: Frogge Emporium engineers have written custom failover scripts to automatically promote a Postgres standby server when the primary goes down for whatever reason. They’ve tested them extensively in the lab and have confidence in the script logic. The lab, though, isn’t like the real world, and they haven’t accounted for replication lag. One of the replicas may be lagging, and can you guess what will come next if the primary fails and the lagging replica happens to be the one that gets promoted?

What will happen is that the other replica(s) will have received more transactions through the WAL than the new primary has. When the lagged replica is promoted to become the new primary, it will be missing these transactions. This will necessitate a complicated procedure to extract the missing transactions from the replicas that have them and re-integrate them into the primary’s timeline and data. Otherwise, the expected recovery point objective (RPO) may not be met. Even worse, this bit of extra WAL will not be compatible with the new primary’s timeline, as the timelines diverged upon promotion. As a consequence, none of the other replicas will be able to follow the new primary without having their WAL *rewound* back to a point before the timeline split. By the term *"follow"*, we mean being able to continue to receive WAL and replay it from that point onwards. *"Rewinding"* is simply returning to an earlier point, respectively.

This is why, instead of rolling your own HA code that needs to account for every corner case, you shouldn’t reinvent the wheel but instead trust solutions written by experts who have considered every possible failure scenario and tested their HA software against it.

Let’s check out another such scenario. Between the two datacenters that contain the primary and standby nodes respectively, we get a network disconnection for a few minutes (what we call a *network partition*). Frogge’s promotion script on the replica node detects that the primary is down (because it is unreachable) and decides to make the replica the new primary. However, the original primary node is still working fine and accepting writes, because it’s just the connection between itself and the standby that has failed. When network connectivity is restored, we’ll have two Postgres nodes acting as primaries, with diverging data. This phenomenon is known as a *split-brain*, and the data inconsistency between the nodes needs to be manually resolved, as above.

A dedicated HA tool is better because it can detect and handle such failures using mechanisms like witness nodes, quorum and fencing to prevent split-brain. HA tools have awareness of the entire database node cluster and every instance’s state and WAL position, which is something that PostgreSQL doesn’t yet do by itself. For this reason, they can effectively coordinate failover and automatically enforce the consistency of WAL timelines using tools such as `pg_rewind`. Some HA tools can even automatically clone standbys from the primary or a backup and integrate them into the HA cluster with a single command. Moreover, most have built-in script hooks and other facilities for monitoring, alerting and conditional operations — such as reconfiguring PgBouncer to reflect the cluster’s new state after a failover.

You can lean on solid open-source solutions like RepMgr (pronounced "rep manager", short for replication manager) and Patroni (pronounced pat-roe-knee) to set up and take care of your high availability cluster with tested failover mechanisms. For the use of PostgreSQL with Kubernetes, there is the CloudNativePG operator, which leverages built-in Kubernetes HA patterns to provide failover, promotion and backup logic that is appropriate for Postgres.

Handling failover and ensuring consistency manually is difficult, susceptible to human error, and may require more time than your organization can afford because of its high availability requirements. Equally, custom scripts often cannot capture the nuances of proper PostgreSQL failover logic and timeline semantics or handle edge cases. Your architecture can be made more robust by taking advantage of the tested features of established HA tools, and you’ll be better equipped to avoid inconsistency, downtime and data loss.

9.7 Summary

- RAID and filesystem snapshots can’t help you reliably recover from corruption, human error or malicious activity. The best way to guarantee your data is safe is to take backups using appropriate tools like `pg_basebackup`.
- Taking full backups only makes you vulnerable to data loss between backups. Leverage Point-in-time recovery with continuous archiving to be able to restore your database to the point before it was damaged.
- Taking backups manually is not robust or reliable, you should instead schedule automated backups, preferably using dedicated software that is PostgreSQL-aware (such as Barman or pgBackRest) and ensuring that you have a redundant copy of the backups in a second location.
- Untested backups can fail when you need them the most so to ensure that they work correctly always attempt a full restore to test your backups. Do not rely solely on automation but verify every step. Avoid using homegrown scripts and prefer tried-and-tested solutions.
- Having a single database server with no provision for failover inevitably leads to downtime. Ensure redundancy by setting up standby nodes via replication.
- Manual failover or custom scripts are risky because of the potential for extended downtime, data divergence or loss. Prefer proven high availability tools such as RepMgr, Patroni or CloudNativePG for Kubernetes to ensure reliable and effective management of your HA cluster.

10 Upgrade/migration bad practices

In this chapter

- Skipping upgrade versions (and their release notes)
- Not testing thoroughly before an upgrade or migration and what can happen
- Accounting for differences between different database types and versions

Upgrading PostgreSQL is pretty easy, while migrating from another Relational Database Management System (RDBMS) to PostgreSQL may be slightly trickier. Both, however, are critical steps that require careful preparation and cannot be taken lightly. If something goes wrong, the upgrade or migration can result in performance issues, outages or even data corruption. Mistakes and oversights can come from misunderstanding the upgrade process for databases in general and PostgreSQL in particular

10.1 Not reading all release notes

We mentioned back in Chapter 7 that PostgreSQL offers great backward compatibility, and that you can generally count on code written for an old Postgres release still working fine on the latest version. For this reason, as well as a conscious decision on the part of the developers, Postgres doesn't generally impose restrictions on upgrading. This means that you can usually skip versions provided there is no chasm between them, like upgrading from a release a decade older. For example, you could upgrade from version 13 to 16, and the upgrade path would usually be very reliable and worry-free.

Our proverbial DBA decides to do just this to take advantage of the new features and performance improvements offered by the latest and greatest, so an upgrade from PostgreSQL 13 to 16 is scheduled and performed. As expected, the upgrade procedure went smoothly, and even though the company arranged for a maintenance window of 30 minutes, `pg_upgrade` made quick work of the task and they were able to finish the upgrade in just a handful of minutes.

All is well until strange things start appearing in the database. Specifically, the loyalty discount applied to gym subscriptions seems off since the upgrade, and the accounts team is asking why. The company offers 1/3 of a year free for loyal gym customers when they sign up for another full year. To illustrate, someone signing up on `2024-01-01` would get a subscription that ended on `2025-04-01`. However, the account team has now noticed that the same subscription beginning on `2024-01-01` would now end on `2024-05-01`, giving the customer an extra free month. The application code around loyalty discounts hadn't changed, so the DBA found the discrepancy very strange indeed and decided to investigate.

The relevant code fragment looked like this:

```
IF existing AND fullyear THEN
    expiry = expiry + '0.333 years';
END IF;
```

Just for existing customers renewing for a full year, this snippet idiomatically adds a third of a year to the subscription expiry date (don't ask — the marketing department operates in mysterious ways).

To verify the discrepancy, the DBA writes this short test:

```
DO $$
DECLARE
    existing boolean; fullyear boolean; expiry timestamptz;
BEGIN
    existing := true;
    fullyear := true;
    expiry = '2025-01-01';
    IF existing AND fullyear THEN
        RAISE NOTICE 'Expiry date: %', (expiry + '0.333 years')::
    END IF;
END $$;
```

This sets `existing` and `fullyear` to `true` and it assumes an original expiry date of `2025-01-01`. The DBA proceeds to run this on a PostgreSQL 13 instance:

```
NOTICE:  Expiry date: 2025-04-01 00:00:00+01
DO
```

This works as expected. Now the DBA runs the same code on a PostgreSQL 16 instance:

```
NOTICE:  Expiry date: 2025-05-01 00:00:00+01
DO
```

This verifies that the result has changed between Postgres 13 and 16! But how and why? After painstaking research in the documentation, the DBA finds the answer: In the section about the `interval` type, the PostgreSQL 13 documentation states:

> Fractional parts of units greater than months are truncated to be an integer number of months

whereas the Postgres 16 documentation says:

> Fractional parts of units greater than months are rounded to be an integer number of months

This single word change, from "truncated" to "rounded" makes all the difference.

To illustrate this further, the DBA runs a more granular query. First, against a PostgreSQL 13 instance where they observe:

```
postgres=# SELECT 1.333*12 as months, ('1.333 years'::interval) a
 months |    months
--------+---------------
 15.996 | 1 year 3 mons
(1 row)
```

And then similarly against a PostgreSQL 16 instance:

```
postgres=# SELECT 1.333*12 as months, ('1.333 years'::interval) a
 months |    months
--------+---------------
 15.996 | 1 year 4 mons
(1 row)
```

Now the difference is obvious and aligns with the explanation in the documentation. A 15.996 month subscription was being truncated to 15 months prior to upgrade, and now is being rounded to 16 months post upgrade.

The DBA read the PostgreSQL 16 release notes but there was no warning about this! However ill-advised adding an `interval` of "a third of a year" to a `timestamptz` may be on the part of the untroubled developer, that is exactly what they were asked to do by the product manager, who in turn was asked by marketing.

Here, the fault lies with the DBA. What they should have done is read all the intervening major release notes to identify the changes made between Postgres 13 and 14, 14 and 15, and finally 15 and 16. Even though skip-upgrading is possible and even desirable, due diligence dictates that you should go through the entire set of release notes. If our DBA had done this, they would have discovered that this change was introduced with PostgreSQL 15, and they would have saved time and effort.

The performance and behavior of PostgreSQL features can change in subtle ways between major releases. In this case, the fractional interval specified in years was previously getting truncated, resulting in an expiry date of April 1st, whereas from version 15 onwards it is getting rounded to the nearest month, giving us an expiry of May 1st.

The PostgreSQL 15.0 release notes from 2022-10-13 state:

```
When interval input provides a fractional value for a unit greate
 months, round to the nearest month (Bruce Momjian)
```

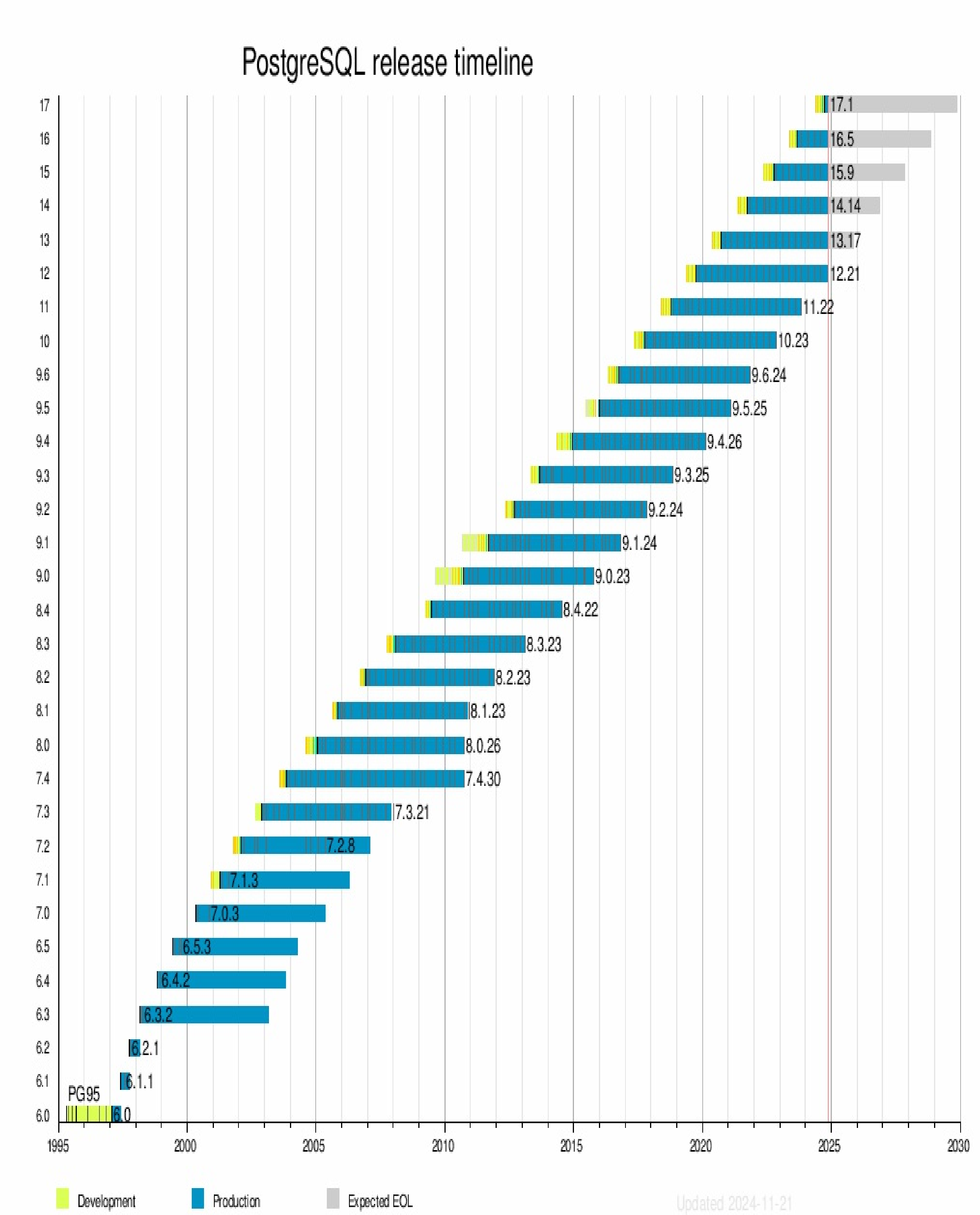
Note

Fractional input to `interval` is explained here in the Postgres docs: https://www.postgresql.org/docs/current/datatype-datetime.html#DATATYPE-INTERVAL-INPUT

What can we learn from this? Well, we can learn that ambiguity in code applying discounts can cost us money, but the more salient point is that upgrading without accounting for all the changes in behavior between two releases can result in all sorts of corner cases manifesting that are not immediately obvious after the upgrade. Bypassing the intervening release notes when you are skipping over even one version is not harmless because one of the releases in between may have introduced a breaking change that you will be unaware of. What you may have missed can take costly time to diagnose and fix later.

Take a look at the PostgreSQL release timeline below, and note how many minor versions are released throughout the lifetime of each major version:

Figure 10.1 A graphical representation of the PostgreSQL release timeline. Generated from data available under the Creative Commons Attribution-ShareAlike 4.0 License using https://en.wikipedia.org/wiki/Template:Timeline_PostgreSQL.



The bottom line is that if you have not read all the release notes between the original and target versions, you have committed a serious upgrading mistake. Make sure to pay attention to function deprecations or changes in name, changes to configuration and default settings, and SQL syntax updates.

10.2 Performing inadequate testing

The mistake in the previous section "Not reading all release notes" would have been caught had more rigorous testing taken place before the upgrade. Let us now look at another case where not testing enough before upgrading or migrating can catch you out.

Frogge Emporium, when upgrading from PostgreSQL 11 to 12, started noticing some performance issues. Specifically, one of their queries (that we saw in the section "Not using CTEs" of Chapter 2 "Bad SQL usage") compiles a list of customer emails who have been notified that they have an unpaid invoice for services (not purchased items). In their monitoring tool, it looks like this query is performing worse, which is a surprise. Didn’t we say elsewhere in this book that code that was written for PostgreSQL 11 will work fine in PostgreSQL 12?

Frogge is intrigued and decides to investigate so they set up one Postgres installation running on version 11 and another on version 12, to run comparative tests. They decide to run the same query through `EXPLAIN ANALYZE` on both instances, in an attempt to detect any differences.

On the PostgreSQL 11 instance, they run this:

```
EXPLAIN (ANALYZE, COSTS OFF, TIMING OFF)
    WITH unp AS (
        SELECT id, customer c, order_group AS og
        FROM erp.invoices
        WHERE paid = false
    ),
    ni AS (
        SELECT og.id
        FROM erp.order_groups og
        JOIN erp.orders o ON o.order_group = og.id
        WHERE o.item IS NULL
    )
    SELECT DISTINCT email
    FROM erp.customer_contact_details ccd
    JOIN unp ON unp.c = ccd.id
    JOIN ni ON ni.id = unp.og
```

```
    JOIN erp.sent_emails se ON se.invoice = unp.id
    AND se.email_type = 'Invoice reminder';
```

The execution plan that results can be seen below, somewhat abridged:

```
                                  QUERY PLAN
-----------------------------------------------------------------
 HashAggregate (actual rows=9 loops=1)
   Group Key: ccd.email
   CTE unp
     ->  Gather (actual rows=1350 loops=1)
           Workers Planned: 2
           Workers Launched: 2
           ->  Parallel Seq Scan on invoices (actual rows=450 loo
                 [...]
   CTE ni
     ->  Gather (actual rows=1350 loops=1)
           Workers Planned: 2
           Workers Launched: 2
           ->  Nested Loop (actual rows=450 loops=3)
                 ->  Parallel Seq Scan on orders o (actual rows=4
                       [...]
                 ->  Index Only Scan using order_groups_pkey on o
 og (actual rows=1 loops=1350)
                       [...]
   ->  Merge Join (actual rows=9 loops=1)
         Merge Cond: (unp.og = ni.id)
         [...]
               ->  Hash Join (actual rows=1350 loops=1)
                     Hash Cond: (unp.id = se.invoice)
                     ->  Hash Join (actual rows=1350 loops=1)
                           Hash Cond: (unp.c = ccd.id)
                           [...]
 Planning Time: 0.216 ms
 Execution Time: 50.033 ms
```

We can see that the two CTEs caused parallel table scans, and their filtered results were made available for subsequent `HashJoins` and finally a `HashAggregate` for grouping, both of which are relatively fast operations for large datasets. The query's execution time was 50 ms.

They then run the same `EXPLAIN` statement on the PostgreSQL 12 instance, and are surprised to see a different execution plan for the same query!

```
                                  QUERY PLAN
```

```
------------------------------------------------------------------
 Unique (actual rows=9 loops=1)
   ->  Sort (actual rows=9 loops=1)
         Sort Key: ccd.email
         Sort Method: quicksort  Memory: 25kB
         ->  Nested Loop (actual rows=9 loops=1)
               ->  Nested Loop (actual rows=9 loops=1)
                     [...]
                          ->  Parallel Hash Join (actual rows=3
                                Hash Cond: (o.order_group =
invoices.order_group)
                                ->  Parallel Seq Scan on orders
rows=450 loops=3)
                                      [...]
                                ->  Parallel Hash (actual rows=4
                                      [...]
                                            ->  Parallel Index S
invoices_pk on invoices (actual rows=450 loops=3)
                                                  [...]
                                            ->  Sort (actual row
loops=3)
                                                  [...]
                                                  ->  Seq Scan o
sent_emails se (actual rows=1350 loops=3)
                                                        Filter:
= 'Invoice reminder'::email_type)
                                                        [...]
 Planning Time: 0.538 ms
 Execution Time: 85.025 ms
```

The PostgreSQL 12 query plan is different: there’s no mention of CTEs and there are two levels of nested loops. The inner nested loop performs an index scan, which means that the index is scanned multiple times because of the outer loop. The filtering also happens after the joins, which means that what we don’t need is eliminated later, after processing more data. Finally, the results are sorted and then passed through Unique. As a result, the query now takes 85 ms to run.

It looks like Postgres has inlined the CTEs and subsequently went down a different execution path. This doesn’t necessarily mean that this query plan is worse in all cases, but it so happens that, in this case, it’s slower.

As we previously mentioned, the behavior of PostgreSQL features can change in subtle ways between major releases, and this is one of these cases.

Starting with Postgres version 12, CTEs began to be automatically inlined when they are referenced just once in the query, as long as they are not recursive and have no side effects.

Something else that changed between releases 11 and 12, and caught out a number of people, was that Just-In-Time (JIT) compilation was enabled by default. This caused some already fast and optimal queries to become slower by default, as Postgres needlessly spent CPU time trying to optimize them further with JIT. If regression tests are not performed with the actual queries, and using version 11 as the baseline, then this sort of slowdown is hard to catch. The reason why it's needed to test the queries themselves is that they may happen to cross the `jit_above_cost` threshold that triggers the automatic JIT optimizer.

What both of these examples tell us is that, instead of assuming that a successful upgrade means that everything will work as expected, you need to do the due diligence to thoroughly test your application and code with the new release. As PostgreSQL can introduce optimizations and behavior changes in the pursuit of ever faster performance, this can lead to completely different execution plans and can have a significant impact on the performance of your queries.

It's important to test your queries with real-world data (or as realistic as is feasible) to detect potential issues. Otherwise, there's simply no guarantee that everything in your upgraded system will behave the same way. Ideally, this testing should be performed in a staging environment before upgrading your production system, and it should include all your critical queries and known edge cases. `pg_upgrade` can be a useful tool for these testing dry runs. Finally, make sure to also test under load as a stress test can reveal how overall performance can be affected by the upgrade.

10.3 Succumbing to encoding chaos

It has become common for organizations to move from other database platforms to PostgreSQL. One of the usual migrations is from MySQL or MariaDB to Postgres, and this is what the proverbial database administrator has been tasked with in the following case. Their organization's database is substantial and contains years of accumulated data, including personal information with international names utilizing various special characters.

The DBA felt that this would not be a difficult migration, as the software used standard SQL, and had been tested and found to be totally compatible with PostgreSQL. The DBA began by performing a dump to export the MySQL database into an SQL file. The next step, predictably, was to import this dump file into Postgres:

```
psql service=staging -f prod_dump.sql
```

They were shocked to find that the terminal started filling with errors of this sort:

```
ERROR:  invalid byte sequence for encoding "UTF8": 0xe9
```

How was that possible? Unicode (UTF-8 in this case) should be able to deal with all the names in the database, as it supports international characters. Doing a little digging by finding the data row that caused the error, the DBA determined that `0xe9` is the hex value of the "Latin 1" code for the character `é`.

Looking into it further, the DBA found that the MySQL release they were using when the application went live was using `latin1` as the default encoding. Even though it had since been upgraded to a version that uses `utf8mb4` as the default encoding, the database kept using `latin1` as its tables had never been explicitly converted.

What is `utf8mb4`, you ask? Why is the MySQL default not `utf8`? It all goes back to MySQL's `utf8` being a flawed UTF-8 implementation that only supports up to three-byte characters. This means that it can't encode many international Unicode characters or emoji. As this was not a true UTF-8, eventually the `utf8mb4` encoding that supports four-byte characters was added to MySQL. Instead of fixing the bad implementation, MySQL chose to add a confusing non-standard name for the very well-understood UTF-8 encoding, while keeping around its old unsuitable `utf8` for backward compatibility.

After converting the `latin1` dump into UTF-8 characters, the DBA retried the import, only to fail again with a new complaint from PostgreSQL:

```
ERROR:  invalid byte sequence for encoding "UTF8": 0x00
```

It seems that some of the data contained *null characters*, also known as the ASCII `NUL` character, represented by hexadecimal zero `\x00` or octal `\0`. By referring to the PostgreSQL documentation, we can find the explanation: "The character with the code zero cannot be in a string constant".

This is another pitfall to be aware of — just because another data source or database (in this case, MySQL) accepts strings containing the `NUL` character it doesn't mean that these strings will be accepted in PostgreSQL, even in the hyper-flexible `UTF8` encoding.

The mistake that was made here was not accounting for character set and encoding differences between MySQL and PostgreSQL. By not determining the correct source and target encodings, and performing any necessary conversion during the migration, we faced "invalid byte sequence" errors. Additionally, by not properly handling illegal characters in the source data, we faced more import failures.

Some of these key differences to be aware of:

- PostgreSQL defaults to `UTF8` and strictly enforces valid UTF-8 encoding while rejecting characters made up of invalid byte sequences and ASCII zeros.
- Older versions of MySQL and MariaDB default to `latin1`, which is also known as `ISO-8859-1` or `Windows-1252` code page, while newer versions may default to `utf8` or `utf8mb4`. As we said, these DBMSs' `utf8` has up to three bytes per character, which means that it is missing support for a lot of Unicode characters.
- Oracle's `UTF8`, from version 8.1.7 onwards, means only "Unicode revision 3.0", so full current UTF-8 support requires the use of yet more strangely-named encodings, such as `AL32UTF8`.
- Microsoft SQL Server text support, predictably, is focused on Windows code pages. Since SQL Server 2012, Unicode support is provided via the `NVARCHAR` data type, which uses the `UTF-16` encoding. `UTF-8` support was only introduced with SQL Server 2019.

Oversights of differences like these can jeopardize migration efforts, not only because they cause delays, but because they may compromise data integrity by causing unseen data corruption. For example, if the target encoding decides to accept characters that it can then no longer decode correctly back to their original form, data may be lost irrevocably.

A safe data migration path would be to:

1. Identify the source encoding.
2. Export the data using that same encoding.
3. Convert the data to UTF-8. An example using the UNIX tool `iconv`:

   ```
   iconv -f latin1 -t utf8 prod_dump_latin1.sql -o prod_dump_utf
   ```

4. Clean the data by removing characters that PostgreSQL cannot accept. For example, removing null bytes using UNIX tools `tr` or `sed`:

   ```
   tr -d '\000' < prod_dump_utf8.sql > prod_dump_clean.sql
   ```

   ```
   sed 's/\x0//g' prod_dump_utf8.sql > prod_dump_clean.sql
   ```

5. Ensure that the target database is configured to use the `UTF8` encoding and an appropriate collation, like so:

   ```
   ENCODING = 'UTF8'
   LC_COLLATE = 'en_US.UTF-8'
   LC_CTYPE = 'en_US.UTF-8'
   ```

6. Import the cleaned data.

Finally, and we really shouldn’t have to say this again, test thoroughly using real or realistic data before proceeding with any conversion and migration.

Tip

Tools like `pgloader` and `ora2pg` can help with the migration task by managing character sets and converting the data automatically. You can find `pgloader` at https://github.com/dimitri/pgloader and `ora2pg` at https://github.com/darold/ora2pg.

10.4 Not using proper BOOLEANs

Another mistake, somewhat related to the previous one, that people often make is failing to pay attention to how boolean values are used inside their database. A quick example that parallels the migration woes we saw in the previous section "Succumbing to encoding chaos" would be to export a table that contains booleans from, let’s say, MariaDB. The table definition is:

```
CREATE TABLE Election2024 (
  VoterID INT AUTO_INCREMENT KEY,
  Voted BOOLEAN NOT NULL DEFAULT false
);
```

Our good DBA exports the table and attempts to load it into PostgreSQL. What ensues is this:

```
psql:prod_dump.sql:24: ERROR:  column "Voted" is of type boolean
 expression is of type integer
LINE 1: ... "Voting"."Election2024" ("VoterID", "Voted") VALUES (

HINT:  You will need to rewrite or cast the expression.
```

Wait a minute — the table column `Voted` is defined as `BOOLEAN`. Let’s see what MariaDB says when we ask for the table definition:

```
DESCRIBE Election2024;
+------------+------------+------+-----+---------+---------------
| Field      | Type       | Null | Key | Default | Extra
+------------+------------+------+-----+---------+---------------
| VoterID    | int(11)    | NO   | PRI | NULL    | auto_increment
| Voted      | tinyint(1) | NO   |     | NULL    |
+------------+------------+------+-----+---------+---------------
```

Oops! It turns out that MariaDB as well as MySQL store `BOOLEAN`s as `TINYINT(1)` internally. A quick look at these databases' documentation for types `BOOL`/`BOOLEAN` confirms it:

> These types are synonyms for TINYINT(1). A value of zero is considered false. Non-zero values are considered true.

This is hardly a standard boolean representation! It means that we can’t import such numeric data before converting it to proper SQL `BOOLEAN` values, as PostgreSQL believes that the literal integer values exported are… integers.

Other database systems also have this issue:

- In Microsoft SQL Server, it's common practice to use the `bit` data type that can take values `0`, `1` and `NULL` to represent booleans.
- IBM DB2 only started supporting `BOOLEAN` as a column type after version 11.1.1.1, released just in 2016. However, it will happily accept the string values `'0'` and `'1'`, as well as the numbers `0` and `1`, in such columns.
- Historically, Oracle has lacked comprehensive support for the `BOOLEAN` data type. Early on, it was standard practice to use `CHAR(1)` to store `Y` and `N` for "yes" and "no" (Anglocentric much?). Later, most people switched to using `NUMBER(1)` instead. Shockingly, support for `BOOLEAN` was only added with version 23c, released in 2023.

PostgreSQL provides proper support for the SQL standard `BOOLEAN` type, making `true` and `false` first-class citizens. Its strict adherence to the standard means that means that other values cannot be stored in booleans.

If the column you are migrating is originally defined as `BOOLEAN` but holds non-standard values, you will need to convert these character or numeric values into `true` and `false` in the dump file to be loaded for the PostgreSQL native boolean type to ingest them correctly.

Even if the columns are defined as pseudo-boolean numeric or character types in the other database, there is no reason to continue this charade inside PostgreSQL. Be aware that queries that implicitly expect a boolean may fail due to the type mismatch. To ensure consistency and standard-compliant behavior, convert these columns to boolean after the data load.

Let's say the table looks like this after the migration:

```
                       Table "Voting.Election2024"
 Column  |  Type   | Collation | Nullable |          Default
---------+---------+-----------+----------+----------------------
 VoterID | integer |           | not null | generated always as i
 Voted   | integer |           | not null | 0
Indexes:
    "Election2024_pkey" PRIMARY KEY, btree ("VoterID")
```

And we have values such as the following:

```
 VoterID | Voted
---------+-------
     500 |     0
     501 |     1
```

We can then run the following conversion:

```
ALTER TABLE "Voting"."Election2024" ALTER "Voted" DROP DEFAULT;
ALTER TABLE "Voting"."Election2024" ALTER "Voted" SET DATA TYPE B
    USING CASE WHEN "Voted" = 1 THEN true ELSE false END;
ALTER TABLE "Voting"."Election2024" ALTER "Voted" SET DEFAULT fal
```

After the conversion has been completed, our table looks like this:

```
                       Table "Voting.Election2024"
 Column  |  Type   | Collation | Nullable |           Default
---------+---------+-----------+----------+----------------------
 VoterID | integer |           | not null | generated always as i
 Voted   | boolean |           | not null | false
Indexes:
    "Election2024_pkey" PRIMARY KEY, btree ("VoterID")
```

We can see that the data inside is now properly stored:

```
 VoterID | Voted
---------+-------
     500 | f
     501 | t
```

To recap, if you want to avoid issues when migrating between databases, make sure that your boolean columns use standard `BOOLEAN` types and convert non-standard pseudo-boolean values (like integers or characters) to `true` and `false` in the data.

10.5 Mishandling differences in data types

We’ve already discussed some of the pitfalls you can encounter when moving from one DBMS platform to another in the preceding sections, so we’re going to keep this one short and sweet.

Databases like MySQL/MariaDB, SAP Sybase/Microsoft SQL Server, Informix, and others use the non-SQL-standard `DATETIME` type to store a date and time, in a `TIMESTAMP`-LIKE way. However, it’s done inconsistently — for example, accuracy-wise, some databases support fractional seconds, others offer accuracy approaching "a few" milliseconds, and others exact milliseconds or fractions thereof. Another inconsistency is that some databases accept nonsense `DATETIME`s into columns of this type; for example, MySQL/MariaDB seem happy to gobble up whatever invalid date you throw at them in non-strict mode (that used to be the default for a long time).

Finally, and most damningly, if you try to convert most of these `DATETIME`s to PostgreSQL’s SQL-compliant type `TIMESTAMP WITH TIME ZONE` you will unfortunately find out that the above implementations don’t support time zones and should be treated as naive (local) timestamps. For more on why that is a bad thing, and why you should not use `TIMESTAMP (WITHOUT TIME ZONE)`, please refer to the corresponding section in Chapter 3.

Inexplicably, some databases such as Oracle use the `DATE` data type to store date AND time information, but restricted to an accuracy of one second only! (Oracle’s `TIMESTAMP` data type also stores date AND time information but does include fractional seconds).

This goes beyond date/time types as well. `NUMBER` in Oracle can store both integers and floating-point values, but PostgreSQL requires you to distinguish between `numeric`, `integer`, and `float`/`double precision` types explicitly. Mapping the data types improperly can result in loss of precision or incorrect calculations.

All of this tells us that you can never rely on the name to tell you what a data type stores and that there are wild inconsistencies out there among DBMSs — possibly because of (unfortunate) design choices early on in their development process. Do not assume that data types sharing the same name are directly compatible with each other, and always check their definition and behavior in the relevant documentation. Use PostgreSQL’s data type conversion functions to ensure compatibility, and take advantage of migration tools such as `pgloader` and `ora2pg`.

10.6 Summary

- Always read the release notes for all versions between your current and target PostgreSQL versions before upgrading. Neglecting to do this can lead to unexpected behavior because of new optimizations or breaking changes that are time-consuming to diagnose and fix.
- PostgreSQL upgrades can introduce subtle changes in behavior or performance that may add up to become a problem in the end. Thoroughly test your application and queries in a staging environment before upgrading, and use realistic data and workloads to uncover potential issues early.
- Neglecting to address character encoding differences and disallowed characters during a database migration can lead to import errors or even data loss. When migrating between different RDBMSs, make sure to properly specify character encodings and the corresponding conversion between them, and clean the data from things such as ASCII nulls. Migration tools can help with this task.
- When migrating boolean data to PostgreSQL, ensure it uses the proper `boolean` type. Convert non-standard representations (e.g., integers or characters) to `true` and `false` to maintain consistency and avoid type mismatch errors.
- Inconsistencies in data type naming, functionality, and precision across DBMSs can lead to migration errors. Always verify and understand data type definitions and behavior and use PostgreSQL’s conversion tools and migration utilities to ensure compatibility.

11 Conclusion

In this chapter

- Exploring how common user profiles shape PostgreSQL mistakes
- Planning proactively to avoid technical debt and problem escalation
- Approaching and improving a poorly designed inherited PostgreSQL database
- Using PostgreSQL thoughtfully to improve performance and reliability

11.1 What type of user are you?

Having discussed errors and potential mishaps at length, it’s now time to take a step back and look at the PostgreSQL experience from a distance for more perspective. One of the reasons why PostgreSQL means so much and is loved by so many different kinds of users is that it can cater to their varied requirements. And yes, PostgreSQL users are not all the same — this much is obvious. From professional experience and talking to people at conferences alike, it’s become clear to me that there is a vast range of people doing all sorts of different stuff with our database of choice, and more use cases crop up every day!

When someone shares a Postgres success story, that is really cool because you get to learn about a new or different use case. When someone shares a story of trying and failing to make something work using Postgres, that is equally interesting — because understanding the underlying reasons for the failure is important for avoiding similar scenarios and seeking alternate paths. Incidentally, that is the whole premise of reliability and safety engineering, and the whole culture that surrounds the discipline.

Reliability and safety culture teaches us that mistakes can occur as a consequence of human error, failure of processes, insufficient training, or simply through misunderstanding or miscommunication. In this book, we have seen errors that can be ascribed to pretty much any of these factors.

Let’s recognize that not all PostgreSQL users are the same and that the user role they occupy in their organization will give them a particular alignment or bias in the way they approach database usage. This way, we can appreciate how their specific focus can lead them to fall prey to mistakes that might be otherwise caught with a multi-faceted look at the problem from an objective standpoint.

Here are some kinds of users and their characteristics — by no means an exhaustive list, but based on observation. PostgreSQL may be involved in the background as part of a professional picture, or in an academic or home setting:

11.1.1 The dabbler

You are a "full-stack" developer or data engineer. As part of your passion for exploring relevant technology, you come across PostgreSQL through word-of-mouth or articles extolling its virtues (or books such as this one)! You may even be an enthusiast working on a personally-led database project. Deciding to see what the fuss is all about, you start looking into how to use Postgres for your data retrieval or research needs, and it seems to fit the bill.

However, it doesn’t seem to scale as well as you had been told it would. It also doesn’t seem to integrate well with the tools you’ve been using so far. Two paths lay out in front of you: you can dive into PostgreSQL head-first, and focus on learning all you can around this technology and ecosystem to achieve your goal, or give up and look for an "easier" solution that you don’t have to tweak to get results.

The first path can lead to gaining deep knowledge about the database and ecosystem, and you can come out the other end a consummate professional or well-informed enthusiast who will — at least — be an expert in this specific area. The second path may indeed uncover some wonder tool that "just works", but in many cases leads to a technology that promises the world but only really covers two-thirds of your use case, and you have to come up with the rest through custom code or manual data munging.

What effectively determines the outcome of each path, is what you really want to use PostgreSQL for. Is the use case even valid for relational or document (JSON) databases? Then, most likely, you can find a way to make everything work fine. Are you relying on a different data paradigm, such as graphs, MapReduce, or specific data formats such as Parquet/Iceberg? Then, your success may hinge on third-party code such as extensions and Change Data Capture (CDC) or other data transformation or replication tools.

Looking for "the right tool" may turn out to be the fruitless pursuit of perfection. If you know any data professionals, you'll have noticed that what they care about the most is the accuracy and correctness of their data. They do appreciate ease of use, but only in a relative way. They know enough to not care about a couple of extra clicks, as long as there's a promise that, at the end of the process, they'll have a stable source of truth and a method that extracts and analyzes the data reliably.

This theoretical "dabbler" may be prone to misusing PostgreSQL features or data types, forgoing SQL conventions and best practices, and misunderstanding (or even skipping entirely) the documentation in search of quick-and-dirty solutions that will yield quick results. As we saw in Chapters 2 (Bad SQL usage) and 3 (Improper data type usage), such shortcuts can lead to significant problems down the line.

11.1.2 The cautious steward

You are a stalwart database administrator and the protector of data in your realm. You know all about best practices because you were the best in your database class or because you've been successfully navigating those waters for the past several years. You may be an experienced devops engineer or Site Reliability Engineer (SRE).

However, there are things that can stump you — a developer asks to use JSON(B) for non-relational data storage, and others reach out to you about distributed technologies, event buses and stream processing. Invariably, you put them back in their place, because PostgreSQL is a relational database, and it's being used in production. Any of these newfangled things may jeopardize the integrity of the data through their lack of an ACID implementation, or impact the system's performance through excessive querying or replication demands, and the list goes on. In your relentless focus on the core tenets of database administration, you may have missed out on the latest PostgreSQL features or emerging data technology trends.

This "cautious steward" may be prone to sticking with what they know through their exposure to another database system, or practices that are outdated, such as relying on logical dump and restore for backups. Their reluctance to try out new or PostgreSQL-specific features (see Chapter 4: Table and index mistakes) may lead them to inflexibility and missing out on efficiencies and synergies with new technologies. As we pointed out in Chapter 7 (Administration bad practices), not keeping up with the latest and greatest — including not upgrading — can paint you into a corner.

11.1.3 The oblivious coder

You may not even know — or care — that you are using PostgreSQL underneath it all, down in the "data layer". The database is something that is provided to you, and "should just work" with your platform of choice, be it language or framework. All you ask for is one database connection (or a few thousand connections, for that matter). As far as you’re concerned, the database is of secondary importance to your task, and the "database people" are obliged to deal with whatever your application or Object-Relational Mapper (ORM) throws their way.

You may be interested in AI and want to explore vectorization and embeddings. Or you may have other specialized uses in mind, like GIS using PostGIS, or other types of specialized extensions that add sets of features to PostgreSQL. However, your narrow focus on these things may not let you see the bigger picture that, in the end, there’s a database system out there holding and processing your data. Alternatively, you may be relying too heavily on your ORM and programming framework, and not enough on the core strengths of relational databases.

Often called the naive (or parametric) end user, the "oblivious coder" can be prone to basic data retrieval or SQL language errors if the SQL interface is exposed to them, such as N+1 queries and filtering in the application. If you recall, we discussed these types of issues in Chapter 6 (Performance bad practices). This is the type of user that is liable to code serialization anomalies inside their application or use text strings to store dates if left to their own devices. Reestablishing context to see how everything is connected and how all components can work optimally together usually helps.

11.1.4 The freefaller

You have been thrust into an unenviable position: You have been dropped into the middle of the operations circle of a highly complicated system, or you are very familiar with RDBMSs but not PostgreSQL in particular. After all, how different can this system, or PostgreSQL be from what you’ve encountered before?

Of course, the answer can be "VERY". There’s a huge variety of Postgres users out there in the industry and, through custom code, it can occupy niches your average person has not even thought about. All these specializations and workflows often require particular morsels of expertise, such as knowing that tables with a high frequency of updates will require an aggressive autovacuum configuration. This means that you may be overwhelmed by the complexity of what has been set up or the PostgreSQL features and techniques that are in use. Not asking for help or clarifications, out of pride or the desire to show that you’re on top of things, can incur risks.

The "freefaller" may be prone to blindly following blog posts that roughly correspond to what has been asked of them, or describing and delegating the task to an LLM, with dubious results. As with every powerful tool, LLMs can be wonderful in the right hands but can be dangerous if you don’t know what you are doing. Feeling they are in freefall, they may succumb to task fixation, making them less aware of the necessity of applying best practices at all times, especially regarding security and reliability — remember Chapter 9 (High availability bad practices).

These descriptions of hypothetical users are not meant to be negative stereotypes but are rather aimed at provoking thought as starting points for self-reflection. Identifying your specific needs as a PostgreSQL user, and acknowledging the expectations, restrictions, conventions and biases tied to your organizational role or alignment are important for self-awareness. Once you know what your particular characteristics are as a database user, you can better understand what comes naturally to you, but also points you need to pay attention to. It’s not about pigeonholing yourself as a particular user type, but about recognizing your strengths and weaknesses when it comes to effective PostgreSQL use on your journey to achieving good outcomes.

Embracing your particulars, aligning your practices with the responsibilities of your role, and leveraging this heightened awareness to learn more or seek guidance from peers can help you prevent mistakes.

11.2 Be proactive, act early

In the world of database management, every decision you make can potentially have cascading effects on performance, reliability, and maintainability. A well-maintained PostgreSQL database does not come about as the result of frantic firefighting efforts but rather through careful examination of issues and forward-thinking planning.

If you notice that a query is a bit slow or is performing worse than before, it means something. Take it as a warning signal that has to be acted upon immediately. Don’t wait until:

- Performance nosedives to start optimizing queries or introducing indexes.
- You lose data to start implementing a robust backup strategy.
- Your server goes down to establish and test redundancy and high availability measures.
- You require a feature from a newer PostgreSQL release to hastily plan an upgrade.
- You start running out of primary key IDs to start looking for a solution for your key column.
- Your table balloons to gigabytes of bloat before you assess and adjust autovacuum settings.
- You accumulate a billion rows in your table to realize that it is necessary to partition it.
- Hardware or cloud provider costs skyrocket before you think about optimizing your database.

When you see these scenarios spelled out, they seem like pretty commonsense actions that any DBA worth their salt would take. And yet, there are constantly new examples of these things getting overlooked time and time again. Often, too much focus on short-term deliverables can detract from long-term stability and performance.

Being vigilant is the first step towards being proactive:

- Review developer code to catch mistakes and inefficiencies.
- Notice data access patterns that may become future bottlenecks.
- Examine database usage patterns to identify anomalies or spots for improvement.

Plan your course of action. Test the proposed solution and apply it to a staging environment that mirrors production as closely as possible. Then, roll it out at your own pace, with plenty of time to spare.

Nobody wants to see an issue potentially escalate into a disaster, and being proactive protects you against that. When the focus is on rapid development, many considerations can be deferred or neglected. However, applying best practices, and planning for scalability, performance, and maintainability are activities that start at day one. This way, you can minimize or even eliminate technical debt. By worrying about predictable challenges and acting on those early on, you can prevent them from coming back to haunt your database in the future.

You are not alone in all this: leverage the PostgreSQL ecosystem to your advantage. Tools for high availability readiness, backing up, monitoring and alerting and statistics analysis and visualization provide numerous ways to have early warning and address potential issues before they disrupt operations.

Finally, commit to continuous learning. Stay current on PostgreSQL and adjacent technologies, and allocate time for training (even in the form of informal knowledge-sharing sessions). Participate in the PostgreSQL community through public fora and events. By staying informed, you can expand your horizons and learn from other people’s experiences. Isn’t this part of why you are reading this book?

Spearhead and cultivate a culture that values foresight and preparation. Encourage your peers and team members to think ahead, share insights, and exchange knowledge.

11.3 All right, so you inherited a bad database

It’s a common story: you join a project and discover that the state of its database leaves much to be desired. However, it’s not the end of the world — let’s explore why.

11.3.1 "Historical reasons"

Sometimes, it happens that you have to manage databases designed by your predecessor. Sometimes it even happens that the team used to not have a DBA. Those "hysterical raisins" can lead to disheartening discoveries, such as finding an `SQL_ASCII` database.

The database you inherit may be a house of horrors — it might be a result of questionable decisions, rushed deadlines, or architectural arrogance. What you have to remember is that whoever built it may have been using all the tools and knowledge they had at their disposal at the time and that this mess may have developed out of an organic growth of the code base and dataset.

11.3.2 What now?

What do you do now, when there are so many things to sort out? Instead of panicking, refer back to the old adage: "Never let a good crisis go to waste". Savor the opportunity to start fixing things before they have actually imploded, and learn from this journey.

There may be many things wrong with the system — bad encoding or object naming choices, overly broad tables with hundreds of columns and multiple uses, too many narrow tables, an ineffective multi-tenancy design with lots of repetition, or spaghetti code. They may have ignored the basics, such as normalizing, enforcing data integrity or creating indexes.

Take a deep breath, remember that you are not alone, and that these are solvable problems. First of all, see if anything is on fire — ask those working with the system for the major pain points, and they will be all too happy to share them with you. They may complain about things working slowly, running out of disk space all the time, or having to reboot frequently because the server runs out of memory.

If there is something you can do to address significant known failure points, take those easy wins, and buy yourself some time to improve the system incrementally and more systematically. Remember not to fall into the trap of the XY problem, identify what's wrong, consult best practices, and refer back to database basics to fix things.

The XY problem

What is known as the *XY problem* is a common miscommunication where the user attempts to get someone to help them by describing what they believe is the solution to their problem ("X") instead of detailing their actual problem ("Y").

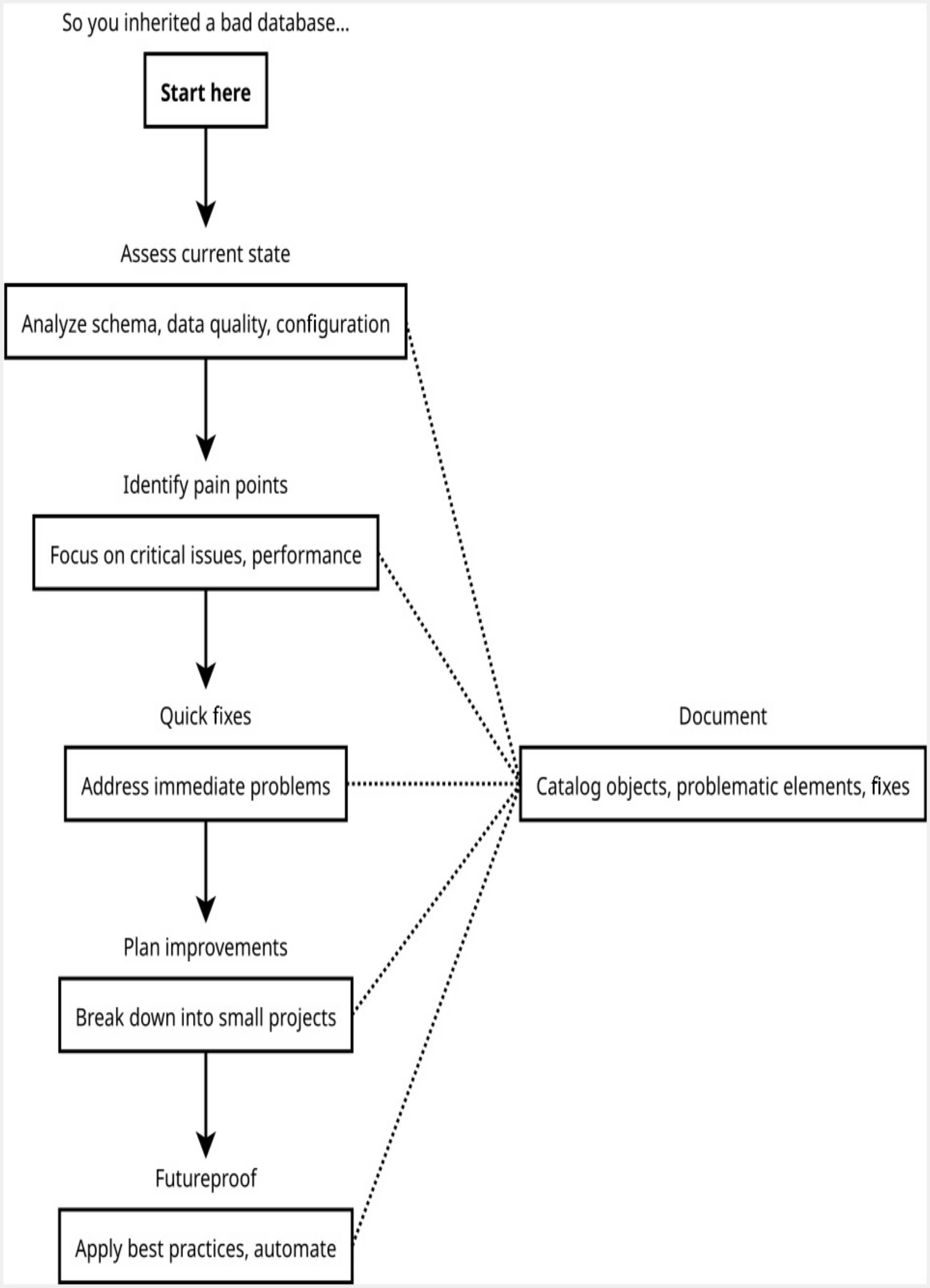
11.3.3 First things first

Set out by assessing the situation and mapping the terrain of what you are dealing with — use `pg_dump` and other tools such as `pgAdmin` or `DBeaver` to extract, visualize, and examine the schema's structure. Then, you can start inspecting the data and its quality by running exploratory queries. This can help you further understand the nature of the database contents. Look at the PostgreSQL configuration and ask yourself if it aligns well with what you've found so far. Monitor the database's logs and performance using `pg_stat_activity`, `pg_stat_statements`, and other relevant tools. This will uncover hints that can lead you back to the source of the problem, whether it's in the application code, database design or configuration, or even the data ingestion pipeline. Break down the proposed improvements into projects of a manageable size with measurable goals instead of trying to fix everything all at once.

Inheriting a bad database isn't just about fixing what's broken — it's also about futureproofing it. To ensure that your hard work pays off:

- Document as much as you can. Keep the documentation of the schema, relationships, configurations and key contextual notes up-to-date.
- Automate as many of the high availability, disaster recovery, and maintenance processes as you can. We've gone over the importance of this, especially in Chapters 7 (Administration bad practices) and 9 (High availability bad practices).
- Share your list of guidelines and best practices when it comes to security, schema and query design, and indexing and optimization with the broader team.

Figure 11.1 A roadmap for systematically assessing, fixing, documenting and improving an inherited database.


So you inherited a bad database...
Start here
Assess current state
Analyze schema, data quality, configuration
Identify pain points
Focus on critical issues, performance
Quick fixes
Address immediate problems
Plan improvements
Break down into small projects
Futureproof
Apply best practices, automate
Document
Catalog objects, problematic elements, fixes

The task of taking over an existing database may feel daunting, but it’s also an opportunity to make a real impact. Even if you don’t manage to turn it into the most enviable of data foundations, you can at least turn something that doesn’t work well into a serviceable, robust and reliable system. Prioritize repairs and take an incremental approach afterward. By being methodical, sticking to best practices, and looking ahead, you can make the database work for you and others, and gain valuable experience.

11.4 Treat Postgres well, and it will treat you well

PostgreSQL is not just a database engine; it’s a versatile powerhouse that has earned its reputation for reliability and adaptability. But, as with any tool, the key to succeeding lies in using it properly and treating it well. As a computational system, Postgres reflects how you interact with it.

This versatility makes PostgreSQL special because it can support a wide variety of use cases, from complex relational tasks on terabytes of data to blended paradigms with JSONB data or highly specialized jobs like geospatial processing. However, this power is also why it requires respect and care.

As Frogge Emporium navigated the sea of the PostgreSQL ecosystem in the pages of this book, it learned the fundamental truth of this concept through experience: it is rewarding to learn from your (and other people’s) mistakes. When pitfalls are revealed, a roadmap for best practices emerges.

With thoughtful use, PostgreSQL can deliver the goods:

- Optimizing your queries, indexing effectively, and configuring the system properly leads to a responsive and performant system.
- Measuring and planning properly allows you to scale your system in accordance with data and user base growth.
- Proactively monitoring performance and performing preventative maintenance with `VACUUM` and other methods guarantees stability and reliability. Chapter 6 (Performance bad practices) talks about the importance of autovacuum.

- Providing security measures, implementing redundancy, and establishing backup and failover strategies ensures the safety of your data and operations — refer to Chapters 8 (Security bad practices) and 9 (HA bad practices).
- Utilizing Postgres's advanced and expressive SQL syntax and NoSQL features gives you the flexibility to choose the right approach for building your application.

To develop this thoughtfulness, you need to:

- Understand your needs. Consider what you are building, and align your goals with PostgreSQL's and its ecosystem's capabilities.
- Follow best practices. Create clean designs and schemas, and architect your system to be safe.
- Keep learning. Stay updated on the latest features and extensions, and stay connected with the community.

In a way, you can treat PostgreSQL like a partner in your database journey. It can help you a lot, but you have to meet it halfway and respect its idiosyncrasies. As an example, adhering to proven design patterns and vacuuming diligently will enhance performance and reliability. When you do your part, Postgres will work as hard as you do.

Closing this book isn't the end as the journey with PostgreSQL extends far beyond these pages. Let the mistakes, solutions, concepts and ideas we discussed inspire you to continue to explore, learn, and innovate.

11.5 Summary

- Misaligning your usage of PostgreSQL with your needs may stem from a lack of self-awareness and can lead to predictable mistakes. Recognizing your user profile and role-specific tendencies, biases, and limitations helps you focus on areas needing improvement to prevent mistakes and optimize your database interactions. Understanding what kind of user you are, following best practices, and seeking guidance allows for a more objective view of potential problems.
- Waiting until problems escalate before intervening on performance,

reliability, or scalability is an unnecessary risk. Plan for future growth and optimize from the beginning to prevent technical debt. Proactive measures like code reviews and usage pattern analysis, coupled with regular monitoring and prompt attention to inefficiencies, are crucial and can save you a lot of trouble.

- Inheriting a poorly designed database means you should address major pain points as a priority before incrementally improving the system. Systematically assess the database using tools for schema inspection, data analysis, and performance monitoring. Along the way, document what you find and what you change, automate processes, share best practices, and take care to avoid the XY problem.
- Failing to recognize PostgreSQL’s requirements, stemming from its versatile nature, can limit its effectiveness. Use it thoughtfully by optimizing queries, indexing effectively and through preventive maintenance to have a performant, stable and reliable system. Stay informed, and treat Postgres, its ecosystem, and its community as trusted partners on your data journey. Recognizing common mistakes and adopting best practices lets you harness PostgreSQL’s potential to build robust, reliable systems.

Appendix A. Frogge Emporium database schema

To recreate the Frogge Emporium database and user, run the following in `psql` as user `postgres`:

```
CREATE USER frogge PASSWORD <password>;
CREATE DATABASE frogge OWNER frogge;
```

Then you can create the schema by running the file `schema.sql` as follows from the command line:

```
psql -U frogge -f schema.sql
```

`schema.sql` can be found at: https://github.com/vyruss/postgresql-mistakes/

The content of `schema.sql` is below:

```
CREATE SCHEMA erp;
CREATE SCHEMA audit;
CREATE SCHEMA support;
CREATE SCHEMA test;

-- Customers go in this table.
CREATE TABLE erp.customers (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    first_name text NOT NULL,
    middle_name text,
    last_name text,
    marketing_consent boolean DEFAULT false NOT NULL
);

-- This is where we hold contact details for customers.
CREATE TABLE erp.customer_contact_details (
    id bigint PRIMARY KEY REFERENCES erp.customers(id),
    email text DEFAULT '' NOT NULL,
    street_address text,
    city text,
    state text,
    country text,
```

```
    phone_no text
);
CREATE INDEX ON erp.customer_contact_details (email);

-- We represent order status by an enumeration.
CREATE TYPE erp.order_status AS ENUM (
    'Placed',
    'Fulfilled',
    'Cancelled'
);

-- Order groups aggregate large orders for multiple items.
CREATE TABLE erp.order_groups (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    status erp.order_status,
    placed_at timestamptz,
    updated_at timestamptz,
    customer bigint REFERENCES erp.customers(id)
);

-- Table to hold orders for individual items or services.
CREATE TABLE erp.orders (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    order_group bigint REFERENCES erp.order_groups(id),
    status erp.order_status,
    placed_at timestamptz,
    updated_at timestamptz,
    item integer,
    service integer
);

-- Each invoice for an order group goes in here.
CREATE TABLE erp.invoices (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    amount numeric NOT NULL,
    customer bigint REFERENCES erp.customers(id),
    paid boolean DEFAULT false NOT NULL,
    order_group bigint REFERENCES erp.order_groups(id),
    updated_at timestamptz DEFAULT CURRENT_TIMESTAMP,
    created_at timestamptz DEFAULT CURRENT_TIMESTAMP
);

-- We hold payments for specific invoices in here.
CREATE TABLE erp.payments (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    tstamp timestamptz NOT NULL,
    amount numeric NOT NULL,
    invoice bigint REFERENCES erp.invoices(id)
```

```
);
CREATE INDEX ON erp.payments (tstamp);

-- Our list of suppliers and their details.
CREATE TABLE erp.suppliers (
    id integer PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    company_name text,
    state text,
    country text,
    phone_no text,
    email text
);

-- We represent the type of each email sent by an enumeration.
CREATE TYPE erp.email_type AS ENUM (
    'Invoice reminder',
    'Welcome',
    'Account closed',
    'Happy birthday'
);

-- This table is the history of all emails sent out to customers.
CREATE TABLE erp.sent_emails (
    tstamp timestamptz PRIMARY KEY DEFAULT CURRENT_TIMESTAMP,
    customer bigint REFERENCES erp.customers(id),
    email_type erp.email_type,
    invoice bigint REFERENCES erp.invoices(id)
);

-- This table records energy usage readings for each of the branc
CREATE TABLE erp.energy_usage (
    branch_id integer NOT NULL,
    reading_time timestamptz NOT NULL DEFAULT CURRENT_TIMESTAMP,
    reading numeric NOT NULL,
    unit varchar DEFAULT 'kWh' NOT NULL
);

-- This table holds customer service ticket details.
CREATE TABLE support.tickets (
    id integer PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    content text,
    status smallint,
    opened_at timestamptz DEFAULT CURRENT_TIMESTAMP NOT NULL,
    closed_at timestamptz
);


-- Logging of user activity for audit purposes.
```

```
CREATE TABLE audit.audit_log (
    id bigint PRIMARY KEY GENERATED ALWAYS AS IDENTITY,
    what text,
    who text,
    tstamp timestamptz
);
```

2 Frogge Emporium database data

You can populate the database with the data for customers and their contact details by loading the file `customer_dump.sql` as follows from the command line:

```
psql -U frogge -f customer_dump.sql
```

`customer_dump.sql` can be found at: https://github.com/vyruss/postgresql-mistakes/

Finally, you can create the rest of the data by running `create_data.sql` as follows from the command line:

```
psql -U frogge -f create_data.sql
```

`create_data.sql` can be found at: https://github.com/vyruss/postgresql-mistakes/

The content of `create_data.sql` is below:

```
-- Data for suppliers table
INSERT INTO erp.suppliers (company_name, state, country, email) V
('Omni Consumer Products', 'MI', 'United States of America',
 'ocp@example.com'),
('Yoyodyne',null,'Japan','yoyodyne@example.com');

-- Data for orders, order_groups, invoices, payments, sent_emails
DO $$
DECLARE _id bigint;
DECLARE _t1 timestamptz;
DECLARE _t2 timestamptz;
BEGIN
SELECT CURRENT_DATE - INTERVAL '1y' INTO _t1;
SELECT CURRENT_DATE INTO _t2;
FOR i IN 1 .. 50000 LOOP
```

```
        INSERT INTO erp.order_groups (status, placed_at, updated_at,
        VALUES ('Fulfilled',
            (_t1 + (i * INTERVAL '1 s')),
            (_t1 + (i * INTERVAL '1 s')),
            TRUNC(RANDOM() * 14000 + 1)) RETURNING id INTO _id;
        INSERT INTO erp.orders (order_group, status, placed_at, updat
            item) VALUES
            (_id, 'Fulfilled',
            (_t1 + (i * INTERVAL '1 s')),
            (_t1 + (i * INTERVAL '1 s')),
            TRUNC(RANDOM() * 1000 + 1));
        INSERT INTO erp.invoices (amount, customer, paid, order_group
            created_at, updated_at) VALUES
            (59.95, (SELECT customer FROM erp.order_groups WHERE id=_
            _id,
            (_t1 + (i * INTERVAL '1 s')),
            (_t1 + (i * INTERVAL '1 s')
            + INTERVAL '30 s')) RETURNING id INTO _id;
        INSERT INTO erp.payments (tstamp, amount, invoice)
        VALUES ((_t1 + (i * INTERVAL '1 s')
            + INTERVAL '30 s'), 59.95, _id);
    END LOOP;
    FOR i IN 1 .. 200000 LOOP
        INSERT INTO erp.order_groups (status, placed_at, updated_at,
        VALUES ('Placed', _t2 - INTERVAL '2 d' + (i * INTERVAL '1 s')
            _t2 - INTERVAL '2 d' + (i * INTERVAL '1 s'),
            TRUNC(RANDOM() * 14000 + 1)) RETURNING id INTO _id;
        INSERT INTO erp.orders (order_group, status, placed_at, updat
            item) VALUES
            (_id, 'Placed', _t2 - INTERVAL '2 d' + (i * INTERVAL '1 s
            _t2 - INTERVAL '2 d' + (i * INTERVAL '1 s'),
            TRUNC(RANDOM() * 1000 + 1));
        INSERT INTO erp.invoices (amount, customer, paid, order_group
            created_at, updated_at) VALUES
            (59.95, (SELECT customer FROM erp.order_groups WHERE id=_
            _id,
            _t2 - INTERVAL '2 d' + (i * INTERVAL '1 s'),
            _t2 - INTERVAL '2 d' + (i * INTERVAL '1 s') + INTERVAL '3
            RETURNING id INTO _id;
        INSERT INTO erp.payments (tstamp, amount, invoice)
        VALUES (_t2 - INTERVAL '2 d' + (i * INTERVAL '1 s') + INTERVA
            59.95, _id);
    END LOOP;
    WITH o AS (SELECT id FROM erp.orders ORDER BY RANDOM() LIMIT 1350
              FOR UPDATE)
        UPDATE erp.orders SET item = NULL, service = 21
        FROM o WHERE orders.id=o.id;
```

```
WITH i AS (SELECT id FROM erp.invoices ORDER BY RANDOM() LIMIT 13
           FOR UPDATE)
    UPDATE erp.invoices SET paid='f' FROM i WHERE invoices.id=i.i
WITH i AS (SELECT id, created_at, customer FROM erp.invoices
       WHERE paid='f')
    INSERT INTO erp.sent_emails (tstamp, customer, email_type, in
        SELECT i.created_at + INTERVAL '1 d', i.customer,
            'Invoice reminder', i.id FROM i;
END $$ LANGUAGE plpgsql;

-- Data for tickets table
INSERT INTO support.tickets (status, content, opened_at, closed_a
    SELECT 20, 'issue text',
    CURRENT_DATE - INTERVAL '2y' + n * (INTERVAL '1 m'),
    CURRENT_DATE - INTERVAL '2y' + n * (INTERVAL '1 m') + INTERVA
    FROM generate_series(1,1000000) n;
INSERT INTO support.tickets (status, content, opened_at)
    SELECT 10, 'issue text',
    CURRENT_DATE - INTERVAL '1y' + n * (INTERVAL '1 m')
    FROM generate_series(1,500) n;
```

Appendix B. Cheat sheet

Bad SQL usage
Don’t use `NOT IN` to exclude a list of values that can include even one null, because that will return an empty result set. Consider the use of `NOT EXISTS`.
Filtering with `BETWEEN`, for example between two timestamps, can return overlapping results in subsequent queries because its ranges are inclusive.
CTEs can not only **improve readability** of queries but also improve **performance**, by letting the optimizer decide to merge and reorder parts of the query.
Quoting identifiers makes them case-sensitive, while the Postgres convention is for all identifiers to be case-insensitive, and this can lead to reduced usability and errors.
Performing division between integers will yield an, often unexpected, truncated integer result.
`count()` ignores `NULL` values so if you count a nullable column, you won’t get the number of rows returned but the number of rows that didn’t have `NULL` in that field.
When you **query indexed data that has had a data transformation** applied to it, Postgres may not use the index at all.

Avoid using nullable columns in composite unique keys when possible. PostgreSQL 15 introduces **`NULLS NOT DISTINCT` to address issues with upserts** but you should probably **use a cleaner design**.
Don’t slow down your queries by **selecting more than strictly necessary**, and don’t fetch more data than you need to the application side — do your filtering and data management operations on the database side.
Use tools to check and lint your SQL for correctness and potential impacts to production, and take advantage of generative **AI to make your work easier** — but be **aware of the limitations** and always recheck and have the final say.

Improper data type usage
There is no benefit to **using `TIMESTAMP (WITHOUT TIME ZONE)`**, as it can lead to time calculation errors due to lack of time zone and DST context. `TIMESTAMP WITH TIME ZONE` is the proper data type for recording timestamps as specific moments in time.
`TIMETZ` and `CURRENT_TIME` have questionable usefulness because time zones have no meaning without the context of dates. Again, it is preferable to use `TIMESTAMPTZ` even if we don’t need to display the date part of the timestamp.
`MONEY` doesn’t store which currency, it suffers from a limited and flawed implementation, and **should be avoided** in favor of using `NUMERIC` or other number formats that can accurately store exact values, potentially in conjunction with storing the currency as a separate column.

The two serial types **`SERIAL` and `BIGSERIAL`** have been effectively **superseded by identity columns**, which have more predictable behavior when it comes to role ownership and use of sequences, and clarity regarding which table the sequence belongs to.
You **don't save storage space by using** the limited character types **`CHAR(n)` and `VARCHAR(n)`**, and the whitespace stored with `CHAR(n)` can be detrimental to performance. Additionally, you run the risk of running into SQL quirks and painting yourself in a corner with maximum lengths — `TEXT` is the better choice.
`XML`is a terrible choice for document storage, unless you're just copying immutable XML data inside the database — if you intend to query/manipulate the data, you should use `JSON(B)`.

Table and index mistakes
If you discovered **table inheritance** and you think you need it, you're **probably wrong. Implement** the parent-child relationships **with foreign keys and triggers** if needed.
You can leverage table **partitioning to make management and maintenance** of large tables **easier**, and speed up the queries hitting those tables.
Take care **when sub-partitioning** because **partitioning by multiple keys is not the same** thing. Unfortunately, it is not obvious from the documentation what the multiple key partitioning syntax does, when best to use it, and what its implications are.

Each index type offered in PostgreSQL **has its strengths and weaknesses**. By adapting your indexing plan to the type of data you have and type of queries you need to run, you can optimize performance and storage space. When you **get it right, your queries can run orders of magnitude faster**.

Improper feature usage
`SQL_ASCII` is not a character encoding so much as the absence of one. If you don’t want to risk mixing encodings irreversibly and you enjoy the ease of automatic character set conversion, make sure you use UTF-8 for your database.
PostgreSQL `RULE`s are not related to rules as defined in other DBMSs. **`RULE`s are complicated to understand** and are mainly there as Postgres internal machinery. In most cases they don’t behave as the user expects them to and `TRIGGER`s are best used instead.
Using JSON(B) values with relational access patterns makes for less efficient SQL which is harder to read and might not perform as well. It’s **better not to mix the SQL and NoSQL paradigms**, but use each facility for what it’s best at doing.
`uuids` take up more storage space than even `bigints` and indexing them is less efficient. They may guarantee **a range of values that you simply don’t require** for your use case, and an integer index might be enough to guarantee uniqueness.
Bi-directional or multi-master replication is more complex than what appears at first sight. For practical use in a production system, there is a very long list of prerequisites, considerations and caveats. If your use case

indeed justifies setting up a multi-master system, you are better off using an established multi-master solution whose developers have given thought to these issues rather than re-inventing the wheel.

All of the above apply to **homemade distributed systems as well and it is not recommended to set out building them** unless your scope is very narrowly focused. You need to consider the potential for distributed serialization anomalies and the very real trade-offs laid out in the CAP and PACELC theorems.

Performance bad practices

PostgreSQL's default configuration is very conservative and in most cases **will not be optimal for a real-world workload.** This can mean that you are leaving your system resources underutilized and leaving potential performance gains on the table.

You can shoot yourself in the foot by **calculating memory allocation settings incorrectly**. You need to take your workload into account, including what types of queries you are running and how memory-hungry they are along with what level of client concurrency you are expecting.

Excessive concurrency can kill your performance rather than allow more work to be performed in parallel because of the way Multi-Version Concurrency Control (MVCC) works. You need to be aware of the risks associated with opening too many sessions inside PostgreSQL, and also the nature of your workload and the limitations of your particular database host.

Connections that are mostly or entirely idle don't come for free; they are associated with computational overhead that may affect PostgreSQL's, and your operating system's, performance in general. **You should try to avoid having connections around that don't do much actual work.** If you can't, you should use a connection pooler that's aware of these connection

semantics, such as PgBouncer in Transaction Mode.
Idle in transaction sessions and sessions with long-running queries can cause unexpected blocking of other queries, leading to application delays or errors. They can also postpone or altogether block autovacuum, and this can lead to performance degradation beacuse of bloat, or more serious errors.
If you let your **transaction rate get out of control, it can** outrun the efforts of autovacuum to prevent XID wraparound failure and **bring down your database**. You can mitigate this by batching, reorganizing, and summarizing data — or even skipping the ingestion of data you aren’t likely to use again.
Autovacuum is essential for the correct operation of your database. Lowering its effectiveness or disabling it altogether to save system resources is a fallacy, because any performance gains will be undone in time by bloat accumulation, inaccurate optimizer statistics, and forced anti-wraparound prevention.
Where there’s evidence that a **query is running slowly, checking its `EXPLAIN`** is a quick and accurate way to identify the reasons why and help troubleshoot it.
Locking objects explicitly can lead to read/write blocking that **can make your application feel sluggish or broken.** Where synchronization is needed, try to use the `SERIALIZABLE` isolation level and make your application able to retry actions.
Indexes can make or break your queries' performance, and PostgreSQL has lots of index types. **Examine your query plans and take advantage of**

indexing to boost performance for your `WHERE`s. Sequential scans are bad because they become linearly slower as the table grows.
Having **indexes that you don’t need can slow down your table** for writing and consume valuable disk space. Identify those that aren’t in use from `pg_stat_all_indexes` and remove them.
Be careful when dropping indexes that appear unused as this statistic is for the local node only, and those **indexes may be in use on another node** you are physically replicating to.

Administration bad practices
Running out of disk space can cause serious problems, so monitor your usage closely. **Rash decisions** like deleting what looks like logs or unnecessary files or resizing volumes **can make the situation worse.** Identify what’s consuming your space, and mitigate by employing multiple volumes.
Storing **PostgreSQL logs on a separate filesystem** from the database helps you **reduce the risk of excessive logging** filling up your disk. You should also implement log rotation and enforce log size limits.
Regularly **checking** PostgreSQL **logs is crucial** for identifying and addressing configuration issues, performance bottlenecks, data integrity concerns, and security incidents in near real-time. This can allow you to deal with problems before they escalate, and you can use pgBadger to help with the task.

Not monitoring your PostgreSQL database can lead to **undetected performance issues**, **security threats**, and **resource exhaustion** that could impact its operation. By using the appropriate tools and metrics to look out for slowdowns, resource spikes, and maintenance needs, you can ensure optimal performance and mitigate risk.
Long-term tracking of PostgreSQL **statistics** is important **for understanding performance trends** and making informed **capacity planning decisions**. You can use the usual monitoring tools, or the lightweight `pg_statviz` extension to capture and visualize these statistics over time without the need for heavy tooling or storage overhead.
If you **don't upgrade** Postgres regularly with minor releases, you can **incur security risks** or **run into bugs** that have been fixed. By not upgrading to the next major release you can and **miss out** on **new features** and **enhancements**. Upgrading is made safe and reliable by well-tested tools and thorough documentation. Don't fear the upgrade — fear the alternative.
Failing to **upgrade the operating system** and **dependency libraries** as well, can lead to obscure PostgreSQL performance issues, bugs and vulnerabilities, negating the perceived stability in pursuit of which you avoided to upgrade.

Security bad practices
Using `psql -W` or **`--password`** **can be confusing** and lead to lapses in security. **Rely on** PostgreSQL's **automatic built-in password prompt** mechanism instead.
Setting **`listen_addresses = '*'`** **can expose** your database **server to**

insecure networks, so you should only enable the trusted network interfaces that are necessary for database connectivity.
Using the **`trust`** method in `pg_hba.conf` **in production** environments **is unacceptable**. You should always **enforce proper authentication** to your server and restrict access as much as is practical.
Having your **databases** and their contents **owned by a superuser** can lead to **security problems** and **accidental damage** to your data. Instead, **create roles** that have only the relevant permissions **to own and manage these databases**, and grant permissions selectively to other roles.
Declaring functions as **`SECURITY DEFINER`** **can cause data leaks and** enable **privilege escalation**. To reduce risk, **use it sparingly** and **with a safe `search_path`**, and prefer the combination of `SECURITY INVOKER` with explicit `GRANT`s.
Not securing your **`search_path`** **can let** others **hijack queries** and **escalate their privileges**. Apply **tight control over object creation** in schemas, and reference **objects owned by trusted users** only in queries.

High availability bad practices
RAID and filesystem **snapshots can’t help you reliably recover from corruption, human error or malicious activity**. The best way **to guarantee your data is safe** is to **take backups** using appropriate tools like `pg_basebackup`.
Taking full backups only makes you **vulnerable to data loss between**

backups. **Leverage Point-in-time recovery** with continuous archiving to be able to restore your database to the point before it was damaged.
Taking backups manually is not robust or reliable, you should instead **schedule automated backups**, preferably **using dedicated software** that is PostgreSQL-aware (such as Barman or pgBackRest), and ensuring that you have a **redundant copy** of the backups **in a second location**.
Untested backups can fail when you need them the most so to ensure that they work correctly **always attempt a full restore to test your backups**. Do not rely solely on automation but verify every step. **Avoid using homegrown scripts and prefer tried-and-tested solutions**.
Having a **single database server** with no provision for failover inevitably **leads to downtime**. **Ensure redundancy by setting up standby nodes via replication**.
Manual failover or custom scripts are risky because of the potential for extended downtime, data divergence or loss. **Prefer proven high availability tools** such as RepMgr, Patroni or CloudNativePG for Kubernetes to ensure reliable and effective management of your HA cluster.

Upgrade/migration bad practices
Always read the release notes for all versions between your current and target PostgreSQL versions **before upgrading**. Neglecting to do this can lead to **unexpected behavior** because of new optimizations or breaking changes that are **time-consuming to diagnose** and fix.

PostgreSQL upgrades can introduce subtle changes in behavior or performance that may add up to become a problem in the end. **Thoroughly test your application and queries** in a staging environment **before upgrading**, and **use realistic data and workloads** to uncover potential issues early.
Neglecting to address **character encoding differences and disallowed characters** during a database migration **can lead to import errors or even data loss**. When migrating between different RDBMSs, make sure to **properly specify character encodings and** the corresponding **conversion between them, and clean the data** from things such as ASCII nulls. **Migration tools can help** with this task.
When migrating boolean data to PostgreSQL, ensure it uses the proper `boolean` type. **Convert non-standard representations** (e.g., integers or characters) **to `true` and `false`** to maintain consistency and avoid type mismatch errors.
Inconsistencies in data type naming, functionality, and precision **across DBMSs can lead to migration errors**. Always **verify and understand data type definitions and behavior and use** PostgreSQL’s **conversion tools and migration utilities** to ensure compatibility.

Conclusion
Misaligning your usage of PostgreSQL with your needs may stem from a **lack of self-awareness** and can lead to predictable mistakes. **Recognizing your user profile** and role-specific tendencies, biases, and limitations helps you **focus on areas needing improvement to prevent mistakes** and optimize your database interactions. Understanding what kind of user you are, **following best practices, and seeking guidance** allows **for a more**

objective view of potential problems.
Waiting until problems escalate before intervening on performance, reliability, or scalability **is an unnecessary risk**. **Plan for future growth and optimize from the beginning to prevent technical debt**. Proactive measures like **code reviews and usage pattern analysis**, coupled with **regular monitoring and prompt attention to inefficiencies**, are crucial and **can save you a lot of trouble**.
Inheriting a poorly designed database means you should **address major pain points as a priority** before incrementally improving the system. **Systematically assess the database** using tools for schema inspection, data analysis, and performance monitoring. Along the way, **document what you find and what you change, automate processes, share best practices**, and take care to **avoid the XY problem**.
Failing to **recognize PostgreSQL’s requirements, stemming from its versatile nature**, can limit its effectiveness. Use it thoughtfully by **optimizing queries, indexing effectively** and through **preventive maintenance** to have a performant, stable and reliable system. **Stay informed, and treat Postgres, its ecosystem, and its community as trusted partners** on your data journey. Recognizing common mistakes and adopting best practices lets you harness PostgreSQL’s potential to build robust, reliable systems.