Clotho: Saving Programs from Malformed Strings and Incorrect String-handling

by

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Certificate

This is to certify that the thesis titled **“Clotho: Saving Programs from Malformed Strings and Incorrect String-handling”** submitted by **Aritra Dhar** for the partial fulfillment of the requirements for the degree of *Master of Technology* in *Computer Science & Engineering* is a record of the bona fide work carried out by him under my guidance and supervision in the Program Analysis Research group at Indraprastha Institute of Information Technology, Delhi. This work has not been submitted anywhere else for the reward of any other degree.

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Abstract

Programs are susceptible to malformed data coming from untrusted sources. Occasionally the programming logic or constructs used are inappropriate to handle all types of constraints that are imposed by legal and well-formed data. As a result programs produce unexpected results or even worse, they may crash. Program behavior in both of these cases would be highly undesirable.

In this thesis work, we present a novel hybrid approach that saves programs from crashing when the failures originate from malformed strings or inappropriate handling of strings. Our approach statically analyses a program to identify statements that are vulnerable to failures related to associated string data. It then generates patches that are likely to satisfy constraints on the data, and in case of failures produce program behavior which would be close to the expected. The precision of the patches is improved with the help of a dynamic analysis. The patches are activated only after a failure is detected, and the technique incurs no runtime overhead during normal course of execution, and negligible overhead in case of failures.

We have experimented with Java `String` API, and applied Clotho to several hugely popular open-source libraries to patch 30 bugs, several of them rated either critical or major. Our evaluation shows that Clotho is both practical and effective. The comparison of the patches generated by our technique with the actual patches developed by the programmers in the later versions shows that they are semantically similar.

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Aritra Dhar

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Dedicated to,

Ma, Baba and Dida

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Chapter 1

Introduction

Modern software applications are large and complex. In addition, they run in diverse environments and get inputs from variety of data sources. As a result, predicting safe behavior for them at runtime can be difficult. Moreover, giving assurances about the quality of service becomes practically impossible when the applications are developed using third party libraries and components. Such applications often exhibit vulnerabilities that can be exploited by providing malicious inputs. In addition, diverse data sources and complex constraints on them make it challenging for programmers to ensure that all data elements are correctly validated and processed. Any deficiencies in this process makes applications prone to failures. Such defects can be hard to detect at the compilation-time, and irrespective of the validation techniques used, some of them may go undetected and exist in the applications even when the applications are in production.

The cost of failures can vary considerably depending on the mission-critical nature of applications. In particular, it would be extremely undesirable for an unmanned aerial vehicle on its mission to allow the control system to crash in case of a failure. Instead a suboptimal functioning for a short while might be acceptable until the system fully stabilizes. Generally speaking, expectations about the quality of service would largely depend on how a failure may impact the business. For example, a commercial online store may not afford a crash while it is listing its products to a customer. Such unpleasant experiences might result in customers

Code Snippets 1.1: Apache Log4j bug example.

```
1 private int substitute() {
2   if (priorVariables == null) {
3     priorVariables = new ArrayList<String>();
4     priorVariables.add(new String(chars, offset, length));
5   }
6 }
```

moving to other online stores making an adverse impact on the business. Similarly, a software company launching a new product would expect it to be stable while the product is undergoing beta-testing. Any crashes occurring at that time would result in negative feedback from the users and loss in the business. To make the matter worse, these failures may occur in software components that do not possess critical functionality, and hence, may even get less attention to their quality at the time of development. Nevertheless, irrespective of the criticality of these components, if the crash occurs it is equally undesirable.

As an example, consider Code 1.1 which depicts a bug that existed in Apache Log4j library version 2.0-beta9 [27] and crashed the logging framework. It was reported as a major bug in spite of the fact that it occurred in logging component. The object `priorVariables` is a `List` of String. On line 4, there is no check on the variables to ensure that invariants such as `offset + length <= chars.length`, `offset > 0`, and `length > 0` hold. In case of a failure, rather than allowing the application to crash, organizations would like to collect diagnostic information to identify the defects and allow the system to run suboptimal behavior for a while until it stabilizes. As long as such suboptimal behavior is within acceptable limits, the program survival would get higher preference. The bug can then be fixed in the later versions.

Several approaches have been proposed in the past to ensure that programs can recover from failures. Some of the approaches are based on static repairing where the patches are synthesized automatically based on the counter examples found in the field [46]. However, it is not always desirable to shut down the system for the post-mortem analysis and then relaunch it after fixing the defect. In order to overcome this weakness, dynamic approaches have been proposed to deal with problems that are related to memory, data, and incorrect programming constructs such as infinite loops [2,25,35]. Some of the approaches work either by identifying and isolating damaged data or memory portions [6, 9, 10], or by delaying the execution until the program self-stabilizes [15], or by finding the alternative execution paths [36], or by disabling suppressing signals and hoping that the program can recover automatically from the errors [28]. Static approaches strive for correctness whereas dynamic approaches are typically optimistic and work on the assumption that some suboptimal behavior under certain conditions is acceptable.

In this work, we propose a novel approach, which is hybrid in the nature and deals with the failures originated from either malformed strings or incorrect handling of strings. The approach first identifies program statements statically that might be vulnerable to string-related failures, and then develops patches by trying to identify origins of errors and constraints on the strings. It uses dynamic analysis to improve the precision of the patches generated by the static analysis. The approach targets string variables for patching, firstly, because strings are used heavily in Java APIs and have been common sources of errors, and secondly, because by targeting a specific type of data the approach can develop patches that are more precise and result in the behavior that would be close to the intended behavior.

This work makes following contributions:

- We present the design and implementation of Clotho (§ 2, § 5 and § 6) that generates effective program patches to handle string-related errors. These patches get activated only in case of program failures during runtime, and save program from crashing ensuring its acceptable behavior.

- We use a finite state machine (FSM) as a formalism (§ 5) to describe the behavior of Java `String` API, and apply it to drive the generation of exception-specific patches.

- We applied Clotho to several hugely popular open-source libraries to patch 30 bugs, several of them rated critical or major, resulting from unhandled runtime exceptions from Java `String` APIs. The results of our study (§ 7) indicate that Clotho can effectively produce patches that save programs from crashing due to failures originating from known bugs. The study also gives insights into the characteristics of the commonly occurring string problems.

- Manual inspection of the CLOTHO-generated patches reveals that in most cases they are semantically similar to the ones produced by the developers in the later versions. Thus, CLOTHO can also guide developers in the process of building patches for the future versions.

We have made our source code and data sets available to the open source community at http://goo.gl/d1zcXD. Github development repository is located at https://github.com/aritradhar/CLOTHO and https://github.com/aritradhar/CLOTHO-TaintAnalysis.

Chapter 2

Motivation and Challenges

Ensuring correctness of a program is an undecidable problem. In order to achieve high scalability static analysis works by making sound approximations, which typically lead to numerous false positives. Complex programming logic and data coming from diverse sources make the problem worse. As a result, successful execution of a real application can never be guaranteed, and unexpected failures may happen. These failures often result in runtime exceptions being thrown by the applications that are generally not handled. The cost of these runtime failures can vary depending on the criticality of the applications and can be very high for mission-critical applications.

Java applications are typically built using libraries, and `String` APIs are commonly used in third party libraries. Common and diverse usage of strings in programs is a significant source of errors. We mined the repository of posts on `stackoverflow` [43] to understand common types of exceptions thrown in case of failures. Table 2.1 lists the most prominent exceptions with the share of higher than 5%. The second column indicates the types of exceptions, whereas the third column indicates their overall percentage share. We observe that strings can play a role in generating all except `SecurityException`. This result coupled with the potentially heavy cost of program crashes motivated us to develop a hybrid technique for automatic repairing of Java programs for failures related to `String` APIs.

Runtime Exception Type	Occurrences	Percentage
NullPointerException	34912	54.94%
ClassCastException	7504	11.81%
IndexOutOfBoundsException	6637	10.44%
SecurityException	5818	9.15%
NoSuchElementException	2392	3.76%
ArithmeticException	2338	3.67%
ConcurrentModificationExceptio	1889	2.97%
DOMException	1024	1.61%
ArrayStoreException	279	0.43%
MissingResourceException	277	0.43%
BufferOverFlowException	161	0.25%
NegativeArraySizeException	122	0.19%
BufferUnderFlowException	66	0.1%
LSException	64	0.1%
MalformedParameterizedTypeExce	38	0.05%
CMMException	8	0.01%
FileSystemNotFoundException	6	0.009%
NoSuchMechanismException	3	0.0045%
MirroredTypesException	1	0.0015%

Table 2.1: Prominent runtime exceptions from stackoverflow [43].

2.1 Overview

Code 2.1 corresponds to methods from from fileUtils class of Apache Common IO library. The method getPathNoEndSeparator() throws a StringIndexOutOfBounds exception on Windows OS, which originates from statement return filename.substring(prefix, index + separatorAdd) on line 13 when the method is called with parameter "/foo.xml". Here, the value of prefix as returned by the method getPrefixLength is 1. It fails to satisfy the constraint implied by the program condition prefix <= index + separatorAdd for substring method which ensures that beginIndex cannot be greater than endIndex. As a result, the exception being thrown.

A closer inspection of this code snippet shows that the string variable filename invokes two methods, namely length and substring on lines 11 and 13 respectively. Java String API documentation specifies that length does not throw any runtime exceptions. The only exception that this invoke statement can throw is when the receiver object referenced by filename is null. However, the check on line 7 indicates that this situation would not arise. However, method

Code Snippets 2.1: Snippet from `fileUtils` class of Apache Commons library.

```
1  public static String getPathNoEndSeparator
2         (String filename) {
3    return doGetPath(filename, 0);
4  }
5  private static String doGetPath
6         (String filename, int separatorAdd) {
7    if(filename == null) return null;
8    int prefix = getPrefixLength(filename);
9    if (prefix < 0) return null;
10   int index = indexOfLastSeparator(filename);
11   if ((prefix >= filename.length()) || (index < 0))
12        return "";
13   return filename.substring(prefix,
14        index + separatorAdd);
15 }
```

Code Snippets 2.2: Patch for `fileUtils` class from Apache Commons library bug.

```
13 String temp = null;
14 try {
15   temp = filename.substring(prefix, index + separatorAdd);
16 } catch(IndexOutOfBoundsException ex) {
17   int length = filename.length;
18   int t = index + separatorAdd;
19   temp = filename.substring(
20     getStart(prefix,t,length), getEnd(prefix,t,length));
21 }
22 return temp;
```

`substring` can throw `IndexOutOfBoundsException` exception that can potentially crash the program. A good patch to handle this failure should take into account all of these observations.

Code 2.2 presents the patch automatically generated by CLOTHO. This patch replaces the invoke statement on line 13 in Code 2.1. The invoke statement is now wrapped inside the `try` block and a `catch` corresponding to `IndexOutOfBoundsException` is added on line 15. This ensures that control passes to the catch block only when the exception is thrown. Line 20 shows two method calls namely `getStart` and `getEnd` that are inserted by CLOTHO. These methods, using the knowledge about the length of `filename` acquired with the help of the code on line 17, compute legally correct indexes required by `substring` method to satisfy the constraint related to `beginIndex` and `endIndex`. Method `substring` now can regenerate the substring ensuring

Code Snippets 2.3: Patch for the Apache Log4j bug.

```java
try {
  temp = new String(chars, offset, length);
} catch(StringIndexOutOfBoundsException ex) {
  int i = chars.length;
  temp = new String(chars,
    IndexRepair.getStart(offset, length, i),
      IndexRepair.getEnd(offset, length, i));
}
priorVariables.add(temp);
```

that the method call would not fail.

The actual patch provided by the developers is semantically similar to the one developed by Clotho and both versions of the program generate exactly the same output. Similarly, the patch developed by Clotho for the bug depicted in Code 1.1 is semantically similar to the actual one provided by the developers and is presented in Code 2.3. Here the object referenced by the string variable `temp` is regenerated after adjusting the offset and ensuring that the constraint represented by the program condition `offset <= length` would never be violated.

We next present in detail the techniques and the algorithms used in our analysis that can produce patches to regenerate string variables under more complex scenarios. Our study presented in § 7 suggests that majority of the string generation scenarios in practice are less complex.

2.2 Historical Context

In recent past, we have seen couple of disastrous failures of critical military and civilian infrastructure system due to system crash/shutdown/restart which is results of some very common runtime exceptions.

- In USS Yorktown, complete failure in propulsion and navigation system by a simple divide-by-zero exception in flight deck database (1998) [49].
- AT&T telephone network failure causing by one faulty switch causing ATC commutation blackout.

- Air-Traffic Control System in LA Airport lost communication with all 400 airplanes caused by a system crash triggered by 32 bit integer overflow [22].
- Mars rover curiosity B-side computer memory overflow causing OS suspend and multiple restart.
- Trans-Siberian Gas Pipeline Explosion in 1982 by deliberate bugs in software controlled valves.
- Near-blackout of the national grid in Austria caused by faulty function call.

All of these incidents have one thing common, all of them were critical systems where availability is the major requirement. Most of the systems are such critical that in case of failure one can not simple shutdown and restart the system like general client applications as it may results in loss of human lives and/or massive amount of money.

Chapter 3

Related Works

3.1 Recent Works on Data Structure Repairing

Automated data-structure repairing techniques are there in the litarature for a while. In the papers [8], [7], [10], [9], [6] the authors mostly concentrated on specific data-structures like `FAT-32`, `ext2`, `CTAS` (a set of air-traffic control tools developed at the NASA Ames research center) and repairing them. The authors represented a specification language by which they able to see consistency property these data-structure. Given the specification, they able to detect the inconsistency of these data-structures and repair them. The repairing strategy involves detecting the consistency constraints for the particular data structure, for the violation, they replace the error condition with correct proposition. In the paper [10], the authors proposed repair strategy by goal-directed reasoning. This involves translating the data-structure to a abstract model by a set of model definition rules. The actual repair involves model reconstruction and statically mapped it to a data structure update. In their paper [14] authors Elkarablieh et al. proposed the idea to statically analyze the data structure to access the information like recurrent fields and local fields. They used their technique to some well known data structures like singly linked list, sorted list, doubly liked list, N-ary tree, AVL tree, binary search tree, disjoint set, red-black tree, Fibonacci heap etc.

3.2 Works on Software Patching

In their paper [35], authors Jeff H. Perkins et al. presented their *Clear view* system which works on windows x86 binaries without requiring any source code. They used invariants analysis for which they used Daikon [16]. They mostly patched security vulnerabilities by some candidate repair patches.

Fan Lon et al in their paper [28] presented their new system `RCV` which recovers applications from divide-by-zero and null-deference error. Their tool replaces `SIGFPE` and `SIGSEGV` signal handler with its own handler. The approach simply works by assigning zero at the time of divide-by-zero error, read zero and ignores write at the time of null-deference error. Their implementation was on $x86$ and $x86 - 64$ binaries and they also implemented a dynamic taint analysis to see the effect of their patching until the program stabilizes which they called as `error shepherding`.

3.3 Genetic Programming, Evolutionary Computation

Reserch works on program repair based on genetic programming and evolutionary computation can be found in the paper of Stephanie Forrest et al. [17] and Westley Weimer et al [47] respectively. In the papers, the authors used genetic programming to generate and evaluate test cases. They used their technique on the well known Microsoft Zune media player bug causing tme to freeze up.

Chapter 4

Finding Origin of Error : Data Flow Analysis

4.1 Example Scenario

We have performed dataflow analysis by extending Soot main class. The objectives of the dataflow analysis are the following:

- For a target statement analyze used and defined variables.
- Extracts other statements which are both above and bellow the target statement in the control flow graph on which the used and defined variables are dependent on.

In the code snippet 4.1, we gave an example code based on java *String* API to demonstrate the analysis.

Code Snippets 4.1: Dataflow analysis

```
void bar()
{
  foo("fname:lname");
}

String foo(String s)
{
  int a = s.indexof(":");
  int b = s.indexOf("&");
  int c = s.indexOf("#");
  int d = 0;
  if(c>0)
  {
    d = 1;
  }
  return s.substring(a,b);
}
```

Let us assume that our target is `s.substring(a,b)` which in this case may throw an array index out of bound exception. In this target statement, `a` and `b` are used variable which are dependent on another String API method i.e `indexOf()` which calculates index of starting of a sub-string or single character in the main string. In case the sub-string or the character does not exist in the main string, `indexOf()` method returns -1 which causes throwing a runtime exception in the `substring()` method call.

By using dataflow analysis we try to understand how these different variables are correlated and based on that how we can effectively apply patching technique so the patching code will have very less footprint in the instrumented bytecode. In the Section 4.2.1, we have given detailed explanations of such analysis.

4.2 Flow Functions

4.2.1 Forward Flow Analysis

Let us define P_i as a program point/ node in the control flow graph. $in(P)$ and $out(P_i)$ respectively denotes in set and out set to and from the node P. We define set IG as the set of methods like `indexOf()`, `codePointAt()`, `CodePointBefore()` etc. which returns an integer which can be used as input to other String methods. We also define set IU which contains the methods which may use the integers produced by the methods in IG Then,

$$out(P_i) = in(P_i) \cup Def(P_i)$$

where statement in P is a invoke statement and method $m \in IG$ and

$$out(P_i) = in(P_i) \cap Used(P_i)$$

where statement in P is a invoke statement and method $m \in IU$. Initial entry set $= \phi$.

We have defined $Def(P_i)$ set as the set of variables and objects which are defined or redefined

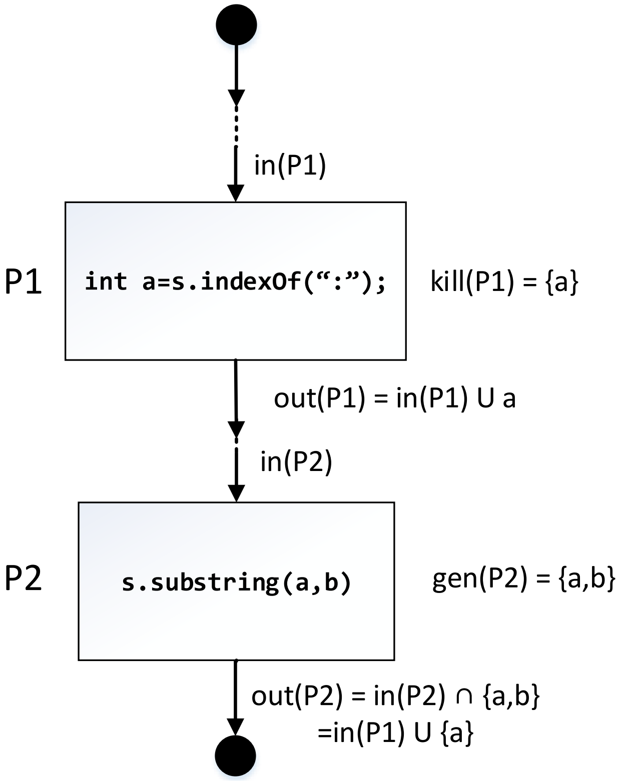


Figure 4.1: Dataflow diagram with in, out set in forward analysis

in the program point P_i. The set $Used(P_i)$ is also a set of variables and objects which are used in the program point P_i.

Example : Consider the program statement `Pi : int a = b.fun(c d)`. Here the variable `a` is initialized, so $Def(P_i) = \{$`a`$\}$ and as `b, c, d` are used, $Used(P_i) = \{$`b, c, d`$\}$

In the figure 4.1, we gave an example of a sample CFG with in set and out set.

Chapter 5

Clotho: Design of the System

5.1 Goals

We identify the broad design goals for a technique to automatically repair malformed `Strings` or incorrect handling of `strings` as follows:

(i) High patch fidelity. We require that the patched program must preserve the intended program behavior, i.e., the patch must be precise, and should not induce any undesirable control flows in the repaired program.

(ii) Non-invasive instrumentation. We require that the technique must ensure no side-effects (aside from optimally repairing objects) during normal program execution, and activate patches only when the program is guaranteed to crash.

(iii) Low system overhead. We desire that the patched program must incur no runtime overhead during normal program execution, and only negligible overhead in case of failures.

5.2 Design

Key Idea. Clotho leverages a combination of program analysis techniques to precisely identify program instrumentation points, and builds upon custom algorithms to generate targeted, high quality patches for repairing programs with potential runtime exceptions, while still satisfying

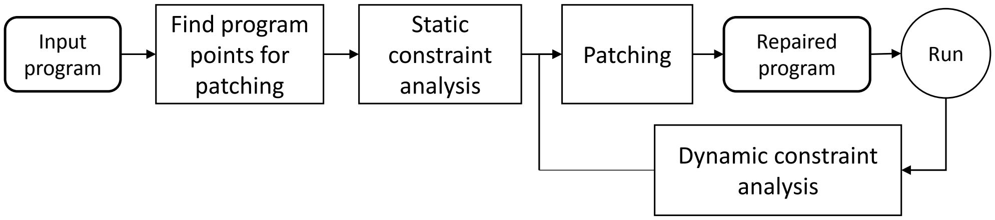

Input program
Find program points for patching
Static constraint analysis
Patching
Repaired program
Run
Dynamic constraint analysis

Figure 5.1: Clotho workflow.

goals mentioned in § 5.1.

Figure 5.2 shows Clotho's workflow, which involves three main stages. First, Clotho uses program analysis techniques to precisely identify points of interest, i.e., string objects or API arguments that must be repaired to prevent runtime exceptions. In the second stage, Clotho leverages custom algorithms to generate relevant patches. Specifically, Clotho performs intra-procedural static and dynamic analyses to identify and evaluate constraints on the string objects under consideration. Third, Clotho uses the constraints evaluated in the earlier stage to programatically generate and embed patches inside `catch` blocks to ensure that they do not get activated during normal program execution.

5.2.1 Precise Identification of Instrumentation Points:

In this stage, Clotho leverages a combination of program analyses to accurately determine the minimum set of points of interest where instrumentation is required to repair. We list several techniques below that help Clotho achieve precision.

(i) Taint analysis. The main purpose of taint analysis is to broadly identify which program statements can be patched (possibly even suboptimally) without affecting the program control flow, i.e., affect only objects that are generated and stay within the application throughout their lifetime. While this principle is not a binding constraint, it ensures that Clotho's repairing mechanism does not adversely affect critical program behavior. We specify a generic set of sensitive sources and sensitive sinks for each input program, to identify critical program paths where a repaired `String` objects (and thus possibly suboptimal) must not flow. For example, Clotho does not repair program statements that lie along a control flow path that leads to an I/O sink, like file system, console, network, GUI, etc.

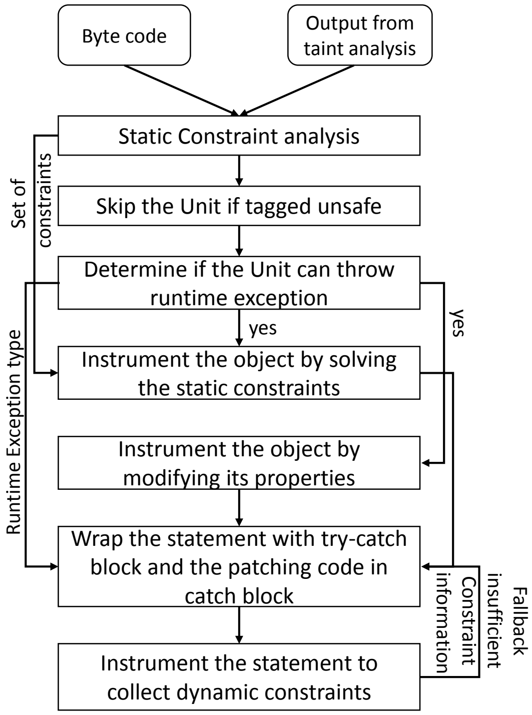

Byte code
Output from taint analysis
Static Constraint analysis
Skip the Unit if tagged unsafe
Determine if the Unit can throw runtime exception
yes
Instrument the object by solving the static constraints
Instrument the object by modifying its properties
Wrap the statement with try-catch block and the patching code in catch block
Instrument the statement to collect dynamic constraints
Set of constraints
Runtime Exception type
yes
Fallback insufficient Constraint information

Figure 5.2: Clotho Patch module flow diagram

The taint analysis module take as input the compiled byte code intended to be repaired, and generates a control flow graph identifying program statements that lie along paths from sensitive sources to sensitive sinks. Since, Clotho targets strings in particular, it must support taint propagation for all Java APIs that support string manipulation, including `StringBuffer` and `StringBuilder`. All `String` objects (whether generated or assigned) that lie along the tainted path from a sensitive source to a sensitive sink are marked as *unsafe* to patch. Subsequently, Clotho does not repair such `String` objects. Tables 5.1 and 5.2 list some common sensitive sources and sinks for several classes in Java.

(ii) Call graph analysis. Clotho leverages call graph analysis to further improve the precision for finding instrumentation points. Although unlikely, it is possible that the developers may themselves handle code that raises runtime exceptions. Thus, Clotho must not instrument program points that are explicitly handled by the developers, since repairing such statements would definitely alter the intended control flow.

Checked runtime exceptions may be placed in the (i) same method, or (ii) upstream in the call chain. While handling the former scenario is trivial, Clotho handles the latter case by

Class	Source
`java.io.InputStream`	`read()`
`java.io.BufferedReader`	`readLine()`
`java.net.URL`	`openConnection()`
`java.util.Scanner`	`next()`
`javax.servlet.ServletRequest`	`getParameter()`
`org.apache.http.HttpResponse`	`getEntity()`
`org.apache.http.util.EntityUtils`	`toString()`
`org.apache.http.util.EntityUtils`	`toByteArray()`
`org.apache.http.util.EntityUtils`	`getContentCharSet()`

Table 5.1: Common sensitive sources in Java.

Class	Sink
`java.io.FileOutputStream`	`write()`
`java.io.OutputStream`	`write()`
`java.io.PrintStream`	`printf()`
`java.net.Socket`	`connect()`
`java.io.Writer`	`write()`

Table 5.2: Common sensitive sinks in Java.

identifying all possible call chains (in the call graph) involving the concerned method using reverse Breadth First search (BFS), and determines ancestor methods where the call site was wrapped in `try-catch` block of compatible exception type or not.

(iii) Reaching definitions analysis. Taint and call graph analyses together provide a set of program points to be instrumented with the patch. However, this set can be further pruned. Clotho performs *reaching definitions* analysis to skip marked statements if (i) the string variables contained in such statements have already been patched upstream in the method, and (ii) the variables have not been redefined along any path that originates from the patched statement. This analysis further reduces instrumentation points in a program.

5.2.2 Patch Generation:

The output from the first stage is essentially a set of program points, typically bytecodes or some other intermediate representation, denoting `String` objects or APIs that are safe to repair. Once these instrumentation points have been identified, Clotho determines the possible patches that can be applied to each of them. Specifically, a program patch constitutes a set of constraints

Minimum length	Maximum length(L)	Prefix 1	Prefix 2	...	Prefix L-1	Contain 1	...	Contain L-1

Figure 5.3: Constraints involving Strings.

Algorithm 1: Patching strategy for `String` objects.

```
Data: Control flow graph $CFG$ for program $P$
Result: Patched program $\hat{P}$
begin
    for ∀ node $N \in CFG$ do
        Statement $S$ in node $N$
        if $S$ contains String API call then
            $str \longleftarrow$ String reference on $S$
        if $S$ can throw RuntimeException then
            Exception class $EC \longleftarrow$ RuntimeException of $S$
            $CES_{str} \longleftarrow$ all conditional statement in $P$ on $str$
            $CS_{str} \longleftarrow$ output of Algorithm 2($CES_{str}$)
            if $str$ have sufficient constraints in $CS_{str}$ then
                /* Static constraint analysis */
                $str \longleftarrow$ output of Algorithm 3($CS_{str}$)
            else if $str$ encountered exception then
                /* Dynamic constraint analysis */
                $CS_{str} \longleftarrow$ output of Algorithm 2($CES_{str}$)
                if $str$ have sufficient constraints in $CS_{str}$ then
                    $str \longleftarrow$ output of Algorithm 3($CS_{str}$)
                else
                    $str \longleftarrow$ output of Algorithm 4($S$)
```

on either the `String` object or the parameters to the `String` API under consideration, such that the new repaired `String` object that is generated will satisfy all constraints and thus the patched program does not throw any runtime exceptions.

Clotho's patch generation mechanism involves two main parts (i) constraint collection and evaluation, and (ii) code generation. We now describe Clotho's patch generation mechanism in detail.

Constraint collection and evaluation. Clotho leverages a hybrid approach to collect all possible constraints that must be satisfied, and thus generates a high quality patch to repair the program. A constraint on a string object is defined as a set of permissible values that can uniquely define the string. Clotho uses a simple constraint set that includes minimum and maximum length, along with set of permissible prefixes and substrings, as shown in Figure 5.3.

Algorithm 2: Constraint collection for `String` objects.

```
Data: Set of conditional statement on string $str$
Result: Constraint set $CS_{str}$
begin
    for $Conditional\ statement \leftarrow i,\ \forall i \in CS_{str}$ do
        $i \Rightarrow str\ *\ OP$ /*where * is the binary operator*/
        if $*$ is $==$ then
            $maxlength_{str} \longleftarrow OP$
            $minlength_{str} \longleftarrow OP$
        else if $*$ is $>$ AND $*$ is $\geq$ then $minlength_{str} \longleftarrow OP$
        else if $*$ is $<$ AND $*$ is $\leq$ then $maxlength_{str} \longleftarrow OP$
        else if $*$ is Prefix Check then $PrefixSet_{str} \cup OP$
        else if $*$ is Contains Check then $ContainSet_{str} \cup OP$
```

The hybrid approach has a static component that makes a forward pass over the program to collect declarative constraints on string objects, such as their length or prefix, etc. Clotho invokes the dynamic component if there are constraints such that the constraint set cannot be evaluated. In such scenarios Clotho (i) generates a patch that itself dynamically collects constraint information, (ii) augments it with the previously collected static constraint details, and (iii) evaluates these constraints on the fly to generate repaired `String` objects, which do not cause the program to throw runtime exceptions. Algorithm 1 gives an overview of this hybrid approach.

- **Static constraint collection**: Clotho's static constraint collection phase identifies all declarative constraints. Algorithm 2 briefly describes the steps to populate the constraint store shown in Figure 5.3. Specifically, Clotho iterates over all program code and analyzes conditional statements involving string objects of the form `if (st.length() == 5)`. Clotho considers only those constraints that the object must satisfy to ensure that the control flows through the *preferred* branch of the conditional. We define the preferred branch as the one that does not throw exceptions or error conditions, like `System.err.print()`. In other words, Clotho only considers the conditional expressions in the branches that do not involve any exceptions or error paths. Note that Clotho also evaluates OP (in Algorithm 2) when collecting constraints, in case OP is a composite mathematical expression $f(x, y, z, ...)$, such as $x + y * z$, where all x, y and z are known to

Algorithm 3: String object constraint evaluation.

```
Data: String object $Str$ and constraint set $CS$.
Result: String object $Str$ such that $\forall i \in CS$, $Str$ satisfies $i$
begin
    $CS_{Str} \longleftarrow$ Get the constraint set for $Str$
    $MinLength \longleftarrow CS_{Str}[0]$
    $MaxLength \longleftarrow CS_{Str}[1]$
    $PrefixSet_{Str} \longleftarrow CS_{Str}[2 \rightarrow MaxLength + 1]$
    $ContainSet_{Str} \longleftarrow CS_{Str}[MaxLength + 2 \rightarrow 2 * MaxLength + 1]$
    for $C \in PrefixSet_{Str}$ do
        if $C$ is Empty then
            continue
        $PrefixLength \longleftarrow$ LENGTH OF $C$
        if $PrefixLength$ is Maximum $\in PrefixSet_{Str}$ then
            Use $C$ to construct $Str$
    for $C \in ContainSet_{Str}$ do
        if $C$ is Empty OR $C \in Str$ then
            continue
        $Str \leftarrow Str$ APPEND $C$
    return $Str$
```

Code Snippets 5.1: Code requiring dynamic string constraint evaluation.

```java
void foo() {
  String st = Input(); /* user input */
  if (st.length() == 5) {/* do something */}
  if (st.contains(Input())) {/* do something */}
  st = st.substring(7, 10);
}
```

be numeric.

- **Dynamic constraint collection**: The constraint set is populated at the end of the static phase, and CLOTHO leverages Algorithm 3 to evaluate these constraints and determine the potential safe values of the string object under consideration. However, there are scenarios, where there are potentially conflicting constraints or no permissible values of the constraints can be calculated statically.

Consider the example shown in Code 5.1, where the function `foo` performs a series of checks on a user entered string before computing a substring on it. Since the constraints on the string `st` cannot be completely collected and evaluated statically. For such cases, CLOTHO instruments

Code Snippets 5.2: Dynamic constraint collection and evaluation corresponding to code 5.1.

```
1 String temp = Input();
2 ConstraintStore.updateSet("<foo()>", st, temp);
3 st = GenerateStringDynamic.init("<foo()>", st);
```

Code Snippets 5.3: Example of parameter tweaking.

```
try{
    c = s.chatAt(4);
} catch(IndexOutOfBoundException ex) {
    c = s.failSafeCharAt(4, s.length());
}
```

the code with statements to dynamically collect constraint information, augment them with previously known static constraints, and evaluate these constraints at runtime. Specifically, Clotho instruments the bytecode with constraint collection code just before the conditional statements under consideration. Thus, Clotho will insert Code 5.2 before line 4 in Code 5.1 to update and evaluate the set of constraints on string `st`.

5.2.3 Code generation

Code generation can be done either statically or dynamically depending on how the constraints are evaluated. In either scenario, a key component of code generation is *object repairing*. Additionally, in certain cases where constraints cannot be satisfied, either statically or dynamically or both, Clotho resorts to *parameter tweaking*.

1. **Object repairing**: Clotho generates the code for the repaired object under consideration after all the constraints have been collected and evaluated. If the constraints are resolved statically, then Clotho updates its constraint data store and instruments the corresponding bytecodes appropriately. However, in case the patch requires dynamic constraint collection, Clotho embeds the code to dynamically collect constraints and generate the patch as well. Line 1 and 3 in Code 5.2 update the constraint set and generate the repaired object, respectively.

Algorithm 4: Parameter tweaking based String patching.

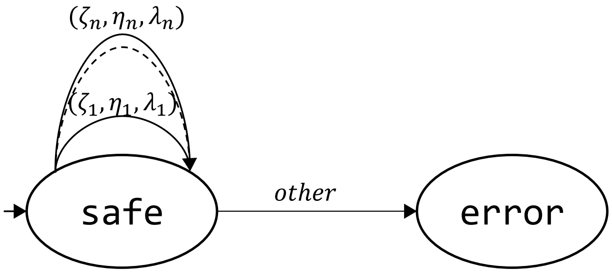
```
Data: String object $Str$ and index set $IS$ which contains $i$ or $i, j$.
Result: Repaired index set containing $Ri$ or $Ri, Rj$ based on input $IS$
begin
    $Length \longleftarrow$ length of $Str$
    if $Length == 0$ then
        $Ri, Rj \longleftarrow 0$
    else if $i > j$ then
        $Ri \longleftarrow j - 1$
    if $i > Length$ OR $j > Length$ then
        $Ri \longleftarrow Length - 1$ or $Rj \longleftarrow Length - 1$ based on condition
        /* more conditions possible */
    if $i < 0$ OR $j < 0$ then
        $Ri \longleftarrow 0$ or $Rj \longleftarrow 0$ based on condition
        /* more conditions possible */
```

2. **Parameter tweaking**: It is possible that as a side-effect of object repairing, the newly patched object may throw runtime errors when invoked with certain string APIs. For example, `c = s.charAt(4);` may still throw runtime errors even if `s` has been repaired. This is possible if the repaired `s` has a length less than 4. In such scenarios, Clotho patches the code with a `try-catch` block around the offending API call, and appropriately inserts the repaired code in the `catch` block but with tweaks to the API arguments, as shown in Code 5.3, to ensure that no further runtime exception is thrown. For example, if the length of the string is greater than 4, then the API works similar to default `charAt` API. However, if the length is 3, then line 4 is invoked with both arguments equal to string length, i.e., 3. Note that parameter tweaking is leveraged to counter a potentially suboptimal object repair that may throw cascading exceptions. Algorithm 4 briefly outlines the mechanism to correctly set the parameters for the offending string API.

5.2.4 Instrumentation:

Clotho embeds the repair in a `try-catch` ladder to ensure that the patches do not get activated during normal program execution, thereby minimizing any side-effects of repairing and preventing any inadvertent changes to the program's intended control flow.

An important task in the instrumentation stage is to determine the kind of exceptions that



$(\zeta_n, \eta_n, \lambda_n)$
$(\zeta_1, \eta_1, \lambda_1)$
safe
other
error

Figure 5.4: Partial constraint representation model : general structure.

may be thrown, and appropriately construct the `catch` blocks. While most APIs throw only a single subclass of `RuntimeException`, it is possible that a statement may throw more than one subclasses, such as `NullPointerException` and `StringIndexOutOfBoundsException`. Clotho generates a `catch` ladder for each kind of exception, which also facilitates exception-specific repairing as well. In other words, a single patch may get distributed over multiple `catch` blocks. This mechanism is achieved with the help of a constraint representation model.

Constraint representation model. We use a finite state machine (FSM) as a formalism to describe the behavior of Java `String` API, and apply it to drive the generation of exception-specific `catch` blocks. The model is precomputed based on the API documentation of Java `Strings`. Formally, we define the constraint representation FSM model $(Q, \Sigma, \delta, q_0, F)$ as follows:

- Q: Set of states where $|Q| = 2$, *legal state*(safe) and *illegal state* (error).

- Σ: Set of symbols. Each symbol is defined as a tuple (ζ, η, Λ), where ζ is a `String` API operation, η is the type of an exception and $\Lambda = \{\lambda_1, \ldots, \lambda_n\}$ is the set of constraints. A constraint λ_i is defined as a constraint on a string that must be satisfied to allow successful execution of ζ.

- δ: Transition function. $safe \rightarrow safe$ is a safe transition and $safe \rightarrow error$ corresponds to the constraint violation.

- q_0: Starting state, here $q_0 = safe$.

- F: Singleton set of accept states which contains q_0.

A partial constraint representation model is depicted in Figure 5.5. It essentially specifies

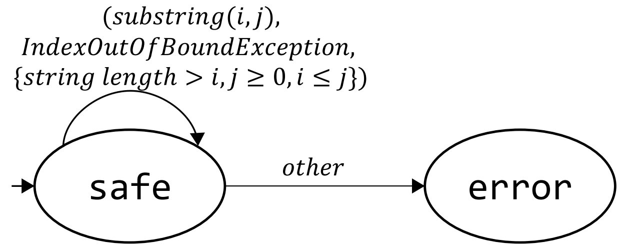


Figure 5.5: Partial constraint representation model.

the constraints that are associated with `substring` method and `IndexOutofBoundException` exception that can be thrown by the method. A complete model would have several such self-looping transitions corresponding to other Java `String` API methods. The repairing mechanism gets triggered when an exception is thrown while performing a string operation after at least one of the constraints on the structure of the associated string is violated. This is represented by the transition labeled by `other`. The patches essentially support the same semantics identified by the transitions with the help of `catch` blocks.

5.3 Limitations

Clotho's major limitation arises from the fact that it is heavily directed towards repairing handling `String` objects and API exceptions. While this may seem to be a limitation, we believe that Clotho's strength lies in the fact that it mines contextual data about runtime exceptions related to `String` objects that helps development of intelligent program patches. Moreover, Clotho's technique is generic and can be ported to any other class of Java APIs.

Clotho generates precise patches considering the program context which avoids cascading exceptions to a great extent producing the intended behavior in case of failures. However, it still cannot give guarantees about elimination of cascading exceptions, particularly when there are heavy object dependencies in the program.

The quality of Clotho's patches also depends on the nature of the constraint solver, which is pluggable. A more sophisticated solver may improve the quality of program repair, and we leave comparison of different solvers for future work.

Chapter 6

Implementation Details

We implemented a prototype of Clotho as described in § 5 for repairing runtime exceptions originating from unhandled Java `String` APIs. Our end-to-end toolchain is completely automated and was written in ∼12.7K lines of Java. We leveraged the Soot [41] framework for bytecode analysis and instrumentation, and InfoFlow [42] for static taint analysis.

We now briefly describe a few salient features of our implementation, which is also available for download at `http://goo.gl/d1zcXD`.

6.1 Taint Analysis

InfoFlow performs its taint propagation over `Units`, which are Soot's intermediate representation of the Java source code. We extended the InfoFlow framework to a) enable seamless coupling with Soot, and b) determine whether it is safe to patch a given Soot `Unit`. Specifically, we added a mapping that retrieves `Units` for statements to be patched given a specified method signature. This is relevant since the same statement, say `int x = 1;` has the exact same representation even if it appears more than once in a same method. We also added a utility method to determine if a `Unit` must be patched if it lies along the path between a source and sink in the call graph (as generated by Soot).

6.2 Call graph analysis

Clotho leverages Soot generated call graph to determine both inter- and intra-method checked runtime exceptions (recall § 5.2.1). Soot uses the `Trap` class to manage exception handling for both classes of exceptions discussed above. Each `Trap` object has start, end and handler unit. We tagged every `Unit` in a `HashMap` if it belonged to an existing `Trap`, so as to exclude it from instrumentation during the repairing phase.

6.3 Constraint Analysis

Clotho makes a forward pass over the `Units` identified by the taint analysis and other program analyses in the first phase to gather constrains over string literals of interest (recall § 5.2.2), and builds a `HashMap` of `ConstraintDataType`, a custom data type to store and evaluate these constrains. Specifically, each `ConstraintDataType` entry stores four key parameters—the permissible prefixes, substrings, minimum and maximum length—that specify constraints corresponding to a `String` literal.

Constraint evaluation over these `ConstraintDataType` entries is done as discussed earlier in Algorithm 3. However, if the gathered constraints can not be satisfied statically, e.g., `if(str.contains(userInput()))`, Clotho instruments the bytecode before the conditional statement with a static invocation to i) populate the corresponding `ConstraintDataType` entry, and ii) recompute the permissible values of the string object with already existing constraints (see Code snippet 5.2).

6.4 String Repairing Phase

The string repairing phase is divided into two sub-phases.

6.4.1 Detecting Potential Point of Failure

We have used specification from JAVA SE official documentation and list all the methods which throws runtime exception. We do forward pass to see if there is any invocation of such methods and if we find any we then cross check it with the results we got from the taint analysis. We also see if there is already some exception handling mechanism provided by the developer using the technique described in § 6.5. We detected such method calls and wrap them in try-catch block. In the catch block we place the appropriate exception type as provided by JAVA SE API documentation.

6.4.2 Catch Block Instrumentation

Catch block instrumentation is done by using `Trap` class in SOOT. In JIMPLE representation, exception handling is represented by `Trap` class which have start `Unit`, end `Unit` which denotes the starting and ending `Units` in the `try` block. To localize the instrumentation, we took a JIMPLEstatement and put in to a new `Trap` object and put appropriate patching `Units` in the catch block.

6.5 Optimizations

CLOTHO performs few other optimizations to improve the precision and quality of the patches.

6.5.1 Minimize constraint analysis:

CLOTHO collects constraints only for those string literals that may be involved in a runtime exception. For example, if a string object does not involve API methods that can throw runtime exception, then it is not required to collect and evaluate constraints on them. This significantly reduces the number of statements analyzed for instrumentation.

6.5.2 Minimize patch instrumentation:

Clotho makes a forward pass over all bytecodes to determine if a specific string object is modified after it has been patched. If the object is not modified then no further patching of statements capable of throwing `NullPointerException` exceptions is required, since the constraint would have been satisfied in the beginning and it would be valid as long as the variable is not changed. Similarly, when the API usage is same and none of the method parameters are changed, no further patching would be required. This reduces the total number of possible instrumentation required.

Chapter 7

Evaluation

We now present an evaluation of Clotho. In § 7.1, we evaluate Clotho's effectiveness by measuring the quality of patches and related instrumentation required. We also measure how the several optimizations described in § 6.5 affect the patches generated by Clotho. In § 7.2, we measure the relative performance and resource penalties incurred with Clotho. In § 7.3, we describe our experiences with some of the major bugs from our data set.

Data Set. We mined bug repositories of several open-source Java-based applications and selected 30 bugs, majority of them being rated either major, critical or blocking. These bugs involved usage of 64+ different APIs from Java's `String`, `StringBuffer`, `StringBuilder`, and Apache `StringUtils` and Google Guava `StringUtils` classes.

Experimental Setup. All our experiments were performed on a laptop with 2.9 GHz dual core Intel i5 CPU, and 8 GB of RAM, and running Microsoft Windows 8.1. We used JDK v1.7 running with 2 GB of allocated heap space. All bug reproduction was done on Eclipse Juno IDE. We used Soot v2.5.0 for bytecode analysis and instrumentation, and InfoFlow snapshot from May'14 for static taint analysis.

7.1 Accuracy

We evaluate the precision of the patch and the effectiveness of Clotho based on several metrics as described below.

- **Effectiveness of the patch**: Precision and effectiveness of a patch is governed by the similarity between a Clotho generated patch and the developer's fix for the same bug. We define **Patch Quality Index (PQI)** as a measure of the effectiveness of the patch.

  $$PQI = \frac{\#\ Constraints_{Similar}}{\#\ Constraints_{Developer}} * \frac{\#\ LOC_{Developer}}{\#\ LOC_{\textsc{Clotho}}} * \frac{Output_{\textsc{Clotho}}}{Output_{Developer}}$$

  Specifically, PQI compares the similarities in constraints and source line of code in Clotho's patch against the developer's version, as well as the actual output generated from both the patches, thereby considering both the logic and the technique to construct an effective patch. A higher value of PQI is preferred. Thus, if Clotho's patch has fewer constraints, or has more lines of code, or has fewer similarities in the output, the PQI will be lesser.

  Determining PQI is a three step process. First, we visually compared Clotho's patch with the developer's version and count the exact similar constraints observed in both patches to determine the closeness in terms of the set of constraints. Second, we disassembled the developer's patch and compared the count of bytecodes generated using Clotho's patch. Third, we observed the actual output of using the Clotho patched class files against the developer provided patch in a later version of the same library. In case the output is primitive or strings, an exact match is considered successful, else we iterate over the properties of the complex object to determine number of exact matches in the two outputs. In case of exception(s), we select the similarity ratio to be 0.5.

  Table 7.1 lists 30 real-world bugs mined from bug repositories of popular open-source libraries. We wrote a driver program to recreate the bug, and then applied Clotho to patch it. We observed that in all cases, Clotho successfully patched the offending class file in the concerned library.

  - We observed that PQI for CLOTHO generated patches was high for most of the bugs, which indicates the effectiveness of the patches. Specifically, for 23 out of 30, i.e., for more than 75% cases, PQI for CLOTHO-generated patches was within 7% of the developer's fix. Note that there was one instance where the concerned bug [19] was still unpatched. In such cases, we looked for the potential or suggested patches in comments and discussion forums, and compared CLOTHO's patch with them.

  - We observed that PQI for bug in Hama 0.2.0 [18] was as high as 1.38. We visually inspected both the CLOTHO-generated patch and the developer's fix and observed that CLOTHO's patch was considerably smaller. Further, we noticed that the developer's patch had i) multiple assertion blocks to make sure the error condition can be avoided, and ii) several additional conditional checks to avoid corner cases. Moreover, the developer's patch also had a completely different implementation of the method on which the bug was reported. Thus, the developer's fix was significantly larger than CLOTHO's patch.

  - We noticed low PQI (between 0.5 and 0.79) for four of the patched libraries, which shows that the quality of the CLOTHO-generated patch was significantly lower than the developer's fix. A major reason for this drop in PQI is the presence of cascaded exceptions observed in the patched versions of these libraries upon execution. We note that CLOTHO in its present shape does not guarantee that the patch will never raise cascaded exceptions. Thus, in these four cases CLOTHO's patches were of lower quality then the original ones. However, we also note that all the cascaded exceptions were in fact checked exceptions, and it is expected that the application developers would handle them appropriately.

  - Note that taint analysis only works when sources and sinks are defined. Since our library benchmarks have no notion of sources or sinks, CLOTHO's bytecode analysis of the libraries did not involve the taint analysis phase. However, even without taint analysis, CLOTHO's patches were of high quality, as demonstrated by the high PQI.

- **Precision of taint analysis**: CLOTHO leverages off-the-shelf tools (INFOFLOW) to perform the taint analysis. We measure precision of our choice of tool by measuring the number of statements in the analyzed code that are deemed unsafe to patch. Since we could not measure the precision of our taint analysis on the library benchmarks (as discussed earlier), we select 3 diverse applications and apply Clotho in its entirety to obtain a measure of the precision of the taint analysis. Specifically, for each application we provided a set of sources, sinks and taint propagators to InfoFlow, which listed the total number of tainted paths, i.e., paths from a sensitive source to a sink and thus must not be patched. Table 7.3 lists the results. We observe that the total number of tainted paths is less than 12% across the applications.

Threats to validity. Note that Clotho is dependent on InfoFlow for achieving precision about the points of instrumentation. However, InfoFlow currently has a major limitation—it does not support taint analysis for multi-threaded programs. Moreover, since it is still under active development, we observed that when applied to certain applications, InfoFlow consumed inordinate amounts of memory and crashed. Thus, Clotho's precision is limited by the accuracy of its dependencies.

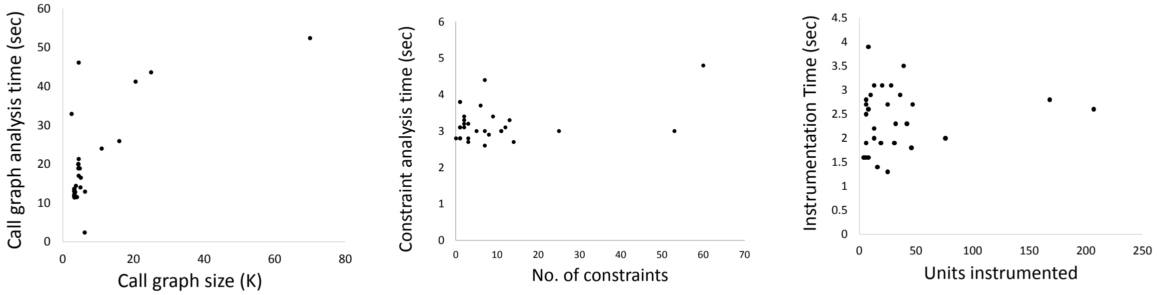
- **Already handled exceptions**: Clotho analyzes the call graph to determine if a potential runtime exception throwing statement is handled higher up in the call chain or in the same method. In such cases Clotho must abort the patching effort considering that the exception is caught with exact exception type or its base type. This is required else patching will disrupt the normal control flow of the program.

  We measure the extent of this optimization, which prevents disruption of the control flow using the **Flow Consistency Index (FCI)** that is calculated as

  $$FCI = n$$

  , where n is the number of exceptions in the application that must be ignored Clotho for forced patching of the bug. Note that $FCI \geq 0$, and a lower value of FCI is desirable. We observe that patching four bugs required Clotho to ignore at most one exception; rest required no changes.

- **Cascaded exceptions**: A cascaded exception arises if the Clotho-generated patch creates objects that when used as inputs to other Java APIs result in further exceptions.



(a) Variation in call graph analysis time with size of call graph.

(b) Variation in static constraint analysis time with number of constraints.

(c) Variation in instrumentation time with `Units` to be instrumented.

Figure 7.1: Clotho evaluation.

Clotho is prone to cascading exceptions because of the limitation of its intra-procedural analysis and a simple constraint evaluation mechanism. However, Clotho's constraint solver is pluggable and a more sophisticated third party solvers can easily be integrated. Specifically, cascaded exceptions may arise if the patch generates `String` objects that represent a malformed string. Further, if we keep the optimization in § 6.5.2, then cascaded failures may occur even for subsequent `String` APIs handling the malformed string following the point of patching. If the optimization is turned off, Clotho will automatically patch all relevant `String` APIs and thus handle all cascaded failures involving malformed `String` objects.

We observe that two benchmarks throw cascaded exceptions even after being repaired. The cascading was one level deep and triggered exception in another non-String code (and thus unpatched), which caused the application to crash.

Detailed evaluation for each of the bugs in our data set is available at `http://goo.gl/d1zcXD`.

7.2 Overhead

We measure the overhead of Clotho across different metrics identified below.

- **Execution overhead**: We randomly selected and patched 5 libraries (Apache Tapestry, Apache Wicket, Eclipse AspectJ Weaver, Hive and Nutch) from Table 7.1 to determine the execution overhead of the patched class files. We observed that CLOTHO reports an average overhead of $\sim$2.32μs per call across the 5 benchmarks for $50K$ runs of the patched functionality in both the developer's version and CLOTHO's patched library. The maximum absolute overhead was observed for Hive at $\sim$3.96μs per call. The above overhead is imperceptible at human response time scales.

- **Call graph**: The size of the call graph directly governs the time and memory consumption for CLOTHO. Figure 7.1a shows the results for the benchmarks analyzed from our data set. The overall analysis time was under a minute for all the benchmarks. We observed that even for a call graph of $\sim 70K$ nodes (for `Wicket`), CLOTHO required just 52.4s and 210MB memory.

- **Constraint set**: CLOTHO performs an exhaustive multi-pass analysis to gather and evaluate the set of constraints for generating patches. A higher number of constraints and their complexity increases the duration of CLOTHO's analysis. Figure 7.1b compares the time required for static constraint collection and evaluation with an increasing number of constraints for the benchmarks used in our data set. We observe that across all the benchmarks used, CLOTHO required at most $\sim$5s for collecting and evaluating the constraints.

- **Instrumentation overhead**: CLOTHO performs bytecode instrumentation for actual patching. Figure 7.1c shows the variation in instrumentation time with increasing number of `Units` to be patched. We observe that even without optimization discussed in § 6.5, CLOTHO takes under 4s to instrument all `Units` across all benchmarks. We believe that this time would be even less with the optimizations enabled, which significantly decrease the number of `Units` to be instrumented, and is evident in Table 7.1 where column $\mathcal{IC}_{WO}$ is much less than $\mathcal{IC}_{NO}$.

7.3 Case studies

We now report on experiences gained when using Clotho to patch several of the bugs reported in Table 7.1.

- The bug [1] as reported in the repository for Apache Aries cited String related issues. However, our investigation showed that the bug was actually in the ASM framework that was invoked by Aries, and not in the was actually not in the Aries framework as originally reported. Thus, we patched the particular ASM methods containing the bugs, and retested it with the Aries framework to ensure conformance.

- The bug in Commons Math [29] had a bug related to incorrect formatting of the input string. However, it threw a completely irrelevant exception (`IndexOutOfBound`) instead of the `NumberFormatException`, which contains the information of the malformed string. The Clotho-generated patch fixes the undesirable behavior.

- The bug in OfBiz [33] throws a custom shutdown exception, when in fact it should throw a `StringIndexOutOfBoundsException` due to a `substring` invocation with incorrect bounds. This ultimately causes the library to throw some high priority exception and ultimately crash if not handed properly by the application. The patched version of the library catches the correct exception.

- The code to trigger bugs in some libraries, including Apache Commons Compress, Commons Lang, Commons Math and Ofbiz, each had string operations wrapped in `try-catch` block that were handled by `Exception` class, i.e., the base type of all exceptions. However, Clotho checks for already handled runtime exceptions during its call graph analysis, and thus did not patch the bugs. We turned off the call graph analysis module to force Clotho to generate the relevant patch for the bug.

- We also noticed several instances where the developer code does not follow proper programming practices regarding exception handling. For example, the SOAP bug [39] was reported for a faulty `substring` call that threw a `StringIndexOutOfBoundsException`.

The entire method was wrapped in a `try-catch` that included the faulty substring call along with other servlet operations. However, the `catch` block handled the generic `Exception`, which is the base class of all exceptions. Thus, both servlet exceptions or `IndexOutOfBoundException` from the `substring` call were handled in a generic fashion. CLOTHO's patched library ensures that exceptions originating from the `substring` call are handled properly.

API	Bug Ref	Priority	$\mathcal{N}_{CG}$	$\mathcal{N}_{Unit}$	PQI	FCI	$\mathcal{IC}_{NO}$	$\mathcal{IC}_{WO}$	$\mathcal{RS}_{CE}$
`Aries`	[1]	Major	$3.5K$	129	1.02	0	42	5	✓
`Commons CLI1.x`	[4]	Critical	$3.2K$	53	0.79	0	19	19	✓
`Commons CLI2.x`	[3]	Major	$3.2K$	21	0.50	1	13	2	×
`Commons Compress`	[5]	Blocker	$4.0K$	134	0.99	0	46	4	✓
`Commons IO`	[23]	Major	$3.3K$	125	1.01	0	76	1	✓
`Commons Lang`	[26]	Major	$5.1K$	240	0.98	0	168	8	✓
`Commons Math`	[29]	Major	$3.4K$	300	1.00	1	36	2	✓
`Commons Net`	[31]	Major	$3.3K$	14	1.07	0	6	1	✓
`Commons VFS`	[45]	Major	$4.5K$	37	1.00	0	20	2	✓
`Derby`	[11]	Major	$4.4K$	40	0.96	0	47	6	✓
`Eclipse AJ Weaver`	[13]	Major	$20.6K$	50	0.52	0	4	1	×
`Eclipse AJ`	[12]	Major	$25.0K$	39	1.03	0	6	1	✓
`FlexDK 3.4`	[37]	Minor	$6.3K$	600	0.96	0	207	25	✓
`Hama 0.2.0`	[18]	Critical	$3.7K$	35	1.38	0	28	5	✓
`HBase 0.92.0`	[19]	Critical	$4.8K$	61	1.01	0	13	2	✓
`Hive`	[20]	Trivial	$4.4K$	23	1.01	0	8	1	✓
`HttpClient`	[21]	Major	$3.3K$	14	1.13	0	6	1	✓
`jUDDI`	[24]	Major	$3.2K$	70	1.13	0	10	2	✓
`Log4j`	[27]	Major	$3.2K$	17	0.97	0	6	1	✓
`MyFaces Core`	[30]	Major	$4.5K$	50	1.00	0	4	2	✓
`Nutch`	[32]	Major	$4.5K$	90	0.98	0	8	1	✓
`Ofbiz`	[33]	Minor	$4.4K$	28	1.01	1	6	1	✓
`PDFBox`	[34]	Major	$4.4K$	23	1.14	0	8	1	✓
`Sling Eclipse IDE`	[38]	Major	$4.5K$	58	1.00	0	39	6	✓
`SOAP`	[39]	Major	$5.0K$	165	0.97	1	32	5	✓
`SOLR 1.2`	[40]	Major	$11.0K$	200	0.98	0	25	4	✓
`Struts2`	[50]	Major	$16.0K$	80	1.03	0	25	2	✓
`Tapestry 5`	[44]	Major	$6.2K$	71	0.98	0	31	5	✓
`Wicket`	[48]	Major	$70.0K$	68	0.96	0	16	1	✓
`XalanJ2`	[51]	Major	$3.3K$	33	1.03	0	13	2	✓

$\mathcal{N}_{CG}$	# nodes in call graph	PQI	Patch Quality Index
$\mathcal{IC}_{NO}$	Instrumentation w/o optimization (recall § 6.5)	$\mathcal{N}_{Unit}$	# `Units` analyzed
FCI	Flow Consistency Index	$\mathcal{IC}_{WO}$	Instrumentation w/ optimization (recall § 6.5)
$\mathcal{RS}_{CE}$	Cascaded exception exists		

Table 7.1: CLOTHO's accuracy results when applied to 30 bugs in popular open-source libraries.

API	$\mathcal{PF}_{CA}$	$\mathcal{PF}_{TA}$	$\mathcal{PF}_{CG}$	$\mathcal{PF}_{IN}$
Aries	3.1/10	0.6/31	12.8/146	2.3/142
Commons CLI1.x	2.8/5	0.5/30	11.6/149	1.9/133
Commons CLI2.x	2.8/5	0.6/32	12/212	2/131
Commons Compress	2.7/5	0.5/30	11.5/209	1.8/130
Commons IO	3/11	0.5/33	12/209	2/141
Commons Lang	3/19	0.57/30	16.5/209	2.8/158
Commons Math	3/20	0.5/30	11.9/209	2.9/152
Commons Net	2.8/6	0.5/33	11.4/212	1.9/132
Commons VFS	3.7/13	1.4/7	46.1/151	3.1/143
Derby	3.3/15	0.5/31	19.9/208	2.7/146
Eclipse AJ Weaver	3.1/18	0.6/34	41.2/212	1.6/142
Eclipse AJ	3.8/24	0.5/34	43.6/214	1.6/156
FlexDK 3.4	4.8/40	0.4/31	12.9/209	2.6/189
Hama 0.2.0	2.6/5	0.5/33	14.4/210	3.1/134
HBase 0.92.0	3.2/15	1.4/11	18.9/212	3.1/144
Hive	3.4/12	1.5/11	20/121	1.6/143
HttpClient	2.8/6	0.5/33	12.3/212	2.7/131
jUDDI	3.1/11	0.5/34	13.6/209	2.9/138
Log4j	2.8/4	0.5/32	13/212	2.5/131
MyFaces Core	3.8/4	0.5/30	17/218	1.6/130
Nutch	3.2/15	1.2/30	32.9/215	3.9/147
Ofbiz	3.1/15	1.3/14	18.9/215	2.8/149
PDFBox	3.3/12	1.5/1	20/212	2.6/143
Sling Eclipse IDE	3/14	0.5/34	21.3/208	3.5/147
SOAP	3.4/19	0.6/30	14/209	2.3/148
SOLR 1.2	4.4/21	0.6/32	24/219	2.7/139
Struts2	3/14	0.5/32	25.9/210	1.3/140
Tapestry 5	2.9/10	0.5/34	2.4/211	1.9/136
Wicket	3/14	0.5/32	52.4/210	1.4/142
XalanJ2	2.7/8	0.5/33	13.5/213	2.2/131

$\mathcal{PF}_{CA}$	Profiling for constraint analysis phase	$\mathcal{PF}_{TA}$	Profiling for taint analysis phase
$\mathcal{PF}_{CG}$	Profiling for call graph phase	$\mathcal{PF}_{IN}$	Profiling for instrumentation phase

Table 7.2: Clotho's profiling results for time and memory footprint

Application	KLOC	Total paths	Tainted paths
Checkstyle	58.0K	1977	88
Jazzy Core	4.9K	270	26
JEdit	4.3K	185	22

Table 7.3: Precision results for taint analysis.

Chapter 8

Conclusion and Future Work

Running programs may crash unexpectedly due to vulnerabilities in the code and malformed data. The cost associated with such crashes can be vary with the criticality of the applications. Therefore, it is hardly a surprise that automatic program repairing has been an actively researched area over the past decade. In this work, we have presented a novel program repairing technique, and a tool Clotho based on it which employs hybrid program analysis to protect a running program from failures originating from string-handling errors leading to a program crash. Our choice of Java `String` APIs is driven mainly by the popular usage of string objects and bugs associated with them. By focusing on a specific data type, and taking the program context into account, Clotho can develop patches that are precise and semantically close to the ones developed by the developers. Hence, when the patches are activated, the program exhibits a behavior which is close to the intended program behaviour. Our study shows that Clotho can handle programs that are real, and can produce patches efficiently. Motivated by the results of our study as well as by the research conducted by other researchers, we intend to extend Clotho in the future by adding support for other Java APIs and also by adding more intelligence to the process of patch generation.

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