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2010

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Contract-based Data Structure Repair Using Alloy

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ENGINEERING

THE UNIVERSITY OF TEXAS AT AUSTIN

May 2010

To my parents, Fatemeh and Davoud, and to my husband, Mahdi,
for their infinite love and support.

Acknowledgments

This material is based upon work partially supported by the NSF under Grant Nos. IIS-0438967, and CCF-0845628, and AFOSR grant FA9550-09-1-0351.

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Contracts and specifications have long been used in object-oriented design, programming and testing to enhance reliability before software deployment. However, the use of specifications in deployed software is commonly limited to runtime checking where assertions form a basis for detecting incorrect program states to terminate the erroneous executions. We present a contract-based approach for data structure repair, which repairs erroneous states in deployed software. The key novelty is the support for rich behavioral specifications, such as those that relate pre-states with post-states of a method to accurately specify expected behavior and precise repair. The approach is based on the view of a specification as a non-deterministic implementation. The key insight is to use any correct state mutations by an otherwise erroneous execution to prune non-determinism in the specification, thereby transmuting the specification to an implementation that does not incur a prohibitively high performance penalty. While invariants, pre-conditions

and post-conditions could be provided in different modeling languages, we leverage the Alloy tool-set, specifically the Alloy language and the Alloy Analyzer for systematically repairing erroneous states. Four different algorithms are presented and implemented in our data structure repair framework. These algorithms can repair a medium sized erroneous data structure in a few seconds. We introduce repair guide annotations defined by the user to improve the accuracy and performance of the repair mechanism. Experiments using complex specifications show the approach holds much promise in increasing software reliability.

Table of Contents

Acknowledgments	v
Abstract	vi
List of Tables	ix
List of Figures	x
Chapter 1. Introduction	1
1.1 Contributions	5
Chapter 2. Example	7
Chapter 3. Background	12
Chapter 4. Tarmeem	16
4.1 Definition of repair	16
4.2 Overview	17
4.3 Algorithms	19
4.4 Instrumentation	32
Chapter 5. Evaluation	36
5.1 Singly Linked List	36
5.2 ANTLR BaseTree	41
Chapter 6. Conclusions and Future Work	45
Bibliography	48
Vita	54

List of Tables

4.1	Comparison of different repair Algorithms.	32
5.1	Faults injected into the programs. Faults 1-7 apply to <code>remove</code> method of singly-linked list, and Faults 8-9 apply to <code>deleteChild</code> method of class <code>BaseTree</code> of ANTLR.	37
5.2	Result of applying Tarmeem on different erroneous singly linked lists of size 10 and 20, and on corrupt <code>BaseTree</code> class of ANTLR package, maximum repair time allowed: 120 seconds.	38

List of Figures

2.1	Singly-linked list in Java.	8
2.2	An erroneous <code>remove</code> method for singly-linked list in Java. . .	9
2.3	Class invariant for <code>LinkedList</code> and post-condition for <code>remove</code> in Alloy.	10
2.4	Linked list example.	11
2.5	Relational representation of the linked list example.	11
4.1	Tarmeem architecture.	18
4.2	Approach 1: the Basic method.	21
4.3	(a) The erroneous output of <code>remove(5)</code> (b) The result of repairing the sample faulty output using Basic approach.	22
4.4	Approach 2: Iterative Relaxation.	23
4.5	(a) The erroneous output of <code>remove(5)</code> (b) The result of repairing the sample faulty output using Iterative Relaxation, Error Localization and Guided Error Localization.	24
4.6	Approaches 3 and 4: Error Localization.	26
4.7	Approaches 3 and 4: helper methods.	27
4.8	(a) Circular linked list: a hypothetical erroneous output of <code>remove(5)</code> (b) The result of repairing the faulty output using Guided Error Localization.	31
4.9	Linked List example pre- and post-state snapshots.	35
5.1	Class invariant for ANTLR <code>BaseTree</code> and post-condition for <code>delete</code> in Alloy.	42
5.2	Input grammar for ANTLR.	43
5.3	<code>deleteChild</code> method of class <code>BaseTree</code>	43

Chapter 1

Introduction

As software has become increasingly integrated with critical systems of high complexity, software failures have become prohibitively expensive and alarmingly frequent. There is now an urgent need for creating new methodologies that deliver reliable software at a lower cost. Much of the existing research effort is devoted to requirements, architecture, design, implementation and testing—activities that are performed before deployment of a software system. In contrast, little effort is devoted to developing methodologies that handle errors that arise during system executions after deployment. While requirements, architecture, design, implementation and testing are fundamental to develop correct programs, unfortunately not all faults are detected or fixed before deployment. The ability to handle runtime errors *on-the-fly* can bring a substantial increase in reliability.

The standard approach when an erroneous program state is detected at runtime, say due to an assertion violation, is to terminate the program, debug it if possible, and re-execute it. While this *halt-on-error* approach is useful to eliminate transient errors or for debugging purposes, it does not present a feasible solution for deployed software that is faulty and cannot be

promptly debugged or re-deployed. A program that is functionally incorrect will continue to exhibit its failure(s) no matter how many times it is re-executed or on how many different machines it is executed. In such a situation, *error recovery*, and in particular repair of erroneous program state is necessary. In addition, errors in persistent data, such as a file system, also necessitate repair mechanisms [2,3].

While repair mechanisms are not in standard use today, repair has featured in various systems over the last couple of decades [2,3,13,27]. However, a limitation of the traditional approaches is to use dedicated repair routines, which must be implemented for each system they are intended to work for. As a result, these routines are mostly ad-hoc and ill-understood.

Recent work introduced constraint-based repair, where data structure constraints are written using first-order logic [9,10] or as Java assertions [11,12,18] and are used as a basis for repairing erroneous states. While these approaches do not necessitate writing a dedicated repair routine, they have a basic limitation: data structure constraints are too weak for general error recovery. To illustrate, in object-oriented programs, the *class invariant* [23] (which defines the data structure constraints for the valid objects of the class) applies to the entry and exit points of all public methods—even though the precise behaviors of the methods may be very different. For example, consider an erroneous implementation of a method to insert an element into a *binary tree*—an acyclic data structure. Previous approaches [10,18] to constraint-based repair would accept an empty tree as a valid structure since it satisfies

the acyclicity constraint. However, an empty tree is unlikely to be a valid output of insert.

Constraint-based repair suffers from several limitations. First, all methods are restricted to use the same class invariants and hence the repair mechanism cannot reflect any specific property of the method. In inserting an element to the binary tree example mentioned earlier, the repair framework cannot detect or recover from states that the method fails to add the new element despite providing a valid binary tree as output. Second, the repair mechanism accepts any correct data structure (including the valid input data structure) as output of any method. Therefore, an empty method satisfies all needed properties according to repair mechanism.

Method contracts [26] naturally suit the repair process since they introduce class invariants, pre- and post-conditions and are widely used for other phases of software development. However, while they have long been used to improve software reliability in different phases of software development life-cycle (from accurately specifying requirements to design, implementation and testing), their common usage follows the same standard *halt-on-error* approach upon detecting an erroneous program state in a deployed software.

We present *Tarmeem*, a novel framework for contract-based data structure repair, which addresses the basic limitations of previous approaches to repair and is based on a novel role for rich behavioral specifications [21]: to repair erroneous executions. We use runtime specification violation as a basis of repairing the program state. Our insight is to transmute the contract

specification—which permits a high degree of non-determinism—into an efficient implementation using the erroneous state. Any correct component of the erroneous state restricts the non-determinism in the specification and enables an efficient generation of a correct program state. While we support several specification languages, such as the Java Modeling Language [22], we translate the specifications to Alloy [15], transform the repair problem into a constraint solving problem and leverage the Alloy tool-set to provide systematic repair.

Tarmeem supports Alloy as the base modeling language. Alloy is a set-based specification language for describing structural properties. Alloy has a rich library and it is simple to define a large class of constraints in it, including set constraints, sequencing constraints, etc. Java Modeling Language (JML) is a behavioral interface specification language for Java modules. Support for JML through translation is made possible by the JForge [32] framework, which uses the Alloy back-end for scope-bounded checking of Java programs. Other languages similar to JML (such as Spec# [5]) can be supported through translation as well.

Rich behavioral specifications accurately describe expected behavior and enable precise repair. Furthermore, it opens up a novel application of contracts in recovering programs from erroneous executions. We note that the use of contracts does not necessarily allow recovering from hardware errors, rather our focus is to recover from errors due to residual bugs or external events that mutate program state but not the execution environment or the contracts.

While pre- and post-conditions have been used in repairing relational data and recovering from erroneous executions in databases [20,31], our work is distinguished in two aspects. Most importantly, previous work does not perform repair based on pre- and post-conditions but only aborts the transaction when expected relationship between pre- and post-states is not met. Secondly, our repair mechanism works on sophisticated pointer-based data structures which differs fundamentally from database schemas.

1.1 Contributions

We introduced the idea of contract-based repair in a one page extended abstract [34]. Our ECOOP2010 paper describes our approach in detail. We make the following contributions [33,34]:

- **Contract-based data structure repair:** We introduce the idea of using rich behavioral contract specifications, including invariants, pre- and post-conditions, as the basis of systematic data structure repair.
- **Repair algorithms:** We present four algorithms that embody the idea. The algorithms leverage the Alloy tool-set to provide systematic repair, and employ heuristics to optimize performance.
- **Similarity metric:** Our approach uses a distance metric for graph similarity to compute the effect of repair on an erroneous program state and to evaluate different algorithms for effectiveness.

- **Evaluation:** We present experimental results to evaluate the feasibility of contract-based repair and demonstrate the promise it holds. We evaluate Tarmeem using a text-book data structure and an open-source application. Our framework can repair erroneous data structures with tens of nodes in seconds.

The rest of this document is organized as follows: Chapter 2 describes an example which we use for further illustration. Chapter 3 provides needed background on the Alloy tool-set. Chapter 4 explains Tarmeem, Chapter 5 presents our experimental results and Chapter 6 concludes.

Chapter 2

Example

To illustrate contract-based repair, consider a singly-linked list data structure (Figures 2.1 and 2.2). As Figure 2.1 shows, each list object has a **header** node and a **size** field that caches the number of nodes in the list. Each node has a **next** node and contains an integer element (**elt**). The method contract provided in JML shows that the **repOk** method (Figure 2.1) is the class invariant. The method **remove** (Figure 2.2) removes all occurrences of the given integer (**x**) from the given list (**this**). This method requires the class invariant to hold at the invocation of the method and should guarantee the class invariant as well as the post-condition after execution.

The user provides the contract including the class invariant for **LinkedList** and the post-condition for **remove** in Alloy (Figure 2.3) or any other specification language that can be automatically translated to Alloy such as JML (Figures 2.1 and 2.2). This flexibility in terms of input specification language enhances the usability of Tarmeem. However the specification which is used as a basis for repairing erroneous outputs is eventually translated to Alloy. Chapter 3 provides a brief survey of Alloy syntax and semantics. In this example, the class invariant requires that the list should be acyclic, contain unique inte-

```

class LinkedList{
    Node header;
    int size; // number of nodes in this

    static class Node{
        Node next;
        int elt;}

    //@ invariant repOk();
    boolean repOk(){
        if(header == null) return (size == 0);
        Set<Node> visited = new java.util.HashSet<Node>();
        visited.add(header);
        Node current = header;
        while(true){
            Node next = current.next;
            if(next == null) break;
            for(Node seen : visited) // unique elements
                if(seen.elt == next.elt)
                    return false;
            if(!visited.add(next)) // acyclicity
                return false;
            current = next;
        }
        if(visited.size() != size) // size OK
            return false;
        return true;}

    ...
}

```

Figure 2.1: Singly-linked list in Java.

```

class LinkedList{
...
    boolean removePostCondition(int x){
        // ensures that remove is performed correctly
    }

    //@ requires repOk();
    //@ ensures repOk();
    //@ ensures removePostCondition(x);
    void remove(int x){ // erroneous implementation
        // removes all nodes that have element x
        if(header == null) return;
        Node pointer = header.next;
        Node prevPointer = header;
        while(pointer != null){
            if(pointer.elc == x){
                prevPointer.next = pointer.next;
                pointer = pointer.next;
                size--;
            }
            else{
                prevPointer = prevPointer.next;
                pointer = pointer.next;
            }
        }
        if(header.elc == x){
            // the next line should be un-commented
            // header = header.next;
            // the next line is incorrect; it should be "size--;"
            size++;
        }
    }
}

```

Figure 2.2: An erroneous `remove` method for singly-linked list in Java.

ger elements, and have correct size. The post-condition additionally requires that the output should not include the element to remove. Back-tick (‘’) in the Alloy model is syntactic sugar to represent post-state [17,25]. Equivalently absence of back-tick is the same as `\old` in JML. Note how the post-condition relates the set of list elements in the post-state with those in the pre-state to precisely specify correctness of `remove`.

To illustrate Tarmeem, consider invoking `remove` on the valid input

```

sig LinkedList{
  header: lone Node,
  header': lone Node,
  size: Int,
  size': Int}
sig Node{
  next: lone Node,
  elt: lone Int,
  next': lone Node,
  elt': lone Int}
pred repOk(l: LinkedList){ // class invariant of LinkedList
  // acyclicity
  all n: l.header.*next | n !in n.^next
  // size OK
  # l.header.*next = int l.size
  // unique elements
  all n, m: l.header.*next | int m.elt = int n.elt => n = m}
pred remove_postcondition(This: LinkedList, x: Int){
  repOk[This]
  This.header.*next.elt - x = This.header'.*next'.elt'}

```

Figure 2.3: Class invariant for `LinkedList` and post-condition for `remove` in Alloy.

list `L0` in Figure 2.4 (a) to remove all nodes with element 5. Figure 2.4 (b) shows the method’s erroneous output list, which has an erroneous size and still includes the element 5. Tarmeem correctly repairs this erroneous output to a correct output (Figure 2.4 (c)). Note that Tarmeem corrected both the erroneous data field as well as the erroneous reference fields.

To contrast with the previous work [10, 18], if we only use the class invariant (`repOk`) as a basis of repair, the erroneous output list (Figure 2.4 (b)) would only undergo one *repair action*, which is to fix its `size` to 3. However, the element 5 would erroneously continue to be in the list, and not be deleted.

Figure 2.4: Linked list example.

Figure 2.5: Relational representation of the linked list example.

Chapter 3

Background

Alloy is a minimal yet powerful specification language for describing structural properties. Alloy uses a set-based syntax which is compatible with an object-oriented model. Alloy Analyzer is a fully automatic analyzer to systematically check Alloy models for a finite scope and is based on a SAT-based model finder called Kodkod [30]. In this chapter, we use the linked list example of Figure 2.3 to describe Alloy syntax and semantics. More details may be found elsewhere [1, 14].

The model is divided into signatures indicated by keyword **sig**. `LinkedList` is a signature in this example whose body includes `header`, `header'`, `size` and `size'`. From object-oriented perspectives, these could be considered fields of data type `LinkedList` with their types following the colon (`:`) symbol. For example, `header` is of type `Node` defined later. Since Alloy is a declarative rather than an imperative language, the order of elements is irrelevant. Keyword `1one` can be read as less than or equal to one, which means that a `LinkedList` is permitted to have no `header`.

From Alloy's set-based perspective which views the world as a collection of atomic objects (atoms) and relations between them, each of `header`, `header'`,

`size` and `size'` is a relation from signature `LinkedList` to the signature type following the colon symbol. Figure 2.5 shows realizations of these relations. Consequently, `lone` and similar keywords have a set-based meaning (e.g. `lone` indicates that the relation is a partial function).

A fact (`fact`) in the Alloy model puts some always true explicit constraints on the model. Functions (`func`) and predicates (`pred`) are other forms of constraints to be applied on the model which are invoked if needed. Here, predicate `repOk` has input parameter `l` of type `LinkedList` surrounded by parenthesis. Note that at the invocation site, brackets are used to pass the arguments. Predicate `repOk` is composed of the conjunction of several constraints. For example, the first constraint enforces acyclicity on the list. The dot (`.`) operator is relational composition, which accesses fields of a signature, where `*` and `^` are reflexive and non-reflexive transitive closures respectively. `l.header.*next` builds the set of all nodes that can be reached by applying zero or more `next` relations on `l.header` which are exactly all nodes of the list. The universal quantifier `all` on the right-hand side of this constraint indicates that the constraint applies to all of the atoms in the set. The left-hand side specifies that no node `n` in the list can reach itself by applying one or more `next` operations, i.e. the list is acyclic.

Further constraints of this example introduce other features of Alloy. Alloy supports basic set operations. The operators `in`, `#` and `-` are set membership, cardinality and complement operations respectively. Alloy also has different types of logical binary operators. As an example, `=>` in uniqueness

constraint stands for implication. Notice that `=` in Alloy stands for equality and not assignment. As we mentioned before, back-tick is the syntactic sugar we add to Alloy to distinguish between pre- and post-states and is not inherent to the language.

Kodkod is the SAT-based back-end of the Alloy Analyzer. It is a constraint solver which works in first order logic with relations, transitive closure, and partial models. Kodkod is able to efficiently find finite models for satisfiable problems and a minimal unsatisfiable core for unsatisfiable ones. It also provides an API to directly build Alloy formulas. To model a problem in Kodkod, a relation should be *bounded* by two sets of tuples: a lower bound and an upper bound. The former represents all tuples that the final solution for the relation *should* contain and the latter is the set of all tuples that it *may* contain. If a relation is bounded exactly to a set (equivalently its lower bound is the same as its upper bound), that set is the unique answer for the relation.

To illustrate how Kodkod works, consider Figure 2.5 (b) which shows the relational representation of Figure 2.4 (b). Assume that we are trying to repair this data structure to meet the constraints of Figure 2.3. For the sake of simplicity, assume that we do not care about `remove_postcondition` and our goal is to transform the faulty linked list to a correct one irrespective of being the output of `remove` method. If we fix the lower and upper bounds of the relations to tuples shown in Figure 2.5 (b) and call Kodkod to find a satisfiable solution for given constraints, Kodkod will have only one candidate which is the same as the faulty output and does not meet the constraints. However,

if we set the lower bound of the `size` relation to the empty set and make its upper bound equal to the set of all possible tuples that show the size of a linked list (i.e. $\{\dots, (L0, -2), (L0, -1), (L0, 0), (L0, 1), (L0, 2), \dots\}$), Kodkod will provide the correct set which is $\{(L0, 2)\}$ as answer. Note that this example was used to illustrate the concept of lower and upper bounds in Kodkod and does not contain the most important contribution of this work which is satisfying the relationship between pre- and post-states of a method.

Chapter 4

Tarmeem

This chapter first defines the repair problem (Section 4.1) and then presents an overview of our framework (Section 4.2) and our core repair algorithms (Section 4.3). It finishes by describing more underlying details of the framework and demonstrating preparation steps that instrument the program to use data structure repair (Section 4.4).

4.1 Definition of repair

We address the following repair problem:

Definition: Let ϕ be a method post-condition that relates pre- and post-states such that $\phi(r, t)$ if and only if pre-state r and post-state t satisfy the post-condition. Given a valid pre-state u , and an invalid post-state s (i.e., $\neg\phi(u, s)$), mutate s into state s' such that $\phi(u, s')$.

The key technical difference in the repair problem as defined here with previous work [10,18] is to allow specifications across different program states, specifically to relate pre-states and post-states. Previous work only supported specifications on the current program state, e.g., class invariants. With this richer definition, we can also repair program functionality error such as incor-

rect implementation of a method by fixing the output during program execution.

4.2 Overview

Tarmeem, our contract-based data structure repair framework, detects and fixes erroneous method executions using method post-conditions. Upon detecting a violation, Tarmeem uses heuristics to determine which fields of the data structure are likely faulty. It iteratively *relaxes* bounds on possible values for those fields (i.e., allows them to take any legal value other than their current one), and invokes off-the-shelf SAT solvers to compute values that satisfy the post-condition. Furthermore, Tarmeem heuristically tries to keep the number of mutations applied on the faulty data structures as low as possible to avoid unnecessary perturbations during the repair process.

We take a relational view of the program heap [16], and view the data structures as edge-labeled graphs. This view enables using *edit distance* [8,29] as a metric for computing the perturbation of the erroneous program state, which undergoes repair. Our algorithms attempt to keep the perturbation to a minimum.

The state of the program is defined as an object graph of its data structures. As an example, we have previously shown the state of a program that only includes a linked list of nodes in Figure 2.4. By using such object graphs, we utilize the edit distance of the faulty and repaired outputs to evaluate effectiveness of repair algorithms. We heuristically try to minimize the

Figure 4.1: Tarmeem architecture.

edit distance between faulty and repaired outputs and measure the amount of perturbation using this metric.

Figure 4.1 shows the core architecture of Tarmeem. Given a Java method and its contract, plus an input and an output that represent an erroneous method execution, Tarmeem applies an abstraction translation [17, 25] to generate an abstract¹ pre-state and an abstract post-state, which are used together with a constraint that represents the post-condition to check if the post-condition holds. If the pre/post-states satisfy the post-condition, a concretization translation [17, 25] is used to generate a repaired output. Note

¹Here, abstraction is to translate the Java data structures to Alloy and concretization is to translate back to Java.

that the very first check of the method output to see if it is faulty does not need an invocation of the SAT solver. Furthermore, even though the translation of the method input and output to/from their corresponding abstraction in Alloy is done via instrumentation and is very fast, one can perform the first check solely as an assertion check to avoid the performance overhead of abstraction after each method call. If the pre/post-states do not satisfy the post-condition, Tarmeem invokes a repair algorithm (Section 4.3) to let some fields of the data structure be modified by the SAT solver (by relaxing the lower and upper bounds in the corresponding Kodkod model on the ranges of field values in the post-state) and uses SAT to compute values for those fields (while holding the pre-state values constant²). More details about the architecture of Tarmeem can be found in Section 4.4. The next section describes our repair algorithms.

4.3 Algorithms

We developed four different approaches to repair a faulty data structure.

1. *Basic Repair* is the direct application of SAT to generate a correct output for a method.
2. *Iterative Relaxation* leverages the fact that there is a relatively few number of errors in the data structure and tries to find a repair by iteratively

²Tarmeem follows the usual meaning of class invariants, and method pre/post-conditions: an incorrect method execution is defined as satisfaction of pre-condition and violation of post-condition.

relaxing the lower and upper bounds of the relations.

3. *Error Localization* concentrates on the specification to precisely locate the errors and fix them.
4. *Guided Error Localization* uses the same approach as Error Localization, but utilizes repair guides provided by the user.

This section describes our repair algorithms in details.

1. Basic Repair. This approach is a direct application of SAT to generate a post-state to satisfy the post-condition. This approach uses the pre-state but is oblivious of the erroneous post-state. Any possible correct output with respect to the contract is a candidate solution for this approach. Therefore, the repaired state may be quite different from the erroneous state. In fact, this algorithm only uses the contract and ignores the code that is already developed and extensively tested. To illustrate, consider the `remove` method (Chapter 2) that should remove all occurrences of the given element from the given list. According to the first approach, any linked list that only has all elements other than the element to delete is a valid answer. This approach does not need to maintain order of elements or other characteristics of the list, although the program whose output is faulty and subject to repair might be intended to maintain these characteristics.

Before describing the algorithm, here we define the state of being *relaxed* for a relation to ignore the current (possibly erroneous) value of that field

```

boolean repairAlgorithm(){
    for(Predicate p : allPredicates) p.ignored = false;
    for(Relation r : allRelations) r.relaxed = true;
    return SAT();
}

```

Figure 4.2: Approach 1: the Basic method.

(relation in set-based perspective of Alloy). Therefore, a relaxed field can take any value suggested by the SAT solver to meet the constraints. In addition, we define the property of being *ignored* for a predicate³. We manipulate this property of the predicates to ignore them in some phases of the algorithms. Essentially, we set a predicate to be ignored in case we do not want to include it in a SAT solver invocation.

Figure 4.2 describes an algorithm that implements this approach. It relaxes the bounds on all relations (in the post-state) as indicated by the assignment `r.relaxed = true`, and solves the problem subject to all the constraints as indicated by the assignment `p.ignored = false`. The method `SAT()` simply calls the SAT solver with these settings and returns true if the SAT solver can find a solution.

Figure 4.3(b) shows a result of running the first approach on the faulty output of our example shown in Figure 4.3(a). The result has changed the

³Remember that predicates are constraints on the correct output and their conjunction builds the post-condition and the invariant. Predicates used in the repair algorithms might have more granularity compared to Alloy predicates mentioned before, meaning that we might choose to pick each property of the correct output (such as acyclicity, size, etc.) as a single predicate in order to improve performance and accuracy of the repair process.

Figure 4.3: (a) The erroneous output of `remove(5)` (b) The result of repairing the sample faulty output using Basic approach.

order of elements and assignment of integers to the nodes. Also, as we will see in Chapter 5 this approach is quite inefficient. However, note that this is a correct repair, since the repaired linked list satisfies the method post-condition with respect to the contract. Indeed, a richer contract that requires the relative element ordering to be preserved would result in a more desirable repaired structure using this approach.

2. Iterative Relaxation. The second approach, called Iterative Relaxation, aims to optimize performance when the number of errors is relatively small. In this heuristic we try to make the output satisfy the conditions by relaxing as few relations as possible. To do so, we take an arbitrary relation, relax it and send the resulting problem to SAT. If the problem is unsatisfiable, we take another relation and repeat the same procedure. If we are not able to solve the problem by relaxing a single relation we try relaxing two relations and so forth. If the underlying repair problem is satisfiable, this approach will solve it, but may need a lengthy trial and error process. In addition, this heuristic will find a relatively similar answer to the faulty output since it prefers relaxing fewer relations.


```

boolean repairAlgorithm(){
    for(Predicate i : allPredicates) i.ignored = false;
    // how many to relax
    for(int count = 1; count <= numOfRelations; count++){
        Set<Relation> choose = pickRelations(count);
        while(choose != null){
            for(Relation i : allRelations){
                if(choose.contains(i)) i.relaxed = true;
                else i.relaxed = false;
            }
            if(SAT()) return true;
            choose = pickRelations(count);
        }
    }
    return false;
}

```

Figure 4.4: Approach 2: Iterative Relaxation.

The pseudo code of this heuristic is shown in Figure 4.4. Having all predicates in mind, we increase `count` starting from one. `pickRelations(count)` returns a new arbitrary set (of size `count`) of relations until all combinations are covered when it returns `null`. We fix all relations except those selected for relaxation to their post-state values. Each time we call `SAT()` to see if we have been able to resolve the problem. Upon failure, we examine other combinations of relations while trying to keep them few until we find an answer or confirm that there is no solution.

Back to removing an element from the linked list, we start by taking a relation, say `size` and let it be free to take any value assigned by the SAT solver. Then we invoke the SAT solver to see if it can find a suitable value for `size` in order to satisfy all conditions. Clearly, this trial fails since there is an error in the elements too. We attempt relaxing `header`, `next` and `elt`

Figure 4.5: (a) The erroneous output of `remove(5)` (b) The result of repairing the sample faulty output using Iterative Relaxation, Error Localization and Guided Error Localization.

separately, none of them ending in a solution. When up to relax two relations instead of one, we will finally try `size` and `header` together. The result of this repair action (applied on Figure 4.5(a)) is shown in Figure 4.5(b).

3. Error Localization. In the third approach, termed Error Localization, we use the post-condition to isolate erroneous parts of the output. The idea is to satisfy predicates of the post-condition one at a time⁴. For each violated predicate, we relax some of its relations until it is satisfied. Therefore, this algorithm heuristically avoids relaxing relations that do not appear in violated predicates.

At first, we ignore all post-condition predicates and find a solution that is compatible with the *definition* of data structure. Definition of a data structure is the set of its signatures and does not include class invariants or method post-conditions. (As an example of data structure definition, consider Figure 2.3 without `repOk` and `remove_postcondition`). Then, we evaluate pred-

⁴We assume that the post-condition is the conjunction of several predicates. (Examples of these predicates in Figure 2.3 are correctness of the size field and absence of the element subject to remove after calling `remove` method.)

icates one by one. (Note that to simply evaluate a predicate, no call to the SAT solver is necessary.) If the solution is already meeting the current predicate, we add this predicate to the set of already satisfied predicates and continue by considering others. Otherwise, we should call the SAT solver to find a satisfiable solution for the set of predicates seen so far, while possibly relaxing more relations.

More detailed description of Error Localization heuristic is as follows. Figure 4.6 called with `guided` set to false shows this heuristic. First, we ignore all predicates and let all relations be *not* relaxed. An ignored predicate would not participate in solving the problem as it does not exist for now. (These predicates will be added and satisfied eventually.) We call the SAT solver with these settings and expect to obtain a satisfiable answer unless there is a contradiction in the output even without applying any constraints. Having this satisfiable answer assists us in evaluating further constraints as we add them without going to the SAT solver level (by using `Evaluator` class at the Kodkod level).

While there is any ignored (i.e, not satisfied) predicate, we add predicates and try to fulfill them. Note that at the beginning of each iteration of the `while` loop, we check all predicates to find out if any of them are satisfiable on our current answer. If any is found, we add it to the set of satisfied predicates by setting `ignored` to false and updating relations seen. The sooner we add satisfied constraints, the easier it is for SAT to find the correct value.

At the next step, we choose an arbitrary predicate which is not satisfied

```

boolean repairAlgorithm(boolean guided){
    // guided is false if Unguided Error Localization
    // guided is true if Guided Error Localization
    for(Relation i : allRelations) i.relaxed = false;
    for(Predicate i : allPredicates) i.ignored = true;
    if(!SAT()) return false;
    while(!ignoredPreds().isEmpty()){
        for(Predicate p : ignoredPreds()){
            if(new Evaluator().evaluate(p)){
                p.ignored = false;
                updateRelationsSeen(p);}
        Predicate f = pickAPredicate(ignoredPreds());
        f.ignored = false;

        // trial 1: without relaxing any new relations
        if(SAT()) continue;

        LinkedList<Relation> candidateRels = candidateRels(f, guided);

        // trial 2: relaxing only one extra relation
        if(solvedByRelaxingOneRel(candidateRels)) continue;

        // trial 3: relaxing several extra relations
        if(solvedByRelaxingFewRels(candidateRels)) continue;

        // trial 4: systematically relaxing relations
        if(solvedBySysRelaxation()) continue;

        return false;}
    return true;}

```

Figure 4.6: Approaches 3 and 4: Error Localization.

yet and attempt to satisfy it by relaxing some extra relations. We watch the previous constraints so that we do not break them by sending all predicates added so far to the SAT solver.

Our trials to satisfy the current predicate proceed as follows:

1. Our first priority is to satisfy the predicate without relaxing any new

```

LinkedList<Relation> candidateRels(Predicate f, boolean guided){
    LinkedList<Relation> candidateRels = new LinkedList<Relation>();
    for(Relation r : allRelations)
        if(f.has(r) && !r.relaxed)
            if(!r.relationSeen){
                r.relationSeen = true;
                candidateRels.addFirst(r);
            }else candidateRels.addLast(r);
    if(guided) moveToFirst(guideSet(f), candidateRels);
    return candidateRels;}

boolean solvedByRelaxingOneRel(LinkedList<Relation> candidateRels){
    for(Relation i : candidateRels){
        i.relaxed = true;
        if(SAT()) return true;
        else i.relaxed = false;}
    return false;}

boolean solvedByRelaxingFewRels(LinkedList<Relation> candidateRels){
    for(Relation i : candidateRels){
        i.relaxed = true;
        if(SAT()) return true;}
    return false;}

boolean solvedBySysRelaxation(){
    for(Relation i : allRelations){
        i.relaxed = true;
        if(SAT()) return true;}
    return false;}

```

Figure 4.7: Approaches 3 and 4: helper methods.

relations. Note that this is different than applying the predicate on current instance; here we call SAT to see if we can find *another* instance with the same relations relaxed that satisfies the new predicate as well.

2. Then, we try to meet the predicate by relaxing only one extra relation prioritizing those which appeared in this predicate for the first time (method `solvedByRelaxingOneRel` in Figure 4.7). The list of non-relaxed

relations of this predicate is constructed in `candidateRels` linked list. In this list, relations seen for the first time (i.e, not used in the previous predicates) come first. Method `candidateRels()` (Figure 4.7) called with `guided` set to false generates this list for each predicate. We intuitively prefer to start by relaxing relations which are new since the already seen relations have been used in previous constraints and have shown no sign of violation.

3. If the predicate is still unsatisfied, we relax several extra relations by invoking method `solvedByRelaxingFewRels` in Figure 4.7. We accumulatively relax relations, meaning that we relax a set of relations as we go along `candidateRels` list.
4. If we were not able to resolve the problem despite relaxing all relations of this predicate, it means that we have made a mistake somewhere in previous predicates. So, by calling method `solvedBySysRelaxation` in Figure 4.7, we systematically relax other relations until we can satisfy the current constraint.

If all of the above trials⁵ fail on relaxing a specific predicate, the method returns false. Otherwise it returns true after satisfying all predicates.

Consider the faulty linked list output of the `remove` method once again (Figure 4.5(a)). At the first iteration, we realize that constraints uniqueness

⁵We also experimented with backtracking to fix previous wrong relaxations, but this approach was not feasible with respect to performance.

and acyclicity are holding without any relaxations. Assume that we continue the loop by trying to satisfy the size constraint. The first relation in `candidateRels` list will be `size` since it is the only new relation of the size constraint (`next` and `header` are already seen in acyclicity and uniqueness). By relaxing `size`, we will be able to meet this constraint and move to the next one. The next constraint is correct remove. Candidate relations would not prefer any of un-relaxed relations over the others since `header`, `next` and `elt` are all seen before. At the worst case the algorithm tries `next` and `elt` before `header` but once it gets to `header` (in addition to already relaxed `size`), all constraints would be satisfied and we obtain Figure 4.5(b) as repaired output. Note that when we first fixed `size`, we set it to 3 since it was the correct list size at that time. However, when we relax `header`, this value of size is not acceptable any more. Yet, there is no need to go back since `size` is still relaxed and the SAT solver will find an acceptable value for it as well.

4. Guided Error Localization. While evaluating repair heuristics, we found that none of them can accurately guess which relation is most likely to be the cause of violating a specific predicate. So, we let the user guide the repair mechanism by indicating which relation is subject to evaluation in each predicate. For each predicate, the user indicates an ordered list of data structure parameters, called the *guide set*, which are intuitively tested under this predicate. To illustrate, consider the constraints of Figure 2.3. Constraint acyclicity mainly checks the `next` pointer to detect cycles so its guide set starts

with `next`. However, it does not evaluate `header` although it uses `header` as well. Therefore, `header` is either not included in the guide set or has less priority. In this figure, constraint size is to check `size` relation, uniqueness evaluates `elt`, and correct remove deals with `next` and `elt`. Including the guide set in the method contract requires adding JML annotations to indicate members of the guide set for each `ensures` statement (for example in Figures 2.1 and 2.2).

Note that providing the guide set is an easier task compared to writing a flawless method. Indicating that the output of a method should satisfy some predicates comes directly from the method specification. Similarly, relations that are important in any predicate come from programmer’s understanding of the predicate and are not tied to any specific method implementation. While using these guides appropriately will help the performance of the repair process considerably, there is no syntactic restriction on the user. In some cases, we can even tolerate wrong guide sets. The guide set is only a hint to prioritize relaxations and the search can revert to an unguided mode if necessary.

To provide the guide set, the user indicates relations tested in each constraint. For example, if we added `next` to the guide set of the uniqueness constraint, we would help the repair method’s performance. However, we did not assume the existence of the best guides in our evaluation.

Figure 4.6 together with Figure 4.7 when `guided` set to true shows the guided version of Error Localization. The only improvement over the unguided approach is moving the guide set to the beginning of `candidateRels` (Figure 4.7), so that they will be checked sooner, protecting the repair process

Figure 4.8: (a) Circular linked list: a hypothetical erroneous output of `remove(5)` (b) The result of repairing the faulty output using Guided Error Localization.

from unnecessary calls to the SAT solver.

Applying this approach on our example (Figure 4.5(a)) might possibly go through exactly the same process (to provide Figure 4.5(b)) as it did for unguided repair since `header` is not among the guide set of correct `remove`. However, the difference shows up when we want to repair the data structure of Figure 4.8(a) as erroneous output. The only satisfied constraint here is uniqueness. Assume that we choose to repair acyclicity first. Since `next` and `header` are both seen before, regular Error Localization does not prioritize any of them. Yet, a good guide set which indicates that the most likely error in breaking acyclicity is in `next` will save us trying `header` to meet acyclicity. The repaired data structure is shown in Figure 4.8(b).

It is worth noticing that for our simple example, all approaches besides the Basic one provide the same output for both Figure 4.5(a) and Figure 4.8(a), which means that all these three approaches are optimized to keep the mutations as low as possible, though they face the restriction of whole relation relaxation instead of edge correction. A differentiation here is which method provides the result faster with fewer SAT solver invocations. Table 4.3 com-

Table 4.1: Comparison of different repair Algorithms.

	Uses post-state	Uses post-condition to optimize	Uses annotations
Basic approach			
Iterative Relaxation	✓		
Error Localization	✓	✓	
Guided Error Localization	✓	✓	✓

compares all four approaches from a high level perspective.

4.4 Instrumentation

In this section, we provide more details on Tarmeem underlying structure (See Figure 4.1). These are the steps Tarmeem takes to instrument the Java program and reach the point that the repair heuristics are applicable.

Alloy input specification: Tarmeem represents the data structure in Alloy and uses the technique of duplicating [19] to distinguish between the state of data structure prior to and after the method execution. Figure 2.3 illustrates the data structure, the invariant and the post-condition for our simple example of a linked list and a method which removes an element from it. This is essentially the same data structure we had in Java with `header`, `size`, `next` and `elt` representing the same fields of the Java program in the pre-state (i.e, before running the method). We use the backtick character (‘’) to represent the same field in the post-state (i.e, after running the method).

Another important aspect of the Alloy model is how to write the constraints. Here we prefer to write the constraints manually since we want to ob-

tain high level constraints. Also we need more manageable constraints since we sometimes desire to break the constraints to several parts to help the heuristics. In general, these more controllable constraints come with the price of dealing with Alloy predicates manually, though the same concepts can be achieved using methods of [19]. In addition, note that method pre- and post-conditions might already be written in Alloy for testing purposes as described in [19], or in JML as in [7]. In the former case, data repair is provided for free using Tarmeem since the Alloy specifications are already written, and in the latter we can use tools that translate JML specifications to Alloy automatically [32].

Abstraction and concretization: Once the specifications are built, the next step is to keep track of the data structure in pre- and post-states. To store the state of the program, we demonstrate the object graph using relations. A part of the framework is dedicated to keeping track of the data structures. This part will be modified by the user to map the Java data structure to its Alloy representative. The user indicates the mapping intended between the Java data structures and Alloy signatures. This manual configuration can be skipped too using techniques described in [19]. Once the part responsible for translating the data structure to Alloy and Kodkod is constructed, the program can traverse data structures automatically and translate them to Alloy and Kodkod. This is the procedure we called abstraction in Figure 4.1. For each object that appears in pre- or post-states there would be one signature instance in Alloy. Before and after running each method of the program,

the abstraction part is called to keep track of the object graphs. If an error occurs in the method execution, these object graphs which are represented as relations will be sent to the SAT solver. Concretization does the reverse action of abstraction and translates a repaired data structure back to Java.

During translation of the program state to Kodkod (abstraction), Tarmeem manipulates the Kodkod file to equip it with the `relaxed` fields; For each relation, a boolean indicates if this relation is relaxed. Also, in abstraction phase all predicates are equipped with the option of being ignored. An ignored predicate will not participate in solving the problem.

Relaxing a relation is the most fundamental concept of Kodkod used by Tarmeem. If a relation is not relaxed, it is bound exactly to its set in the post-state. For example, if the relation `next` is not relaxed in the linked list example (Figure 4.5(a)), it is set to $\{(N0, N1), (N1, N2)\}$ (the value in the post-state). If it is relaxed, its lower and upper bounds will be relaxed and it can take any set that has the correct settings (i.e, maps nodes to nodes) such as $\{(N0, N1), (N0, N2), (N2, N0)\}$. By relaxation, we mean removing the bounds that are enforced on the relation by the post-condition and letting the output have any legitimate set of tuples for that relation. This means taking out `boundExactly` from the Kodkod translation, so that instead of imposing the set of tuples provided by the faulty output, we let the relation take any set of tuples ranging from $\emptyset$ to the set of all legitimate tuples. Note that no constraints, even those which indicate the basic definition of the data structure (e.g, there is at most one `next` for each node as “`next: lone Node`” states in

```

pred pre-state{List.header = N0 && List.size = 3 && N0.next = N1
  && N1.next = N2 && no N2.next && N0.elc = 5 && N1.elc = 3 && N2.elc = 7}
pred post-state{List.header = N0 && List.size = 4 && N0.next = N1
  && N1.next = N2 && no N2.next && N0.elc = 5 && N1.elc = 3 && N2.elc = 7}

```

Figure 4.9: Linked List example pre- and post-state snapshots.

Figure 2.3) applies at this level. These type of constraints will be applied later with each SAT solver call.

Run code: When the Java method executes and generates the output data structure, once again Tarmeem collects all objects and assigns Alloy signature instances to them. Then, it takes post-state snapshots using the abstraction part. The translation of Figure 2.4 (a) (input) and Figure 2.4 (b) (faulty output) to Alloy is shown in Figure 4.9. Snapshots are taken by the abstraction part.

Chapter 5

Evaluation

We evaluate Tarmeem using a text-book data structure and an open-source application. Throughout the evaluation, we ran each experiment 5 times and reported the averages. All experiments used a 2.50GHz Core 2 Duo processor with 4.00GB RAM. We used SAT4J [4], a SAT solver in Java which is shipped with Kodkod by default.

5.1 Singly Linked List

This data structure is the same as the example singly linked list (Figure 2.3). Each list has a header that points to the first node of the list. Each node has an integer element and a pointer to the next node. The list is acyclic and no duplications are allowed. The list also has a size element which shows the number of nodes.

We implemented several faulty `remove` methods for this data structure which are described by Table 5.1. The table displays corrupted fields of the output data structure, constraints that are violated by the erroneous `remove`, and the programmer mistake that can cause such an error.

We ran Tarmeem to fix the output of each incorrect `remove` method for

Table 5.1: Faults injected into the programs. Faults 1-7 apply to `remove` method of singly-linked list, and Faults 8-9 apply to `deleteChild` method of class `BaseTree` of ANTLR.

	Fault name	Erroneous fields	Violates	Program error
1	Fail to fix the size	size (auxiliary int)	Size	Omission
2	Delete another element too	next (primary pointer)	Correct remove	Commission
3	Cycle	next (primary pointer)	Acyclicity	Commission
4	Broken List	next (primary pointer)	Correct remove and size	Omission
5	Fail to remove the element	elt (primary int)	Correct remove	Omission
6	Null header	header (primary pointer)	Correct remove	Commission
7	Duplicate an element and wrong size	elt (primary int) size (auxiliary int)	Uniqueness and size	Commission and Omission
8	Fail to delete	children (primary pointer) childIndex (auxiliary int)	Delete	Omission
9	Fail to update ChildIndex	childIndex (auxiliary int)	childIndex relations	Omission

linked lists of size 10 and also for linked lists of size 20. Equation 5.1 presents the relationship that holds between several different measures with t being the total repair time and alg being the time consumed to do the heuristic algorithm (in sections between calls to the SAT solver). $\#SAT_invoc$ is the total number of SAT solver invocations to repair this specific fault with desired approach and it excludes evaluation calls used to evaluate constraints at the Kodkod level without going to the SAT solver level. SAT_tr_{avg} and SAT_sl_{avg} are average translation and solving times over calls to the SAT solver to resolve this specific error. These are measured to give a sense on how SAT translation and solving are time consuming and how a good heuristic which calls the SAT solver fewer times with suitable settings (i.e. relaxations) can be beneficial.

$$t = alg + \#SAT_invoc * (SAT_tr_{avg} + SAT_sl_{avg}) \quad (5.1)$$

Table 5.2: Result of applying Tarmeem on different erroneous singly linked lists of size 10 and 20, and on corrupt `BaseTree` class of `ANTLR` package, maximum repair time allowed: 120 seconds.

Measure	Alg	Erroneous method from Table 5.1															
		Linked list with 10 nodes							Linked list with 20 nodes							ANTLR	
		1	2	3	4	5	6	7	1	2	3	4	5	6	7	8	9
Time(ms)	BM	7567	7314	8675	3809	7629	5057	5987	-	-	-	-	-	-	-	-	-
	IR	726	851	1038	911	883	591	1764	1061	9697	15784	9534	2582	831	5744	-	2659
	EL	614	13113	926	1160	939	820	1416	783	25581	18622	8852	2495	949	4325	-	6907
	GL	598	1060	870	1031	919	719	1136	807	14265	21180	13147	2266	1240	3522	13852	2196
Edit distance	BM	38	33	38	33	32	32	34	-	-	-	-	-	-	-	-	-
	IR	2	12	15	14	19	1	19	2	29	31	28	38	1	39	-	10
	EL	2	13	15	12	18	1	19	2	26	30	29	38	1	40	-	10
	GL	2	15	15	14	19	1	22	2	30	30	29	39	1	40	12	10
#SAT_invo	BM	2	2	2	2	2	2	2	-	-	-	-	-	-	-	-	-
	IR	4	3	4	4	4	3	10	3	4	3	4	3	3	9	-	3
	EL	3	5	4	5	4	6	6	4	6	5	3	4	4	6	-	5
	GL	3	4	3	4	4	6	6	4	4	4	3	4	5	7	7	3
#vars _{avg}	BM	8531	8531	8531	8531	8531	8531	8531	-	-	-	-	-	-	-	-	-
	IR	725	1774	1421	1355	2569	46	2720	2175	11460	15829	13620	5656	146	7580	-	15824
	EL	320	2496	1406	1518	2725	351	3536	432	7592	17732	13300	4525	100	6688	-	15564
	GL	320	1475	1645	1475	2349	128	1495	336	15481	15510	13650	4466	78	5382	34359	8505
#clauses _{avg}	BM	28836	28836	28836	28836	28836	28836	28836	-	-	-	-	-	-	-	-	-
	IR	2147	4855	3892	3699	8828	105	8995	6724	34816	48196	41454	19061	286	24447	-	50766
	EL	1106	7733	3851	4384	9366	1190	11989	1494	23277	54082	39426	15249	197	21883	-	48951
	GL	1106	4176	4507	4176	8075	406	4625	1162	46354	47279	40706	15048	153	17263	106822	28319
#vars _{avg}	BM	407	407	407	407	407	407	407	-	-	-	-	-	-	-	-	-
	IR	118	100	157	145	209	72	272	179	316	350	316	478	108	597	-	807
	EL	21	133	30	75	195	90	311	29	102	162	122	375	220	710	-	544
	GL	21	48	33	48	185	151	275	22	140	140	130	420	340	683	810	576
SAT _{avg} (ms)	BM	320	333	317	319	315	318	346	-	-	-	-	-	-	-	-	-
	IR	133	173	163	135	169	137	140	259	397	646	395	482	221	502	-	503
	EL	128	134	137	112	163	88	154	133	283	525	352	329	176	258	-	995
	GL	124	127	153	123	154	88	128	139	452	512	481	378	200	245	1579	277
SAT _{avg} (ms)	BM	3382	3242	3939	1493	3420	2131	2531	-	-	-	-	-	-	-	-	-
	IR	4	57	64	59	26	2	15	11	2080	4691	2362	227	3	93	-	256
	EL	4	2279	58	81	28	5	37	7	3826	3592	2214	167	2	421	-	142
	GL	4	73	67	73	21	2	11	6	3035	4711	3242	118	1	265	283	243

The *edit distance* is defined as the minimum number of edge additions or deletions to transform a graph to another and is the same as well-known maximum common subgraph metric under a specific cost function [8, 29]. Our computation of edit distance is simplified because we have an object graph that is evolved from another one through a sequence of mutations, since the repaired output is an altered version of the faulty output.

Table 5.1 includes experimental results for singly linked lists of size 10 and also 20. $\#SAT_invoc$ represents number of SAT solver invocations, $\#vars_{avg}$, $\#clauses_{avg}$ and $\#pvars_{avg}$ stand for the average number of variables, clauses and primary variables in SAT solver calls respectively. SAT_tr_{avg} and SAT_sl_{avg} are average translation and solving times for SAT solver as before. *BM*, *IR*, *EL* and *GL* are abbreviations of Basic Method, Iterative Relaxation, Error Localization and Guided Error Localization.

In repairing a singly linked list of size 10, while no approach consistently outperforms all others, Iterative Relaxation and Guided Error Localization are the best heuristics. The efficiency of Iterative Relaxation in some cases is because the number of errors in the data structure is assumed to be few and iteratively relaxing relations one at a time will find an error faster if it is only in one parameter. The reason that the Guided Error Localization was not able to defeat Iterative Relaxation in all cases is because in this experiment we preferred to write guide sets in an intuitive fashion. Although such sets are not necessarily optimal, we expect the user to write them as a starting point. In later experiments in Section 5.2 we will see how to write more effective

guide sets by considering repair process.

The most challenging faulty methods are those which introduce different kinds of errors. For the linked list of size 10, all faulty outputs except the output of erroneous `remove` number 7 can be repaired in less than 1 second. This method takes at least 1.136 seconds because the error corrupts two parameters of the data structure. However, these types of errors are unlikely in deployed code because it has been systematically tested and also since period checking of post-conditions prohibits propagation of errors in data structures.

In a linked list of size 10, the Basic approach which directly utilizes the post-condition to solve the problem with SAT solver produces some results given sufficient time. However, when we move to 20 nodes, the Basic method can no longer generate the correct output in less than 120 seconds. This shows how applying different heuristics and using the correct parts of the corrupt output can help the repair process. Table 5.1 also presents the result of repairing a singly linked list of size 20. The results are similar to those for a singly linked list of size 10.

Here, outputs of methods 2, 3, and 4 take more time to repair since they have corrupted the `next` pointer, a relation which has many possible candidates. One can easily see how solving time of the SAT solver is considerably higher for these three methods. As the data structure size grows, the complexity of the corrupted relation becomes the dominant problem in repair. A possible improvement would be going inside the relation and keeping correct edges instead of relaxing the whole relation, but this solution needs manip-

ulating the model finder or the SAT solver. Note that even for a linked list of size 20 and with the intuitive guide sets, and the most complicated errors, there is at least one heuristic which can finish the repair process in about 15 seconds or less. The bottleneck is the SAT solver, which takes up to 5 seconds to translate and solve in each invocation.

5.2 ANTLR `BaseTree`

ANTLR: (ANother Tool for Language Recognition [28]), a part of the DaCapo benchmark [6], is a tool that builds recognizers, interpreters, compilers and translators from grammars. **ANTLR** receives a formal grammar as input and evaluates a given sentence against the grammar. **ANTLR** uses rich data structures, since it needs sophisticated intermediate forms to recognize and interpret grammars. These data structures are known to be a major source of errors when manipulated incorrectly. This feature makes **ANTLR** an excellent case study for data structure repair. **ANTLR**, with 29710 lines of Java code, has a download rate of about 5000 per month and is extensively used to generate programs.

ANTLR represents the grammar internally as a tree. Abstract class `BaseTree` is a generic tree implementation used to abstract several trees such as `ParseTree` used in building a parser. **ANTLR v.3** uses a list of children instead of the usual parent child approach in `BaseTree`. Each tree node maintains a `list` of children as its successors while each of these children keeps the correct pointer to their parent. Each tree node also keeps integer values `startIndex`,

```

sig BaseTree{
  root: lone Tree,
  root': lone Tree}
sig Tree{
  children: lone Tree,
  parent: lone Tree,
  next: lone Tree,
  startIndex: lone Int,
  stopIndex: lone Int,
  childIndex: lone Int,
  children': lone Tree,
  parent': lone Tree,
  next': lone Tree,
  startIndex': lone Int,
  stopIndex': lone Int,
  childIndex': lone Int}
pred repOk(b: BaseTree){ // class invariant of BaseTree
  //acyclicity
  all n:b.root.*(children.*next)|n !in n.^(children.*next)
  //parent and child relationship
  no b.root.parent
  all n:b.root.^(children.*next)|n in n.parent.children.*next
  //childIndex Relations
  all n:b.root.*(children.*next)|
    no n.next || int n.next.childIndex = (int n.childIndex)+1
  //first childIndex is 0
  all n:b.root.*(children.*next).children|int n.childIndex = 0}
pred delete_postcondition(This: BaseTree, x: Int){
  repOk[This]
  //NoOneNew
  all n:This.root'.*(children'.*next')|n in This.root.*(children.*next)
  //KeepOthers
  all n:This.root.*(children.*next)|
    n !in This.root'.*(children'.*next')=>
      (n in This.root.children.*next && int n.childIndex=x)
  //Delete
  all n:This.root.children.*next|
    int n.childIndex=x => n !in This.root'.*(children'.*next')}

```

Figure 5.1: Class invariant for ANTLR BaseTree and post-condition for delete in Alloy.

```

grammar CommandLanguage;
greeting : interjection subject;
interjection : 'Hello';
subject : 'World!';

```

Figure 5.2: Input grammar for ANTLR.

```

public Object deleteChild(int i){
    if(children==null) return null;
    // faulty implementation number 8:
    // use .get(i) instead of .remove(i)
    Tree killed = ((Tree)children).remove(i);
    // walk rest and decrement their child indexes
    // faulty implementation number 9:
    // ignore the child indexes freshen call
    this.freshenParentAndChildIndexes(i);
    return killed;
}

```

Figure 5.3: `deleteChild` method of class `BaseTree`.

`stopIndex` and `childIndex` for bookkeeping purposes. For example, `childIndex` represents the node’s place in its parent’s `children` list, counting from zero. In order to be able to use Tarmeem to repair instances of `BaseTree` data structure, we added class invariants and post-conditions to `BaseTree` based on comments provided by ANTLR as well as the program logic. The Alloy specification of this data structure is shown in Figure 5.1.

We used ANTLR v.3.1.3 to parse the simple grammar shown in Figure 5.2, which generated 27 instances of class `BaseTree` in total. Figure 5.3 shows `deleteChild` method of class `BaseTree` in ANTLR package with our annotations to inject errors. Table 5.1 demonstrates the result of repairing with Tarmeem. Note that as this table suggests, no heuristic except Guided Error Localization was able to repair the output of error number 8 (See Figure 5.3

and Table 5.1) in less than 120 seconds. With a good guide set which prioritizes relations that are most possibly faulty but do not take a huge set of candidates, we enforce fast returning from the SAT solver whenever this specific relaxation is not indeed the answer and quick finding of the faulty relations. Guided Error Localization could repair the faulty output of all sorts of errors in less than 14 seconds.

Chapter 6

Conclusions and Future Work

We introduced the use of rich behavioral specifications extracted from method contracts for systematic data structure repair using the Alloy tool-set as an enabling technology. Four repair algorithms were presented and evaluated using a text book data structure and an open-source application. Our algorithms can repair erroneous data structures with tens of nodes in seconds. The results are encouraging and show the feasibility of repairing complex structures of small sizes with a small number of faults.

The primary contributions of our repair framework, Tarmeem, are the algorithms for repair based on rich behavioral specifications and a demonstration of the feasibility and potential of such an approach, specifically for structurally complex data. The performance of our prototype is encouraging and we believe repair can increase reliability of real applications because of the following reasons:

- A deployed system that has been well-tested can be assumed to have a few errors and focusing repair on likely erroneous fields to reduce the non-determinism in the specification is likely to provide effective pruning of the search space and to minimize the number of SAT invocations. Note

that when no contract violation happens, no repair is performed and SAT/constraint solving is not executed. Hence the overhead of using Tarmeem with a correct program is of the same order of magnitude as that of enforcing contracts using runtime checking.

- Despite the NP hard nature of the SAT problem, advancements in SAT technology over the past decade have been substantial. In addition, our heuristics attempt to reduce the size of the SAT problem by focusing on the erroneous parts of the data structure. Our algorithms provide a solid basis for developing more effective algorithms to precisely identify the error and improve the scalability of Tarmeem.
- Our approach is not limited to repair of program state at runtime. For example, data structure repair frameworks can provide useful feedback to perform program repair and automate debugging [24].

Our current use of SAT represents a bottleneck for scaling the algorithms to larger structures. While previous work on assertion-based repair [12] suffers from ignoring post-conditions, it is approximately 10 times faster than our framework since it uses Korat [7] instead of SAT. Our limited experiments show that Tarmeem can achieve the same speed-up using Korat. In addition, we believe a tighter integration with SAT holds much promise. We are investigating techniques to guide SAT backtracking, so that SAT is not invoked multiple times to perform repair, rather the SAT search is tailored

directly based on the repair algorithms. Moreover, we believe a use of specialized solvers, such as integer constraint solvers and string constraint solvers, in conjunction with SAT will allow us to scale contract-based repair to larger structures and to develop it into a viable technique for improving reliability of real applications. Empirical rigorous evaluation (including an evaluation on more real world applications) as well as developing better heuristics to accurately find the violating parts of the program state is a part of the future work. Using repair feedback to improve the program is another promising research avenue.

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Vita

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This thesis was typeset with L^AT_EX[†] by the author.

[†]L^AT_EX is a document preparation system developed by Leslie Lamport as a special version of Donald Knuth's T_EX Program.