

Barely Broken — Testing Highly Structured Inputs

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Abstract

Current test generators are limited in the inputs they produce. This leads to an imbalance in the program parts tested, with significant program parts receiving insufficient attention, particularly with programs expecting inputs that are highly structured. In this work, I propose two measurements to evaluate different approaches and find which parts of programs are under-tested. *Input correctness* provides a level to which an input satisfies the expected structure, measured either against an implementation or specification. *Input interestingness* checks the distance to equivalence class boundaries.

I present the distribution of *input correctness* from an initial evaluation of different approaches on a C compiler, suggesting significant limitations of existing approaches. I further propose three approaches to closing the gap in testing all input parts.

CCS Concepts

• **Software and its engineering** → **Software testing and debugging**; *Dynamic analysis*; • **Theory of computation** → *Grammars and context-free languages*.

Keywords

Automated Testing, Grammars, Test Generator Evaluation

ACM Reference Format:

Valentin Huber. 2018. Barely Broken — Testing Highly Structured Inputs. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation email (Conference acronym 'XX)*. ACM, New York, NY, USA, 4 pages. <https://doi.org/XXXXXXX.XXXXXXX>

Doctoral Symposium Information. I am in year 1 out of expected 4 in my PhD, supervised by Prof. Dr. Andreas Zeller.

1 Introduction

Programs processing input typically do so in distinct steps, with the programs in Figure 1 passing increasingly more of these:

- (1) **Lexing:** Unstructured input is split into an unstructured list of tokens. (P1) will be rejected by the lexer of a C compiler.
- (2) **Syntactic Parsing:** If the input is syntactically valid, it can be parsed into structures. While (P2) consists of exclusively valid tokens, they do not appear in the correct structure.

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Conference acronym 'XX, Woodstock, NY

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ACM ISBN 978-1-4503-XXXX-X/2018/06

<https://doi.org/XXXXXXX.XXXXXXX>

- (3) **Semantic Checks:** The parsed structures are then subject to tests on their semantics. (P3) for example can be parsed, but is invalid because the variable *i* is not defined.
- (4) **Business Logic:** Finally, the input is processed by a program's inner logic, e.g. translated into an executable.

My observation is that test generators generally produce inputs that test only a subset of the steps above, depending on their internal model of the input structure. Some of my previous work [8, 9] has explored this by building purpose-built fuzzers that ensure (partial) correctness of inputs.

1.1 Categorization of Existing Approaches

Imagine the input space of a program as a bush, with bugs represented by berries spread throughout, as shown in Figure 2.

Purely random input generation [11] is unlikely to test anything but the lexing stage; it is therefore similar to reaching only the very bottom of the bush (I).

In a next step, coverage-guided fuzzing was proposed, which is able to incrementally find inputs that reach deeper into the program with random mutation [15] and thus reaches further up the tree (II).

| |
|---------------------------------------|
| (P1): VBq-"7.6arK w;zu%6\$K>%OTV"ryD* |
| (P2): && float += % " (; == [|
| (P3): int main() { return i; } |
| (P4): int main() { return 0; } |

Figure 1: C programs that are lexically (P1), syntactically (P2) and semantically (P3) invalid and fully valid (P4).

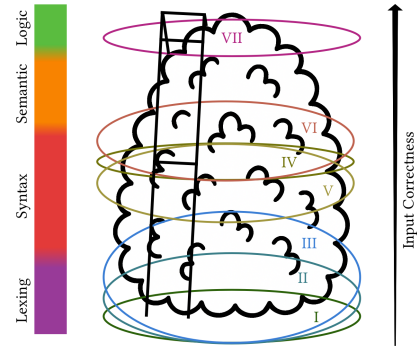


Figure 2: Bush representing the input space of a program, where increasing height represents increasing correctness of a certain input

These approaches were extended with instrumentation and logic that allow them to produce increasingly correct inputs [4, 7], thus extending their reach once more (III).

By manually providing the test generator with a model of the target input structure, an analyst can help a test generator produce increasingly correct inputs. This is the equivalent of helping a test generator climb on the first step of a ladder.

One widely used approach is to provide a test generator with a context-free grammar, based on which it can produce inputs that will, by construction, not be rejected by the parser and thus reach further into the program (IV). From there, they can produce inputs that validate their inner model [2, 5] to reach further down (V), or attempt to pass additional semantic checks [6] (VI).

Recent advancements provide a generic model for input testers to receive a complete model of the PUT input structure [16], which allows testing the business logic (VII).

To the best of my knowledge, there is no systematic evaluation of representatives of these approaches — we do not know the extent of their reach. Following this, we do not know what parts of targets remain untested, even when multiple approaches are combined.

Based on this insight, I present the following contributions:

- (1) I propose two measurements based on which to compare the distribution of inputs from different test generators: *input correctness*, and *input interestingness* (Section 2).
- (2) I provide initial experiments and their results, which suggest that existing input generators are incapable of testing all program logic (Section 3).
- (3) I propose three approaches to creating input generators that fill these holes (Section 4).

2 Evaluating Test Input Quality

Test generators can be evaluated along multiple, orthogonal axes. The most common measurement is the code coverage reached when executing a certain input on an instrumented implementation of the PUT. While code coverage is comparatively easy to measure due to the availability of instrumentation passes in popular compilers [1] and binary-only fuzzing tools [10], it has two fundamental limitations: (1) It assigns equal weight to all branches, and (2) assumes any value covering a new branch is equally interesting.

2.1 Input Correctness

Limitation (1) of using code coverage assigns the same score to test generators that reach far into the PUT but only provide valid inputs, compared to a test generator exploring all error paths in the initial input validation steps of a program. As an alternative, I propose evaluating test generators for *input correctness*. The correctness of an input with regards to a PUT can be defined and measured in two ways:

- (1) First, one can test inputs **against an implementation** of a PUT, measuring the ratio of accepted to rejected inputs at each stage of the input processing pipeline. This can be achieved with one of the following:
 - (a) Manual annotations of steps, similar to [3, 12].
 - (b) Based on a diverse set of valid seed inputs, count edges of generated inputs that are executed by *all*, or *any* valid input.

- (2) Alternatively, inputs can be evaluated **against an abstract specification** of the language expected by a PUT. Such specifications are usually given in natural language. Recent works have explored how to express such specifications in a structured way, as a combination of a context-free grammar and additional constraints over nodes in this grammar [16]. Evaluating the correctness against specification may be done in different steps:

- (a) For inputs that cannot be parsed, existing literature provides algorithms to measure the closeness of an input to a context-free grammar [13].
- (b) For grammar-valid inputs, the ratio of fulfilled to violated constraints is used.

2.2 Input Interestingness

Not all inputs are equally interesting, even if they are all fully correct or are all processed by the exact same instructions (as described in Limitation (2)). Assume a constraint checking whether a person is over 18. According to the principle of equivalence classes, mutating their age to random values, say from 27 to 43, is unlikely to trigger a new bug. Changing it to values near the boundaries of equivalence classes, in this case 18 or 19, is a more promising strategy to discover edge case bugs, such as off-by-one errors. Based on this insight, I define *Input interestingness* as the distance of an input to equivalence class boundaries.

Previous work proposed mutating input parts to contain generally interesting values, such as 0, −1, or 2^{16} [15]. However, the lack of approaches to specify input correctness fully meant that evaluating distance of an input to equivalence class boundaries was limited by an analyst's ability to manually annotate select boundaries [3]. With the advent of abstract full input specifications [16], one can now test this automatically:

- (1) **Semantic Interestingness:** Inputs are more interesting if they are closer to boundaries of constraints, as described in the example above.
- (2) **Syntactic Boundaries:** If an input part can be repeated an arbitrary number of times, repeating it 0, 1, or 999999 times is more interesting.

3 Evaluating Existing Test Generators

Section 1 introduces potential limitations of existing input generators. To evaluate this claim, I test representatives from a subset of the proposed categories against the C compiler clang. I evaluate the different approaches according to *input correctness*, as measured through manual annotation of additional instrumentation in the target.

Table 1 presents the ratios of inputs generated by the evaluated approaches that reach a certain step during program execution. Approach (IV) is represented by a pure grammar-based test generator. For (V), outputs from the grammar test generator are used, both unchanged and binary mutated. (VI) is represented by a coverage-guided grammar test generator. All representatives were run twice, once with only self-created seeds, and once with an additional set of 10 high-quality, manually written seeds using different aspects of the target language.

Table 1: Ratio of inputs rejected by program steps and total coverage across approach categories in clang. Approaches marked with * receive an initial corpus of valid C programs.

| | Other | Lexing | Syntax | Semantic | Valid | Cov |
|-------|--------|--------|--------|----------|--------|-------|
| * | 0.000% | 0.000% | 0.000% | 0.000% | 1.000% | 12772 |
| (IV) | 0.086% | 0.181% | 0.108% | 0.623% | 0.001% | 13074 |
| (IV)* | 0.085% | 0.177% | 0.106% | 0.627% | 0.004% | 13076 |
| (V) | 0.085% | 0.176% | 0.108% | 0.629% | 0.001% | 13074 |
| (V)* | 0.086% | 0.183% | 0.110% | 0.618% | 0.004% | 12921 |
| (VI) | 0.000% | 0.000% | 0.503% | 0.497% | 0.000% | 12787 |
| (VI)* | 0.000% | 0.002% | 0.498% | 0.500% | 0.000% | 12787 |

The results confirm the suspected inability of the presented approaches to test program parts past the semantic checks. They do, however, have significant limitations and only partially adhere to general evaluation best practices [14]. I am only testing against one implementation for one target, which requires highly structured inputs. I am evaluating only on *input correctness*, in coarse-grained steps, and not against a specification. Finally, the examples were only run once, for 12 hours each.

In future work, I want to expand on these experiments by extending the number and kind of targets, measurements, and evaluation robustness. I further want to test additional approaches and multiple implementations in each; along with test generators purpose-built for a specific target.

4 Reaching the Rest of the Tree

The results in Section 3 suggest that current approaches for test generators are limited — large parts of clang remain untested. Section 1 provides a conceptual explanation for these limitations. Building on top of these, I present three approaches that may extend the parts of a PUT that are effectively tested by automated test generators:

- (1) **Reach down from the top:** Similarly to out-of-grammar test generation, I want to explore out-of-language generation, where constraints of a full specification are iteratively and deliberately violated while the remaining constraints are still fulfilled. This approach could further be improved by out-of-grammar construction of the inputs that are evaluated for constraints, giving the test generator theoretical reach from the top of the ladder, all the way to the ground.
- (2) **Incremental steps towards the top:** Writing fully correct specifications for tools like Fandango is considerable work, due to a current lack of automated specification generation. However, providing a few simple constraints to an existing grammar may be enough to allow a test generator to reach code it was previously unable to test. This, by design, will additionally produce inputs that do not match the full specification, thus leading to a similar effect as approach (1).
- (3) **Targeted testing:** Due to the availability of tools able to use full input specifications, I would like to explore test generators producing inputs that reach higher interestingness in their test cases by steering input generation towards

boundaries of both the input semantics (i.e., the constraints) and the syntax (the structure).

5 Conclusion

In this work, I present two measurements to evaluate different test generation approaches. *Input correctness* measures either how far an input gets along the input processing pipeline of a target program, or to what extent it fulfills analyst-given lexical, syntactic, and semantic constraints. *Input interestingness* refers to the distance between an input and equivalence class boundaries.

I then present results of an initial experiment showing that current generic test generators fail at testing significant parts of a C compiler, as measured by *input correctness*. Finally, I propose three approaches to creating test generators that are able to test previously untestable program parts. To achieve improved *input correctness*, systematically violate semantic and syntactic rules of an input specification, or extend current, structure-aware test generators based on context-free grammars with additional, incomplete semantic constraints. To produce inputs with increased *input interestingness*, prioritize inputs closer to equivalence class boundaries.

Acknowledgments

This work is funded by the European Union (ERC S3, 101093186). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

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Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009