VUzzer: Application-aware Evolutionary Fuzzing

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Overview

- Introduction
- Motivation
- Design and technique details
- Evaluation results
- Conclusions

Introduction

- Fuzzing, like AFL, is a dynamic analysis technique
  - Pros: high throughput, scalability
  - Cons: ineffective in deep execution and strict conditions due to blindly mutation
- Hybrid Fuzzing: concolic execution + AFL, like Driller
  - Pros: solve some strict conditions.
  - Cons: sacrifice scalability(key strength for Fuzzing) and time.

More limitations: Magic value

- 1. Because AFL is hard to detect if condition, AFL may focus on exploring *else* branch.
- 2. Even if concolic execution helps AFL to calculate these offsets in *if* branch, AFL may again mutate these offsets again, which waste processing power and time

```
1 ...
2 read(fd, buf, size);
3 if (buf[5] == 0xD8 && buf[4] == 0xFF) // notice the order of CMPs
4     ... some useful code ...
5 else
6     EXIT_ERROR("Invalid file\n");
```

More limitations: Deeper path

- 1. AFL will give some prioritize efforts to the both first *if* and *else* branch, AFL will not be able to prioritize efforts to focus on the interesting path, such as any bugs inside the nested *if* code

```
1 ...
2 read(fd, buf, size);
3 ...
4 if (...) {
5       if (...)  // nested IF
6           ...
7 } else {
8       ...
9 }
```

Motivation

- VUzzer is both scalable and fast to discover
  - Scalability: not use symbolic execution that hard to scale
  - Fast to discover: Utilize control-flow and data-flow features based on static and dynamic analysis to find more properties of the target application. And then use these to enable faster generation of interesting inputs.

Design Overview

1. The two main components of VUzzer are a static analyzer(shown on the left) and the main (dynamic) fuzzing loop (shown on the right).
2. VUzzer continuously pumps this information back into the evolutionary mutation and crossover operators to help generate better inputs in the next generation.
3. VUzzer uses static analysis to gain some information
4. Execute evolutionary fuzzing loop with information from static analysis.
    1. Input test cases
    2. Use Dynamic taint analysis to monitor execution
    3. Evaluate input cases by fitness function.
    4. Mutate
    5. Repeat step 1

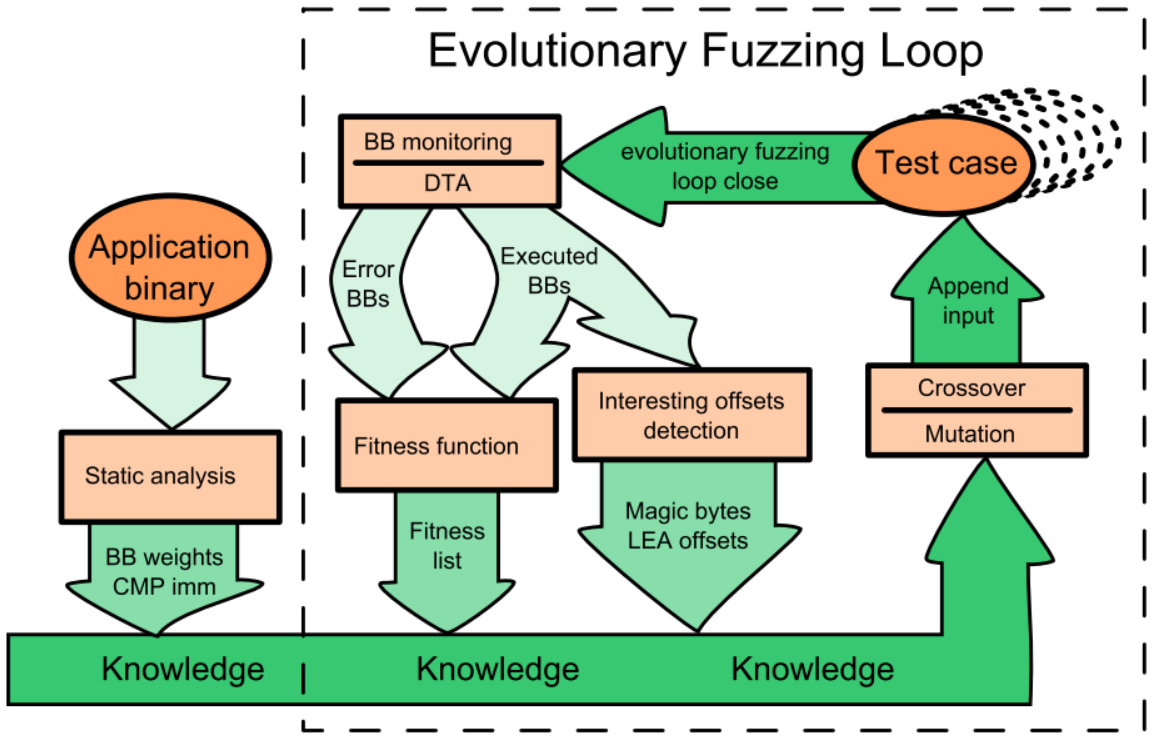


Fig. 1. A high-level overview of VUzzer. BB: basic block, CMP imm: `cmp` instruction with one immediate operand, DTA: dynamic taint analysis, LEA: *load effective address* instruction.

Data-flow features: Magic values

- 1. Data-flow features provide information about the relationship between input data and computations in the application
- 2. VUzzer uses taint analysis to infer the structure of the input in terms of the types of data at certain offsets in the input, such as by instrumenting each instruction of the *cmp* family to determine which input bytes (offsets) it uses and against which values it compares them.
- 3. VUzzer can determine which offsets are interesting to mutate and what values to use at those offsets

Control-flow features

- Two purposes by control-flow features:
  - 1. Infer the importance of certain execution paths: identifying such error-handling blocks may speed up the generation of interesting inputs
  - 2. Concerns the reachability of nested blocks: assigning weights to individual basic blocks
    - Basic blocks are part of error-handling code get a negative weight
    - Basic blocks in hard-to-reach code regions obtain a higher weight
  - We use control-flow features to deprioritize and prioritize paths

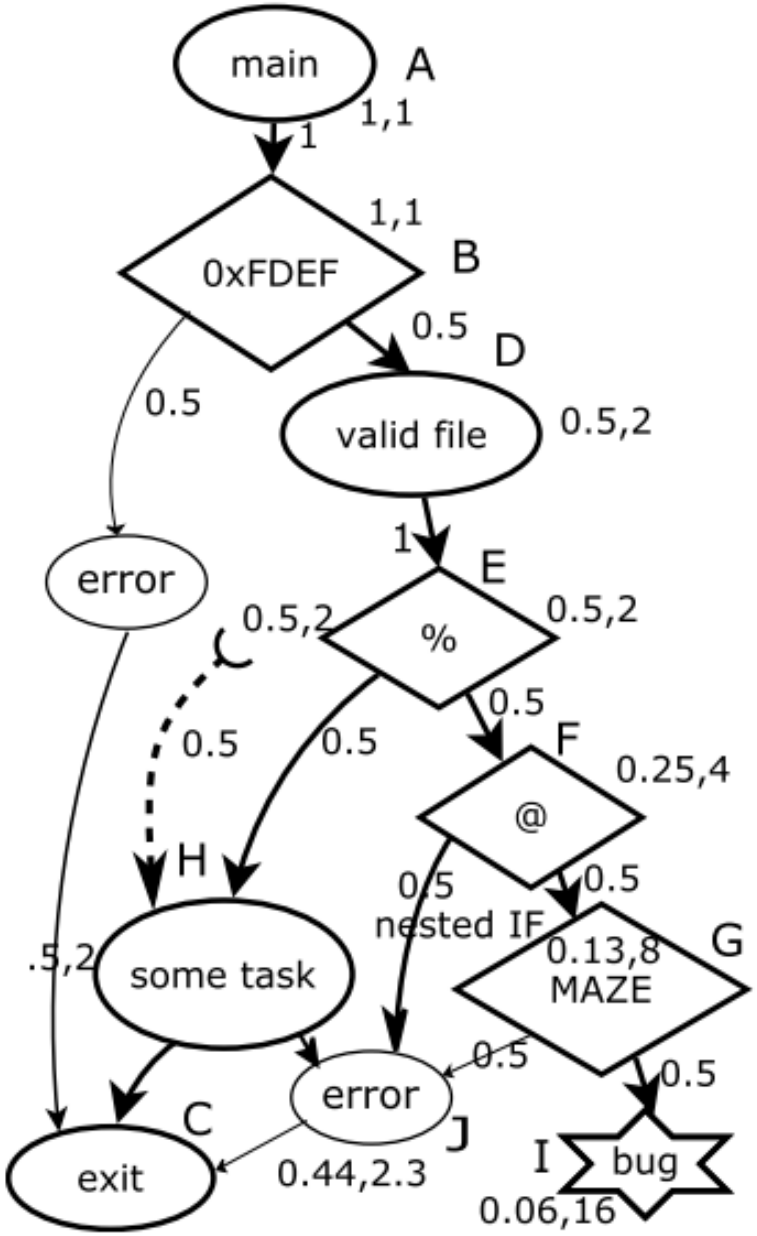
The static analyzer

- At the beginning of the fuzzing process, we use a lightweight intraprocedural static analysis
  - Obtain immediate values of the cmp instructions by scanning the binary code of the application, a list L_{imm}
  - Compute the weights for the basic blocks of the application binary, a list of L_{BB}

The static analyzer

- A list L_{imm} of byte sequences {0xEF, 0xFD, %, @, MAZE}

- Model the CFG of each function as a Markov model, and the weight w_b of each basic block b as 1/ p_b, which is the probability p_b of reaching each basic block b in a function



The main fuzzing loop: Evolutionary Algorithm

Algorithm 1 Pseudo-code of a typical evolutionary algorithm

```
INITIALIZE population with seed inputs
repeat
    SELECT1 parents
    RECOMBINE parents to generate children
    MUTATE parents/children
    EVALUATE new candidates with FITNESS function
    SELECT2 fittest candidates for the next population
until TERMINATION CONDITION is met
return BEST Solution
```

INITIALIZE step

- Purposes: gain an initial set of control-flow and data-flow features

- Implement: run dynamic taint analysis for all initial seed inputs to capture common characteristics, like magic-byte and error-handling code detection

SELECT1 parents

- Purposes: select two inputs(parents) for generating new inputs

- Implement:
  - VUzzer uses fitness functions to calculate fitness scores for all taint inputs and sorts it to gain a sorted lists L_{fit}
  - Fetch top n% of L_{fit} and set as ROOT set
  - Select two inputs(parents) from ROOT

RECOMBINE

- Purposes: combine two inputs to generate two children for next step, MUTATE

- Implement: two inputs are combined by choosing an offset (cut-point) and exchanging the corresponding two parts to form two children

MUTATE

- Purposes: use a single parent input to form one child

- Implement:
  - Mutation uses several sub-operations, such as addition, deletion, replacement, and insertion of bytes at certain offsets in the given input.
  - The mutation operator makes use of the data-flow features to generate new values, for example, use characters from L_{imm}

EVALUATE

- Purposes: use a fitness function to assess the suitability of the input

- Implement:
  - Fitness calculation: sum the weights, list L_{BB}, of the frequencies of executed basic blocks
  - Provide high scores to inputs that execute basic blocks with higher weights and thereby prioritize the corresponding paths

SELECT2 and repeat

- Purposes: select fittest candidates for the next population

- Implement: choose the highest fitness score from the fitness function for next generation of inputs.

Evaluation results

- DARPA CGC binaries: VUzzer found crashes in 29 of the CGC binaries, whereas AFLPIN found only 23 crashes.

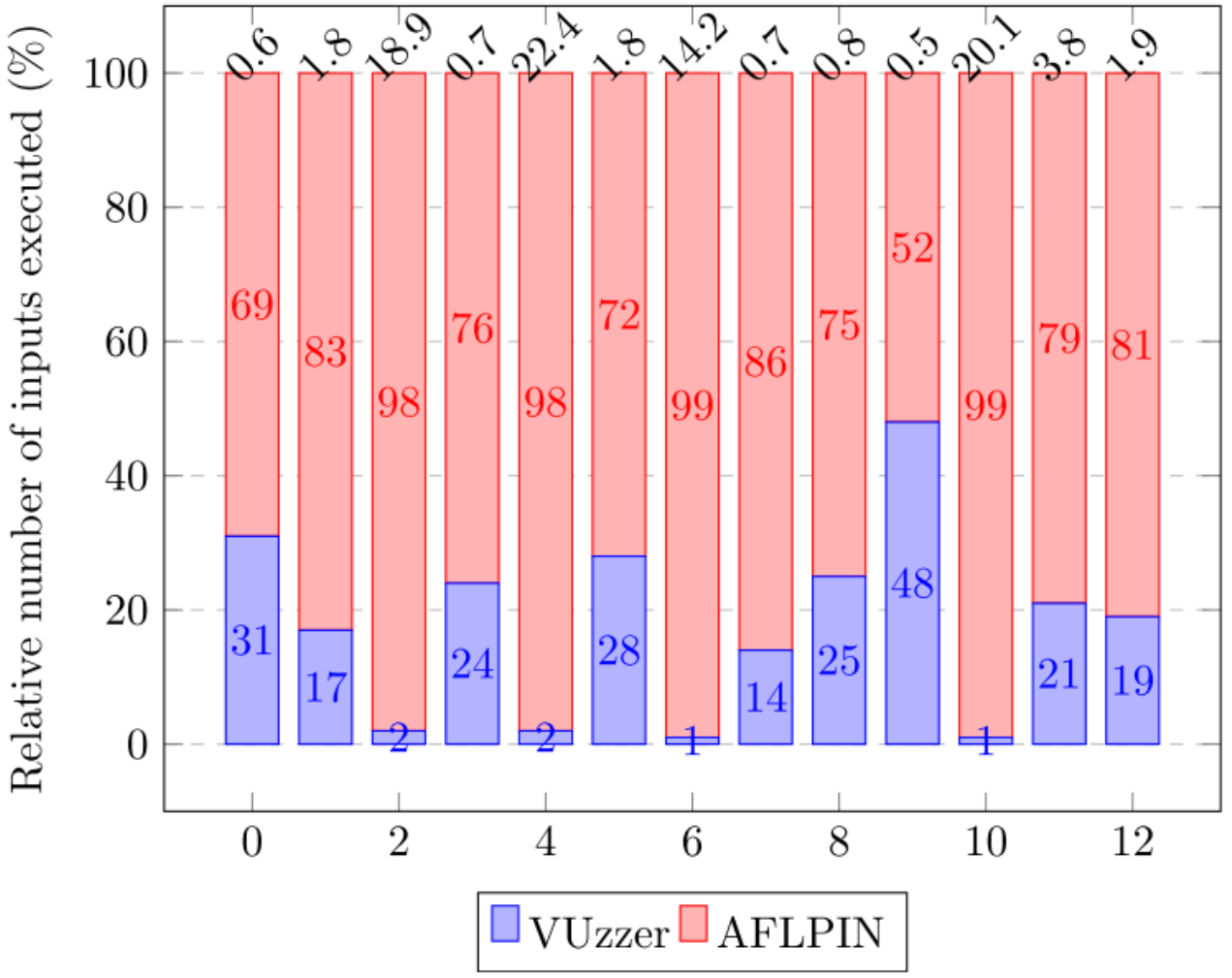


Fig. 4. Relative number of inputs executed for each of the CGC Binaries, wherein both VUzzer and AFLPIN find crashes. The numbers above the bars are the total number of inputs (in thousands) executed.

Evaluation results

- LAVA Dataset
  - FUZZER: a coverage-based fuzzer
  - SES: symbolic execution and a SAT-based approach

TABLE II. LAVA-M DATASET: PERFORMANCE OF VUZZER COMPARED TO PRIOR APPROACHES.

Program	Total bugs	FUZZER	SES	VUzzer (unique bugs, total inputs)
`uniq`	28	7	0	27 (27K)
`base64`	44	7	9	17 (14k)
`md5sum`	57	2	0	1*
`who`	2136	0	18	50 (5.8K)

Evaluation results

- Various Applications (VA) Dataset

TABLE IV. VA DATASET: PERFORMANCE OF VUZZER VS. AFL.

Application	VUzzer		AFL	
	#Unique crashes	#Inputs	#Unique crashes	#Inputs
mpg321	337	23.6K	19	883K
gif2png+libpng	127	43.2K	7	1.84M
pdf2svg+libpoppler	13	5K	0	923K
tcpdump+libpcap	3	77.8K	0	2.89M
tcptrace+libpcap	403	30K	238	3.29M
djpeg+libjpeg	1[7]	90K	0	35.9M

Conclusion

- They leverage control-flow and data-flow features of the application to infer several interesting properties of the input, which enables much faster generation of interesting inputs.

- Scalable and faster

Thank you & Question