Keynote Talk: On Estimating Incorrectness in the Absence of Evidence

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Abstract

In this keynote, we introduce a statistical framework for automated software testing, including fuzzing, that allows us to estimate, extrapolate, and explain various interesting properties of a testing campaign. We show how to quantify our confidence in the correctness of a program after a long-running testing campaign that has found no bugs. We explain how Shannon's entropy is a non-parametric measure of testing efficiency and why the cost of bug finding appears to be exponential even if testing is embarrassingly parallel. We extend the approach to statistical program analysis and make progress on the statistical problem itself. Finally, we talk about our most recent work on estimating incorrectness (of an LLM-generated program) in the absence of an oracle.

CCS Concepts

• **Software and its engineering → Software testing and debugging**.

Keywords

Empirical Program Analysis, Oracle Problem, Residual Risk

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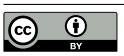
1 Estimating Error in the Absence of Evidence

> Program testing can be a very effective way to show the presence of bugs, but is hopelessly inadequate for showing their absence.
>
> *Edsger W. Dijkstra; ACM Turing Lecture 1972*

The utility of automated software testing as a bug finding technique is entirely obvious; but what if a long-running testing campaign finds no bugs? In practice, this is (thankfully!) the much more frequent case. The question that naturally arises is: What does the absence of evidence in an ongoing testing campaign say about the absence of bugs? Intuitively, we will have more confidence in a campaign that has run for one month than in one that has run for one minute. Can we objectively and systematically quantify this confidence in the presence of uncertainty?



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In this keynote, we introduce a statistical framework for automatic software testing [1] which allows us to explain various, interesting phenomena of automatic software testing that practitioners have previously observed but that have never been empirically studied or formally explained. We explain why whitebox fuzzing is conceptually the most effective testing technique, and why, nevertheless, black- and greybox fuzzing often outperform whitebox fuzzing, in practice [4]. We discuss why the cost of bug finding appears to be exponential even though testing is embarrassingly parallel [2]. We formally establish Shannon's entropy, a well-known measure of information and diversity [7], as non-parametric measure of testing efficiency [3] and discuss how our entropy-based power schedule ended up powering large fuzzing infrastructures at Google and Microsoft where it helps to continuously sweep thousands of important software systems for critical security flaws.

Meanwhile, we show how our statistical framework has evolved, from its initial goal of quantifying the confidence which a testing campaign inspires that has found no bugs, to a framework for the statistical analysis of a wide variety of binary[1] or quantitative[2] program properties, particularly in the absence of evidence [5]. For instance, while we can, in general, not *decide* whether even a single, specific program state is reachable, we can efficiently *estimate* the total number of reachable states (or coverage elements) [6].

2 Estimating Error in the Absence of an Oracle

So far, we have assumed that there exists an automatic oracle that decides for any execution whether or not a bug is revealed. A typical example of automatic oracles in fuzzing is the crash oracle which may indicate a security flaw. However, in automatic code generation, where an LLM or an agentic system translates a programming task, expressed in natural language, into a program that implements the task, such an oracle does not practically exist.

In the absence of such an oracle, can we estimate the likelihood that the generated program is correct? We explore this question in the second part of the keynote with reference to a recent paper that appears at AAAI'26 [8]. The key idea is to consider the program, that is generated for a programming task, as a random variable. This allows us to introduce a probabilistic notion of correctness with respect to an unknown, deterministic ground-truth implementation for that task. We approximate the expected incorrectness using a quantity, we define as *incoherence*, i.e., the probability that two programs randomly generated for the same task compute different output for some input. We offer PAC-style bounds to establish sampling efficiency and propose to leverage the statistical framework introduced in the first part to estimate incoherence in practice.

[1] An execution does or does not exhibit a specific behavior.
[2] An example of a quantitative property is the time an execution takes.

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