On the **Surprising Efficiency** and **Exponential Cost** of Fuzzing

Marcel Böhme
Software Security
MPI-SP & Monash

Keywords: Vulnerability Discovery, Automated Software Testing, Effectiveness, Efficiency, Scalability, Guarantees
On the **Surprising Efficiency and Exponential Cost of Fuzzing**

We might have **strong intuitions about a problem**, but without a deep understanding of the problem our intuitions might lead us astray.

**Marcel Böhme**
Software Security
MPI-SP & Monash

Keywords: Vulnerability Discovery, Automated Software Testing, Effectiveness, Efficiency, Scalability, Guarantees
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

        if(crash == 1) abort();
}
Whitebox Fuzzing

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!' )
                    crash = 1;
    if(crash == 1) abort();
}
```

Path Conditions

✓ $\phi_1 = (s0 \neq 'b')$
Whitebox Fuzzing

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}

Path Conditions

✓ $\phi_1 = (s0 \neq 'b')$
✓ $\phi_2 = (s0 = 'b') \land (s1 \neq 'a')$
Whitebox Fuzzing

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    
    if (crash == 1) abort();
}

Path Conditions
✓ $\varphi_1 = (s_0 \neq 'b')$
✓ $\varphi_2 = (s_0 = 'b') \land (s_1 \neq 'a')$
✓ $\varphi_3 = (s_0 = 'b') \land (s_1 = 'a') \land (s_2 \neq 'd')$
✓ $\varphi_4 = (s_0 = 'b') \land (s_1 = 'a') \land (s_2 = 'd') \land (s_3 \neq '!')$
✗ $\varphi_5 = (s_0 = 'b') \land (s_1 = 'a') \land (s_2 = 'd') \land (s_3 = '!')$
void crashme (char s0, char s1, char s2, char s3) { 
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if (crash == 1) abort();
}

Path Conditions
✓ $\phi_1 = (s0 \neq 'b')$
✓ $\phi_2 = (s0 == 'b') \land (s1 \neq 'a')$
✓ $\phi_3 = (s0 == 'b') \land (s1 == 'a') \land (s2 \neq 'd')$
✓ $\phi_4 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 \neq '!')$
✗ $\phi_5 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 == '!')$
Whitebox Fuzzing: Most Effective!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}
```

Path Conditions

- $\phi_1 = (s0 \neq 'b')$
- $\phi_2 = (s0 == 'b') \land (s1 \neq 'a')$
- $\phi_3 = (s0 == 'b') \land (s1 == 'a') \land (s2 \neq 'd')$
- $\phi_4 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 \neq '!')$
- $\phi_5 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 == '!')$

It can prove the absence of assertion violation, by enumerating all paths and modulo some assumptions.
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if (crash == 1) abort();
}

Path Conditions
✓ φ₁ = (s₀ != 'b')
✓ φ₂ = (s₀ == 'b') \ (s₁ != 'a')
✓ φ₃ = (s₀ == 'b') \ (s₁ == 'a') \ (s₂ != 'd')
✓ φ₄ = (s₀ == 'b') \ (s₁ == 'a') \ (s₂ == 'd') \ (s₃ != '!')
✗ φ₅ = (s₀ == 'b') \ (s₁ == 'a') \ (s₂ == 'd') \ (s₃ == '!')

Whitebox Fuzzing: Quite Efficient!
Whitebox Fuzzing: Quite Efficient!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}

We only need 3 inputs to find the bug, on average, if we choose each path at random without replacement.

Choose a random path from the multivariate hypergeometric (i.e., enumerate).
Choose some input that exercises that path (by constraint solving).

Path Conditions
✓ $\varphi_1 = (s0 \neq 'b')$
✓ $\varphi_2 = (s0 == 'b') \land (s1 \neq 'a')$
✓ $\varphi_3 = (s0 == 'b') \land (s1 == 'a') \land (s2 \neq 'd')$
✓ $\varphi_4 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 \neq '!')$
✗ $\varphi_5 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 == '!')$
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if (crash == 1) abort();
}
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();  // It can never prove the absence of assertion violation!
}

Blackbox Fuzzing: just random, really.

For each parameter, choose 1 of 256 values uniformly at random.

August 1969
NOTES ON STRUCTURED PROGRAMMING by prof.dr.Edsger W.Dijkstra

On the reliability of mechanisms.
Corollary of the first part of this section:
    Program testing can be used to show the presence of bugs, but never to show their absence!
Blackbox Fuzzing: just random, really.

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}
```

For each parameter, choose 1 of 256 values uniformly at random.

It can never prove the absence of assertion violation!

Well, that's not entirely true. We can estimate a "residual risk".

August 1969

NOTES ON STRUCTURED PROGRAMMING by prof.dr.Edsger W.Dijkstra

On the reliability of mechanisms.

Corollary of the first part of this section:

Program testing can be used to show the presence of bugs, but never to show their absence!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if(crash == 1) abort();
}

For each parameter, choose 1 of 256 values uniformly at random.

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after \((1/256)^4\)^{-1} \approx 4 \text{ billion inputs}, in expectation.
Blackbox Fuzzing: just random, really.

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if (crash == 1) abort();
}

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after \( (1/256)^4 \approx 4 \text{ billion inputs} \), in expectation.

So, whitebox fuzzing is better, right?
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if (crash == 1) abort();
}

Blackbox Fuzzing: just random, really.

For each parameter, choose 1 of 256 values uniformly at random.

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after \((1/256)^4 \approx 4 \text{ billion inputs}\), in expectation.

So, whitebox fuzzing is better, right? Wrong. At least not always.
Partition Testing Does Not Inspire Confidence

Dick Hamlet, Member, IEEE, and Ross Taylor

This study was undertaken because partition testing did not live up to its intuitive value in two earlier studies. In their brief for random testing [3], Duran and Ntafos published a precise comparison between it and partition testing. Their surprising result is that the two methods are of almost equal value, under assumptions that seem to favor partition testing. Random testing has a decidedly spotty reputation, probably because it makes almost no use of special information about the program being tested. It is certainly counterintuitive that the best systematic method is little improvement over the worst. Hamlet [5] corroborates this result using a different sampling model. He shows random testing to be superior to partition testing, its superiority increasing with more partitions and with the program confidence required.
"Whitebox Fuzzing"

Partition Testing Does Not Inspire Confidence

Dick Hamlet, Member, IEEE, and Ross Taylor

This study was undertaken because partition testing did not live up to its intuitive value in two earlier studies. In their brief for random testing [3], Duran and Ntafos published a precise comparison between it and partition testing. Their surprising result is that the two methods are of almost equal value, under assumptions that seem to favor partition testing. Random testing has a decidedly spotty reputation, probably because it makes almost no use of special information about the program being tested. It is certainly counterintuitive that the best systematic method is little improvement over the worst. Hamlet [5] corroborates this result using a different sampling model. He shows random testing to be superior to partition testing, its superiority increasing with more partitions and with the program confidence required.
Blackbox Fuzzing: Super fast!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if(crash == 1) abort();
}
```

- Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
- Blackbox Fuzzer: Discovers the bug after \( ((1/256)^4)^{-1} \approx 4 \text{ billion inputs} \), in expectation.

If our whitebox fuzzer takes too long per input, our blackbox fuzzer outperforms!

» There is a maximum time per test input!

[FSE'14] On the Efficiency of Automated Testing, M Böhme, S. Paul,
Blackbox Fuzzing: Super fast!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}
```

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after \((1/256)^4\)^{-1} \approx 4 \text{ billion inputs}, in expectation.
  
  On my machine, this takes 6.3 seconds.
  On 100 machines, it takes 63 milliseconds.

[FSE’14] On the Efficiency of Automated Testing, M Böhme, S. Paul,
Blackbox Fuzzing: Super fast!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!'')
                    crash = 1;
    if(crash == 1) abort();
}

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.

On my machine, this takes 6.3 seconds.
On 100 machines, it takes 63 milliseconds.

So, if we have sufficiently many machines (to maximize execs/sec), blackbox fuzzers are the best we can get, right?
Blackbox Fuzzing: Super fast!

void crashme(char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.

So, if we have sufficiently many machines (to maximize execs/sec), blackbox fuzzers are the best we can get, right? Wrong.

On 100 machines, it takes 63 milliseconds.
On my machine, this takes 6.3 seconds.
On 100 machines, it takes 63 milliseconds.
Blackbox Fuzzing: **Super fast!**

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if(crash == 1) abort();
}
```

- Whitebox Fuzzer: Discovers the bug after **3 inputs**, in expectation.
- **Generational** Blackbox Fuzzer: Discovers the bug after **4 billion inputs**, in expectation.

So, if we have sufficiently many machines (to maximize execs/sec), blackbox fuzzers are the best we can get, right? **Wrong.**

Instead of generating inputs from scratch, can we reuse existing inputs?
Blackbox Fuzzing: Super fast!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!'')
                    crash = 1;
    if(crash == 1) abort();
}

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• **Generational** Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.
• **Mutational** Blackbox Fuzzer mutates a random character in a seed.

So, if we have sufficiently many machines (to maximize execs/sec), blackbox fuzzers are the best we can get, right?  

Wrong.

Instead of generating inputs from scratch, can we reuse existing inputs?
Blackbox Fuzzing: **Super fast!**

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}
```

- Whitebox Fuzzer: Discovers the bug after **3 inputs**, in expectation.
- **Generational** Blackbox Fuzzer: Discovers the bug after **4 billion inputs**, in expectation.
- **Mutational** Blackbox Fuzzer mutates a random character in a seed.
  - Started with the seed **bad**?
  - Discovers the bug after 
    
    $$((4^{-1})(2^{-8}))^{-1} \approx 1024 \text{ inputs},$$

So, if we have sufficiently many machines (to maximize execs/sec), blackbox fuzzers are the best we can get, right? **Wrong.**
Blackbox Fuzzing: **Super fast!**

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}
```

- Whitebox Fuzzer: Discovers the bug after **3 inputs**, in expectation.
- **Generational** Blackbox Fuzzer: Discovers the bug after **4 billion inputs**, in expectation.
- **Mutational** Blackbox Fuzzer mutates a random character in a seed.
  - Started with the seed **bad?**
  - Discovers the bug after $((4^{-1})^*(2^{-8}))^{-1} \approx 1024$ inputs, in expectation.
Blackbox Fuzzing: Super fast!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}
```

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Generational Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.
• Mutational Blackbox Fuzzer mutates a random character in a seed.
  • Started with the seed bad?
  • Discovers the bug after $((4^{-1})^8)^{-1} \approx 1024$ inputs, in expectation.
Blackbox Fuzzing: Super fast!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if (crash == 1) abort();
}

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Generational Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.
• Mutational Blackbox Fuzzer mutates a random character in a seed.
  • Started with the seed bad?
  • Discovers the bug after \((4-1)^* (2^{-8})^{-1} \approx 1024\) inputs, in expectation.
Blackbox Fuzzing: **Super fast!**

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}
```

- **Whitebox Fuzzer**: Discovers the bug after 3 **inputs**, in expectation.
- **Generational** Blackbox Fuzzer: Discovers the bug after 4 **billion inputs**, in expectation.
- **Mutational** Blackbox Fuzzer mutates a random character in a seed.
  - Started with the seed **bad**?
  - Discovers the bug after $$((4^{-1})*(2^{-8}))^{-1} \approx 1024$$ **inputs**, in expectation.
Blackbox Fuzzing: Super fast!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• **Generational** Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.
• **Mutational** Blackbox Fuzzer mutates a random character in a seed.
  • Started with the seed bad?
  • Discovers the bug after \(((4^{-1})^*(2^{-8}))^{-1} \approx 1024\) inputs, in expectation.

Alright, we cheated. We chose a good seed to start with.
Blackbox Fuzzing: Super fast!

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if (crash == 1) abort();
}

- Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
- **Generational** Blackbox Fuzzer: Discovers the bug after 4 billion inputs, in expectation.
- **Mutational** Blackbox Fuzzer mutates a random character in a seed.
  - Started with the seed bad?
  - Discovers the bug after $(4^{-1})(2^{-8})^{-1} \approx 1024$ inputs, in expectation.

Alright, we cheated. We chose a good seed to start with.

What if we could automatically discover this seed?
Greybox Fuzzing: “Enumerate”

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}
```

- **Greybox Fuzzing**: Add generated inputs to the corpus which increase coverage!
Greybox Fuzzing: “Enumerate”

void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}

• **Greybox Fuzzing**: Add generated inputs to the corpus which increase coverage!

---

[CCS'16] Coverage-based Greybox Fuzzing as Markov Chain
M Böhme, V.T. Pham, A. Roychoudhury (extended in IEEE TSE journal)
Greybox Fuzzing: “Enumerate”

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;

    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;

    if(crash == 1) abort();
}
```

- **Greybox Fuzzing**: Add generated inputs to the corpus which increase coverage!

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>( (1\times 4^{-1}\times 2^{-8})^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>b***</td>
<td>b***</td>
<td>1024</td>
</tr>
<tr>
<td>b***</td>
<td>ba**</td>
<td>2048</td>
</tr>
<tr>
<td>b***</td>
<td>ba**</td>
<td>3072</td>
</tr>
<tr>
<td>b***</td>
<td>ba**</td>
<td>4096</td>
</tr>
<tr>
<td>b***</td>
<td>bad*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total: 10240</td>
</tr>
</tbody>
</table>

[CCS’16] Coverage-based Greybox Fuzzing as Markov Chain
M Böhme, V.T. Pham, A. Roychoudhury (extended in IEEE TSE journal)
Greybox Fuzzing: “Enumerate”

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
    if(crash == 1) abort();
}
```

- **Greybox Fuzzing**: Add generated inputs to the corpus which increase coverage!
- **Greybox Fuzzing** started only with **** in the seed corpus discovers the bug after 10k inputs (in 150 microseconds)!

---

**Coverage**

<table>
<thead>
<tr>
<th>****</th>
<th>b***</th>
<th>((1 \times 4^{-1} \times 2^{-8})^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>****</td>
<td>ba**</td>
<td>((1/2 \times 4^{-1} \times 2^{-8})^{-1})</td>
</tr>
<tr>
<td>****</td>
<td>ba**</td>
<td>((1/3 \times 4^{-1} \times 2^{-8})^{-1})</td>
</tr>
<tr>
<td>****</td>
<td>bad*</td>
<td>((1/4 \times 4^{-1} \times 2^{-8})^{-1})</td>
</tr>
<tr>
<td></td>
<td>bad!</td>
<td></td>
</tr>
</tbody>
</table>

Total: 10240
• **Greybox Fuzzing**: Add generated inputs to the corpus which increase coverage!

• Greybox Fuzzing started only with **** in the seed corpus discovers the bug after 10k inputs (in 150 microseconds)!

• **Boosted** Greybox Fuzzing started with **** in the seed corpus discovers the bug after 4k inputs (in 55 microseconds)!

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>((1 \times 4^{-1} \times 2^{-8})^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>****</td>
<td>b***</td>
<td>(= 1024)</td>
</tr>
<tr>
<td>****</td>
<td>ba**</td>
<td>((1 \times 4^{-1} \times 2^{-8})^{-1})</td>
</tr>
<tr>
<td>****</td>
<td>bad*</td>
<td>(= 1024)</td>
</tr>
<tr>
<td>****</td>
<td>bad!</td>
<td>((1 \times 4^{-1} \times 2^{-8})^{-1})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total: <strong>4096</strong></td>
</tr>
</tbody>
</table>

[CCS’16] Coverage-based Greybox Fuzzing as Markov Chain
M Böhme, V.T. Pham, A. Roychoudhury (extended in IEEE TSE journal)
More Machines!

Awesome! We have a really efficient fuzzers. Let’s throw more machines at the problem!

- Blackbox Fuzzer: Discovers the bug after \((1/256)^4)^{-1} \approx 4 \text{ billion inputs}\), in expectation. On my machine, this takes \textbf{6.3 seconds}.
  - On 100 machines, it takes \textbf{63 milliseconds}.
More Machines!

X times more machines means X times more bugs, right?

- Blackbox Fuzzer: Discovers the bug after \((1/256)^4\)^{-1} \approx 4 \text{ billion inputs}, in expectation. On my machine, this takes 6.3 \text{ seconds}.
  On 100 machines, it takes 63 \text{ milliseconds}.
Blackbox Fuzzer: Discovers the bug after \((1/256)^4\)^{-1} \approx 4 \text{ billion inputs}, in expectation.

More Machines!

X times more machines means X times more bugs, right?

Wrong.

- Blackbox Fuzzer: Discovers the bug after \((1/256)^4\)^{-1} \approx 4 \text{ billion inputs}, in expectation.
  - On my machine, this takes 6.3 seconds.
  - On 100 machines, it takes 63 milliseonds.
Figure 1: Each vuln. discovery requires exponentially more machines (left). Yet, exponentially more machines allow to find the same vulnerabilities exponentially faster (right).

Fuzzer Test Suite (45min campaigns)
Explaining Exponential Cost

Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $\{q_i\}_{i=1}^S$ each.
Explaining Exponential Cost

Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $\{q_i\}_{i=1}^S$ each.)
Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $\{q_i\}_{i=1}^S$ each. 
Explaining Exponential Cost

Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $\{q_i\}_{i=1}^S$ each.)
Explaining to Exponential Cost

Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $\{q_i\}_{i=1}^S$ each.
Intuitively, each new vulnerability requires some more resources (time or machines) than the previous vulnerability.
On the Cost of Vulnerability Discovery

A constant rate of vulnerability discovery requires exponential amount of resources.

*This is a fundamental limitation of fuzzing!
Whitebox Fuzzing: Most Effective!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
                if (crash == 1) abort();
            if (crash == 1) abort();
        if (crash == 1) abort();
    if (crash == 1) abort();
}
```

It can prove the absence of assertion violation, by enumerating all paths and modulo some assumptions.

Path Conditions
✓ $\phi_1 = (s0 \neq 'b')$
✓ $\phi_2 = (s0 == 'b') \land (s1 \neq 'a')$
✓ $\phi_3 = (s0 == 'b') \land (s1 == 'a') \land (s2 \neq 'd')$
✓ $\phi_4 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 \neq '!')$
✗ $\phi_5 = (s0 == 'b') \land (s1 == 'a') \land (s2 == 'd') \land (s3 == '!')$

Blackbox Fuzzing: Super fast!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!')
                    crash = 1;
                if (crash == 1) abort();
            if (crash == 1) abort();
        if (crash == 1) abort();
    if (crash == 1) abort();
}
```

If our whitebox fuzzer takes too long per input, our blackbox fuzzer outperforms!
» There is a maximum time per test input!
• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after $(1/256)^9 \approx 4$ billion inputs, in expectation.

On my machine, this takes 6.3 seconds. On 100 machines, it takes 63 milliseconds.

Greybox Fuzzing: “Enumerate”

• **Greybox Fuzzing**: Add generated inputs to the corpus which increase coverage!

• **Greybox Fuzzing** started only with **** in the seed corpus discovers the bug after 10k inputs (in 150 microseconds)!

• **Boosted Greybox Fuzzing** started with **** in the seed corpus discovers the bug after 4k inputs (in 55 microseconds)!

Greybox Fuzzing:

<table>
<thead>
<tr>
<th>Input Pattern</th>
<th>Number of Additional Species Discovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>**** b***</td>
<td>$(1 \times 4^{-1} \times 2^{-9})^{-1}$ = 1024</td>
</tr>
<tr>
<td>**** b*** ba**</td>
<td>$(1 \times 4^{-1} \times 2^{3})^{-1}$ = 1024</td>
</tr>
<tr>
<td>**** b*** ba**</td>
<td>$(1 \times 4^{-1} \times 2^{3})^{-1}$ = 1024</td>
</tr>
<tr>
<td>**** b*** ba** bad*</td>
<td>$(1 \times 4^{-1} \times 2^{3})^{-1}$ = 1024</td>
</tr>
</tbody>
</table>

Total: 4096

Exponential Cost of Vulnerability Discovery

Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $(q_i)^S_i$ each).
Whitebox Fuzzing: Most Effective!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!
                crash = 1;
    if(crash == 1) abort();
}
```

It can prove the absence of assertion violation, by enumerating all paths and modulo some assumptions.

Path Conditions
- $\phi_1 = (s0 \neq 'b')$
- $\phi_2 = (s0 = 'b') \land (s1 \neq 'a')$
- $\phi_3 = (s0 = 'b') \land (s1 = 'a') \land (s2 \neq 'd')$
- $\phi_4 = (s0 = 'b') \land (s1 = 'a') \land (s2 = 'd') \land (s3 \neq '!)$
- $\phi_5 = (s0 = 'b') \land (s1 = 'a') \land (s2 = 'd') \land (s3 = '!)$

If our whitebox fuzzer takes too long per input, our blackbox fuzzer outperforms!

• Whitebox Fuzzer: Discovers the bug after 3 inputs, in expectation.
• Blackbox Fuzzer: Discovers the bug after $(1/256)^4 \approx 4$ billion inputs, in expectation.

Blackbox Fuzzing: Super fast!

```c
void crashme (char s0, char s1, char s2, char s3) {
    int crash = 0;
    if (s0 == 'b')
        if (s1 == 'a')
            if (s2 == 'd')
                if (s3 == '!
                crash = 1;
    if(crash == 1) abort();
}
```

On 100 machines, it takes 63 milliseconds.
On my machine, this takes 6.3 seconds.

If you want to take a deeper dive:
* Read our interactive text book: The Fuzzing Book
* Read our IEEE Software article: “Fuzzing: Challenges and Reflections”
* Apply for PhD / PostDoc in my group at MPI-SP, Bochum, Germany.

Web: [https://mboehme.github.com](https://mboehme.github.com) Twitter: @mboehme_

Greybox Fuzzing: “Enumerate”

• Greybox Fuzzing: Add generated inputs to the corpus which increase coverage!

• Greybox Fuzzing started only with **** in the seed corpus discovers the bug after 10k inputs (in 150 microseconds)!

• Boosted Greybox Fuzzing started with **** in the seed corpus discovers the bug after 4k inputs (in 55 microseconds)!

**Greybox Fuzzing** as Markov Chain

<table>
<thead>
<tr>
<th>States</th>
<th>Arrival Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>****</td>
<td>(1×4⁻¹×2⁻⁹⁻¹)⁻¹ = 1024</td>
</tr>
<tr>
<td>b***</td>
<td>(1×4⁻¹×2⁻⁹⁻¹)⁻¹ = 1024</td>
</tr>
<tr>
<td>b***</td>
<td>(1×4⁻¹×2⁻⁹⁻¹)⁻¹ = 1024</td>
</tr>
<tr>
<td>b***</td>
<td>(1×4⁻¹×2⁻⁹⁻¹)⁻¹ = 1024</td>
</tr>
<tr>
<td>b***</td>
<td>(1×4⁻¹×2⁻⁹⁻¹)⁻¹ = 1024</td>
</tr>
<tr>
<td>Total:</td>
<td>4096</td>
</tr>
</tbody>
</table>

Figure 10. Number of additional species discovered in a fixed time budget as the number of machines increases (5 random samples of $q_i$ for each.)