Database-Backed Applications in the Wild: How Well Do They Work?

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ABSTRACT

Most modern database-backed applications are built using Object Relational Mapping (ORM) frameworks. While ORM frameworks ease application development by abstracting persistent data as objects, such convenience often comes with a performance cost. In this paper, we present OMAS, a tool that examines the application logic and its interaction with databases via the Ruby on Rails ORM framework. OMAS comes with a static program analyzer and a synthetic data and workload generator that profiles applications to understand their performance characteristics. With OMAS, we performed the first comprehensive study of real-world ORM framework-based applications, where we analyzed the performance and programming patterns across 26 open-source applications, covering domains such as forum, e-commerce, project management, blogging, etc. Based on our study, we make a number of observations and analyze their implications on the design of ORM frameworks and databases. Furthermore, we discuss new research directions on data management and software engineering that our study raises, and how OMAS can help in implementing them.

1. INTRODUCTION

Object-relational mapping (ORM) frameworks have been widely used to construct applications that interact with database management systems (DBMS) . While there are many implementations of such frameworks (e.g., Ruby on Rails [17], Django [7], Entity Framework [9], Hibernate [10]), the design principle and goal behind remain the same: rather than embedding SQL queries within application code, ORM frameworks present persistently stored data as heap objects and enable developers to manipulate persistent data in a similar way as regular heap objects via a provided API [6] [8]. These API calls are translated by the ORM frameworks into queries and sent to the DBMSs for execution. This approach raises the level of abstraction and allows developers to implement their entire application using one single programming language, which greatly enhances code readability and maintainability.

However, this increase in programmer productivity comes at a cost. By hiding the details of the DBMS behind an API, ORM frameworks do not have access to high-level semantic information about the application, such as how persistent data is used. In addition, abstracting queries into API calls prevents application compilers from optimizing such calls, as compilers can only treat such API calls as unknown external functions that cannot be altered.

Both aspects make applications built on top of ORM frameworks vulnerable to performance problems. Such issues are well-known in both the data management [19] and software engineering research communities [31] [32], along with developer communities as well [14]. Unfortunately, as application performance, in terms of both latency and throughput, is often of critical concern for many applications that are constructed using ORM frameworks [13] [20], developers often end up needing to “hand-tune” their ORM-based applications such as implementing caches for persistent data [3] [4] or customizing physical design for each application [12] [11]. Sadly, doing so greatly complicates the application, and defeats the original purpose of using ORM frameworks.

Addressing the performance issues associated with ORM-based applications requires understanding how such applications are built and used, and doing so requires examining both the application, the ORM framework, and the DBMS in tandem. While there has been prior work in optimizing ORM-based applications [31] [30] [32], they are limited in addressing only a few specific performance issues that arise in specialized domains. It is unclear whether these issues exist in general domains; it is also unclear what other performance issues exist in real-world ORM-based applications. On the other hand, while there are various tools for detecting and measuring application performance, they target either the application or the DBMS, and none exists that examine both.

In this paper, we describe OMAS, a new tool that analyzes ORM-based applications by examining the application, the ORM framework, and the DBMS that the ORM framework interacts with. OMAS currently targets ORM-based applications that are built using the Ruby on Rails (Rails) framework based on its popularity, and consists of two components:

1. A static code analyzer that infers potential queries that the application might issue, the uses of such queries, and application state changes via user interactions. The analyzer returns the results using a new data structure called the Action Flow Graph (AFG).
2. A synthetic data generator based on users’ interactions with the application. OMAS comes with a dynamic analyzer that executes the application using the generated data, records the queries that are executed, and collects runtime information such as execution time.

The above components enable OMAS to gather comprehensive information about ORM-based applications by examining both potential queries that can be issued by the application along with actual queries executed under synthetic workloads.

Using OMAS, we performed, to the best of our knowledge, the first comprehensive study of ORM-based applications “in the wild.” Specifically, we collected a large number of real-world applications that are built using Rails and studied them using OMAS. We purposefully chose applications from a wide range of application domains where we expect different DBMS usage profiles (e.g., amount of data reads and writes), and examined applications’ interactions with DBMS via Rails by analyzing the queries issued. We present our findings along three dimensions: individual queries, queries issued as a result of a single user action (e.g., a page load...
request), and queries that are executed across multiple actions (e.g., a user session). Finally, based on our analysis results, we describe new and exciting research topics in performance optimization, the design of ORM frameworks, application scalability, and performance testing.

In summary, this paper makes the following contributions:

- We built OMAS, a tool for analyzing applications that are built using the Ruby on Rails ORM framework. OMAS studies applications using static analysis and generates action flow graphs, which describe the flow of persistent data among the application, the ORM framework, and the DBMS. OMAS also performs dynamic analysis and profiles applications using generated data.
- We used OMAS to perform the first comprehensive study of 26 real-world applications built on top of Rails. Our study encompasses a broad range of domains including forums, social networking, e-commerce, etc. Our results show that many applications expose the same or similar patterns. For example, coding practices following good logic division can lead to performance issues, traditional performance modeling and testing methods are insufficient in analyzing ORM applications, etc.
- Based on our observations, we proposed new research opportunities in both data management and software engineering research, along with suggestions for future designs of ORM frameworks.

In the following we review the design of ORM frameworks and how they are used to construct database-backed applications in Section 2. In Section 3, we describe OMAS and our study. Then in Section 4, we present the results from our study, followed by discussion on new research topics in Section 5.

2. BACKGROUND

In this section we give an overview of Ruby on Rails (which we refer to as "Rails" below), a widely-used ORM framework, the architecture of applications built using Rails, and how Rails implements object relational mapping.

![Architecture of a Rails application](image)

Figure 1: Architecture of a Rails application

2.1 Design of Rails applications

In our study of open-source ORM-based applications, we pick Rails as our target framework due to its popularity. Many well-known websites such as Airbnb, Shopify, and Hulu are built on top of Rails. Figure 1 shows the typical structure of a web application built with Rails (which is similar to those constructed using other ORM frameworks), where the application is hosted on an application server (e.g.,) with the Rails framework installed. The Rails application is organized into Model, View, and Controller (MVC) components. While the separation of logic allows to the independent development of these three components, their separation can lead to performance issues, as we will discuss in Section 4.

Upon receiving a user’s request, say to render a web page, (step 1 in Figure 1), the appropriate action in the application’s controller is triggered according to the routing rules defined by the application (shown in Figure 2). The action creates model objects and calls ORM functions implemented in models (2). Persistent data is abstracted into objects that are represented as models, and Rails translates ORM function calls into SQL queries that are issued to the DBMS (3). Upon receiving query results (4), data is serialized into objects and that are returned to the action (5). The retrieved objects are then passed to the view (6), which constructs the webpage (7) that is returned to the user to be rendered (8).

To illustrate, Figure 2 shows the code of a sample blogging application. While the controller and model are written in Ruby, the view code is implemented using a mix of ruby and web mark-up languages like HTML. There are two actions defined in the controller: show and index. Those actions call ORM functions User.where, User.some_blogs, and Blog.where that are translated to SQL queries for data retrieval. show passes the retrieved data to render to construct the output webpage based on the view allBlogs.erb (and correspondingly index and oneBlog.erb), where the blog excerpts (b.excerpt) and their contents (b.content) are inserted as part of the generated webpage.

2.2 Object relational mapping in Rails

By default, Rails like many other ORM frameworks maps each model class or the entire class hierarchy into a single table. As shown in Figure 2, the User class is backed by the User table in the DBMS, and similarly for the Blog class. Programmers can specify which subset of fields in a model class to be physically stored in the corresponding database table, and define relationships among model classes via association, such as has_one and has_many. For example, in Figure 2 each Blog object belongs_to one User, hence Rails stores the unique user_id associated with each Blog rather than the entire User record. Rails provides a rich set of functions that support CRUD (create, read, update, delete) operations on persistent data.

3. OMAS AND STUDY METHODOLOGY

After reviewing how ORM-based applications are built, we now describe how OMAS analyzes such applications, and the application corpus that was chosen for our study.

3.1 Static program analysis

The static code analyzer in OMAS takes in Rails application source code, examines its interaction with the DBMS, and generates a Action Flow Graph (AFG) for each application. The design of AFGs is based on Program Dependence Graphs (PDG) that capture control and data flow in general-purpose programs. In addition, AFGs contain next action edges between pairs of controller actions ($c_1$, $c_2$), where $c_2$ can be invoked from $c_1$ as a result of user interactions (e.g., clicking a link or filling a form on a webpage).

To build AFGs, OMAS first infers control and data flow for each controller action using classical algorithms, except:

1 While many ORM frameworks enforce such relationships as functional constraints on tables, Rails does not do so and relies on the programmer to maintain them in their applications.
OMAS performs type inference as Ruby is dynamically typed.

OMAS inlines all render calls in controllers with the corresponding view (i.e., .erb files). When inlining, OMAS only keeps the ruby code from the view and ignore other code such as HTML or Haml.

OMAS inspect two types of library functions: i) functions that issue SQL queries (we refer them as “query functions” in Figure 3), to analyze the potential database queries issued in the application; ii) functions that generate URL links in the output webpage (e.g., link_to in Figure 2), to infer next action edges.

To infer next action edges, OMAS applies the routing rules (e.g., those listed in Figure 2) to determine which controller action is triggered by each function call identified by step (ii) discussed above. As an example, Figure 3 shows the AFG that corresponds to the code shown in Figure 2.

### 3.2 Dynamic application profiling

OMAS also performs run-time profiling to get in-depth knowledge about the application performance. To do so, OMAS first populates the DBMS where persistent data for the Rails application is stored, and then measures the execution time of the application while scaling the size of the DBMS.

#### 3.2.1 Synthetic data generation

Given a Rails application, OMAS populates the DBMS where persistent data is stored by randomly visiting pages from the application, and filling out pages that correspond to forms with randomly generated data. Submitting these forms triggers the application to insert data into the DBMS.

We use OMAS to populate different sizes of DBMS for each application, ranging from 200 to 200K records. The resulting sizes of the DBMS then range from 1MB to 6GB.

#### 3.2.2 Runtime profiling

Once the DBMS is populated, OMAS simulates user behavior by running a web crawler on the client side. For a single user, the crawler first visits the homepage of the application and randomly chooses a link to visit the next webpage. If the visited webpage contains a form, OMAS fills in the form with random data. OMAS currently only profiles each application using a single client and leaves multi-clients profiling as future work.

On the server side, we deploy the application server on Amazon AWS node with 4 CPUs, each with 16GB of memory. OMAS records the running time of each controller action as it generates a response to an HTTP request. It also keeps track of the queries issued to the DBMS, the time spent on each query, as well as a detailed breakdown (which we will discuss in Section 5.2).

### 4. OBSERVATIONS AND IMPLICATIONS

In this section we describe our comprehensive study of Rails applications using OMAS. The goals of the study are to investigate:

- the sources of query parameters, how is a query issued, and how query results are used for individual queries (Section 4.2).
- dependencies among queries within single controller action (Section 4.3).
- relationships among queries across multiple controller actions (Section 4.4).
- the physical design used in applications (Section 4.5).

In the following we present our findings and point out their implications, where many of them suggest optimization opportunities for both the DBMS and ORM framework implementation.

#### 4.1 Application corpus

We conduct a large scale case study of 26 open-source Rails applications. Applications were selected from github based on their popularity (76.92% of them have more than 200 stars), number of contributors (84.62% of them have more than 10 contributors), number of commits, and category.

The applications, their category, and lines of code are shown in Table 1. Overall, they cover a broad range of characteristics in terms of DBMS usage: transaction-heavy (e-Commerce), mostly read-only (social networking), write-intensive (blogging, forum), data that can be horizontally-partitioned based on users (blogging, task management), or heavily-shared among users (forum, collaboration). We believe that these represent all major categories of ORM-based applications.

#### 4.2 Life of a single query

We now present the results from our study. Starting from the analysis of the data source for query parameters, we follow the life of individual queries, and look into how each query is issued, the result set sizes, and how the result sets are used by the application.
4.2.1 Where do query parameters come from?

First, we study the sources of query parameters. To do so, we examine each node with a query function in the AFG in each controller action, and trace backwards along dataflow edges till we find another node with query function, or a node with no incoming dataflow edge. We refer to those as the source nodes of a query function and categorize them as follows: (1) read query functions, (2) user inputs, (3) constant values, (4) utility function calls (for example, Time.now), and (5) global variables.

A query can have multiple source nodes if it has multiple parameters or a parameter is computed using multiple sources. We calculate the average number of source nodes for each query, breaking down by the types of source. Unless noted, all of our results in this paper are path insensitive, meaning that if there is a branch, we examine the code in both branches.

Figure 4 shows the breakdown of the source nodes averaged across all read query functions (i.e., they only issue read-only SQL queries) and Figure 5 shows the result for write query functions (i.e., they can issue both read and write SQL queries).

### Observation:
For write queries, the greatest contributor to the source is constants (42.6%). For read queries, the greatest contributor to the source is other read queries (40.1%).

### Implication 1:
For write queries, program analysis can determine all possible values that might be written, especially if the written values are constants.

### Implication 2:
For read queries, if a query uses other queries’ results as parameters, then this query and its source queries may be chained into a single query.

Figure 4: Source breakdown for read query functions

As an illustration of the first implication, one needs to trace the data source of the assignment of a field to determine the value range of that field. Listing 1 shows code abridged from publify [15], where an article written by a user can have only one of the three states: draft, published, or withdrawn. Program analysis reveals that the state field is only assigned in the code fragment shown in Listing 1 meaning that the value range of this field can only be one of the above three strings, and knowing such information will help in query processing, for instance in selectivity estimation.

Listing 1: Assignment to “state” field

```ruby
Listing 1: Assignment to “state” field

```class ArticleController
def create
  article.state = "published"
def autosave
  article.state = "draft"
def withdraw
  article.state = "withdrawn"
end
```

Listing 2: Defining association

```ruby
Listing 2: Defining association

class User
  has_many :todos, class => Todo
class Todo
  has_many :projects, class => Projects
  users = User.where(id = params[user_ids])
todos = users.todos
  projects = blogs.projects
```

Listing 3: Queries issued via association

```ruby
Listing 3: Queries issued via association

SELECT User.* FROM User WHERE id IN params[user_ids]
SELECT Todo.* FROM Todo WHERE user_id IN users.id
SELECT Projects.* FROM Comment WHERE todos_id IN todos.id
```

Listing 4: Combining queries which are issued via association

```ruby
Listing 4: Combining queries which are issued via association

SELECT u.*, t.*, p.* FROM User AS u WHERE u.id IN params[user_ids] INNER JOIN Todo as t ON t.
  user_id = u.id INNER JOIN Project as p ON p.
  blog_id = t.id
```

4.2.2 How are queries issued?

We next study queries that are issued via association, and queries that are issued in loops. The first class of queries exposes opportunities for combining multiple queries into a single query, while the latter may make the application vulnerable to scalability issues.

### Queries issued via association:

```ruby
Listing 2: Defining association

class User
  has_many :todos, class => Todo
class Todo
  has_many :projects, class => Projects
  users = User.where(id = params[user_ids])
todos = users.todos
  projects = blogs.projects
```

Listing 3: Queries issued via association

```ruby
Listing 3: Queries issued via association

SELECT User.* FROM User WHERE id IN params[user_ids]
SELECT Todo.* FROM Todo WHERE user_id IN users.id
SELECT Projects.* FROM Comment WHERE todos_id IN todos.id
```

Listing 4: Combining queries which are issued via association

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Listing 4: Combining queries which are issued via association

SELECT u.*, t.*, p.* FROM User AS u WHERE u.id IN params[user_ids] INNER JOIN Todo as t ON t.
  user_id = u.id INNER JOIN Project as p ON p.
  blog_id = t.id
```
Rails provides explicit data retrieval functions such as `where` and `join` that directly translate to SQL queries. In addition, persistent data can also be retrieved implicitly via `associations`. Retrieving associated objects is the same as accessing a class member of an object that is already retrieved from the DBMS. If the accessed class member has not been retrieved yet, a SQL query is issued.

As an example, Listing 2 is an abridged code from tracks [21]. In this application, each user has many blogs, and each blog has multiple comments. These associations are defined on Line 2 and Line 4 in Listing 2. Line 5 issues a SQL query (shown on Line 1 in Listing 3) using explicit query function where, while class member accesses on Line 6 and Line 7 trigger SQL queries to be executed via association, as shown on Line 2 and Line 3 in Listing 3.

Figure 6 shows how many queries are issued in a loop in our application corpus, and how many are issued in loops with loop-carry dependencies. If statements within a loop body form a dependence, the loop has loop-carry dependence. The loop-carry dependence analysis is conducted using traditional compiler techniques [22].

**Observation:** On average, 30% of all queries are issued in loop. Most (95%) of the loops containing queries do not have loop-carry dependencies.

**Implication:** Optimizations for queries issued in loop is important since they are prevalent in all applications and may become a performance bottleneck. Since most loops do not have loop-carry dependencies, queries inside these loops can be easily batched or executed in parallel.

Prior work has explored using program analysis to batch queries in loops [34] [40]. These methods can be applied to ORM applications, and we show that they may improve performance significantly due to the prevalence of queries issued in loop. Reducing the time spent on loops is important since loops can make applications vulnerable to scalability problems, which we will discuss more in Section 5.2.

### 4.2.3 How large are result sets?

After a query is executed, its results are returned to the application. If a query returns a large result set, subsequent computation using the results may take a long time to complete.

As shown in Listings 2 and Listing 3, each class member access can trigger a database query, unless the class member has been previously retrieved. Furthermore, accessing N different class members inside a loop will lead to the “N+1” problem [14], where N queries are issued to fetch each individual class member. Such queries can be combined into a single join query. For example, the queries in Listing 3 can be combined into a single query as shown in Listing 4. The combined N-way join query exposes more query optimization opportunities due to increased number of ways to perform the joins.

To reduce the number of roundtrips in association queries, Rails allows developers to eagerly load the objects retrieved via association by combining multiple SQL queries into a single join. However, we find that for all the queries that are issued via association, only 5% of them are combined into a join using eager loading. Furthermore, among all uses of eager loading, more than 30% of them load more objects than actually needed. This is likely due to the lack of knowledge about the data to be needed subsequently in the application, especially in the case where application development is split across multiple teams of developers. Moreover, the logic separation of MVC prevents the model developer from fully understanding which data to be used in controller or presented in view. Static program analysis can identify such data retrieval via association and determine when eager loading should be used.

**Queries issued in loops:** A query could be repeatedly issued in a loop, with potentially different query parameters in each iteration.

**Queries issued via association:** Queries issued in loops with loop-carry dependencies.

**Queries not in loop:** Queries not in loop.

Prior work has explored using program analysis to batch queries in loops [34] [40]. These methods can be applied to ORM applications, and we show that they may improve performance significantly due to the prevalence of queries issued in loop. Reducing the time spent on loops is important since loops can make applications vulnerable to scalability problems, which we will discuss more in Section 5.2.

**Implication:** Optimizations for queries issued in loop is important since they are prevalent in all applications and may become performance bottlenecks. Since most loops do not have loop-carry dependencies, queries inside these loops can be easily batched or executed in parallel.

We study the result size of each generated SQL query, and how it scales with the database size. If a query always returns a single value (e.g., a COUNT query), a single record (e.g., retrieving using a unique identifier), or has a LIMIT keyword, the number of returned result/record of that query is bounded. For all other SQL queries generated by Rails, we consider their result sizes to be unbounded and hence likely scale with the database size. We calculate the average number of queries returning bounded or unbounded result set in each controller action, and the results are shown in Figure 8.
A large result set can make subsequent processing of the result set running for a long time. For example, if each record in the result set need to be shown in the view, and each record triggers a partial view construction (which generates partial webpage), then view rendering may become extremely slow as the database size scales. To further study the impact of result set size on application performance, we calculate how often the result set size affects the following computation time after the data is retrieved. We find out among all the loops in an application, more than 49% are one-by-one processing query results. This suggests that half of the loops has running time directly depending on the size of returned query results. Section 5.2 will discuss more on how the queries returning unbounded records affect application scalability.

4.2.4 How are query results used?

In addition to analyzing sources of query parameters, we look into how query results are used by studying the data sink of queries. We also analyze how much data is unnecessarily retrieved.

**Uses of query results:** To perform the analysis of how query results are used, we start from each node in the AFG with a read query function, and trace forward along dataflow edges until we reach either a node with a query function, or a node having no outgoing dataflow edge. We refer to such nodes as the read query sinks. We subsequently categorize sinks into the following: (1) query parameters in subsequent queries; (2) rendered in the view; (3) used in a branch conditions; and (4) assigned to global variables. Figure 9 shows the average breakdown of different sinks for read queries.

![Figure 9: Breakdown of sink node for each read query](image)

**Observation:** A non-trivial number of queries (35%) return unbounded result sets. **Implication:** Many applications are likely to vulnerable to scalability problems, as they execute queries that return unbounded result sets.

We will discuss more about the implication regarding the branches as query sink in Section 5.3.

**Unused query results:** Most Rails query functions fetch entire rows (i.e., SELECT *) from the database, unless programmers use the Rails select function to retrieve specific fields (i.e., columns) from the table. Unfortunately, the select function is rarely used, which causes many retrieved fields to never been used.

We quantify the amount of unused data in query results in the following manner: for fields with undetermined length (for instance, field with type “text”), we assume it is 2450 bytes otherwise half the value of the limit (assuming the field size is evenly distributed). For fields of fixed size, we use their actual size when stored in the database. If a query returns a complete record, we compute the total size of fields used in subsequent parts of the program, and treat the rest fields as unused and compute the total size of these unused fields. We calculate the average size of query results by byte, breaking down by being/not being used in the subsequent program. The results are shown in Figure 10.

![Figure 10: Unnecessary data retrieval](image)

**Observation:** Applications frequently retrieve data that is unused. More than 45% of all data retrieved in applications are not used. **Implication:** Static program analysis can identify retrieved data that is used later and rewrite the query function to access only useful data. Such optimization can improve performance significantly by reducing data retrieval.

Chen et al. has studied this as the redundant data access problem [31], but only looked at queries issued via association which only contribute to 35.1% of queries in ORM applications, and they evaluated in only two applications. Our study confirms the severity of this issue across all types of queries and application domains.

4.3 Dependency among queries

In this section, we examine the control and data dependencies among queries that are issued within one controller action. To do so, we consider each controller action, and for each AFG node with query function we trace back in terms of control and data flow edges to see if it is connected to another query function node. If query $Q_1$ is data-dependent on another query $Q_2$, then the two queries can only be executed sequentially unless they are combined. However, if $Q_2$ is control-dependent on $Q_1$, then it might be possible to execute $Q_2$ speculatively. Figure 11 and Figure 12 show the number of queries that control and data dependent on others.

**Observation:** Many queries (83%) are control-dependent on other queries, and fewer (46.7%) are data-dependent on others. **Implication:** Speculation or branch prediction algorithms can help exploit parallelism opportunities to improve the performance of ORM applications.

Pavlo et al. [45] use Markov model to speculatively execute queries. Although the model is used for distributed transactions, similar techniques may be applied to predict which query will be executed. Traditional branch prediction techniques [41] can also be helpful for speculative query execution.
4.4 Life of a user session

In this section we analyze query behavior across groups of controller actions, with the idea that each group represents the web-pages that are visited by the user over one session. To identify such groups, we use the next action edges in the AFG to identify controller actions that can be executed sequentially via user interactions (e.g., page clicks).

After collecting the data, one aspect that we noticed is that the set of queries that are issued in consecutive controller actions often have substantial overlap. However, since deciding the equivalence between arbitrary SQL queries is an open problem, we only consider syntactically equivalent queries or queries with the same template when computing overlap.

Listing 5 shows two controller actions in the BlogController class where show_published displays the published blogs written by the current user while show_draft displays the user's drafts. These two controller actions form a next action pair.

**Syntactically equivalent queries:** The before_filter callback defined on Line 2 checks if the current user exists in the database using a SQL query that is executed before either action. Hence, the user check query is repeated across the two consecutive controller actions, as shown in Listing 6 and Listing 7.

**Queries with the same template:** Note that the two actions each issue another query (Line 8 and Line 10 in Listing 5) that is based on the same template but with different parameters (state in particular). In our study we analyzed how frequent such scenarios happen across the different applications.

```ruby
class BlogController
  before_filter: user_authentication
  def user_authentication
    user = User.where(id => params[user_id])
    if user.is_active == false
      raise "Current user not active!"
  def show_published
    blogs = user.blogs.where(state='published')
  def show_draft
    blogs = user.blogs.where(state='draft')
Listing 5: Controller code for showing blogs
```

We use both static analysis and dynamic profiling to count the two types of overlapping queries described above. We used dynamic profiling to count the number of syntactically equivalent queries, and divided by the total number of queries executed in the next action. We also recorded the execution time of the same queries, divided by the total running time of all queries in the next action. Similar calculations are done for queries with the same template. Both results are shown in Table 2.

Additionally, we used static analysis to count the query overlap. Using AFG we can find all next-action pairs, and for each pair, we calculate the same query functions in current and next action, ignoring the parameters fed to the query functions. Since the same query function will issue the query with the same template, we use the portion of same query functions as an indication of the overlap of queries with the same template, as shown in Figure 13.

**Observation 1:** Although a non-trivial portion of queries (more than 28%) issued by consecutive controller actions are syntactically equivalent, the time spent on executing those queries is relatively small, about 17% in average.

**Observation 2:** Static analysis shows that more than 58.4% of potential queries in consecutive controller actions share the same template. Profiling confirms that such queries are significant both in terms of proportions (more than 40% of all queries issued) and execution time (over 37%).

**Implications:** Naive caching of the query results (e.g., using the entire SQL query string as cache key) only offers trivial performance gain. However, caching by query template can have much more performance improvement.

Our results suggest opportunities in query caching. While Rails does not implement caching across controller actions by default, it provides a caching API that programmers can use. Unfortunately, using the caching API requires specifying the key and value for the cache and implementing a cache invalidation strategy. This is both tedious and error-prone. Only 15 out of the 26 applications we studied use Rails cache API, and most of them apply a simple invalidation strategy based on a fixed timeout. Not only that, it is difficult for developers implementing controller actions to design a

| App    | Syntactically equivalent query | Query with the same template |
|--------|-------------------------------|-----------------------------|
|        | % in query number | % in query time | % in query number | % in query time |
| lobsters | 34.21% | 12.31% | 47.23% | 12.31% |
| publify | 56.40% | 27.43% | 78.36% | 56.15% |
| sugar   | 32.61% | 18.33% | 63.91% | 43.41% |
| tracks  | 34.61% | 10.01% | 37.57% | 12.67% |
| kandan  | 28.72% | 17.23% | 41.39% | 37.03% |

Table 2: Query overlap calculation with dynamic profiling: the same query and query with the same template

Sel ect User.* FROM User WHERE id = 1
Sel ect Blog.* FROM Blog WHERE user_id = 1 AND
state = 'published'

Listing 6: Queries issued by the show_published controller action

Sel ect User.* FROM User WHERE id = 1
Sel ect Blog.* FROM Blog WHERE user_id = 1 AND
state = 'draft'

Listing 7: Queries issued by the show_draft controller action
4.5 Physical design

In this section we analyze the physical design of the applications and study how that impacts performance.

As discussed in Section 2, Rails creates a table for each model class, and programmers specify which class member variables from the model need to be physically stored in the DBMS. However, making the optimal decision (in terms of storage space and application performance) is often difficult, especially when models and the rest of the application are developed by different teams. We quantify this aspect by statically analyzing the usage and assignment of fields across different tables.

We first examine the usage of each physically stored table column using the AFGs of all controller actions. For each column c of table f that is mapped to field f in model class M, we calculate the number of times that f is used by tracking each instance of M and adding up the uses of field f across all instances. We then analyze the amount of computation required for f: for all assignments to f, we calculate the average number of instructions needed to compute the assigned value.

Intuitively, if f is derived from user inputs, it should always be physically stored. However, if f can be derived from non-user inputs (e.g., from existing values stored in the DBMS), then it should be physically stored only if it is frequently used, has a small size, and requires a considerable amount of computation to derive. To avoid repeated computation. On the other hand, if f can be easily computed and is rarely used, it should not be physically stored to reduce table sizes, especially when the size of f is large. As one can imagine, there is a spectrum of possibilities here, and making the optimal decision is not easy.

Figure 13 shows the results for all applications, with each point representing a physically stored field (different color shows different data types). The X-axis shows the average usage in one action and Y-axis shows the amount of computation required. Figure 14 shows the number of table columns that are derived from user input (top above the double line), and a breakdown of columns that are not derived from user inputs (below the double line).

Observation 1: The values of most derivable fields are computed relatively easily: more than 91.6% of the fields can be computed using fewer 500 instructions, and most of such fields are used frequently. Among these fields, 6% are of text type that can be potentially large, while others are of fixed size.

Implication 1: There is a lot of flexibility in deciding whether a field that does not involve user input should be physically stored or not, since most of such fields are easy to compute.

Observation 2: A significant portion of columns (51.8%) can be derived from other columns.

Implication 2: Program analysis can be used to determine a non-negligible number of functional dependencies.

5. OTHER FINDINGS & IMPLICATIONS

The previous section has listed the findings from our study along with optimization opportunities based on those findings, and pointed out that static analysis plays an important role in these optimizations. In this section, we further discuss how our study results lead to further research topics beyond data management, including software engineering, performance modeling, and testing of ORM-based applications.

5.1 Programming Practices

In this section we evaluate whether programmers make good use of the abstraction provided by ORM, and whether they separate the application logic following the MVC pattern as discussed in Section 2.

5.1.1 ORM query functions or SQL

As mentioned in Section 1 ORM framework improves programming productivity by hiding data access details so that programmers do not need to embed relational queries directly in their applications. However, the developers community often advocates for writing explicit SQL query strings instead of using Rails API functions for performance concerns[19].

For example, in the sharetribe application[18], the programmer sends a SQL string to the database to update the priorities of all

![Figure 13: Query in next action with same template, comparing to total number of query in next action](image1)

![Figure 14: Usage frequency and compute effort for each table field](image2)

![Figure 15: Table fields with functional dependencies on other fields](image3)
categories that a bunch of orders belong to, as shown in Listing 8. Since Rails does not support batched updates with complex conditions like the CASE...WHEN in Listing 8, programmers need to write explicitly construct a SQL query to avoid record-by-record updates, where doing so breaks the ORM abstraction.

```ruby
sql = "UPDATE categories SET sort_priority = CASE id
update = params[orders] do |(cat_id, priority)|
  sql += "WHEN #{cat_id} THEN #{priority} |n"
end
update += "END WHERE id IN (#{params[priorities]});
ActiveRecord.connection.execute(update)
```

Listing 8: Code for updating categories’ priority

To understand how programmers make the tradeoff between programmability and performance, we calculate the number of queries issued by explicit SQL strings, and the number of queries issued by ORM query translator. The results are shown in Figure 16.

Despite the performance improvement, programmers rarely (7.6% of the queries) write SQL strings. This suggests that developers favor programmability over performance.

For queries that are constructed explicitly with SQL strings, we manually examine them and find that 73.3% of them are performing queries whose logic causes ORM to issue multiple queries if one uses ORM functions to implement. Examples include batching update as shown in Listing 8 queries involving INSERT REPLACE, queries involving ORDER...CASE...WHEN, etc. By using explicit SQL, developers combine multiple queries into a single query to improve performance.

### 5.1.2 MVC or not

As mentioned in Section 2, Rails application design follows the MVC architecture. In MVC, all the persistent-data-access logic should be defined in the model and these access functions defined in the model should be invoked only by the controller, while the view should use the object data passed by the controller in building pages. However, when inspecting the application code, we find that some queries are issued in the view.

As shown in Figure 17, on average 5.9% of queries are issued in the view, with an example shown in Listing 10. Such a deviation from MVC architecture hurts software modularity and maintainability. We further look into those queries, and find that 86% of them are issued via association. As discussed in Section 4.2, queries can be combined with eager loading. If loaded appropriately, class member accesses in the view should not trigger further SQL queries. The issuing of queries in views shows that the eager-loading problem exists even across components, and an optimized loading scheme can help with not just performance but also improve software modularity.

### 5.2 Scalability analysis

The scalability of applications as database size increases has become important in the big-data era. As database size grows with time and application popularity, the application is expected to still respond quickly even when it is dealing with more data. However, programmers often do not have a test database large enough to help assess and refine application performance at large scale, and hence are likely to build applications with scalability problems. This section studies the scalability of ORM applications: how does the response time change when the database size increases, and what optimizations can help make response time scale-independent.

We first use profiling results to show how the running time of a controller action changes as the database size increases. Due to space constraints, we only pick a few representative controller actions from each application, showing the action running time and the breakdown of the time spent on database, view rendering, and other application logic.
Figure 18 shows that i) the response time may scale linearly or super-linearly with the database size, reaching up to 10 seconds in 5 out of 7 profiled applications, which is annoyingly slow for user-interactive web applications [13]; ii) the time spent in each of the three parts may increase super-linearly as the database size increases. We provide more insights on the scalability of each part below by analyzing examples from studied applications.

**Database time:** The time spent in executing each single query and the number of queries together determine the database time. Since scale-(in)dependent queries have been studied before [25], we focus on the latter issue.

Here is an example where the number of queries issued may increase linearly with database size. The code fragment shown in Listing 9 deletes all the comments made by a user, while for each comment (Line 5), it retrieves the blog that the comment belongs to (Line 6), and updates the comment count of that blog (Line 6). When the size of table Message increases, the number of loop iterations increases linearly. And since the execution time of the query issued by Line 5 is scale-dependent, the overall time to execute batch_delete increases super-linearly with database size.

```ruby
class MessagesController
  def batch_delete
    msgs = User.sended_messages
    msgs.each do |m|
      count = m.recipient.unread_messages.count
      TrafficRecord.update("#m.recipient.id:
      unreadmsgs", count)
    end
    m.delete
  end
end
```

Listing 9: Deleting all messages sent by a user, abridged from the lobsters application

**View rendering time:** In Listing 10, the forums are iterated over in a loop (Line 7), and for each forum, the application lists all the links to the forum moderators (Line 9). Consequently, the link creation is inside a nested loop, with each loop iteration increases linearly with the database size, making the total view rendering time increase super-linearly.

```ruby
class ForumsController
  def index
    forums = Forum.all
    render 'index.erb' do forums
      forums.group_by(&:category).each do |cat, fs|
        fs.each do |f|
          f.modulators.map do |m|
            link_to '/forum/#{f.id}/moderator/#{m.id}'
          end
        end
      end
    end
end
```

Listing 10: Showing forum descriptions by categories, and the links to forums’ moderator; code abridged from the forem application

**Application time:** The code snippet in Listing 11 updates all todo projects for the current user and inserts predecessors to these projects. Called within a loop (Line 5), this nested loop to process query results thus makes the total execution time for the application logic increase super-linearly with the database size.

```ruby
class TodosController
  def save_multiple_todos
    current_user.todos.each do |todo|
      params[predecessors].each do |p|
        todo.precdecessors.add(p) unless todo.
        predecessors.include?(p)
      end
    end
end
```

Listing 11: Saving multiple todos, abridged from tracks application

Based on the above analysis and our careful study of all the applications, we find that when database size increases, the controller action time will possibly increase due to the following factors:

- the increase in the execution time of a single query;
- the increase in the number of query issued to the database;
- the increase in the number of records returned, which makes the subsequent processing of these records taking longer time to finish.

However, it is desirable for the application response time to be scale-independent, or scale sublinearly with the database size. Some applications have comparatively good performance in terms of scalability, for instance, sugar (among 40 actions we profiled, roughly 27 actions has constant running time, 7 sublinearly scaled, 5 linearly scaled, and 1 action superlinearly scaled); while some applications are vulnerable to scalability problem, for instance, publify (among 32 actions we profiled, 11 linearly scaled and 3 actions superlinearly scaled).

Following our study, we provide the following suggestions on improving ORM-application’s scalability in terms of database size:

- For the time spent in a single query, Armbrust et al. [25] discuss how to convert scale-dependent queries into scale-independent queries by preprocessing.
- For the number of queries issued to the database, combining queries inside loops can reduce the total number of queries executed, as discussed in Section 4.2.
- For the number of records returned, programmers can limit the number of returned records and the number of objects to show on a single webpage. One approach is to divide contents to be shown into multiple pages. For example, in sugar, forum posts are listed page by page with each page only showing 10 posts.

As we have shown, OMAS can identify the three factors that affect application’s scalability, and thus can help predict scalability bottleneck, build scalability model, and guide performance scalability testing.

5.3 Testing ORM Software

Functional testing and performance testing are crucial for all types of software, consuming 30–40% of software development resources [47]. This section explores whether ORM software imposes new challenges to software testing.

5.3.1 Functional testing

The quality of functional testing is often measured by code coverage, such as branch coverage. Much research has been conducted to help generate test inputs that can drive the testing to achieve high coverage [25, 29]. Unfortunately, existing input-generation techniques do not consider database content, and hence may not be sufficient for ORM-based software. This problem is already indirectly revealed by Figure 9, which shows that one of the major usages of query results is to determine branch outcomes. Here, we directly check which branches’ outcome depends on database content.

For every branch inside a controller action, we find all the source nodes of its branch condition on AFG. If any of these nodes include database queries, the outcome of this branch could depend on database content and this branch is categorized as DB-sensitive.

Figure 19 shows the average numbers of DB-sensitive and DB-oblivious branches in each controller action. For all applications, a significant portion of branches, 31.1% on average, are DB-sensitive.
Performance testing aims to discover performance problems before code release, which include both absolute execution slowness and relative execution slowness [48]. The former has been discussed to some extent in Section 5.2. The latter happens when a small change in an input value leads to vastly different execution speed, which could be annoying and confusing to end users but are often difficult to discover during testing. Here, we demonstrate how static analysis can potentially help discover such performance problems in ORM performance testing.

Figure 20: Difference in the number of queries when an input-affected branch is taken or not taken.

For every branch whose outcome could be affected by a user input (decided based on AFG), we calculate the difference in the number of queries issued between when the branch is taken and when the branch is not taken. Clearly, when the difference is large, whether the branch is taken or not, which is affected by this specific user input, will have large impact on the application response time.

Figure 20 shows that for most applications, only a small portion (4.1%) of the inputs reaches very uneven branch (i.e., differs more than 40 queries between taken and un-taken). Performance testing can put more emphasis on these inputs to discover relative execution-slowness problems.

6. RELATED WORK

Prior work has been done in many of the topics we discussed in this paper. We mainly list some of the work in the following categories: web applications involving databases, ORM systems, holistic optimization of program and databases, and performance analysis for general-purpose programs.

Web application involving databases. It is widely recognized that the central database server is often the performance bottleneck in a web database system. A common approach to improve web application performance is to cache database queries. Garrod et al. [38] designed a scalable proxy-based query result cache, in which cache hit is determined by query template. There are many other caching systems including DBCache [23] and CacheGenie [39]. However, most of the above work focuses on the cache policy and system design, and does not leverage the application information in the design. In our work we point out that static program analysis can help identify the potential queries to be issued next and thus improve cache hit rate.

ORM systems. The “impedance mistach” between the object oriented and relational paradigm invokes a lot of research in the ORM field. Bernstein et al. have done deep studies in mapping application data to persistent storage, including general mapping mechanism [26], incremental mapping [27], query rewriting [42], etc.

Besides the above, there are many empirical analysis on ORM systems. Chen et al. point out some specific problems relating ORM: redundant data access [32] and slow one-by-one query result processing [31]. However, they only evaluated the problem under a small number of applications. In the developer's community, ORM performance issues are widely discussed. Most mentioned problems and developing tips include “N+1” query problem [14], using customized SQL query instead of ORM functions [19], smart cache design [3], etc.

All these research work and blog posts point out the importance of a comprehensive empirical study on ORM framework that analyzes and evaluates the ORM-related problems. Our work not only summarized these problems, but also proposed general solutions that can be done in ORM frameworks.

Holistic optimization of program and database. More and more research is focusing on the holistic analysis of program and database recently [40], and many tools are built using such analysis: DBridge [30], a program analysis and transformation tool that optimizes database application performance by query rewriting; Sloth [34] and Pyxis [33], tools that use program analysis to reduce the network communication between the application and DBMS; Quro [51], a tool to reorder queries in transactions to improve the performance of OLTP systems; to name a few.

Besides using program analysis to change queries or how queries are issued, there are also interesting research about extracting and synthesizing queries from application program [45] [49].

Most of the above work targets at general program with embedded SQL queries, and each of them targets at a specific aspect of optimization. Our study shows that some of the work can be applied to ORM applications, and analyzes how much potential improvement can be gained across a wide range of applications.

Performance analysis for general-purpose programs. A lot of techniques have been developed to study the performance of general programs. These techniques are used for automatically detecting performance issues, such as low-utility data structures [50], inefficient loops [43] [44], and object bloating [47], designing performance testing, such as load testing [53] and regression testing [46], and profiling [22] [56].

However, these techniques becomes insufficient because they do not handle applications that issue queries to databases, and these queries can affect the overall application performance greatly. Our study reveals what changes may bring by ORM applications to the performance analysis, and makes suggestions on doing performance modeling and testing for such ORM applications.

7. CONCLUSION

In this paper we studied the common programming and performance patterns on a set of 26 real-world database-backed web applications, which are built using ORM frameworks. We built
OMAS to perform static analysis on these applications, examining how they interact with database systems using ORM, together with dynamic profiling to understand their performance in real situations. Our findings cover wide range of topics crossing data management, ORM design and software engineering, revealing how common coding practices and ORM features can affect the data access and the overall application performance. For each finding we also point out research opportunities on how to leverage such findings to implement general optimizations that works for most applications. We believe our study can benefit both the developers’ community by helping them avoid performance issues during application development, data management researchers by pointing out how to use application information to optimize data access, and software engineering researchers by showing what changes should be done to adopt traditional modeling and testing practices on general program to database-backed applications.

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