datAFLow: Towards a Data-Flow-Guided Fuzzer

Adrian Herrera, Mathias Payer, Antony L. Hosking

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whoami

- PhD student at ANU
- Interests in fuzzing, binary analysis, program analysis

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Registered Report: Dissecting American Fuzzy Lop

A FuzzBench Evaluation

Other research directions instead explored different instrumentation techniques to study better forms of feedback. A popular form of feedback, usually considered the de-facto standard in the fuzzing community, is *code coverage*. This approach rewards the fuzzer when a new target execution results in a different coverage value, computed over the control flow graph (CFG) of the target application. In general, we refer to this family of approaches as *coverage-guided* fuzzing techniques.

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Registered Report: NSFuzz: Towards Efficient and State-Aware Network Service Fuzzing

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Registered Report: Dissecting American Fuzzy Lop

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Registered Report: Fuzzing Configurations of Program Options

While it is expected that different configurations could result in different part of code being executed, there is no prior study that focuses on understanding how tuning a program's configurations would affect a fuzzer's results in terms of code coverage. The answer to this question can be used to motivate the design of a fuzzer that fuzzes configurations.

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RQ1 is the overall question of whether any variant of fuzzing using mutants increases standard fuzzing evaluation metrics (unique faults detected and code coverage). **RQ2-RQ4** consider some of the primary choices to be made in implementing fuzzing mutants.

Registered Report: NSFuzz: Towards Efficient and State-Aware Network Service Fuzzing

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Registered Report: Fine-Grained Coverage-Based Fuzzing

Problem. In order to select which of the generated inputs will be saved for subsequent mutation, current fuzzers run the PUT with these inputs and measure some form of branch coverage.

coverage = control-flow coverage

This is changing…

Fuzzing with Data Dependency Information

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The Use of Likely Invariants as Feedback for Fuzzers

Andrea Fioraldi, *EURECOM;* Daniele Cono D'Elia, *Sapienza University of Rome;* Davide Balzarotti, *EURECOM*

https://www.usenix.org/conference/usenixsecurity21/presentation/fioraldi

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Data flow is becoming a "first-class citizen"

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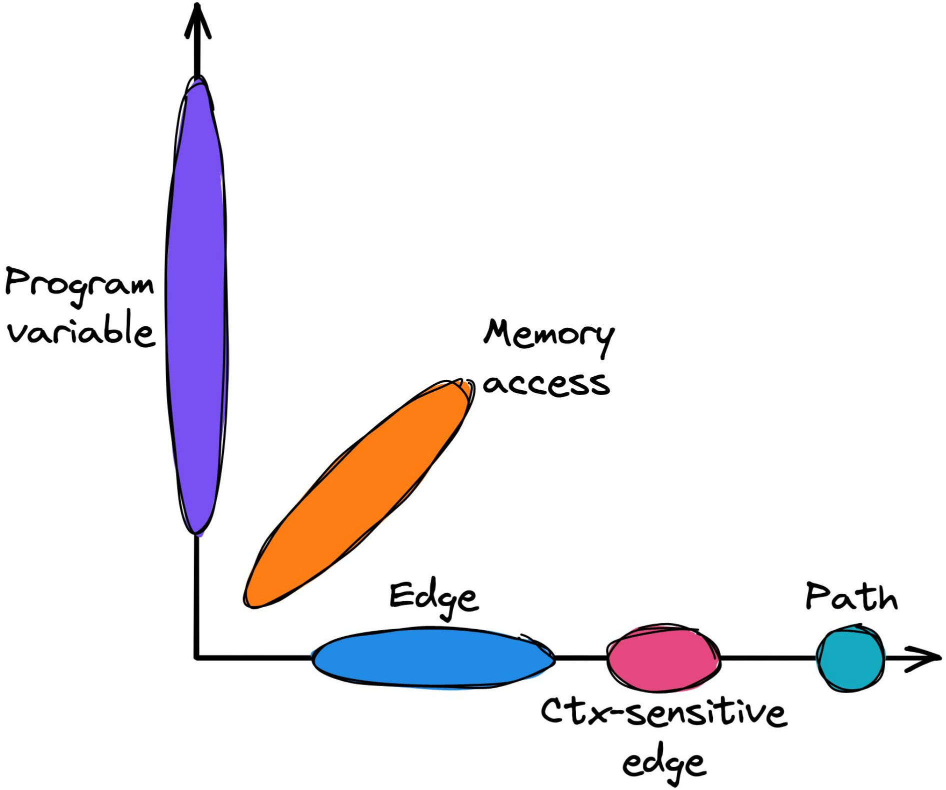
The “coverage spectrum”*



* Not to scale

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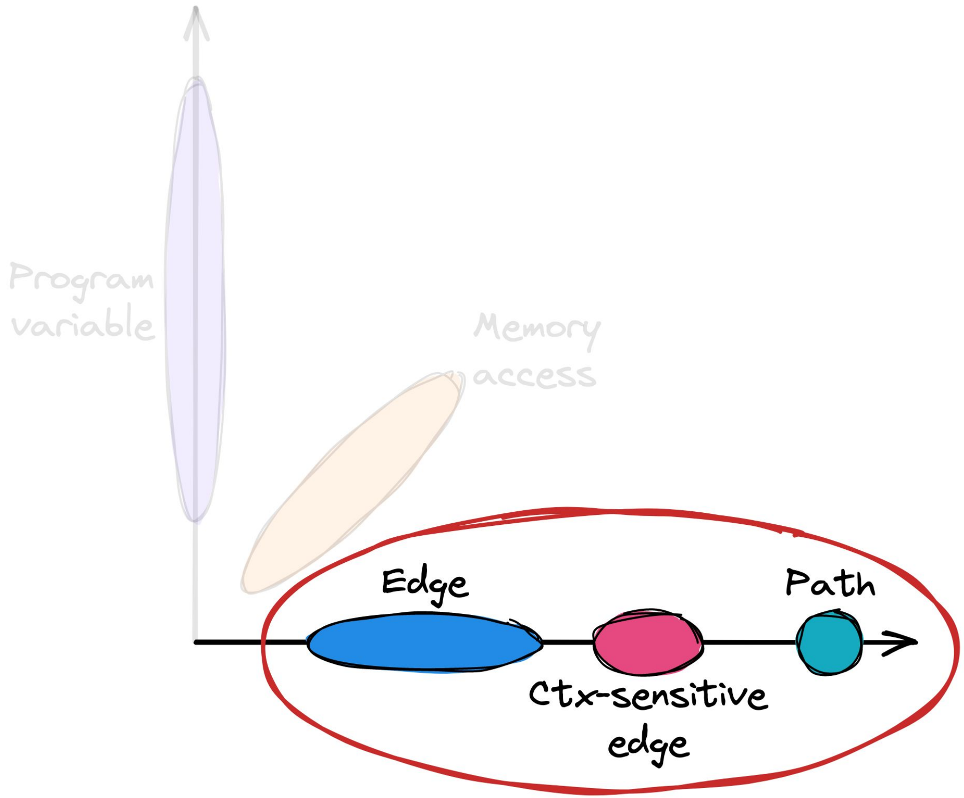

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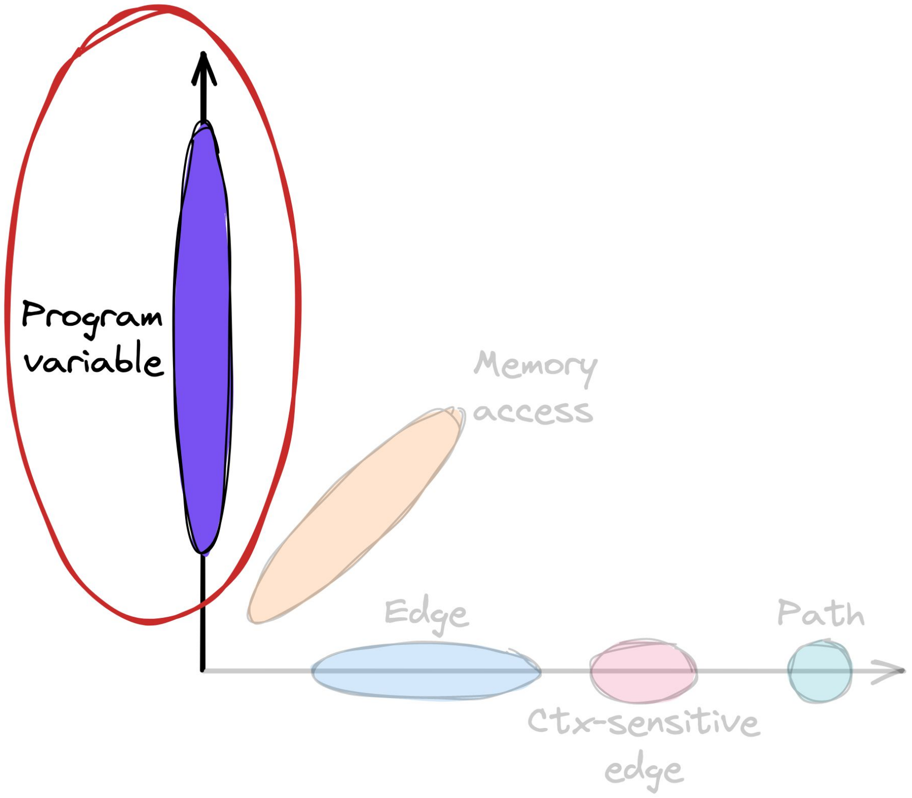

Requirements

1. Define “data-flow coverage”
2. Efficiently track data flows
3. Data flows → fuzzer coverage
4. Evaluate!

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1. Defining “data-flow coverage”

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ARTICLE

Data flow analysis techniques for test data selection

Authors: Sandra Rapps, Elaine J. Weyuker Authors Info & Claims

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1. Defining “data-flow coverage”

Data Flow Analysis Techniques for Test Data Selection

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Abstract

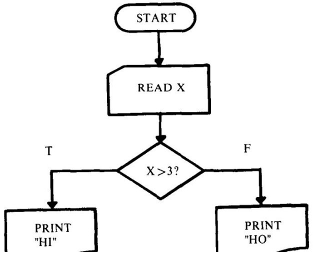
This paper examines a family of program test data selection criteria derived from data flow analysis techniques similar to those used in compiler optimization. It is argued that currently used path selection criteria which examine only the control flow of a program are inadequate. Our procedure associates with each point in a program at which a variable is defined, those points at which the value is used. Several related path criteria, which differ in the number of these associations needed to adequately test the program, are defined and compared.

Introduction

Program testing is the most commonly used method for demonstrating that a program actually accomplishes its intended purpose. The testing procedure consists of selecting elements from the program's input domain, executing the program on these test cases, and comparing the actual output with the expected output (in this discussion, we assume the existence of an "oracle", that is, some method to correctly determine the expected output). While exhaustive testing of all possible input values would provide the most complete picture of a program's performance, the size of the input domain is usually too large for this to be feasible. Instead, the usual procedure is to select a relatively small subset of the input domain which is, in some sense, representative of the entire input domain. An evaluation of the performance of the program on this test data is then used to predict its performance in general. Ideally, the test data should be chosen so that executing the program on this set will uncover all errors, thus guaranteeing that any program which produces correct results for the test data will produce correct results for any data in the input domain. However, discovering such a perfect set of test data is a difficult, if not impossible task [1,2]. In practice, test data is selected to give the tester a feeling of confidence that most errors will be discovered, without actually guaranteeing that the tested and debugged program is correct. This feeling of confidence is

select paths through the program whose elements fulfill the chosen criterion, and then to find the input data which would cause each of the chosen paths to be selected.

Using path selection criteria as test data selection criteria has a distinct weakness. Consider the strongest path selection criterion which requires that *all* program paths $p_1, p_2, \ldots$ be selected. This effectively partitions the input domain D into a set of classes $D = \cup D[j]$ such that for every $x \in D$, $x \in D[j]$ if and only if executing the program with input x causes path p_j to be traversed. Then a test $T = \{t_1, t_2, \ldots\}$, where $t_j \in D[j]$ would seem to be a reasonably rigorous test of the program. However, this still does not guarantee program correctness. If one of the D[j] is not revealing [2], that is for some $x_1 \in D[j]$ the program works correctly, but for some other $x_2 \in D[j]$ the program is incorrect, then if x_1 is selected as t_j the error will not be discovered. In figure 1 we see an example of this.



based on the dataflow coverage criteria. We have adapted these dataflow coverage definitions to define realistic dataflow coverage measures for C programs. A coverage measure associates a value with a set of tests for a given program. This value indicates the completeness of the set of tests for that program. We define the following dataflow coverage measures for C programs based on Rapps and Weyuker's[7] definitions: block, decision, c-use, p-use, all-uses, path, and du-path.

Precisely defining these concepts for the C language requires some care, but the basic ideas can be illustrated by the example in Figure 1. We define the measures to be intraprocedural, so they apply equally well to individual procedures (functions), sets of procedures, or whole programs.

Block. The simplest example of a coverage measure is basic block coverage. The body of a C procedure may be considered as a sequence of basic blocks. These are portions of code that nor-

Figure 1. Sum.c computes the sum and product of numbers from 0 to *N*.

```
#include <stdio.h>
main()
{
    int n, i, k, sum, prod;

    printf("Enter an integer and 0 for +, 1 for *: ");
    scanf("%d %", &n, &k);
    sum = 0;
    prod = 1;
    i = 1;
    while (i <= n)
    {
        sum += i;
        prod *= i;
        i++;
    }
    if(k == 0)
        printf("n = %d, sum = %d\n", n, sum);
    if(k == 1)
        printf("n = %d, prod = %d\n", n, prod);
```

A definition of variable *i*

Uses of variable *i*

A basic block

A decision predicate involving variable *k*

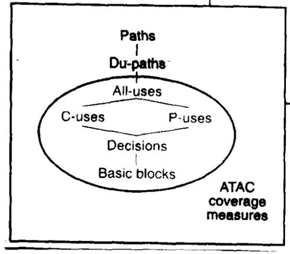


Figure 2. A hierarchy of control and dataflow coverage measures.

gram behavior, presumably due to one or more faults in the code.)

Figure 2 suggests an ordering of the coverage criteria. In this hierarchy, block coverage is weaker than decision coverage, which in turn is dominated by p-use coverage. C-use coverage dominates both block and decision coverage but is independent of p-use coverage; both c-use and

Data-flow coverage is the tracking of def/use chains executed at runtime

1. Defining “data-flow coverage”

Def site: Variable allocation site (static and dynamic)

Use site: Variable access (read and/or write)

Def-use chain: Path between a def and use site

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How to efficiently implement this?

Requirements

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4. Evaluate!

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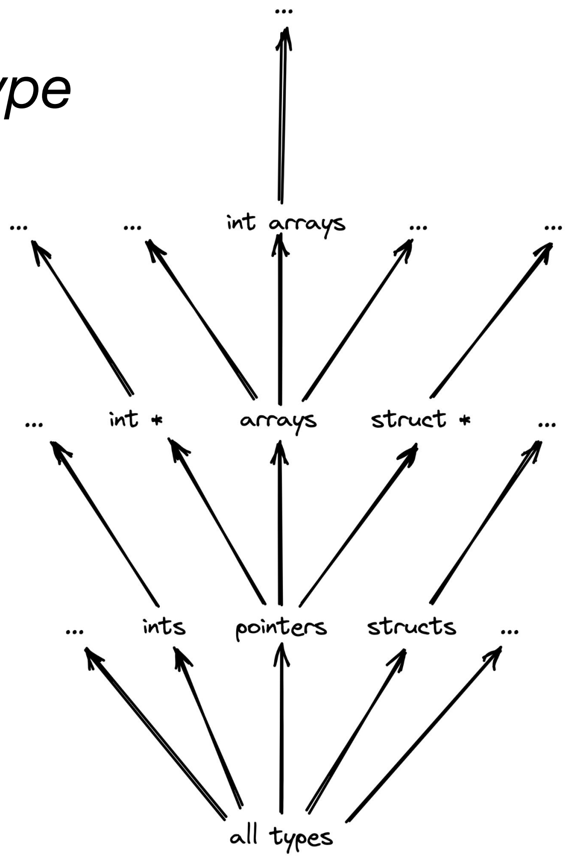
Problem: Tracking *all* data flows is infeasible

Solution: Track data flows at varying *sensitivities*

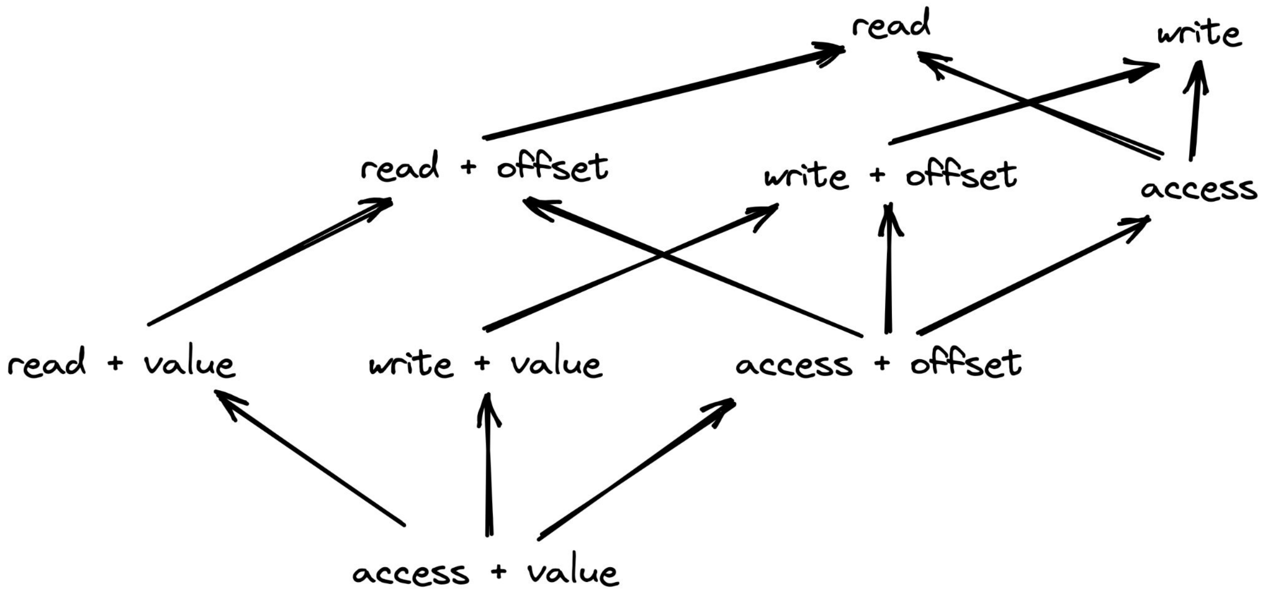
2. Efficiently track data flows

Partition def sites by *type*



2. Efficiently track data flows

Partition use sites by *access*



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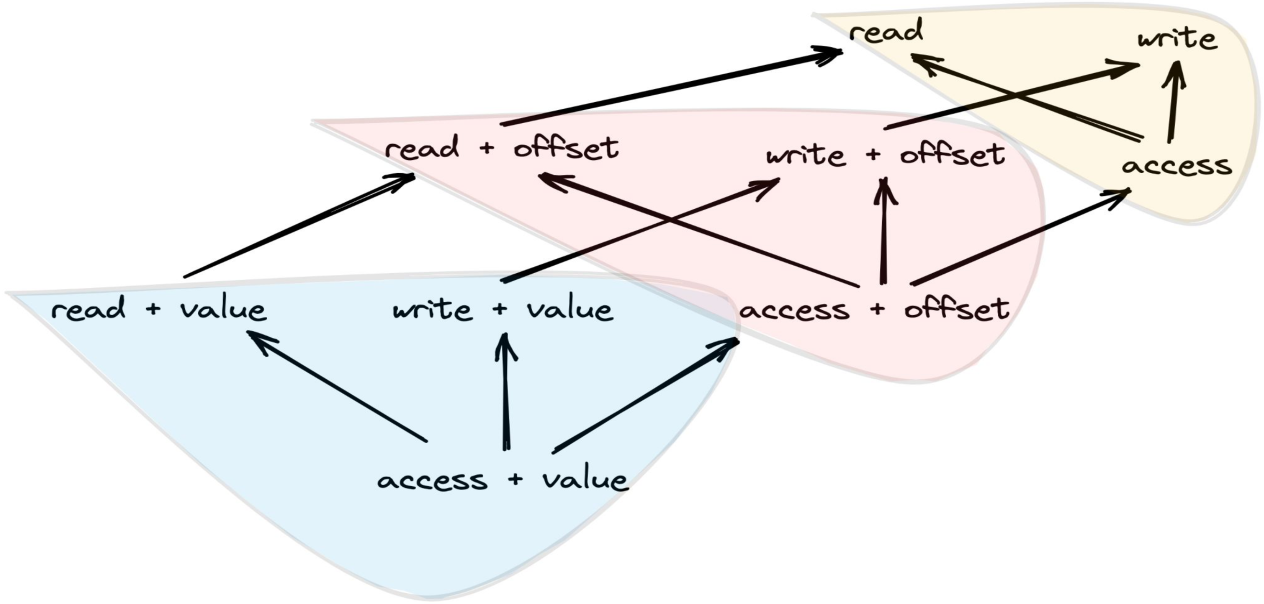
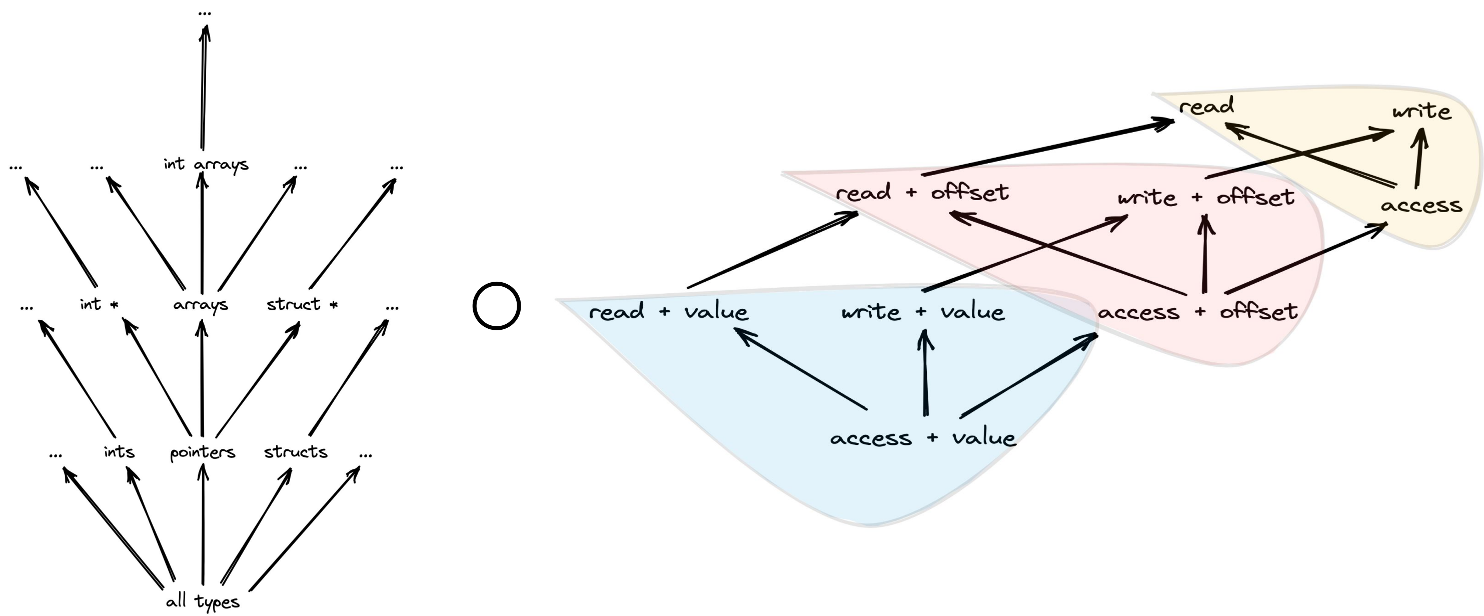
2. Efficiently track data flows

Partition use sites by *access*



2. Efficiently track data flows

Compose def/use lattices to realize desired sensitivity



Do efficient implementations exist?

Requirements

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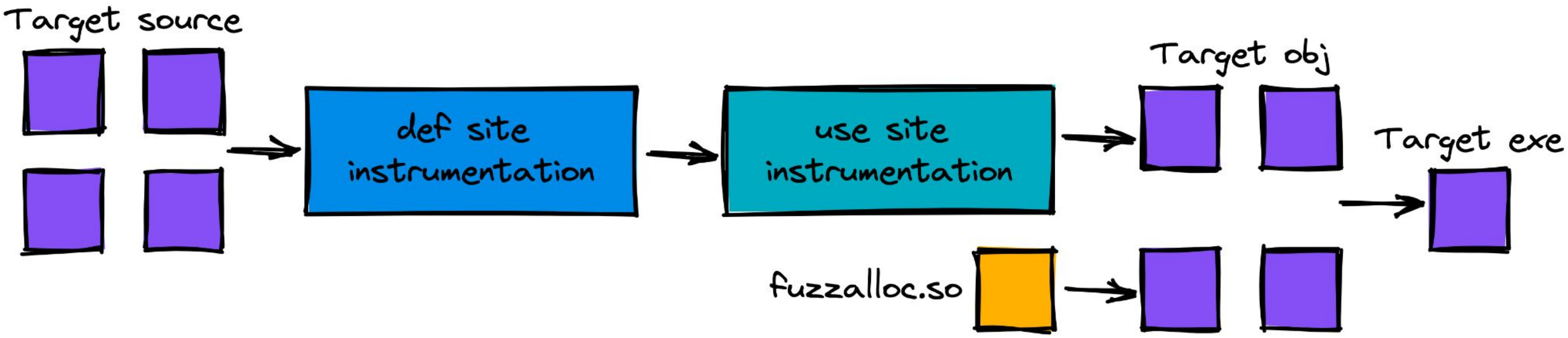
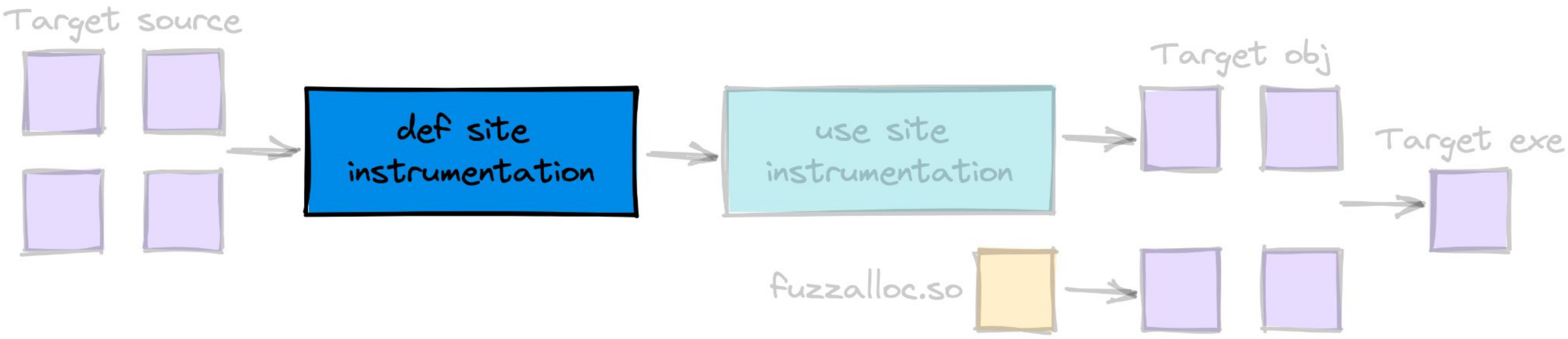
3. Data flows → fuzzer coverage



3. Data flows → fuzzer coverage



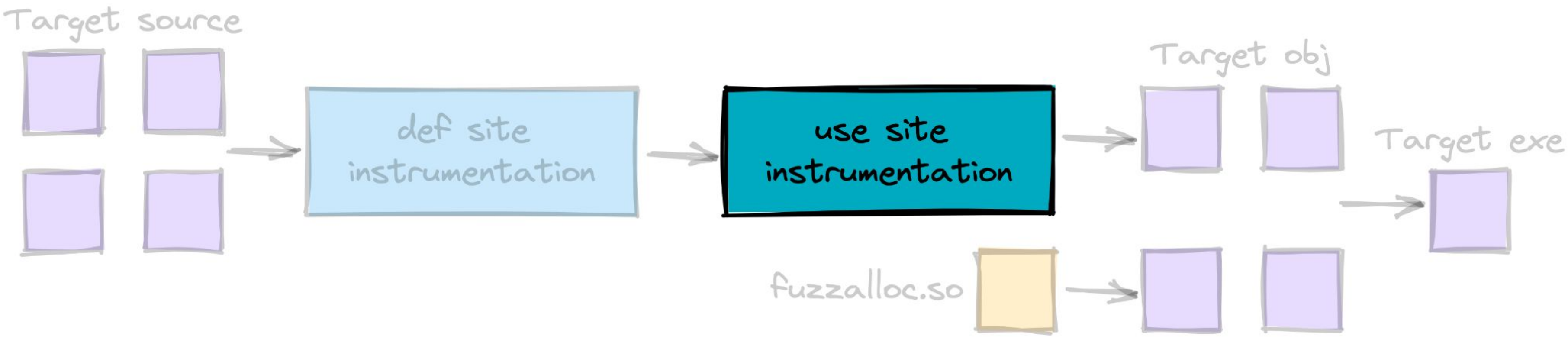
Def site instrumentation

1. Identify allocation sites (static and dynamic) based on desired sensitivity

2. Replace dynamic allocations with tagged allocation

3. “Heapify” static allocations (and tag)

3. Data flows → fuzzer coverage



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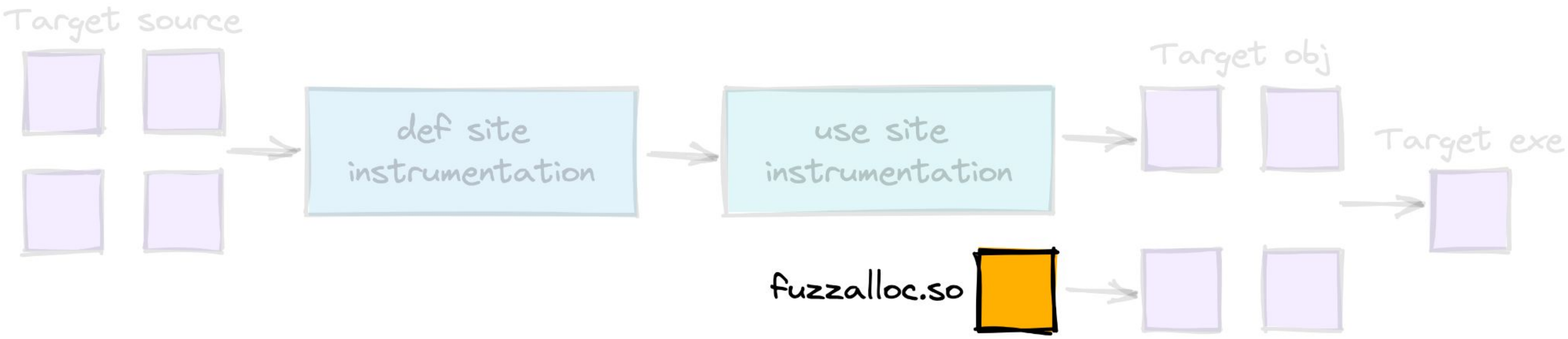
Use site instrumentation

1. Identify based on desired sensitivity (read/write/access)

2. Identified via runtime address

3. Data flows → fuzzer coverage



`fuzzalloc.so`

- Data-flow tracking is reduced to metadata management

- Def site IDs are the metadata to retrieve at use site

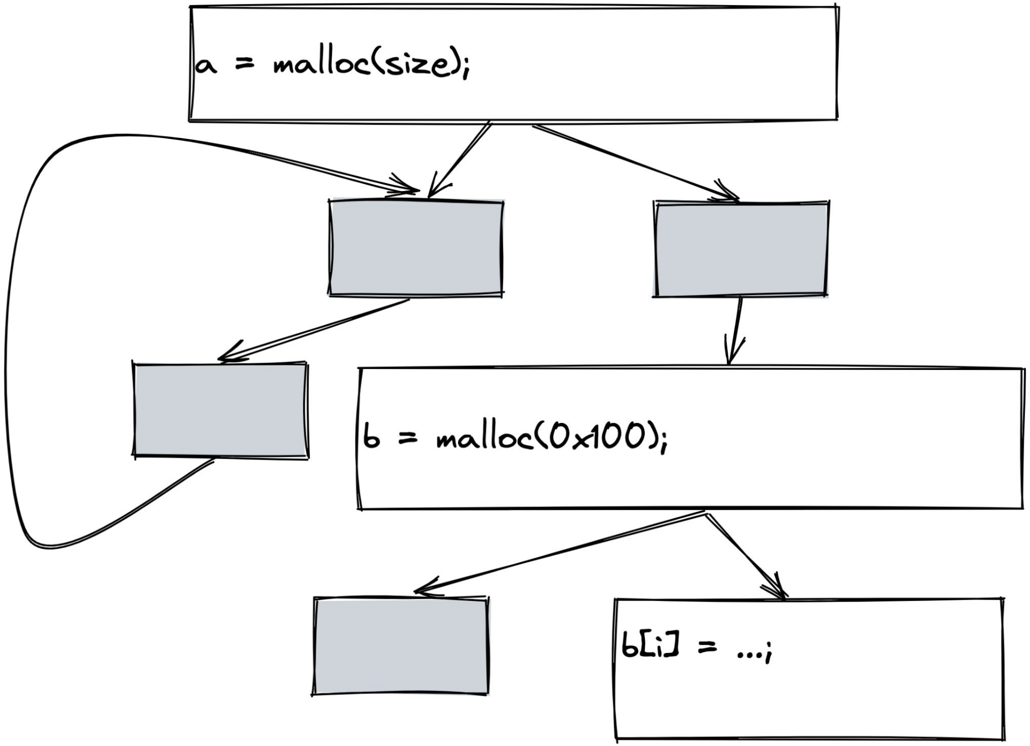
`fuzzalloc.so`

- Data-flow tracking is reduced to metadata management

- Def site IDs are the metadata to retrieve at use site

Achieved via mid-fat pointers + custom memory allocator

fuzzalloc.so



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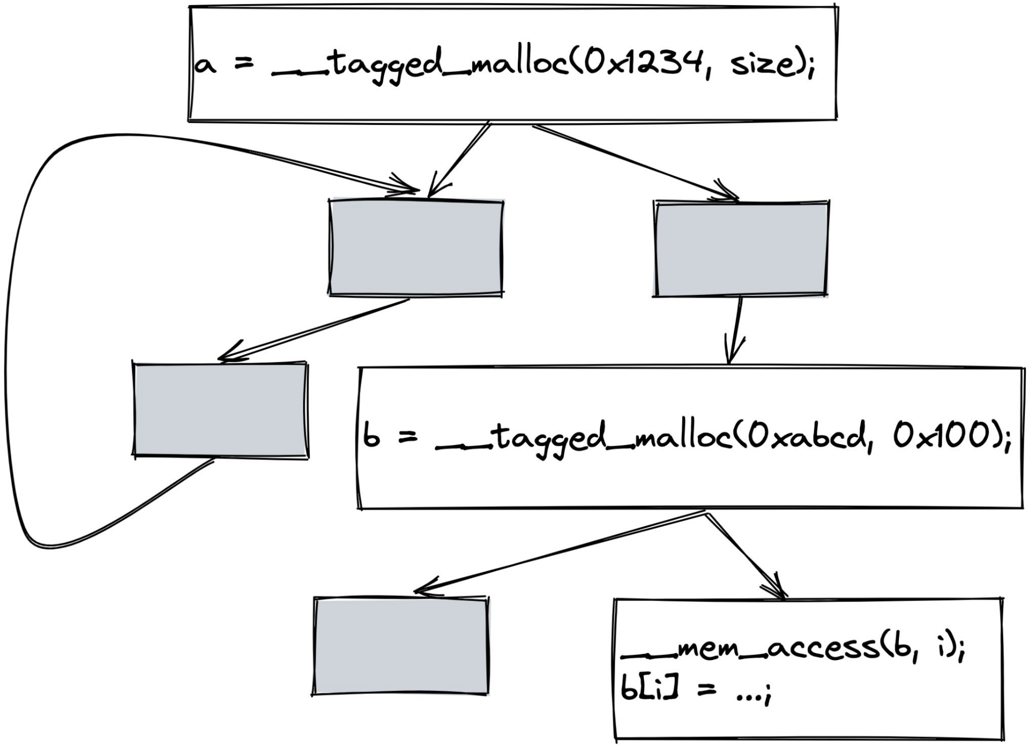

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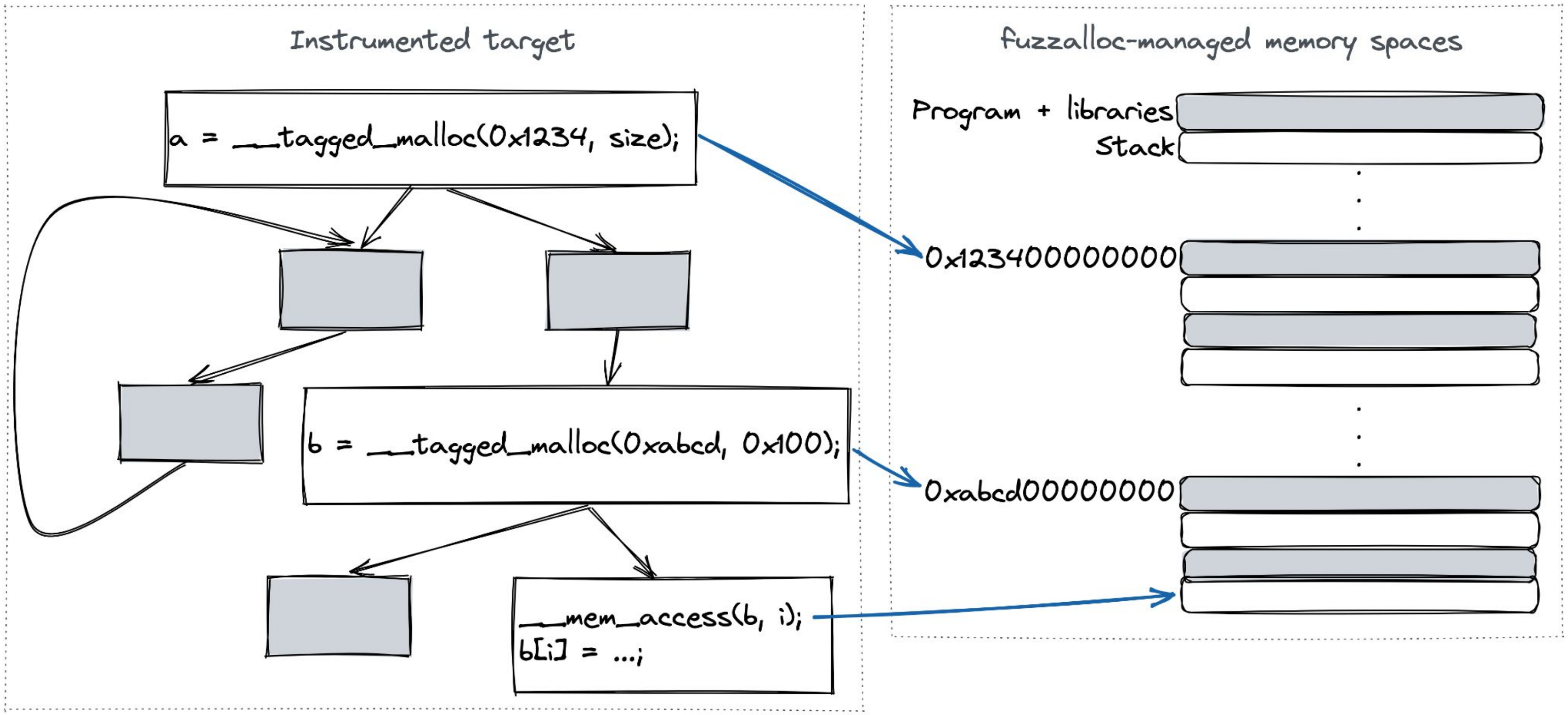

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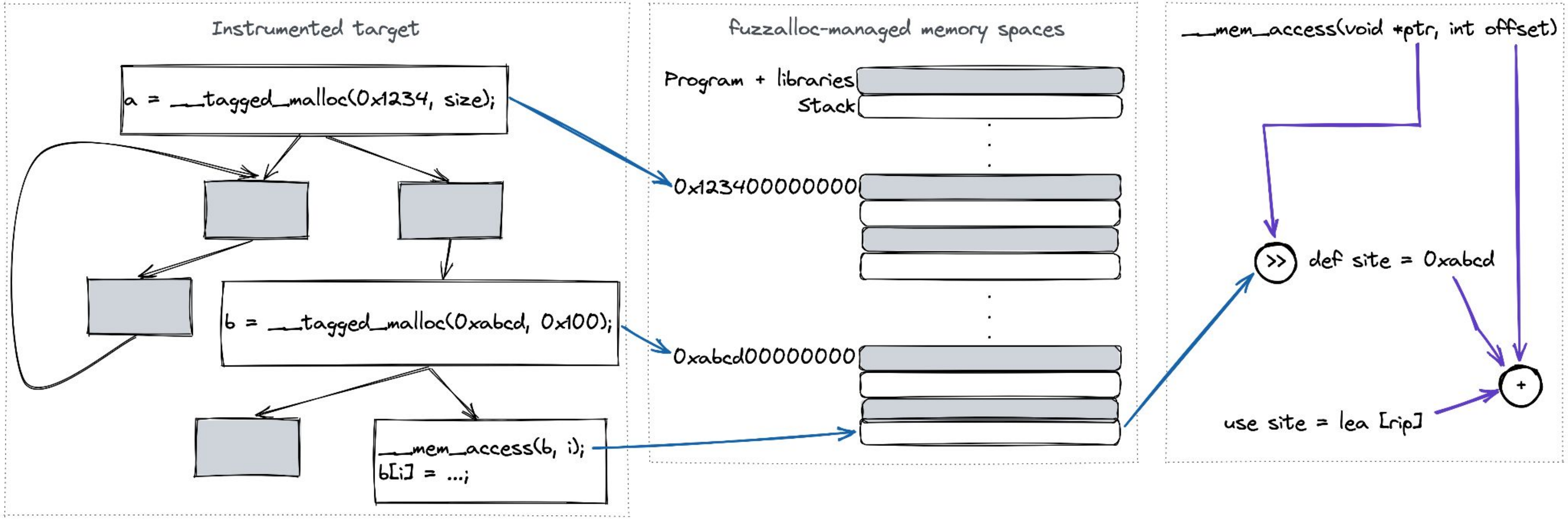

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Targets

- Magma benchmark suite (🐛)
- `jq` JSON parser (📈)

Fuzzers

- datAFLow (with different use site sensitivities)
- AFL++ (with/out cmplog)
- Angora

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4. Evaluate!

Bug-finding results

- datAFLow found less bugs than other fuzzers

- Found two previously-undiscovered bugs
  - In Lua interpreter

4. Evaluate!

Code-coverage results

- AFL++ subsumed least-sensitive def/use coverage
- datAFLow performed slightly-better when more-sensitive metric used

4. Evaluate!

Evaluation plan

- Improve performance
- Characterizing target programs
- Quantifying data-flow coverage
- Fuzz!

4. Evaluate!

Research Qs

- RQ1: Can we characterize target programs for control- vs. data-flow coverage?
- RQ2: How can we quantify data-flow coverage?
- RQ3: Is def-use chain fuzzing effective?

FIN

- Paper @ https://www.ndss-symposium.org/wp-content/uploads/fuzzing2022_23001_paper.pdf
- Code @ https://github.com/HexHive/datAFLow

Registered Report: DATAFLOW
Towards a Data-Flow-Guided Fuzzer

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***Abstract*—Coverage-guided greybox fuzzers rely on feedback derived from *control-flow* coverage to explore a target program and uncover bugs. This is despite control-flow feedback offering only a coarse-grained approximation of program behavior. *Data flow* intuitively more-accurately characterizes program behavior. Despite this advantage, fuzzers driven by data-flow coverage have received comparatively little attention, appearing mainly when heavyweight program analyses (e.g., taint analysis, symbolic execution) are used. Unfortunately, these more accurate analyses incur a high run-time penalty, impeding fuzzer throughput. Lightweight data-flow alternatives to control-flow fuzzing remain unexplored.**

We present DATAFLOW, a greybox fuzzer driven by lightweight data-flow profiling. Whereas control-flow edges represent the order of operations in a program, data-flow edges capture the dependencies between operations that produce data values and the operations that consume them: indeed, there may be no control dependence between those operations. As such, data-flow coverage captures behaviors not visible as control flow and intuitively discovers more or different bugs. Moreover, we establish a framework for reasoning about data-flow coverage, allowing the computational cost of exploration to be balanced with precision.

We perform a preliminary evaluation of DATAFLOW, comparing fuzzers driven by control flow, taint analysis (both approximate and exact), and data flow. Our initial results suggest that, so far, pure coverage remains the best coverage metric for uncovering bugs in most targets we fuzzed (72 % of them). However, data-flow coverage does show promise in targets where control flow is decoupled from semantics (e.g., parsers). Further evaluation and analysis on a wider range of targets is required.

I. INTRODUCTION

Fuzzers are an indispensable tool in the software-testing toolbox. The idea of fuzzing—to test a target program by subjecting it to a large number of randomly-generated inputs—can be traced back to an assignment in a graduate Advanced Operating Systems class [1]. These fuzzers were relatively primitive (compared to a modern fuzzer): they simply fed a randomly-generated input to the target, failing the test if the target crashed or hung. They did not model program or input structure, and could only observe the input/output behavior of the target. In contrast, modern fuzzers use sophisticated program analyses to model program and input structure, and continuously gather dynamic information about the target.

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Leveraging dynamic information drives fuzzer efficiency. For example, *coverage-guided greybox fuzzers*—perhaps the most widely-used class of fuzzer—track code paths executed by the target.[1] This allows the fuzzer to focus its mutations on inputs reaching new code. Intuitively, a fuzzer cannot find bugs in code never executed, so maximizing the amount of code executed should maximize the number of bugs found. Code coverage serves as an approximation of program behavior, and expanding code coverage implies exploring program behaviors.

Coverage-guided greybox fuzzers are now pervasive. Their success [2] can be attributed to one fuzzer in particular: American Fuzzy Lop (AFL) [3]. AFL is a greybox fuzzer that uses lightweight instrumentation to track edges covered in the target's control-flow graph (CFG). A large body of research has built on AFL [4–12]. While improvements have been made, most fuzzers still default to edge coverage as an approximation of program behavior. *Is this the best we can do?*

In some targets, control flow offers only a coarse-grained approximation of program behavior. This includes targets whose control structure is decoupled from its semantics (e.g., LR parsers generated by `yacc`) [13]. Such targets require *data-flow* coverage [13–17]. Whereas control flow focuses on the order of operations in a program (i.e., branch and loop structures), data flow instead focuses on how variables (i.e., data) are defined and used [14]: indeed, there may be no control dependence between variable definition and use sites (see §III for details).

In fuzzing, data flow typically takes the form of *dynamic taint analysis* (DTA). Here, the target's input data is *tainted* at its definition site and tracked as it is accessed and used at runtime. Unfortunately, accurate DTA is difficult to achieve and expensive to compute (e.g., prior work has found DTA is expensive [18, 19] and its accuracy highly variable across implementations [18, 20]). Moreover, several real-world programs fail to compile under DTA, increasing deployability concerns. Thus, most widely-deployed greybox fuzzers (e.g., AFL [3], libFuzzer [21], and honggfuzz [22]) eschew DTA in favor of higher fuzzing throughput.

While lightweight alternatives to DTA exist (e.g., REDQUEEN [23], GREYONE [19]), the full potential of control- vs. data-flow based fuzzer coverage metrics have not yet been thoroughly explored. To support this exploration, we

[1]Miller et al.'s original fuzzer [1] is now known as a *blackbox* fuzzer, because it has no knowledge of the target's internals.