# Collaborative Research: SHF: Small: Feedback-Driven Mutation Testing for Any Language

## 1 Overview and Objectives

Mutation testing research dates back to the 70s, and has long aimed to render mutation testing useful for constructing high quality test suites and, by extension, software. Most of this previous research focuses on computing a mutation score, a measure of adequacy for a given test suite. However, this is computationally intensive for realistic projects, because it requires requires running many tests on many modified versions of a software system. Reducing that computational cost is thus a major thrust of mutation testing research [71].

Moreover, although test suite adequacy is certainly a useful thing to measure, the most important goal of mutation testing — and indeed its original use case [18] — is to help *improve* a test suite. For this purpose, neither a score nor a vast list of all unkilled mutants (which will exist for even very good tests of realistic software systems) is not useful. An undifferentiated list of unkilled mutants typically contains mostly uninteresting or redundant mutants, and a much smaller number of *actionable mutants* that are maximally useful for improving tests. Examining all unkilled mutants is sometimes impractical even for formal verification efforts or critical systems. Examining surviving mutants in even those settings is time-consuming and unpleasant, as PI Groce and co-authors noted in prior work on using mutants to drive formal verification and automated testing [56, 60, 9]. That work proposed a novel approach to formal verification and automated testing combining Karl Popper's falsification-based notion of scientific discovery [109, 110] with mutation testing [56, 60, 9]. The heart of the idea is (1) a surviving non-equivalent mutant *falsifies* the claim that a given formal verification or test effort captures a full notion of correctness and (2) refining a verification or testing effort by repeated efforts at falsification is the most effective method for ensuring the quality of verification and testing efforts. The approach allowed Groce and colleagues to identify multiple previously unknown faults in the Linux kernel's RCU [28, 62, 90] module and the `pyfakefs` Python mock file system [92], despite the existence of very-high-quality automated test generation efforts for these systems [89, 58]. Follow-up preliminary work for this proposal has uncovered significant opportunities to improve the Slither static analysis tool for smart contracts [33**?** ]. This prior work proposed a number of algorithms and methods for finding bugs in testing and verification harnesses. At a high level, however, the core concept was simple: users should examine all unkilled mutants, and for each mutant either understand why it is equivalent or uninteresting, or actually construct a way to kill it. This harkens back to the earliest ideas about mutation testing, but with much more automated support, for both understanding the mutants and actually killing them.

Unfortunately, the methods proposed were, while useful, limited in applicability. They simply assumed that the number of unkilled mutants was small, and focused on helping a developer or test engineer kill surviving mutants. In practice, however, human attention does not scale to analyzing large numbers of unkilled mutants without considerable assistance in "triaging" them. The process bears a resemblance to the problem of manual confirmation of results from a machine-learning classifier [55, 76], where even highly-motivated scientific users are unwilling to examine more than a few tens of potentially incorrect results [117]. This prior approach suffers the same problems as other mutation testing efforts: it provides no way to scale human efforts to such a needle-in-a-haystack setting.

This project aims to make the falsification-driven approach to verification and testing feasible for larger projects, and those with (much) lower mutation scores. Our goal is to enable *Just Enough Mutation Testing*: We propose a mutation testing framework that identifies and interactively presents a few, very different, ranked mutants, and then *works with the user* to effectively improve the program, the test suite, or both.

Figure 1 shows the basic outline of a proposed workflow. Our framework aims to generate a small, diverse set of mutants, chiefly characterized by their novelty, to present to the developer or test engineer. The framework further works *with* the test engineer to improve the SUT or the underlying tests, and incorporate user feedback to determine which mutants are worth examining. This results in a constantly-updated ranking of mutants, based on actions and feedback from the engineer.

A key insight behind our proposed approach is to view mutant triage as analogous to the bug triage (a.k.a. "fuzzer taming") problem in random testing/fuzzing [23, 65, 134, 135]: a user wants to quickly find mutants that indicate the most important "holes" in a testing or verification effort, and act on those most-critical gaps, possibly revealing faults in the System Under Test (SUT). An unkilled mutant *is*, conceptually, a failing test — of the testing effort! Fuzzers tend to produce very large numbers of failing tests for a much smaller number of distinct bugs. Finding the set of distinct bugs, and identifying important bugs that need to be fixed immediately is difficult, because the important bugs may be represented by only one or two failing tests in a set of thousands of failing tests, most of which are duplicates. Users do not (usually) care much about finding the group of all tests failing due to a fault, or the set of all mutants killable by the same extension to a test suite or generator, but about seeing *many very different test failures* or *many different unkilled mutants* quickly, to maximize the chance of discovering the most important faults or holes in a testing effort. Previous efforts to identify "critical" mutants tend to focus on subsumption and potential to resolve other mutants, but this may be counterproductive for identifying the mutants most critical to resolve, which are likely to not subsume other mutants, precisely because they correspond to subtle assumptions in testing, not broad gaps in testing (e.g., not testing logging output). Our approach thus fundamentally seeks to identify a small set of maximally different, *maximally interesting* mutants to present to the user, based on feedback and project context, not mere dominance hierarchy.

A second important principle behind our approach is to take advantage of user feedback in refining the list of interesting mutants and improving the SUT. A test engineer has valuable insight — and the final word — about which unkilled mutants are uninteresting or equivalent, and which require changes to the system itself or the test harness. We propose to explicitly take this feedback into account, refining the analysis accordingly, as the user improves their system. Beyond allowing for more effective mutation analysis, this new paradigm provides a stopping rule other than patience, time available, or "every last mutant": since mutants are ranked by likely payoff, once a user has examined several mutants in a row without benefit, or mutants that are highly similar in behavior to other mutants, a user may reasonably stop, knowing that the low-hanging fruit have probably all been picked. It also enables a new way to improve the efficiency of mutation testing: even for a very large project, it only has to build and execute a small set of mutants, because it only runs the test suite on mutants currently predicted to be of likely interest to the user.

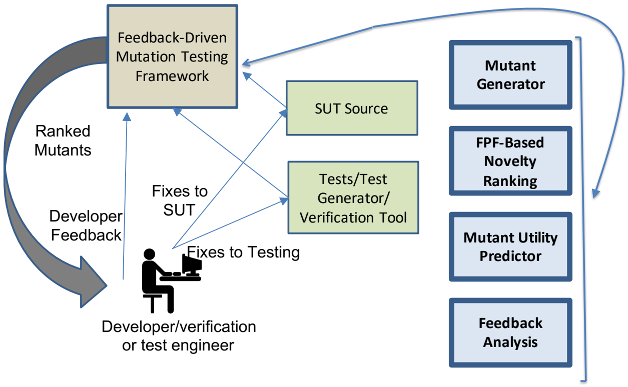

Feedback-Driven Mutation Testing Framework
SUT Source
Tests/Test Generator/ Verification Tool
Ranked Mutants
Fixes to SUT
Developer Feedback
Fixes to Testing
Developer/verification or test engineer
Mutant Generator
FPF-Based Novelty Ranking
Mutant Utility Predictor
Feedback Analysis

Figure 1: Proposed mutation workflow.

Overall, our approach requires several fundamental research novelties:

- **Efficient, any-language mutation testing.** Our goal of user-interactive mutation testing, integrated directly into the development and test process, requires that mutation generation be *source-level* and *multi-language*. Bytecode-level mutation is highly effective for computing mutation scores [24, 64]. However, developers or test engineers reason more naturally about a mutant's implications when mutations are presented in the source language in question. Moreover, modern mutation testing frameworks are limited to specific languages, or to IR-defined ecosystems like LLVM or Java bytecode. This leaves out popular languages like Python, Ruby, or Go, not to mention project-specific Domain Specific Languages (DSLs) [34]. Meanwhile, the vast majority of real-world software projects are written in multiple languages [111]. We therefore propose novel mechanisms for *efficient, any language mutation testing* based on our novel recent work on language-agnostic declarative program transformation [133].

- **Mutant prioritization and selection.** Our proposed framework will present a small, maximally-informative ranked list of mutants to the user. Current mutation testing approaches make no real effort, with few exceptions [107, 21] to prioritize mutants. Other than (arguably) some efforts to incorporate dominance results [102], mutation testing approaches currently offer no way to maximize the novelty of presented mutants than stratified sampling [41], which does not aim at (or achieve) significant semantic novelty. Thus, we propose to adapt clustering optimization techniques based on novelty [36] to the problem of mutant selection, informed by a set of novel diversity metrics for the domain.
- **User feedback elicitation and analysis.** A user's feedback about the most critical-to-test aspects of the code, or hard work examining some mutants, has no influence on the kinds of sampling currently proposed in the mutation testing literature. Even creating simple clusters of mutants that are not killed due to the same underlying omission in tests requires manual effort, with users, e.g., writing a Python script scanning mutants for certain strings and assuming all mutated code with that string is part of the same "equivalence class." This is a tedious and error-prone process, and only even possible once a "kind" of unkilled mutant is discovered, largely by ad hoc scanning of the list of unkilled, uncategorized, mutants. We propose "feedback-driven" mutation analysis that elicits and incorporates user input on mutants, tests, and the SUT, supporting a concise, updating list of mutants to inspect based on expected utility or payoff for the user. Feedback also opens up new ways to execute fewer mutants, often in parallel with useful user activity.

## 1.1 Problem Statement

Overall, this project aims to make the use of program mutants practical in non-research settings, in a way that meets developers' actual needs: to make it possible for someone creating or enhancing a test suite to (1) use "just enough" mutation testing for their needs, maximizing benefit gained in exchange for work performed, and to (2) work in any programming language(s) without worrying about the quality of tool support, using intuitive source-based mutants and easy customization. In addition to traditional manual testing, this proposal targets property-driven testing and formal verification, in order to be practical in the future, when many systems will be so safety- or mission- critical that even "good" manual testing is simply not acceptable, by extending Test-Driven-Development (TDD) to become Mutation-Driven-Development (MDD).

**Problem:** Develop highly automated methods and tools that allow the practical application of mutation testing to real-world software in a feedback-driven way, where user and mutation testing framework cooperate to improve testing efforts, while minimizing user effort and maximizing the ability to quickly find the most important weaknesses of testing or verification.

## 1.2 PI Qualifications

PI Groce has been a user of, and contributor to, mutation testing tools for many years. He combines a long research track record in software testing, including mutation testing, with actual experience testing critical software systems at NASA's Jet Propulsion Laboratory. PI Groce's long-running interest in improving mutation testing arises from frustration in his efforts to apply mutation to the Mars Science Laboratory's flight software, in particular to the file system [49, 50, 54]. This practical orientation informs his recent work on using mutation testing in a falsification-driven approach to improving verification and automated testing efforts [56, 60, 9]. PI Groce has extensive experience in developing mutation tools for new languages [80, 87, 61], including the first reliable tools for mutation of Haskell, Python, and Swift, as well as in user-facing (vs. researcher-oriented) automated software testing tools [66, 37]. He additionally has expertise in driving testing of machine learning systems through user interaction [76, 55].

PI Le Goues is an expert in applied program analysis, program transformation, and testing, most relevantly through her pioneering work in automated program repair (including heuristic [84] and semantic [83, 75] dynamic approaches, and approaches guided by static analysis [132]). She has significant experience with testing, mutation testing for fault localization and program repair particularly [127], and the challenges of syntactic program modification and transformation. In particular, her recent work has developed novel mechanisms for efficient and expressive language-agnostic syntactic program transformation [133], with applications for, e.g., program repair [132], fuzz test triage [135], and static analysis customization [131].

The PIs provide a detailed work and collaboration plan in the Collaboration Plan supplementary document.

### 1.3 Intellectual Merit

This project addresses core problems not limited to practical application of mutation testing, but generalizable to fundamental issues in software engineering and program semantics, e.g., how to represent source changes and (mostly statically) predict the similarity of their impact on semantics, and predict which tests are likely to detect these changes. How can novelty of information presented to a user be effectively balanced with a-priori predictions of the utility of that information, where likely-high-utility data points may also be similar to each other? How can user feedback best be incorporated into such efforts? This project also considers connections raised by preliminary work, concerning new methodologies for testing/verification effort development. Can theoretical ideas about the nature of scientific discovery [109, 110, 78] be applied to such efforts? Is falsification by alternative hypotheses about the power of a testing/verification effort translatable to an actionable, effective approach for building systems [56, 60]? The work on any-language mutation testing looks at syntactic patterns common to almost all programming languages, and relies on categorizing languages into families based on similarity, and how they share common meaningful syntactic changes that translate to interesting semantic changes.

## 2 Research Plan

Figure 1 shows the basic outline of a proposed workflow and components needed to support feedback-driven mutation testing. These components serve to organize the research plan.

### 2.1 Mutant Generator

The most widely-used mutation testing tool in the real world is PIT [24], which targets Java bytecode. There are recent attempts to provide the same kind of support for other languages, especially C, by targeting LLVM IR [64, 22]. This poses several problems for feedback-driven mutation testing. First, bytecode- or IR-level mutation works well to compute a score for a test suite, but is not not suitable for presentation to developers or test engineers, who need to reason about a mutant's implications for their source or test code. That is, Java developers think in terms of Java, not compiled bytecode; C and C+++ developers certainly do not generally understand LLVM IR; test engineers are even less likely to appreciate such low-level descriptions. Even when possible, translation may not help: a bytecode-level mutation may not have a simple source-level equivalent, especially if the bytecode has been optimized. Second, features that help identify semantically similar (or dissimilar) mutants are hard to identify at the bytecode level. Even if the mutant is, for example, a constant replacement in one case and an arithmetic operator replacement in another, the fact that both take place inside an argument to a logging function with an `INFO` argument may be enough to predict that their effects are redundant. Finally, IR-specific tools are by construction limited to their associated language ecosystems, excluding a large body of code written in other languages, as well as project-specific DSLs. Moreover, the vast majority of software projects are written in multiple languages [111]. Our desire for real-world applicability thus motivates polyglot analysis and testing infrastructure.

Thus, our first research task is to develop a novel `mutant generator` that (1) operates at the source level, with output that is easy for developers to understand and the framework to analyze; (2) is, as much as possible, *language independent*, and applicable to projects written in a heterogeneity of languages; and finally (3) is efficient. The PI's recent advances in universal mutation [61, 47] and language-agnostic declarative program transformation using parser combinators [133] provide key motivation and starting points for this component.

```
\+ ==> -                      == ==> !=                 (\D )(\d +)(\D ) ==> \1(\2+1)\3
".+" ==> ""                   while ==> if              (^\s *)(\S +.*)\n ==> \1\2\n \1break;\n
```

Figure 2: Some universal mutation rules

### 2.1.1 Background and preliminary work

The PI's combined prior work provides evidence for the feasibility of any-language mutation:

**The universalmutator.** First, PI Groce and colleagues released a fully functional, regular-expression-based mutant generator [61, 47]. The `universalmutator` does not attempt to parse source code, but simply defines mutation operators by a set of regular-expression-defined text transformations. These are organized into a hierarchy, so that if a program is, e.g., written in Swift, the "universal" mutation operators that apply to all programming languages are first applied, then operators for "C-like" languages, and finally a set of Swift-specific rules are applied. Figure 2 shows some of the "universal" rules applied to all languages.

Importantly, PI Groce demonstrated that the `universalmutator` tool generated numbers of mutants and kill ratios for Java code comparable to PIT [24] and Major [73]. For falsification-driven verification, the regular-expression-based approach produced mutants of equal value to those produced by Andrews' tool [12] and Muupi [87] for C and Python, respectively. This preliminary work demonstrates that multi-language, syntax-driven, source-level mutation is feasible and, indeed, effective, producing results competitive with state-of-the-art single-language mutation tools. However, it has significant limitations for long-term utility, motivating the proposed research below: Because the source code is not parsed, and applies the regular expressions to lines of code, not larger blocks, the technique generates many mutants that are invalid and cannot be compiled, or that are trivially equivalent because they, e.g., mutate "source code" in a large comment block. Fundamentally, regular expressions are only occasionally a natural notation for expressing source-level mutation; source in all languages differs from arbitrary unstructured strings.

**Comby: Declarative, any-language transformation.** Fortunately, recent work by PI Le Goues and collaborators introduced a powerful new representation to declaratively transform richer syntactic structures in programs across multiple languages [133]. The key innovation is to convert declarative transformation templates into parsers that directly match and transform source code of interest. Parser combinators [68] define how to match nested structures (much like traditional AST visitor traversals) but without the need to define or build an intermediate AST. Our parser combinator mechanism elegantly encapsulates the complexity of heterogeneous, multi-language syntax as a composition of small parsers (some being language-specific, and others being language-general). Conversely, defining and building a generic parse tree data structure (i.e., to encompass the complexity of multi-language syntax, which may be inherently incompatible across languages) *after* parsing is comparably difficult.

This work has already shown its practical utility by performing lightweight refactors in more than 10 languages (including those targeted by `universalmutator`). The associated tool, `comby` [1], enables a new language-general way of expressing transformations that regular expressions cannot typically recognize (e.g., nested code blocks). We showed that `comby` has equivalent expressive power for a variety of nontrivial syntactic transformations in existing language-specific refactoring tools. `Comby` is highly performant at scale (owing to the parser-driven approach), processing upwards of a quarter billion lines of code in 42 minutes (parallelized over 20 cores).

Coupling with declarative syntax manipulation that goes beyond the limits of regular expressions promises to yield more effective mutation testing by (a) targeting more sophisticated properties of programs, and (b) delivering more user-accessible tools for developing mutation transformations. Our joint advances in real-world tooling (i.e., in `universalmutator` and `comby`) suggest that this goal is imminently feasible. At heart, this line of work represents the conviction of the PIs that mutation testing (like automated program repair) is simply an instance of the general field of automated program transformation [105].

**Using differential mutation analysis to evaluate and improve static analysis tools.** Finally, we have used the universalmutator and our basic idea to formulate a novel way to evaluate and (most relevant to this proposal) *improve* static analysis tools. This work is TODO: ICSE result (either accepted to ICSE or in submission).

The proposed approach is simple in outline:

1. Run each tool on a set of unmutated source code target(s), and determine the *baseline*: the number of (non-informational/stylistic) static analysis findings produced.
2. Generate mutants of the source code targets and run each tool on each mutant of each target. Consider a mutant killed if the number of findings for the mutated code is greater than the number for the baseline, un-mutated version of the target.
3. Compute, for each tool, the *mutant ratio*: the mutation score ($\frac{|killed|}{|mutants|}$) divided by (mean) baseline. If the (mean) baseline is zero, use a baseline equal to either one or the lowest non-zero baseline for any tool in the comparison set[1].
4. Discard all mutants not killed by at least one tool and all mutants killed by all tools. What remains allows *differential* analysis. Examine the remaining mutants in the difference in *prioritized* order to qualitatively understand tool differences, or improve a tool.

Rather than using a sophisticated prioritization scheme, we used a simple textual, ad-hoc scheme, in order to examine the most interesting mutants in the “diff” between static analysis tools. This was helpful for understanding our general results, showing differences in Solidity, Java, and Python static analysis tools and confirming known rankings of such tools based either on user impressions or more limited experiments. However, it was essential for the most relevant part of this work to this proposal: using our results, and the set of mutants in the “diff” of three Solidity smart contract analysis tools to improve the best of those tools. Improving the best of the tools was a wise use of our efforts, in that we found that differences between tools were mostly rooted in differences in the quality of the underlying analysis engine, not in differences in detectors. Using prioritized mutants, we were able to identify three new candidate detector patterns for the Slither tool, based on mutants killed by Securify, SmartCheck, or both, but not by Slither: Boolean constant misuse, type-based tautologies, and loss of precision due to ordering of arithmetic operations.

All three of these detectors were submitted as PRs to the Slither project, vetted over an internal benchmark set of contracts used by the Slither developers to evaluate new detectors, and accepted for release in the public version of Slither. All three detectors produce some true positives (actual problems, though not always exploitable) in benchmark contracts, have acceptably low false positive rates, and were deemed valuable enough to include as non-informational (medium severity) detectors. The first mutants in prioritized rank exhibiting the issues, shown above, were the 2nd, 9th, and 12th non-statement-deletion mutants ranked for SmartCheck, out of over 800 such mutants. Using our prioritization, it was possible to identify these issues by examining fewer than 20 unkilled mutants. Without prioritization, on average a developer would have to look at more than 200, 80, and 400 mutants, respectively, to find instances of these problems. Examining the first 100 mutants in the unprioritized lists for SmartCheck and Securify, ordered by contract ID and mutant number (roughly source line mutated) we were unable to identify *any* obviously interesting mutants, suggesting that it is indeed hard to use mutation analysis results without prioritization. A large majority of the mutants we inspected involved either the missing `return` problem noted in the introduction, or replacing `msg.sender` with `tx.origin`; Slither has a detector for misuses of `tx.origin`. SmartCheck and Securify tend to identify most (though not all) uses of `tx.origin` as incorrect, while Slither has a more selective rule, intended to reduce false positives.

[1] Unless the number of programs used for evaluation is small, a zero mean baseline for a tool is extremely unlikely to arise in practice.

### 2.1.2 Proposed work: Any language mutation

Our goal is a source-level mutant generator that can apply to any language, maximizing applicability and usability. The `universalmutator` provides an initial source of mutants that satisfies this requirement for initial experimentation, but for long-term effectiveness is both inefficient and inexpressive.

We therefore propose to use `comby` [1, 133] for specifying transformations and generating mutants. `Comby` uses declarative templates that describe before/after changes for program fragments. For example, the following transformation swaps the first two arguments of the function `memcpy`:

```
memcpy(:[1], :[2], :[3]) ==> memcpy(:[2], :[1], :[3])
```

Hole syntax `:[1]` binds syntax to a variable. A unique property of `comby` templates is that variables *only* bind to syntax that occurs inside well-balanced delimiters (like parentheses), whitespace is handled intelligently, and syntax otherwise matches literally. Concretely, this means that the template above seamlessly transforms syntax structure in complex fragments as in the following:

```
memcpy(*stream->main_data + stream->md_len,        memcpy(mad_bit_nextbyte(&stream->ptr),
       mad_bit_nextbyte(&stream->ptr),        ==>         *stream->foo_data + stream->md_len,
       frame_used = md_len - si.main_data_begin);         frame_used = md_len - si.foo_data_begin);
```

At a high-level, `comby` performs context-free parsing of syntactic structures that typically correspond to nested expressions and blocks in the underlying AST; regular expressions are not powerful enough to recognize such program terms in general. Templates offer a *declarative* description for matching and rewriting these structures in a way that is syntactically close to the source code. In addition, `comby` can distinguish between code, strings, and comments. Templates contextually match these dimensions of a program. `Comby` is language-aware in the sense that small language definitions describe whether syntax should be balanced (e.g., parentheses or braces) or delineate strings or comments. These definitions describe a coarse structural decomposition of programs (as typically understood by compilers) rather than just a sequence of characters (as treated by regex). Language definitions already exist for 20+ languages, and `comby` supports a simple extension mechanism for new languages (e.g., Solidity) or custom DSLs (`https://comby.dev/#faq-language-support`). One ongoing limitation of mutation testing is that tools are often research projects, and eventually become unusable due to lack of support, even in mainstream languages such as Java and C [40]. This is because mutation tools that fully parse a language and guarantee generation of valid programs in the source language are complex, hard-to-maintain-and-extend systems; language complexity makes such a tool for C++, for example, an extremely daunting task. From this development and maintenance perspective, `comby` provides a considerable benefit in being able to adapt to new language syntax and tree structures at a coarse level, while maintaining a crucial language-aware ability for recognizing and parsing high-level program constructs.

Accessible structural syntax manipulation can achieve a leap in expressivity and effectiveness for mutation testing. For one, targeted structural and contextual changes are more likely to produce well-formed syntactic programs that exercise interesting paths in a test suite. We propose to extend `universalmutator` to generate mutants from `comby` templates, and to evaluate the efficacy of multi-language mutation testing with structural code changes.

We propose to further enhance the expressive power of mutation operators by incorporating static semantics (e.g., type information and variable scope) via a DSL for structural syntax changes. The Language Server Protocol [5] aims to provide a queryable interface for such static program properties, significantly reducing the burden of maintaining compiler infrastructure in a singular tool. This new capability, firmly outside the realm of regular expression approaches, will go beyond syntax and yield greater, semantic-driven precision.

The generator will also need to be improved to allow users to easily specify novel build environments and plug-ins for checking Trivial Compiler Equivalence [103] to make the entire feedback-driven mutation process workable. Interactive, human-in-the-loop workflows for large-scale automated code changes have proven essential over the last decade, and are now widely adopted in industry [3, 2, 4]. Interactive prompts incorporate human oversight before the code is changed, e.g. as in Facebook's dart code mod tool `https://pub.dev/packages/codemod`. We propose to adapt these existing interactive workflows to enable a feedback-driven mutation process. For example, the user is presented a source-level mutation, and interacts with a prompt to indicate a `yes/no` signal to validate and refine desirable mutations generated by new plugins. Because some distance metrics (described below) may require compiling mutants, which is costly, a specialized projection of the distance only requiring textual analysis will need to be developed, to allow generation, compilation, and execution of only high-priority mutants for very large projects.

## 2.2 FPF-Based Novelty Ranking

Our vision of feedback-driven mutation testing is predicated on selecting and ranking a small set of highly interesting mutants to present to the developers. An unkilled mutant is, conceptually, very similar to a failing test. It presents information of possible relevance to a developer. The mutant or test *may* indicate the presence of a previously unknown fault that needs to be fixed, either in the SUT or in testing. It may indicate the presence of a previously unknown fault of less importance. It may also indicate an even less interesting result: an equivalent mutant or an inherently flaky test. Additionally, an unkilled mutant or failing test may contain information that is uninteresting because *it duplicates information already examined.* While examining an equivalent mutant is not always useless (e.g., it may indicate an opportunity for refactoring or improving the efficiency of code [69, 60]), examining a mutant that is equivalent to, or extremely similar to, an already-understood mutant is almost never worthwhile. A key research challenge is thus to select and prioritize mutants that provide maximum utility to a user.

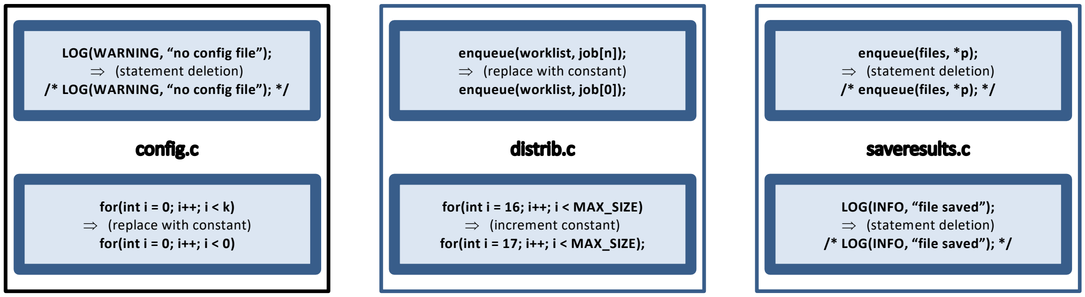
As noted above, with a few exceptions [107, 21, 102], current mutation testing approaches offer little in the way of prioritization beyond dominance (which requires executing tests on mutants) or stratified sampling [41, 102]. Stratified sampling does not aim at semantic novelty, and can present many mutants from the same class, if applied at the method level, even if those mutants are highly similar in impact. Other work [38] proposes random sampling as the most effective way to select mutants. Unfortunately, when an important class of unkilled mutants has only a few members, random sampling is almost guaranteed to fail to present any of them. Our preliminary results argue, however, that novelty-based clustering is a promising approach for solving this problem.

### 2.2.1 Background and preliminary work

The mutant selection and prioritization problem is analogous to a similar problem in fuzz testing and triage: a user wants to see a few, critical results, that maximize payoff in terms of bugs found or information gained.

**Furthest point first and fuzzer taming.** Fuzzer taming [23] was a solution PI Groce and colleagues proposed to the problem of triaging test failures in automated test generation [134]. Like mutant generators, fuzzers tend to produce very large numbers of failing tests (mutants) for a much smaller number of distinct bugs (interesting behaviors). Finding the set of distinct bugs, and identifying important bugs that need to be fixed immediately is difficult, because the important bugs may be represented by only one or two failing tests in a set of thousands of failing tests, most of which are duplicates. The fuzzer taming work proposed that rather than highly imprecise clustering, which does not work well in practice, and handles outliers in a way that does not match the "power law" distribution of bugs, an algorithm matching the goal of ranking maximally-different test failures highly was appropriate.

The *furthest-point-first* (FPF) algorithm of Gonzalez [36] does precisely this. FPF, beginning with any randomly chosen test (or mutant, in the present setting), always ranks next the point in a metric-defined space that has the *greatest distance from the previously ranked point to which it is closest.* That is, for each point (test or mutant) not yet presented to the user, FPF finds the closest among all already-ranked points, and associates each unranked point with the distance to that closest point. The unranked point with



```
LOG(WARNING, “no config file”);
⇒ (statement deletion)
/* LOG(WARNING, “no config file”); */

for(int i = 0; i++; i < k)
⇒ (replace with constant)
for(int i = 0; i++; i < 0)
```

```
enqueue(worklist, job[n]);
⇒ (replace with constant)
enqueue(worklist, job[0]);

for(int i = 16; i++; i < MAX_SIZE)
⇒ (increment constant)
for(int i = 17; i++; i < MAX_SIZE);
```

```
enqueue(files, *p);
⇒ (statement deletion)
/* enqueue(files, *p); */

LOG(INFO, “file saved”);
⇒ (statement deletion)
/* LOG(INFO, “file saved”); */
```

Figure 4: Which mutants are most similar? If the user marked the mutant in the upper left corner as uninteresting and added a test to kill the mutant in the upper middle, which mutant should she examine next?

the largest such distance is then added to the ranking, and the process is repeated. FPF can be computed by a greedy algorithm, and is known to approximate novel-item discovery for an optimal clustering [36]. Preliminary work on the fuzzer taming problem using FPF-based techniques [23, 65] can be directly applied to the different problem of ranking unkilled mutants such that novel mutants are presented first.

**Preliminary use of FPF-based mutant ranking.** In collaboration with security analysts at Trail of Bits, PI Groce implemented a prototype version of mutant prioritization, without feedback, using a manually constructed distance metric tailored to Solidity smart contracts. This was an essential step in an effort to use mutation analysis to compare three static analysis tools for smart contracts [33, 115, 129]. The comparison of three such tools over 100 random contracts from the Ethereum blockchain [19, 139] required analysis of 46,769 mutants, with 46,752 of these not killed by at least one static analysis tool. The aim of the analysis was to (1) find cases where mutation caused each tool to flag a *new* issue with the source code (thus differentially identifying kills), then (2) find cases where at least one tool flags a mutant, while others do not, and finally (3) baseline this with respect to general warning rates for the tools over the same contracts. Sorting through the surviving mutants to understand weaknesses of the tools was simply not possible without using a simple version of the FPF ranking algorithm, combined with an *ad hoc* distance metric. With even this rudimentary, untuned version of our approach, PI Groce and Trail of Bits engineers identified three significant new detectors, which were implemented and added to the Slither static analysis tool [33]. These are currently in use by Trail of Bits for security audits, and will be released to the public after tuning. Without the FPF ranking, finding these three opportunities for improving Slither would not have been feasible. To our knowledge, the use of mutation to compare and improve static analysis tools, rather than test suites, in this *differential* (both within tools and across tools) sense, is novel, and we believe that feedback-driven approaches are essential in this setting, since kill rates will obviously always be relatively low for purely static analysis without a specification. The preliminary results from the Solidity mutation analysis are available at `https://github.com/agroce/slithermutate`.

### 2.2.2 Proposed work: Mutant Novelty Ranking using FPF

Ranking unkilled mutants according to how much “new” information they might provide to users requires more than simply using the FPF algorithm as in fuzzer taming. The key difference is the problem of determining how similar two mutants are. In fuzzer taming, it is possible to extract a large amount of information about similarity of failing tests from executing the tests, and, in fact, from executing the tests on program mutants [23, 65]. There is no obvious equivalent to “just run the test” for mutants, and in fact avoiding the expense of running the test suite on uninteresting mutants is one of the goals of feedback-driven mutation testing in the first place.

FPF requires a distance metric, and a distance metric requires a *representation* of mutants. Mutants can be similar because they modify the same line, function, class, or module, but also because, despite being located in very different parts of a program, they are very semantically similar. E.g., a mutant to the parser of a compiler, to an I/O error-handling routine in the code generator, and to a complex optimization pass may all be very "similar" in the only meaningful sense if all three mutants modify logging statements that don't have any actual effect on the state of the compiler. Figure 4 shows the fundamental problem. It is not, a priori, obvious which mutants here are most (dis-)similar. Every mutant has multiple plausible "nearest neighbors" — another mutant in the same file (likely to impact the same aspects of correctness), another mutant with very similar code (likely to have the same kind of semantic impact on the local context), or another mutant with the same operator (perhaps likely to have some similarity, though probably of a lower importance than the previous two types of similarity). Are all logging statements equivalent, or are only `INFO` logging calls similar, while every `WARNING`, `ERROR` or `FATAL` is unique? Some of these decisions are likely to be project-independent, or even developer-expertise-driven, and so a good metric may well change during feedback-driven mutation testing, in response to information from users (see Section 2.4 below).

Elements of the distance metric obviously include, at minimum, mutant location, mutation operator, and some representation of the code element modified — language construct, functions called, variables modified, and so forth. These static aspects may also be augmented with user feedback (as noted above), but also with dynamic information obtained during the process, such as frequency with which tests cover the mutated statements/modules, or the way the mutant changes the program path from the unmutated code in tests. PI Le Goues, with collaborators, has proposed dynamic metrics over execution behavior for heuristic program repair, including those measured over program state [25, 101] and observations of intermediate predicate behavior [30] (mutation testing has strong conceptual analogies to program repair [137], suggesting natural application of these prior measures to this new domain).

In fact, there may need to be two distance metrics: one for selecting likely candidate mutants to execute, that uses only static information and user feedback, and one that uses dynamic results from compiling and testing mutants to refine the notion of similarity for likely-novel mutants. This is therefore a quite complex problem in representation and weighting of elements of a representation, especially for a language- and project- agnostic metric, that is also open to tuning via feedback analysis. One approach to the problem is to exploit metric learning methods [77], which were used in some of PI Groce's previous work [106]. But, to avoid over-fitting to even a set of good examples, the final metric may have to be largely hand-tuned, and designed to incorporate feedback and dynamically extracted information, which is not easily handled with learned metrics. In part this is due to the difficulty of establishing large amounts of ground truth data, and the reality that cross-project data will be less valuable than project-specific data from users; there are unsupervised approaches to metric learning [116, 128], but most popular approaches require supervision.

### 2.3 Mutant Utility Predictor

Novelty with respect to previously analyzed mutants is not the only important characteristic of a mutant. Presenting a novel, but likely equivalent mutant is often a waste of time, though some equivalent mutants can be useful for identifying optimization opportunities or refactorings. Furthermore, of two similar mutants next to be presented, it is better to present one that is higher in the mutant dominance hierarchy (the one such that its tests will kill more other mutants). There has been some initial work on predicting mutant quality attributes and utility [102, 21], including estimating how hard mutants will be to kill, statically. In addition to advancing the state-of-the-art in that respect, feedback-driven mutation testing also requires determining how to balance the need for novelty and the predicted utility of a mutant. For example, a utility-driven ranking might suggest avoiding a highly novel mutant because it is likely equivalent; however, it may be that labeling this mutant as equivalent lets the FPF ranking avoid numerous other similar mutants — e.g., postponing labeling a logging statement as confirmed equivalent by the user may be a bad idea.

### 2.4 Feedback Analysis

The "feedback-driven" aspect of feedback-driven mutation analysis requires that information from the user be given high priority in the process, a process with no clear equivalent in any previously proposed mutation testing work. The most straightforward example is that if a user adds a test to kill a mutant, and marks that as a "high impact" action (the omitted testing was potentially allowing serious faults to pass without detection) or even "fault-revealing" (the new test detected a real fault in the system), then it may be most effective to abandon the search for novelty and instead search for very similar mutants still not killed by any test, in the expectation that these may also result in high impact or fault-revealing tests. If a user marks a mutant as "equivalent, but indicative of a refactoring opportunity", the same logic may apply: similar mutants in other parts of the code base may show the same problem with code quality, even if they are predicted to be equivalent, and are not highly novel. In addition to informing the system of how useful various analyzed mutants were, a user should also be able to inform the system about correct and incorrect novelty rankings: if the system presents a mutant that is, from the user's POV, a (near-)duplicate of an already handled mutant, the user should be able to express this fact, and avoid future similar bad novelty estimates.

While large-scale crowdsourcing of user feedback is likely only possible in some unusual industrial settings [107, 69], it may also be possible to apply mini-crowdsourcing techniques developed in the context of testing machine-learning classifiers to mutant ranking and analysis [120]. For high-visibility, high-criticality code such as, e.g., Linux kernel modules, this may be a very powerful tool. The challenge in such a case is to allow communication between feedback-driven mutation efforts, splitting work both so as to minimize duplication and to target appropriate developers, as in automated assignment of bug reports [16, 72].

## 2.5 Mutation-Driven Development

The primary focus of this project is to develop feedback-driven mutation testing. However, the ideas of Test-Driven Development (TDD) [15, 70], which repeatedly turns requirements into specific test cases, then implements just enough functionality to pass the current tests, can be generalized into a mutation-driven form. A potential weakness (and, of course, an actual goal) of TDD is that the code will be narrowly tailored to the requirements, which produce the tests, which means that missing requirements will almost always be omitted both from the tests and the code. For "shall" type behaviors [67], this is not a key problem. But for security and safety, "shall not" requirements that are omitted can be disastrous. Mutation-Driven Development (MDD) in its simplest form would require an application of feedback-driven mutation to the test suite at each development step, to ensure that code not only does what the tests require, but that the tests also sufficiently constrain the code to capture many implicit shall-nots. Since such a process implemented by modifying TDD-driven tests would likely break the clean and appealing mapping between tests and requirements, and manual tests are inherently weak, for high-criticality systems, MDD should focus on augmenting TDD-driven tests with falsification-driven formal verification and automated testing. One way to do this would be to "elaborate" TDD-produced unit tests into parameterized unit tests [126, 125], perhaps using a tool like DeepState [37] for C/C++. In such a process, weakness exposed by feedback-driven mutation testing would be addressed by taking an existing unit test and generalizing some parameters and assertions to kill the relevant mutants, letting, e.g., AFL [142], libFuzzer [118], or a symbolic execution tool [121, 122, 91] identify specific inputs. The focus of the MDD process would be on producing test harnesses [44, 66] that can kill *all* interesting mutants. More radically, MDD could be implemented via a radical departure from normal TDD, with a single testing or model checking harness iteratively enhanced, always requiring the ability to kill (most) mutants of the current implementation. This would not produce the usual large set of TDD tests, but instead produce a single high-powered test generator and formal specification.

Rather than a separate research focus, the idea of mutation-driven-development will inform the other research topics. In particular, once tools reach sufficient maturity, they will be used to conduct preliminary experiments in MDD as a methodology.

## 2.6 Core Research Questions

The component-focused sections above provide an overview of the research problems to be addressed by this proposal, but it is also useful to consider the high-level research questions as a whole:

1. What advances are required in order to maximize the efficiency and usability of any-language mutation?
2. How can a domain-specific language enable new, more expressive mutation operators for structural code changes without compromising on the usability of a regular search-and-replace approach?
3. What is a good generalized, language-agnostic mutant representation and distance metric?
4. How can FPF-based selection of mutants for novelty best incorporate predictions of mutant equivalence, outcome, dominance, and productivity? Is novelty or expected utility more important?
5. How can feedback-driven mutation testing most effectively incorporate feedback, including from crowds?
6. How can we perform on-the-fly and parallel mutant evaluation/generation guided by (predicted) FPF?
7. Can we predict the *cause* of mutant unkillability (e.g., oracle, coverage, equivalence, or nondeterminism)?
8. How can we most effectively use already generated killing tests and counterexamples to prune mutants?
9. Is distance-based clustering plus timing information useful for quickly eliminating killable mutants similar to already-killed mutants? How does this relate to Predictive Mutation Testing (PMT)?

## 2.7 Evaluation Plan

We propose a multi-prong evaluation strategy, including (1) proxy metrics suitable for evaluating program transformation and mutation testing, and the individual components of the overall research program, (2) a series of lab studies on tool usability and mutation-driven development as a paradigm generally, and (3) qualitative experiences using and evaluating the tool, ideally in collaboration with industrial partners.

**Proxy metrics for individual research components.** Just computing a mutant kill matrix for a test suite can partially evaluate novelty rankings, by ranking killed, rather than unkilled mutants. This experiment realistically represents an early stage of test suite construction by feedback-driven mutation testing, especially if the mutants are only killed by a relatively small set of tests. If mutant X and mutant Y are both highly ranked, but killed by a very similar set of tests, this indicates a possible problem with the measure. In real-world feedback-driven mutation testing, it is highly desirable not to compute the full kill matrix for all mutants. But, for evaluation purposes, determining the extent to which kill vector similarity agrees with FPF distance metric similarity serves as a basic, if imperfect, sanity check on the novelty ranking. Another automated way to evaluate a novelty ranking is to use automated testing to generate multiple tests to kill each mutant in ranked order. A good ranking will mean that each additional mutant is unlikely to be killed by the killing tests for any previous mutants. A similar, but more robust, measure of mutant similarity is how much adding a test that kills one mutant as the seed in a fuzzer [142, 118] improves time required to kill a (supposedly) similar mutant, on average.

Evaluation of the mutant generator can also be partly automated, by comparing the output set of mutants to that of other tools, to ensure no important mutants are omitted; the regular-expression based approach will probably generate valid mutants not generated by other tools, since it aims at a rich operator set, in accord with the suggestions of multiple previous papers on detecting faults via mutation [74, 41]. We will further evaluate and delineate the relative effectiveness of the new modes of expressive power (proposed in Section 2.1.2) compared to regular expressions: We will catalog the efficiency of new mutant operators that rely on structural syntax changes both with and without incorporation of static program properties (like type information). Efficiency gains (e.g., removal of invalid or equivalent-by-construction mutants) can be measured by simple, traditional measures.

**Lab studies.** We will conduct pilot and lab studies to evaluate tool design and usability. These studies will generally involve asking programmers to perform a set of constructed software testing, bug finding/fixing, or maintenance tasks, with or without a tool. The results of such studies can be evaluated using both quantitative measures (like time and success rate on the provided tasks) as well as qualitative and theory-building techniques to surface important challenges or benefits to the tooling or underlying Mutation-Driven Development methodology. We can enhance external validity by basing the programming tasks on common forum postings, as we have done previously for studies of debugging challenges in particular contexts [141];

other researchers have demonstrated this type of methodology useful for tool pilot studies [124]. We may also construct implementation tasks around small, but easy-to-get-wrong code problems like binary search and AVL trees, especially when evaluating the potential benefits and key challenges for MDD. Methods used in our previous studies to control for user expertise and prior knowledge of problems will generally carry over, as we expect not to encounter prior expertise in mutation testing itself in this setting.

In addition to traditional testing tasks, we will also conduct studies on the enhancement of random testing harnesses, with one set of experiments focusing on enhancing specifications/properties, and another set focusing on enhancing the set of generated tests (controlling for specification by using a reference implementation for differential testing).

We may make use of "dummy" or "Wizard of Oz" versions of elements of the framework to isolate the effects of specific features, like the FPF-based novelty metric, or various choices for feedback elicitation or analysis. We will use think-aloud protocols [32], in which participants are instructed to continuously verbalize what they are thinking/attempting. This method helps the examiners determine why participants behave in particular ways, and to identify and isolate sources of confusion. These barriers can then be used to improve the underlying research technique. Again, to mitigate the risk of highly varying programmer skill, we will use a counterbalanced, within-subjects design, exposing each participant to both experimental and control conditions. The design just outlined has been profitably used in many experiments about programming tools and methodology [31, 123]. PI Le Goues has experience in both lab studies involving think aloud protocols [141] as well as qualitative analysis generally [7], and will lead the design and execution of these lab studies at CMU. Note that, to our knowledge, these experiments will also provide the first well-founded human studies of the baseline value of mutants in improving test suites in a traditional development setting[2], not just of our proposed methods; in itself this is a major research contribution.

**Experiential, qualitative evaluations.** Evaluation for this proposal includes both human-performed assessment via trying to use feedback-driven mutation for actual test improvement tasks and automated evaluations with more objective criteria, but a weaker relationship to the actual goal of helping expert developers in real projects quickly find the most important unkilled mutants. For the human portion, informal evaluation will be performed by the research team itself, using known programs with known testing weaknesses; this will help tune the approach and experiment with new ideas. However, for more advanced assessment, expert users outside the team will be offered the chance to use the system once it is in suitable shape. In the past, PI Groce has worked with IBM Distinguished Engineer Paul E. McKenney on using mutants to improve Linux kernel test suites, and has discussed similar efforts with Richard Hipp, the lead developer of the SQLite database, a famously well-tested program, with some resulting improvements to both test suites. Other potential users with whom PI Groce has a working relationship include NASA/JPL engineers working on upcoming CubeSat missions, colleagues working on the DeepState [37] parameterized unit testing interface to fuzzers and symbolic execution engines, and the developers of `pyfakefs`. This type of evaluation is, of necessity, somewhat qualitative. A more unbiased retrospective version that retains the core element of human rating of the value of mutants can be performed by examining actual mutants that resulted in improvements to the rcutorture [89] tests for the Linux kernel and the `pyfakefs` tests [60], and comparing them to highly ranked mutants: could the highly ranked mutants have exposed the same problems?

**Mutation-Driven Development.** The evaluation of techniques and tools developed in this proposal will also serve a dual purpose with respect to Mutation-Driven-Development. Using an MDD approach to implement various small, but easy-to-get-wrong, code projects, such as binary search and AVL trees, will make it possible both to see how effective the tools for feedback-driven mutation testing are, and to see how effective an MDD approach to development is. In addition, using various versions of actual TDD efforts, with the

[2] The only previous study of which we are aware was both limited in scope and only applied in a Test-Driven Development context [114].

associated test suites for each step of development, it should be possible to evaluate how much additional testing power MDD would have required at each step of development.

# 3 Closely-Related Work

**Mutation Testing.** There is a vast body of work on mutation testing or analysis, an area whose foundations date to the late 70's [26, 18]. Mutation analysis has been shown to subsume multiple coverage measures, including all the basic coverage measures [94, 100] and data flow subsumption measures [88]. Andrews et al. [13, 14] found that ease of detection of mutants was similar to that of real faults. The relationship between mutation score and test case effectiveness is sometimes empirically stronger than coverage [74]. However, Papadakis et al. [104] recently showed in a large scale study that: "mutants provide good guidance for improving the fault detection of test suites, but their correlation with fault detection [is] weak." Ahmed et al. reached similar conclusions [8]. This is a foundational assumption of this proposal.

The most closely related work in a sense is that of Roman and Mnich [114], which studied the effectiveness of introducing mutation testing into the test-driven development (TDD) process in a student setting. They showed that test written using TDD with the additional aid of mutation analysis had better code coverge on the code from TDD-only groups than the TDD-only tests did, and found more post-release defects in the TDD code. However, the number of groups was limited to four for each approach (TDD, TDD+mutants), and the post-release defects were concentrated in the code of one group. This study is promising, in that it suggests that mutants can indeed be useful in real testing tasks, but extremely limited in that the evaluation was only within a TDD context, not including "legacy testing," only involved completely manual test development, and (most critically) the approach suggested simply could not scale to large numbers of mutants, without the addition of feedback techniques such as we propose. Our experiments would, we suggest, ideally confirm and extend these results.

Similarly, a paper by Petrović et al., to appear at ICSE this year [108], while limited in various ways (e.g., relying on Google's rule of only looking at one mutant per line, using mutant exposure and review requests rather than directly measuring use of mutants to derive tests, and using a control group of different projects), shows that even a limited examination and application of mutants results in visible positive effects on test quality and fault detection. We believe that our approach will enable much more aggressive and efficient use of mutants in critical development efforts, and without the required context of industrial code reviews.

Numerous approaches seek to reduce the cost [71] of mutation analysis. Offutt and Untch [99] categorize these, as: do *fewer* (e.g., operator selection, mutant sampling or clustering), do *smarter* (i.e., intelligent organization to reduce time taken for the entire analysis), and do *faster* (i.e., in terms of single mutant evaluation time) approaches. Determining relative merits of selective mutation strategies such as operator selection and random sampling has long been an active field of research [138, 93, 144, 39, 119, 85] Namin et al. [95, 96] formulated the concept of *sufficient mutation operators*, and others [130, 27] even proposed simply using statement deletion as "the" mutation operator. We offer a fundamentally different *do-fewer/do-smarter* method that combines FPF-novelty, utility prediction, and user interaction for a more radical reduction in mutants run, and runs most mutants while users are examining early results.

**Practical Mutation Analysis.** The above work largely focuses on computing or at least estimating the total mutation score of a test suite. The assumption is that mutation testing is meant to be, like a coverage metric, an "evaluation" of a test suite, a number used to say "this is a good test suite." In contrast, this proposal focuses on the problem of presenting unkilled mutations to a developer or test engineer in a way that facilitates the improvement of a test suite and the detection of faults, inspired by PI Groce's previous work on using mutation to find defects in verification and test generation efforts [56, 60, 9].

Recent work by Papadakis et al. has aimed, unusually, at predicting the "quality" of [102] or even prioritizing [21] mutants, to rank fault-revealing mutants highly so that users can produce tests to find faults, focusing on a single static pass to rank mutants by their fault-revealing potential, informed by (possibly cross-project) data on fault-revealing tests. There is no feedback loop, or ability to indicate the *importance* of various faults, and only LLVM bitcode mutants are targeted.

Google is well known for applying mutation testing to real-world projects [107]. Their approach uses a notion of feedback, but this is essentially manual, and based on using a classification scheme to heuristically throw out "arid" (likely not to be actionable) mutants; due to the size of Google's code base and the integration of their approach in Google's code review process, there is also as noted above, a decision to only allow one mutation (initially randomly decided) per line of code. While the underlying motivation, of giving developers actionable information, is similar, and the idea of using some form of "feedback" is common, our approach in contrast targets the individual(s) developing, testing, or verifying a particular software element (either a small project, or a component of a project), and assumes an iterative process, where developers consider one unkilled mutant at a time. The Google approach does not attempt to prioritize unkilled mutants it surfaces, or support custom mutation operators, or learn an individual testing effort's characteristics. It is an attempt to select mutants in an industrial code review setting, not an effort to propose a new way to construct or enhance test suites; e.g., it only even proposes mutants of code in a diff with a previous version of the code. Further, it uses Google-wide coding conventions and developer suggestions to fix heuristics such as "avoid mutation of logging statements" rather than trying to learn (with human assistance) such heuristics for projects that may vary widely in language and coding style. The techniques used in this proposal may be useful in enhancing an effort such as Google's, and share the focus on mutants as tools for focusing developer/tester attention and producing action on the part of humans, not computing a mutation score. The Google report itself allows that their approach does not truly scale, since it requires extensive manual support for each heuristic and language, a problem this proposal directly addresses.

More broadly, a paper by the authors of the Google report and a group of academic mutation testing researchers [69], uses the Google effort to propose a notion of productive and unproductive mutants. Their concepts are highly related to this proposal's goals, but again centered on a diff-focused, large-scale industrial setting, rather than an approach that, like TDD, may also be applied to smaller coding efforts in a more isolated setting, such as development of embedded software, where crowdsourcing is impractical or irrelevant. Another key difference is that, while their work used EvoSuite to enhance a test suite to kill additional mutants, the assumption was that most suite enhancement would be due to developers adding manual tests. Furthermore, we argue mutants are neither "productive" or "unproductive" in an absolute sense, but rather the value of a mutant depends on previous mutants a developer has manually examined, and the results of that examination.

A second thrust of the efforts in this proposal is to simplify the development, maintenance, and (especially) extension of mutation testing tools by expanding the expressive power for mutation operators through domain-specific templates, and separating the generation of mutants from language or build-environment specific techniques for pruning invalid mutants. This aspect of the proposal primarily builds on PI Groce's initial work on the topic of regular-expression-based mutant generation [61] and PI Le Goues's work on declarative transformation for multiple languages [133]. Language agnostic mutation is also critical in PI Groce and PI Le Goues' in-progress work, using Comby [133], to enable low-effort high-quality fuzzing for compilers, which has resulted in the detection of over 80 faults in a variety of compilers, including security-critical bugs in the Solidity smart contract language's compiler that resulted in the awarding of a substantial bug bounty [48, 43**?** ].

**Bug Triage and Distance Metrics in Software Engineering.** This proposal's approach is centered on the idea of computing distances between mutants. The use of distance metrics in software engineering for a variety of purposes is long-standing. Almost all such uses are essentially spectrum-based [113] (that is, using counts of coverage of code entities), except for some work in model-checking [42, 20] and some of the metrics in PI Groce's recent fuzzer taming work [23]. Reneiris and Reiss initially proposed using distance between executions to localize faults [112], and Liu and Han [86], Vangala [136], and others have followed this line with various metrics. Methods for clustering to identify bugs all rely on a distance [35]. PI Groce's previous work has used distance metrics for a variety of purposes [23, 53, 143, 65]. Work on presenting a few well-chosen mutants is also related to PI Groce's own work on end-user testing of machine learning systems [76, 55], where the limits of human patience are a key factor.

# 4 Broader Impacts

**Improving Software System Reliability:** A key element of broader outreach will be to report bugs discovered during testing experiments, and contribute improved test suites to critical open source projects. To that end, this proposal will primarily target real world systems in experiments, in hopes of improving their quality, and the quality of their testing. Infrastructure developed in preliminary work includes automated testing for the Linux kernel RCU module, Google and Mozilla JavaScript engines, a variety of C, smart contract, and Go compilers (including GCC and LLVM), YAFFS2 [140] and other file systems, a large set of Unix utilities, and critical Python libraries (including key scientific, ML, and numeric analysis tools). Discussions with working test engineers at Mozilla, Google, Trail of Bits, and NASA have significantly informed the PIs' research efforts, and this is likely to continue. PI Groce is discussing plans for incorporating advanced automated test generation into NASA's open source F Prime flight architecture [17, 97], and F Prime components are a likely target for evaluation efforts in this project. Such efforts will result in a documented process for incorporating feedback-driven mutation testing and MDD into flight software development. Better, cheaper, high-quality testing for small budget CubeSat [98] missions could lead to advances in various fields, especially Earth observation and space-based physics. CubeSat focuses on providing a low-cost way for educational institutions and non-profits to conduct space-based research, and thus is related to education and outreach. In the long term, an MDD paradigm might result in easier development of critical software in tandem with an extremely high-quality, specification-defining automated test suite. The existence of such suites might make modifying critical systems easier, since the in-place test suite would be likely to identify even subtle problems introduced during changes. With the growing impact of embedded, cyberphysical, and Internet-of-Thing systems on the physical world, this has potential safety benefits for the general public.

**Education and Outreach:** The proposed research yields several opportunities for enhancing CS education, recruiting new CS majors, and retaining CS students, particularly members of underrepresented groups. PI Groce will work with the NAU Student ACM Chapter to present a series of "excursions in testing" that introduce automated testing to students, using feedback-driven mutation testing and Mutation-Driven-Development (MDD) on real code, including code from media player libraries. The work of Guzdial [63] has shown that media computation is a potentially effective way to both recruit and retain female and under-represented minority students in computer science.

**Undergraduate research mentorship:** The PIs are fundamentally committed to widening the pipeline of students interested in and equipped to pursue a research career. PI Le Goues is co-director of the REUSE@CMU summer program (funded in part by NSF CNS-1852260, a renewal of CNS-1560137, on which she is a Co-PI). The site trains students in all elements of research, and specifically seeks students representing underserved demographic groups, early in their undergraduate careers, and at schools without traditional research opportunities. So far, the REUSE program has resulted in undergraduate research by 89 total students, of whom 48 (54%) identified as women; 24 (27%) were drawn from racial and ethnic groups that are under-represented in computing (some are both). More than 80% of the graduated students are now doing research full-time, either in graduate school or at national or corporate research labs.

Undergraduate researchers could contribute to multiple areas of the proposed work, from design and implementation to evaluation. For example, undergraduates Zhen Yu Ding (University of Pittsburgh '21) and Yiwei Lyu (Carnegie Mellon University '21) designed and evaluated the study of diversity metrics for novelty-promoting search-based software engineering that informs some of the proposed work in novelty measurement; as an REU summer student, David Widder (University of Oregon '17, now a CMU PhD student) designed and conducted half of the talk aloud studies in the qualitative work PI Le Goues conducted with collaborators on the challenges of framework debugging [141]. We will continue to integrate undergraduates both in the summer program and throughout the school year in the proposed project.

# 5 Results From Prior NSF Support

PI Groce has received support as PI or co-PI from three NSF grants. The most relevant and recent is “Diversity and Feedback in Random Testing for Systems Software” (CCF-1217824, $491,280, 9/2012–9/2017), a collaborative proposal with John Regehr at the University of Utah. **Intellectual Merit:** The results of CCF-1217824 included a preliminary exploration of how to “tame” fuzzer output, a problem also central to this proposal [23]. In previous work, the goal was to find an algorithm for using hand-chosen distance metrics to identify bugs in tests. Many other key results [10, 143, 51, 52] used mutation testing as an evaluation method. **Broader Impacts:** CCF-1217824 has contributed to the discovery of previously unknown faults in multiple open-source and commercial software systems, including core compilers and system libraries. The development of the central swarm testing techniques has furthered many efforts to improve the quality of compilers, including LLVM and GCC, and to test core language tools in general [81, 79, 29, 82]. **Research Products:** Publications resulting from CCF-1217824 were numerous [52, 23, 143, 53, 51, 10, 59, 66, 57, 11, 66, 45], along with three PhD theses. Source code for software systems developed or enhanced during CCF-1217824 [46, 58] is available on GitHub.

Le Goue’s most closely-related prior NSF grant is CAREER Quality Matters: Dynamic, Static and Proactive Analyses for Automated Program Repair (CCF-1750116, $525,000, 3/2018 – 2/2023). **Intellectual Merit:** The results of this award have so far included novel techniques for static program repair [132], an initial exploration of diversity-enhancing dynamic repair techniques [30], and the Comby tool and associated mechanism for declarative, language-agnostic program transformation using parser parser combinators [133]. Neither mutation testing nor language-agnostic program transformation primitives are the core focus of the prior award, however, which instead focuses specifically on developing push-button automatic program repair techniques. This new proposal seeks to extend the work on declarative program transformation, with a particular application to mutation testing. **Broader Impacts:** The award has so far supported two REU students, including one member of an underrepresented group in computing and another student without access to traditional research opportunities at their home institution. Sophia Kolak recently gave a well-received talk at ROSCon 2019 on her summer research; Zhen Yu Ding is the first author on a published paper on his work [30]. Both are continuing their research with the PI and have expressed plans to attend graduate school in Computer Science. Additionally, the tools and techniques developed in the research so far are open source and available on GitHub, and the PPC work has been presented to a mixed audience of academics and developers at StrangeLoop [6], an important form of outreach to the engineering community.

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