A Chaos Engineering System for Live Analysis and Falsification of Exception-handling in the JVM

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Abstract—Software systems contain resilience code to handle those failures and unexpected events happening in production. It is essential for developers to understand and assess the resilience of their systems. Chaos engineering is a technology that aims at assessing resilience and uncovering weaknesses by actively injecting perturbations in production. In this paper, we propose a novel design and implementation of a chaos engineering system in Java called \textsc{ChaosMachine}. It provides a unique and actionable analysis on exception-handling capabilities in production, at the level of try-catch blocks. To evaluate our approach, we have deployed \textsc{ChaosMachine} on top of 3 large-scale and well-known Java applications totaling 630k lines of code. Our results show that \textsc{ChaosMachine} reveals both strengths and weaknesses of the resilience code of a software system at the level of exception handling.

I. INTRODUCTION

Chaos engineering is a new field that consists in injecting faults in production systems to assess the resilience of a software system [6]. The core idea of chaos engineering is active probing: the chaos engineering system actively injects a controlled perturbation into the production system and observes the impact of the perturbation as well as the reaction of the system under study [2], [10], [17]. This aids developers in gaining confidence in the resilience of their system, and can help them to find weaknesses in error handling and disaster recovery routines [3], [6].

Chaos engineering is complementary to static analysis and testing, as it also 1) generates new knowledge about the system under study and 2) identifies strengths and weaknesses. Unlike static analysis and testing, chaos engineering directly acts and observes the system in production [15], [21]. An example of chaos engineering system is Netflix ChaosMonkey, which randomly shuts down servers to make sure that the overall system is capable of spawning new ones automatically.

In this paper, we present the design and implementation of a novel chaos engineering system called \textsc{ChaosMachine}. Its core novelty and uniqueness is that it considers error-handling capabilities at the fine-grain level of programming language exceptions. While bad exception-handling is known to be the cause of up to 92\% of critical failures [31], it remains to be done to apply the chaos engineering vision to exception-handling. The contribution of this paper is \textsc{ChaosMachine}, which is capable of revealing the resilience strengths and weaknesses for every try-catch block executed in production.

\textsc{ChaosMachine} is designed around three components. For each service of the system under study, there is a monitoring sidecar (component #1) and a perturbation injector (component #2) attached to it. The monitoring sidecar is responsible for collecting all information needed for the resilience analysis, and the perturbation injector is able to throw a specific exception at runtime. Component #3 is the chaos controller, which controls all the perturbation injectors and analyzes the information collected by every monitoring sidecar. Eventually, the chaos controller produces a report that gives developers unique and actionable knowledge about the resilience of their system.

We evaluate \textsc{ChaosMachine} by applying it to 3 large-scale and well-known open-source Java applications in the domains of file-sharing, content-management system and e-commerce. All the experiments are conducted in a production-ready environment with end-user level workload. The results show that \textsc{ChaosMachine} is capable of analyzing the resilience of 339 try-catch blocks located in 212 Java classes. \textsc{ChaosMachine} successfully identifies the strongly resilient try-catch blocks (18/339) that should remain resilient in subsequent versions. It also identifies the weakest ones, called silent try-catch blocks (34/339), which are possible debug nightmares when developers try to understand failures happening in production.

To sum up, our main contributions are the following.

- The conceptual foundations of chaos engineering in the context of exception-handling in Java: 1) the definition of four categories of try-catch blocks according to their resilience characteristics; 2) a systematic procedure based on fault injection to assess resilience of try-catch blocks.
- A novel system, called \textsc{ChaosMachine}, that assesses exception-handling capabilities in production. \textsc{ChaosMachine} is based on bytecode instrumentation and remote control of fine-grained fault injection. It provides valuable and actionable feedback to the developers. The system is publicly-available for future research (https://github.com/KTH/chaos-engineering-research).
- An empirical evaluation of \textsc{ChaosMachine} on 3 real-world Java systems totaling 630k line of codes, containing 339 try-catch blocks executed by the considered production traffic. It shows the effectiveness of \textsc{ChaosMachine} to reveal both strengths and weaknesses of a software system’s resilience at the exception-handling
II. BACKGROUND ON CHAOS ENGINEERING

In this section, we give some background on chaos engineering [6] for readers who are not familiar with the concept.

A. Brief Overview

Let us first start with a metaphor: chaos engineering is vaccination for software. In medicine, people are vaccinated to prevent particular diseases. Vaccination consists in injecting a potentially dangerous, yet controlled preparation that resembles a virus, which helps the body strengthen its immune system against this virus. Chaos engineering is such a technology in software engineering: it consists in injecting a potentially dangerous perturbation that resembles a failure or heavy load, which helps the developers understand and improve the resilience of their system [23].

Basiri et al.'s seminal paper [6] about chaos engineering tells us that the main goals of chaos engineering are: 1) to verify error-handling capabilities and resilience in production settings; 2) to learn about error handling behavior in production. The mantra of chaos engineering is to experiment with the system in production. To this extent, Schermann et al. [28] consider chaos engineering as one facet of continuous experimentation.

Let us now discuss a concrete example. Consider two micro-services interacting with each other to provide a feature. Those two micro-services have error-handling code to deal with problems in the communication link. Chaos engineering on this system would mean injecting perturbation in the communication link in production. If the system continues to provide the expected service under this perturbation, the developers gain confidence in the error-handling code. If any perturbation breaks the system's provided features, it means that the developers need to fix the error-handling code. This is the meaning behind the primary idea of chaos engineering: “experimenting on a distributed system in order to build confidence in the system’s capability to withstand unexpected conditions in production” [1].

B. Core Concepts

Chaos engineering is founded on the following concepts.

A perturbation is a change in the application execution flow, or state, or environment, it is made in a pro-active and controlled manner. Working with our prior example, one can inject a timeout into a communication link between two micro-services. An example of perturbation in the system environment is when one cuts down the memory available to the system to see how the application reacts.

A hypothesis is a stipulated relation between a perturbation and some monitored behaviors. In the case of a video streaming service, one monitored behavior can be the number of streams started per second. The behaviors of interest can be caught using a wide range of tools: core business metrics (number of streams), system-level invariants, execution traces, environment metrics like I/O usage, etc. For example, a hypothesis may be: in our web page rendering system, if one stops the cache (perturbation simulating that the cache subsystem is broken), the correct content is still delivered to users (monitored behavior).

An experiment is the process of validating or falsifying a hypothesis. An experiment includes injecting perturbations into the system, monitoring how the system reacts and inferring validation and falsification. In the example above, an experiment for this hypothesis is: 1) to inject an exception into the page rendering service and 2) to monitor the system’s reaction. If one still gets the correct output, the experiment validates the hypothesis, indicating that the error-handling code works well under such a perturbation. Otherwise, if there is a difference between the behavior under injection and the normal behavior, the experiment is considered to have falsified the hypothesis.

The blast radius defines the impact level of a perturbation. In practice, it is undesirable that perturbations cause too much trouble to the service. For example, some perturbations might cause a long waiting time for some end users. Controlling the blast radius here would mean to ensure that the waiting time is not too long, so as not to lose users because of an unacceptable quality of service.

C. Basic Chaos Methodology

Per [1], there are four main steps to apply chaos engineering to a system.

The first three steps are related to designing the hypothesis. First of all, one must find metrics which capture the essential performance and correctness characteristics of the system's steady state. The steady state is characterized by a range of metric values, with departure from that range meaning the system should be considered impacted. Secondly, one defines perturbations which simulate real world possible events, such as connection timeout, hard drive exhaustion, thread death, etc.

Then one defines two phases: a control phase and an experimental phase. A control phase is a monitoring period without perturbation, while the experimental phase is a study of the system behaviors under perturbation. At the end of these first three steps, the hypothesis and the experiment design are set.

Fourth, one performs the actual experiment, consisting of injecting perturbations into the system and monitoring the metrics. A report is eventually generated by analyzing the differences in the effect of the perturbation between the control phase and experimental phase. There are two possible outcomes: 1) when a hypothesis is validated, the confidence in the system resilience capability is improved; 2) when a hypothesis is falsified, the issue is reported to the development team, which then has to fix the error-handling code.

D. Concrete Example

Arguably, the most famous chaos engineering system to date is Netflix’ ChaosMonkey. ChaosMonkey is used to randomly
shutdown systems that are part of a fleet providing a service in production and to then analyze impact on that system. Developers at Netflix use the number of video starts per second as a metric to define system’s steady state [8]. In this context, 1) an hypothesis is that one instance terminating abnormally has no influence on the number of served videos; 2) a perturbation is ChaosMonkey shutting down a specific instance; 3) a chaos experiment is the whole procedure of applying ChaosMonkey and analyzing the system’s behavior to validate or falsify the hypothesis.

III. DESIGN OF A CHAOS SYSTEM FOR EXCEPTIONS

This section presents our system for controlled chaos engineering in the Java Virtual Machine, called CHAOSMACHINE. Its core novelty is that it does chaos engineering at the level of exception handling and try-catch blocks, which is more fine-grained than all chaos engineering systems we are aware of.

A. Overview

The goal of CHAOSMACHINE is twofold: 1) falsify hypotheses and 2) discover hypotheses. The former is the classical goal of chaos engineering systems [6], and the latter is the key contribution of this paper.

**Hypotheses.** CHAOSMACHINE considers error-handling hypotheses in Java applications. We define the following four chaos engineering hypotheses at the level of try-catch blocks, from the most beneficial to the most problematic:

- **Resilience hypothesis.** A try-catch block is said to be resilient if the observable behavior of the catch block, executed upon exception, is equivalent to the observable behavior of the try-block when no exception happens [11].
- **Observability hypothesis.** A try-catch block is said to be observable if an exception caught in the catch block results in user-visible effects, see Listing 2.
- **Debug hypothesis.** A try-catch block is said to be debuggable if an exception caught in the catch block results in an explicit message in the application logs, see Listing 3.
- **Silence hypothesis.** A try-catch block is said to be silent if it fails to provide the expected behavior upon exception while providing no troubleshooting information whatsoever, i.e., it is neither observable nor debuggable. If the silent try-catch block later causes a user-visible failure, it would be extremely hard for the developers to understand that the root cause is the silent try-catch block, and to fix the failure accordingly, see Listing 4.

For each application, these hypotheses need to be refined with concrete metrics and domain knowledge. For example, for the resilience hypothesis, the developers would describe what “behavior equivalence” means in their domain. For instance, in a web application, receiving an HTTP 200 code with the same content as the original non-perturbed request may be considered equivalent.

| Listing 1. Try-catch Satisfying the Resilience Hypothesis |
|---|
| state = SystemState.A; |
| try { |
| ... // an error is thrown |
| state = SystemState.B; |
| } catch (Exception e) { |
| ... // handles the exception |
| state = SystemState.B; |
| } |
| // After leaving the try-catch, the state stays the same |

| Listing 2. Try-catch Satisfying the Observability Hypothesis |
|---|
| try { |
| contentsToUsers.add("content A"); |
| contentsToUsers.add("content B"); |
| } catch (Exception e) { |
| contentsToUsers.add("content C"); |
| } |
| render(contentsToUsers); |
| // When exception occurs, contents for users are different |

| Listing 3. Try-catch Satisfying the Debug Hypothesis |
|---|
| state = SystemState.A; |
| try { |
| state = SystemState.B; |
| contentsToUsers.add("content A"); |
| } catch (Exception e) { |
| state = SystemState.C; |
| contentsToUsers.add("content A"); |
| // Nothing about the exception is logged |
| render(contentsToUsers); |
| // Users are not aware of the error, but system state is different when an exception occurs, which may lead to other exceptions |

| Listing 4. Try-catch Satisfying the Silence Hypothesis |
|---|
| state = SystemState.A; |
| try { |
| state = SystemState.B; |
| contentsToUsers.add("content A"); |
| } catch (Exception e) { |
| state = SystemState.C; |
| contentsToUsers.add("content A"); |
| // Nothing about the exception is logged |
| render(contentsToUsers); |
| // Users are not aware of the error, but system state is different when an exception occurs, which may lead to other exceptions |

**Experiments.** CHAOSMACHINE performs two kinds of experiments:

- **Falsification experiments.** They aim at validating or falsifying a hypothesis about the behavior of a try-catch block. This hypothesis can be stated upfront by developers or can be discovered through exploration experiments.
- **Exploration experiments.** They aim at monitoring the behavior of try-catch blocks under perturbation in order to discover new hypotheses.

**Modes.** When CHAOSMACHINE performs exploration experiments, it is said to be in exploration mode. When CHAOSMACHINE performs falsification experiments, it is in falsification mode. Finally, when CHAOSMACHINE does not introduce chaos, it is simply in observation mode.

B. Input to ChaosMachine

CHAOSMACHINE works on arbitrary software written in Java, no manual change is required in the code. To use...
ChaosMachine, the application is deployed in production as usual, ChaosMachine is attached to it in an automated manner, in observation mode by default. Optionally, developers can also feed ChaosMachine with manually-written hypotheses.

C. Architecture of ChaosMachine

Figure 1 presents the main components of ChaosMachine and their interactions. ChaosMachine is meant to be deployed on any modern internet application, such as search engines or transaction systems. Those applications typically are distributed over several different servers, where the servers either provide different services (as shown in the figure with three different services), or provide redundancy and elasticity for the same service. Per the best practices, and without loss of generality, all services are considered deployed in separate virtual machines for the sake of isolation.

ChaosMachine attaches a monitoring sidecar and a perturbation injector into each service. The monitoring sidecar (Section III-C1) collects information to study the outcome of chaos experiments. The perturbation injector (Section III-C2) is responsible for injecting perturbations according to a given perturbation model. The chaos controller (Section III-C3) is a standalone component that is separated from the application services, and it has three responsibilities: 1) controlling the behavior of perturbation injectors; 2) aggregating monitoring information from each monitoring sidecar; 3) generating a report for the developers about the quality of error-handling in their code, which contains novel and actionable feedback about error-handling in production. We further describe these outputs in Section III-D.

1) Monitoring Sidecars: Chaos engineering consists of studying the influence of perturbations on the system behavior, as captured by metrics [1]. Example metrics include the number of streamed videos for Netflix and the HTTP response code for web applications. These metrics are part of evaluation of whether the system can provide acceptable services, even under perturbation. The main role of the monitoring sidecars is to collect these metrics at runtime.

In order to gather sufficient information about error-handling in Java applications, ChaosMachine uses the following monitoring scheme. For each try-catch block found in code as it is loaded into the JVM, it notes: 1) their position in the code, 2) the type of the caught exception, 3) the number of executions (both in observation mode and in exploration mode), 4) whether exceptions are recorded in application logs.

Monitoring sidecars also collect the following generic metrics:

- The application logs.

2) Perturbation Injectors: The main responsibility of a perturbation injector is to generate a specific perturbation when the chaos controller sends the corresponding command, i.e., throwing an exception at the beginning of a try-catch block, resulting in short-circuiting the try-block. An injector is added to every try-block, using automated code instrumentation. Each injector can be activated (in exploration mode or in falsification mode) and deactivated individually.

As argued in [11], injecting the exception at the beginning of a try-block has two key advantages. First, it drastically reduces the injection space, since there is only one possible injection location per try-block. Second, it simulates the worst-case type of exception where none of the intended effects of the try-block have been performed. Note that the injectors in ChaosMachine can be overridden, for example, to allow developers to throw the exception just before the statement(s) that could throw that exception.

Listing 5. The Application Code is Automatically Transformed for Injecting Perturbations

```java
try {
    // injection point #1, type: Exception1
    if (perturbationInjector1.isActive()) {
        throw new Exception1();
    }
    if (perturbationInjector2.isActive()) {
        throw new Exception2();
    }
    ...original code...
} catch (Exception1 e1) {
    ...original code...
    try {
        if (perturbationInjector3.isActive()) {
            throw new Exception3();
        }
        ...original code...
    } catch (Exception2 e2) {
        ...original code...
    } catch (Exception3 e3) {
        ...original code...
    }
}
```

Listing 5 gives an example about how this perturbation injector works. There are two try-blocks in this code snippet, Exception1 and Exception3 might happen in the first try-block during the execution of the omitted code at line 9, and Exception2 might happen in the second try block at line 16. Consequently, there are three injection points in total, corresponding to each caught exception type. When an injector is activated in exploration or falsification mode, it throws the corresponding exception. Each injector can be controlled separately.

3) Chaos Controller: The chaos controller has two goals: 1) discover new hypotheses and 2) falsify existing hypotheses.

a) Hypothesis discovery: Hypothesis discovery consists of proactively analyzing every executed try-catch block. To do so, the chaos controller iterates over them one after the other, to activate the corresponding perturbation injector, and then analyzes all output as captured by the monitoring sidecars. If
the discovered hypothesis is considered as acceptable by the developers, the new hypothesis is saved permanently, so that ChaosMachine could conduct falsification experiments on it later on.

b) Hypothesis falsification: To falsify a hypothesis, the chaos controller activates the specific perturbation injector which corresponds to the try-catch block in the hypothesis. For example, it only activates the injector of the try-catch block on line 42 of Foo.java, and keeps it activated for 10 seconds. Then, the controller analyzes the information recorded by the monitoring sidecars and reports whether the injected perturbation has broken the hypothesis under consideration.

The chaos controller is also responsible for containing the blast radius. It decides how many perturbation injectors are active concurrently, as well as how long the perturbation injectors are active. The roles of the above three components in different modes are shown in Table I.

### Table I

|                     | Observation Mode                              | Exploration Mode                             | Falsification Mode                           |
|---------------------|-----------------------------------------------|----------------------------------------------|----------------------------------------------|
| Monitoring Sidecar  | Monitors all the relevant execution information | Monitors how the system reacts according to a perturbation | Monitors whether an hypothesis is falsified |
| Perturbation Injector| Not active                                    | Injects a specific perturbation              | Injects a specific perturbation              |
| Chaos Controller    | Deactivate all the perturbation injectors to keep the system running as usual | Controls perturbation injectors to conduct a sequence of chaos experiments so as to discover new hypotheses | Controls perturbation injectors according to a specific hypothesis |

Both the monitoring sidecars and the perturbation injectors are woven into the application services using a JVM agent [14]. The agent adds the monitoring and injection code using binary code transformation with the ASM library. The chaos controller is a standalone service communicating with the monitoring sidecars and the injectors using sockets. For sake of open-science, the code is made publicly available at https://github.com/KTH/chaos-engineering-research.

### IV. Evaluation

In our evaluation, we apply ChaosMachine to 3 different real-world Java projects, including TTorrent (a peer-to-peer file downloading tool based on the BitTorrent protocol), BroadLeaf (a web-based commercial system) and X-Wiki (a web-based wiki system). Following the chaos engineering principles, all applications are set up in a production environment. In the following, we present the protocol, experimental results, case studies, and discussions for each project.

All the experiments rely on the same basic principles: 1) the chaos controller evaluates try-catch blocks one by one in the loading order of classes, 2) it only activates one perturbation injector at a time and 3) the activation duration for every injector is identical for all tasks. Once the application is set up, ChaosMachine verifies and evaluates try-catch blocks following the procedure described in Section III-A.

### A. Evaluation on TTorrent

1) Overview of the BitTorrent protocol: BitTorrent is a peer-to-peer data transfer protocol, which is widely used to
download files over the Internet. The core concept of the BitTorrent protocol is that users who want to download a file also serve to other users the parts that they have already downloaded. There are 4 parts in a typical file transfer scenario with the BitTorrent protocol: 1) a torrent file which includes information about the shared files and the tracker servers; 2) several tracker servers which receive client registrations and announce resource information to new clients; 3) clients who want to download files, and then get the torrent files and register their download status with the tracker server; 4) clients who have already downloaded files and provide pieces of the files to others (called the “seeders”).

2) Experiment protocol: In this experiment, we consider the Bittorrent client called TTorrent (version 1.5), written in Java. It is built as a .jar file and can be used on the command line. We attach CHAOSMACHINE to this client, and then use it to download ubuntu-14.04.5-server-i386.iso, a Linux distribution installer of 623.9MB from the Canonical company. This means that we use tracker servers from somewhere else in the Internet, and use many seeders that are providing pieces of the downloaded file.

First, we classify try-catch blocks in TTorrent by refining the four hypotheses discussed in Section III-A with the combining monitoring metrics specific to this application domain.

- **Resilient try-catch block.** Despite injected exceptions in this block, the client successfully downloads the file and exits normally. The chaos controller also detects some error messages in the application log. Even though there is an exception thrown at the very beginning of the try-catch block, the application still fulfills the user’s requirement correctly. This kind of try-catch block contributes to the application’s resilience, as the application still supports the users’ requests even though the entire logic of the try-block has been discarded.

- **Observable try-catch block.** A try-catch block is said observable if the client directly crashes or exits with an error message under perturbations, i.e., the perturbation in this try-catch block causes user-visible behaviors of the client.

- **Debuggable try-catch block.** A try-catch block is said debuggable if the system metrics become abnormal or the exception information is captured in application logs when an exception is injected. The information is useful for developers to debug and improve the system’s resilience.

- **Silent try-catch block.** When an exception occurs in this block, the client does not download the file and just keeps running indefinitely. Worse still, there is not any error information about the injected error. This is a bad case for both users and developers: users are not made aware that the download is stalled and developers have no feedback whatsoever about the problem. Developers can improve them so as to be able to detect and debug such a problem if it happens naturally in production.

Then, in an initial observation mode, the client downloads the full file once until successful completion. During this phase, CHAOSMACHINE analyzes the client’s behavior.

Next, for the covered try-catch blocks, CHAOSMACHINE executes the procedure defined in Section III-A while re-downloading the file, and gathers the data shown in Table II. In exploration mode, the perturbed clients might not be able to exit normally, so CHAOSMACHINE keeps the client alive for at most 300 seconds. After this delay, the client is killed and information is logged indicating that the client was killed after this timeout.

3) Experimental results: Table II reads as follows: there are 27 try-blocks covered by the production traffic, i.e., the code in the try-blocks is executed while the client is downloading the file. Each row contains the information of one try-block. The first column is the basic information about each try-catch block, including the class and method names, caught exception type and a number which is used to identify different catch blocks when there is more than one catch block for a single try-block. The second column records the number of executions, in both the observation mode and exploration mode. The third column indicates whether the developers have logged the exception in their application logs when such an exception is caught. The forth column shows whether the client has successfully downloaded the file when exceptions are injected in this try-block. The fifth column records the client’s exit status. The sixth column indicates differences in system metrics (if any) between the observation mode and the exploration mode. Finally, the last four columns indicate how this try-catch block meets our pre-defined four hypotheses.

Since injected exceptions change the execution flow of the application, the number of executions in analysis mode and exploration mode are not necessarily the same.

Take the first row as an example, it shows that there is a try-catch block in the getBytes method inside the BEValue class, which handles a ClassCastException. Through the entire process of downloading the file, it is executed 41 times. When the perturbation injector throws a ClassCastException exception at the beginning of the try-block, the client does not download the file and crashes. The chaos controller also detects that a specific error message is logged in the application log before its crash. Based on these behaviors, this try-catch block validates the observability hypothesis (OH) and debug hypothesis (DH).

In total, there are 27 try-catch blocks covered by this file-download operation in production. Some of them are executed only once, others up to 90805 times (cf. Column Execution Anal. of Table II). This information is very important for the developer. Thanks to CHAOSMACHINE, the developer is able to identify: 6 resilient try-catch blocks, 7 observable try-catch blocks, 20 debuggable try-catch blocks, and 3 silent try-catch blocks.

4) Case studies: In the following we detail 4 case studies.

Listing 6. ClassCastException in BEValue/getBytes
```java
class BEValue {
    public byte[] getBytes() throws ClassCastException {
        try {
            return (byte[])this.value;
        } catch (InvalidBEncodingException e) {
            throw new ClassCastException(e.getMessage());
        }
    }
}
```
Listing 6 shows a part of the `getBytes` method, containing a single try-catch statement. This try-catch statement is executed 41 times. When perturbed with an exception injection, the chaos controller verifies that two core hypotheses are validated in production: the exception is logged, and the client exits with an error status. The developer has no further action to take because this try catch is both observable and debuggable.

Listing 7. `InterruptedException in Announce/run`
```
while (!this.stop) {
    try {
        Thread.sleep(this.interval * 1000);
    } catch (InterruptedException ie) {
        // Ignore
    }
}
```

Listing 7 shows the `run` method in class `Announce`. The try-block is a piece of code running in a sub-thread. The announce thread starts by making the initial “started” announce request to register on the tracker and get an interval value. In the observation mode, the try-catch block is executed once. However, in the exploration mode with exception injection, the try-catch block is executed 760 times. Indeed, due to the skip of the `Thread.sleep`, the while loop runs more times before reaching its objective. When the perturbation injector injects the exception, the catch-block simply “swallows” this exception and does not do anything to handle the exception. This results in using more computing resources. As shown in the comment, the developer knows about this behavior. However, thanks to CHAOSMACHINE, she is made aware that ignoring the exception is not good for performance, and she is even given a quantitative measurement (per the system metrics collected by the monitoring sidecar).

Listing 8. `AnnounceException in Announce/run`
```
if (!this.forceStop) {
    try {
        this.getCurrentTrackerClient().announce(event, true);
    } catch (AnnounceException ae) {
        logger.warn(ae.getMessage());
    }
}
```

Listing 8 is also from the `run` method in the `Announce` class. The exception type is `AnnounceException` and this try-catch block is executed once in the observation mode, and once in the exploration mode. When the perturbation injector injects the exception, the file is still correctly downloaded. Once the client finishes the download, it exits with a normal exit code, and some error messages about this exception appear in the application log. In this case, the try-catch block successfully blocks `AnnounceException` to break the system.

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**TABLE II**

**The Results of Chaos Experimentation With Exception Injection on 27 Try-catch Blocks in the uTorrent BitTorrent Client**

| Try-catch block information       | Execution Occur./Expl. | Log. | Downl. | Exit status | Sys. metrics | RH | OH | DH | SH |
|----------------------------------|------------------------|------|--------|-------------|--------------|----|----|----|----|
| BEValue/getBytes,ClassCastException,0 | 41 / 1                 | yes  | no     | crashed     | -            | x  | x  |
| BEValue/getBytes,ClassCastException,0 | 15 / 1                 | yes  | no     | crashed     | -            | x  | x  |
| BEValue/getBytes,ClassCastException,0 | 37 / 1                 | yes  | no     | crashed     | -            | x  | x  |
| BEValue/getBytes,UnsupportedEncodingException,1 | 37 / 1                 | yes  | no     | crashed     | -            | x  | x  |
| ClientMain/main,CmdLineParser$OptionException,0 | 1 / 1                 | yes  | no     | crashed     | -            | x  | x  |
| ClientMain/main,Exception,1 | 1 / 1                   | yes  | no     | crashed     | -            | x  | x  |
| Announce/run,AnnounceException,0 | 1 / 60                  | yes  | no     | stalled     | -            | x  | x  |
| Announce/run,InterruptedException,2 | 1 / 760                | no   | yes    | normally    | threads+      | x  |    |
| Announce/run,InterruptedException,3 | 1 / 760                | no   | yes    | normally    | threads+      | x  |    |
| Announce/run,InterruptedException,4 | 1 / 1                  | yes  | yes    | normally    | no diff      | x  |    |
| Announce/run,AnnounceException,4 | 1 / 1                  | yes  | yes    | normally    | no diff      | x  |    |
| ConnectionHandler/run,SocketTimeoutException,0 | 1290 / 1              | no   | yes    | normally    | no diff      | x  |    |
| ConnectionHandler/run,IOException,1 | 1290 / 1               | yes  | yes    | stalled     | cpu+         | x  |    |
| ConnectionHandler/run,IOException,2 | 1290 / 2               | yes  | no     | stalled     | no diff      | x  |    |
| ConnectionHandler/stop,IOException,0 | 1 / 1                  | no   | yes    | normally    | no diff      | x  |    |
| Handshake/craft,UnsupportedEncodingException,0 | 50 / 50               | yes  | no     | stalled     | no diff      | x  |    |
| Handshake/craft,UnsupportedEncodingException,0 | 50 / 48               | yes  | no     | stalled     | no diff      | x  |    |
| PeerExchange/send,InterruptedException,0 | 90763 / 1             | no   | no     | stalled     | no diff      | x  |    |
| PeerExchange/stop,InterruptedException,0 | 46 / 44                | no   | yes    | normally    | no diff      | x  |    |
| PeerExchange/stop,InterruptedException,0 | 90805 / 1             | no   | no     | stalled     | cpu+         | x  |    |
| PeerExchange/stop,InterruptedException,1 | 90763 / 288           | no   | no     | stalled     | no diff      | x  |    |
| PeerExchange/stop,InterruptedException,2 | 90805 / 43            | yes  | no     | stalled     | no diff      | x  |    |
| PeerExchange/stop,InterruptedException,3 | 90763 / 46            | yes  | no     | stalled     | no diff      | x  |    |
| Piece/validate,NoSuchAlgorithmException,0 | 2564 / 5427           | yes  | no     | stalled     | no diff      | x  |    |
| HTTPAnnounceRespMessage/parse,InvalidBEncodingException,0 | 3 / 30                | yes  | no     | stalled     | no diff      | x  |    |
| HTTPAnnounceRespMessage/parse,InvalidBEncodingException,1 | 3 / 30                | yes  | no     | stalled     | no diff      | x  |    |
| HTTPAnnounceResponseMessage/parse,UnknownHostException,2 | 3 / 30                | yes  | no     | stalled     | no diff      | x  |    |
| total: 27 / 52                      | 460926 / 32992950     | 18   | 8      | 7           | 4            | 6  | 7  | 20 | 3  |
Even though there is only a logging action in the catch block, our manual analysis has revealed that developers have built the resilience mechanism outside this particular catch block. Thanks to CHAOSMACHINE, the developer has gained confidence in this specific catch block's exception-handling capability.

Listing 9. InterruptedException in PeerExchange/send
```java
public void send(PeerMessage message) {
    try {
        this.sendQueue.put(message);
    } catch (InterruptedException ie) {
        // Ignore, our send queue will only block if it contains
        // MAX_INTEGER messages, in which case
        // we’re already in big 
        // trouble, and we’d have to be
        // interrupted, too.
    }
}
```

Listing 9 shows method send in class PeerExchange. It is executed 90,763 times in the observation mode and 210 times in the exploration mode. In this case, when the perturbation injector injects an InterruptedException, the client just keeps running until some external entity (the user or CHAOSMACHINE) kills the process. No information is logged in the application logs. This means that, when this exception happens naturally, users have absolutely no debug information to give to developers. Here, CHAOSMACHINE helps the developer to identify “nightmare” debug cases of the form of purely silent try-catch blocks. Based on CHAOSMACHINE report, the developer is urged to change the exception-handling behavior.

5) Falsification on next version: It is of utmost importance that the resilience capabilities do not degrade over time. We try to falsify all hypothesis in a version of TTorrent (1.6) that is subsequent to the analyzed one, with the same protocol. The result is that no hypothesis discovered on version 1.5 are falsified on version 1.6, which means that the resilient try-catch blocks are still capable of handling unanticipated exceptions and keeping the system steady.

### Main result of the TTorrent experiment

| Class | User Requests |
|-------|---------------|
| 3 | 178 GET requests and 10 POST requests on rendering pages, contains: 97 GET requests directly on downloading resources, 41 POST requests on logging in, adding comments, updating user data, and 1 GET request on logging out. |
| 2 | 4 POST requests on logging in, adding comments, updating user data, and 1 GET request on logging out. |
| 1 | 97 GET requests directly on downloading resources, 41 POST requests on logging in, adding comments, updating user data, and 1 GET request on logging out. |

B. Evaluation on XWiki

1) Introduction of XWiki: XWiki is a widely-used open-source wiki system developed in Java, and is active over the past 14 years. XWiki requires external dependencies like a database server and a web application server.

2) Experiment protocol: We use a full-fledged production setup of XWiki version 9.11.1, which is deployed into Tomcat-8.5.29 and configured to connect to a MySQL server. We collect end-user traffic performed through a web browser: 1) visit pages, 2) log in with a username and a password, 3) add some comments on the main page and on a specific user page, 4) update personal page information and 5) log out. We record every HTTP user request, as well as the associated HTTP responses (including response code, header and body).

This end-user traffic is replayed on the production system to perform each experiment, per the chaos engineering practices observed in previous work [26]. First, CHAOSMACHINE runs the observation mode to monitor all the dynamic try-catch information and the normal behavior without any perturbation. Then, an exploration mode is activated. CHAOSMACHINE activates the corresponding perturbation injector for each covered try-catch block. The injector is active for 1 minute and CHAOSMACHINE collects the HTTP responses, which are then compared to those collected in observation mode.

In XWiki’s experiment, we define the four classes of try-catch blocks as following:

- **Resilient try-catch block.** Despite injected exceptions in this block, users still get the expected response content or succeed in adding comments and updating personal profile.
- **Observable try-catch block.** A try-catch block is said observable if the response code changes from “200 OK” to others. Consequently users also get an error page or request redirection under the corresponding exceptions.
- **Debuggable try-catch block.** A try-catch block is said debuggable if the the exception information is captured in application logs when an exception is injected.
- **Silent try-catch block.** A silent try-catch block only causes response body change while the response code stays the same as usual, and there is no error information about the injected exception in application logs.

3) Experimental results: There are 290 user requests we recorded: 276 GET requests and 14 POST ones. This traffic contains: 97 GET requests directly on downloading resources, 178 GET requests and 10 POST requests on rendering pages, 4 POST requests on logging in, adding comments, updating user data, and 1 GET request on logging out.

In total, 1567 try-catch blocks are registered in CHAOSMACHINE, and 268 of them are covered by the traffic we recorded. Table III summarizes the data aggregated over packages. The first column is the abbreviated package name. The second column shows the number of try-catch blocks that are covered by the traffic. The third column is the total number of try-catch block executions in both the observation mode and exploration mode. Finally, the last four columns indicate the number of try-catch blocks which meet our predefined four hypotheses described in Section III-A, including: 7 resilient try-catch blocks, 33 observable try-catch blocks, 233 debuggable try-catch blocks, and 23 silent try-catch blocks.
Take the row "org/xwiki/s/*" as an example. For all the try-catch blocks in the package whose name begins with org/xwiki/s, there are 15 try-catch blocks covered by this set of chaos experiments. Under normal conditions, these 15 try-catch blocks are executed 20522 times. When CHAOS-MACHINE activates the corresponding perturbation injectors in these try-catch blocks, the same blocks are executed 31826 times in total. After classification by CHAOS-MACHINE, the developer knows that: 1) 2 try-catch blocks satisfy the resilience hypothesis, 2) 5 try-catch blocks satisfy the observable hypothesis, 3) 15 try-catch blocks satisfy the debug hypothesis and 4) none of the try-catch blocks satisfy the silence hypothesis.

With the help of this report, developers gain more knowledge on XWiki’s error-handling capabilities in production. They are also encouraged to take action: 1) go over the silent try-catch blocks to confirm whether they need to record more information when an exception occurs and 2) focus on the try-catch blocks which have serious impact on system’s steady state, i.e. the observable ones. For example, if there is an exception in a specific try block, which leads to the system to generate an 500 response code instead of 200. As a result, the response contents also change to an error page for users. The chaos experiment provides more clues for developers to review the try-catch block and help them improve the fault tolerance ability.

4) Case studies: In the following, we detail two interesting cases found in the XWiki experiment.

Listing 10 shows part of method authenticateUser in class XWikiCachingRightService. There is only one try-catch block in this method. It is executed 151 times in observation mode and 153 times with perturbation. When the exception occurs, this catch block logs the error information. According to the monitored behavior, this perturbation actually has a visible impact on certain requests: it leads to an HTTP response code 302 (Redirect) instead of 200. Per our definition, this try-catch block satisfies both the observability and the debug hypothesis.

Listing 11 shows part of method runInternal in class DefaultSolrIndexer’s private inner class Resolver. This try block is executed 11 times in observation mode and is executed only once with perturbation. CHAOS-MACHINE identifies that this perturbation does not influence the output of any request. The monitoring sidebar also detects that the exception is caught in the application log. As we can see from the source code, developers log the exception information and also assign queueEntry to RESOLVE_QUEUE_ENTRY_STOP in the catch block which is a valid error-handling strategy in this context. Through the chaos experiment, the developers gain more confidence that this exception-handling design actually works in production.

### Main result of the XWiki experiment

CHAOS-MACHINE analyzes 268 try-catch blocks and identifies 7 that satisfy the resilience hypothesis, and 23 try-catch blocks that are silent, violating the silence hypothesis. This experiment shows that our prototype implementation of CHAOS-MACHINE scales to a system with 440k LOC and 1567 try-catch blocks loaded in the JVM.

### C. Evaluation on Broadleaf

1) Introduction on Broadleaf: Broadleaf Commerce is a set of open-source products in an eCommerce platform...
TABLE IV
RESULTS ON CHAOS EXPERIMENTATION ON 44 TRY-CAUGHT BLOCKS IN BROADLEAF COVERED BY THE CONSIDERED WORKLOAD

| Packages                   | Covered | Executions in Obsc. / Expl. | RH | OH | DH | SH |
|----------------------------|---------|-----------------------------|----|----|----|----|
| o/b/cms/file*              | 1       | 53 / 50                     | 0  | 1  | 0  | 0  |
| o/b/cms/url*               | 3       | 288 / 111                   | 2  | 0  | 0  | 1  |
| o/b/com/audit*             | 2       | 40 / 13                     | 0  | 0  | 1  | 1  |
| o/b/com/classloader*       | 2       | 1596 / 849                 | 0  | 2  | 2  | 0  |
| o/b/com/AlreadyPresent*    | 1       | 10660 / 51                 | 0  | 1  | 1  | 0  |
| o/b/com/persistence*       | 1       | 24 / 2                      | 0  | 0  | 1  | 0  |
| o/b/com/security*          | 2       | 14 / 40                     | 0  | 1  | 2  | 0  |
| o/b/com/tail*              | 1       | 30 / 21                     | 0  | 1  | 1  | 0  |
| o/b/com/web*               | 4       | 188 / 60                    | 0  | 2  | 3  | 1  |
| o/b/core/catalog*          | 1       | 2 / 2                       | 0  | 0  | 0  | 1  |
| o/b/core/order*            | 5       | 34 / 84                     | 0  | 3  | 5  | 0  |
| o/b/core/payment*          | 1       | 1 / 1                       | 1  | 0  | 0  | 0  |
| o/b/core/pricing*          | 1       | 5 / 21                      | 0  | 1  | 1  | 0  |
| o/b/core/rating*           | 2       | 6 / 6                       | 0  | 0  | 2  | 0  |
| o/b/core/search*           | 2       | 44 / 38                     | 0  | 2  | 2  | 0  |
| o/b/core/web*              | 10      | 615 / 340                  | 1  | 5  | 7  | 2  |
| o/b/core/audit*            | 3       | 16 / 14                     | 0  | 1  | 1  | 2  |
| o/b/profile/core*          | 1       | 3 / 2                       | 1  | 0  | 0  | 0  |
| o/b/vendor/sample*         | 1       | 1 / 1                       | 1  | 1  | 1  | 0  |

Total 44/555 1,5620 / 1706 5 21 31 8

written in Java. There are three components in Broadleaf which can be deployed separately into different servers: administration website, end-user shopping website and data fetching APIs.

2) Experiment protocol: We choose to conduct chaos experiments on Broadleaf version 5.0.0-GA. It provides an embedded Tomcat server, a HyperSQL database and a startup script, which simplifies deployment. For this experiment, we focus on the end-user shopping website. Similar to the experiments on XWiki, we deploy Broadleaf and randomly interact with the website system, including: 1) visiting product pages, 2) logging in with a username and a password, 3) adding products to a shopping cart, 4) checking out, and 5) logging out. As before, we record every user request and its associated response. In this experiment, we define resilient, observable, debuggable, silent try-catch block as per the XWiki experiment in Section IV-B2, since they are both web systems with the same core characteristics.

3) Experimental results: The recorded operations include 384 requests in total. There are 362 requests responsible for directly downloading files, all of which are GET requests. There are 15 GET requests about rendering pages. All of the 6 functional requests are POST, including logging in, updating the shopping cart, and checking out. The request for logging out is a request of type GET. These requests are replayed by GoReplay all the time during the experiments, and the time to finish this sequence of operations is less than 90 seconds.

First, CHAOSMACHINE keeps a 90 seconds observation mode to gather the system’s normal behaviors. At the same time, it also obtains information about covered try-catch blocks. Then, for each covered try-catch block, CHAOSMACHINE runs in exploration mode for 90 seconds. The results are generated and discussed next.

Table IV summarizes the results. The recorded traffic covers 44 try-catch blocks. In the first step of the experiment, we leave CHAOSMACHINE running automatically. In this case, it does not detect any resilient try-catch blocks, which leads us to do some further analysis. In the second step, we manually analyze all logs generated by monitoring sidecars. This analysis reveals that some of the diff-logs are semantically equivalent, but the monitoring sidecar marks the output as different if it is not the same (verbatim).

For instance, Broadleaf uses JSON objects to handle the prices of products with different properties. The price of an XL-size black T-shirt is $17, which is displayed as {"options": [1, 14], "price": 17}. In the snippet, number 1 stands for "XL" and number 14 stands for "black". It is obvious that {"options": [14, 1], "price": 17} has the same meaning. However, the current implementation of our monitoring sidecar regards these as different outputs. This phenomenon reflects one limitation of the monitoring sidecar: it is not sophisticated enough to determine semantical equivalence.

Following the manual comparison between the response bodies, the revised report about try-catch resilience is: 5 resilient try-catch blocks, 21 observable try-catch blocks, 31 debuggable try-catch blocks, and 8 silent try-catch blocks.

4) Case studies: Next, we discuss one of the most interesting cases found in the chaos experiment on Broadleaf.

Listing 12. NoResultException in CountrySubdivisionDaoImpl/findSubdivisionByCountryAndAltAbbreviation

```java
public CountrySubdivision findSubdivisionByCountryAndAltAbbreviation(...)
{
    TypedQuery<CountrySubdivision> query = new ...
    try {
        return query.getSingleResult();
    } catch (NoResultException e) {
        return null;
    }
}
```

As shown in Listing 12, CHAOSMACHINE identifies this try-catch block as a resilient one. As the method name suggests, the method is used for obtaining the sub-division of a country. The method is executed 3 times in observation mode and 2 times in exploration mode. When the perturbation injector is activated, the query result is always "null". The reason why the response content stays the same is that in observation mode, the user’s country information does not contain sub-divisions. Thus, no matter if there is an exception, the query result remains "null". However, this try-catch block may impact the system’s output if a specific user has sub-division information.

This phenomenon exposes another limitation of CHAOSMACHINE. Since it uses production traffic to evaluate the resilience of try-catch blocks, the traffic might not be sufficient to give definitive conclusions. For some try-catch blocks that are currently classified as resilient, different traffic may be able to falsify the hypotheses. The accuracy of the report of CHAOSMACHINE can be optimized by inputing more varied production traffic and analyzing output using more detailed domain-specific knowledge.
that Chaos engineering, we discuss here the related yet completely different areas of fault-injection and error-handling static analysis.

Fault injection is a well-researched area in the field of software dependability. It is traditionally applied offline to evaluate error-handling capabilities. Kanawati et al. [18] proposed FERRARI, a tool for the validation of dependability properties. Han et al. [16] designed DOCTOR, an integrated environment for assessing distributed real-time systems, and Lee et al. [20] proposed SFIDA, a tool to test the dependability of distributed applications on the Linux platform. All of these tools are based on injecting hardware-related faults, in a testing setup. Montrucchio et al. [24], Segal et al. [5], [29], Arlat et al. [4] also presented similar injection techniques for simulating hardware faults. Kao et al. [19] invented “FINE”, a fault injection and monitoring tool to inject both hardware-induced software errors and software faults. All those systems are not meant to be used in production, because, in the literature, fault tolerance analysis is done at design or testing time. More importantly, it is actually not possible to use them in production out-of-the-box, either because they require the source code or because they impose an unacceptable overhead. On the contrary, ChaosMachine is designed for fault injection in production in order to give precious insights of error-handling capabilities in a live setting.

Netflix [10] is well known for its ChaosMonkey, which randomly shuts down Amazon instances in production. It is used to ensure that the user experience is not impacted by a loss of an Amazon instance. This methodology has been extended to more failure types both at Netflix [17] and other companies [25]. An example of cloud oriented tool is by Sheridan et al. [30], who presented a fault injection tool for cloud applications, where faults are resource stress or service outage. While those tools conduct chaos experiments between services at the OS level or the network level, ChaosMachine is, to the best of our knowledge, the first to perform chaos experiments in a white-box fashion. It perturbs the runtime status inside the JVM, and enables developers to detect internal weaknesses at the code level (not the service interaction level).

Now we discuss exception analysis. Alexandre L. Martins et al. [22] presented VeriﬁEx to test Java exceptions by inserting exceptions at the beginning of try blocks. Their goal is to improve test coverage and not to assess error-handling contracts as done in ChaosMachine. Byeong-Mo et al. [9] gave a comprehensive review on exception analysis. Fu and Ryder [13] described a static analysis method for exception chains in Java. Magiel Bruntink et al. [7] proposed a characterization and evaluation method to discover faults in idiom-based exception handling. Zhang and Elbaum [32] presented an approach that amplifies test to validate exception handling. Cornu et al. [11] proposed a classiﬁcation of try-catch blocks at testing time. Here, the problem domain and implementation techniques are different: those authors use modiﬁed source code and test suites to study resilience. On the contrary, ChaosMachine operates in production with Java bytecode, using real production traffic to conduct the analysis.


d) Overhead of the ChaosMachine

Now, we discuss the overhead of the ChaosMachine in the context of TTorrent. We calculate the overhead of ChaosMachine in three aspects: 1) at the application level, by measuring downloading-time increase between the original version and the instrumented version, 2) at the system level, by measuring CPU and memory usage increase, and 3) at the binary code level, by measuring code bloat due to instrumentation. For statistical purposes, we conduct the same measurement 5 times and calculate the average number. The results are presented in Table V.

The instrumentation done by ChaosMachine has little influence on downloading time, memory usage and file size. We observe a 50% higher CPU time; this is due to the fact that ChaosMachine turns on all the monitoring sidecars to print more information. Note that in falsification mode, when ChaosMachine focuses on some specific hypotheses, the overhead of CPU time is significantly reduced to less than 1%. As a summary, the overhead of chaos experiments on TTorrent can be considered as compatible with production requirements.

V. Related work

Chaos engineering is a new field which is little researched, hence the closely related work is relatively scarce. Beyond

TABLE V

| Evaluation Aspects | Original Version | Instrumented Version | Variation |
|--------------------|------------------|----------------------|-----------|
| Downloading time   | 102.2s           | 96.4s                | -6%       |
| CPU time           | 2288             | 3410                 | 50%       |
| Memory usage       | 289M             | 332M                 | 15%       |
| Peak thread count  | 119              | 116                  | -3%       |
| Class files size   | 350 Kb           | 334 Kb               | 1.3%      |

5) Discussion of Broadleaf experiment: Through this experiment, we finally succeed in analyzing Broadleaf’s error-handling resilience capabilities under unanticipated exceptions. However, it is necessary to invest more manual work compared to experiments on XWiki. The limitations of the monitoring sidecar makes ChaosMachine unable to determine which try-catch blocks really influence the system’s steady state. In the first step of the experiment, ChaosMachine detects 0 resilient try-catch blocks. However, it is practicable to improve the abilities of the monitoring sidecar to calculate differences. The variety of production traffic also limits the identifications performed by ChaosMachine.

Main result of the Broadleaf experiment

ChaosMachine identifies 5 resilient, 8 silent ones, 21 observable ones, and 31 try-catch blocks. This experiment exposes two important facts: (a) the monitoring sidecar may need to embed some domain-specific knowledge in order to better interpret the application output and logs, and (b) the length of the captured production traffic during chaos experimentation matters.
Czek et al. [12] described a methodology for modeling fault effects on system behavior. They construct a behavior model based on a small set of workloads and use the model to infer the fault behavior of other workloads. In comparison, CHAOSMACHINE is directly applied to the production system to make and falsify hypotheses about its resilience. Finally, chaos engineering relates to failure-oblivious computing [27]: both are engineering techniques for production failures, yet failure-oblivious computing is not about the active injection of faults in the production systems.

VI. CONCLUSION

This paper presented CHAOSMACHINE, which analyzes and falsifies exception-handling hypotheses in Java programs running in production. We showed, on three large applications, that CHAOSMACHINE is able to produce actionable reports for developers to gain more confidence about the resilience of their system, and to point out critical try-catch blocks that need more attention. In future work, we will improve the monitoring sidecar to capture more precisely the steady state of the system. We will also design more advanced perturbation models, for example by changing the timing of methods invocation or with finer-grained strategies to control the blast radius of chaos engineering experiments.

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