RESTORE: Retrospective Fault Localization Enhancing Automated Program Repair

Tongtong Xu, Liushan Chen, Yu Pei, Tian Zhang, Minxue Pan, Carlo A. Furia
RESTORE: Retrospective Fault Localization Enhancing Automated Program Repair

Tongtong Xu, Liushan Chen, Yu Pei, Tian Zhang, Minxue Pan, Carlo A. Furia

Abstract—Fault localization is a crucial step of automated program repair, because accurately identifying program locations that are most closely implicated with a fault greatly affects the effectiveness of the patching process. An ideal fault localization technique would provide precise information while requiring moderate computational resources—to best support an efficient search for correct fixes. In contrast, most automated program repair tools use standard fault localization techniques—which are not tightly integrated with the overall program repair process, and hence deliver only subpar efficiency.

In this paper, we present retrospective fault localization: a novel fault localization technique geared to the requirements of automated program repair. A key idea of retrospective fault localization is to reuse the outcome of failed patch validation to support mutation-based dynamic analysis—providing accurate fault localization information without incurring onerous computational costs.

We implemented retrospective fault localization in a tool called RESTORE—based on the JAIID Java program repair system. Experiments involving faults from the DEFECTS4J standard benchmark indicate that retrospective fault localization can boost automated program repair: RESTORE efficiently explores a large fix space, delivering state-of-the-art effectiveness (41 DEFECTS4J bugs correctly fixed, 8 of which no other automated repair tool for Java can fix) while simultaneously boosting performance (speedup over 3 compared to JAIID). Retrospective fault localization is applicable to any automated program repair techniques that rely on fault localization and dynamic validation of patches.

I. INTRODUCTION

Automated program repair has the potential to transform programming practice: by automatically building fixes for bugs in real-world programs, it can help curb the large amount of resources—in time and effort—that programmers devote to debugging [1]. While the first viable techniques tended to produce patches that overfit the few tests typically available for validation [2], [3], automated program repair tools have more recently improved precision (see Section V-B for a review) to the point where they can often produce genuinely correct fixes—equivalent to those a programmer would write.

A crucial ingredient of most repair techniques—and especially of so-called generate-and-validate approaches [4]—is fault localization. Imitating the debugging process followed by human programmers, fault localization aims to identify program locations that are implicated with a fault and where a patch should be applied. Fault localization in program repair has to satisfy two apparently conflicting requirements: it should be accurate (leading to few locations highly suspicious of error), but also efficient (not taking too much running time).

In this paper, we propose a novel fault localization approach—called retrospective fault localization, and presented in Section III—that improves accuracy while simultaneously boosting efficiency by integrating closely within standard automated program repair techniques. By providing a more effective fault localization process, retrospective fault localization expands the space of possible fixes that can be searched practically. Retrospective fault localization leverages mutation-based fault localization [5], [6] to boost localization accuracy. Since mutation-based fault localization is notoriously time consuming, a key idea is to perform it as a derivative of the usual program repair process. Precisely, retrospective fault localization introduces a feedback loop that reuses, instead of just discarding them, the candidate fixes that fail validation to enhance the precision of fault localization. Candidate fixes that pass some tests that the original (buggy) program failed are probably closer to being correct, and hence they are used to refine fault localization so that other similar candidate fixes are more likely to be generated.

We implemented retrospective fault localization in a tool called RESTORE, built on top of JAIID [7], a recent generate-and-validate automated program repair tool for Java. Experiments with real-world bugs from the DEFECTS4J curated benchmark [8] indicate that retrospective fault localization significantly improves the overall effectiveness of program repair in terms of correct fixes (for 41 faults in DEFECTS4J, 8 more than any other automated repair tool for Java at the time of writing) and boosts its efficiency (cutting JAIID’s running time to a third or less). Other measures of performance, discussed in detail in [Section IV], suggest that retrospective fault localization improves the efficiency of automated program repair by supporting accurate fault localization with comparatively moderate resources.

Generality. While our prototype implementation is based on the existing tool JAIID, retrospective fault localization should be applicable to any program repair tools that use fault localization and rely on validation through testing. To demonstrate the approach’s generality, we extended SimFix [9]—another state-of-the-art automated repair tools for Java—with retrospective fault localization. The experimental results comparing SimFix with and without retrospective fault localization (reported in Section IV-B3) indicate that retrospective fault localization is applicable also to different implementations, where it similarly brings considerable performance improvements without decreasing effectiveness.

Contributions. This paper makes the following contributions:

1) Retrospective fault localization: a novel fault localization approach tailored for automated program repair tech-
niques based on validation;
2) **RESTORE**: a prototype implementation of retrospective fault localization, demonstrating how retrospective fault localization can work in practice;
3) An experimental evaluation of **RESTORE** on real-world faults from **DEFACTS4J**, showing that retrospective fault localization significantly improves the efficiency by boosting effectiveness and, simultaneously, performance.
4) An implementation of retrospective fault localization atop the SimFix program repair technique, indicating that it is viable to improve also other generate-and-validate repair techniques.

**Replication.** A replication package with **RESTORE**’s implementation and all experimental data is publicly available at: [http://tiny.cc/9xff3y](http://tiny.cc/9xff3y)

II. AN EXAMPLE OF **RESTORE** IN ACTION

The Closure Compiler is an open source tool that optimizes JavaScript programs to achieve faster download and execution times. One of the refactorings it offers—renaming classes so that namespaces are no longer needed—is based on class `ProcessClosurePrimitives` whose methods modify calls to common namespace manipulation APIs. In particular, method `processRequireCall` processes calls to the `goog.require` API and determines if they can be removed without changing program behavior.

**Listing 1** shows part of the method’s implementation, which is defective \[1\] according to the tool documentation, a call to `goog.require` should be removed (lines 5 and 7) if (i) the required namespace can be resolved successfully (provided != null), or (ii) the tool is configured to remove all the calls to `goog.require` unconditionally (requiresLevel.isOn()). But the code in **Listing 1** only checks condition \[7\] on line 5 and hence does not remove unsolvable calls even when condition \[ii\] holds.

Using some of the tests that come with **Closure Compiler**’s source code, the **RESTORE** tool described in the present paper produces the fix shown in **Listing 2** which is identical to the one written by **Closure Compiler**’s tool developers—and completely fixes the bug. At the time of writing, **RESTORE** is the only automated program repair tool capable of correctly fixing this bug.\[2\]

The features of method `processRequireCall` and its enclosing class `ProcessClosurePrimitives` contribute to making the bug challenging for generate-and-validate automated repair tools. First, class and method are relatively large (Class `ProcessClosurePrimitives` has 1233 lines and method `processRequireCall` has 40 lines), which is a challenge in and of itself for precise fault localization. Second, attribute `requiresLevel` is never referenced in the faulty version of `processRequireCall` and is used only once after initialization in the whole class; thus, expression `requiresLevel.isOn()`—which is needed for the fix—is unlikely to be selected by techniques that look for fixing “ingredients” mainly in a fault’s context.

**RESTORE**’s retrospective fault localization is crucial to ensure that the necessary fixing expression is found in reasonable time: **RESTORE** takes around 32 minutes to produce the fix in **Listing 2** and to rank it first in the output. This indicates that **RESTORE**’s search for fixes is not only efficient but also effective.

In the rest of the paper we explain how **RESTORE** works (Section III), and demonstrate its consistent performance improvements on standard benchmarks of real-world bugs (Section IV).

III. HOW **RESTORE** WORKS

Retrospective fault localization is applicable in principle to any generate-and-validate automated program repair technique to improve its efficiency. To make the presentation more concrete, we focus on how retrospective fault localization is applicable on top of the **JAI'D** [7] automated program repair tool. We call the resulting technique, and its supporting tool, **RESTORE**.

A. Overview

**Figure 1** illustrates how **RESTORE** works at a high level, and how it enhances a traditional automated program repair technique by retrospective fault localization (boxes in grey in **Figure 1**).

**Input.** **RESTORE** inputs a Java program \( P \) (a collection of classes), with a faulty method \( \text{fixme} \), and a set \( T \) of test cases exercising \( P \); precisely, tests \( T \) are partitioned into passing tests \( T^\checkmark \) and failing tests \( T^\times \). Since each run of **RESTORE** actually only uses tests that exercise \( \text{fixme} \), we assume, without loss of generality, that \( T \) only includes such tests.

**Fault localization** identifies program locations and states (called **snapshots**) that are indicative of faulty behavior. According to heuristics based on dynamic and static measures, each snapshot receives a **suspiciousness score**—the higher, the more suspicious; snapshots ranked according to their suspiciousness score are input to the next step: fix generation.

\[1\] Fault Closure113 in **DEFACTS4J** [8] and Table III

```
private void processRequireCall(NodeTraversal t, 
    Node n, Node parent) {
  ProvidedName provided = providedNames.get(...);
  ...
  if (provided != null) {
    parent.detachFromParent();
    compiler.reportCodeChange();
  }
}
```

**Listing 1**: Faulty method `processRequireCall` from class `ProcessClosurePrimitives` in project **Closure Compiler**.

```
if (provided != null || requiresLevel.isOn()) {
```

**Listing 2**: Fix written by tool developers (replacing line 5 in **Listing 1**), and also produced by **RESTORE**.

\[2\] Nopol was able to produce a valid, but incorrect, fix to the fault [10].
**Fix generation** builds several modifications of input program $P$ for each snapshot in order of suspiciousness. The modifications try to mutate $P$'s behavior in a way that avoids reaching the suspicious snapshot’s state. Fix generation’s output is a sequence of candidate fixes that needs to be validated.

(Full) **fix validation** tests each candidate fix to determine whether it actually fixes the fault exposed by $T$. In traditional automated program repair, fix validation runs all available tests $T$ against each fix candidate, and only outputs candidates that pass all tests—ranked according to the suspiciousness of the snapshots they were derived from. Hence, fix validation is often the most time-consuming step of traditional automated program repair. Since it is done downstream from fix generation—as the last step of the whole fixing process—validation requires a large number of fix candidates to maximize the chance of finding some valid, possibly correct, fixes, which exacerbates the performance problem.

**Partial fix validation** is the lightweight form of validation of candidate fixes used by **RESTORE** to support retrospective fault localization. By only running a subset of the available tests $T$, partial fix validation aims to quickly detect behavioral changes in some of the candidates with respect to the program $P$ under fix.

**Mutation-based fault localization** improves the precision and effectiveness of fault localization by using retrospective information coming from partial validation. Based on this information, the suspiciousness score of snapshots is revised to become more discriminatory.

**Exploring a larger fix space.** With retrospective fault localization, the top-ranked snapshots have a higher chance of leading to valid fixes when used in the following phases of the repair technique—and thus to correct fixes ranked high in the overall output. Conversely, a higher-precision fault localization technique means that fewer candidates need to be generated and (fully) validated, leading to an overall faster process. In turn, **RESTORE**’s more efficient search of the fix space allows it to explore a larger space in comparable—often shorter—time, ultimately leading to discovering fixes that are outside Jaid’s fix space.

**B. Basic Automated Program Repair**

This section describes the basic process of automated program repair—as implemented in generate-and-validate repair tools such as Jaid and **RESTORE**. Then, Section 3-C presents retrospective fault localization in **RESTORE**, showing how it enhances the basic repair process described here.

1) **State abstraction: snapshots**. Snapshots are fundamental abstractions of a program’s runs. A snapshot is a tuple $(\ell,e,v)$, where $\ell$ is a location in the program’s control-flow graph, $e$ is a Boolean expression, and $v$ is a Boolean value (true or false). Intuitively, $(\ell,e,v)$ records the information that a program’s run reaches location $\ell$ with expression $e$ evaluating to $v$.

**RESTORE** builds snapshots by enumerating different Boolean expressions $e$ that refer to program features visible at $\ell$, and by evaluating such expressions in all runs of tests $T$.

2) **Fault localization**: Fault localization assigns a suspiciousness score $su(s)$ to each snapshot $s$. Intuitively, $su(s)$ should capture the likelihood that $s$ is the source of failure.

Tools like Jaid use a form of spectrum-based fault localization [11], which roughly corresponds to giving a higher suspiciousness to $s = (\ell,e,v)$ the more often $e$ evaluates to $v$ at $\ell$ in runs of failing tests than in runs of passing tests. In **RESTORE**, we call Jaid’s fault localization basic fault localization; **RESTORE** uses it to determine a suspiciousness score $su_B(s)$ for each snapshot $s$—bootstrapping the fix generation phase.

More precisely, Jaid applies Wong et al.’s Heuristic III [12] to classify the suspiciousness of snapshots rather than statements—as more commonly done in fault localization. A snapshot $s$’s suspiciousness combines a static analysis score (measuring the syntactic similarity of the snapshot expression $e$ and the code around location $\ell$) and a dynamic score (measuring the relative frequency with which $e = v$ in a failing rather than in a passing test). Some recent experiments [13] indicate that Jaid’s effectiveness does not significantly depend on the details of the spectrum-based fault localization algorithm: running Jaid using other common algorithms for fault localization (such as Ochiai [11] or Tarantula [14]) leads to very similar numbers of valid and correct fixes.
3) **Fix generation:** For each snapshot \((\ell, e, v)\), fix generation modifies \(P\)'s method \(\text{fixme}\) (the one being fixed) in ways that affect the value of \(e\) at \(\ell\). Fix generation processes all candidate fixes in decreasing order of suspiciousness, building multiple modifications of \(\text{fixme}\) for the same snapshot; each modification is a fix candidate.

\(\text{RESTORE}\) generates fix candidates in two steps. First, it enumerates code snippets (called actions in [7]) that (a) modify the state of an object referenced in \(e\), (b) modify a subexpression of \(e\) in the statement at \(\ell\), (c) if \(\ell\) is a conditional statement \(\text{if}(c)\ldots\), modify expression \(c\), or (d) modify the control flow at \(\ell\) for example with a return statement. Second, it injects a code snippet action into \(\text{fixme}\) using any of the five schemas in Figure 2; oldStatement is the statement at \(\ell\) in \(\text{fixme}\), which the whole instantiated schema replaces to generate a fix candidate.

Each fix candidate \(C\) can be seen as a mutant of input program \(P\) that originates from one snapshot \(s\); we write \(\sigma(C) = s\) to denote the snapshot \(s\) that candidate \(C\) originates from. To cull the search space of generated fixes, it is customary to build candidates for at most the top \(N\) snapshots; in order of suspiciousness; in \(\text{AID}\), \(N = N_0 = 1500\).

- **Schema A:** action; oldStatement;
- **Schema B:** if \((c == v)\) { action; } oldStatement;
- **Schema C:** if \((c != v)\) { oldStatement; }
- **Schema D:** if \((c == v)\) { action; } else { oldStatement; }
- **Schema E:** /* oldStatement; */

Figure 2: Schemas to build candidate fixes from a code snippet action built from snapshot \((\ell, e, v)\), where oldStatement is the statement at \(\ell\) in method \(\text{fixme}\) under fixing.

4) **Fix validation (and ranking):** Since fix generation is “best effort” and based on the partial information captured by snapshots, it is followed by a validation step that reruns all available tests. A fix candidate \(C\) is valid if it passes all available tests \(T\); tests \(T_x\) failing on the input program are passing on \(C\), and tests \(T_v\) passing on the input program are still passing on \(C\) (no regression errors).

Typically, more than one fix candidate \(C\) fixing the same input program \(P\) is valid; we rank all such valid fixes in decreasing order of suspiciousness of the snapshot used to generate \(C\)—that is in decreasing order of \(su(\sigma(C))\). The overall output of automated program repair is thus a list of valid fixes ranked according to suspiciousness.

**C. Retrospective Fault Localization in Restoration**

The ultimate goal of automated program repair is finding fixes that are not only valid—pass all available tests—but correct—equivalent to those a competent programmer, knowledgeable of the program \(P\) under repair, would write. The traditional automated program repair process presented in Section III-B can be quite effective at producing correct fixes but is limited in practice by two related requirements: 1) since the accuracy of fault localization greatly affects the chances of success of the whole repair process, we would like to have a fault localization technique that incorporates as much information as possible; 2) since the process is open loop (no feedback), we have to generate as many candidate fixes as possible to maximize the chance of finding a correct one.

Improving accuracy and generating many candidate fixes both exacerbate the already significant problem of long validation times (for example, validation takes up 92.8% of \(\text{AID}'s\) overall running time [7]). More crucially, they require to bound the search space of possible fixes to a size that can be feasibly explored. But, by definition, shrinking the fix space makes some bugs impossible to fix.

Retrospective fault localization, as implemented in \(\text{RESTORE}\), addresses these two requirements with complementary solutions: 1) it performs a preliminary partial fix validation, which runs much faster than full validation and whose primary goal is to supply more dynamic information to fault localization; 2) using the information from partial validation, it complements \(\text{AID}'s\) fault localization with precise mutation-based fault localization. Such a feedback-driven mutation-based fault localization drives more efficient further iterations of fix generation, producing a much smaller, often higher-quality, number of candidate fixes that can undergo full validation taking a reasonable amount of time. The greater efficiency is then traded off against fix space size: \(\text{RESTORE}\) can afford to explore a larger space of candidate fixes, thus ultimately fixing bugs that are out of \(\text{AID}'s\) (and other repair tools') capabilities.

1) **Initial fix generation:** The initial iteration of fix generation in \(\text{RESTORE}\) works similarly to basic automated program repair: fault localization (Section III-B) assigns a basic suspiciousness score \(su_B(s)\) to every snapshot \(s\) (using spectrum-based fault localization as in \(\text{AID}\)); and fix generation (Section III-B3) builds fix candidates for the most suspicious snapshots.

As we have already remarked, \(\text{AID}'s\) spectrum-based fault localization often takes a major part of the total fixing time, as it involves monitoring the values of many snapshot expressions in every test execution; for example, it takes 51%–99% of \(\text{AID}'s\) total time on 16 hard faults [7]. To cut down on this major time cost, \(\text{RESTORE}\) selects a subset \(T_b\) of all tests \(T\) to be used in basic fault localization using nearest neighbor queries [15]. The selected tests \(T_b\) include all failing tests \(T_x\) as well as the passing tests with the smallest distance to those failing. The distance between two tests \(t_1, t_2\) is calculated as the Ulam distance \(U(\phi(t_1), \phi(t_2))\), where \(\phi(t)\) is a sequence with all basic blocks of \(\text{fixme}\)'s control-flow graph sorted according to how many times each block is executed when running \(t\). This way, passing tests that are behaviorally similar to failing tests are selected as “more useful” for fault localization since they are more likely to be sensitive to fixes of the fault. Take, for example, the conditional at lines 5–7 in Listing 2; two tests \(t_1\) and \(t_2\) such that provided != null at line 5 both execute the conditional block, and hence will have a shorter Ulam distance than \(t_1\) and another test \(t_3\) that...
skips the conditional block (such that provided \(\texttt{== null}\) at line 5). Subset \(T_B\) is used only to bootstrap \(\text{RESTORE}'s\) initial fix generation without dominating the overall running times.

During initial fix generation, \(\text{RESTORE}\) builds fix candidates for the \(N_I = N_S \cdot N_P\) most suspicious snapshots (whereas \(\text{JAD}'s\) builds candidates for the \(N_S\) most suspicious snapshots). Parameter \(N_P\) is 10\% (i.e., \(N_P = 0.1\)) by default; this works because retrospective fault localization can be as effective as \(\text{JAD}'s\) basic fault localization with a fraction of the snapshots.

2) Partial fix validation: Partial fix validation aims at quickly extracting dynamic information about the many candidate fixes built by the initial iteration of fix generation. To strike a good balance between costs (time spent on running tests) and benefits (information gathered to guide mutation-based fault localization), partial fix validation follows the simple strategy of running only the tests \(T_x\) that were failing on the input program \(P\). This is efficient—because \(|T_x|\) is often much smaller than \(|T|\) (see columns \(F\) and \(P\) in Table III)—and still has a good chance of providing valuable information for fault localization, since it detects whether the failing behavior has changed in any of the fix candidates.

If a candidate fix happens to pass all tests \(T_x\), it immediately undergoes full validation (Section III-C6) for better responsiveness of the fixing process (outputting valid fixes as soon as possible).

3) Mutation-based fault localization: In mutation-based fault localization \(6, 3\), we compare the dynamic behavior of many different mutants of a program.

A mutant is a program variant produced by changing the program's code in some ways—for example, by changing a comparison operator. A mutation \(M\) of a program \(P\) is killed by a test \(t\) when \(M\) behaves differently from \(P\) on \(t\); that is, either \(P\) passes \(t\) while \(M\) fails it, or \(P\) fails \(t\) while \(M\) passes it. A killed mutant \(M\) indicates that the locations where \(M\) syntactically differs from \(P\) are likely (if \(M\) fails) or unlikely (if \(M\) passes) to be implicated with the failure triggered by \(t\).

\(\text{RESTORE}'s\) retrospective fault localization treats candidate fixes as higher-order mutants—that is, mutants of the input program \(P\) that may include multiple elementary mutations—and interprets partial fix validation results of those higher-order mutants in a similar way to help locate faults more accurately. In particular, adapting \(6\)'s heuristics to our context, we assign a suspiciousness score \(s_{SU}(C)\) to each candidate fix \(C\):

\[
s_{SU}(C) = \frac{|T_x \cap \text{killed}(C)|}{|T_x| |\text{killed}(C)|},
\]

where \(\text{killed}(C) \subseteq T_x\) is the set of all tests that kill \(C\)—and thus \(T_x \cap \text{killed}(C)\) are the tests that fail on input program \(P\) and pass on \(C\). Formula (1) assigns a higher suspiciousness to a candidate fix the more failing tests it manages to pass, indicating that \(C\) might be closer to correctness than \(P\).

In order to combine the output of mutation-based and basic fault localization, we assign a suspiciousness score \(s_{SU}(s)\) to each snapshot \(s\) based on the suspiciousness (1) of candidates. Each candidate fix \(D\) is generated from some snapshot \(\sigma(D)\); let \(SU(D)\) be the largest suspiciousness score of all candidate fixes \(E\) generated from the same snapshot \(\sigma(D)\) as \(D\):

\[
SU(D) = \max \{ s_{SU}(E) | \sigma(E) = \sigma(D) \}.
\]

Then, the mutation-based suspiciousness score \(s_{SU}(s)\) of a snapshot \(s = (\ell, e, v)\) is the average of \(SU(D)\) across all candidate fixes \(D\) generated from a snapshot with the same location \(\ell\) as \(s\) (and any expression and value):

\[
s_{SU}((\ell, e, v)) = \frac{1}{|D|} \sum_{D \in E} SU(D | \sigma(D) = (\ell, e, v)).
\]

The maximum selects, for each snapshot, the candidate fix generated from it that is more “successful” at making failing tests pass. Then, all snapshots with the same location get the same “average” suspiciousness score. Intuitively, the average pools the information from different fixes that target different locations and pass partial validation.

Finally, we combine the basic suspiciousness score \(s_{BI}\) and the mutation-based suspiciousness score \(s_{SU}\) into an overall total ordering of snapshots according to their suspiciousness:

\[
s_1 \leq s_2 \iff \begin{cases} \ell_1 \neq \ell_2 \land s_{SU}(s_1) \geq s_{SU}(s_2) \lor \\ \ell_1 = \ell_2 \land s_{SU}(s_1) \geq s_{SU}(s_2). \end{cases}
\]

where \(s_1 = (\ell_1, e_1, v_1)\) and \(s_2 = (\ell_2, e_2, v_2)\). That is, snapshots referring to different locations are compared according to their mutation-based suspiciousness, and snapshots referring to the same location are compared according to their basic suspiciousness—because they have the same mutation-based suspiciousness score. As discussed in Section III-B2, \(\text{RESTORE}\) assigns a basic suspiciousness score to each snapshot; whereas the mutation-based suspiciousness score (2) is the same, by definition, for all snapshots with the same location.

An example of how MBFL works: To get a more intuitive idea of how mutation-based fault localization can help find suitable fix locations in \(\text{RESTORE}\), let’s consider again fault \(\text{Closure113}\) in \text{DEFECTS-I}\)—shown in Figure 1 and discussed in Section II. A single failing test case \(C = \{t_x\}\) triggers the fault by reaching line 3 with provided \(\texttt{!= null}\) for \(\text{null}\). execution skips the then branch (lines 6 and 7), which eventually leads to a failure.

During the initial round of fix generation, \(\text{RESTORE}\) does not produce any valid fix, because a key fix expression \text{requireLevel}.isOn(\(i\)) is further out in the fix search space. However, it generates 16 candidate fixes that happen to pass the originally failing \(t_x\) because they all force execution through lines 6 and 7 by changing condition \text{provided \(\texttt{!= null}\) on line 3} for example, one such fixes replaces it with \text{provided \(\texttt{null || provided == null}\)}.

None of these 16 candidates is valid (because they all fail other, previously passing tests) but, instead of simply being discarded, they all are reused as evidence—to increase the suspiciousness score of line 3 (i) \(s_{SU}(C) = 1\) for each of these 16 candidates, because \(|T_x| = 1\) and \(\text{killed}(C) = T_x\); (ii) \(SU(C) = s_{SU}(C)\) for the same candidates, because they all have the same (maximum) value of suspiciousness;
order of suspiciousness against the originally passing tests called R ranked according to suspiciousness.

If fewer candidate fixes (Section III-C5) selected according to basic automated program repair: first, it often has to consider mutation has a higher chance of being significantly faster than in automated program repair, full—that is, uses 

- **RQ1:** What is RESTORE’s effectiveness in fixing bugs?
  - In RQ1, we consider RESTORE from a user’s perspective: how many valid and correct fixes it can generate.

- **RQ2:** What is RESTORE’s performance in fixing bugs?
  - In RQ2, we consider RESTORE’s efficiency: how quickly it runs versus how large a fix space it explores.

- **RQ3:** How well does retrospective fault localization (RFL) work in RESTORE?
  - In RQ3, we focus on RESTORE’s fault localization technique to assess how efficiently it drives the search for a valid fix.

- **RQ4:** How robust is RESTORE’s behavior when its internal parameters are changed?
  - In RQ4, we evaluate the impact of disabling features like partial validation and of changing some parameters that regulate retrospective fault localization.

- **RQ5:** Is retrospective fault localization generally applicable to generate-and-validate program repair techniques?
  - In RQ5, we look for evidence that retrospective fault localization is applicable not only to IAD but also to other automated program repair techniques.

**Comparison to other tools.** We compare RESTORE’s results on high-level metrics to the 13 state-of-the-art automated program repair systems for Java listed in Table II. To our knowledge these 13 tools include all recent Java repair tools available in the major software engineering conferences in the last couple of years.

### A. Subject Faults

As it has become customary when evaluating automated program repair tools for Java, our experiments use real-world faults in the DEFECTS4J curated collection [8]. DEFECTS4J includes hundreds of faults from open-source Java projects; each fault comes with at least one test triggering the failure—in addition to other passing or failing tests—as well as a programmer-written fix for the fault. Table I shows basic measures of size for DEFECTS4J’s 357 faults in 5 projects.
B. Experimental Protocol

Each experiment uses RESTORE, JAI D, or another tool to completion on a fault in DEFECTS4J. In each run we record several measures such as:

- \#v: number of valid fixes in the output;
- c: rank of the first correct fix in the output;
- T: overall wall-clock running time;
- T2V: wall-clock time until the first valid fix is found;
- T2C: wall-clock time until the first correct fix is found;
- C2V: number of fixes that are checked (generated and validated) until the first valid fix is found;
- C2C: number of fixes that are checked (generated and validated) until the first correct fix is found.

Measures C2V and C2C include all kinds of validation. For example, RESTORE performs partial and full validation (see Section III-C2 and Section III-C6); JAI D uses only one kind of (full) validation.

Correctness. We determined correct fixes by manually going through the output list of valid fixes and comparing each of them to DEFECTS4J’s manually-written fix for the fault under repair: a valid fix is correct if it is semantically equivalent to the fix manually written by the developers and included in DEFECTS4J. Conservatively, we mark as incorrect fixes that we cannot conclusively establish as equivalent in a moderate amount of time (around 15 minutes per fix).

Hardware/software setup. All the experiments ran on the authors’ institution’s cloud infrastructure. Each experiment used exclusively one virtual machine instance, running Ubuntu 14.04 and Oracle’s Java JDK 1.8 on one core of an Intel Xeon Processor E5-2630 v2 with 8 GB of RAM.

1) Statistics: Table IV reports detailed summary statistics directly comparing RESTORE to JAI D. For each measure \( m \) taken during the experiments (e.g., time \( T \)), let \( J_{m,k} \) and \( R_{m,k} \) denote the value of \( m \) in JAI D’s and in RESTORE’s run on fault \( k \). We compare RESTORE to JAI D using these metrics (illustrated and justified below) \([17]\):

\[
\sum_{\text{RESTORE}} \sum_{\text{JAI D}} J_{m,k} / \sum_{\text{JAI D}} R_{m,k} \text{ expressing the relative cost of RESTORE over JAI D for measure } m,
\]

\[
\text{mean(RESTORE) - mean(JAI D)}: \text{ the mean difference (using arithmetic mean) } \text{mean}(J_{m,k} - R_{m,k}) \text{ expressing the average additional cost of JAI D over RESTORE for measure } m.
\]

\( b_i, \hat{b}, b_h: \) the estimate \( \hat{b} \) and the 95% probability interval \( (b_i, b_h) \) of the slope \( b \) of the linear regression \( R_{m,k} = a + b \cdot J_{m,k} \) expressing RESTORE’s measure \( m \) as a linear function of JAI D’s.

\( \hat{\chi}, \chi_h: \) for the same linear regression, the estimate \( \hat{\chi} \) and the 95% probability upper bound \( \chi_h \) of the crossing ratio (where the regression line crosses the “no effect” line).

Each summary statistics compares RESTORE to JAI D on faults on which the statistics is defined for both tools; for example, the mean difference of measure \( c \) (rank of first correct fix) is over the 23 faults that both RESTORE and JAI D can correctly fix.

Interpretation of linear regression. A linear regression \( y = a + b \cdot x \) estimates coefficients \( a \) (intercept) and \( b \) (slope) in a way that best captures the relation between \( x \) and \( y \). A linear regression algorithm outputs estimates \( \hat{a} \) and \( \hat{b} \) and standard errors \( c_a \) and \( c_b \) for both coefficients: the “true” value of a coefficient \( c \) lies in interval \( (c_l, c_h) \), where \( c_l = \hat{c} - 2 \cdot c_e \leq \hat{c} \leq \hat{c} + 2 \cdot c_e = c_h \), with 95% probability.

In our experiments, values of \( x \) measure JAI D’s performance and values of \( y \) measure RESTORE’s\(^4\) thus, the linear regression line expresses RESTORE’s performance as a linear function of JAI D’s. The line \( y = x \) (that is, \( a = 0 \) and \( b = 1 \)) corresponds to no effect: the two tool’s performances are identical. In contrast, lines that lie below the “no effect” line indicate that RESTORE measures consistently lower than JAI D; since for all our measures “lower is better”, this means that RESTORE performs better than JAI D. Plots such as those in Figure 4 display the estimated regression line with a shaded area corresponding to the 95% probability error interval; thus we can visually inspect whether the difference with respect to the dashed “no effect” line is significant with 95% probability by checking whether the shaded area lies under the dashed line.

Analytically, RESTORE is significantly better than JAI D at the 95% probability level if the 95% probability upper bound \( b_h \) on the regression slope’s estimate satisfies \( b_h < 1 \): the slope is different from (in fact, less than) the “no difference” value 1 with 95% probability.

Since this notion of significant difference does not consider the intercept, it only indicates that RESTORE’s is better asymptotically; to ensure that the difference is significant in the range of values that were actually measured, we consider the crossing ratio \( \hat{\chi} = (\hat{\tau} - \min(\text{JAI D})) / (\max(\text{JAI D}) - \min(\text{JAI D})) \), which expresses the coordinate \( x = \hat{\tau} \) where the regression line \( y = \hat{a} + b \cdot x \) crosses the “no effect” line \( y = x \) relative to JAI D’s range of measured values (the crossing ratio upper bound \( \chi_h \) is computed similarly but using the upper bounds \( a_h \) and \( b_h \) of \( a \)'s and \( b \)'s 95% probability intervals). A large crossing ratio means that RESTORE is better than JAI D only on “hard” faults, whereas a small crossing ratio means that RESTORE is consistently better across the experimented range, as illustrated in the example of Figure 3.

Summarizing data with linear regression. Using linear regression to model data that doesn’t “look” linear may seem unsound. However, it is not a problem in our case given how we use linear regression: not to predict the performance of RESTORE on yet to be seen inputs, but simply to summarize the

\( x \) measures SimFix’s performance and \( y \) measures the performance of SimFix+ (SimFix with retrospective fault localization).

---

\(^4\)In Section IV-C5 \( x \) measures SimFix’s performance and \( y \) measures the performance of SimFix+ (SimFix with retrospective fault localization).

---

Table I: Basic measures of size for projects in DEFECTS4J. For each project in DEFECTS4J, its full name, the size KLOC in thousands of lines of code, the number of tests #TESTS, and the number of distinct faults #FAULTS.

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>FULL NAME</th>
<th>KLOC</th>
<th>#TESTS</th>
<th>#FAULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chart</td>
<td>JFreechart</td>
<td>96</td>
<td>2205</td>
<td>26</td>
</tr>
<tr>
<td>Closure</td>
<td>Closure Compiler</td>
<td>90</td>
<td>7927</td>
<td>133</td>
</tr>
<tr>
<td>Lang</td>
<td>Apache Commons-Lang</td>
<td>22</td>
<td>2245</td>
<td>65</td>
</tr>
<tr>
<td>Math</td>
<td>Apache Commons-Math</td>
<td>85</td>
<td>3602</td>
<td>106</td>
</tr>
<tr>
<td>Time</td>
<td>Joda-Time</td>
<td>27</td>
<td>4130</td>
<td>27</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>320</td>
<td>20109</td>
<td>357</td>
</tr>
</tbody>
</table>
cut-off time equal to twice overall running time of $R$ available for a fault, we do not run $R$ with valid fixes, the number of faults repaired with correct changing each parameters affects the number of faults repaired with these different settings. In Section IV-C4, we report how $N$ performs $R$ fix generation (Section III-C5). To understand whether these validation, we built $N$ fault localization, and performs $R$ ESTORE's behavior, we modified one of them at a time and ran $R$ by adding retrospective fault localization. Just like $R$, $R+$ undergoes a feedback loop after a few candidate fixes are generated, their partial validation results inform a more accurate iteration of fault localization. In $R+$, each iteration of the feedback loop uses $M_{R+}$ more code snippets for each suspicious statement to generate a few candidates fixes to “seed” retrospective fault localization. $M_{R+}$ is set to 20% for the initial iterations and 10% for the others, which is usually sufficient to generate enough candidates to drive the process; if this is not the case (namely, it generates less than 20 candidates), $R+$ repeatedly increases $M_{R+}$ by 10% each time, until at least 20 candidates are produced or all code snippets are used.

2) Robustness of retrospective fault localization: As described in Section III-C2 retrospective fault localization initially performs a partial validation of candidate fixes—using only failing tests. To understand the usefulness of partial validation, we built $R-$FULL: a variant of $R$ that only performs full validation—always using all available tests. In Section IV-C4 we compare $R$ and $R-$FULL on DEFECTS4I faults. In its current implementation, $R$'s behavior depends on several parameters: it uses the $N_S = 1500$ most suspicious state snapshots for fixing $R$; it adds $N_P = 10%$ more snapshots in each iteration of retrospective fault localization, and performs $N_I = 0$ extra iterations after a new suspicious location has been found (Section III-C); it targets the $N_L = 5$ most suspicious locations for final fix generation (Section III-C5). To understand whether these parameters influence $R$'s behavior, we modified one of them at a time and ran $R$ on the same DEFECTS4I faults with these different settings. In Section IV-C4 we report how changing each parameters affects the number of faults repaired with valid fixes, the number of faults repaired with correct fixes, and the running time across all faults where $R$ is able to produce at least one valid fix.

3) General application of retrospective fault localization: To support our claim that retrospective fault localization is applicable to program repair tools other than $JAI$, we implemented it atop the SimFix [9] automated program repair system. We picked SimFix because it is a state-of-the-art repair technique for Java (as shown in Table II it correctly fixes the largest number of DEFECTS4I bugs when only one fix per bug is considered) and because its source code and replication package are publicly available.

The key mechanism of retrospective fault localization is the feedback loop that uses the information gathered during partial validation of candidate fixes to tune fault localization; this mechanism is general—and hence it is present both in $R$ and SimFix+. On the other hand, how the feedback loop collects and processes information, and precisely when it does so depends on the details of the technique to which retrospective fault localization is applied. Let’s see what peculiarities of SimFix affected our implementation of retrospective fault localization in SimFix+.

A key difference between $JAI$ (and hence $R$) and SimFix is that the latter’s fault localization process, like most automated repair techniques’, targets statements as possible fault locations—rather than snapshots. Precisely, SimFix applies the Ochiai [11] spectrum-based fault-localization technique to rank statements according to their suspiciousness. For each statement above a certain suspiciousness rank, SimFix searches for “donor code” (code snippets in the same project that are similar to those close to the suspicious statement), extracts modification patterns from the donors, and builds candidate fixes by matching these patterns to the suspicious statement. To winnow the many candidate fixes that are generated by this process, it tries to match them against a “catalog” of fixes—which is generated by mining programmer-written repairs during a preliminary phase done once before running SimFix on all bugs. As soon this process determines one fix that is valid (i.e., passes all available tests), SimFix stops.

We call SimFix+ the modified version of SimFix we built by adding retrospective fault localization. Just like $R$, $R+$ undergoes a feedback loop after a few candidate fixes are generated, their partial validation results inform a more accurate iteration of fault localization. In $R+$, each iteration of the feedback loop uses $M_{R+}$ more code snippets for each suspicious statement to generate a few candidates fixes to “seed” retrospective fault localization. $M_{R+}$ is set to 20% for the initial iterations and 10% for the others, which is usually sufficient to generate enough candidates to drive the process; if this is not the case (namely, it generates less than 20 candidates), $R+$ repeatedly increases $M_{R+}$ by 10% each time, until at least 20 candidates are produced or all code snippets are used.

Since full validation may blow up the running time when many tests are available for a fault, we do not run $R-$FULL to completion but set a cut-off time equal to twice overall running time of $R$ on the fault.

We used the latest revision c2a5339 from SimFix’s repository https://github.com/xgdsmileboy/SimFix.
TABLE II: A quantitative comparison of RESTORE with 13 other tools for automated program repair on DEFECTS4J bugs. For each program repair TOOL, the table references the source of its experimental evaluation data reported here: the number of bugs that the tool could fix with a VALID fix; the number of bugs that the tool could fix with a CORRECT fix; and the resulting PRECISION (CORRECT/VALID) and RECALL (CORRECT/357, where 357 is the total number of DEFECTS4J faults used in the experiments). For tools whose data about the POSITION of fixes in the output ranking is available, the table breaks down the data separately for fixes ranked in ANY POSITION, in the FIRST POSITION, and in the TOP-10 POSITION. (These measures do not change for tools that output at most one fix per fault.) The rightmost column UNIQUE lists the number of distinct bugs that only the tool can correctly fix. Question marks represent data not available for a tool.

<table>
<thead>
<tr>
<th>TOOL</th>
<th>VALID</th>
<th>ANY POSITION</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CORRECT</td>
<td>PRECISION</td>
<td>RECALL</td>
<td>CORRECT</td>
<td>PRECISION</td>
<td>RECALL</td>
<td>CORRECT</td>
<td>PRECISION</td>
<td>RECALL</td>
<td>CORRECT</td>
<td>PRECISION</td>
</tr>
<tr>
<td>RESTORE</td>
<td>98</td>
<td>41</td>
<td>42%</td>
<td>11%</td>
<td>19</td>
<td>20%</td>
<td>5%</td>
<td>29</td>
<td>30%</td>
<td>8%</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>ACS [19]</td>
<td>23</td>
<td>18</td>
<td>78%</td>
<td>5%</td>
<td>18</td>
<td>78%</td>
<td>5%</td>
<td>18</td>
<td>78%</td>
<td>5%</td>
<td>12</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>CapGen [20]</td>
<td>25</td>
<td>22</td>
<td>88%</td>
<td>6%</td>
<td>21</td>
<td>84%</td>
<td>6%</td>
<td>22</td>
<td>88%</td>
<td>6%</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Elixir [21]</td>
<td>41</td>
<td>26</td>
<td>63%</td>
<td>7%</td>
<td>26</td>
<td>63%</td>
<td>7%</td>
<td>26</td>
<td>63%</td>
<td>7%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HDA [22]</td>
<td>?</td>
<td>23</td>
<td>?</td>
<td>6%</td>
<td>13</td>
<td>?</td>
<td>4%</td>
<td>23</td>
<td>?</td>
<td>6%</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>JAIr [7]</td>
<td>31</td>
<td>25</td>
<td>81%</td>
<td>7%</td>
<td>9</td>
<td>29%</td>
<td>3%</td>
<td>15</td>
<td>48%</td>
<td>4%</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>jGenProg [23]</td>
<td>27</td>
<td>5</td>
<td>19%</td>
<td>1%</td>
<td>5</td>
<td>19%</td>
<td>1%</td>
<td>5</td>
<td>19%</td>
<td>1%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>jKali [23]</td>
<td>22</td>
<td>1</td>
<td>5%</td>
<td>0%</td>
<td>1</td>
<td>5%</td>
<td>0%</td>
<td>1</td>
<td>5%</td>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nopol [23]</td>
<td>35</td>
<td>5</td>
<td>14%</td>
<td>1%</td>
<td>5</td>
<td>14%</td>
<td>1%</td>
<td>5</td>
<td>14%</td>
<td>1%</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>SimFix [9]</td>
<td>56</td>
<td>34</td>
<td>61%</td>
<td>10%</td>
<td>34</td>
<td>61%</td>
<td>10%</td>
<td>34</td>
<td>61%</td>
<td>10%</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>SketchFix [24]</td>
<td>26</td>
<td>19</td>
<td>73%</td>
<td>5%</td>
<td>9</td>
<td>35%</td>
<td>3%</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ssFix [25]</td>
<td>60</td>
<td>20</td>
<td>33%</td>
<td>6%</td>
<td>20</td>
<td>33%</td>
<td>6%</td>
<td>20</td>
<td>33%</td>
<td>6%</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>xPar [22, 19]</td>
<td>?</td>
<td>4</td>
<td>?</td>
<td>1%</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>4</td>
<td>?</td>
<td>1%</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Like in RESTORE, partial validation in SimFix+ runs only the failing tests for the current bug. As soon it finds a candidate fix that passes at least one failing test (“the mutant is killed”), the candidate’s fixing location increases its suspiciousness score, and hence SimFix+ immediately begins a new iteration that generates all fixes at that location and validates them. This behavior is different from RESTORE’s—where a new iteration only begins after all candidates have undergone partial validation—but is consistent with SimFix’s standard behavior of stopping as soon as it finds one valid fix.

In Section IV-C5, we experimentally compare SimFix and SimFix+ by running both on DEFECTS4J faults. Each fixing experiment used exclusively one virtual machine instance running Ubuntu 16.04 on two cores of an Intel Xeon Processor E5-2630 and 8 GB of RAM. Using the same setting as in the original experiments [9], each SimFix (and SimFix+) run is forcefully terminated after a 300-minute timeout if it is still running.

C. Experimental Results

In this section, we report the experiment results as answers to the research questions.

1) RQ1: Effectiveness: RQ1 assesses the effectiveness of RESTORE in terms of the valid and correct fixes it can generate. Since most automated program repair tools for Java have been evaluated on the same DEFECTS4J bugs as RESTORE, we can compare precision and recall of the various tools in Table II.

RESTORE and JAIr can output multiple, ranked valid fixes for the same bugs; in contrast, other tools often stop after producing one valid fix. We keep this discrepancy into account in Table II by reporting different values of precision and recall according to whether we consider all valid fixes, only those in the top-10 positions, or only those produced in the top position (the first produced).

Valid fixes. RESTORE produced at least one valid fix for 97 faults in DEFECTS4J. As shown in Table II, that is more than any other automated repair tools for Java.

On the 36 faults that JAIr can also handle, RESTORE often produces fewer valid fixes than JAIr; overall, RESTORE produces 56% (1 – 0.44) fewer valid fixes than JAIr; and produces more valid fixes for only 13 faults. As we’ll see later, RESTORE also produces more correct fixes than JAIr; thus, fewer valid fixes per bug can be read as an advantage in these circumstances.

Correct fixes. RESTORE produced at least one correct fix for 41 faults in DEFECTS4J—when considering all fixes for the same bug. As shown in Table II, that is more than any of the other automated repair tools for Java, and constitutes a 21% increase (7 faults) over the runners-up SimFix and SketchFix according to this metric. RESTORE correctly fixed 8 faults that no other tool can currently fix, in addition to the 6 faults that only RESTORE and JAIr can fix. This indicates that RESTORE’s fix space is somewhat complementary to other repair tools for Java.

The output list of valid fixes should ideally rank correct fixes as high as possible—so that a user combing through the list would only have to peruse a limited number of fix suggestions. For the 23 faults that both RESTORE and JAIr correctly fix, the two tools behave similarly on the majority of bugs: RESTORE ranks the first correct fix 1 position higher than
TABLE III: Summary of the experimental results. For each fault in DEFECTS4J (identified by its PROJECT name and ID) that Restore or JAD can correctly fix: the size LOC of the faulty method being repaired (in lines of code), and the number of Passing and Failing tests exercising the method; for each tool Restore and JAD: the number \#V of Valid fixes; the position \#C of the first Correct fix in the output; the wall-clock running time T to completion; the wall-clock running time until the first valid fix (T2V) and the first correct fix (T2C) are found. All times are in minutes.

<table>
<thead>
<tr>
<th>FAULT ID</th>
<th>PROJECT ID</th>
<th>LOC</th>
<th>P</th>
<th>F</th>
<th>#V</th>
<th>C</th>
<th>T</th>
<th>T2V</th>
<th>T2C</th>
</tr>
</thead>
<tbody>
<tr>
<td>chart</td>
<td>1</td>
<td>32</td>
<td>37</td>
<td>1</td>
<td>291</td>
<td>221</td>
<td>28.5</td>
<td>7.5</td>
<td>21.6</td>
</tr>
<tr>
<td>chart</td>
<td>9</td>
<td>38</td>
<td>1</td>
<td></td>
<td>17</td>
<td>-</td>
<td>14.4</td>
<td>3.3</td>
<td>-</td>
</tr>
<tr>
<td>chart</td>
<td>11</td>
<td>32</td>
<td>15</td>
<td>1</td>
<td>1</td>
<td>19.4</td>
<td>17.6</td>
<td>17.6</td>
<td>-</td>
</tr>
<tr>
<td>chart</td>
<td>24</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>26.7</td>
<td>25.0</td>
<td>25.0</td>
<td>2</td>
</tr>
<tr>
<td>chart</td>
<td>26</td>
<td>108</td>
<td>23</td>
<td>22</td>
<td>213</td>
<td>3</td>
<td>32.7</td>
<td>11.5</td>
<td>12.2</td>
</tr>
<tr>
<td>closure</td>
<td>5</td>
<td>98</td>
<td>56</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>247.3</td>
<td>186.3</td>
<td>186.3</td>
</tr>
<tr>
<td>closure</td>
<td>11</td>
<td>18</td>
<td>2261</td>
<td>2</td>
<td>434</td>
<td>20</td>
<td>846.8</td>
<td>167.5</td>
<td>201.5</td>
</tr>
<tr>
<td>closure</td>
<td>14</td>
<td>97</td>
<td>3005</td>
<td>3</td>
<td>1</td>
<td>355.0</td>
<td>123.5</td>
<td>123.5</td>
<td>0</td>
</tr>
<tr>
<td>closure</td>
<td>18</td>
<td>122</td>
<td>3929</td>
<td>1</td>
<td>1</td>
<td>561.4</td>
<td>101.5</td>
<td>101.5</td>
<td>5</td>
</tr>
<tr>
<td>closure</td>
<td>31</td>
<td>122</td>
<td>3835</td>
<td>1</td>
<td>12</td>
<td>570.6</td>
<td>118.4</td>
<td>118.4</td>
<td>9</td>
</tr>
<tr>
<td>closure</td>
<td>33</td>
<td>27</td>
<td>259</td>
<td>1</td>
<td>171</td>
<td>141</td>
<td>290.8</td>
<td>19.2</td>
<td>266.7</td>
</tr>
<tr>
<td>closure</td>
<td>40</td>
<td>46</td>
<td>305</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>25.9</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>closure</td>
<td>46</td>
<td>11</td>
<td>10</td>
<td>3</td>
<td>161</td>
<td>116</td>
<td>24.1</td>
<td>4.2</td>
<td>21.3</td>
</tr>
<tr>
<td>closure</td>
<td>62</td>
<td>45</td>
<td>45</td>
<td>2</td>
<td>122</td>
<td>90</td>
<td>37.5</td>
<td>10.3</td>
<td>30.4</td>
</tr>
<tr>
<td>closure</td>
<td>63</td>
<td>45</td>
<td>45</td>
<td>2</td>
<td>122</td>
<td>49</td>
<td>34.8</td>
<td>8.8</td>
<td>20.3</td>
</tr>
<tr>
<td>closure</td>
<td>73</td>
<td>70</td>
<td>482</td>
<td>1</td>
<td>1</td>
<td>49.2</td>
<td>39.4</td>
<td>39.4</td>
<td>1</td>
</tr>
<tr>
<td>closure</td>
<td>86</td>
<td>39</td>
<td>52</td>
<td>7</td>
<td>1</td>
<td>87.8</td>
<td>32.5</td>
<td>32.5</td>
<td>0</td>
</tr>
<tr>
<td>closure</td>
<td>113</td>
<td>39</td>
<td>26</td>
<td>1</td>
<td>1</td>
<td>48.7</td>
<td>32.5</td>
<td>32.5</td>
<td>0</td>
</tr>
<tr>
<td>closure</td>
<td>115</td>
<td>69</td>
<td>151</td>
<td>5</td>
<td>761</td>
<td>1</td>
<td>853.4</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>closure</td>
<td>118</td>
<td>23</td>
<td>19</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>33.0</td>
<td>24.6</td>
<td>29.7</td>
</tr>
<tr>
<td>closure</td>
<td>119</td>
<td>124</td>
<td>764</td>
<td>1</td>
<td>12</td>
<td>113.5</td>
<td>94.9</td>
<td>113.4</td>
<td>0</td>
</tr>
<tr>
<td>closure</td>
<td>125</td>
<td>15</td>
<td>538</td>
<td>1</td>
<td>103</td>
<td>103</td>
<td>154.1</td>
<td>13.1</td>
<td>151.0</td>
</tr>
<tr>
<td>closure</td>
<td>126</td>
<td>95</td>
<td>71</td>
<td>2</td>
<td>39</td>
<td>1</td>
<td>103.6</td>
<td>7.7</td>
<td>7.8</td>
</tr>
<tr>
<td>closure</td>
<td>128</td>
<td>9</td>
<td>61</td>
<td>1</td>
<td>14</td>
<td>1</td>
<td>97.8</td>
<td>9.3</td>
<td>9.3</td>
</tr>
<tr>
<td>closure</td>
<td>130</td>
<td>36</td>
<td>301</td>
<td>1</td>
<td>15</td>
<td>4</td>
<td>239.1</td>
<td>216.9</td>
<td>221.4</td>
</tr>
<tr>
<td>lang</td>
<td>6</td>
<td>24</td>
<td>35</td>
<td>1</td>
<td>51</td>
<td>5</td>
<td>123.1</td>
<td>6.6</td>
<td>19.7</td>
</tr>
<tr>
<td>lang</td>
<td>33</td>
<td>11</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>11.7</td>
<td>11.6</td>
<td>11.6</td>
<td>7</td>
</tr>
<tr>
<td>lang</td>
<td>38</td>
<td>6</td>
<td>33</td>
<td>1</td>
<td>69</td>
<td>18</td>
<td>67.7</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>lang</td>
<td>45</td>
<td>37</td>
<td>0</td>
<td>1</td>
<td>40</td>
<td>-</td>
<td>35.6</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>lang</td>
<td>51</td>
<td>51</td>
<td>0</td>
<td>1</td>
<td>37</td>
<td>1</td>
<td>81</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>lang</td>
<td>55</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>29</td>
<td>10</td>
<td>12.5</td>
<td>1.1</td>
<td>3.0</td>
</tr>
<tr>
<td>lang</td>
<td>59</td>
<td>17</td>
<td>2</td>
<td>1</td>
<td>12</td>
<td>7</td>
<td>31.7</td>
<td>5.0</td>
<td>11.8</td>
</tr>
<tr>
<td>math</td>
<td>5</td>
<td>22</td>
<td>5</td>
<td>1</td>
<td>225</td>
<td>1</td>
<td>43.1</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>math</td>
<td>32</td>
<td>52</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>102.2</td>
<td>9.2</td>
<td>9.2</td>
<td>5</td>
</tr>
<tr>
<td>math</td>
<td>33</td>
<td>40</td>
<td>21</td>
<td>1</td>
<td>2</td>
<td>114.9</td>
<td>74.0</td>
<td>74.1</td>
<td>0</td>
</tr>
<tr>
<td>math</td>
<td>50</td>
<td>125</td>
<td>3</td>
<td>1</td>
<td>812</td>
<td>94</td>
<td>489.2</td>
<td>98.5</td>
<td>137.6</td>
</tr>
<tr>
<td>math</td>
<td>53</td>
<td>5</td>
<td>19</td>
<td>1</td>
<td>10</td>
<td>9</td>
<td>60.0</td>
<td>25.2</td>
<td>51.3</td>
</tr>
<tr>
<td>math</td>
<td>59</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>math</td>
<td>80</td>
<td>15</td>
<td>16</td>
<td>1</td>
<td>1450</td>
<td>936</td>
<td>86.9</td>
<td>13.2</td>
<td>65.2</td>
</tr>
<tr>
<td>math</td>
<td>82</td>
<td>15</td>
<td>13</td>
<td>1</td>
<td>44</td>
<td>22</td>
<td>63.9</td>
<td>3.6</td>
<td>25.5</td>
</tr>
<tr>
<td>math</td>
<td>85</td>
<td>43</td>
<td>12</td>
<td>1</td>
<td>235</td>
<td>5</td>
<td>16.7</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>time</td>
<td>19</td>
<td>31</td>
<td>721</td>
<td>1</td>
<td>38</td>
<td>30</td>
<td>15.5</td>
<td>10.4</td>
<td>14.8</td>
</tr>
</tbody>
</table>

| TOTAL    |           | 1887| 19518| 88| 5560| 6047.1| 1645.0| 425.9| 10433| -8998.7| 2747.7| 2625.0|

TABLE IV: Summary statistics of the experiments. For each MEASURE: the relative cost \(\frac{\text{TEST}}{\text{JAD}}\) of Restore over JAD; the mean cost difference \(\frac{\text{JAD} - \text{TEST}}{\text{JAD}}\) between JAD and Restore; the estimate \(b\) of slope \(b\) expressing Restore’s cost as a linear function of JAD, with 95% probability interval \((b_l, b_h)\); the estimate \(\chi\) and upper bound \(\chi_u\) on the crossing ratio \(\chi\).

<table>
<thead>
<tr>
<th>MEASURE</th>
<th>(\frac{\sum \text{TEST} - \sum \text{JAD}}{\sum \text{JAD}})</th>
<th>(\text{JAD} - \text{TEST})</th>
<th>slope (b); 95% crossing (\chi)</th>
<th>(b_l)</th>
<th>(b_h)</th>
<th>(\chi)</th>
<th>(\chi_u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#V</td>
<td>0.44</td>
<td>181</td>
<td>0.2 0.3 0.4 0.02 0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.98</td>
<td>1</td>
<td>0.6 0.7 0.8 0.05 0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>0.32</td>
<td>214</td>
<td>0.2 0.2 0.3 0.02 0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2V</td>
<td>0.29</td>
<td>83</td>
<td>0.1 0.1 0.2 0.02 0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2C</td>
<td>0.42</td>
<td>64</td>
<td>-0.0 0.1 0.2 0.03 0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2V</td>
<td>0.43</td>
<td>1498</td>
<td>0.2 0.3 0.4 0.03 0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2C</td>
<td>0.64</td>
<td>602</td>
<td>-0.2 -0.1 0.3 0.11 0.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
than Jaid, since it can also use expressions outside method
fixme in the same class to build fixes (Section III-C5). In all
experiments when Restore could produce valid fixes, 68,344
candidate fixes produced during final fix generation belong to
the extended fix space (and hence cannot be produced by Jaid).
Among them, 2,094 candidates are valid (corresponding to 52
faults); and 9 are correct (one for each of 9 faults). In all, the
extended fix space enabled Restore to generate valid fixes for
17 more bugs than Jaid, correct fixes for 9 more bugs than
Jaid; and correct fixes for 5 of the 8 bugs that only Restore
can correctly fix among all tools (Table II).

Multi-line fixes. Four of the bugs correctly fixed by Restore
(Closure40, Closure46, Closure115, and Closure128) have
programmer-written fixes in Defects4J that change multiple
lines. For example, project developers fixed the buggy method
of bug Closure128:

```java
static boolean isSimpleNumber(String s) {
  int len = s.length();
  for (int index = 0; index < len; index++) {
    char c = s.charAt(index);
    if (c < '0' || c > '9') return false;
  }
  return len > 0 && s.charAt(0) != '0';
}
```

by adding `if (len == 0) return false;` before line 3 and
changing line 7 to `return len > 0 && s.charAt(0) != '0';`. Restore,
instead, just changed line 7 to

```java
if (len == 1) return true;
  else return len > 0 && s.charAt(0) != '0';
```

Restore’s conditional return is equivalent to the program-mer-
written fix even though it only modifies one location. Such
complex fixes demonstrate how Restore manages to combine
bug-fixing effectiveness and competitive performance: this fix
was the first valid fix in the output, generated in less than 10
minutes.

RESTORE can correctly fix 41 faults in Defects4J when
allowing multiple fixes for the same bug; 19 of these faults
are fixed by the first fix output by Restore. Restore trades
off a lower precision for a larger fix space, which includes
correct fixes for 8 faults that no other tools can fix.

2) RQ2: Performance: RQ2 assesses the performance of
Restore in terms of its running time.

Total time. Restore’s wall-clock total running time per fault
ranged between 1.5 minutes and 21 hours, with a median
of 53 minutes. This means that Restore achieves a speedup
of 3.1 (1/0.32) over Jaid. Figure 4c indicates that the major
difference in favor of Restore is particularly marked for the
harder faults—which generally require long running times.

Comparing with other tools in terms of running time would
require to replicate their evaluations using uniform experimen-
tal settings—something we did not do in this experimental
evaluation. Nevertheless, it is plausible other tools have an
overall significant running time too: HDA, ACS, ssFix, Elixir,
CapGen, and SimFix are all based on mining external code
to learn common features of correct fixes; this process is
likely time consuming—even though it would be amortized
over a consequent long run of the tools—but is not present in
Restore (or Jaid). This indicates that Restore’s performance
is likely to remain competitive overall, and that retrospective
fault localization can bring a performance boon. Performing
more fine-grained experimental comparisons belongs to future
work.
**Time to valid/correct.** Especially important for a repair tool’s practical usability is the time elapsing until a fix appears in the output. All else being equal, shorter times mean that users can start inspecting fix suggestions earlier—possibly supporting a more interactive usage—so that the whole repair process can be sped up. On average, ESTORE outputs the first valid fix 83 minutes before JAIĐ—a 3.4 speedup (1/0.29) according to the linear regression line; and the first correct fix 64 minutes before JAIĐ—a 2.3 speedup (1/0.43). While Figure 4d and Figure 4e suggest that these averages summarize a behavior that varies significantly with some faults, it is clear that ESTORE’s is substantially faster in many cases—especially with the “harder” faults that require long absolute running times. Cutting the running times in less than half on average in these cases results in speedups that often span one order of magnitude, and sometimes even two orders of magnitudes.

ESTORE’s performance is the combined result of exploring a larger fix space than JAIĐ (which takes more time) and using retrospective fault localization (which speeds up fault localization). That ESTORE finds many more correct fixes while simultaneously often drastically decreasing the running times indicates that its fault localization techniques bring a decidedly positive impact with no major downsides.

| # LOCALIZED CANDIDATES SHARPENING PLAUSIBLE |
|---|---|---|---|
| CORRECT | 41 | 23,529 | 2,582 | 511 |
| VALID | 98 | 84,989 | 7,348 | 2,762 |
| ALL | 357 | 495,399 | 9,854 | 3,377 |
| SINGLE | 74 | 61,530 | 5,307 | 2,108 |

3) RQ3: Fault Localization: Retrospective fault localization is ESTORE’s key contribution: a novel fault localization technique that naturally integrates into generate-and-validate program repair algorithms. RQ1 and RQ2 ascertained that retrospective fault localization indirectly improves program repair by supporting searching a larger fix space while simultaneously improving performance. In RQ3 we look into how retrospective fault localization is directly more efficient.

**Checked to valid/correct.** To this end, we follow Section III-C3’s survey of fault localization in automated program repair and compare the number of fixes that are checked (generated and validated) until the first valid fix (C2V, called NFC in [26]) and the first correct (C2C) fix is generated. The smaller these measures the more efficiently fault localization drives the search for a valid or correct fix.

ESTORE needs to check 57% fewer (1 − 0.43) fixes than JAIĐ until it finds the first valid fix. ESTORE significantly improves measure C2C too: it needs to check 36% (1 − 0.64) fewer fixes than JAIĐ until it finds the first correct fix. Even though JAIĐ is more efficient on some faults, Figure 4d and Figure 4e show that ESTORE prevails in the clear majority of cases, as well as in the harder cases that require to check many more candidate fixes (exploring a larger search space); the difference is clearly statistically significant (slope under 0.4 with 95% confidence, and the overlap of regression line and “no effect” line is only for small absolute values of C2V and C2C, as also reflected by the crossing ratio). These results are direct evidence of retrospective fault localization’s greater precision in searching for fault causes.

**Candidate fixes as mutations.** Retrospective fault localization treats candidate fixes as mutants. As described in Section III-C3, a candidate that passes at least one previously failing test (during partial validation) increases the suspiciousness ranking of all snapshots associated with the candidate’s location. Such candidate fixes sharpen fault localization, and hence we call them sharpening candidates. If a sharpening candidate is furthermore associated with a location where a correct fix can be built (according to the correct fixes actually produced in the experiments or in DEFEETS4J) we call it plausible.

Table V measures sharpening and plausible candidates in different categories. Only 2% of all candidates are sharpening; however, the percentage grows to 9% for faults ESTORE can build a valid fix for; and to 12% for faults ESTORE can build a correct fix for. These cases are those where retrospective fault localization achieved progress; in some cases (plausible candidates) it even led to finding program locations where a correct fix can be built. Table V also shows that sharpening and plausible candidates are 9% for faults with a single failing test case in DEFEETS4J. These can be considered “hard” faults because of the limited information about faulty behavior; retrospective fault localization can perform well even in these conditions.

Table VI looks at ESTORE’s fault localization feedback loop, which is repeated until retrospective fault localization has successfully refined the suspiciousness ranking. While some faults require as many as ten iterations, in most cases only one iteration is needed to achieve progress. This suggests that candidate fixes are often “good mutants” to perform fault localization—and they provide information that is complementary to that available with simpler spectrum-based techniques.
TABLE VI: How many times retrospective fault localization iterates. Among all faults in DEFECTS4J that RESTORE could repair with a VALID or a CORRECT fix, how many ITERATIONS RESTORE’s feedback loop went through to sharpen fault localization.

<table>
<thead>
<tr>
<th>ITERATIONS</th>
<th>VALID</th>
<th>CORRECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE VII: Comparison between RESTORE’s and RESTORE-full’s effectiveness and performance. The number of DEFECTS4J faults with VALID fixes, with CORRECT fixes, and the average running TIME (in minutes) per fault in RESTORE compared to those in RESTORE-full (RESTORE with only full validation).

<table>
<thead>
<tr>
<th></th>
<th>VALID</th>
<th>CORRECT</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESTORE</td>
<td>98</td>
<td>41</td>
<td>122.4</td>
</tr>
<tr>
<td>RESTORE-full</td>
<td>87</td>
<td>27</td>
<td>160.6</td>
</tr>
</tbody>
</table>

**Partial validation.** Table VII summarizes some key performance measures about RESTORE, and compares them to the same measures for RESTORE-full—a variant of RESTORE that only uses full validation as discussed in Section IV-B2.

Restoring’s retrospective fault localization improves the efficiency of the search for correct fixes: on average, 57% fewer fixes need to be generated and checked until a valid one is found. The candidate fixes generated by RESTORE are effective as mutants to perform fault localization.

4) RQ4: Robustness: RQ4 investigates whether RESTORE’s overall effectiveness and running time are affected by changes in features and parameters of its algorithms.

Partial validation. Table VII summarizes some key performance measures about RESTORE, and compares them to the same measures for RESTORE-full—a variant of RESTORE that only uses full validation as discussed in Section IV-B2.

Restoring’s retrospective fault localization is clearly less effective than RESTORE, as the former misses valid fixes for 11 faults and correct fixes for 14 faults that the latter can find. It is also slower than RESTORE; in fact, much slower than what suggested by the 40-minute difference per fault reported in Table VII. Remember that RESTORE-full is forcefully terminated after it runs for twice as long as RESTORE on each fault. With this cap, RESTORE-full could not complete its analysis for 17 of the 98 faults where RESTORE produces valid fixes, and it could not even finish the first round of mutation-based fault localization for 13 of them. (RESTORE could produce a correct fix for 11 out of these 13 faults.) Therefore, partial validation is an important ingredient to make retrospective fault localization scale up, and hence be effective.

Parameters. Table VIII shows how some key performance measures about RESTORE change as we individually change the value of each of four parameters $N_S$, $N_P$, $N_I$, and $N_L$.

The more snapshots $N_S$ are used for fixing, the more valid and correct fixes RESTORE can generate. A closer look indicates a monotonic behavior: if RESTORE can fix a fault using $s$ snapshots, it can also fix it using $t > s$ snapshots. Unsurprisingly, increasing $N_S$ also increases the running time. Since the number of correctly fixed faults increases only by a few units, whereas the running time increases substantially, it seems a case of diminishing returns.

In contrast, the effects of changing the percentage $N_P$ of snapshots used in each iteration of retrospective fault localization are very modest—both on the running time and on the number of valid and correct fixes. Increasing $N_I$—that is, iterating retrospective fault localization even after it has contributed to refining the ranking of suspicious locations—also has a modest effect on effectiveness but noticeably increases the running time. Overall, RESTORE’s behavior is not much affected by how snapshots are sampled, but repeating retrospective fault localization beyond what is needed tends to decrease RESTORE’s efficiency without any clear advantage.

The default value of parameter $N_L$—the number of most suspicious locations used for final fix generation—seems to strike a good balance between effectiveness and efficiency: increasing $N_L$ does not lead to fixing more faults, but visibly increases the running time; decreasing it reduces the running time, but also fixes fewer faults.

5) RQ5: Generalizability: By comparing SimFix to SimFix+ (our variant of SimFix that implements retrospective fault localization) RQ5 analyzes the applicability of retrospective fault localization to tools other than RESTORE.

Both SimFix and SimFix+ can build valid fixes for the same 64 faults in DEFECTS4J. SimFix can generate valid fixes for another 4 faults that SimFix+ cannot, and hence can fix 68 faults in total; conversely, SimFix+ can generate valid fixes for another 7 faults that SimFix cannot, and hence can fix 71 in total. In the case of the 4 faults that only SimFix
can repair, SimFix’s simple spectrum-based fault localization was sufficiently precise to guide the process to success (by ranking high locations that lead to suitable donor code). In contrast, the donor code leading to candidates that are useful for mutation-based fault localization (see Section IV-B3) was ranked low; thus, SimFix+’s retrospective fault localization took multiple iterations and a long time to go through the many candidates, and ended up hitting the tool’s 300-minute timeout. The cases of the 7 faults that only SimFix+ can repair are opposite: spectrum-based fault localization was imprecise, hampering the performance of SimFix, whereas mutation-based fault localization could successfully complete its analysis and sharpen the suspiciousness ranking as required by these 7 faults.

As shown in Figure 5, both SimFix and SimFix+ can build correct fixes for the same 33 faults in DEFECTS4J. SimFix can generate correct fixes for 1 other fault that SimFix+ cannot, and hence can correctly fix 34 faults in total; conversely, SimFix+ can generate correct fixes for another 2 faults that SimFix cannot, and hence can correctly fix 35 in total. As in the case of the valid fixes, the differences are due to higher ranks of locations that lead to suitable donor code against lower ranks of donor code that is useful for mutation-based fault localization (or vice versa) in certain conditions.

How does SimFix+ compare to SimFix on the large majority of DEFECTS4J faults where both tools are successful? For the 64 DEFECTS4J faults that both can repair with at least a valid fix, Figure 6a and Figure 6c visually compare total running time (T2V) and number of candidates checked (C2V) until a valid fix is found. When both SimFix and SimFix+ are successful, the latter is decidedly more efficient: the summary statistics of Table IX confirm that it takes 69% of the running time, and needs to check 60% as many candidates. For the 33 DEFECTS4J faults that both tools can repair with a correct fix, the advantage of SimFix+ over SimFix in terms of total running time (T2C) and number of candidates checked (C2C) until a correct fix is found is also evident, as shown in Figure 6b, Figure 6d and Table IX.

Unlike RESTORE—which "uses" some of the efficiency brought by retrospective fault localization to explore a larger fix space than JAFD—SimFix+ has exactly the same fix space as SimFix. What we found in this section’s experiments is consistent with this design choice: SimFix+ has an effectiveness that is very similar to that of SimFix (precisely, slightly better precision and recall); retrospective fault localization brings clear improvements but mostly in terms of efficiency. Trading off some of this greater efficiency to explore a larger fix space belongs to future work.

D. Threats to Validity

Construct validity. Threats to construct validity are concerned with whether the measurements taken in the evaluation realistically capture the phenomena under investigation.

Since SimFix and SimFix+ stop after one valid fix is built, total running time T and running time T2V until a valid fix is found coincide.

Figure 5: Faults in DEFECTS41 bugs for which SimFix and SimFix+ can build correct fixes.

TABLE IX: Summary statistics of the experiments on SimFix and SimFix+.

For each MEASURE: the relative cost \( \frac{\sum_{\text{SimFix}}}{\sum_{\text{SimFix+}}} \) of SimFix+ over SimFix; the mean cost difference mean(SimFix−SimFix+) between SimFix and SimFix+; the estimate \( b \) of slope \( b \) expressing RESTORE's cost as a linear function of SimFix, with 95% probability interval \((b_l, b_u)\); the estimate \( \chi \) and upper bound \( \chi_u \) on the crossing ratio \( \chi \).

<table>
<thead>
<tr>
<th>MEASURE</th>
<th>( \frac{\sum_{\text{SimFix}}}{\sum_{\text{SimFix+}}} )</th>
<th>mean(SimFix−SimFix+)</th>
<th>slope ( b )</th>
<th>95% crossing ( \chi )</th>
<th>( b_l )</th>
<th>( b_u )</th>
<th>( \chi )</th>
<th>( \chi_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2V</td>
<td>0.69</td>
<td>14</td>
<td>0.5 0.6</td>
<td>0.7 0.03 0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2C</td>
<td>0.63</td>
<td>9</td>
<td>0.3 0.5</td>
<td>0.6 0.06 0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2V</td>
<td>0.60</td>
<td>238</td>
<td>0.4 0.5</td>
<td>0.6 0.02 0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2C</td>
<td>0.55</td>
<td>166</td>
<td>0.3 0.5</td>
<td>0.7 0.01 0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Comparison of SimFix and SimFix+ on various measures. For each measure \( m \), a point with coordinates \( x = u, y = v \) indicates that SimFix costed \( u \) on a certain fault while SimFix+ costed \( v \) on the same fault. As in Figure 4, the dashed line is \( y = x \); the solid line is the linear regression with \( y \) dependent on \( x \).
An important measure is the number of correct fixes—fixes that are semantically equivalent to programmer-written fixes for the same fault. Since correctness is manually assessed, different programmers may disagree with the authors’ classifications in some cases. To mitigate the threat, we follow the common approach of being conservative: fixes that do not clearly have the same behavior as the programmer-written ones are regarded as incorrect.

Several measures could be used to assess the performance of automated program repair tools. In our evaluation, we focus on measures that have a clear impact on practical usability—especially number of valid and correct fixes, and running time.

When, in Section IV-C3, we zoom in to analyze the behavior of different aspects of ESTORE’s fault localization technique, we use the number of fixes generated and validated until the first valid fix is found. This measure has been used by other evaluations of fault localization in program repair because it assesses the overall effectiveness of fault localization in guiding the search for valid fixes—instead of measures, such as the rank of program locations, narrowly focused on the standard output of fault localization without context.

Our summary statistics in Table IV follow recommended practices; in particular, we used statistics that are easy to interpret, and based statistical significance on whether “an estimate is at least two standard errors away from some […] value that would indicate no effect present”.

Internal validity. Threats to internal validity are mainly concerned with factors that may affect the evaluation results but were not properly controlled for.

One obvious threat to internal validity are possible bugs in the implementation of ESTORE, or in the scripts we used to run our experiments. To address this threat, we reviewed our code and our experimental infrastructure between authors, to slash chances that major errors affected the soundness of our results.

Another possible threat comes from comparing ESTORE to tools other than JAID based on the data of their published experimental evaluations—without repeating the experiments on the same system used to run ESTORE. This threat has only limited impact: we do not compare ESTORE to tools other than JAID on measures of performance—which require a uniform runtime environment—but only on measures of effectiveness such as precision and recall—which record each tool’s bug-fixing capabilities on the same DEFECTS4J benchmark.

External validity. Threats to external validity are mainly concerned with whether our findings generalize—supporting broader conclusions.

DEFECTS4J has become accepted as an effective benchmark to evaluate dynamic analysis and repair tools for Java, because of the variety and size of its curated collection of faults. At the same time, as with every benchmark, there is the lingering risk that new techniques become narrowly optimized for DEFECTS4J without ascertaining that they do not overfit the benchmark. As future work, we plan to carry out evaluations on faults from different sources, to strengthen our claims of external validity.

Both the implementation and the evaluation of ESTORE are based on the JAID repair system, and hence the fine-grained evaluation of ESTORE focused on how it improves over JAID. To demonstrate that most of the ideas behind retrospective fault localization are applicable to other generate-and-validate automated program repair techniques, we also implemented retrospective fault localization on top of SimFix—another state-of-the-art program repair technique for Java. Generalizing retrospective fault localization to work with repair techniques that are even more different—for example, based on synthesis—belongs to future work.

V. RELATED WORK

Research in automated program repair has gained significant traction in the decade since the publication of the first works in this area—often taking advantage of advances in fault localization. In this section, we focus on reviewing the approaches that have more directly influenced the design of ESTORE. Other publications provide comprehensive summaries of fault localization and automated program repair techniques.

A. Fault Localization

The goal of fault localization is finding positions in the source code of a faulty program that are responsible for the fault. The concrete output of a fault localization technique is a list of statements, branches, or program states ranked according to their likelihood of being implicated with a fault. By focusing their attention on specific parts of a faulty program, such lists should help programmers debugging and patching. While this information may not be enough for human programmers, it is a fundamental ingredient of automated program repair. Thus, research in fault localization has seen a resurgence as part of an effort to improve automated repair.

Spectrum-based fault localization techniques are among the most extensively studied. The basic idea of spectrum-based fault localization is to use coverage information from tests to infer suspiciousness values of program entities (statements, branches, or states); for example, a statement executed mostly by failing tests is more suspicious than one executed mostly by passing tests.

Several automated program repair techniques use spectrum-based fault localization algorithms. Generating a correct fix, however, typically requires more information than the suspiciousness ranking provided by spectrum-based techniques; an empirical evaluation of 15 popular spectrum-based fault localization techniques found that the typical evaluation criteria used in fault-localization research (namely, the suspiciousness ranking) are not good predictors of whether a technique will perform well in automated program repair. This observation buttresses our suggestion that fault localization should be co-designed with automated program repair to perform better—as we did with retrospective fault localization.
Fault localization needs sources of additional information to be more accurate. One effective idea—pioneered by delta debugging [40]—is to modify a program and observe how small local modifications affect its behavior in passing vs. failing runs. More recently, ideas from mutation testing [41] and delta-debugging have been combined to perform mutation-based fault localization: randomly mutate a faulty program, and assess whether the mutation changes the behavior on passing or failing tests.

Metallaxis [6] and MUSE [5, 42] are two representative mutation-based fault localization techniques. Experiments with these tools indicate that mutation-based fault localization often outperforms spectrum-based fault localization in different conditions [5, 6]. In our work, we used a variant of the Metallaxis algorithm, because it tends to perform better than MUSE with tasks similar to those we need for automated program repair. The main downside of mutation-based fault localization is that it can be a performance hog, because it requires to rerun tests on a large amount of mutants. Thus, a key idea of our retrospective fault localization is to reuse, as much as possible, validation results (which have to be performed anyway for program repair) to perform mutation-based analysis.

In retrospective fault localization, a simple fault-localization process bootstraps a feedback loop that implements a more accurate mutation-based fault localization. ESTORE currently uses a spectrum-based technique for the bootstrap phase (see Section III-B2); however, other fault localization techniques—such as those based on statistical analysis [43, 44], machine learning [45, 46], or deep learning [47]—could be used instead. Even techniques that are not designed specifically for fault localization may be used, as long as they produce a ranked list of suspicious program entities. For example, MintHint [48] performs a correlation analysis to identify expressions that should be changed to fix faults. The expressions, or more generally their program locations, could thus be treated as suspicious entities for the purpose of initiating fault localization.

B. Automated Program Repair

Generate-and-validate (G&V) remains the most widespread approach to automated program repair: given a faulty program and a group of passing and failing tests, generate fix candidates by heuristically searching a program space; then, check the validity of candidates by rerunning all available tests. GenProg [30, 49] pioneered G&V repair by using genetic programming to mutate a faulty program and generate fix candidates. RERepair [50] works similarly to GenProg but uses random search instead of genetic programming. AE [51] enumerates variants systematically, and uses simple semantic checks to reduce the number of equivalent fix candidates that have to be validated. Par [38] uses patterns modeled after existing programmer-written fixes to guide the search toward generating fixes that are easier for programmers to understand.

This first generation of G&V tools is capable of working on real-world bugs, but has the tendency to overfit the input tests [3]—thus generating many fixes that pass validation but are not actually correct [2]. A newer generation of tools addressed this shortcoming by supplying G&V program repair with additional information, often coming from mining human-written fixes. AutoFix [39] uses contracts (assertions such as pre- and postconditions) to improve the accuracy of fault localization. SPR [52] generates candidate fixes according to a set of predefined transformation functions; Prophet [53] implements a probabilistic model, learned by mining human-written patches, on top of SPR to direct the search towards fixes with a higher chance of being correct. HDA [22] performs a stochastic search similar to genetic programming, and uses heuristics mined from fix histories available in public bug repositories to guide the search toward generating correct fixes. ACS [19] builds precise changes of conditional predicates, based on a combination of dependency analysis and mining API documentations. Genesis [54] learns templates for code transformations from human patches, and instantiates the templates to generate new fixes. ssFix [25] matches contextual information at the fixing location to a database of human-written fixes, and uses this to drive fix generation. JAD [21] uses rich state abstractions in fault localization to generate correct repairs for a variety of bugs. Elixir [21] specializes in repairing buggy method invocations, using machine-learned models to prioritize the most effective repairs. SimFix [9] combines the information extracted from existing patches and snippets similar to the code under fix to make the search for correct fixes more efficient. CapGen [20] improves the effectiveness of expression-level fix generation by leveraging fault context information so that fixes more likely to be correct are generated first. SketchFix [24] expresses program repair as a sketching problem [55] with “holes” in suspicious statements, and uses synthesis to fill in the holes with plausible replacements. ESTORE and SketchFix both work to better integrate phases that are normally separate in automated repair—fault localization and fix validation in ESTORE, and fix generation and fix validation in SketchFix. Most of these tools are quite effective at generating correct fixes for real bugs; several of them do so by mining additional information. Further improvements in G&V repair hinge on the capability of improving the precision of fault localization. A promising option is using mutation-based fault localization, which was recently investigated [56] on data from the BugZoo repair benchmarks. [56] found no significant improvement on the overall repair performance—supposedly because the single-edit mutations used in the study may be too simple to reveal substantial differences between programs variants.

In our retrospective fault localization, we combine mutation testing with a G&V technique that can generate complex “higher-order” program mutants, and tightly integrate fault localization and fix generation. This way, ESTORE benefits...

[https://github.com/squaresLab/BugZoo]
from the additional accuracy of mutation-based fault localization without incurring the major overhead typical of mutation testing.

**Test selection and prioritization** has been studied in the context of G&V automated program repair to improve the efficiency of fix evaluation. For example, techniques based on genetic programming—such as GenProg [30] and PAR [39]—can become very computationally expensive if they evaluate all program mutations on all available tests. To improve this situation, one could use all the failing tests but only a small sample of the passing tests—selected randomly [57] or using an adaptive test suite reduction strategy [58]. Another approach is the FRTP technique [59], [50], which gives higher priority to a test the more fixes it has invalidated in previous iterations. RESTORE currently uses a very simple test selection strategy for partial validation (Section III-C2), consisting in just running the originally failing tests. This was quite economical, yet effective, in the experiments with DEFECTS4J, but cannot replace a full validation step. To achieve further improvements we will consider more sophisticated test selection strategies in future work.

**Correct-by-construction** program repair techniques [60], [61], [37], [62], [63] express the repair problem as a constraint satisfaction problem, and then use constraint solver to build fixes that satisfy those constraints. Relying on static instead of dynamic analysis makes correct-by-construction techniques generally faster than G&V ones, and is particularly effective when looking for fixes with a restricted, simple form.

**VI. Conclusions**

We presented retrospective fault localization: a novel fault localization technique that integrates into the standard generate-and-validate process followed by numerous automated program repair techniques. By executing a form of mutation-based testing by byproducts of automated repair, retrospective fault localization delivers accurate fault localization information while curtailing the otherwise demanding costs of running mutation-based testing.

Our experiments compared RESTORE—implementing retrospective fault localization—with 13 other state-of-the-art Java program repair tools—including JAIL, upon which RESTORE’s implementation is built. They showed that RESTORE is a state-of-the-art program repair tool that can search a large fix space—correctly fixing 41 faults from the DEFECTS4J benchmark, 8 that no other tool can fix—with drastically improved performance (speedup over 3, and candidates that have to be checked cut in half).

Retrospective fault localization is a sufficiently general technique that it could be integrated, possibly with some changes, into other generate-and-validate program repair systems. To support this claim, we implemented it atop SimFix [9]—another recent automated program repair tool for Java—and showed it brings similar benefits in terms of improved efficiency. As part of future work, we plan to combine retrospective fault localization with other recent advances in fault localization—thus furthering the exciting progress of automated program repair research.

**References**


