MONASH University

Fuzzing

Challenges and Reflections

Marcel Böhme
ARC DECRA Fellow
Senior Lecturer (A/Prof)
Monash University
@mboehme_

2019 Shonan Meeting on Fuzzing and Symbolic Execution:
Reflections, Challenges, and Opportunities

Organizers

Abhik Roychoudhury

Cristian Cadar

Marcel Böhme

Keynote Speakers

Patrice Godegroid @Microsoft

Kostya Serebryany @Google

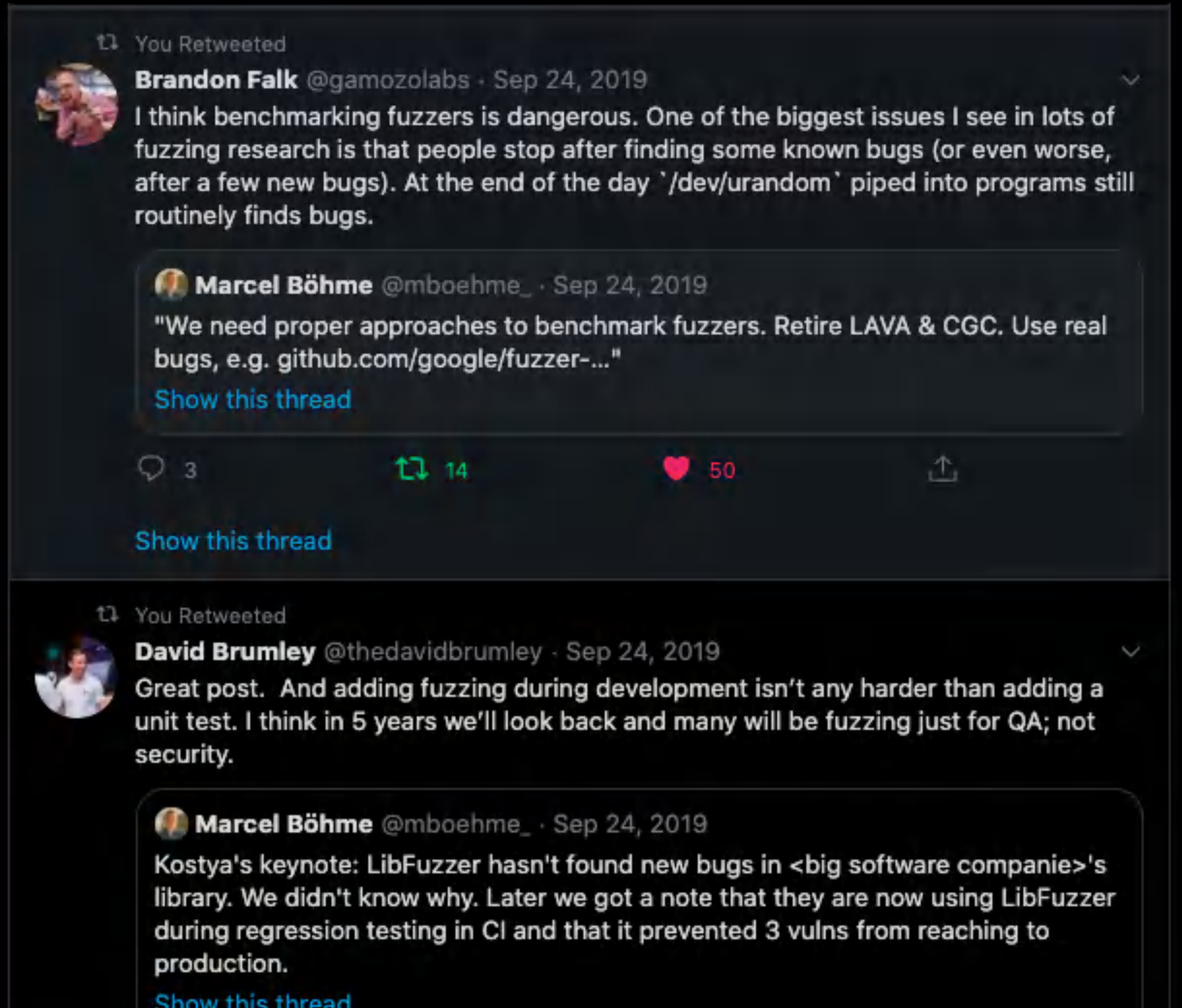
FUZZING and SYMBOLIC EXECUTION

SEPTEMBER 24-27, 2019

Cristian Cadar
Nozhiro Yoshida
Michael Pradel
Filip Nikšić
Patrice Godefroid
Marcel Böhme
Willem Visser
Sergey Mechtaev
Antonio Bertolino
M. Christakis
Martin Vechev
Xiangyu Zhang
Sarfraz Khurshid
Tevfik Bultan
Thuan Pham
David Trabish
Kostya Serebryany
Yue Jia
Liang Gao
Caroline Lemieux
Brendan Dolan-Gavitt
Alessandra Gorla
Andreas Zeller
Peter Goodman
Darko Marinov
Paul Nathiuescu
Milos Gligoric

Caroline Lemieux
@cestlemieux

Live Tweets bringing discussions to the larger community



Survey validating our findings with the larger community

Section 1 of 5

Fuzzing: Challenges and Reflections

Fuzzing is an emerging research field. We are currently writing up a short paper, with some directions on important topics in fuzzing. We are now organizing a survey to collect the diverse opinions of various researchers in the field. Please find the draft at https://www.dropbox.com/s/oljac6pt1uuueai/FuzzingChallenges.pdf?dl=0 (6 pages). The paper is a result of a recent Shonan meeting on "Fuzzing and Symbolic Execution: Reflection Challenges and Opportunities" (https://shonan.nii.ac.jp/seminars/160/).

It takes about 10 minutes to fill this questionnaire.
There are three very short and two longer sections.

Among these high-level challenges, choose 3 that you find most important to be addressed going forward?

- [ ] Fuzzing Theory (Fundamental limitations of different approaches to fuzzing)
- [ ] Security Auditor in the Loop (Usability, interactive fuzzing w/ human-in-the-loop)
- [ ] Automation (Improving scalability, efficiency, effectiveness, deep bugs)
- [ ] Fair evaluation of specialized fuzzers (Level playing field)
- [ ] Valid measures of effectiveness/efficiency (coverage, synthetic bugs, known bugs, time budget)?
- [ ] How do we evaluate techniques instead of tools?

Reflections

we are all stakeholders of secure open-source.

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

Reflections

we are all stakeholders of secure open-source.

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

```
$ git clone https://github.com/google/oss-fuzz
$ ls -1 oss-fuzz/projects | wc -l
356
```

- **Encryption/Decryption** (openssl, gnutls, cryptlib, mbed, wolfssl)
- **Compression** (bzip2, brotli, gzip, lzma, xz, lz4, libarchive)
- **Streaming** (ffmpeg, gstreamer, libvlc)
- **Parser libraries** (xml, json, jpg, png, gif, avi, mpg, pcre)
- **Databases** (mysql, redis, postgre, derby, sqlite)
- **Compilers/Interpreter** (gcc, llvm [clang,..], php, javascript)
- **Protocol implementations** (http/http2, ftp, smtp, ssh, tls/ssl, rtsp)
- **Server implementations** (httpd, nginx, node.js, tomcat, lighthttpd)
- **Operating systems** (ubuntu, debian, android, glibc)

Reflections

fuzzing is having substantial impact!

https://www.darpa.mil/program/cyber-grand-challenge

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.

Reflections what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.

1. The worldwide information security market is forecast to reach $170.4 billion in 2022. (Gartner)
2. 62% of businesses experienced phishing and social engineering attacks in 2018. (Cybint Solutions)
3. 68% of business leaders feel their cybersecurity risks are increasing. (Accenture)
4. Only 5% of companies' folders are properly protected, on average. (Varonis)
7. 52% of breaches featured hacking, 28% involved malware and 32–33% included phishing or social engineering, respectively. (Verizon)
19. The average cost of a data breach is $3.92 million as of 2019. (Security Intelligence)

From https://www.varonis.com/blog/cybersecurity-statistics/

Who led the digital transformation of your company?

A) CEO
B) CTO
C) COVID-19

Reflections

what enabled this recent surge of interest?

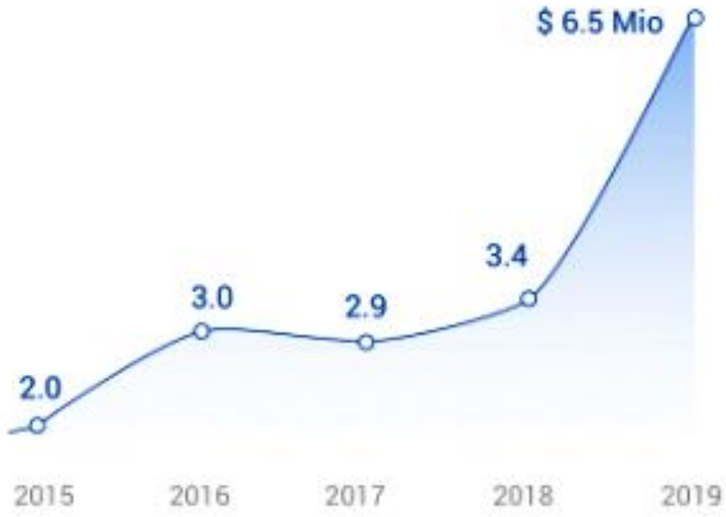
- There is a tremendous **need** for automatic vulnerability discovery.

Google has paid security researchers over $21 million for bug bounties, $6.5 million in 2019 alone

Emil Protalinski
@EPro
January 28, 2020 12:50 PM

Security

VentureBeat.com



Facebook Paid $2.2 Million in Bug Bounty Rewards in 2019

By Ionut Arghire on February 10, 2020

SecurityWeek.com

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.

Mozilla Security Blog

Firefox has one of the oldest security bug bounties on the internet, dating back to 2004. From 2017-2019, we paid out $965,750 to researchers across 348 bugs, making the average payout $2,775 – but as you can see in the graph below, our most common payout was actually $4,000!

Tom Ritter | April 23, 2020

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.

HACKERS EARN RECORD-BREAKING $100 MILLION ON HACKERONE

May 27, 2020

https://www.hackerone.com/press-release

- **214%**: Year-over-year hacker-powered security growth in the federal government
- **85.6%**: The year over year growth in total bounty payments, with 17.5% increase since February when COVID-19 was declared a pandemic.
- **343%**: The increase in signups over the past year on Hacker101 — HackerOne's free online classes for aspiring hackers.
- **Over 170,000**: The number of vulnerabilities hackers have uncovered in nearly 2,000 customer programs

Reflections

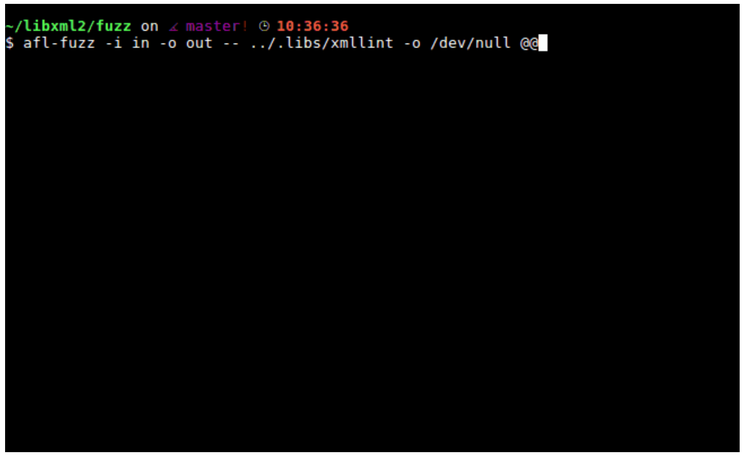
what enabled this recent surge of interest?

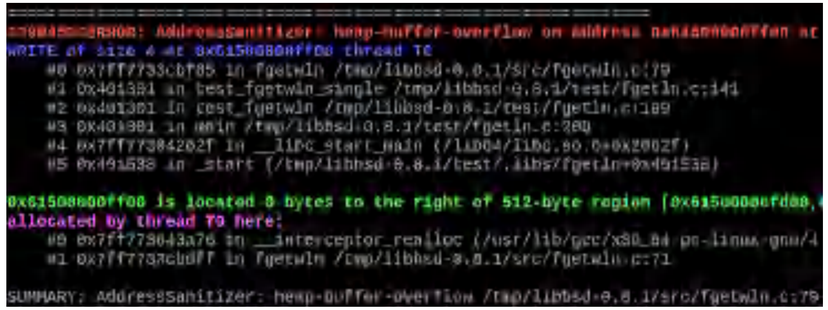
- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.
- We now have the **tools** for automatic vulnerability discovery.

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.
- We now have the **tools** for automatic vulnerability discovery.





- **open-source** and freely available.
- **easy to use** (modulo Matt's concerns 😅)
- **very successful** in finding bugs!

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.
- We now have the **tools** for automatic vulnerability discovery.
- **Meaningful engagement** between industry and academia (via open-science) leading to rapid advances in fuzzing!

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.
- We now have the **tools** for automatic vulnerability discovery.
- **Meaningful engagement** between industry and academia (via open-science) leading to rapid advances in fuzzing!

FUZZCON EUROPE

Community building

Entropic @ **ClusterFuzz**

Industry adoption

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.
- We now have the **tools** for automatic vulnerability discovery.
- **Meaningful engagement** between industry and academia (via open-science) leading to rapid advances in fuzzing!

https://github.com/AFLplusplus

About

The fuzzer afl++ is afl with community patches, AFLfast power schedules, qemu 3.1 upgrade + laf-intel support, MOpt mutators, InsTrim instrumentation, unicorn_mode, Redqueen and a lot more!

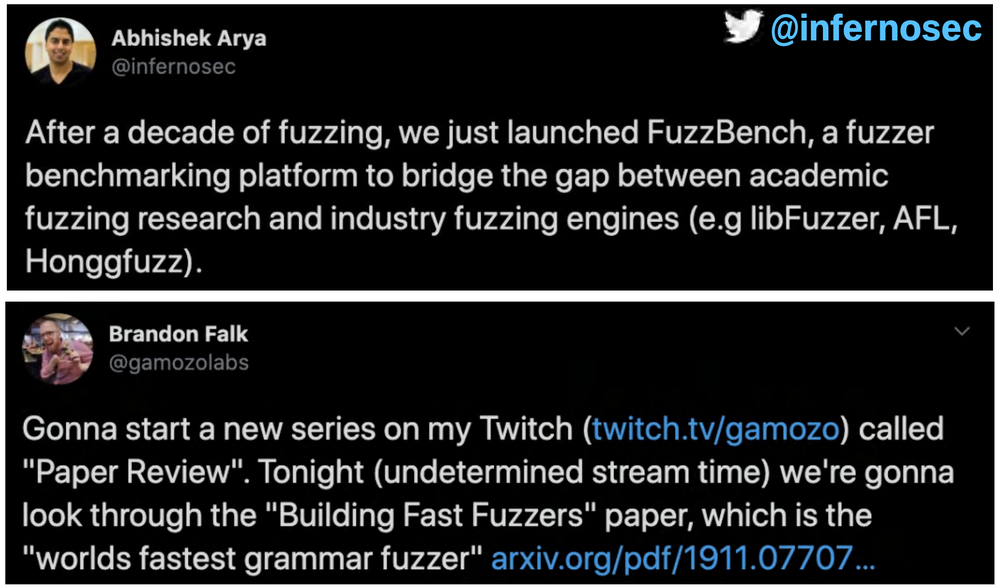
aflplus.plus

Industry adoption

Reflections

what enabled this recent surge of interest?

- There is a tremendous **need** for automatic vulnerability discovery.
- We now have the **incentives** and the required mindset.
- We now have the **tools** for automatic vulnerability discovery.
- **Meaningful engagement** between industry and academia (via open-science) leading to rapid advances in fuzzing!



FuzzBench (compute resources and infrastructure for fuzzer benchmarking)

Paper Reviews et al. (twitch.tv/gamozo)

Challenges

Disclaimer:

We put forward only questions.

We have no answers (only ideas).

Challenges

- **Automating** vulnerability discovery.
  Considered most important challenge.

Challenges

- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?

Challenges

- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?

We know how to fuzz command line tools (e.g., AFL).
We know how to fuzz individual units / functions (e.g., libfuzzer).

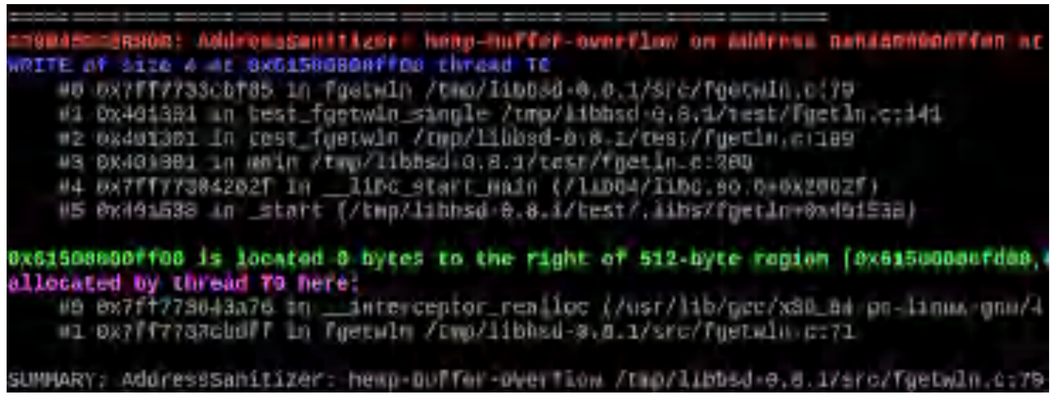
What about cyber physical systems, machine learning systems, stateful software, polyglot software, GUI-based software, .. ?

Challenges

- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?
  - [C.2] How can the fuzzer identify more types of vulnerabilities?

Challenges

- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?
  - [C.2] How can the fuzzer identify more types of vulnerabilities?
    - How to detect various **side-channels** (incl. information leaks)?
    - How to detect **domain-specific vulns.** (incl. sandbox escapes, kernel exploits)?
    - How to detect **language-specific vulns**?
    - How to detect **other causes** of arbitrary / remote code execution?



We need to go beyond memory corruption bugs (ASAN, TSAN).

Challenges

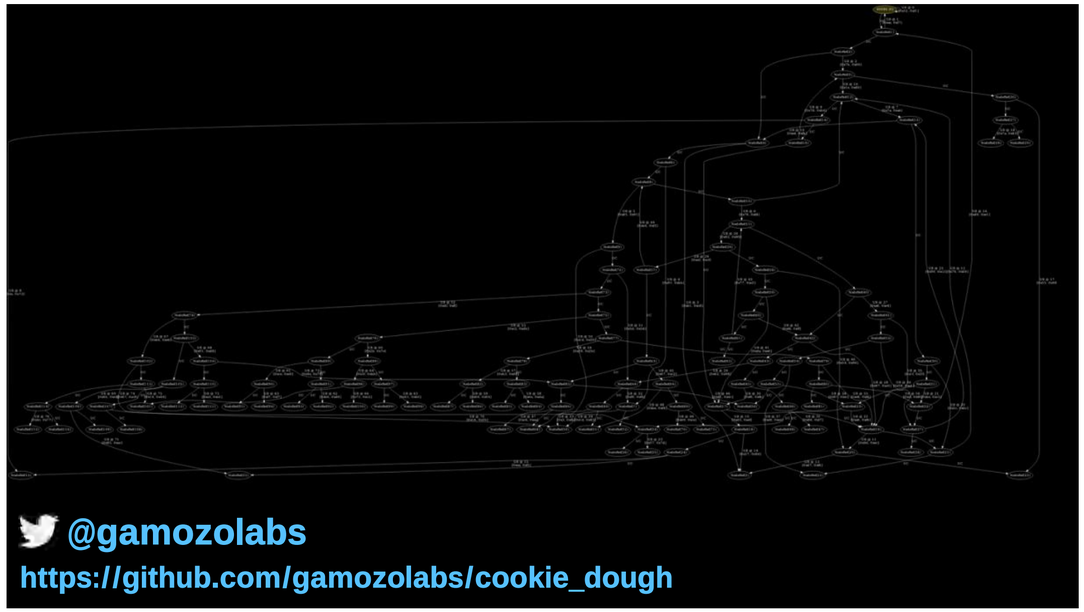
- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?
  - [C.2] How can the fuzzer identify more types of vulnerabilities?
  - [C.3] How can we find “deep bugs” that have evaded detection?

Challenges

- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?
  - [C.2] How can the fuzzer identify more types of vulnerabilities?
  - [C.3] How can we find “deep bugs” that have evaded detection?
    - How to mine dictionaries, grammars, and protocols?
    - How to identify input dependencies (e.g. checksums)?
    - How identify and rectify fuzzer roadblocks?

Challenges

- **Automating** vulnerability discovery.
  - [C.1] How can we fuzz more types of software systems?
  - [C.2] How can the fuzzer identify more types of vulnerabilities?
  - [C.3] How can we find “deep bugs” that have evaded detection?
  - [C.4] What is the empirical nature of undiscovered vulnerabilities?



- Which types of vulnerabilities are difficult to discover by fuzzing and why?
- What are fuzzer roadblocks?

Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
  - [C.5] **HITL**: How can fuzzers leverage the ingenuity of the auditor?

We need the auditor-in-the-loop.

Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
  - [C.5] **HITL**: How can fuzzers leverage the ingenuity of the auditor?

@NedWilliamson
Project Zero

1. Write a good fuzzer harness
2. Identify fuzzer roadblocks (via code coverage).
3. Patch out roadblocks.
4. Goto 2 - until vulnerability is found.
5. Patch back roadblocks, “repair” reproducer.

Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
  - [C.5] **HITL**: How can fuzzers leverage the ingenuity of the auditor?
  - [C.6] **Usability**: How can we improve the usability of fuzzing tools?

Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
  - [C.5] **HITL**: How can fuzzers leverage the ingenuity of the auditor?
  - [C.6] **Usability**: How can we improve the usability of fuzzing tools?

We need

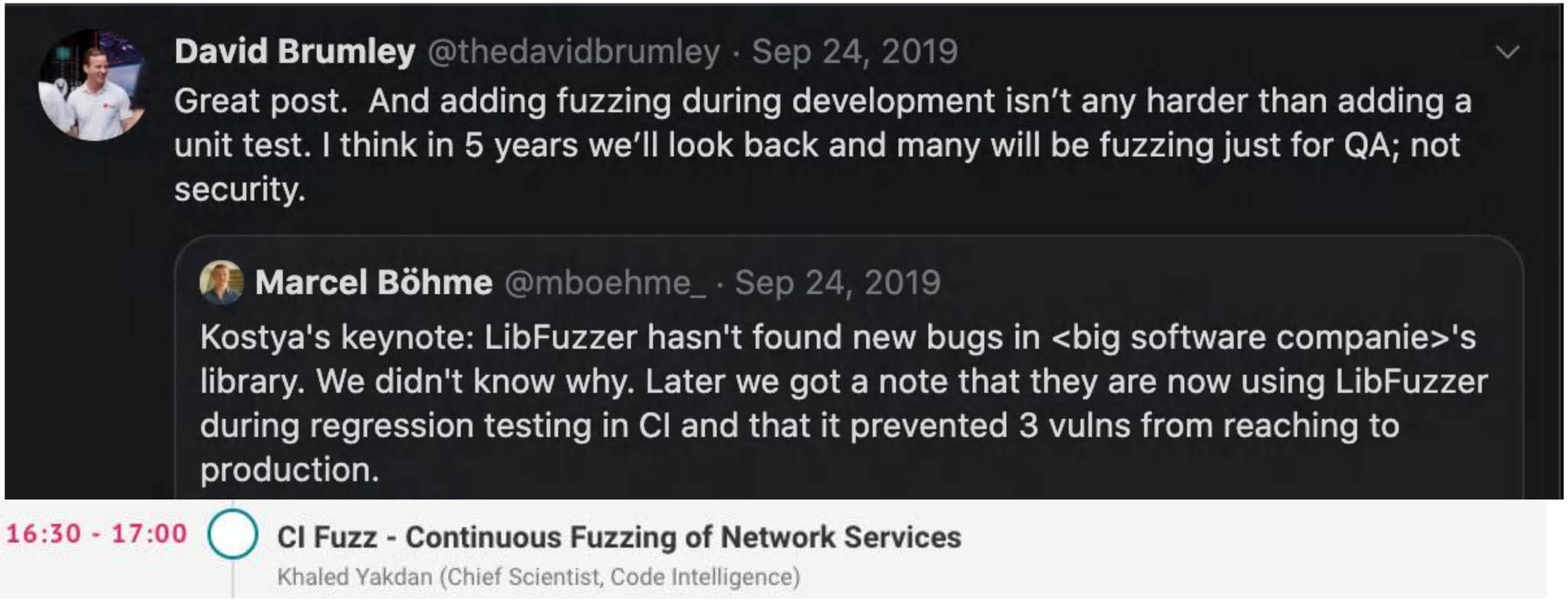
Fuzzing in Continuous Integration / Deployment

Fuzzing in IDEs (JUnit-like Fuzzing)

Fuzzing in processes (Fuzz-driven Development)

Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
  - [C.5] **HITL**: How can fuzzers leverage the ingenuity of the auditor?
  - [C.6] **Usability**: How can we improve the usability of fuzzing tools?



Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
- **Fuzzing theory** and scientific foundations.
  Considered second most important challenge.

Challenges

- **Automating** vulnerability discovery.
- The **human component** in fuzzing.
- **Fuzzing theory** and scientific foundations.
  - [C.7] How can we assess residual security risk if the fuzzing campaign was unsuccessful?
  - [C.8] What are **fundamental limitations** of each approach?

How much more efficient is an attacker that has an order of magnitude more computational resources?

When to stop fuzzing? How to deal with adaptive bias?

We need foundations.

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs
within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
  - [C.9] How can we evaluate specialised fuzzers?
    - Works only in a specific program domain
      Command line, parser libraries, network protocols, GUIs, browsers, compilers, kernels, Android apps)
    - Focusses on a specific use case
      CI/CD [directed fuzzers], specific classes of bugs [UAF, concurrency, deserialization attacks]
    - Suggestion was:
      - Make available special benchmark categories for specialised fuzzers (as in Test-Comp).

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
  - [C.9] How can we evaluate specialised fuzzers?
  - [C.10] How can we prevent overfitting to a specific benchmark?

Goodhart's Law

"When a measure becomes a target, it ceases to be a good measure." —

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
  - [C.9] How can we evaluate specialised fuzzers?
  - [C.10] How can we prevent overfitting to a specific benchmark?
    - Suggestions were:
      1. **Submit and peer-review benchmarks** in addition to fuzzers (Test-Comp).
      2. Regularly evaluate on **new and unseen benchmarks** (Rode0Day).
      3. **Continuous evaluation** on a large and **growing** set of diverse, real-world benchmarks (FuzzBench).

Goodhart's Law

"When a measure becomes a target, it ceases to be a good measure." —

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  Considered third most important challenge.

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

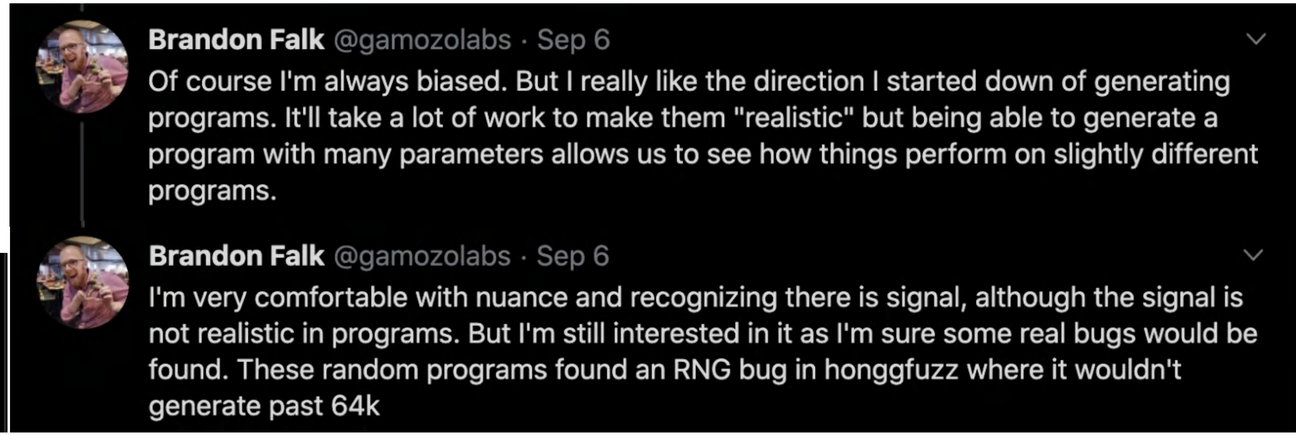
- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  - [C.11] Are synthetic bugs representative?
    - Fuzzer developers can synthesize a large number of benchmark subjects for their special use case, or domain.

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  - [C.11] Are synthetic bugs representative?
    - Fuzzer developers can synthesize a large number of benchmark subjects for their special use case, or domain.

"Time to retire Lava & CGC, they are actively harmful"
KCC @ Shonan



"I really like the direction [..] of generating programs. [..] These random programs found an RNG bug in honggfuzz."
Brandon Falk @ Twitter

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  - [C.11] Are synthetic bugs representative?
  - [C.12] Are real bugs representative?
    - Is your set of real bugs large enough to be representative?

Magma has 114 CVEs + 4 bugs in 7 open-source C programs.

A ground-truth binary fuzzing benchmark suite based on real programs with real bugs.

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  - [C.11] Are synthetic bugs representative?
  - [C.12] Are real bugs representative?
    - Is your set of real bugs large enough to be representative?
    - Are discovered bugs representative of undiscovered bugs?

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  - [C.11] Are synthetic bugs representative?
  - [C.12] Are real bugs representative?
  - [C.13] Is code coverage a good measure of fuzzer effectiveness?
    - Measuring coverage achieved is cheaper than measuring the number of bugs found.
    - Coverage feedback is the classic measure of progress in greybox fuzzing.
    - If small correlation, how are bugs/vulnerabilities distributed over the code?

We need more empirical studies.

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
  - [C.11] Are synthetic bugs representative?
  - [C.12] Are real bugs representative?
  - [C.13] Is code coverage a good measure of fuzzer effectiveness?
  - [C.14] What is a fair choice of time budget?

We need more empirical studies.

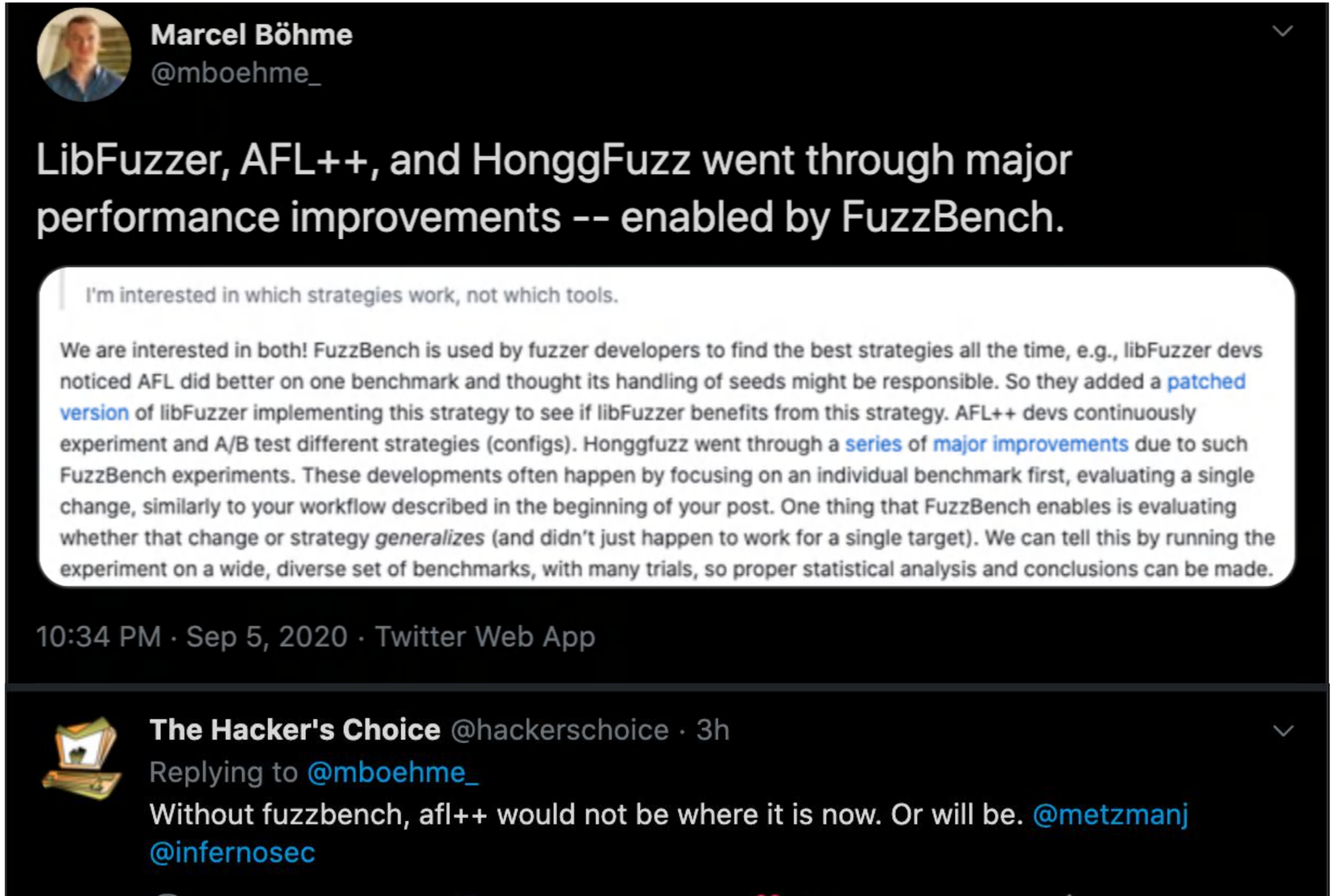
Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a **fair fuzzer benchmark**?
- What is a **good measure** of **fuzzer performance**?
- How do we evaluate **techniques, not implementations**?

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?



Marcel Böhme
@mboehme_

LibFuzzer, AFL++, and HonggFuzz went through major performance improvements -- enabled by FuzzBench.

> I'm interested in which strategies work, not which tools.

We are interested in both! FuzzBench is used by fuzzer developers to find the best strategies all the time, e.g., libFuzzer devs noticed AFL did better on one benchmark and thought its handling of seeds might be responsible. So they added a patched version of libFuzzer implementing this strategy to see if libFuzzer benefits from this strategy. AFL++ devs continuously experiment and A/B test different strategies (configs). Honggfuzz went through a series of major improvements due to such FuzzBench experiments. These developments often happen by focusing on an individual benchmark first, evaluating a single change, similarly to your workflow described in the beginning of your post. One thing that FuzzBench enables is evaluating whether that change or strategy *generalizes* (and didn't just happen to work for a single target). We can tell this by running the experiment on a wide, diverse set of benchmarks, with many trials, so proper statistical analysis and conclusions can be made.

10:34 PM · Sep 5, 2020 · Twitter Web App

The Hacker's Choice @hackerschoice · 3h
Replying to @mboehme_
Without fuzzbench, afl++ would not be where it is now. Or will be. @metzmanj @infernosec

FuzzBench

- Continuous benchmarking.
- Open-source (Submit PRs).
- Submit your fuzzer.
- Submit your benchmarks.
- Submit your feature requests.
- **Free Compute !!!**

Rode0day
A continuous bug finding competition

hexhive Magma

Test-Comp
Tool Competition

And many others..!

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this **at scale**?
  - **Open-source**, **open-science**, **open discourse**
    - has fostered a **meaningful engagement** between industry and academia,
    - has fostered **tremendous recent advances**
      - in symbolic execution-based whitebox fuzzing, and
      - in coverage-guided greybox fuzzing.

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this **at scale**?
  - **Open-source**, **open-science**, **open discourse**
    - has fostered a **meaningful engagement** between industry and academia,
    - has fostered **tremendous recent advances**
      - in symbolic execution-based whitebox fuzzing, and
      - in coverage-guided greybox fuzzing.

Friday, September 18 • 12:00 - 13:00 @Cppcon

Introducing Microsoft's New Open Source Fuzzing Platform

Opportunities

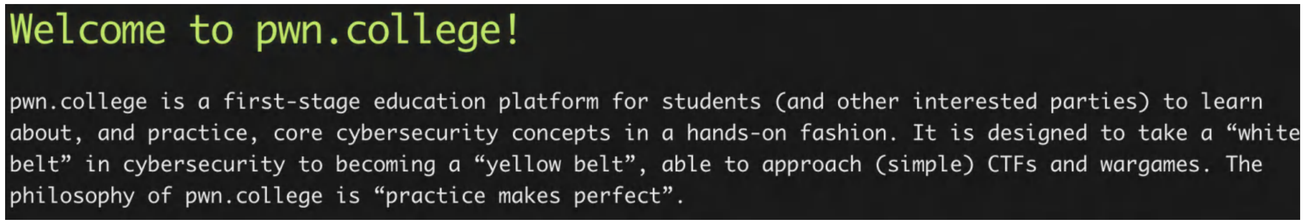
The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this **at scale**?
  - **Open-source**, **open-science**, **open discourse**.
  - **Educate** developers and students on fuzzing.

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this **at scale**?
  - **Open-source**, **open-science**, **open discourse**.
  - **Educate** developers and students on fuzzing.
    - Develop **educational content**, such as tutorials and textbooks.
    - Integrate **software security courses** into university curriculum.



`pwn.college`: MOOC-style ASU Computer Systems Security / CTF course

An ethical hacker about **https://fuzzingbook.com**

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this **at scale**?
  - **Open-source**, **open-science**, **open discourse**.
  - **Educate** developers and students on fuzzing.
  - **Get organised** and support others.
    - As organization, take matters into your hands.
      - **Adopt fuzzing** (e.g., in continuous integration).
      - Make your **tools available** as open-source.
      - Establish competitive **bug bounty programs**.
      - Join **cross-organisational security efforts**.
        (Open Source Security Foundation; https://openssf.org/)

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this **at scale**?
  - **Open-source**, **open-science**, **open discourse**.
  - **Educate** developers and students on fuzzing.
  - **Get organised** and support others.
    - As organization, take matters into your hands.
    - As individual, take matters into your hands.
      - **Join the fuzzing community**
        - Submit PRs to Klee, AFL++, LLVM LibFuzzer, OSS-Fuzz,…
        - Make your tools available as open-source.
      - **Organize and support** hackathons, capture-the-flags, hacking clubs, ethical hackers.
      - **Support an open-source project**
        (e.g., add it to OSSFuzz or fund it on hackerone.com).

MONSEC @ 2019 Cyber Security Challenge Australia (CySCA)

Reflections

- What enabled this recent surge of interest?
  - There is a tremendous need for automatic vulnerability discovery.
  - We now have the incentives and the required mindset.
  - We now have the tools for automatic vulnerability discovery.
  - Meaningful engagement between industry and academia (via open-science) leading to rapid advances in fuzzing!

Challenges

- Automating vulnerability discovery.
- The human component in fuzzing.
- Fuzzing theory and scientific foundations.

Evaluation and Benchmarking

Which fuzzer finds a larger number of important bugs within a reasonable time in software that we care about?

- What makes a fair fuzzer benchmark?
- What is a good measure of fuzzer performance?
- How do we evaluate techniques, not implementations?

Opportunities

The Internet and the world's Digital Economy runs on a shared, critical OSS infrastructure that no one is accountable for.

- How do we address this at scale?
  - Open-source, open-science, open discourse.
  - Educate developers and students on fuzzing.
  - Get organised and support others.