



Assignment of master's thesis

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Instructions

Object-relational mapping (ORM) libraries enable to naturally connect objects written in a given programming language with their representation stored in a database. There are lots of such libraries for JavaScript (JS) and TypeScript (TS), but each comes with its own set of compromises. Explore and describe available open-source frameworks, provide example implementations of application showcasing their advantages and downsides. In the benchmark application test primarily feature richness of framework, efficiency, type support for TypeScript and ability for relational data fetching. Discuss good and best practices for use with each library and what project they fit in.

Guidelines:

- 1) Research existing JS and TS libraries and explore their problems and benefits by gathering users' experiences.
- 2) Design a benchmark database and example application, implement the application in each framework.
- 3) Describe and test the frameworks with a focus on their functionality, efficiency of database usage, speed and usability.
- 4) Provide outcomes of the tests, analyze their results. Describe which framework has an advantage in each situation.
- 5) Recall on gathered experience, discuss findings, propose improvements and continuations.



**FACULTY
OF INFORMATION
TECHNOLOGY
CTU IN PRAGUE**

Master's thesis

Object-relational mapping for database access in JavaScript

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April 24, 2023

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THANKS (remove entirely in case you do not wish to thank anyone)

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In Prague on April 24, 2023

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Abstract

In this thesis, we investigate the role of Object Relational Mapping (ORM) and query builder packages in JavaScript, focusing on the support of TypeScript. Such comparison is important due to modern applications' proliferation of database access. The study aims to compare various packages, assessing their flexibility and performance overhead to facilitate an informed decision-making process for developers.

Keywords SQL, ORM, Object-relational mapping, Query builder, JavaScript, TypeScript

Abstrakt

Tato práce se porovnává frameworky objektově relačního mapování (ORM), respektive pro tvorbu SQL dotazů v jazyce JavaScript. Práce se zaměřuje na podporu jazyka TypeScript. Používání ORM je běžně využito pro úsporu času při vývoji pomocí abstrakce, kterou balíčky poskytují. Cílem studie je porovnat různé balíčky, posoudit jejich flexibilitu a výkonnostní režii a usnadnit tak vývojářům informované rozhodování a použití a případném výběru.

Klíčová slova SQL, ORM, Objektově-relační mapování, Query builder, JavaScript, TypeScript

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Acronyms

API Application Programming Interface

BSD Berkeley Software Distribution

CLI Command Line Interface

HTML Hypertext Markup Language

I/O Input / Output

JSON JavaScript Object Notation

MVC Model - View - Controller

OOP Object Oriented Programming

ORM Object relational mapping

QB Query builder

RDBMS Relational Database Management System

SQL Structured Query Language

XML Extensible Markup Language

Introduction

In the modern world, data have become an essential aspect of almost every field. From e-commerce to healthcare, education to finance, data is everywhere and plays a critical role in decision-making processes. The advent of Web 2.0[1], which brought with it the concept of user-generated content, was largely supported by connecting the Web to databases. Social media platforms, for example, rely heavily on data to provide personalized recommendations, targeted advertising, and other features that keep users engaged. Even non-Web entities and applications often need significant data storage and, as a result, the ability to manage and manipulate data has become a critical skill for developers and organisations alike.

Relational databases such as SQL Server and PostgreSQL are by far the most popular type of databases for data storage used in business-level applications. These databases use the relational data model, which is based on tables with rows and columns, to store and manipulate data.

Object-oriented programming languages and languages incorporating parts of the paradigm, such as Java, Python, Ruby, and JavaScript, have gained popularity[2] due to their ability to create complex software systems that can handle large amounts of data efficiently. Object-oriented programming (OOP) is a programming paradigm that represents concepts as “objects” that have attributes (data) and behaviours (methods). This makes it easier to write, maintain, and reuse code, which is essential when working with large-scale software systems.

Despite the popularity of object-oriented programming languages, there

is often a disparity between OOP languages and the relational data model used by many databases. OOP languages are designed to work with objects, whereas relational databases are designed to work with tables. This can make it challenging for developers to work with databases using OOP languages.

Object-Relational Mapping (ORM) has become a popular solution for developers who need to connect object-oriented programming languages with relational databases [3]. ORM allows developers to work with relational databases using object-oriented programming languages, eliminating the need to write complex SQL queries. By abstracting away the details of the underlying database, ORM allows developers to focus on the application logic and reduces the amount of boilerplate code that needs to be written. This makes it easier for developers to work with databases and reduces the potential for errors.

The paper aims to conduct a comprehensive analysis of the most popular ORM packages and SQL query builders for Typescript. This analysis will provide an objective measurement of their relative strengths and weaknesses in terms of functionality, type support, performance, and package quality. Also included are noncomparative examples of syntax and usage to illustrate strengths and weaknesses and to showcase the functionality of the modules. By evaluating each package's performance in these key areas, the paper aims to provide a comprehensive comparison that will be useful to developers who are looking for the best ORM or SQL query builder package for their Typescript project.

While there are existing comparisons, most of them are created from the point of a biased actor, usually a competitive or alternative solution developer [4] [5]. This work aims to provide an unbiased comparison.

Before we start with the full comparison of ORMs that support TypeScript, we must first define what counts as an Object-Relational Mapping Package, what are SQL Query Builders, and other technologies and terms used further in this work. Then we explain how the packages further analysed were selected and by which criteria they are ranked and reviewed.

Terminology Used

Object-Relational Mapping

Object-relational mapping is a way to access relational data in an object-centred programming language [6]. The primary purpose is manipulating data without switching concepts from object-oriented paradigms to the relational representation of data in which most databases operate. The scope of this translation layer can (as shown later in this work) vary. Different people define packages as ORMs while providing diverse levels of functionality [7].

At its base level, ORM provides an intermediary layer between applications' OOP model and database which is usually relational (but can be graph or document focused). The layer allows the developer to work with objects in the code, while the package translates it into a relational structure when saved to the database. These packages are often used on projects that are heavily connected to a database model, as ORMs are most beneficial when using a database is commonplace. When used only occasionally, it usually brings too expansive a setup to translate into gains in code readability and maintenance costs compared to executing premade SQL queries [3].

In addition to the basic functionality of translating between different styles of data representation, ORMs often include functionality such as connection pooling, support for read-only data replications, caching, or database migrations. When using such modules, developers can avoid writing boilerplate code that is typically required.

SQL Query Builder

SQL query builder is derived from its function to create SQL queries and OOP pattern, which it implements, called “builder”. Object-oriented programming design patterns are reusable solutions commonly encountered during software development in OOP languages. These patterns propose interactions between objects and their internal structure. There is no single authority on how these patterns are defined, nor a comprehensive list of these patterns, as every author prioritises different patterns and functionalities [8].

The Builder pattern is one such pattern, providing API for the complex creation process of objects. This pattern is one of the 23 defined in “Design Patterns” by Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides [9], which has been highly influential in software engineering. Its purpose is to separate the creation of an object from its representation, allowing for the separation of parts that initially were parts of one construction method into several.

SQL Query is made up of several clauses, which each serve distinct functions. For example, the **SELECT** clause specifies which columns are to be retrieved, and the **FROM** clause specifies which table or tables the columns should be [10]. Once the builder pattern is applied to the SQL query, each of these clauses (or even smaller fragments) can be created by calling the Builder’s methods, creating a programmatic way to create SQL queries. The Builder also allows developers to abstract minor differences between different SQL implementations.

As the ability to create queries based on multiple criteria is one of the basic functionalities of ORMs, they are almost always built on some query builder. These can be available standalone or fully integrated into the ORM package. Often, query builders are sufficient for the purposes of database access in most applications, so they were included in the comparison. While they certainly lack feature sets and, compared to ORMs, query builders usually require SQL knowledge, they can be easier to set up and maintain while also being faster and allowing fine-tuned adjustments to a query.

PostgreSQL

One of the most popular database engines today, PostgreSQL, is an open-source object-relational database management system. Originally developed under the name Postgres [11] (short for Post-Ingres) as a new generation after a successful relational database called Ingres, it was first released under this name in 1989. After several years of development at the University of California at Berkeley, the name was changed to focus on SQL compliance. The whole project moved to open-source, community-focused development in 1996. Currently, the project is maintained by The PostgreSQL Global Development Group, and releases and source code are provided under an open-source BSD-style licence free of charge [12].

PostgreSQL is, at the time of writing, one of the most popular SQL databases available, owing to its widespread adoption to reliability and high scalability while supporting most of the SQL standard and being fully ACID compliant [13]. ACID is an acronym for Atomicity, Consistency, Isolation, and Durability, which are four fundamental tenets specifying properties for reliability and consistency of transactions.

Some of the features that often make PostgreSQL stand out amongst other RDBMS are its support for many different and advanced data types [14] out of the box, such as the ability to natively store JSON objects and arrays, XML data or geometric types. With extensibility being a significant focus, a lot of functionality can be installed or optionally enabled, further improving the reach and applicability.

There are extensive implementations of the API for many programming languages, including C [15], Python [16], Java [17], and JavaScript [18]. PostgreSQL also offers extensive documentation of both its API and internal functionality, which supports its growth and popularity.

Lazy loading

Lazy loading is a technique for optimizing data retrieval to increase application performance [19]. It is a strategy consisting of only loading data when it is needed rather than all at once, therefore reducing the initial load in exchange

for the need to do additional loading later. Lazy loading is usually achieved by breaking down larger datasets into smaller ones and loading each one only when necessary. Such practice is commonplace in web development, as asset sizes (such as images or JavaScript) have only grown in the evolution of the web.

Some of the most common implementations of Lazy Loading come in the way of only loading low-quality images unless the user is focused on them or splitting code into multiple files, which are fetched when necessary, providing quick first page-load time at the cost of adding additional requests [8, p. 200].

When talking about ORMs and database access, lazy loading usually takes place as replacing data retrieval from an object with a call to retrieve the data from the database. In other words, the data of the database object does not need to be loaded when the object representation or its part is created in the program. This technique is often used for loading relations so that only one table needs to be queried to create the essential representation of the object while skipping the need for additional fetches or joins that are only invoked once needed.

Eager loading

Eager loading is the programming practice of loading all the required data at once, optimizing the number of requests that must be made to retrieve everything [20]. This is done with the expectation that one expensive request will minimize the amount of additional data that would need to be sent between the two parties. This can lead to faster load times and improved application performance.

It is usually achieved by sending a singular request and caching the data in memory, even though it might only be needed later. There are obvious downsides to this, such as higher memory usage or often loading more data than is necessary. The concept of eager loading is antithetical to the lazy loading approach, and that is on purpose. Each approach prefers a different focus, and thus each is fit for different usage; lazy loading is practical when a first look or first results matter the most, and eager loading is when the focus is on one large result, which would be slowed down by too many small

requests, which would need to be made for the total result.

In the context of object-relational mapping frameworks, we are most likely to encounter eager loading when fetching related entities. This way, when there is an expectation for data about the currently approached entity, the ORM can optimize the query so that the data are already loaded in memory when it is requested later.

Circular dependence

A common problem in software development, circular dependency occurs when two or more parts of code depend on each other, making it impossible to resolve their dependence onto a dependency graph. Such a graph must conform to limits set out for tree graphs and, therefore, cannot contain a loop. Due to the way how modules are loaded in Node.js [21], such a problem would lead to a deadlock and is therefore resolved by trying to run the modules in a specific order. However, such an approach is only sometimes feasible, so other solutions must be used. The issue of circular dependency is also present in the compilation because, while TypeScript does allow asynchronous references of types between files using `import type` term [22], if we need to import not only the type but also the value, TypeScript will not be able to resolve the type, and the compilation will fail. There are many solutions to this problem, the most common being dependency injection or lazy loading.

In ORMs and database representation in OOP languages, this problem is generally connected to the bidirectional nature of relations, as its explicit representation will inevitably create circular dependency [23]. Therefore, for most schema definitions, there needs to be a functionality built in that allows users to define bidirectional relations without sacrificing type safety or encountering a deadlock with importing modules.

Database transaction

Transaction isolation is a concept used in database management to represent a unit of work. The transaction is typically a series of one or more database operations that are supposed to be completed on the all-or-nothing principle.

In addition to performing database queries atomically, the transaction also needs to provide additional functionality, such as coordination of reads and handling operations in a reliable and recoverable manner.

As database transactions are the base for the basic functionalities of modern RDBMS [24], their handling is essential when considering the ORM framework. Often an operation can only be performed when the previous one succeeded or has to be made strictly in order without another operation having access to the data in between [13]. This can be achieved only through the database transaction, and support for them is necessary for many use cases.

Database connection pool

A database connection pool is a component that collects and manages several database connections and allocates them to individual requests to the database. It works by creating either a fixed number of connections at the beginning or scaling up the number of connections based on usage. In this way, querying the database does not have to wait for the connection to be established, and the request can be routed through the database connection pool to the currently unused connection [25]. Additionally, due to having multiple connections, multithreaded and asynchronous applications can coordinate connections to the database. Single connection applications can be stalled while waiting for a single otherwise non-blocking request, while others could be served by the database. Such connections must be coordinated with transaction management, as the transaction is inherently connected with the connection that spawned it.

Read replica

A read replica is a special kind of database instance, a read-only instance of the database presenting additional query points for the applications accessing the database without having to resolve consistency between instances. With usual databases supporting multiple instances, concurrent writes to alternative machines could produce an inconsistent state in the database. With a read-only replica, consistency is not threatened; the only negative is the possibility

that the connections will receive a state that is delayed when the replica is not synced to the latest consistent state of the primary instance [26].

Creation and usage of read replicas can significantly speed up database performance as queries are no longer constrained by single hardware, which usually bottlenecks query speed. Duplicating the data over two instances can double disk read speeds; if different physical devices are used, slow sequential scans over data can run independently and finish faster.

JavaScript

A high-level dynamically typed programming language developed in the mid-1990s at Netscape Communications Corporation to add dynamic content to web pages. Initially called Mocha, it was later renamed multiple times to finally settle on JavaScript to use the (at the time very high) popularity of Java [27].

Before JavaScript, websites were almost always purely static documents that were displayed in web browsers (such as Netscape at the time or Google Chrome or Firefox currently). The logic for any web application had to be handled purely on the server side. With the introduction of JavaScript, web pages were able to be more interactive and dynamic. While initially designed to be used when writing HTML documents and executed by web browsers, it outgrew its client-side roots and conquered large parts of the server-side development and even mobile app and desktop application environments. The advantage of JavaScript is that it can be a completely full-stack language that provides exact parity of logic between client and server and allows for significant code portability.

Until the last few years, JavaScript had an exclusive reign over interactive web content, which made it one of the most used programming languages in the world [2]. With multiple deficiencies known and unfixable without massive problems with incompatibility, multiple additions which build atop JavaScript and even whole languages which compile into JavaScript were developed. Some complied languages are, for example, CoffeeScript [28], Dart [29] or TypeScript [30]. These languages exist to provide additional features and functionality that are not easily or at all possible in pure JavaScript.

ECMAScript

Soon after the introduction of JavaScript, it became apparent that establishing standards would be a necessary step for compatibility between implementations in different web browsers. Following this consensus, Ecma (originally an acronym for European Computer Manufacturers until 1994 [31]) International standards association meeting was held, and the first edition of the document specifying the new standard specification was adopted in June 1997.

The document, coded under the name ECMA-262 [32], is a comprehensive document that has gone over several versions over the years and specifies the syntax, semantics, and behaviour of the language. There is also an extensive description of data types, operators, flow control structures, built-in objects, and API.

ECMAScript is currently used primarily for client-side scripting, with primary implementations being those used in web browsers, such as SpiderMonkey (Firefox) [33], V8 (Google Chrome, Opera) [34] and JavaScriptCore (Safari) [35]. Increasingly with new revisions of the standard, even server-side applications and services have started migrating to ECMAScript from other standards (primarily CommonJS), but many constructs are not directly compatible or translatable.

CommonJS

One of the alternative specifications which reflected missing functionality in ECMAScript is CommonJS. Created to establish conventions on modularisation for JavaScript outside the web browser, it has also standardised several APIs and internal features [36].

Started in 2009 by an engineer at Mozilla, the project was initially called ServerJS, with its flagship feature being the synchronous loading of modules. This means that once a module is imported, its exported components are immediately available to be used [37]. This simplifies working with modules and was necessary for the expansion of JS code into server-side development and is used widely today.

Since its conception, gripes with the ECMAScript specifications were largely

fixed with further iterations, making it also usable in server-side development. Popular packages, including those exclusively used in server development, have migrated their codebase to ECMAScript.

TypeScript

A statically typed language built on top of the JavaScript foundation, TypeScript was developed by Microsoft Corporation with the focus on allowing developers to catch errors at compile time before the problem is encountered during runtime, which usually requires extensive testing. TypeScript code is written in enhanced syntax and then compiled into regular JavaScript, with several standards supported, including CommonJS and ECMAScript [22].

TypeScript was designed to address several shortcomings that have been present in the ecosystem for a lost time, especially when creating large-scale applications. JavaScript applications are very flexible with their dynamic and loosely typed nature and prototype usage, but with flexibility comes a large surface area for errors and mistakes.

Today, TypeScript is widely used for web development and JavaScript server-side development. Most popular frameworks provide at least partial support for TypeScript, and some (such as Angular and React) have even switched to it as the preferred language. TypeScript has support in many JavaScript-integrated development environments, such as Microsoft's Visual Studio Code [38] or JetBrains WebStorm [39]. With solid typing comes the ability for more substantial and consistent code completion, guaranteed automated refactoring, and error checking.

Other projects have tried to fix the same issues as TypeScript fixes. For example, Dart [29], which is developed by Google, works in the same way, although further from the traditional syntax. It is also compiled into standard ECMAScript syntax. However, it never gained the same traction, and its focus was changed from alternative to JavaScript to the primary language for development in the multi-platform framework Flutter.

Node.js

Node.js is an open-source, cross-platform JavaScript based on the V8 engine, which was originally developed by Google for Google Chrome. It is designed to allow for server-side usage of JavaScript, with focus on network applications [40]. Released by Ryan Dahl in 2009 [41], it has since become standard for server-side JavaScript development, especially web applications. The framework has gained popularity thanks to its alternative execution model, which separates it from traditional server-side languages. Instead of spawning different threads or workers for connections, it works with a non-blocking asynchronous I/O model, where many concurrent connections can be handled with only a small overhead [42].

This is achieved through asynchronous programming, where multiple tasks can be executed concurrently without blocking the main execution. Node.js supports asynchronous programming through the concepts of callbacks and promises. Callbacks are functions passed as arguments that are executed in finished or failed states, ensuring that logic can be applied sequentially after the asynchronous operation is finished. Promises provide a more structured and object-focused way to handle asynchronous operations and have become the preferred way. A promise is a representation of value which might not be available yet, containing a status variable and reference for the result once achieved, allowing for code execution while the operation status is updated in the background. When the value of the promise is necessary, the promise can be checked or awaited by using the `async/await` constructs [43].

While Node.js is currently the most dominant, there are other alternatives available with their own approaches and focuses. The most popular one is Deno, also developed by Ryan Dahl, intending to address some of the security and design issues of Node.js. Deno [44], for example, contains extensive tools and utilities within its standard library or uses better sandboxing between modules as supported by V8, the engine on which both it and Node.js run.

npm

One of the key benefits of the Node.js ecosystem is the large number of third-party packages that can be incorporated into projects. For example, many popular web frameworks, such as Koa or Express.js, are built for Node. Database drivers are also provided in module form, and therefore there needs to be a tool which allows users to incorporate such modules into their projects efficiently.

Originally an acronym for Node Package Manager [45], the three-letter name has been retroactively stripped of such meaning [46]. The first release was published in 2010, and it has since become the default Node.js package manager. Npm consists of a command line client, which is also called npm, and an online database of packages called the npm registry, which is hosted at www.npmjs.com.

Although npm is the default package manager, alternatives that were created with different focuses and compromises exist, for example, yarn [47].

JSON

JavaScript object notation (JSON) is a lightweight data-interchange format that is widely used in web development. Introduced as an alternative to the complex XML format that was previously used, it is based on a subset of JavaScript representation of values. It consists of key-value pairs in objects, arrays, and primitive types. One of the main benefits is its simplicity and readability for humans, which makes it useful for places where data could need to be interpreted by both humans and machines.

JSON has been standardised in the ECMA-404 [48] document by Ecma International. The document specifies syntax and semantics, ensuring its reliability, consistency, and portability throughout systems and applications.

Unit of Work

Unit of Work is a software design pattern used most commonly in ORMs and similar frameworks to manage persistence and consistency between application

and database state. The pattern is used to group all database operations relating to a single transaction or process and only execute the final state, ensuring they can be performed atomically without requiring lengthy and expensive locking of database rows or tables or risking deadlocks through database transactions [8, p. 184].

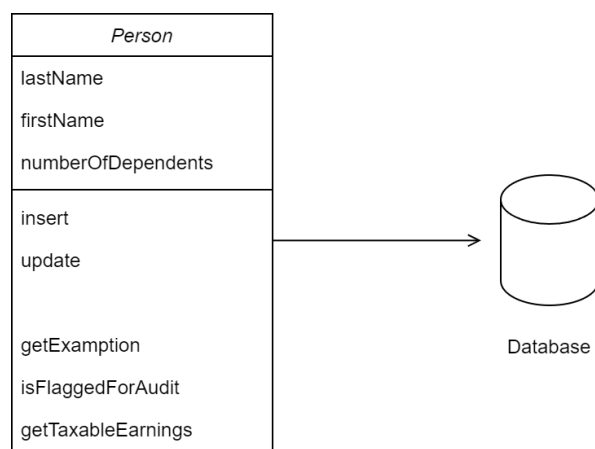
The main idea is to track changes across the object in memory, and instead of committing every change into the database, only the last state change is executed. This can be applied not only across one object instance but also across whole swathes of objects. While atomicity is undoubtedly necessary on many occasions, and unit of work on the ORM side can significantly reduce the number of requests to the database, it can also lead to inconsistency when multiple applications access the database and data which are currently loaded in memory on one machine are modified by a different one.

Active record

The Active Record pattern is a design pattern defined by Martin Fowler in his book "Patterns of Enterprise Application Architecture" [8, p. 160] and is commonly used to represent database records in an application.

The goal of the pattern is to encapsulate logic for interacting with the database table into a single object. Each instance of the object represents a

Figure 1.1: Active pattern class diagram, recreated from Patterns of Enterprise Architecture



single record, and modifications made on it are then usually flushed with a method call into the database. The base class also provides static methods for CRUD (create, read, update, delete) operations and possibly additional business logic.

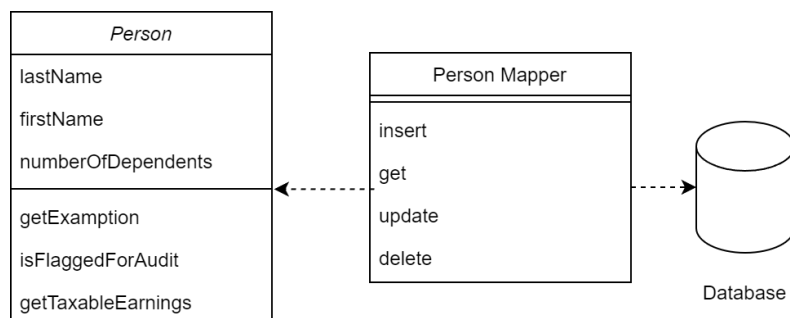
The main benefit of the Active Record pattern is a simple and intuitive interface for objects and tables. Modifications of the object can be made right on the data in languages, which allow setters and getters on attributes, and static methods provide a simple gateway to work with the table.

Limitations of the pattern come in the tight coupling between the application and database logic, as the object instance is inherently tied to the database representation. This makes it harder to test the implementation and often requires additional abstraction or mocking. Additionally, the pattern does not easily allow for the management of relations, so a database schema with complex relations might not be able to represent the data easily.

Data mapper

The Data Mapper pattern, as described by Martin Fowler in his seminal work on enterprise application architectures, provides a clear separation between domain models and their underlying data storage. This approach enables developers to create complex and expressive domain models without being constrained by the relational database schema or various storage options. By decoupling in-memory representations from the data storage mechanisms, the Data Mapper pattern promotes a clean separation of concerns and enhanced

Figure 1.2: Data Mapper class diagram, recreated from Patterns of Enterprise Architecture



flexibility in application design [8, p. 165].

Distinguished from the Active Record pattern, the Data Mapper pattern ensures that business logic and data access responsibilities remain separate. In this approach, a single entity represents the table or collection, while distinct entities represent individual records. The Data Mapper serves as a data access layer that performs operations on the data storage representation without creating any direct bindings between in-memory objects and the database. This responsibility is solely managed by the Data Mapper, which takes care of any objects that utilize it.

This separation enables applications that employ the Data Mapper pattern to adhere to the Single Responsibility Principle, one of the SOLID principles of software design popularized by software engineer Robert C. Martin [49]. By limiting the responsibilities class must service and ensure that it is not accountable for multiple unrelated tasks, the single responsibility principle aims to create more straightforward and more maintainable classes. Consequently, the Data Mapper pattern contributes to a more robust and modular software architecture that is easier to develop, maintain, and extend.

However, the Data Mapper pattern has drawbacks. One notable downside is the increased complexity introduced by the additional layer of abstraction. This added complexity could lead to a steeper learning curve for developers unfamiliar with the pattern, as well as the potential for increased development time. Moreover, the mapping process between domain objects and the persistence layer may introduce performance overhead, which can be a concern for applications with stringent performance requirements. Additionally, implementing the Data Mapper pattern often necessitates extensive configuration and mapping code, which can be time-consuming to write and prone to errors.

MVC architecture

The Model-View-Controller (MVC) architecture is a prevalent design pattern in software development, emphasizing the separation of concerns by organizing application components into three distinct roles. This architectural pattern, originating from the work of Trygve Reenskaug in the 1970s, has found

widespread use in modern web development across various programming languages and frameworks [50].

The three components of the MVC architecture, Model, View, and Controller, each serve specific purposes. The model represents the application's underlying data structure and business logic, encapsulating core functionality, ensuring data consistency and handling the data storage and representation. In contrast, the view is tasked with rendering data and presenting them to users in an intelligible format. The controller functions as an intermediary between the model and the view, processing user input, manipulating the model, and updating the view as needed [8, p. 330].

Separation of these components from the MVC architecture facilitates modularity, maintainability, and testability in software design. Each component can be developed, tested, and updated without interaction with the other layers, simplifying the development process and making it more manageable to identify and resolve issues. Furthermore, the separation of concerns allows developers to concentrate on a single aspect of the application at a time, resulting in more organized and efficient code.

However, the MVC architecture has drawbacks. One notable disadvantage is the added complexity resulting from the additional layers of abstraction, which might be challenging for inexperienced developers and could prolong the development process. Additionally, some critics contend that the strict separation of concerns can create a rigid structure that might need to be better suited for applications with rapidly changing requirements or unconventional designs. Such structure may be too complex for many projects, which would benefit from more concise and flexible architecture.

Framework selection

Selecting the optimal framework for any project can be difficult, with many parameters and options to consider, and quite often, there are better options than the most popular. The JavaScript ecosystem is rich in choice, as throughout the years, many developers and companies have aimed to create packages in their image. Mainly due to this plethora of choices, there is a need for an overview, which would present advantages and disadvantages. However, only some frameworks can be reviewed; therefore, at least essential criteria need to be established.

The selected packages were selected for their support of TypeScript, with varying levels of compatibility, which will be shown in further detail later. Additional criteria considered were popularity and support as separate factors, leading to the inclusion of widely-used packages with currently limited support and development and lesser-known packages with solid support.

2.1 Typescript support

The primary selection criterion for the packages was TypeScript compatibility. Each package had to have at least a basic functionality working and typed, requiring only reasonable effort to integrate. The degree of support varies among the packages, and their level was also measured in comparison, but the base level was necessary to be considered.

The functionality considered essential is not easy to define either, but as the level of type support varied, the minimum settled on was package and

connection setup and simple querying. The package had to have connection options typed, at least for primary usage, as listing all options for all connections is not necessary for most uses. Querying and updating database records is the most common activity for which ORMs and connection builders will be used, so the types they provide are some of the most useful. The result of a simple non-joined query on one table should be able to return exact and correct types, and an update of the record should also at least suggest the attributes which can be changed.

2.2 Popularity and Support

Popularity was inherently a factor in the selection of packages; if the package was known more, its likelihood of being found was smaller. We researched popularity in several ways; the primary source was searching by name and keyword ORM on the npm repository [51]. Secondary sources were articles on ORM and database access in Node.js [52], [53]. The npm repository provides statistics about the packages listed on it, the most prominent being weekly downloads. The statistic is good for basic orientation but is not a great indicator of the exact number of users, as users can download the package multiple times, most packages are cached by third parties, which automatically download a version when it is released and many more ways, which skew the number. Additional input for popularity was the number of issues and stars the project currently holds on GitHub.

Support is a secondary attribute that is highly linked to popularity. Although all packages reviewed are open-source, only maintainers can merge code into the main branch or release versions onto the registry. If they are no longer active, the project effectively stops. While they can be released under a new name if the licence permits such a thing, no packages missing implementation into the benchmark have forks that would relieve the issues encountered. High-quality support is crucial for addressing issues, incorporating new features and compatibility with changes in underlying technologies.

2.3 Implementation criteria

Although some packages were initially selected for comparison, as previously mentioned, problems that needed to be more severe were encountered during their implementation into the included benchmarks. They will still be introduced, and the issues explained; however, they will only be included in comparisons within the basic summary.

Ranking and Grading of the Frameworks

This chapter outlines and explains the criteria for evaluating ORM and SQL query builder packages chosen for the comparison. These criteria will be the core points which will be considered, but other specific notes will be made about each package. The main criteria were the level of TypeScript support, range of compatible database management systems, popularity, support, documentation quality, dependency count, and performance in different scenarios.

3.1 Quantifiable Criteria

The main section of the evaluation criteria focuses on technical aspects of the frameworks, specifically their usage of TypeScript, support for different databases, and difficulty composing queries. As these qualities are quantifiable, they were given the highest priority in comparing the packages.

3.1.1 TypeScript Support

The quality and extent of TypeScript support vary among the packages, with some offering better integration and type safety without the need for casts. In contrast, others only provide basic typing or require result type definitions to be written into each request, which amounts to the same behaviour as if the result was cast. Such functionality often comes when the package initially

written for JavaScript is not rewritten in TypeScript but is only provided with a `types` file, which specifies call signatures, but cannot provide other assurances.

3.1.2 Database Compatibility

Database compatibility is not necessary when working with a large project that may encompass many services or when choosing a toolchain for a team, as the one database may not satisfy all the needs the team might have, and building experience with multiple frameworks could be considered unnecessary spending. Providing a unified API over multiple databases can be one of the benefits of query builders or object-relational mapping frameworks.

3.1.3 Flexibility and Performance

Flexibility and performance are crucial in a database access framework. Suppose the package would restrict the ability to access the data, requiring roundabout ways to deal with basic operations. In that case, there are better ways to simplify development, just as if the framework creates excessively suboptimal queries or adds excessive overhead. One of the requirements for a comprehensive ORM framework is the ability to support many use cases and represent and work with many different data models. If ORM cannot allow use cases or cannot represent commonly used database design patterns, it is lacking in some ways compared to one that does.

Performance is often secondary when choosing an ORM framework, as quite often, even frameworks adding significant overhead and creating suboptimal queries are not noticeably slowing down the application. As the application grows, the performance can become significantly more critical, and the resources needed can be more expensive to scale. A high-performing package can support this growth by maintaining efficacy under load and effectively using its available resources.

Performance was measured in multiple ways; the first metric was the execution time of a single query to measure the latency added by using the framework, compared to using other frameworks or plain database drivers. Benchmarking this way provides information about the amount of overhead

the framework requires to function, and if the connection pool is well initialized, connections are assigned optimally, and data are correctly retrieved. The second benchmark run repeats the test multiple times to eliminate any inconsistency that could occur in a single run.

3.1.4 ECMAScript and CommonJS compatibility

There are two different primary standards for JavaScript syntax, ECMAScript and CommonJS. They primarily differ in how the inclusion of modules is written and the mechanism of the module import. While CommonJS was prevalent in the server backend space for a long time, however, ECMAScript modules are becoming significantly more popular, with support added in both Node.js and TypeScript.

Combining packages from both ecosystems can still lead to problems. The best way to support all possible combinations is to provide both types of dependency declarations.

3.1.5 Licence

As developers consider integrating packages into their projects, it is crucial to consider and understand the significance of licences governing their use. Open-source software is often regarded as a valuable resource, offering a large amount of reusable code and often the best solution. However, it is essential to understand that open-source does not necessarily equate to unregulated use. Licences still dictate the terms under which the package and its code can be employed, modified and redistributed. Therefore, developers must examine the licences of potential packages to ensure their intended use aligns with the terms granted.

The most permissive licences allow for usage, modification and redistribution without any requirement to credit the original author/authors or maintain the same licence in derivative works. Examples of such permissive licences are *MIT License*[54] or *Apache License 2.0*[55]. These are generally preferable for projects that demand flexibility in their use of the software.

While still free, the opposite side to the permissive licences are copyleft licences, which impose more stringent requirements on the usage, especially

modifications and redistributions of the software. The primary example of such a licence is *GNU General Public License* [56], which requires derived works to be distributed under the same licence.

Since copyleft or other provisions might limit the usability of libraries such as ORMs for many projects, it is necessary to include the licence as a grading criterion.

3.2 Package Properties Criteria

However, technical criteria are only some that should be considered when selecting a framework. Many of these factors are interconnected; often, success in one is either caused by or preceded by doing well in others. For example, while the popularity of the package can show the reliability and usability of the package, it also often results in more issues reported and fixed, and more users are more likely to create community resources supplying or improving official documentation.

3.2.1 Popularity

Popularity measures usage, as indicated by package downloads, the number of issues, and the number of users on GitHub who have shown interest in the repository. While all imperfect measures for absolute popularity, they help compare popularity between packages by their relative difference. In the case that the package usage requires multiple dependencies to be installed, for example command line interface for development and runtime dependency, the highest number is listed.

3.2.2 Support

The number of resolved and still open issues can be used to show popularity and support of the project. With such a metric, support can be measured; however, more important than that are the patterns of behaviour which maintainers have shown previously. If the release schedule is predictable, bugs and security issues are fixed quickly, hesitant adopters can be assured that this pattern will continue, and the framework is a safe investment. On the contrary,

a project which is officially or probably no longer supported can be assumed to be a wrong choice, as it cannot react to newly found errors and problems with dependencies and might be unusable due to changes with TypeScript or Node.js runtime.

3.2.3 Dependencies

As dependencies require maintenance due to their changes and vulnerable versions, their amount should also be manageable. Otherwise, it might increase the maintenance cost for the package and application size. Even though data storage is less critical than previously, having a more storage-conscious package is still beneficial.

3.2.4 Documentation Quality

Documentation quality is critical for new adoption and onboarding for working with the framework. It also cannot be measured with reasonable objectivity. Perceived quality depends on language understanding and users' previous experience with the programming language and similar frameworks. Evaluation of documentation will therefore summarize clarity, extensiveness and whether features such as JSDoc annotations [57] which can be parsed by IDEs are used to contain or link to the documentation.

The following chapters aim to provide a comprehensive and in-depth analysis of packages compared by evaluating each package by these comprehensive criteria with additional added when.

Benchmark database schema design

This chapter describes the database used for performance testing of the ORM and query builder packages. The database is designed around imaginary data collection about cats, their home domiciles and toys found within these houses, and the toys' manufacturers. The database comprises six main entities - `cat`, `cat colours`, `colour hex codes`, `houses`, `toys` and `toy producers`.

4.1 Cat Entity

The `cat` entity instances represent individual cats which we want to monitor. Each has a unique identifier, name and date of birth, all of which are nullable except for the identifier. This entity aims to represent the basic database table and to verify the correct handling of the data type from Postgres, as JavaScript Date time represents a moment, including time [58]. In contrast, the database entry would only contain the date [59]. Additionally, the `cat` entity uses big integer data type, and handling numbers beyond the standard range allocated in JavaScript is tested. The `cat colour` and `colour hex code` are two entities that represent the cat colour by its name and by its hex code. The entities are intentionally split in this way to use identifying relation [60] - the primary key of the hex colour entity is also a foreign key referencing the id of the cat colour entity.

4.2 House and Toy Entities

The **house** entity represents domiciles where the cats spend their time at their behest. The relation must also account for ambitious cats using several houses as their homes. The main aim is to test the difficulty of implementing and using simple many-to-many relations. The only attribute that provides new data type or behaviour is the simple **has_dog** attribute, specified as a Boolean. It is one of several attributes that test the frameworks' ability to correctly type and convert the data recovered from the database.

The houses can be equipped with many toys for the cats to use. The relation between houses and toys is modelled through a decomposition table which contains attributes representing the number of the same toy in the house. While the primary keys are the identifiers of the house and toy, the decomposition with the amount, rather than several records with an additional identifier, is designed to test the ability to insert a record if it does not exist or update the value referencing its previous state. If more toys are purchased, the owner of the house does not suddenly throw out all toys they already

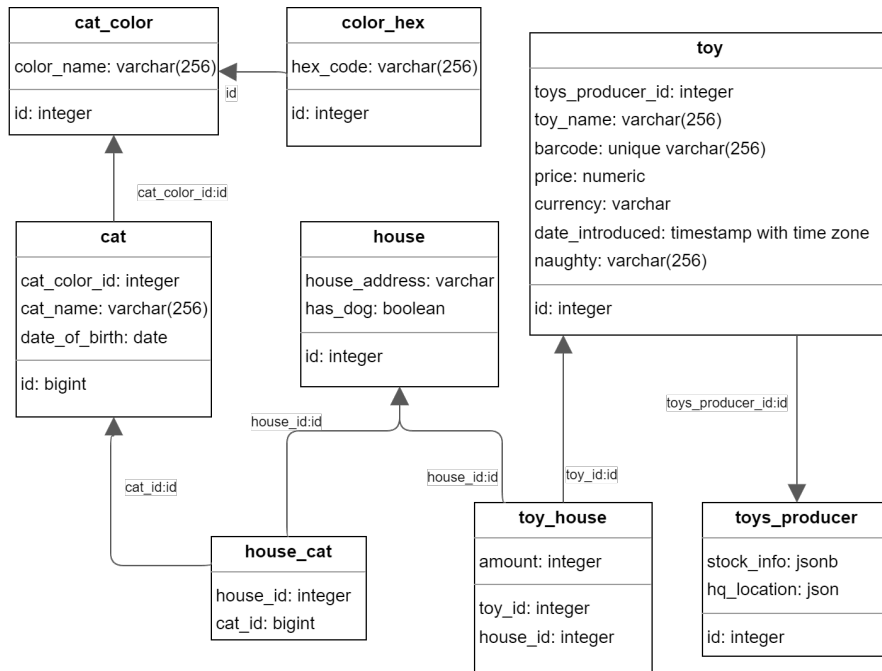


Figure 4.1: Schema of benchmark database

had; they will add them to their current pile. This operation is often called *upsert* - a combination of update and insert, and some database engines, such as CockroachDB [61], implement it explicitly under this name. PostgreSQL achieves it using the `ON CONFLICT` statement in `INSERT` query [62]. It also tests the handling of composite primary keys, a standard paradigm in many databases.

4.3 Toy Entity

The `toy` entity purpose in testing is in numeric data type used in `price` attribute and usage of additional column attributes such as `CHECK` constraints or `DEFAULT` values in the column [63]. Column `naughty` is focused on commonly problematic strings in software development, such as special Unicode characters, emojis and other issues that could come up in handling data from the database, especially if the encoding is not correctly handled. Toys producers host the `JSON` columns to test if it is possible to use advanced `JSON` traversal and query operators provided in PostgreSQL [64] (and their equivalents in other database management systems).

Benchmark Framework Design

The benchmarking process was designed to compare the performance of various ORM and SQL query builder packages. As such, it was important to ensure that the benchmarking framework was developed in the same environment as the packages themselves. To achieve this, the framework was implemented in TypeScript, the same language used by the packages being tested.

The benchmarking framework had to be designed to accommodate errors that could occur during development and testing of the packages. Additionally, it had to support testing of multiple database schemas and allow results to be exported in a variety of formats for further analysis. The resulting benchmarking framework provides a robust and comprehensive means of comparing database access packages.

5.1 Test Suite and Schema Separation

The benchmarking framework was designed to support separation of tests into multiple test suites, a common practice with JavaScript test frameworks such as Jest [65] or Mocha [66]. Test suite separation allows for organization of tests by subject and contains specifications about the database schema and data expected to be executed. Input and output parameters must be typed to test types support, and the framework should provide sufficient functionality to avoid the need for casting.

The tests are expected to be run simultaneously with snapshots of the

database schema and should not interfere with data used by another test suite. As a deliberate choice, this limits the scope of each test's modifications over the database and data. However, it eliminates the need to reset the database to the original state after each test suite, reducing the time it takes to run the benchmark.

5.2 Test type and Error Handling

The framework needs to support multiple tests to ensure the validity of any results it produces. If performance is measured, multiple runs can reduce the impact of statistical anomalies, which can occur due to the innumerable number of external events.

Along with performance, the correctness of both query types, resulting runtime types, and the result value are essential. As types are only visible before compilation, and with typed test suite definitions TypeScript compiler would not compile the code, as it would raise type inconsistency. Even incorrect types will be necessary to be cast into their expected value. However, even just the need for such modification means the package must allow more type definitions.

Resulting runtime types and values are validated using the node module `node:assert` [67], which provides assertion functions. It is provided to function with testing frameworks such as mocha, which do not offer verification functions. Included are even deep equality checking functions. The main advantage, however, comes from being included in the Node.js standard library, meaning that no additional package has to be included.

Returning an incorrect result is one of many ways the benchmark test can be failed; the package can return an unexpected error, or the test is impossible to perform. Both are fail-states, which the benchmark suite must account for with error handling. One choice during the design process was that a single failure would mark the real test as failed, even though other iterations succeeded. If the package caused the issue, that means the package is not reliable enough.

5.3 Multi-Framework support

The benchmarking bootstrap is designed for sequential testing of multiple packages. This design, rather than separate execution, allows for comprehensive comparison under the same conditions, ensuring accurate results. As managing the dependencies could prove problematic if packages had different dependencies required, npm workspaces [68] were selected as a project structure. That way, top-level dependencies of the framework can be separated from the individual implementations.

5.4 Reporters - Output options

An integral part of the design was the inclusion of reporters. Reporters provide an interface and implementation of multiple output options, enabling the results to be saved and shown in various formats. Standard test frameworks utilize reporters to make code coverage or detailed error stack inspectable. The reporters can interpret the data in different formats with a benchmarking framework. The reporter interface is designed to be extensible, allowing for the easy addition of other output options or data interpretations in the future.

Benchmark implementation

The design of the benchmark overhead leads directly to its implementation. The benchmark functionality, written in TypeScript, involves two main components: the **BenchmarkRunner** and **BenchmarkSuite** classes. The classes work together to manage the ordering of tests, database administration, and execution of test suites, as well as handling packages, test suites, and reporters. The simplified class schema is shown in Figure 6.1.

6.1 BenchmarkRunner

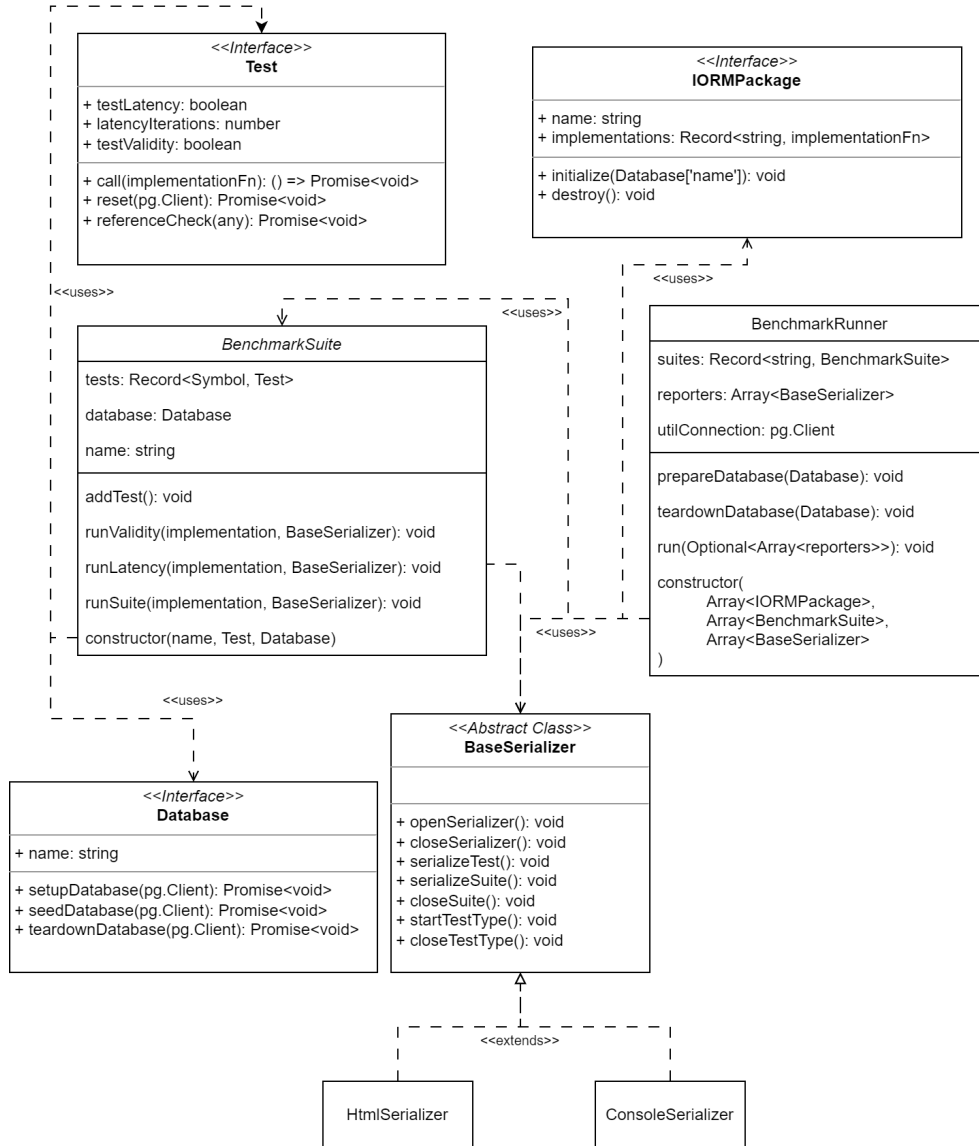
The **BenchmarkRunner** class is responsible for managing the benchmark's overall execution. It holds information about the test suites, ORM and query builder packages being tested, and the reporters. The class has responsibility for database administration while also ordering and executing the test suites on their respective database schemas.

Database administration tasks include setting up and tearing down example databases used in testing. Tests are currently written only for the database examined in chapter 4, therefore this functionality is only used to initialize the database to preserve a consistent state. In order to perform these tasks, **BenchmarkRunner** maintains its database connection using the default **pg** module.

The benchmark runner is also responsible for ordering, initialization and execution of individual packages and tests. Each package is declared using a unified interface, which defines initialization and destruction methods for

6. BENCHMARK IMPLEMENTATION

Figure 6.1: Simplified schema of the Benchmark class architecture



efficient memory usage, implemented test suites and package name. The order of executions is guided by the database schema selected, the package, and individual test suites. If any suites are not implemented in the individual package declaration, the reporters are notified, and the tests can be marked as not implemented in the report.

6.2 BenchmarkSuite

As the name suggests, **BenchmarkSuite** represents each test suit of the benchmark. It covers the specification of each test, including validation function, name, parameters and options for running the test. This design ensures type safety for running the tests as they implement the interface defined for the suite. The options include which tests should be performed or how many loops to execute for repeated tests. Class methods implement individual types of tests, error handling for individual runs and measuring the execution time of each test run.

Two implemented test workflows, validity test and latency test; validity test runs each implementation once, tests if the value is equal to reference in both value and the runtime type and returns test result. The latency test executes the tests in a loop, intending to show if the framework can create well-crafted queries without adding significant overhead.

6.3 Reporters

As the output of the benchmarks is meant to be interpreted by humans, the measured data needs to be transformed into a human-readable format. Test objects contain vital information, but the benchmark output consists of thousands of such objects; therefore, they must be converted into valuable data. Two reporters were implemented for this benchmarking framework, with an interface for further reporters.

6.3.1 Console Reporter

The primary reporter for use in development intends to provide simple benchmark results in table form. While running the benchmark, it allows for quick

assessment of any errors and monitors the progress of the run.

6.3.2 HTML Reporter

The HTML reporter is the primary source for any data analysis of the benchmark run. It consists of a template file and the reporter. The reporter receives data from the benchmark using the unified API, parses it, and inserts it into the template file as a JSON string once the benchmark is finished. Along with the data, cascading style sheets are also inserted, as they are written in **Sass** language [69], which must be compiled before the HTML file viewer uses them. After the template is completed, the file is saved separately, and graphs are created on runtime using JavaScript.

While the data could be served dynamically, this separate file allows for multiple runs to be saved and be independent of the server which would provide the data. The JSON is available and can be inspected if further analysis is needed.

6.4 Benchmarks

This section will list and describe all the benchmarks developed to compare individual packages. In addition to comparing performance, the requirements for implementation are comparison, as an easily implemented framework is better than one that's difficult to, provided they both perform similarly.

6.4.1 MVP Benchmark

This test suite was only implemented under the *Knex.js* package as its purpose is to test the functionality of the benchmarking framework and does not test any database functionality. It is proof of concept for correct validation and exception handling tests for the benchmark suite and runner implementation. It consists of a small number of tests, including a fully passing test, a test expecting **Skipped** exception, which is used for marking tests which are not implemented, tests whose results are mismatched in value or runtime type, and a test that throws generic error on execution. Additionally, MVPBench

examines if test configurations are working as they should be, testing both validity and latency settings.

6.4.2 Entity Traversal Benchmark

One of the generally provided functionalities of ORMs is the ability to define entities and their relations. This benchmark aims to test the ability to use these defined relations to find objects using these connections. The first test of the suit focuses on finding a cat's colour in hex by traversing two relations, one of which is identifying. The framework starts with the cat's ID and needs to fetch the `color_hex` instance through its connection to the `cat_color` instance. Thanks to the relation design, there is a guarantee that only one result will be returned at any time. The second test counts cats by their colour hex code, traversing the relations from the first test in the opposite direction. Instead of selecting, the test counts the cats, testing if the query difficulty changes if we use aggregate functions instead of basic `SELECT` query. The third test in this benchmark selects all toys available to a cat, primarily focusing on the format of the returned data and how well the decomposition table can be accessed or avoided. The decomposition table exists because of the M:N relation between toys and houses, but the additional amount attribute is not used.

6.4.3 Edge Cases Benchmark

The edge cases benchmark aims to evaluate database adapter performance in specific situations that may not be commonly encountered but can potentially cause problems. The two tests in this benchmark focus on data type conversion and parameter handling.

`BigIntColumn` test examines the data type conversion for the `BigInteger` type in PostgreSQL. JavaScript's `Number` type can lose precision when handling large integers since the maximum safe integer for `Number` is $2^{53} - 1$ [70], while PostgreSQL's `bigint` type can store numbers up to $2^{63} - 1$ [71]. Although the `BigInt` primitive [72], which can store integers with arbitrary precision, was introduced in ECMAScript 2020 (ES11) [32] and has been implemented in Node.js since 2018 [72], not all frameworks handle this type

correctly. The frameworks can either cast the value to `Number`, losing precision and failing the test, or return the value as a string or, ideally, as a `BigInt` primitive.

SQL Injection test assesses the framework’s basic handling of parameters. One of the main reasons for using a database access package over a basic driver is to improve security against SQL injection attacks. The code will return all records if the parameter is sent as part of the SQL query. If the package incorrectly escapes the query, it will result in no results returned. Only the correct handling of arguments will return the specific Cat with the fascinating name a “’ or true --”. It is important to note that this test does not evaluate whether the package is entirely vulnerable to SQL injection attacks but rather if the basic handling of arguments is not vulnerable.

6.4.4 Special SQL Actions Benchmark

The Special SQL Actions benchmark evaluates the performance of frameworks in scenarios that go beyond basic querying, focusing on unique ways of interacting with the database. This benchmark comprises several tests, each targeting different aspects of database interactions.

The *upsertToysToHouse* test examines whether the package contains an upsert operation method and assesses its flexibility, such as the ability to differentiate between the insertion and update objects, as well as the capacity to reference the updated value. The test uses a `CatDatabase` schema that includes a decomposition table called `ToysHouse`, which stores references between houses and toys and the quantity of each toy type in the house.

The suite also contains tests which evaluate the handling of JSON columns in the database. The *JSONColumn* test checks the ability to parse JSON values from the database, while the *JSONWhere* test focuses on querying based on the value of an object key inside the JSON column. PostgreSQL provides two ways to query the value: extraction operator `->>` for simple comparisons or `@>` operator for more complex comparisons with JSONB datatype [64], which are useful for developers using SQL, but the abstraction of ORM might remove the access to these methods.

The *transactionalOperations* test investigates how individual packages han-

dle transactions, assessing the full range of operations available for reverting changes to the data.

Lastly, the *likeQuery* test examines the methods each framework uses for pattern-matching queries, evaluating basic search functionality in the database by searching for a part of a house address.

By understanding how different frameworks handle these particular SQL actions, developers can make informed decisions when selecting a database adapter that aligns with their project's unique requirements. The benchmark ensures that developers are aware of each package's various capabilities and limitations, enabling them to choose the most suitable solution for their specific use cases.

Individual packages

In the following chapters, we will discuss each package in detail, highlighting its essential characteristics and the results it produced when tested using the custom-designed benchmarking framework. This comparative analysis will enable us to evaluate the packages objectively and provide valuable insights for developers seeking the most suitable ORM or query builder for their TypeScript projects. The results for each package will be examined in the context of the package, with a simplified summary at the end.

7.1 pgTyped

PgTyped, primarily developed by Adel Salakh [73], is an open-source package that, while not technically an ORM or query builder, offers unique functionality for TypeScript developers. It analyzes SQL queries written by developers and, through database introspection, creates typed helper methods for executing those queries. The final usage is shown in Listing 1. This package is designed specifically for TypeScript, resulting in excellent typing but occasionally leading to complex errors, a common issue with other highly typed language-based packages like Kysely.

The package is compatible only with PostgreSQL, as each database requires its own parser and introspection process. PgTyped uses the 'pg' connection package, which is only compatible with PostgreSQL. It provides complete SQL flexibility with minimal overhead, allowing developers to use it without limitations that come with pure SQL queries. However, it lacks the

abstraction typically found in ORM or query builder packages, making direct comparisons challenging.

PgTyped supports both ESM and CommonJS dependency initialization, ensuring excellent compatibility at the expense of a slightly larger package size. It is released under the MIT license, a highly permissive option. Its popularity ranks relatively low, with its main package, "`@pgtyped/cli`" receiving only about 10,000 downloads weekly [74]. On GitHub, it has more stars but still falls within the lowest third of the packages compared.

The package is well-supported, with regular version releases and active issue resolution. Most long-lasting issues are feature requests rather than bug reports. As the package is divided into development and runtime components, the CLI package can afford more dependencies than combined packages. The runtime dependency has only three direct dependencies: the widely-used `chalk` and `debug` packages, and the parser dependency, which adds `antlr4ts` for ANTLR 4 (ANother Tool for Language Recognition) grammar functionality in TypeScript/JavaScript [75].

The documentation is brief [76], providing examples and a quick start guide that covers the essentials for using the package. While the generated types lack method information, the original query is included in the Javadoc annotation, making it easily accessible during development. PgTyped is a unique and flexible package for TypeScript developers working with PostgreSQL. However, it may provide a different abstraction level for those seeking a traditional ORM or query builder solution.

Performance in benchmarks

In line with expectations, the pgTyped package outperformed all other packages examined in the study. Most pgTyped operations are executed before or during compile time, yielding performance metrics comparable to those achieved using the plain *pg* driver. While the package does not offer explicit support for parsing esoteric primitive types such as Decimal or Big Integer—resulting in their return as strings (akin to the *pg* driver’s approach)—it does provide a specific type for `JSON` and `JSONb` columns. However, these types must be sufficiently generic, which limits their overall value.

```
// -- File: EntityTraversal.sql
/* @name countCatsByColor */
SELECT
  COUNT(*)
FROM
  cat
  JOIN cat_color ON cat_color.id = cat.cat_color_id
  JOIN color_hex ON color_hex.id = cat_color.id
WHERE
  color_hex.hex_code = :hexCode;

// -- File: EntityTraversal.ts
import {
  countCatsByColor,
} from './EntityTraversal.queries'

return countCatsByColor
  .run({ hexCode }, getClient())
  .then(result => Number(result[0].count))
```

Listing 1: Usage of pgTyped

As is typical with intricate TypeScript interfaces, the errors frequently encountered when using pgTyped can be challenging to interpret and offer limited guidance regarding type hinting. Despite this, the package proves advantageous in error detection.

It is important to note that the pgTyped package solely supports single-command queries. Consequently, each query had to be separated during the transaction tests, with the commands for initiating and rolling back transactions explicitly written as SQL code. This limitation warrants consideration when selecting a package for implementation within a context.

7.2 @databases/pg

The @databases/pg package is developed by Lindsay Forbes, a prominent contributor to the Node.js ecosystem with hundreds of published packages. The package offers a simple interface for CRUD operations on individual tables in

TypeScript. The package's typed interface is derived from schema definitions in interfaces, which can be generated using the `@databases/pg-schema-cli` [77] package. However, the package lacks support for table joining, making it suitable only for basic queries. Complex queries require a combination of templated SQL and conditions written using module functions with types.

Though not as feature-rich as a typical ORM, the package simplifies basic querying more than a standard query builder. It is exported as an ES module and was initially licensed under GPLv3 but is now published under the MIT License. The `@databases` project supports multiple databases via modular drivers, with official support for Postgres, MySQL, SQLite, and Expo/WebSQL [78]. Postgres has the most advanced support, with additional databases supported through modular drivers.

The package has 517 stars on GitHub and 26,613 weekly downloads which makes it the fourth least downloaded and the second least known on GitHub [79]. The project is actively developed and comprises numerous subpackages, with new databases being added and bugs frequently addressed. The package depends solely on internal modules or widely used packages, for example `assert-never` and `cuid`, along with the `pg` driver as a dependency.

While the documentation quality could be better, offering basic information, a quick-start guide, and examples, there is no inline documentation requiring developers to consult the online documentation. Database migrations can be managed and executed using the `@databases/pg-migrations` package, supporting both `.sql` and `.ts` formats. However, no interface is provided for TypeScript migrations, necessitating custom scripts, and no schema modification methods are included in the package.

`@databases/pg` is a package that simplifies basic querying in TypeScript by providing a straightforward interface for CRUD operations. Although it lacks the extensive functionality of a traditional ORM, it offers compatibility with multiple databases and has an active development community. However, the absence of inline documentation and limited support for complex queries and migrations may require developers to rely on additional resources and tools.

Performance in benchmarks

As anticipated, packages with minimal abstraction, such as `@databases/pg`, tend to exhibit superior performance in latency tests. Notably, this package is among the few capable of automatically converting Big Integer values to their corresponding JavaScript type.

The benchmarks depended a lot on queries which were at least majorly manually written, only providing shortcut methods for basic operations and helpers for parameter insertion.

Nevertheless, the `insertOrUpdate` method [78], meant for upsert operations, has a limitation, as it cannot differentiate between objects designated for updates and those for inserts. This constraint poses challenges for operations such as value incrementation or decrementation.

While `@databases/pg` does offer support for transactions, the package lacks an API for managing these transactions. Instead, it only provides the functionality to encapsulate operations within a transactional context. This aspect should be considered when evaluating the suitability of this package for particular applications.

7.3 Zapatos

The Zapatos package, developed by George MacKerron, is designed to provide type safety for database querying in TypeScript, specifically for PostgreSQL through the `pg` driver. It generates a TypeScript schema of the database via introspection, offering methods for basic CRUD operations that are instantly typed and function as shortcuts for generic queries. Additionally, it features tagged templates for writing arbitrary SQL [80].

Unlike `pgTyped`, which analyses queries and generates types, Zapatos disallows the inclusion of any data not specified in the manually typed query. This approach can lead to issues if the type is not defined correctly initially, potentially resulting in an unreliable type and is less explicit way to cast the result. Despite this limitation, the package supports lateral joins, enabling the return of nested objects, a feature typically not found in packages with such low abstraction levels. However, as with other TypeScript-dependent

packages, Zapatos can generate compilation errors that are difficult to parse.

Released under the MIT license, the package uses ESM module dependencies and has 14,933 weekly downloads and 980 GitHub stars, ranking it third least downloaded and starred. It is regularly updated, and none of the reported issues in the repository significantly limit its use. The package has no runtime dependencies, only development dependencies.

While the documentation quality is generally good, it is brief but covers most of the necessary information for getting started, although lacking in detail. Similarly, the annotations for types provide only brief information, insufficient for guiding development on their own.

In summary, Zapatos is a package that provides type safety for database querying with PostgreSQL, offering typed CRUD operations and tagged templates for SQL. Although it takes a different approach to type generation than `pgTyped`, it supports lateral joins and nested objects. The package concise but sufficient documentation for most users [81]. However, the package's limitations include possible type inaccuracies due to developer error and challenging compilation errors.

Performance in benchmarks

In the performance evaluation, the Zapatos package proved notable, as it was, for example, among the few packages that permitted the utilization of distinct objects for updates and inserts during `upsert` operations without requiring a complete query. This package exhibited low latency in explicitly written queries and shortcut functions, typically only surpassed by `pgTyped` or `@database/pg`, which both employ a more rudimentary representation of the SQL language.

However, a significant challenge was encountered during the Big Integer data type test, as the identifier's value was altered due to its conversion to a number before being returned. This issue was resolved by employing an explicit SQL query instead of the shortcut function `db.selectExactlyOne`. This unexpected result is particularly striking, given that the framework conducts introspection over the database, correctly identifying the schema as `int8`. Nevertheless, the shortcut function converts the column value into

```
// Value incorrectly converted into a number
db
  .selectExactlyOne('cat',
    { cat_name: name },
    { columns: ['id'] })
  .run(pgPool)
  .then(data => BigInt(data?.id ?? 0))

// Correct value returned as string
db.sql<
  schema.cat.SQL,
  schema.cat.Selectable[]
>`SELECT * FROM ${'cat'}
  WHERE ${'cat_name'} = ${db.param(name)}`
  .run(pgPool)
  .then(rows => BigInt(rows[0].id ?? 0))
```

Listing 2: Zapatos number precision loss

a JavaScript number runtime type, which, according to the specification, is represented by C++ double (float64) or equivalent [70]. Although both PostgreSQL and JavaScript use the same number of bytes to represent the value, the PostgreSQL type can accommodate a significantly more extensive range of integer values, as it utilizes decimal precision [71].

It was necessary to compose numerous queries using explicit SQL (as depicted in the final comparison table), including transaction rollbacks. The framework only performs this task autonomously if the transaction encounters an error (and subsequently rethrows the error).

A unique and valuable feature of the Zapatos package is its support for lateral joins, which the framework advocates. This approach generates nested objects that align more naturally with the object-oriented programming paradigm.

Initially, due to limitations in the typings of Objection.js, the framework had to be compiled with the `StrictNullChecks` option of TypeScript disabled. This decision conflicted with the way Zapatos does its type checking. This option is one of the most common problems with out-of-date type definitions, so Zapatos will not be valid for projects that have to keep this option disabled due to other dependencies.

7.4 Knex.js

Knex.js is a highly popular and versatile query builder in the JavaScript and TypeScript ecosystem, with a substantial following of 1,346,100 weekly downloads and 17,419 stars on GitHub. Initially developed by Tim Griesser [82], it has since grown to involve numerous contributors actively participating in its maintenance and development. Its popularity statistics may be skewed, as the package is used in various ORMs, such as Bookshelf.js and Objection.js, contributing to its download count.

One of the key strengths of Knex.js is its broad support for a wide range of databases, including but not limited to PostgreSQL, Oracle Database, CockroachDB, and Amazon Redshift. This flexibility extends to accommodating multiple drivers for databases like PostgreSQL and MySQL, where several popular drivers exist. With this extensive compatibility, Knex.js caters to a diverse audience of developers working with different databases and drivers [83].

Knex.js offers non-abstracted function-based query building, representing each SQL term with a function call. This approach allows developers to construct queries in a granular and modular manner. The package also supports type templating and table definitions, which can be autogenerated using the `knex-types` [84] package, further streamlining the development process.

However, Knex.js faces limitations in type guarantees due to its benevolent implementation in JavaScript and having separately written types. These constraints result in type support not extending to more advanced features, such as join suggestions or multi-table joins, potentially limiting the package's utility in more complex scenarios. Additionally, when the `.first()` method is called, Knex.js does not automatically assume that the query is fetching single and not multiple objects, leaving the typing responsibility to the developer.

Compatibility-wise, Knex.js is built to work seamlessly with both ES module and CommonJS syntax, ensuring its usefulness across various development environments. The package is licensed under the MIT Licence, a popular choice for open-source projects.

Although Knex.js benefits from active support for its basic functionality, the vast range of databases it supports inevitably leads to a considerable

upkeep workload. Consequently, many bugs remain unaddressed for extended periods, potentially impacting developers who rely on the package for their projects.

Regarding documentation, Knex.js stands out with high-quality online resources, guiding users through setup and usage. As with many other packages in this comparison, the documentation is created using `vitepress` package and has excellent readability and searchability. However, the package does not have annotated types or function calls, which may result in developers needing to refer back to the online documentation more frequently than desired.

The package has several dependencies, mostly utility packages, such as `colorette` for styling command line output or `lodash` for collection and advanced data structures manipulation. While Knex is inflating the download numbers of these packages by a significant amount, they are also popular and supported on their own accord. None seem to have any outstanding or long-lasting issues.

Performance in benchmarks

The package evaluation demonstrated the ability to formulate queries for the benchmarks as flexibly as the SQL language. However, a notable limitation was its inability to accommodate operators with the `?` character [85]. This issue arises due to the package's utilization of `?` as a parameter replacement character. Consequently, this poses challenges for PostgreSQL when checking key existence in JSONB data types and even generates complications in Oracle databases when conducting regex comparisons, as documented in issue #3112 [86] on the Knex GitHub repository. Despite its persistence since at least 2019, no resolution for this issue appears imminent.

Regarding type checking, the typing offered by Knex.js is insufficient at best. Consequently, calls to the package are almost equivalent to manually composing the query. Furthermore, many methods are specific to the database engine and offer minimal abstraction, necessitating frequent consultation of the package's high-quality documentation.

7.5 Kysely

Kysely is a relatively young query builder in the TypeScript ecosystem, aiming to replace Knex.js by offering the same query composition power while providing superior type support for query composition and results. Although its development only began in earnest in 2021, the package has gained traction since 2022, as it matured and continued to be actively developed, which also means possible breaking changes.

Compared to Knex.js, Kysely supports fewer database engines and SQL dialects out-of-the-box, with native support for MySQL, PostgreSQL, and SQLite. However, third-party drivers are available for several other (albeit more exotic) databases [87]. One of the driving forces behind Kysely's creation was Knex.js's excessive permissiveness, which limited its type support capabilities [88]. Kysely addresses this issue while retaining the strengths of query composition. Though the order of operations in Kysely may sometimes differ from SQL, this does not pose a significant problem.

Its excellent type guarantees make it an attractive choice, especially compared to more expressive packages. Kysely can also be further enhanced with Model classes through the third-party package *kysely-orm*. However, due to its limited usage and lack of updates reflecting the latest Kysely API changes, it was not considered for comparison here. To generate type definitions, developers can use introspection with the *kysely-codegen* package [89] or an alternative schema specification via *prisma-kysely* [90]. Kysely also provides in-built support for database migrations, although it lacks the CLI that other packages, like Knex.js provide.

Distributed with both CommonJS and EcmaScript dependency specifications, Kysely is compatible with both dialects and is licensed under the MIT Licence. Despite its youth, the package has already amassed over 53,000 weekly downloads on npm and over 4,600 stars on GitHub [88]. Most issues reported are enhancement suggestions, however due to the package's young age, there obviously can't be any issues open for as long as some in older repositories.

Kysely's active development has led to frequent updates and enhancements, such as improved documentation published during the writing of this

thesis. While the web document may be brief compared to more established packages like Knex, it covers all essential information. The package's type annotations provide excellent documentation, explanations, and multiple usage examples and are the best example of function annotation in all packages considered in this comparison. With zero dependencies apart from peer dependencies for database drivers, Kysely is a lightweight and efficient solution.

In summary, Kysely is a promising query builder in the TypeScript ecosystem, seeking to surpass Knex.js with its superior type support and powerful query composition capabilities. Although it currently supports fewer database engines and SQL dialects, its performance and type guarantees make it an attractive choice for developers. Its active development, compatibility with various dependency specifications, and high-quality documentation contribute to Kysely's growing appeal within the TypeScript community.

Performance in benchmarks

Regarding performance, the Kysely package consistently outperformed or at least matched Knex, which boasts a comparatively rich set of features for a query builder. While Kysely does not offer parsing for types such as Big Integer, its handling remains consistent with that of the pg driver. Like many other packages, Kysely lacks support for explicit transaction control, above encapsulation into one. However, this is at least supplemented with raw SQL queries inside the encapsulation. This will however result in additional call of COMMIT or ROLLBACK at the end of the encapsulation, even though the transaction was finished manually, and such behaviour is usually reserved for ORMs which abstract the database access further than common query builders.

Another advantage of Kysely is its utilization of tagged strings, akin to the approach employed by @databases/pg when composing raw SQL queries. This method proves more comprehensible than the combination of bindings and function calls implemented by Knex. Consequently, the Kysely package offers an appealing balance of performance and usability, making it a viable option for various database management tasks.

7.6 MikroORM

MikroORM, a project developed by Czech programmer Martin Adámek, has emerged as an ORM solution that offers both versatility and ease of use. With a focus on implicit transactions using the Unit of Work pattern, MikroORM distinguishes itself from other ORM packages by offering native support for NoSQL databases, specifically MongoDB, alongside support for traditional relational databases such as MySQL, MariaDB, PostgreSQL, and SQLite [91]. At the time of writing, MikroORM has garnered decent attention, with 189,128 weekly downloads and 5,777 stars on GitHub [92] [93].

The internal architecture of MikroORM for relational databases is powered by Knex, a popular SQL query builder library, which allows developers to access the underlying query builder with type support provided by MikroORM's definitions. Users can therefore utilize the full power of knex while benefiting from the additional features and abstractions MikroORM provides. Database models are represented using classes with decorators, making creating relationships between entities intuitive through explicit `@OneToOne`, `@OneToMany`, and `@ManyToMany` decorators that translate seamlessly from the conceptual schema of the database. Furthermore, MikroORM offers an EntityGenerator package that allows developers to generate these definitions based on an existing database schema automatically.

Regarding compatibility, MikroORM supports compiled TypeScript and native TypeScript execution using ts-node. However, it does not support alternative runtimes like Deno due to various limitations, including dependencies [94]. Speaking of dependencies, MikroORM relies on several well-known JavaScript packages for parsing and metadata reflection, which the package utilizes for establishing relationships and maintaining context.

The documentation for MikroORM is comprehensive, providing all the necessary information for developers to utilize the package effectively [95]. While the types do not direct link to the documentation, they include basic descriptions of the methods, which aids in understanding their usage. MikroORM also offers support for migrations and seeding, with migrations generated by analysing the differences between the database schema and the schema defined within MikroORM. It also supports read replica connections using random se-

lection for which instance to use for the query.

In summary, MikroORM represents a robust and flexible ORM solution that caters to many database types, from traditional relational databases to NoSQL databases like MongoDB. With its focus on implicit transactions and an intuitive approach to defining relationships through decorators, MikroORM has become an attractive choice for developers seeking a versatile and user-friendly ORM package.

Performance in benchmarks

The Mikro ORM package distinguished itself in performance benchmarks primarily due to its unique features. In addition to standard query handling, the package facilitates field matching using JavaScript native regular expressions, which are subsequently parsed and translated into SQL queries. Another remarkable result was observed in the JSONColumn latency test, where MikroORM significantly outpaced even the pgTyped package. This achievement is not attributed to superior database connection performance but to the package's Entity Manager. This internal cache/repository is designed for particular contexts. It caches the current state based on the object's primary key values, enabling rapid data retrieval from application memory rather than querying the database [96]. However, this approach may introduce inconsistencies, prompting MikroORM to implement optimistic locking for fields potentially impacted by such issues.

Relations are incorporated using the `populate` option, which permits dot notation for further related entities and filtering. While not strictly typed, simple nested objects have enough type support to provide essential information for query composition and function as anticipated. The results are well-typed, although `BigInteger` and `Decimal` types are returned as strings. Transaction support with a direct control sequence API is also implemented. For instances where the integrated interface lacks flexibility, pre-typed Knex is accessible for most queries.

Entities in MikroORM are straightforward to implement, although documentation for their use with complex decomposition tables is limited and has to be implemented through a standard relations between three tables. A mi-

nor issue arose due to an undocumented difference between the `columnType` and `type` options; however, the package’s developer promptly addressed the concern. Overall, MikroORM offers a compelling balance of features and performance, making it a viable choice for various applications.

7.7 Prisma ORM

PrismaORM has rapidly gained popularity in the development community due to its innovative and modern approach to creating database clients and object-relational mapping. Adopting a unique method for defining database schemas, PrismaORM utilizes its schema language [97], which aims to represent the database structure using concepts more closely aligned with relational syntax rather than complex objects found in traditional object-oriented programming paradigms. An example definition of model in the schema language is shown in Listing 3.

The schema in PrismaORM comprises three main components: the data source definition, the output specification for the schema (such as the Prisma database client), and the database schema itself. A custom client is generated from this schema (and, optionally, a context like the current system architecture, if not specified). This client includes type definitions for type safety, ensuring a robust and reliable database interaction experience. However, one potential drawback of this approach is the increased binary size of the generated client. For example, the resulting binary size in a test database was approximately 15 MB, which may lead to cold start issues in serverless environments. To address this concern, PrismaORM provides specific instructions for each cloud platform to optimize the binary result and configuration as much as possible.

The Prisma suite also includes a migration platform that automatically transforms schema changes into corresponding database updates. PrismaORM boasts impressive adoption rates, with 1,057,351 weekly downloads and 30,431 GitHub stars, making it the second most popular package by the GitHub metric [98] [99]. The package supports both Node.js and Deno as runtime environments, catering to various developers and project requirements.

However, it should be noted that Prisma supports CommonJS imports

```
model cat {
  id          BigInt      @id(map: "pk_cat")
  ↪ @default(autoincrement())
  cat_color_id Int?
  cat_name     String?     @db.VarChar(256)
  date_of_birth DateTime?  @db.Date
  cat_color     cat_color? @relation(fields: [cat_color_id],
  ↪ references: [id], onDelete: Cascade, onUpdate: NoAction,
  ↪ map: "fk_cats_cat_color")
  house_cat     house_cat[]
}
```

Listing 3: Example of Prisma schema language model definition

by default and does not offer an official method for generating ECMAScript module-compatible code [100]. This limitation may challenge developers who prefer using ECMAScript modules in their projects.

Performance in benchmarks

PrismaORM, a competitive ORM package, has demonstrated performance on par with other leading ORM solutions, such as Sequelize and TypeORM. In the `getToysAvailableToCat` test, which measures relation traversal performance, PrismaORM generated a significantly faster query by employing multiple nested queries instead of the `LEFT JOIN` and `LEFT OUTER JOIN` operations utilized by its competitors. However, in the `countCatsByColor` test, the package produced an overly complicated query with redundant conditions. The complexity of the query plan resulted in the database’s planning phase consuming nearly as much time as the query execution itself, taking almost twice as long as queries generated by rival frameworks.

Regarding functionality, PrismaORM stands out as the only ORM that did not necessitate using raw SQL for any query, which is an accomplishment in and of itself. The package supported incrementing and decrementing operations in upsert queries, and although the filter objects became relatively complex, they remained comprehensible. While the transaction implementation does not allow for explicit handling, this approach is more understandable

within an ORM context, where SQL queries are already opaque, as opposed to a query builder such as Kysely, which employs a similar methodology.

Furthermore, PrismaORM can accurately convert and type unconventional runtime types, including Big Integer and JSON values. This capability enhances the versatility and applicability of the package for various use cases.

7.8 TypeORM

TypeORM is a pioneering ORM framework designed to support TypeScript and leverage its features. It is compatible with both active directory and data mapper patterns, allowing for easy exchange of entity definitions during development. TypeORM supports a wide range of database engines, including MySQL, PostgreSQL, SQLite, Oracle DB, and SAP Hana, and even has experimental support for the NoSQL database MongoDB.

The framework employs its own query builder and uses Model classes with property decorators to describe its methods. TypeORM supports Lazy Loading and Eager loading when working with models and is compatible with CommonJS and ECMAScript. It offers automatic migrations based on its models and manually written migrations. However, it lacks support for seed files, requiring them to be included as migrations if executed through its CLI.

TypeORM is highly popular, boasting the second-highest download number and the highest amount of stars among those compared, with 1,192,427 weekly downloads [101] and 30,947 stars on GitHub [102]. Released under the MIT License, TypeORM is the ORM with the highest number of downloads and full support for TypeScript, as Sequelize only outperforms it when considering the *sequelize* package's download numbers [103], not the *sequelize-typescript* package [104] used for comparison.

Despite its stable support, TypeORM's development has shifted towards maintaining existing features in 2018 due to the amount of work for purely volunteer supported development [105]. This maintenance mode has led to 1,873 open issues as of now [102]. Although the project has now resumed development due to receiving financial support, it primarily focuses on more minor updates every few weeks. It is not as actively developed as other "active" projects in this analysis.

The documentation for TypeORM is of good quality, providing all the necessary information for development. However, it needs more formatting and chapters, making it easier to follow even if the developer does not know what precisely they are looking for [106]. The model methods include brief descriptions but are mostly limited to a single-sentence short explanation.

TypeORM has the highest number of dependencies among the packages compared, with many dependencies like "buffer" being necessary to support various runtimes, including browser or React Native environments that lack the same standard library support as Node.js. These dependencies are actively developed and have high download numbers, posing no additional risk to the toolchain. However, TypeORM's early adoption of the TypeScript ecosystem has largely overlooked its JavaScript functionality, as evidenced by the documentation and example projects.

Performance in benchmarks

When examining the performance of TypeORM in various benchmarks, it was observed that this ORM solution closely competes with its main rival, Sequelize. In most tests, TypeORM either slightly outperformed or marginally fell behind Sequelize, with negligible differences in performance. These outcomes can be attributed minimally to disparities in the generated queries, as both ORMs are comparable in their query generation and execution capabilities.

However, TypeORM's query generation approach raises some concerns when working with complex joined tables. The generated queries are often complex for humans to read due to excessive naming or using hashes instead of more recognizable names. This complexity necessitates additional parsing for developers to effectively understand and work with these queries, one such query is shown in Listing 4. Moreover, TypeORM often prefers LEFT JOINS, which are computationally more demanding than INNER JOINS and, in this case, will yield the same output thanks to the database schema.

Another issue encountered with TypeORM relates to its handling of automatically generated primary keys. The ORM disregards user input for these columns if they can be generated automatically, limiting developers' flexibility

when working with databases. For instance, this constraint poses challenges when inserting seed data with hard-coded IDs.

In terms of upsert functionality, TypeORM, like Sequelize, does not provide support for increment operations. Additionally, it is impossible to formulate an equivalent query using the included query builder, as the syntax does not allow for custom update SQL and only supports ignoring specific data that would be otherwise inserted.

When handling transactions, TypeORM lets developers create an explicit transaction handler that includes entity manager methods and functions for starting, managing, and ending transactions. While the filter types are only lightly typed, they offer sufficient guidance for developers navigating the available filtering options.

7.9 Objection.js

Objection.js is an ORM based on the Knex.js query builder and is closely connected to the Knex ecosystem. Developed partially by the same team, it supports SQLite3, Postgres, and MySQL while also being compatible with many other database engines supported by Knex [107]. Unlike Sequelize or TypeORM, Objection.js does not provide extensive abstraction; it only offers Models that assist with query composition, types, and relation fetching. The Models primarily serve as a starting point for SQL queries rather than offering the complex functionality of ActiveRecord or DataMapper patterns. This results in syntax which is quite similar to Knex que

The package has 128,872 weekly downloads [108] and 6,972 stars on GitHub [107]. Objection.js predates the popularization of TypeScript. Its leading developer admits that the package requires a significant rewrite of types to compete in TypeScript support, which is not feasible due to the workload required [109]. Objection.js was not maintained for over a year, accumulating technical debt and leading to incompatibility with TypeScript 4.8 and newer due to enhancements to the `strictNullChecks` option. A new version has since been published [110], fixing some issues that arose during that time. New developers have started working on maintaining the project as of writing this thesis.

```

SELECT
  "Toy"."id" AS "Toy_id",
  "Toy"."toy_name" AS "Toy_toy_name",
  "Toy"."barcode" AS "Toy_barcode",
  "Toy"."price" AS "Toy_price",
  "Toy"."currency" AS "Toy_currency",
  "Toy"."naughty" AS "Toy_naughty",
  "Toy"."date_introduced" AS "Toy_date_introduced",
  "Toy"."toys_producer_id" AS "Toy_toys_producer_id"
FROM "toy" "Toy"
  LEFT JOIN "toy_house" "Toy__Toy_toyHouses"
    ON "Toy__Toy_toyHouses"."toy_id" = "Toy"."id"
  LEFT JOIN "house"
    ↪ "Toy__Toy_toyHouses__Toy__Toy_toyHouses_house"
    ON "Toy__Toy_toyHouses__Toy__Toy_toyHouses_house"."id" =
    ↪ "Toy__Toy_toyHouses"."house_id"
  LEFT JOIN "house_cat" "859f7912[...]aab7b94c"
    ON "859f7912[...]aab7b94c"."house_id" =
    "Toy__Toy_toyHouses__Toy__Toy_toyHouses_house"."id"
  LEFT JOIN "cat" "521c7a07[...]88acfd85"
    ON "521c7a07[...]88acfd85"."id" =
    "859f7912[...]aab7b94c"."cat_id"
WHERE ("521c7a07[...]88acfd85"."id" = 1)

```

Listing 4: TypeORM Query generated for getToysAvailableToCat benchmark (hashes were shortened)

The package is released under the MIT Licence and offers high-quality web documentation, including extensive usage guides and a detailed API Reference [111]. A unique feature of Objection.js is the ability to provide JSON Schema validation for inserted objects, ensuring database data consistency.

Objection.js has only three dependencies for full functionality: Knex, AJV, and db-errors. The AJV dependency provides JSON Schema validation, while db-errors, originating from the same company that published Objection.js, aims to deliver a unified API for handling various errors produced by different database engines. Although the db-errors package has not been updated for over four years, it is unlikely to pose a significant security threat to the package. Objection.js now also supports both ESM and CommonJS, with the

```
// Knex.js
knexInstance
  .select('stock_info')
  .from('toys_producer')
  .where('id', '=', id)
  .first()
  .then(data => data?.stock_info ?? {})

// Objection.js
ToysProducer.query()
  .select('stock_info')
  .where('id', '=', id)
  .first()
  .then(data => data?.stockInfo ?? {})
```

Listing 5: Comparison of Knex.js and Objection.js syntax for count query

latest release fixing ESM compatibility issues.

Performance in benchmarks

Objection.js was included in the performance benchmarks only after its typings were updated to be compatible with TypeScript 4.8 and later while maintaining `strictNullChecks`, a requirement for the proper functioning of other packages like Zapatos. Once the compatibility issues were resolved, Objection.js demonstrated performance largely on par with other ORM packages such as MikroORM and TypeORM. However, a notable exception was observed in the `getCatColor` test, where Objection.js was significantly slower than its counterparts.

This performance discrepancy was traced back to the method that was used for fetching related entities: `withGraphFetched`, the only type-supported way to fetch relations beyond a single relationship in Objection.js without resorting to plain Knex query builder calls [111]. This method was selected for type support, but it also caused the speed issue encountered. The method retrieves data through three separate, dependent database calls, resulting in considerably longer query execution times even with minimal latency. While this approach may offer some benefits in specific scenarios, such as apply-

ing limits to individual queries to alleviate the load on massive databases, it generally falls short of the performance optimization capabilities offered by relational database management systems (RDBMS) that utilize single, more complex queries.

Another challenge posed by `Objection.js` lies in its limited typing support. Many inherited methods from `Knex` lack template variables to specify the result, despite their original counterparts providing such functionality. Consequently, developers often need to cast the results manually to ensure the correct final type, except for the most basic queries.

The composition of `Objection.js`, which positions itself as not quite an ORM nor a pure query builder, often requires developers to have direct access to the query. However, this approach often obscures vital information, forcing developers to rely on experience or testing to understand certain aspects of the system. For instance, the table name is hidden when using predefined relations for joining. Developers must determine the alias assigned to the joined table for `WHERE` clauses without any clear guidance from the package.

7.10 Sequelize

Sequelize is one of the oldest, still popular, and actively supported ORM frameworks for the JavaScript ecosystem, with development starting in 2010. After over 12 years of development, it supports various databases, including PostgreSQL, MySQL, and SQLite3 [112]. Its popularity is attributed to its simple syntax and flexible usage. Sequelize supports read replication, using round-robin scheduling for read queries and a write pool for write or explicitly marked database calls. It also provides a command-line interface for managing schema and data, offering migration and seeding options.

Sequelize can use either manually written migrations or automatically generated ones based on Model definitions. The framework also supports programmatic synchronization of the database state to reflect the Model definition using the `sequelize.sync()` method. Unlike other ORMs discussed in this work, Sequelize does not expose a query builder interface, only allowing for raw query execution when integrated entity fetching is insufficient.

Full TypeScript support for the main project is still in progress [113].

However, a separate project called *sequelize-typescript* [104] offers support for TypeScript native definitions, using decorators for Model and property specifications. One of the original features of Sequelize is its support for the automatic creation and update of timestamp fields on database tables and the option for "paranoid" tables [114]. In this mode, calling a deletion method sets the `deletedAt` attribute instead of removing the record. The framework behaves like the deleted records do not exist unless previously restored.

Both Sequelize and *sequelize-typescript* are provided under the MIT Licence and actively supported. Due to its extensive user base, the framework has over 750 reported issues [115], with a minority marked as bugs and the majority being feature requests. The central repository of the package has 27,729 stars on GitHub and the largest number of weekly downloads out of all packages compared, at 1,505,485 [103].

Sequelize has 16 dependencies, plus TypeScript-specific helpers required for usage with the current TypeScript version. These dependencies primarily relate to inflexion, code analysis for model dependency graphs, and various data types supported by the framework, including GeoJSON and advanced Date types. While the package offers extensive documentation, differences in Model definition when using TypeScript can be confusing. Documentation for additional operators and decorators is lacking, as it is primarily contained in several Markdown files in its repository.

Performance in benchmarks

In performance benchmarks, the Sequelize ORM demonstrated competitive results, closely matching its main rival, TypeORM. Sequelize generated efficient queries for basic operations and performed within 10-50% of the reference pgTyped implementation. However, with more complex queries, Sequelize preferred using LEFT OUTER JOINS when they were not necessarily based on the conceptual schema of the database. Consequently, these test scenarios took 50-150% of the reference solution execution time.

While query execution remained relatively fast, the increased complexity due to unnecessary LEFT JOINS may lead to performance issues that necessitate manual optimization in some instances. As the LEFT JOINS are some of

the more complex operations databases perform, and their complexity grows rapidly with the amount of data joined, this approach can quickly impact the application's overall performance.

Sequelize's filter types were limited, as even essential attribute matching for search by attribute equality is not typed. This lack of typing support increases the likelihood of developers making errors that may only become apparent during runtime. Furthermore, Sequelize does not provide a dedicated API for WHERE clauses on joined tables, requiring developers to rely on dot notation and unchecked fields to define such filters.

While defining models is documented, the example code provided was found to throw errors related to shadowing attribute names. Although the solution to this issue can be quickly addressed using the TypeScript "declare" keyword, it is essential to mention such features in the introductory documentation for models to minimize confusion for developers.

Like most other ORMs, Sequelize does not support abstracting upsert operations with increments or decrementation on updates. As a result, developers must resort to implementing such operations using raw queries.

7.11 Disqualified frameworks

While originally included for analysis and experimentation, some frameworks were not successfully implemented. This approach had to be taken as the packages were found to be lacking in features required for inclusion, such as basic TypeScript support, or execution under the testing environment was unattainable, usually due to outdated code or dependencies or not functioning as described in the documentation. We were unable to fix the issues. These packages are nonetheless included with a basic description of their advertised features and the issues for their exclusion for this comparison.

7.11.1 RDB

RDB, a lesser-known ORM package, was initially selected for comparison due to its distinctive model definition approach and appearance in the npm repository under the ORM tag. At the time of selection, RDB had only 284 weekly

```
export interface Table {  
  primaryColumn(column: string): ColumnDef;  
  column(column: string): ColumnDef;  
  join(table: Table): Join;  
  hasMany(join: JoinRelation): HasMany;  
  hasOne(join: JoinRelation): HasOne;  
  formulaDiscriminators(...discriminators: string[]) : Table;  
  columnDiscriminators(...discriminators: string[]) : Table;  
}
```

Listing 6: RDB entity model type definition

downloads [116] and 291 stars on GitHub [117], making it the least popular package among those considered. What set RDB apart was its alternative model definition method, which relied on method calls to create the entity model, unlike the schema-based approaches employed by other frameworks.

However, further examination of RDB revealed several limitations that led to its disqualification from the comparison. Firstly, the package does not provide any types for methods beyond connection and model initialization. This lack of typing support significantly hinders its compatibility with TypeScript, making it challenging to work with in a typed environment.

Additionally, RDB does not offer a solution for circular dependency issues that may arise when defining models across multiple files. Consequently, developers must either use a singleton method to encapsulate the definition or repeat it for each file, both of which are suboptimal approaches. Given these limitations, RDB is most suited for single-file projects that can initially define their database logic.

The framework also lacks typings for search method attributes and resulting object types, further limiting its usefulness in TypeScript-based projects. Due to these issues, as well as the file separation requirements of the benchmark, RDB was ultimately disqualified from the comparison. The full interface is shown in Listing 6 and as shown does not contain any methods for referencing the model attributes. Its documentation is quite simple, written in Markdown and consisting of mostly plain examples [118].

In conclusion, while RDB presents an interesting alternative approach to

model definition, its limitations in typing support and handling of multi-file projects make it less appealing for developers seeking a robust and flexible ORM solution, mainly when working with TypeScript.

7.11.2 Bookshelf.js

Despite its last update occurring in July 2020 [119], Bookshelf.js remains a popular database access package on npm, with 103,607 weekly downloads at the time of writing this thesis. Started by Tim Grissier, who also initiated the development of the query builder Knex, Bookshelf.js is an ORM which is based on Knex and implements the Data Mapper pattern for entities in the database. Designed to work with PostgreSQL, MySQL, and SQLite3, Bookshelf.js has not been actively developed for an extended period, resulting in compatibility issues with more recent versions of Knex [120].

The last officially supported Knex version for Bookshelf.js was 0.21.17, whereas the current Knex version is 2.4.2. This discrepancy has led to several type errors and incompatibilities as the Knex API has evolved over time. While there are forks of the repository that address significant issues, the package still suffers from limited type support, primarily because the entire project is developed in pure JavaScript, with types generated as an afterthought [121].

The primary reason for disqualifying Bookshelf.js from the comparison was the numerous dependencies with unmaintained and outdated versions, which pose significant security risks. These risks include prototype pollution [122] and SQL injection attacks [123], making the package unsuitable for modern, secure applications. The package itself cannot run unless these dependencies are installed or at least overridden.

7.11.3 Waterline

The Sails framework, an MVC-style architecture framework for JavaScript, is designed for building modern web applications. As part of this framework, the Model component is implemented using an ORM called Waterline. Sails is relatively less popular in the JavaScript ecosystem, with only 31,492 downloads, which pales in comparison to giants like Express (28,825,585 weekly downloads [124]) or Koa (1,600,532 weekly downloads [125]). While Water-

line’s primary purpose is to serve as a component within the Sails framework, it is also available as a standalone package.

However, during the implementation process, several issues were encountered with Waterline. The package does not provide its own types but relies on optional types from the `@types` repository [126], which is maintained by volunteers. Unfortunately, these types are outdated, as they only cover version 0.13.x, while the latest Waterline version is 0.15.2. As a result, these types do not accurately reflect the package’s functionality, and initialization using them does not work. Similarly, following the documentation for a standalone setup, as shown on the framework’s website, also proved non-functional as the documentation [127] is written mainly for the full framework usage, with pure waterline usage being an afterthought.

Due to these inconsistencies and the inability to overcome them, Waterline was disqualified from the comparison.

Observations

In this final chapter, we will discuss the performance of various ORM packages based on the benchmarks conducted. The chapter is divided into three main sections: Package Information, Flexibility Assessment, and Performance Test Results.

The Package Information section provides an overview of each package, including the supported database engines, the version used for comparison, popularity statistics, and runtime support. This information is essential for understanding the background and scope of each ORM package and its suitability for different project requirements.

Next, the Flexibility Assessment section evaluates each package's adaptability by determining whether the test was implemented using native ORM functions, the query builder, or raw SQL with parameters. This section will also highlight any issues or challenges encountered while working with each ORM framework. Understanding the flexibility of each package enables developers to make informed decisions regarding the ORM that best fits their needs and project constraints.

Finally, the Performance Test Results section presents the outcomes of each test, focusing on cases where query composition, operator selection, or introduced overhead could play a measurable role in the package's performance. These tests were conducted using the BenchmarkRunner, the frameworks connected to a PostgreSQL instance in Docker, on an AMD Ryzen 6850U processor @ 2.7GHz, Debian GNU/Linux 11 (bullseye) operating system, 32GB of LPDDR5-6400 RAM, and SSD storage.

By examining the performance of each ORM package in these three areas, developers can gain valuable insights into the advantages and limitations of each framework, ultimately guiding them in choosing the most appropriate solution for their projects.

8.1 Package Information

While evaluating the ORM frameworks, the latest stable branch version was used for testing at the time of writing. It is important to note that a new version 3.0.2 of Objection.js was released after the testing was completed; however, this update does not introduce any new features, only addressing issues with types and ESM support.

Table 8.1 provides the exact versions used for each package, along with the number of runtime dependencies required (excluding optional packages and database drivers). To assess the availability and popularity of these packages, Table 8.2 lists each package with popularity metrics such as weekly downloads from the npm repository and GitHub stars given to the project. The data was collected on the 10th of April, 2023.

Table 8.1: Runtime package information in test environment

Package	Runtime dependencies	Tested Version
PgTyped	3	2.0.1
Zapatos	0	6.1.4
@Databases/pg	15	5.4.1
Objection.js	2	3.0.1
MikroORM	7	5.6.16
PrismaORM	1	4.10.1
TypeORM	14	0.3.12
Knex.js	14	2.4.2
Sequelize	16	6.31.0

Table 8.2: Popularity and homepage of packages

Package	npm weekly downloads	GitHub Stars	Homepage
PgTyped	9937	2348	https://github.com/adelsz/pgtyped
@databases/pg	26613	517	https://atdatabases.org/docs/pg
Zapatos	14933	980	https://jawj.github.io/zapatos/
Knex.js	1346100	17419	https://knexjs.org/
Kysely	53635	4683	https://kysely.dev/
MikroORM	189128	5777	https://mikro-orm.io/
PrismaORM	1057351	30431	https://prisma.io/
TypeORM	1192427	30947	https://typeorm.io/
Objection.js	128872	6972	https://vincit.github.io/objection.js/
Sequelize	1505485	27729	https://sequelize.org/
RDB	284	291	https://github.com/alfateam/rdb
Bookshelf.js	103607	6315	https://bookshelfjs.org/
Waterline	29086	5387	https://waterlinejs.org/

8.2 Flexibility Assessment

The primary aspect of the comparison between individual ORM packages is their ability to implement advanced SQL constructs using a more unified API for the programming language. Although abstraction introduces additional logic that requires processing power, it should offer functionality that approaches the capabilities of direct SQL usage. A framework requiring developers to introduce abstraction but still necessitates writing SQL queries, as the request cannot be expressed through the API, is considered less effective as an abstraction layer than one that can perform such requests.

Tables 8.3, 8.4, and 8.5 showcase the layers used to perform the required functionality for the benchmark. A requirement for each implementation was that the logic had to be consistently implemented on the database, with the framework only composing the query and parsing the result. For example, it was not allowed to check for an existing object in an upsert operation by querying the database independently.

The order for implementation was as follows:

1. Native methods that abstract the database logic (Native)
2. The integrated query builder (QB)
3. Manually written queries in SQL (SQL)

If the operation was impossible to perform or resulted in problems, the lower level was attempted, and the first successful one is listed in the tables.

Several notable observations can be made from the flexibility comparison. PrismaORM stands out as the only ORM capable of natively implementing the entire logic for each test, thanks to its unique support for increment and decrement logic over upsert operations. The other full-fledged ORM packages in the comparison, such as Sequelize, TypeORM, and MikroORM, performed similarly but could not express upsert incrementation natively.

MikroORM held an advantage over TypeORM, using Knex.js as its query builder, which could express the operation. In contrast, TypeORM's internal query builder could not. On the other hand, Zapatos was the only package that partially failed in any test. It could not correctly parse bigint values from PostgreSQL as strings or BigInt primitives in JavaScript when using native methods, casting the result into a number instead. However, this issue was resolved when a manually written query was used.

Lastly, it is worth noting that only @databases/pg parsed bigint values into JavaScript BigInt primitives. All other packages returned character representations of the value.

Table 8.3: Entity Traversal Benchmark implementation methods

Package	getCatColor	countCatsByColor	getToysAvailableToCat
@Databases/pg	SQL ¹	SQL ¹	SQL ¹
Knex	QB	QB	QB
Kysely	QB	QB	QB
MikroORM	Native	Native	Native
Objection.js	Native	Native	Native
PgTyped	SQL	SQL	SQL
PrismaORM	Native	Native	Native
Sequelize	Native	Native	Native
TypeORM	Native	Native	Native
Zapatos	Native	SQL ¹	SQL ¹

¹ With type support in template fields

Table 8.4: Special SQL Actions Benchmark implementation methods

Package	Upsert	JSON type	JSON Where	Transaction	Like Query
@Databases/pg	SQL ¹	Native	Native	Native	SQL ¹
Knex	QB ²	QB	QB	QB	QB
Kysely	QB ²	QB	QB	QB	QB
MikroORM	QB ²	Native	Native	Native	Native
Objection.js	QB ²	QB	QB	Native	QB
PgTyped	SQL	SQL	SQL	SQL	SQL
PrismaORM	Native	Native	Native	Native	Native
Sequelize	SQL	Native	Native ³	Native	Native
TypeORM	SQL	Native	Native	Native	Native
Zapatos	Native ²	Native	SQL ¹	Native	SQL ¹

¹ With type support in template fields

² Raw SQL for increment on update

³ Raw SQL for fetching key value as promoted nested keys did not result in syntactically correct query

Table 8.5: Edge Cases Benchmark implementation methods

Package	SQL Injection	BigInt handling
@Databases/pg	SQL ¹	Native ⁴
Knex	QB	QB ³
Kysely	QB	QB ³
MikroORM	Native	Native ³
Objection.js	QB ²	QB ^{2,3}
PgTyped	SQL	SQL ³
PrismaORM	Native	Native ³
Sequelize	Native	Native ³
TypeORM	Native	Native ³
Zapatos	SQL ¹	SQL ^{3,5}

¹ With type support in template fields² Query builder attached to model³ Value returned as string⁴ Value returned as BigInt⁵ Native method converted value to Number, losing precision

8.3 Latency benchmark results

The second aspect of the benchmarking process involved evaluating the performance of the various packages. This evaluation focused on the optimality of the queries formulated by each package and the overhead introduced by the composition of the queries and result parsing. Through code analysis, the pgTyped package was expected to exhibit minimal overhead and the most efficient manually written queries. Consequently, pgTyped was employed as a reference for optimal queries and minimal performance.

Several noteworthy observations emerged from the testing process. The most apparent performance loss occurred with Objection.js during the getColorLatency test shown in 8.1. This performance loss resulted from Objection.js favouring multiple dependent queries over a single query with joins when utilizing the withGraphJoined method. While it would have been possible to rewrite the query using the integrated query builder and resolve the issue, this approach would compromise the flexibility testing and be thus considered inadvisable.

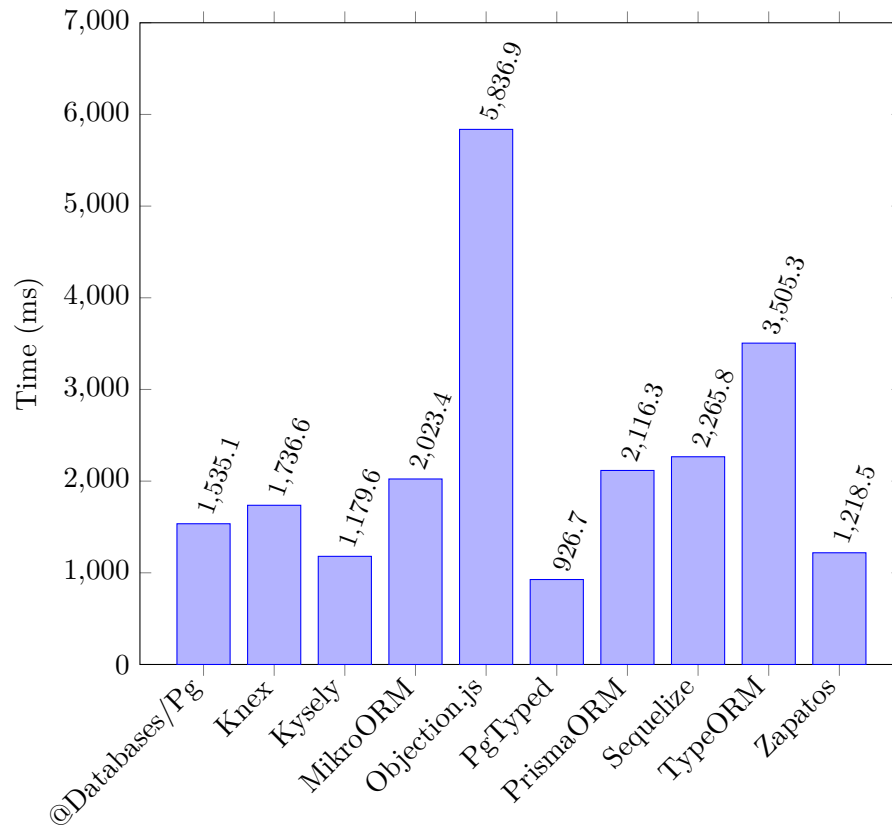
Another fascinating result was the exceptional performance of MikroORM in the JSONColumn test, results of which are in figure 8.4, where it surpassed even the pgTyped reference. This performance advantage can be attributed to MikroORM's caching mechanism, which leverages primary keys within its entityManager to prevent repeated database queries for the same data, yielding faster results than the reference. This feature can be highly beneficial for a skilled developer, but can also cause problems, if the developer does not know about it.

Kysely demonstrated comparable capabilities to Knex while offering an enhanced developer experience through type safety. Both Sequelize and TypeORM exhibited similar performance levels; however, TypeORM provided superior types for methods and filters. MikroORM, though smaller in scale, proved to be functionally rich and benefited from access to the well-established and thoroughly tested Knex.js query builder when model methods were insufficient.

Most ORMs lost out to query builders mainly because they prefer left joins over stricter inner joins for many select operations. This behaviour is primarily caused by the inability to specify precisely all the details necessary for the realization of a query in a relational schema using the model schema these packages used. PrismaORM avoided many of these mistakes thanks to its more expressive and purpose-built prisma schema, which can be more expressive than class or object definition.

Other than the few noted exceptions, the test results were as expected, with packages using less abstraction of the database logic being able to use optimal queries, which gave them an advantage over generic ORM queries. Object-relational mapping packages carry a drawback of possible less optimal data path resolution, as shown by Objection.js results in Figure 8.1 or Figure 8.3. However, the drawback is only prominent when dealing with complex queries involving multiple joins. It is preferable to use ORMs where the amount of data in the database will not result in suboptimal computation time, as the overhead of the package itself is negligible. Figures 8.2, 8.4, 8.5, 8.6 and 8.7 show that while the relative performance of the queries is almost double that of reference, it is still minor for the amount of data usually considered for most smaller projects. When considering enterprise-level databases,

Figure 8.1: getColorLatency Results



the toll in which the suboptimal queries can result will accumulate. It can result in redundant work as the application must be repeatedly optimized while the ORM obfuscates which application operation is causing the slowdown.

Figure 8.2: countCatsByColor Results

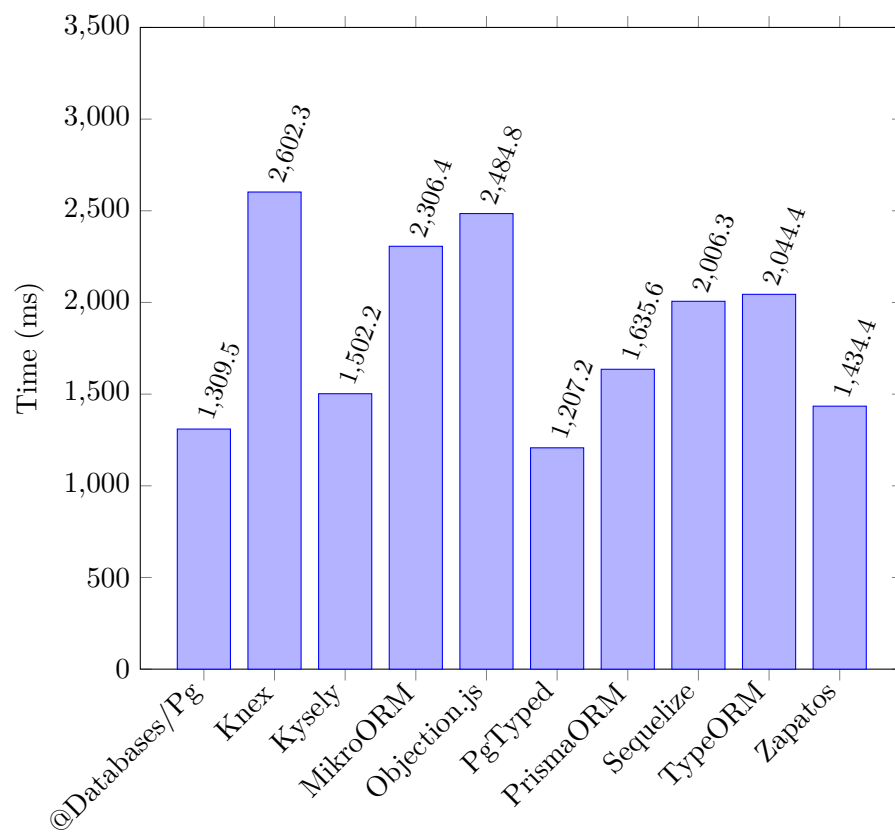


Figure 8.3: getToysAvailableToCat Results

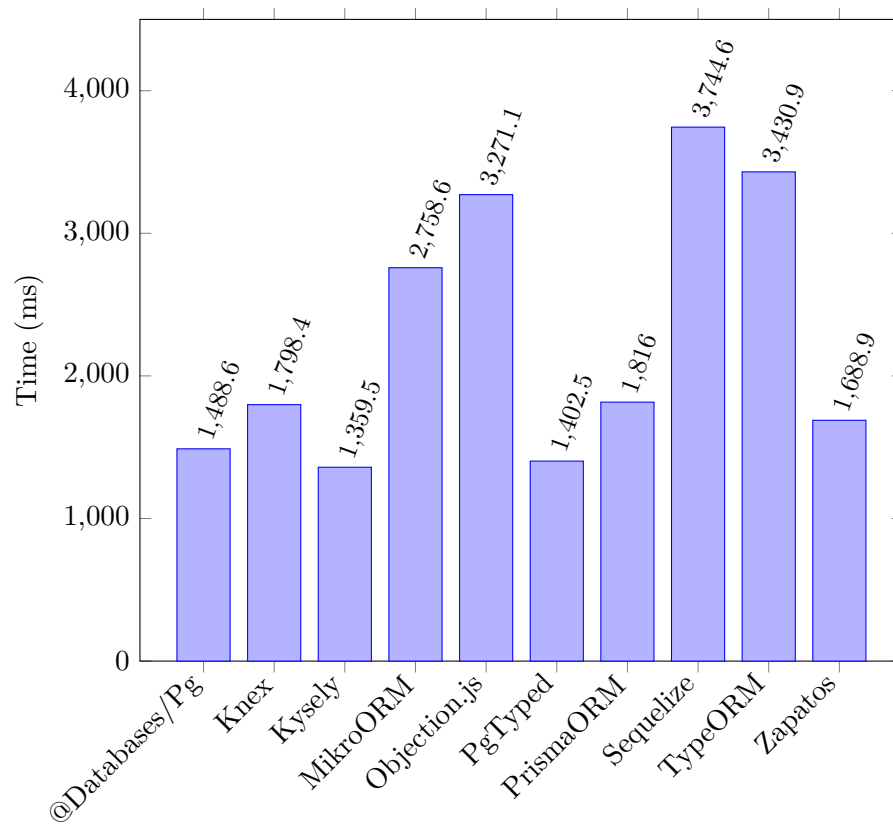


Figure 8.4: JSON Column handling Results

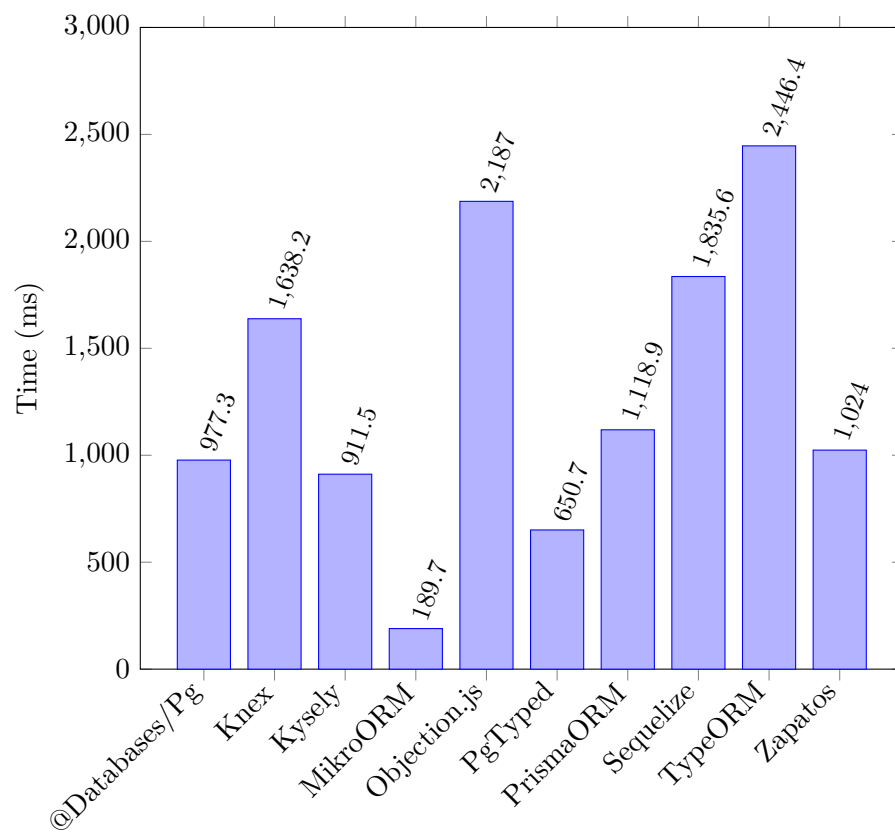


Figure 8.5: JSON Where query Results

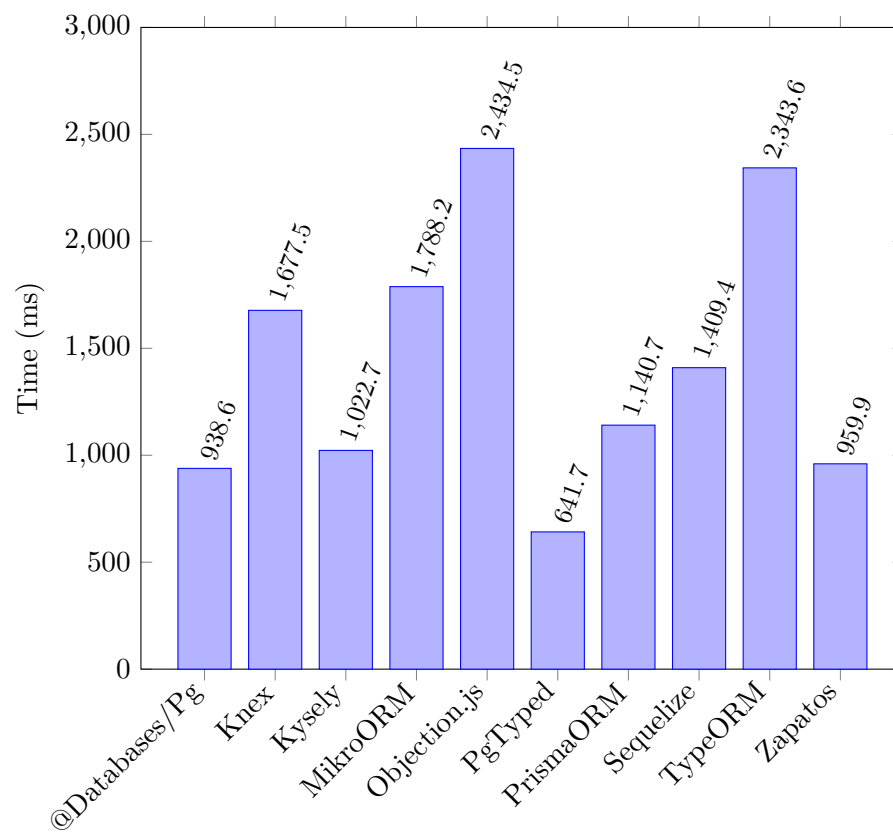


Figure 8.6: Transactional operations Results

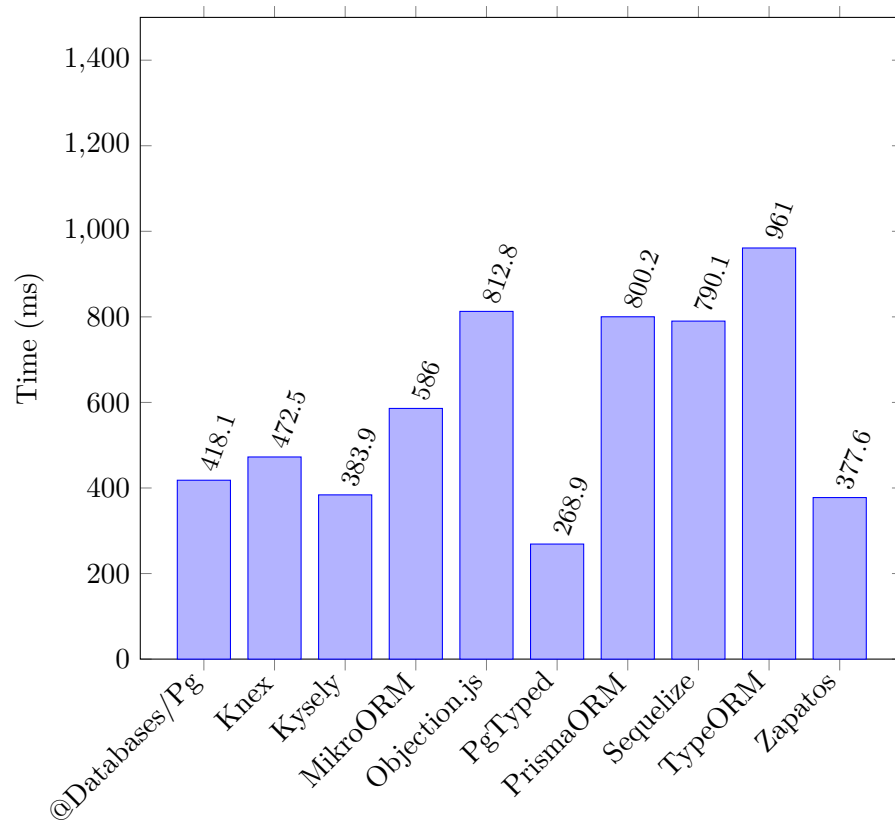
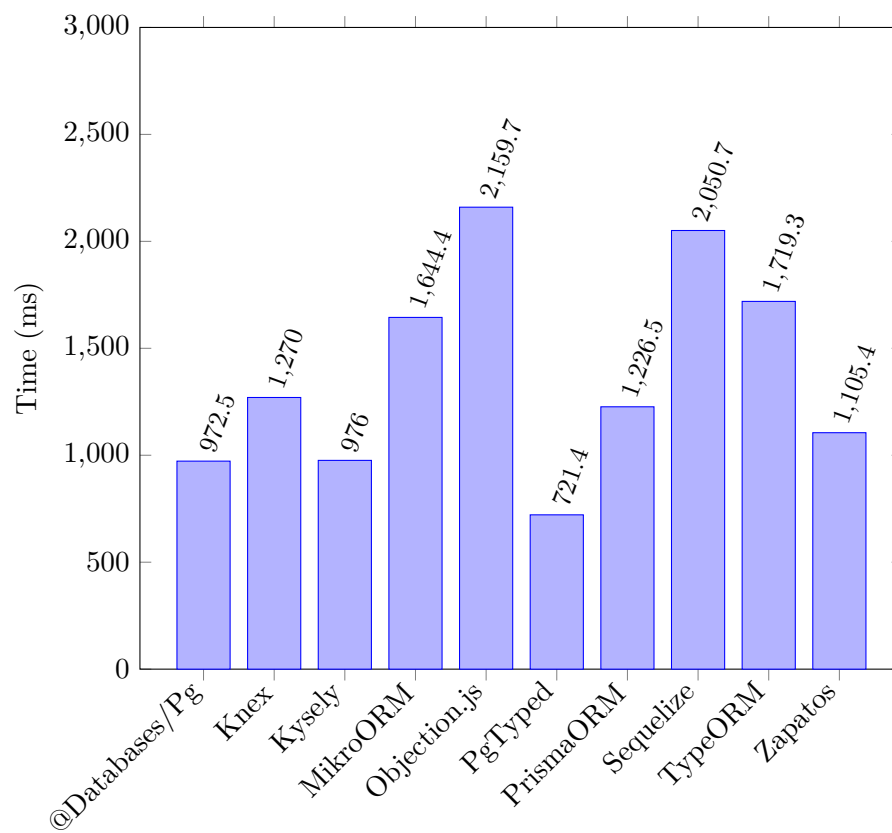


Figure 8.7: Pattern Matching (likeQuery) Results



Conclusion

In conclusion, this thesis has successfully investigated the spectrum of database access options available to developers within the TypeScript ecosystem. The research has led to the development of a scalable benchmarking framework designed to evaluate the capability of various packages to execute database operations. This framework accommodates additional test databases and suites, providing opportunities for future research and expansion.

Several avenues for future work emerge from the findings of this thesis. These include extending the benchmark framework to incorporate a more comprehensive array of packages and databases, evaluating the capacity of these packages to describe database schemas, and devising additional test suites to assess the flexibility and performance of the packages under investigation.

The results of the benchmarking process provide valuable insights into the performance and capabilities of several prominent ORM frameworks. While there appeared to be negligible performance differences between TypeORM and Sequelize, the two leading ORM frameworks, TypeORM demonstrated significantly better support for TypeScript features, utilizing them to its advantage. Furthermore, two lesser-known packages, Kysely and MikroORM, displayed remarkable utility and flexibility in their respective domains.

Kysely, a query builder alternative to the more popular Knex, exhibited superior type support while delivering faster results and maintaining an equal capacity for query creation. Kysely has significant potential to become a compelling alternative for developers seeking a more type-safe and performant query builder.

9. CONCLUSION

MikroORM surprised with its extensive feature set, excellent type support, and the ability to leverage Knex for crafting highly complex queries. Its performance in the benchmarks underscores the potential value of MikroORM for developers who require a more feature-rich and type-safe ORM solution while still retaining the flexibility to utilize Knex when necessary.

The findings of this thesis emphasize the importance of considering lesser-known packages in addition to the most popular solutions when selecting a suitable ORM framework or query builder. By doing so, developers can make more informed decisions that align with their specific requirements, maximizing the benefits of the chosen package and optimizing the overall development process.

Moreover, the development of the extensible benchmarking framework in this thesis serves as a foundation for future research in the field. As the ecosystem of TypeScript-compatible database access packages continues to evolve, the framework can be updated and expanded to ensure that developers stay well-informed about the strengths and weaknesses of emerging solutions. Such service would enable them to make better-informed decisions when selecting a package that best suits their project's needs, ultimately contributing to more efficient and robust application development.

In summary, this thesis shed light on the diverse landscape of TypeScript-compatible database access packages, providing valuable insights into their capabilities and performance. With the knowledge gained from this study, developers stand better equipped to select the most suitable package for their specific requirements, ensuring a more streamlined and effective development process.

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Contents of enclosed medium

	readme.txt	the file with CD contents description
	exe	the directory with executables
	src	the directory of source codes
	wbdcm	implementation sources
	thesis	the directory of \LaTeX source codes of the thesis
	text	the thesis text directory
	thesis.pdf	the thesis text in PDF format
	thesis.ps	the thesis text in PS format