

Bug Histories as Sources of Compiler Fuzzing Mutators

Lingjun Liu

North Carolina State University
Raleigh, NC, USA
lliu39@ncsu.edu

Owolabi Legunsen

Cornell University
Ithaca, NY, USA
legunsen@cornell.edu

Feiran Qin

North Carolina State University
Raleigh, NC, USA
fqin2@ncsu.edu

Marcelo d’Amorim

North Carolina State University
Raleigh, NC, USA
mdamori@ncsu.edu

Abstract

Bugs in compilers, which are critical infrastructure today, can have outsized negative impacts. Mutational fuzzers aid compiler bug detection by systematically mutating compiler inputs, i.e., programs. Their effectiveness depends on the quality of the mutators used. Yet, no prior work used compiler bug histories as a source of mutators.

We propose **ISSUEMUT**, the first approach for extracting compiler fuzzing mutators from bug histories. Our insight is that bug reports contain hints about program elements that induced compiler bugs; they can guide fuzzers towards similar bugs. **ISSUEMUT** uses an automated method to mine mutators from bug reports and retrofit such mutators into existing mutational compiler fuzzers.

Using **ISSUEMUT**, we mine 587 mutators from 1760 GCC and LLVM bug reports. Then, we run **ISSUEMUT** on these compilers, with all their test inputs as seed corpora. We find that “bug history” mutators are effective: they find new bugs that a state-of-the-art mutational compiler fuzzer misses—28 in GCC and 37 in LLVM. Of these, 60 were confirmed or fixed, validating our idea that bug histories have rich information that compiler fuzzers should leverage.

Keywords

compiler testing, bug histories, mutational fuzzing

1 Introduction

Compilers are broadly used in software development. Ensuring their correctness is therefore critical. An impressive number of fuzzers were proposed to find compiler bugs [7, 11, 34, 35]. Mutational fuzzers [1, 10, 27, 41, 62, 65] were recently shown to be effective. But, it is challenging to explore the state space of a mutational fuzzing campaign—expressible as a graph with input programs as nodes and all possible mutations of those inputs as vertices. So, high-quality mutators [11, 41] that can effectively produce syntactically valid inputs (i.e., self-contained code snippets) to trigger deep compiler behaviors are needed.

We observe that existing mutational fuzzers do not leverage an important ingredient in creating mutators: the history of previous bugs. Yet, we conjecture that bug reports contain important hints that can be used to drive a fuzzer to areas of the search space that are likely to reveal bugs. *This paper evaluates this conjecture.*

Leveraging bug histories for bug finding was explored in other contexts [9, 42, 48, 50, 67], including compiler fuzzing [12, 45, 62, 68]. But, no prior work derived mutators for mutational fuzzing from bug histories. Recently, **METAMUT** [41] used large language models

(LLMs) to obtain mutators for a mutational fuzzer, but **METAMUT** does not leverage bug reports.

Our study is based on **ISSUEMUT**, an approach to extract mutators from bug histories and fuzz compilers with them. **ISSUEMUT** has two components: (1) a *mining component* that semi-automatically reverse engineers mutators from bug reports, and (2) an *enhanced fuzzer* that retrofits the resulting mutators into an existing fuzzer. We next briefly introduce these two components (§3 has details).

ISSUEMUT’s *mining component* takes as input past reports of fixed bugs, and outputs mutators that can drive a mutational fuzzer towards similar bugs. Mining is done in four steps. First, **ISSUEMUT** automatically extracts bug-triggering input programs—henceforth called *positive inputs*—from bug reports. Bug reports with (i) no inputs or with (ii) inputs that crash the compiler are discarded; the former are not useful and the latter indicate that a compiler bug is still present. Second, **ISSUEMUT** automatically obtains *negative inputs*: slight modifications of positive inputs that do not trigger the reported bugs. Third, we manually confirm that the negative input does not trigger the bug as the positive input does. Fourth, **ISSUEMUT** uses LLM agents to automatically generate mutators (i.e., programs that make simple semantic-changing code transformations) from the positive and negative inputs. A mutator should transform negative inputs into positive ones. **ISSUEMUT** prevents from generating overfitting mutators by validating them against additional test cases generated from the mutation description.

ISSUEMUT’s *enhanced fuzzer* retrofits the “bug history” mutators into **METAMUT** [41], a state-of-the-art (SoTA) mutational fuzzer that was shown to outperform leading generational and mutational fuzzers (AFL++ [13], Csmith [61], YARPGen [28], and GrayC [11]) with respect to coverage and unique crashes triggered. **METAMUT** provides an interface to incorporate new mutators.

We evaluate **ISSUEMUT** in two ways. First, we use it to carry out a mining campaign on bug histories of GCC and LLVM, two widely used C compilers. We obtain **587 code mutators** from 1760 reports (1457 in GCC and 303 in LLVM). Second, we integrate all mined mutators into **METAMUT** and conduct 24h per-compiler fuzzing campaigns using all GCC and LLVM regression tests as seed corpora. We evaluate **ISSUEMUT** across four dimensions:

1. How does **ISSUEMUT** compare against other mutational fuzzers?
2. How do the mutators from **ISSUEMUT** and **METAMUT** differ?
3. How beneficial is it to run fuzzing campaigns with only “successful” crash-revealing mutators?
4. How useful are the bugs reported with **ISSUEMUT**?

Considering the *first dimension*, we compare ISSUEMUT with GRAMMARINATOR, KITTEN, and METAMUT. We find that METAMUT and ISSUEMUT—as coverage-guided techniques—achieve higher coverage compared to the other techniques. We observe a positive correlation between number of files generated—much higher in KITTEN—and number of crashes reported. Overall, ISSUEMUT and KITTEN report high number of unique crashes in a 24h fuzzing campaign. Considering the *second dimension*, we find that ISSUEMUT and METAMUT mutators have important similarities and differences. For example, we find that, for both sets, most successful mutators only reveal one bug and that most bugs are triggered by inputs obtained from one mutation. But, the sets of mutators are also inherently different—ISSUEMUT’s mutators focus on finding bugs that use elements from previously reported ones, while METAMUT’s mutators relies on what the LLM learns. A concrete manifestation of this difference is that ISSUEMUT can mine successful mutators by transforming program elements from the recent C23 specification [22], since recent bugs are related to those elements [14, 31–33]. We also find that ISSUEMUT and METAMUT mutators are effective. For example, we find that both trigger several compiler crashes, with ISSUEMUT triggering 64 unique crashes that METAMUT did not find. Considering the *third dimension*, fuzzing with only successful mutators triggers more new crashes and triggers them relatively faster, compared to running separate campaigns that run the original, (larger) sets of mutators for longer. Intuitively, fuzzing using only successful mutators enables more exhaustive coverage of the search space with mutators that are more likely to help find bugs. We find, e.g., that a more focused fuzzing campaign triggers 20 crashes that are not triggered by longer-running campaigns with the full set of ISSUEMUT or METAMUT mutators. Considering the *fourth dimension*, we find that GCC and LLVM developers reacted positively; they confirmed 60 out of 65 bugs that we report from the crashes triggered by ISSUEMUT’s mutators.

Finally, we compare ISSUEMUT with FUZZ4ALL [59], a recent generational LLM-based fuzzer for systems like compilers. We use their shared artifacts to set up a fuzzing campaign using a 24-hour time budget for the fuzzing loop. We also used a similar GPU setup as in their paper, but fuzzed more recent compiler versions to facilitate our comparison. We repeat this experiment 7 times. The campaigns generate a similar number of compiler inputs as in the original FUZZ4ALL paper (~450,000 in total out of 14 runs, 7 for GCC and 7 for LLVM), but they are much fewer than those generated by ISSUEMUT in 24h (~6,700,000). FUZZ4ALL triggers 11 crashes, two of which are duplicate. Of the 9 unique crashes, 4 are also triggered by ISSUEMUT.

This paper makes the following contributions:

- ★ **Idea.** We propose the ISSUEMUT approach for “recycling” data from bug histories into simple, yet effective fuzzing mutators. We focus on C compilers, but there is no fundamental reason why “bug history” mutators should not apply more broadly.
- ★ **Mutators.** We curate a set of 587 C code mutators, which reflect salient code features that helped find previously reported bugs.
- ★ **Evaluation.** We comprehensively evaluate ISSUEMUT against several comparison baselines (e.g., GRAMMARINATOR, KITTEN, METAMUT, and FUZZ4ALL). We find 65 bugs and show that many of those bugs are unique.

```
static int __sync_lock_test_and_set_4 (volatile int*, int);
int v;
int sync_lock_test_and_set (int a)
{ return __sync_lock_test_and_set(&v, a); }
```

Listing 1: Bug present in Clang since version 12; still present in version 20. This bug was revealed from two mutations applied to a seed file; they introduce a declaration for the function call `__sync_lock_test_and_set` and replace the `extern` keyword (not visible) with the `static` keyword.

- ★ **Lessons learned:** We present several lessons from this study (§ 5.4). For example, we find that mutators exploring recently-proposed compiler features—as those proposed in the C23 standard [22]—are promising for revealing bugs and encourage fuzzers to test more files with those features.

2 Example

We present a bug-revealing input that ISSUEMUT obtains using “bug history” mutators and provide an overview of ISSUEMUT’s steps.

2.1 Clang bug #120083

The code snippet below is part of GCC’s test suite [53]:

```
int v;
int sync_lock_test_and_set (int a)
{ return __sync_lock_test_and_set (&v, a); }
```

Listing 1 shows a variant of this snippet that triggers a crash in Clang version 20 (revision 9bdf683). That crash occurs during LLVM’s IR code generation for method `sync_lock_test_and_set`. LLVM developers confirmed our bug report, saying that the root cause of the crash has been in the codebase since Clang version 12.0.0, which was released on April 14, 2021.¹ Two mutations yield the code in Listing 1. The first mutation, **M17**, adds a missing declaration to a function used in the original input; that declaration uses the `extern` qualifier. The second mutation, **M3** (Table 1), replaces the `extern` keyword—introduced by M17—with the `static` keyword. We apply each mutation separately and find that both are needed to reproduce the bug. The effects of mutations M3 and M17 in Listing 1 are shown in green and yellow, respectively.

2.2 Overview

2.2.1 Positive and Negative Examples. ISSUEMUT uses a semi-automated approach to obtain positive and negative examples from bug reports (see § 3). We next summarize how ISSUEMUT obtains these examples for mutators M17 and M3.

M17. We use the following input from GCC bug report #108777 [16] to obtain a *positive test* for M17:

```
extern void *memcpy(void *, const void *, __SIZE_TYPE__);
extern void *memmove(void *, const void *, __SIZE_TYPE__);
extern void *memset(void *, int, __SIZE_TYPE__);
void foo(void *p, void *q, int s) { memcpy(p, q, s); }
void bar(void *p, void *q, int s) { memmove(p, q, s); }
void baz(void *p, int c, int s) { memset(p, c, s); }
```

The discussion in the report explains that when explicit external function declarations (e.g., `extern void *memcpy(...)`) are present in code, GCC treats them as regular external function references rather than built-in functions. That treatment prevents GCC from

¹Playground reproduction: <https://godbolt.org/z/v3zEGx1xn>

applying built-in function optimizations and transformations. **ISSUEMUT** replaces these explicit extern function declarations with standard headers to obtain a *negative test case*, so that the compiler recognizes these functions as built-ins and apply instrumentation. To sum up, from these examples, **ISSUEMUT** creates a mutator (M17) that analyzes the code to determine the signatures of functions with a missing declaration, then it adds a function declaration with an extern modifier.

M3. We use the following input from GCC bug report #108449 [15] to obtain a *positive test* for M3:

```
static int vfork(); void f() { vfork(); }
```

The bug report explains that this input manifests a regression in the compiler. GCC-13 raises an Internal Compiler Error (ICE) when compiling code with a static and undefined function declaration. In that case, the compiler internally attempts to convert the static declaration to extern declaration, but it fails. The corresponding negative input behaves similarly, i.e., the corresponding mutator replaces the static modifier in a function declaration with extern to simulate the problematic scenario reported in this regression. To sum up, from this pair of examples, **ISSUEMUT** creates a mutator (M3) that replaces the keyword extern with the keyword static.

2.2.2 Mutator Creation. The following simplified code snippet implements mutator M17 as an Clang AST visitor [55]:

```
// Mutator M17
class AddExternDeclaration ... {
  std::set<const FunctionDecl*> FunctionDecls;
  // collect signatures of function calls
  bool VisitCallExpr(CallExpr *Call) { ... }
  // manipulate AST to introduce function declaration
  // with extern keyword at the beginning of the file.
  bool mutate() { ... } }
```

M17 is a context-sensitive mutator that needs to collect information before mutating the code. But, in most bug reports that we analyze, we find that mutators do *not* require contextual information. In those cases, a sed-like approach is sufficient to create mutators. Mutator M3 is an example of a context-insensitive mutator. It is implemented with this generic bash script, passing “extern” and “static” as parameters PATTERN and REPLACEMENT, respectively:

```
#!/bin/bash
FILE=$1
PATTERN=$2
REPLACEMENT=$3...
# Replace a string matching regex $PATTERN with
# string $REPLACEMENT at line ln in file $FILE
sed -i -E "${ln}s/$PATTERN/$REPLACEMENT/" $FILE
```

2.2.3 Summary. **ISSUEMUT** mines 587 mutators from GCC and LLVM bug histories and systematically applies them using 35,472 files —test cases from GCC and LLVM— as seed corpora in a fuzzer built on top of a SoTA mutational compiler fuzzer, **METAMUT** [41]. **ISSUEMUT** finds 65 bugs, 64 of which **METAMUT**’s mutators miss.

3 Approach

We describe each component of **ISSUEMUT** in more detail. §3.1 describes **ISSUEMUT**’s automated miner that obtains mutators from bug reports. §3.2 describes **ISSUEMUT**’s fuzzing framework.

3.1 Mutator Mining

Figure 1 shows the workflow of **ISSUEMUT**’s mutator mining. We describe each of the steps in the following.

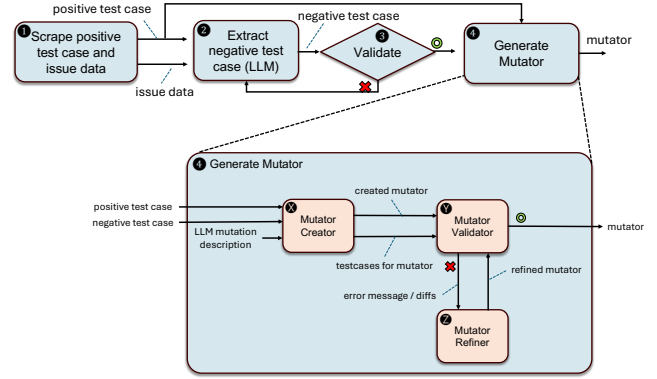


Figure 1: The workflow of **ISSUEMUT**’s mutator miner.

```
Product: gcc
Component: tree-optimization
Keywords: ice-on-valid-code ...
$ cat z1.c
static int vfork();          ### FILE ###
void f() { vfork(); }        ### FILE ###
$ gcc-13-20230115 -c z1.c -O2
during GIMPLE pass: cddce
z1.c: In function 'f':
z1.c:2:1: internal compiler error: in \
      eliminate_unnecessary_stmts, at \
      tree-ssa-dce.cc:1512
      2 | void f() { vfork(); }
        | ^~~~
0xe0f0dc eliminate_unnecessary_stmts
..././gcc/tree-ssa-dce.cc:1512...
0xe11e55 execute
..././gcc/tree-ssa-dce.cc:2069
```

(a) Issue metadata and stack trace. A valid input (z1.c) reveals an Internal Compiler Error (ICE) during an optimization step in GCC.

When we have static declaration without definition we diagnose that and turn it into an extern declaration. That can alter the outcome of maybe_special_function_p here and there is really no point in doing that, so do not.

(b) Relevant fragment of the issue discussion.

```
# positive test case      # negative test case
static int vfork();        extern int vfork();
void f() { vfork(); }      void f() { vfork(); }
```

(c) Positive and negative test cases.

Figure 2: Fragment of bug report [15] and corresponding positive and negative test cases.

3.1.1 Scrape positive test case and issue data (1). We write scripts to scrape test cases from fixed and closed issues created in the period from January 2023 to October 2024 (22 months). A total of 1457 and 303 candidate issues from GCC and Clang, respectively, satisfy these criteria. We manually analyze candidate issues in chronological order. To do so, we run the test of a given issue in a recent version of the corresponding compiler and discard the issue if a crash occurs. The rationale is that such crashes would have been detected via regression testing. If no crash is detected, this step reports a pair of issue and associated test case as output. We say the test cases from issues are positive because they contain program elements that trigger a bug in a previous compiler version. (The presence of an issue associated with the test demonstrates

that ability.) Figure 2a shows a fragment of a GCC bug report, including the affected compiler component (tree-optimization), the bug consequence (ice-on-valid-code), the bug-revealing test file (see “### FILE###”), and a stack trace fragment. Figure 2b shows a portion of the discussion explaining the bug.

3.1.2 Extract negative test case (②). This step produces a negative test case from a given pair of issue and a positive test case that is mined from ①. For example, if the issue indicates that adding `__attribute__((noipa))` reveals a bug when used in a function, the negation of that positive test case removes that attribute. We use an LLM to solve this task, due to its ability to handle text and code. We use GPT-4o mini [39] because we find it to offer a reasonable trade-off between accuracy and cost. To optimize the prompt engineering process, we employed PromptPerfect [17], an AI prompt optimization tool designed to enhance the quality of LLM outputs. The optimized prompt we obtain was:

```
You are an experienced C developer. Your task is to read a bug
report and corresponding bug-revealing input and produce a similar
input that does not manifest the bug. The response should only
include the description of the mutation and the mutated C code.
### Bug Report: ...
### Bug-revealing Input: ...
```

Figure 2c shows an example of a negative test case (simplified for clarity) for the corresponding issue and positive test case.

3.1.3 Validate negative test case (③). We manually check if the negative test case compiles and if it is consistent with the issue description. If the negative test case does not reflect the issue, we repeat the query in ② with another LLM—Claude or o1-mini. We discard the issue if we cannot validate the test case.

3.1.4 Generate mutators (④). This step creates mutators for a pair of positive and negative test cases. A mutator is a function that identifies target locations and changes the code at one or more of those locations. We empirically find that most mutators are context-insensitive, i.e., they check preconditions at the change location (see §2.2.2). Based on this observation, we developed an automated pipeline that generates mutators by deriving sed-like transformations from positive and negative test case pairs. More precisely, `ISSUEMUT` automatically creates mutators that transform a negative test case into the corresponding positive one. We use a LangChain-based [6] agentic architecture powered by the Gemini 2.5 Pro model. The architecture is based on three agents:

Mutator Creator. This agent performs three tasks to create a script for a mutator: *Generalize Mutation*, *Generate Tests*, and *Create Script*. First, the task *Generalize Mutation* reverses the description of how the LLM mutates a positive test case into a negative test case, as obtained in step ②, and removes the specific parts from the description (e.g., literals). For example, given LLVM issue #113692 [30], the agent first reverses the mutation description “Changed the inline assembly constraint from `+f` to `+x` to use SSE registers instead of the x87 floating point stack..”, and then generalizes it to obtain the description: “Change an inline assembly constraint from one that uses an SSE register to one that uses the x87 floating point stack.” Second, the task *Generate Tests* generates a given number (3 default) of test cases (i.e., C code input-output pairs) to validate the mutation description, i.e., to ensure the mutator works beyond the original negative-positive input pair. This step is crucial to create generalizable mutators and prevent “overfitting”. For the issue above, an example test case pair is:

```
void func(float a) { __asm__("fsqrt" : "+x"(a)); } // input
void func(float a) { __asm__("fsqrt" : "+f"(a)); } // output
```

Third, the task *Create Script* synthesizes a generic sed-based bash script from a mutation description. We use the template command `sed -i -E 's/<r>/<s>/g' <file>`, which replaces all strings matching the regular expression `<r>` with the string `<s>` in the input `<file>`. Our artifacts contain the prompt (see Appendix A.1) that this agent uses to obtain a bash script.

Mutator Validator. This agent validates the mutator script by running it against all test cases, i.e., the original test case (§3.1.1 and §3.1.2) and the additional test cases (task “Generate Tests”). Recall that a test artifact is an input-output pair of C code. So, testing consists of checking whether running the script on the input produces the expected output. The validator agent produces one of four outcomes for a mutator: (1) *Correct* - all 4 test cases pass, resulting in a finalized mutator; (2) *Partially Correct* - 3 out of 4 test cases pass; (3) *Error* - the execution of the test harness fails; (4) *Wrong* - passes in fewer than 3 test cases. We report a mutator if the agent labels it as “Correct” or “Partially Correct”. We trigger a refinement step when observing the “Error” and “Wrong” outcomes. More precisely, we send the corresponding error message and test output diffs to the “Mutator Refiner” agent along with the request to refine the mutator.

Mutator Refiner. This agent refines likely invalid mutator scripts using the error messages obtained during the validation step. The refiner agent iterates until the script can pass on the majority of the tests or until it reaches five iterations. Our artifacts include the prompt (see Appendix A.2) that the Mutator Refiner agent uses to refine a bash script. For the LLVM issue #113692 [30], the final mutator script is:

```
#!/bin/bash
FILE=$1
PATTERN='\"+x\"(\\s*\\([\\^\\)]*\\))'
REPLACEMENT='\"+f\"\\1'
sed -i -E 's/$PATTERN/$REPLACEMENT/' $FILE
```

For the few cases where contextual information is necessary to transform the code, we use Clang’s AST visitors [55], like `META-MUT`. §2.2.2 shows a simplified version of a bash script and AST visitors that we use to implement these mutators. It is worth noting that syntactic duplicates can arise when creating mutators. We look for duplicates by searching for hash collisions in a hash table. We compute a hash for a mutator by applying the mutator on a random sample of our seed inputs representative of the entire seed corpus with 99% confidence and 1% margin of error [52]. We apply a mutator on each of these inputs and use the `sha256sum` UNIX command to obtain an aggregate hash from the outputs. We find a total of 16 duplicate mutators (14 from GCC and 2 from LLVM). We exclude these 16 from those that we mine. Of the 587 (=603-16) mutators that remain, 412 are from GCC and 175 are from LLVM. There is no fundamental reason for this imbalance; it only reflects that we started our experiments with GCC. In the rest of this paper, we use **bhis** (bug history) to refer to this set of 587 mutators.

3.2 Enhanced Mutational Compiler Fuzzer

Generational fuzzers create inputs anew, whereas mutational fuzzers modify existing inputs [65]. We focus on mutational fuzzing due to its ability to efficiently create variations of existing inputs. In

compiler testing, inputs are self-contained code snippets. A mutational fuzzer randomly applies mutations to files present in a queue, initialized from a seed corpus. The seed corpus that we use include all test cases from GCC [53] and LLVM [56]. Fuzzing stops after a time budget. It is worth noting that many recent mutational fuzzers use coverage to drive fuzzing. Coverage-guided fuzzers (CGF) save mutations that uncover new branches [54] of a program under test in its queue for additional fuzzing.

We integrate all ISSUEMUT-mined mutators into METAMUT [41], a recently-proposed SoTA coverage-guided mutational fuzzer [64] of C programs that revealed bugs in GCC and LLVM. METAMUT mutators use abstract syntax tree (AST) visitors [44] to transform C files. As of now, METAMUT only checks for crashes, but there is no fundamental reason METAMUT could not be adapted to detect other kinds of bugs, such as miscompilations through differential testing [36]. We use the stacktrace-based procedure provided in METAMUT to de-duplicate alarms raised during our fuzzing campaigns. That procedure considers the top two stack frames, including the program counter and ignores helper functions.

4 Evaluation

Research Questions. Our evaluation addresses four questions:

- RQ1.** How does ISSUEMUT compare against other mutational fuzzers in terms of coverage and bug-finding effectiveness?
- RQ2.** How do ISSUEMUT and METAMUT mutators differ (e.g., rate of crashes reported over time, number unique crashes, and diversity of crashes)?
- RQ3.** How beneficial is fuzzing with *only successful* ISSUEMUT mutators, compared to fuzzing with all mutators?
- RQ4.** How useful are the bug reports of ISSUEMUT?

The first question contrasts the performance of ISSUEMUT against SoTA mutational fuzzers in terms of coverage and ability to reveal bugs. The second question makes an in-depth comparison between ISSUEMUT and METAMUT quantitatively (e.g., crashes over time) and qualitatively (e.g., static and dynamic characteristics). Recall that ISSUEMUT corresponds to METAMUT augmented with mutators mined from bug history. The third question evaluates the benefits of restricting the set of mutators in a fuzzing campaign to only include mutators that previously triggered crashes. Intuitively, using fewer mutators can lead to better search space coverage. The fourth question evaluates the usefulness of the bug reports we submitted as a result of ISSUEMUT’s fuzzing campaigns.

4.1 Baselines

Our primary comparison baseline is **METAMUT** [41], a recently-proposed SoTA mutational fuzzer that is *extensible* with user-provided mutators; it (i) achieves 5.4% and 6.1% higher code coverage than leading generational and mutational compiler fuzzers, respectively, (AFL++ [13], Csmith [61], YARPGen [28], and GrayC [11]) and (2) detects three times more unique crashes than these tools. METAMUT uses LLMs to create mutators within a space of possible actions (e.g., Add) and program elements (e.g., Expression). METAMUT provides two sets of mutators that differ based on whether human supervision is used to obtain them: **mu.s** and **mu.u**. The set **mu.s** (supervised) includes 68 mutators obtained through interactions with GPT-4 [40]. METAMUT authors created

these mutators by analyzing, debugging, and validating the generated AST-based mutators (§2.2.2). They refined LLM prompts throughout this process, and considered prompts to be fully refined after roughly two weeks. After that, they ran their workflow *without* human supervision for 100 iterations using the same GPT-4 model and obtain another set of 50 mutators, referred to as **mu.u** (unsupervised). We compare these two sets of METAMUT mutators with the set of “bug history” mutators that ISSUEMUT mines, which we refer to as **bhis**² (§3.1).

Our secondary comparison baselines include gramxmar-based mutational fuzzing techniques, namely **GRAMMARINATOR** [20] and **KITTEN** [60]. They represent SoTA grammar-based fuzzers with support for C. GRAMMARINATOR utilizes grammars as models to enable both generational and mutational fuzzing. It generates test cases from scratch using grammar rules and mutates existing tree structures through recombination and tree transformations. KITTEN is a language-agnostic program generator that performs tree-level mutations (splicing, replacement, deletion, and repetition) on parse trees and token-level mutations (insertion, deletion, and replacement) on token sequences from seed programs to generate syntactically valid and invalid test programs for compiler testing.

Section 5 also reports on a lightweight comparison against **Fuzz4ALL** [59]. It is worth noting that Fuzz4ALL requires GPUs to generate files whereas METAMUT and the comparison baselines only require CPUs.

4.2 Setup

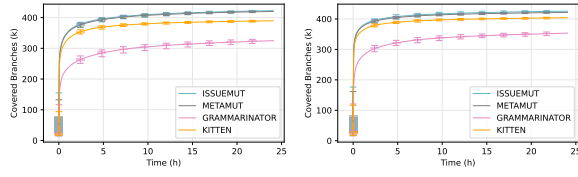
We run experiments on an Ubuntu 22.04.5 LTS DELL PowerEdge R6625 server, equipped with two 96-core AMD EPYC 9684X processors and 755 GB of memory. Each fuzzing technique is allocated 30 physical cores to ensure fair comparison across all approaches. We configure METAMUT (and ISSUEMUT) to run 30 agents in parallel (`-j 30`), configure KITTEN with a 30-thread setting (`-threads=30`), and run GRAMMARINATOR with 30 concurrent processes (we wrote a bash script to spawn independent processes).

As in prior work on compiler fuzzing [41], we set a time budget of **24h** for each fuzzing technique and focus on the `-O2` optimization level. For the sake of reproducibility, we fix two recent compiler revisions: GCC 15 (87492fb) and Clang 20 (9bdf683). However, we only report bugs in the most recent revisions of these compilers. Finally, to account for the inherent nondeterminism in the experiment, we run each experiment for five times.

4.3 Answering RQ1

We report a comparison of ISSUEMUT with SoTA mutational fuzzers, namely KITTEN, GRAMMARINATOR, and METAMUT. ISSUEMUT corresponds to METAMUT configured with the set of mutators we propose in addition to the default set of mutators. We select KITTEN and GRAMMARINATOR as baselines because they are grammar-based mutational fuzzers that offer program-agnostic capabilities, applicable to arbitrary C programs. To ensure fair comparison, we used the same seed corpora across all techniques. For GRAMMARINATOR, we configured its parser using the ANTLR C grammar to translate our seed corpora into the expected input format. For crash analysis,

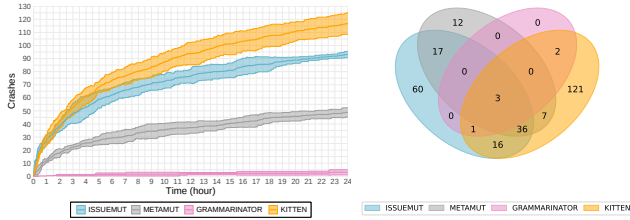
²bhis is shorthand for **bug history** mutators.



(a) Coverage: GCC (left) and LLVM (right).

Technique	Number of files
ISSUEMUT	6.7M
METAMUT	5.9M
GRAMMARINATOR	0.7M
KITTEN	22.1M

(b) Number of files generated by techniques.



(c) Crashes: progress (left) and uniqueness (right)

Figure 3: Comparison of ISSUEMUT against baselines on coverage (3a), number of files (3b), and crashes (3c).

we used METAMUT’s crash deduplicator to identify unique crashes consistently across all techniques.

Figure 3 shows the results. Figure 3a shows that METAMUT and ISSUEMUT cover more code than other baselines within 24h. This is expected as these two techniques are coverage guided. The progress plots and venn diagram from Figure 3c indicate that ISSUEMUT reveals more unique crashes compared to METAMUT and GRAMMARINATOR but less unique crashes compared to KITTEN. The ability of KITTEN to generate more files within 24h partially justifies this observation (Figure 3b). Note that ISSUEMUT inherits the runtime (in)efficiency of METAMUT and future work can integrate mutators from issues into KITTEN.

We observe that design choices in engineering the fuzzers highly influence the number of generated files and, consequently, influence their ability to reveal crashes within a time budget. KITTEN generates far more files than METAMUT (and ISSUEMUT) whereas GRAMMARINATOR generates far fewer files than METAMUT. KITTEN parses each seed file once into a tree structure and maintains all trees in memory throughout the fuzzing process, reducing I/O and parsing overhead. When performing tree-level mutations, KITTEN directly manipulates the in-memory tree structure to produce both the mutated source code and the corresponding tree instance. The mutated tree can be immediately added to the seed pool without reparsing. In contrast, METAMUT does not provide such caching mechanism and, consequently, incurs in significant time inefficiency. In summary, KITTEN trades memory –unbounded in this experiment– with time, enabling the fuzzer to generate more mutants in 24h. This explains

KITTEN’s efficiency advantage over METAMUT in the current setup. For GRAMMARINATOR, we note that the cost of parsing is prohibitive when compared to the other baselines. GRAMMARINATOR uses a general-purpose library for parsing (ANTLR) and accesses the parser through Python bindings. It is also worth noting that the small efficiency advantage of ISSUEMUT over METAMUT is due to the higher amount of sed-based mutators in ISSUEMUT.

When inspecting for differences in crash-revealing files (Figure 3c), we observed the following breakdown for KITTEN: 72 from tree-level splicing, 22 from tree-level replacement, 3 from tree-level repetition, 11 from token-level insertion, 4 from token-level deletion, and 9 from token-level replacement. Note that 59.5% (72 out of 121) of KITTEN’s unique crashes originate from tree-level splicing, a mutation strategy that replaces a subtree in the parse tree of a seed program with a subtree from another seed program. In one of those cases, KITTEN replaces `__attribute__((vector_size(16)))` with `__attribute__((vector_size(1 << 28)))`, where the pure numeric expression `1 << 28` is obtained from another seed program. ISSUEMUT is unable to manifest crashes that arise from interactions between different seed files; it applies self-contained mutations that originate from previous bug reports. It remains to evaluate how to combine the two complementary strategies.

RQ1 (Comparison with SoTA)

ISSUEMUT and KITTEN outperformed the other comparison baselines w.r.t. number of unique bugs detected. More importantly, they reveal several bugs and many of these bugs are distinct. We find compelling evidence that the mutators from ISSUEMUT can be useful to complement mutators from a mutation fuzzer.

4.4 Answering RQ2

We assess how ISSUEMUT and METAMUT mutators compare from different angles: static (§4.4.1), dynamic (§4.4.2), crashes over time (§4.4.3), crash uniqueness (§4.4.3), and crash diversity (§4.4.4).

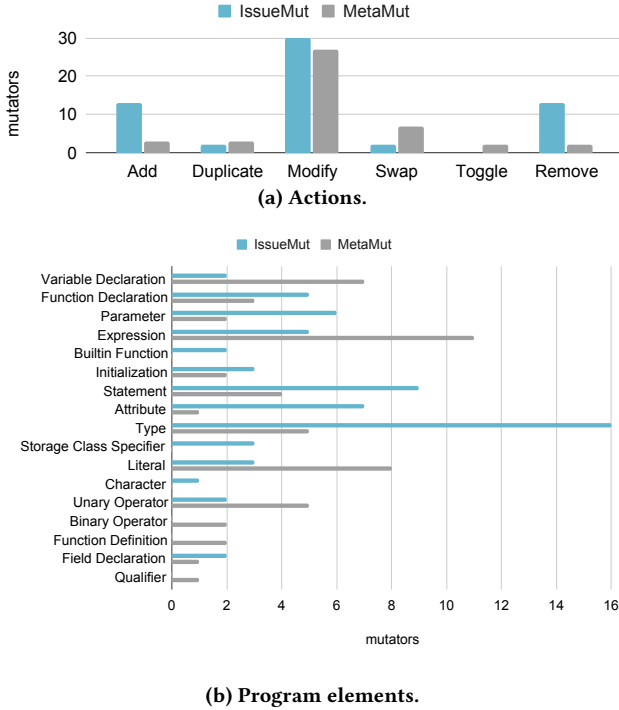
4.4.1 Static Characteristics. We focus on two characteristics of a mutator: the kind of change it makes (e.g., code addition) and the program elements it manipulates (e.g., expression).

Our artifacts include a list of ISSUEMUT mutators that contributed to expose at least one crash. Table 1 shows a representative list of ten ISSUEMUT mutators that contributed to revealing at least three bugs. Column “Id” is the identifier of a mutator, “Src.” shows the compiler targeted by the mutator (G=GCC or L=LLVM), “Action” and “Program Element” indicate, respectively, the transformation and the target program element for that transformation, and “Description” is a short description of the mutator. The symbol ★ denotes mutators related to the recent C23 standard [22].

Figures 4a and 4b show, respectively, the distributions of transformations and target program elements for *successful* ISSUEMUT and METAMUT mutators. For simplicity, we combined both sets of mutators from METAMUT in these plots; the goal of this question is to understand characteristics (as opposed to establish superiority). Figure 4a indicates a discrepancy in the proportion of actions between these two mutator sets. ISSUEMUT mutators most often add, modify, or delete program elements. In contrast, most METAMUT mutators perform modifications.

Table 1: Representative list of mutators revealed more than three crashes from ISSUEMUT. ★ =C23 standard

Ⓐ=Attribute Ⓑ=Built-in function Ⓒ=Unary Operator Ⓓ=Function Declaration Ⓔ=Literals Ⓕ=Initialization Ⓖ=Parameter Ⓗ=Expression Ⓖ=Storage Class Specifier Ⓖ=Statement Ⓖ=Type Ⓖ=Variable Declaration Ⓖ=Character					
Id	Src.	Action	Pgm. Elements	Description	
M1	G	Add	Ⓑ Ⓗ	Adds built-in function <code>__builtin_assoc_barrier()</code> around the return expression.	
M2	G	Swap	Ⓗ	Swaps two arguments of function calls.	
M3	G	Modify	Ⓖ	Replaces extern storage class specifier with <code>static</code> .	
M4	G	Remove	Ⓒ	Removes a type cast operator.	
M5	G	Modify	Ⓖ Ⓖ	Replaces const pointer parameters with non-const non-pointer parameters.	
M6	G	Modify	Ⓗ	Replaces a variable reference with a call expression.	
M7	L	Remove	Ⓖ	Removes the size expression from an array variable declaration.	
M8	L	Modify	Ⓔ	★ Replaces integer literals with a large numeric value using a new integer literal suffix. (e.g., changing 123 to 66666...wb (The wb suffix is a bit-precise integer literal suffix introduced in the C23 standard)).	
M9	L	Modify	Ⓔ	★ Replaces integer zero literals into binary zero literals, which is introduced in the C23 standard (e.g., 0b0).	
M10	L	Add	Ⓐ Ⓓ	Adds <code>__attribute__((target_clones("default, avx")))</code> to function declarators.	

**Figure 4: Static characterization.**

Analyzing the data in Figure 4b, we find that some groups of program elements are only targeted by only one of the techniques, i.e., their corresponding mutator sets. We attribute this observation to how METAMUT and ISSUEMUT create mutators. ISSUEMUT uses bug histories and METAMUT uses an LLM. METAMUT focuses on specific AST elements to reduce task definition scope in prompts.

RQ2 (Static Characteristics)

ISSUEMUT and METAMUT mutators differ on the actions they perform and the program elements they manipulate. This difference can be attributed to how these mutators originate. ISSUEMUT uses bug histories while METAMUT uses an LLM to obtain mutators.

4.4.2 Dynamic Characteristics. We further compare ISSUEMUT with METAMUT by considering the number of crashes they reveal and examining the lengths of the mutation chains associated with the detected crashes. The histograms from Figure 5a show the number of mutators (y-axis) that reveal a given number of crashes (x-axis). For example, eight of ISSUEMUT’s mutators reveal three crashes. Results indicate that, a higher number of mutators mined with ISSUEMUT reveals more than one crash compared to METAMUT (mu.s and mu.u combined).

Figure 5b compares the lengths of ISSUEMUT and METAMUT mutation sequences that produce crash-triggering inputs. It is worth noting that to measure the length of such chains we minimize mutation sequences a posteriori. Results indicate that the vast majority of crash-triggering inputs (88% in ISSUEMUT and 82% in METAMUT) are produced by a single mutation. The presence of crashes triggered using inputs resulting from multiple mutations indicate that (i) one mutation increased compiler coverage so the file was added to the queue; and (ii) the other mutator changed that file in a way that triggered a crash. Note that all three mutator sets (two from METAMUT and one from ISSUEMUT) perform *one* mutation at a time, like in first-order mutants in mutation testing [24]. But, the fuzzing campaign can apply multiple mutations in subsequent steps, like in high-order mutants [23].

RQ2 (Dynamic Characteristics)

ISSUEMUT and METAMUT mutators have similar dynamic behaviors: most successful mutators trigger a single crash and most crash-triggering inputs result from one mutation.

4.4.3 Coverage and Crashes Triggered over Time. Figures 6a and 6b show the trends in coverage and crashes detected over time for each set of mutators, namely **bhis**, **mu.s**, and **mu.u**. We find that differences in coverage are negligible.

The shaded areas in the progress plot on Figure 6b (left) represent the 95% confidence interval of the distributions of crashes at a given point in time. It is worth noting that crashes are deduplicated on each run to avoid inflation of results.

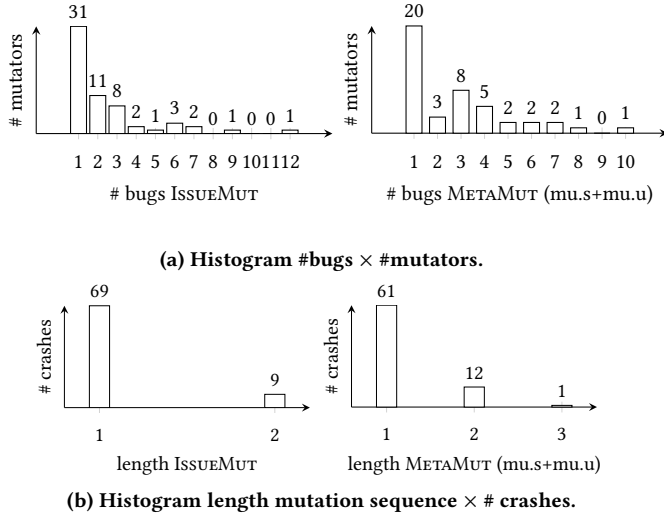
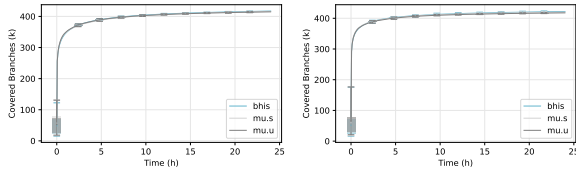
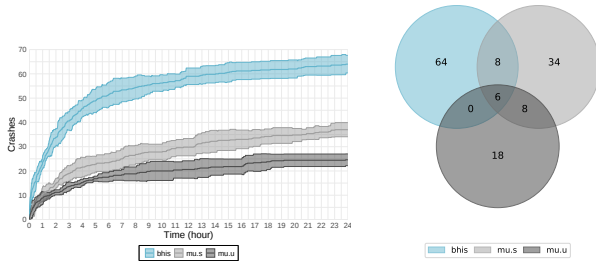


Figure 5: Dynamic characterization.



(a) GCC and LLVM coverage.



(b) Differences in bugs revealed by techniques.

Figure 6: Progress of crash detection over time (left) and differences of crashes each mutator set detects (right).

RQ2 (Crashes over time)

On average, ISSUEMUT’s mutators reveal more crashes (**64.0**, on average) over time when compared to METAMUT’s mutator sets (**37.0** and **24.6**, on average).

We analyze the number of distinct crashes that each set of mutators finds at the end of fuzzing campaigns. The venn diagram in Figure 6b (bottom right) shows the relationships among crashes found by each mutator set. The diagram merges results by taking the union of the observed crashes across the various runs of the fuzzer for a given mutator set.

Table 2: Kinds of crashes and their distribution over modules.

	ISSUEMUT		METAMUT	
	Clang	GCC	Clang	GCC
Kind				
Segmentation Fault	5	7	4	2
Assertion Failure	33	14	41	7
Hang	0	0	1	0
Internal Compiler Error	2	17	3	16
Affected compiler modules				
Front-End	14	8	20	10
IR Generation	16	17	20	5
Optimization	6	9	2	0
Back-End	4	4	7	10

RQ2 (Uniqueness of crashes)

Fuzzing with **bhis** (ISSUEMUT) mutators reveals several crashes that **mu.s** and **METAMUT** (METAMUT) miss **64** unique crashes in the union of **bhis**-induced crashes, respectively. So, there is evidence that “bug history” mutators complement and improve the bug-finding effectiveness of SoTA mutators.

4.4.4 Diversity. Table 2 shows the kinds of crashes that ISSUEMUT and METAMUT find and their distributions across compiler modules. Assertion Failures and Internal Compiler Errors (ICE) are more common than hangs or segmentation faults. The proportions of these classes of crashes are similar for ISSUEMUT and METAMUT. Also, crashes in the Front-End and in IR Generation are more common, compared to others. ISSUEMUT and METAMUT find bugs deeper in the compiler stack, but they do so in lower numbers.

RQ2 (Diversity of crashes)

ISSUEMUT and METAMUT trigger crashes of different kinds and in different modules. Overall, “bug history” mutators are distinct compared to the set of mutators from METAMUT.

4.5 Answering RQ3

We evaluate the benefits of restricting the size of the set of mutators used in a fuzzing campaign by including only “successful” ones: those that previously triggered crashes. Intuitively, using fewer mutators can cover more of the search space within a time budget. Prior work explores strategies to calibrate exploitation-exploration before [3, 43, 63]. We report on a limit study to exploit such successful mutators. Such set includes 60 mutators from ISSUEMUT (listed in our artifacts) and 44 mutators from METAMUT.

Figure 7 shows the number of distinct crashes obtained after merging runs across multiple seeds with union. The venn diagram shows the differences in crashes found by each mutator set: **bhis**, **mu.s**, **mu.u**, and **successful** (104 mutators from all three sets). The fuzzing campaigns with “successful” mutators triggers **20** crashes that are *not* triggered by any other campaign. Of these, 6 crashes

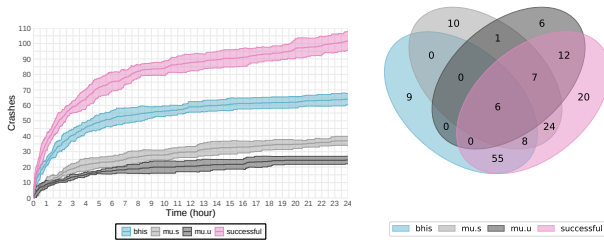


Figure 7: Comparison between fuzzing with bhis, mu.s, mu.u mutators and fuzzing with successful mutators (104).

are due to ISSUEMUT’s mutators *alone*: 5 in LLVM (149368, 149369, 149371, 149372, one does not crash on trunk), and 1 in GCC (119177). As expected, the campaign with only “successful” mutators also reveals crashes faster. Figure 7 shows the progress of crashes triggered over time. For example, at the 2-hour mark, fuzzing with only “successful” mutators had triggered an average of 50.8 distinct crashes.

RQ3 (Fuzzing with only “successful” mutators)

Running fuzzing campaigns with only “successful” mutators is beneficial: the focused campaign (i) triggers **20** crashes *not* triggered by campaigns that use all mutators (**mu.s**, **mu.u**, and **bhis**) in an 24h time budget; and (ii) triggers crashes faster.

4.6 Answering RQ4

We report on the ability of ISSUEMUT’s mutators to reveal bugs (as opposed to crashes). The bug reporting process spanned several months as we iteratively improved ISSUEMUT. Throughout this process, we conducted multiple fuzzing campaigns to evaluate ISSUEMUT’s bug-finding ability. We reported bugs immediately upon discovery and ensured that newer versions consistently found a superset of crashes from prior campaigns. To contextualize our findings, compiler testing researchers report various numbers of bugs in their studies. For example, GrayC [11] evaluated their approach on GCC, LLVM, MSVC, and Frama-C. Considering GCC and LLVM alone (i.e., the two compilers that we use), they found, respectively, 11 and 10 bugs that were confirmed and fixed by compiler developers.

For bug reporting, we use *all* 78 crashes from the set bhis, represented in the venn diagram from Figure 6b (merged with union). Our artifacts show a list of all bugs we reported to developers. Of these, 52 bugs were only found by bhis mutators. Table 3a lists bugs that LLVM and GCC developers *fixed*. Column “Id” shows bug identifiers in the corresponding bug-tracking system, “Status” is the status of the bug report at the time of writing, and “Mutators” shows the number of mutators that contributed to finding the bug. For the “Mutators” column, once we detect a crash, we identify the length of the chain of mutations that produced the crash-triggering input and manually eliminate mutations that are unnecessary for crash reproduction. The notation “ $M_1 \oplus M_2$ ” indicates that we can reproduce a bugx by applying M_1 or M_2 to a seed file. The artifacts

Table 3: Reported bugs.

(a) Fixed bugs reported with ISSUEMUT. Highlighted rows indicate crashes that only ISSUEMUT finds (unique). The full list bugs reported can be found in our artifacts.

LLVM bugs			
Id	Status	Mutators	
118892	Fixed	M5 $\oplus$ M6	
123410	Fixed	M3	
144771	Fixed	M4	
GCC bugs			
Id	Status	Mutators	
118061	Fixed	M11 $\oplus$ M18 $\oplus$ M14 $\oplus$ M23	
118674	Fixed	M2	
118868	Fixed	M1	
118948	Fixed	M54	
119001	Fixed	M7	
119204	Fixed	M30	

(b) Summary of reported bugs.

C Compiler	Reported	Confirmed	Duplicate	Fixed
LLVM	37	28	6	3
GCC	28	14	3	6
Σ	65	42	9	9

show examples of bugs that require a sequence of mutations. Highlighted rows in Table 3a indicate bugs that *only* bhis mutators find, i.e., a subset of the 64 unique crashes from Figure 6b.

Table 3b shows a summary of the reported bugs, indicating the current category of the report. Note that we report fewer bugs compared to the number of crashes we observe: 78 (=64+8+4) crashes observed versus 65 bugs reported. The reason for the difference is that we only report bugs that we can reproduce in the most recent compiler release. It is also worth noting that we find duplicate bugs. As in prior work [27, 41], we mention these bugs here as we could get credit if reported earlier. Overall, results show that (i) 5% of ISSUEMUT’s mutators revealed at least one bug; and (ii) developers confirmed or fixed majority of our bug reports.

RQ4 (Usefulness of crashes for bug finding)

Developers acknowledged **60** (confirmed, fixed, or duplicate) out of **65** bugs that we report in LLVM (37) and GCC (23). Of these, **52** are uniquely manifested with ISSUEMUT, i.e., the two METAMUT’s mutator sets missed them.

It is worth noting that METAMUT’s authors report bugs in a longitudinal study, i.e., across several compiler versions and over several months. A side-by-side longitudinal comparison with METAMUT considering number of bugs reported would be unfair and unproductive as we would need to match compiler revisions and METAMUT authors reported bugs in those revisions earlier, so bugs could be already fixed (as METAMUT’s authors accessed corresponding revisions earlier).

4.7 Threats to Validity

The main threat to *internal validity* consists of the bias that we might have inadvertently introduced in our implementation. To mitigate that threat, we built ISSUEMUT by retrofitting bhis mutators

onto the METAMUT framework, which is our baseline in experiment. The main threat to *construct validity* is the stochastic nature of the result that could have favored our results. To mitigate that threat we repeat our experiments multiple times with random seeds. The main threat to *external validity* is the selection of issues we selected. We follow a well-defined method to assure that we only analyze bugs that have been already fixed.

5 Discussion

We compare ISSUEMUT with FUZZ4ALL (§5.1), discuss sample bugs that we report to LLVM and GCC developers (§5.2), include a qualitative comparison of ISSUEMUT’s mutators with existing mutation-based fuzzing tools (§5.3), and present a list of lessons that we learned in this work (§5.4).

5.1 Comparison with FUZZ4ALL [59]

FUZZ4ALL uses LLMs to generate inputs for fuzzing compilers and other systems. FUZZ4ALL’s workflow has two stages. First, it uses auto-prompting [47, 58, 69] to distill user-provided documentation, examples, or specifications into prompts for querying an LLM. Then, it implements a fuzzing loop that continuously generates inputs iteratively, updating prompts with previously generated inputs and using different strategies. FUZZ4ALL’s compute requirements differs from ISSUEMUT’s. FUZZ4ALL runs on a GPU that fits the LLM, but ISSUEMUT runs on CPUs. So, fair side-by-side comparison is impractical. Nevertheless, given FUZZ4ALL’s recency and similar goal, we attempt to replicate and compare its results with ISSUEMUT’s.

Setup. We run FUZZ4ALL using its author’s original setup in a 24-hour fuzzing campaign, compared to ISSUEMUT’s 24h, on the same compiler versions as ISSUEMUT: GCC (87492fb) and Clang (9bdf683). Note that FUZZ4ALL’s original evaluation used older versions of these compilers, e.g., they use GCC 13, but we use GCC 15, which is in development. We run FUZZ4ALL on an NCSA Delta A40 GPU node [38] with a 64-core AMD EPYC 7763 CPU, an NVIDIA A40 GPU, and 128GB RAM, running RHEL 8.8. We repeat our 24-hour campaigns 7 times each for GCC and Clang (including auto-prompting) or a cap of one million generated inputs, whichever comes first. In all experiments, we use the configurations in [59], including using standard C library documentation as input, and the Docker containers provided in the replication package.

Results. FUZZ4ALL produces 244,722 and 203,483 inputs for Clang and GCC, respectively, which are close to the numbers in [59] (e.g., their five 24-hour GCC campaigns produce 260,221 inputs). Our FUZZ4ALL campaigns collectively triggered 11 crashes: 7 in Clang and 4 in GCC. Our analysis shows that (i) 9 of these 11 crashes are unique; and (ii) 4 of 9 unique crashes were also triggered by ISSUEMUT (§4.4). We leave as future work the investigation of how FUZZ4ALL performs in other revisions of GCC and LLVM, and the effects of incorporating FUZZ4ALL’s generated inputs into METAMUT’s seed corpora.

5.2 ISSUEMUT-triggered bugs sample

LLVM bug #123410. This ISSUEMUT input triggers a crash in Clang:

```
#include <mm_malloc.h>
- #define extern
+ #define static
```

```
#define __inline
#include <immintrin.h>
```

The crash occurs because mutator **M3** (Table 1) replaces the `extern` keyword with `static`, changing the behavior of functions in `immintrin.h`. Developers fixed the bug, saying, “*Seems we missed to add AMX FP8 intrinsics into X86LowerAMXType.cpp*”.

LLVM bug #120086. This input also triggers a crash in Clang:

```
#include <stdint.h>
struct A { char i1; };
- int printf(const char *fmt, ...);
+ int printf(char fmt, ...);
void test(struct A *a) { __builtin_dump_struct(a, printf); }
```

The crash occurs because applying mutator **M5** (Table 1) results in an undeclared `printf` function and an assertion failure during LLVM IR generation for `__builtin_dump_struct()`. (**M5** replaces a type with `char` while transforming negative to positive test cases.) LLVM developers confirm that this bug is a regression: “*... git bisect points to this commit that caused the regression: ef395a4... We really should land a fix ASAP, this is now three regressions linked to the same change*”.

GCC bug #118868. This input triggers a crash in GCC:

```
#include <stdlib.h>
void *wrapped_malloc(size_t size) {
- return malloc(size); }
+ return __builtin_assoc_barrier(malloc(size)); }
```

The crash occurs because applying mutator **M1** (Table 1) causes a failure to validate the correctness of generated GIMPLE IR. (That mutator wraps return expressions in a call to `__builtin_assoc_barrier()`.) GCC developers confirmed the bug, saying, “*the ICE (Internal Compiler Error) started happening since r12-1608-g2f1686ff70b25f*”. So, the bug had been in GCC for over three years.

GCC bug #119001. This input also triggers a crash in GCC:

```
union U4 {
- char a[4];
+ char a[];
int i; }; const union U4 u4[2] = {{"123"}};
```

The crash occurs because applying mutator **M7** (Table 1) revealed missing initialization. (That mutator removes literal array size in array declarations.) GCC 15 —under development— adds support for flexible array members in unions, but does not correctly handle their initialization in arrays of unions. Developers fixed the bug, saying “*r15-209 allowed flexible array members inside unions, but as the test case shows, not everything has been adjusted*”.

5.3 Comparison of Mutators with Prior Tools

We conducted a qualitative study to compare the set of mutators ISSUEMUT generates with those used in existing mutation testing and mutational compiler fuzzers. Specifically, we analyzed the extent to which the 587 mutators ISSUEMUT created overlap with those in GrayC [11], Universal Mutator [8], GRAMMARINATOR [20], KITTEN [60], and Nautilus [2]. ISSUEMUT provides 587 mutators and the tools we analyze provide, on average, 21 mutators.

We analyze each of ISSUEMUT’s mutators and classified them in three cases: identical, similar, and other. We classify an ISSUEMUT mutator as *similar* if its application could be produced by one of the mutators of the compared tool provided the right circumstances, as the right selection of the mutation target. We classify an ISSUEMUT mutator as *identical* if it performs the same transformation as a

Table 4: Comparison of ISSUEMUT’s 587 mutators against other mutation tools.

Technique	# Mutators	ISSUEMUT	
		# Similar	# Identical
GrayC	13	104	0
Universal Mutator	74	14	10
Grammarinator	7	29	0
Kitten	6	113	0
Nautilus	9	30	0

mutator from the compared tool. We classify all remaining mutators as *other*. Table 4 reports the numbers of ISSUEMUT’s mutators that are similar or identical to those of prior tools, along with the total number of mutators in each tool. Results suggest that there is a significant difference between the mutators of these tools and those obtained with ISSUEMUT, extracted from bug history.

Overall, only a small fraction of ISSUEMUT’s mutators were found to be similar or identical to existing ones, highlighting the novelty and complementarity of ISSUEMUT’s approach, which is informed by real-world bug reports. The high-level explanation for such differences is that ISSUEMUT mutators originate from bug report, i.e., they are specialized to reproduce the circumstances that once manifested a bug. In contrast, the mutation tools we compare are generic. For that reason, they offer a typically small number of mutators (Table 4).

5.4 Lessons Learned

We list actionable lessons that we learn from our ISSUEMUT work:

- (1) “Bug history” mutators find many bugs missed by mutators obtained via other means, e.g., through program-agnostic transformations (§ 4.3) or LLMs (§4.4). So, we recommend finding more of these mutators and to use them in existing mutational fuzzers;
- (2) Most successful mutators reveal only one bug. Likewise, triggering most bugs requires only one mutation (§4.4.2). Bounded-exhaustive fuzzing [4] is a promising direction to explore all combinations of files and (single) mutations, so coverage would be unnecessary, thereby accelerating compilation, the main bottleneck;
- (3) Identifying “hot” features is a promising direction for bug hunting. For example, we find that mutators related to the recent C23 standard were successful (§ 4.4.1);
- (4) Tree-level splicing mutators (i.e., the combination of parts of different seeds) is very effective to reveal bugs and should be incorporated in mutational fuzzers (§4.3);
- (5) Caching ASTs –to avoid I/O and parsing costs– can dramatically speed up mutational fuzzers and should be used (§4.3) to find more bugs within a given time budget.
- (6) Fuzzing with only successful mutators is effective (§4.5). Developers could prioritize successful mutators over others in evolutionary contexts;

6 Related Work

6.1 Generation-Based Fuzzing

Generational fuzzing methods test compilers by generating inputs and checking properties on them (e.g., absence of crashes).

CSmith [61] generates random C programs that have successfully exposed hundreds of latent defects across various C compiler implementations. Analogous to CSmith, CCG [37] produces chaotic C89 code designed specifically to induce compiler crashes through rigorous stress-testing. More recently, YARPGen [28, 29] creates semantically diverse programs free from undefined behavior, effectively addressing the saturation issue encountered with earlier generation tools such as CSmith [1]. Fuzz4All [59] is a generational LLM-based fuzzer for systems like compilers. Additional generation-based tools include those targeting Java compilers [5], Java Virtual Machines (JVMs) [51], Rust compilers [46], JavaScript engines [21], FPGA synthesis frameworks [19], and the Polyglot program synthesizer [18]. Generational fuzzer can produce seed corpora for mutational fuzzers. Future work can evaluate such integration.

6.2 Mutation-Based Fuzzing

Mutational fuzzing methods test compilers by modifying existing inputs. Orion [25, 25] introduced Equivalence Modulo Inputs (EMI), a methodology that creates semantically equivalent program variants with respect to specific input sets. Athena [26] extends Orion’s capabilities by employing Markov Chain Monte Carlo optimization to facilitate the deletion and insertion of code into un-executed regions. Hermes [49] preserves program semantics while mutating live code regions. Skeletal Program Enumeration (SPE) [66] systematically enumerates all possible variable usage patterns within syntactic structure-based skeletons. GrayC [11] implements coverage-guided mutation-based fuzzing with semantics-aware mutation operators. KITTEN [60] proposes program-agnostic transformations and a caching mechanism to efficiently evaluate them. METAMUT [41] leverages large language models (LLMs) to generate mutators for mutation-based compiler testing. Differently from these approaches, ISSUEMUT extracts mutators from real-world bug reports using a semi-automated approach. In the future, we plan to explore how to speed up ISSUEMUT (e.g., caching parse trees [60]). Also, as part of future work, we plan to incorporate our mutators in other mutational fuzzers (e.g., KITTEN).

6.3 Mutation Testing and Bug Fixes.

Tufano *et al.* [57] proposed to mutate source code from bug fixes. Their idea is similar to ours but the context is different. Their work is on mutation testing, which focuses on evaluating test-suite quality. ISSUEMUT’s purpose is fundamentally different: we focus on creating mutations that guide the exploration of the mutational compiler fuzzing search space towards areas that are likely to trigger bugs.

7 Conclusions

Ensuring the reliability of compilers is an important problem. Mutational fuzzers were recently shown to out-perform several prior compiler fuzzers, but their effectiveness depends on the availability of high-quality mutators. We report on a comprehensive study showing that bug histories are good starting points for semi-automated creation of effective mutators. Our study is supported by ISSUEMUT, an approach and an enhanced fuzzer that we also propose. ISSUEMUT mines “bug history” mutators and retrofits them into a SoTA mutational fuzzer, METAMUT [41]. ISSUEMUT finds 65 bugs that METAMUT mutators miss. We share several actionable lessons and plans for future work in this direction.

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Appendix

A.1 Mutator Creator Prompt

You are a C code mutation expert, specializing in creating
****generic**** ``sed`` scripts.

****TASK 1: GENERALIZE MUTATION****

Reverse the following specific description into a general rule,
 avoiding specific names or values.

Respond ONLY with the text inside ``<description>`` tags.

EXAMPLE:

Input: "In function 'foo', change the type of parameter 'bar'
 from 'int*' to 'const int*'. "

Output: `<description>`Add a 'const' qualifier to a pointer type
 in a function parameter.`</description>`

Description to Reverse:

```
```
{description_to_reverse}
```
```

****TASK 2: CREATE TEST CASES****

Based on the general rule you just created, provide three new,
 varied input/output C code pairs.

The transformation from input to output MUST match the rule.

Format your response EXACTLY as shown, with no extra text:

```
<input1>...</input1><output1>...</output1>
<input2>...</input2><output2>...</output2>
<input3>...</input3><output3>...</output3>
```

****TASK 3: GENERATE MUTATOR SCRIPT****

Create a single, ****generic**** Bash script using ``sed`` that performs
 the mutation.

This script must correctly transform all three test cases

AND the original example pair below.

GUIDELINES:

1. ****Generic `sed`****: Use regular expressions.

Do NOT hardcode names/values.

2. ****In-place Edit****: Use ``sed -i``. The target file is
 the first argument (``$1``).

3. ****Complete Script****: Provide the full script in a
 single ``<code>`` block.

No comments and explanations.

Do not write non-generic code specific for each test case!

Original Example Pair:

```
- Input:
```c
{negative input}
```

- Output:
```c
{positive input}
```
```

Reference Script Example (Adds no-prefix to target attribute):

```
```bash
{example bash code}
```
```

A.2 Mutator Refiner Prompt

You are an expert ``sed`` script debugger.

The provided script for the goal "`{mutation description}`" is faulty.

****Analysis****: {refinement context}

****Test Cases****: {test case context}

****Task****:

Rewrite the entire bash script to fix the issue.

The script must be ****generic**** and robust.

Respond with ONLY the complete, corrected bash script in a ``<code>`` block.

No comments and explanations.

Do not write non-generic code specific for each test case.

****Original Script to Refine****:

```
```bash
{mutator bash script}
```
```