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Exploring the Correlation between Transactional Bugs and Isolation Levels

Master Thesis

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Abstract

This thesis aims to create a testbed for easily replicating and analysing Database Management System (DBMS) transactional or isolation bugs, use this testbed to replicate and analyse a set of known bugs, and use the gained insights for developing a novel bug-finding tool.

First, we create a testbed leveraging containerisation technology to easily spin-up and run a variety of custom versions of DBMSs. The testbed provides an easy way of running concurent transaction workloads, and generates logs of the transactions being executed. It also provides an easy way of starting multiple MySQL shells connected to arbitrary versions of the MySQL, MariaDB and TiDB DBMSs.

We then use the testbed to replicate and analyse a set of known bugs in the MySQL, MariaDB and TiDB DBMSs. We find that in the overwhelming majority of the replicated bugs, the isolation level does not have any impact, as bugs manifest under all isolation levels supported by the DBMS.

Finally, we develop a novel bug-finding technique, which leverages dependencies graphs between transactions computed using SQL-level instrumentation for finding isolation bugs in DBMSs. We also implement this technique on top of the TxCheck fuzzer.

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Chapter 1

Introduction

1.1 Problems and Motivations

Modern database management systems, which often rely on a relational model, were introduced in the 1970s [1]. Since then, the amount of data that needs to be stored and processed and the usecases of DBMSs has grown exponentially, which lead to the development of an entire industry of database software. The growing discrepancy between storage capacity and processing power, and the cost efficiency of buying multiple smaller machines [2] pushed towards the development of concurency mechanisms and of distributed databases, able to distribute load across multiple machines and users. Distributed databases are essential for virtually all modern large-scale applications, such as social networks, e-commerce, cloud computing or reseach.

Like all software, DBMSs are prone to bugs, especially considering the diminishing returns of optimizing their performance, which is in many cases the bottleneck of the entire system. While unit and integration tests are essential in the development of any software [3], they are not enough to ensure the correctness of such complex systems. This is why, many current testing strategies rely on the use of fuzzing, a technique that generates random inputs to the system under test, in order to find bugs [4].

The motivation and goal of this project is to replicate existant DBMS transactional bugs reported to their respective issue trackers, and reported by or analysed in other works [5, 6, 7, 8], in order to undestand how they corelate with isolation levels. Then, using the gained insights and using a novel fuzzing technique introduced by Jiang, Z. et al. [5] based on SQL instrumentation, we try to find new bugs. We aim to generate the set of Adya dependencies [9] of randomly generated concurent transactions, and to use this information to detect bugs in the concurrency and isolation mechanisms of a distributed database.

1.2 Contributions

Overall, we make the following contributions in this project.

1. We develop a new testing framework, levraging containerisation techniques for starting specific versions of DBMS servers, and automatically replicating DBMS bugs.
2. Using the testing framework, we replicate TODO bugs in the *MySQL*, *MariaDB* and *TiDB* DBMSs.
3. We analyse the reports of the replicated bugs, and we explore the corelation between isolation levels and the reported bugs.
4. We develop a novel black-box fuzzing technique, based on SQL instrumentation and Adya dependency graphs.
5. TODO: We implement the fuzzing technique, by modifying an existing fuzzing framework [5].

Chapter 2

Background

2.1 Database Management Systems

Modern database management systems (DBMS) are complex software systems that provide a high-level interface for users to interact with the underlying data. DBMSs such as *MySQL* [10] offer a large set of features, including data storage, retrieval and manipulation.

Relational DBMSs, usually exposing *SQL* as a query language, form an overwhelming majority of the database systems in use today, with the 4 most popular DBMSs being relational [11]. The relational model was introduced by Edgar Codd in 1970 [1], and offers application developpers a high-level manipulation capacity of the stored data. Information is modeled as collections of relations between properties, commonly represented as tables and rows.

Modern *SQL* offers a *Data Definition Language* (DDL) to create and modify the structure of the underlying data, and a *Data Manipulation Language* (DML) to interact with the data. The DDL is composed of statements such as *CREATE* and *DROP*, while DML is composed of statements such as *SELECT*, *INSERT*, *UPDATE*, and *DELETE*.

2.2 Transactions

A transaction is a sequence of instructions executed as a single isolated unit of work. In other words, either all of the instructions in the transaction are correctly executed and saved to the database, or none of them are. Transactions offer the ACID properties [12], a set of properties that guarantee that database transactions are processed reliably. The ACID properties are as follows:

- **Atomicity**: A transaction is an atomic unit of work, meaning that the database will either execute all of the instructions in the transaction, or none of them.

- **Consistency**: A transaction will bring the database from one consistent state to another consistent state. In other words, the database will always be in a consistent state, regardless of the state of the running transactions.

- **Isolation**: Multiple transactions can be executed concurrently, and, depending on the isolation level, the transactions will not interfere with each other.

- **Durability**: Once a transaction is committed successfully, the DBMS guarantees that the changes made by the transaction will be saved to the database.

2.3 Isolation Levels

The isolation between transactions is defined by the isolation level. Stricter isolation levels offer more consitency guarantees, at the cost of concurrency and performance. While many isolations levels have been formalized, the ANSI isolation levels supported by most database systems [13] are as follows:

- **Read Uncommitted**: The lowest isolation level. Transactions can read uncommitted data from other transactions.

- **Read Committed**: Transactions are visible only after being committed.

- **Repeatable Read**: Transactions are visible only after being committed, and multiple reads of the same data will return the same result. Note that new data can be become visible to the transaction.

- **Serializable**: The strongest (and slowest) isolation level, in which transactions can be assumed to be executed serially.

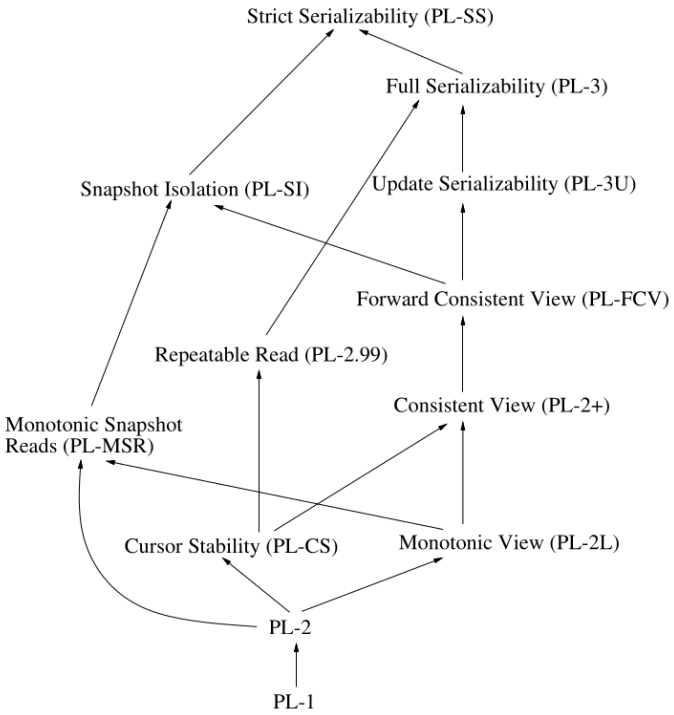

Figure 2.1: The Adya isolation levels [9].

In modern DBMSs, the isolation levels are implemented by levraging concurrency control techniques such as locking and multi-version concurrency control (MVCC). The choice of isolation level is a trade-off between consistency gurantees and concurency performance, and is usually made by the application developer.

For instance, a banking application which needs to avoid double-spending will use the *Serializable* isolation level, while a school grading system might want to use the *Read Committed* isolation level.

2.4 Transaction and Isolation Bugs

DBMSs are complex software systems, with their complexity constantly increasing as dimishing returns push for more and more complex optimizations. Like all software, DBMSs are prone to bugs, which can lead to data corruption, loss of data, or crashes.

Transaction and isolation bugs are part of a specific class of bugs residing in the transaction and isolation handling mechanisms of a DBMS. Such bugs are tricky to detect, as they often require multiple concurent transactions, might

occur sporadically due to the nondeterministic nature of the concurency, and might not be easily reproducable.

While similar, transactional and isolation bugs are slightly different:

- **Transactional bugs**: Logic bugs that occur when one or multiple transactions are being run. Possible manifestations include unexpected failures, missing data, or incorrect behavior.
- **Isolation bugs**: Bugs that occur when the specified isolation level is not respected. Possible manifestations include forbidden behavior, such as dirty reads, non-repeatable reads, or phantom reads.

2.5 Previous Work

The topic of database testing is not new, with multiple techniques and tools being developed over the years. Recent work has focused on fuzzing techniques, combined with novel methods of detecting errors in random transactions [5, 6, 7, 14]. A recent paper by Cui, Z. et al. [8] makes a comprehensive survey of reported transactional bugs, a large portion discovered with the help of the before-mentioned fuzzing techniques.

Our work is inspired by the surveying work of Cui, Z. et al. [8], and aims to replicate and analyze bugs, by providing an easy way to test them. In the best of our knowledge, the authors of the survey did not actually replicate the collected bugs, due to constrainst on the DBMS versions (often a Git commit), and time consumption, and relied on the original bug reports.

In the second part of our project, we also build on the work of Clark, J. et al. [14] which find bugs by checking violations of the Adya dependency graph [9] in a white-box fashion, and on the work of Jiang, Z. et al. [5] which introduces the novel idea of SQL instrumentation. Using these two techniques, we introduce a new technique for finding isolation bugs using Adya dependency graphs in a black-box fashion, levraging the SQL instrumentation technique.

Chapter 3

Developping a DBMS Transactional Testing Framework

3.1 Overview

This chapter presents the design, implementation and usage of a testing framework for replicating DBMS transactional bugs. Using the testing framework, we replicate a set of transactional bugs in the *MySQL*, *MariaDB* and *TiDB* DBMSs. We then analyse the reports of the replicated bugs, and we explore the corelation between isolation levels and the reported bugs.

3.2 Design

The testing framework, is implemented in *Python*, and heavily relies on *Podman*, a container manager [15] for managing DBMS instances. The tool works on `x64 GNU/Linux` systems, and we developped it in *VSCode*, with the help of *Github Copilot* [16].

The framework is modular, helping any future developer to easily extend it (for instance for adding support for new DBMSs). The main components in the bug testing pipeline (see Figure 3.1) are the following:

- The *podman connector*: This component handles the interaction with the *Podman* engine, and is responsible for starting, stopping, downloading and managing containers running DBMS instances.
- The *test parser*: This component handles the parsing of testcases, using a specific format, and is responsible for creating the internal representation of the testcases.
- The *mysql connector*: This component handles the connection to a DBMS instance (running within a container), and is responsible for executing statements in order and extracting the results.

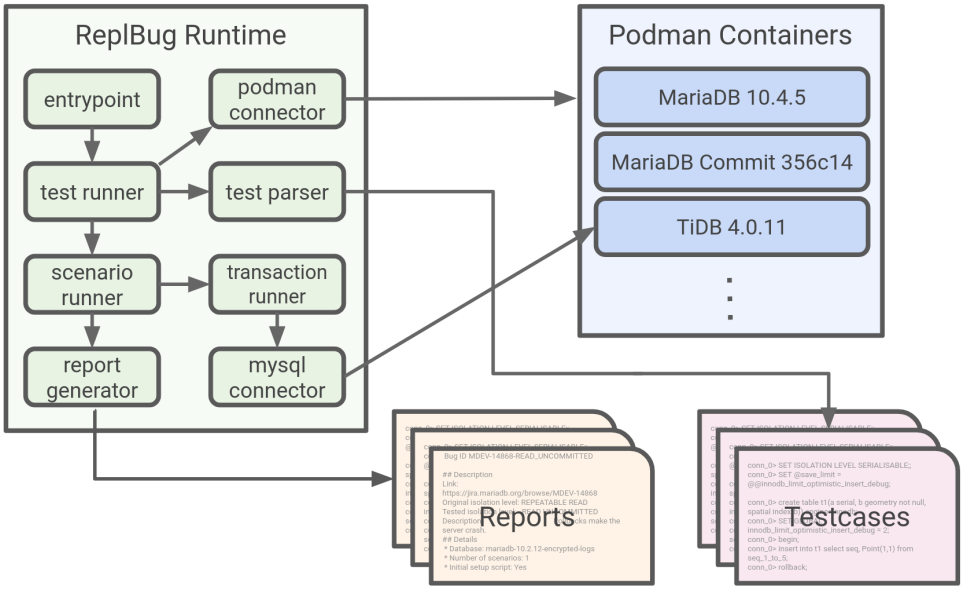

Figure 3.1: Design of the *ReplBug* testing framework

- The *transaction runner*: This component handles the execution of all the statements in a transaction, and runs on different threads for concurrency.
- The *scenario runner*: This component runs testcases under a specific configuration.
- The *test runner*: This component orchestrates the execution of all required testcases under all specified configurations.

3.3 Custom DBMS Version

Some bugs are specific to a certain version of a DBMS, which might not be available as pre-built binaries. For instance, versions with serious vulnerabilities are usually removed from official repositories, or intermediary versions tied to a specifig *Git* commit are not released as binaries.

For the mentioned reasons, we consider the ability to built DBMSs from source essential. To simplify the process, we provide sample *Dockerfile* templates, which can be used to test specific DMBS versions. A sample *Dockerfile* for *TiKV* can be seen in Figure 3.2.

In our project, we provide *Dockerfiles* for *MySQL*, *MariaDB* in release or debug mode, and *TiDB* with or without *TiKV*. Creating a new docker file only requires the *Git* commit, and then running the *build* command integrated into *ReplBug*.

```
FROM golang:1.19-alpine AS builder

# Install git and other dependencies
RUN apk add --no-cache git make bash gcc wget binutils-gold \
    musl-dev curl tar

# Set the working directory inside the container and
# create necessary directories
RUN mkdir -p /go/src/github.com/pingcap
WORKDIR /go/src/github.com/pingcap

ARG TIDB_COMMIT=c9288d246c99073ff04304363dc7234d9caa5090

# Clone the TiDB repository
RUN git clone --depth 1 https://github.com/pingcap/tidb.git \
    && cd tidb \
    && git fetch --depth 1 origin "$TIDB_COMMIT" \
    && git checkout "$TIDB_COMMIT" \
    && make -j \
    && mv bin/tidb-server /usr/local/bin/tidb-server \
    && cd .. \
    && rm -rf tidb

EXPOSE 4000
WORKDIR /usr/local/bin
CMD ["./tidb-server", "-P", "4000"]
```

Figure 3.2: Sample *Dockerfile* for building a specific version of *TiDB*

3.4 Usage

The testing framework, called *ReplBug* is invoked from the CLI. The main features it offers, exposed by the executable as subcommands are the following:

- `shell` (See Figure 3.3): Starts one or multiple *MySQL*, *MariaDB* or *TiDB* shells, connected to a specific version of the DBMS. If the version is not present on the local machine, the tool will attempt to pull the image from Docker Hub.
- `server` (See Figure 3.4): Starts a specific version of the *MySQL*, *MariaDB* or *TiDB* DBMS and provides the required details (host, port, user) for connecting to the server.
- `test` (See Figure 3.5): Runs the scenarios of some known bugs (which have to be written in a specific format prior), and automatically gener-

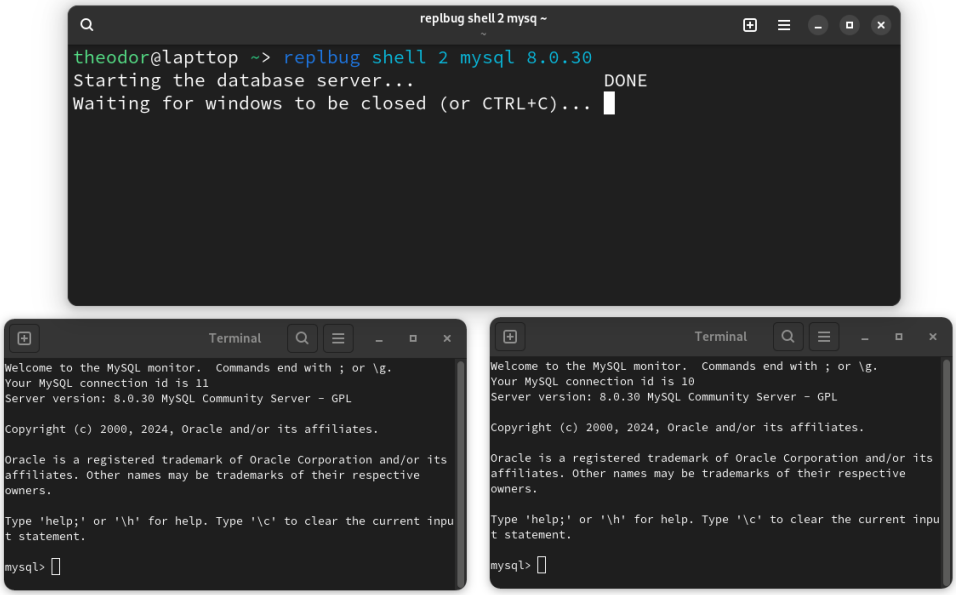

Figure 3.3: Using *ReplBug* to start 2 *MySQL v8.0.30* shells

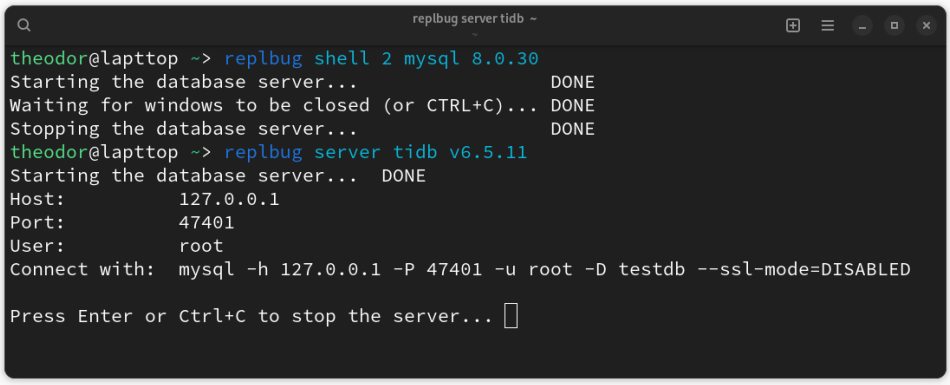

Figure 3.4: Using *ReplBug* to start a *TiDB v6.5.11* server

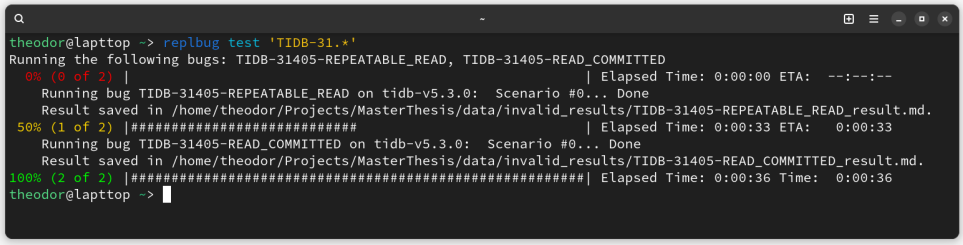

Figure 3.5: Using *ReplBug* to generate reports of some known bugs

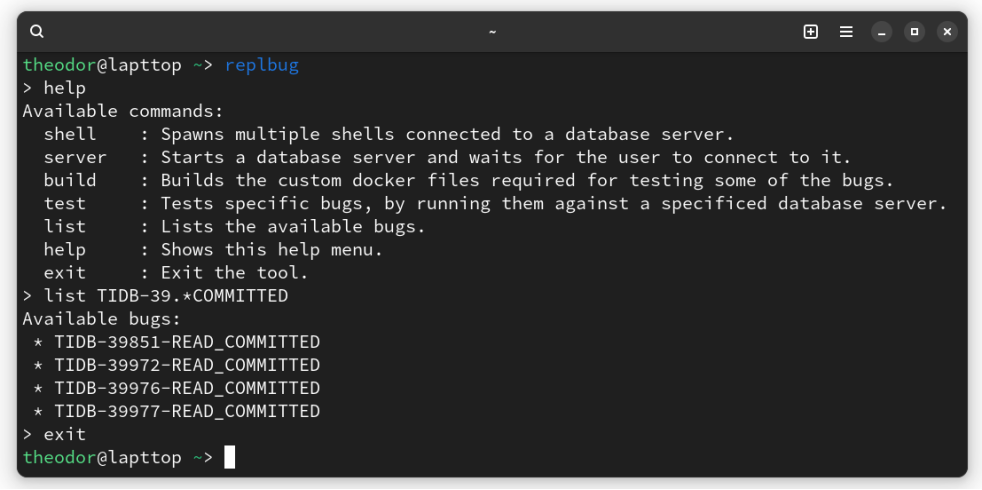

Figure 3.6: Using *ReplBug* in interactive mode

ates reports of the execution.

- `list`: Returns a list of the testcases available in the tool (optionally a *regex* can be passed to filter the results).

The tool can be either used from the CLI by passing arguments, or in interactive mode, where the tool exposes a shell that can be used by the user (see Figure 3.6).

Chapter 4

Replicating Transactional Bugs in MySQL, MariaDB and TiDB

4.1 Overview

With the help of the *ReplBug* testing framework, we were able to replicate *MySQL*, *MariaDB* and *TiDB* transactional, logical and isolation bugs.

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