Automated Software Testing with Blackbox Fuzzing

Vaggelis Atlidakis

University of Southern California,
Nov 2023, Invited Talk

BROWN

Why software testing?

- U.S. companies lost > $2 trillion in 2022 due to poor software quality[1]
  - ~10% of U.S. Gross Domestic Product (GDP)

- Bugs found earlier are easier to fix
  - A bug found in coding/unit testing takes ~3x less time to fix than in post-release[2]

This talk: Automated software testing with blackbox fuzzing

- RESTler [ICSE '19]: Collaboration with Microsoft research
- IvySyn [USENIX SEC '23]: Collaboration with Brown University

[1] "Cost of Poor Software Quality: A 2022 Report," Consortium for Information & Software Quality

[2] "Impact of Inadequate Infrastructure for Software Testing, 2022," National Institute of Standards & Technology

Outline

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RESTler: Stateful REST API Fuzzing

What

- Test cloud services with REST APIs
- Find ``500 Internal Server Errors''

Why

- Past approaches were not automated
- Testing one API request each time

How: *Stateful REST API Fuzzing*

- Generate *stateful* sequences of API requests

Test example on GitLab[1]

Delete a file from a project

1. Create a gitlab project
2. Create a file
3. Delete the file

➢ “500 Internal Server Error”

producer of: project-id

```
curl --request POST --header "PRIVATE-TOKEN: <your-token>" \
     --header "Content-Type: application/json" --data '{
        "name": "new_project", "description": "New Project", "path": "new_project",
        "namespace_id": "42", "initialize_with_readme": "true"}' \
     --url "https://gitlab.example.com/api/v4/projects/"
```

project-id: 13083

consumer of: project-id

producer of: file-name

```
curl --request POST --header 'PRIVATE-TOKEN: <your_access_token>' \
     --header "Content-Type: application/json" \
     --data '{"branch": "main", "author_email": "author@example.com", "author_name": "Firstname Lastname",
              "content": "some content", "commit_message": "create a new file"}' \
     "https://gitlab.example.com/api/v4/projects/13083/repository/files/app%2Fproject%2Erb"
```

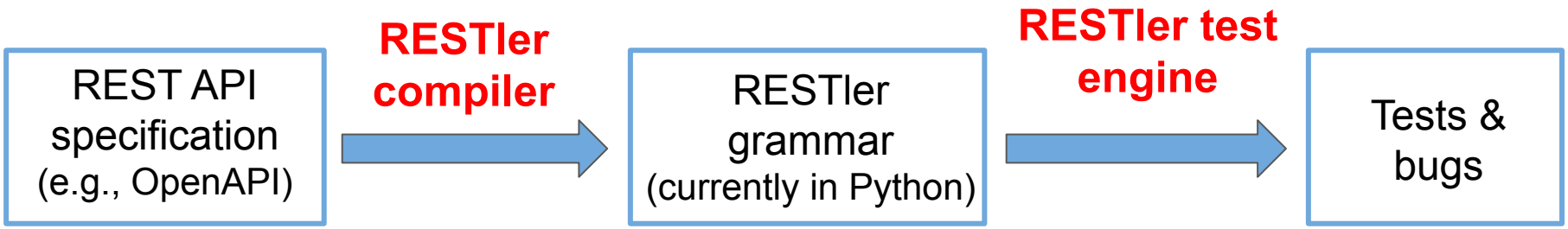
consumer of: project-id, file-name

file-name: app/project.rb

```
curl --request DELETE --header 'PRIVATE-TOKEN: <your_access_token>' \
     --header "Content-Type: application/json" \
     --data '{"branch": "main", "author_email": "author@example.com", "author_name": "Firstname Lastname",
       "commit_message": "          "}' \
     "https://gitlab.example.com/api/v4/projects/13083/repository/files/app%2Fproject%2Erb"
```

[1] https://about.gitlab.com/

System overview



- Identify producer-consumer relationships
- Generate code to parse responses

- Generate tests (state-space exploration)
- Drop invalid requests

Selected evaluation results

- Q1: Do RESTler tests help increase code coverage?
- Q2: Bugs found with RESTler?

Study subject: Gitlab

- Complex backend (> 350 KLOCs; mostly ruby-on-rails)
- Hundrends of API endpoints
- Complex API request payloads

Deeper service exploration (Q1)

API Family	Total API Requests	Seq. Len.	Code Coverage (lines of code)	Tests
Gitlab	15 (*11)	1	598	1
Commits		2	1108	7
		3	1196	250
		4	1760	2220
		…	…	…

Testing APIs with RESTler (5h per API family)

- Longer sequences increase service-side code coverage

Deeper service exploration (Q1)

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- Progress in large search space

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Testing APIs with RESTler (5h per API family)

- ❖ Longer sequences increase service-side code coverage
- ❖ Progress in large search space

Example: Testing for 5 hours

- ➢ **Brute-force**: 741 million sequences
- ➢ **RESTler:** 2220 total test sequences
  - ✓ Producer-consumer request dependencies
  - ✓ Dynamic service feedback

Bugs found with RESTler (Q2)

Gitlab Bug [#50268]

1. Create a gitlab project
2. Create a file with a proper commit message
3. Delete the file with an empty commit message

➢ "500 Internal Server Error"

➢ Found 28 confirmed such bugs in Gitlab in 2018

➢ …and many more in production cloud services

RESTler since 2019

- Uncovered 100s of bugs in production Azure, Bing, and Office365 services
  - Including "*severe critical bugs*[1]"
- Open-sourced at: https://github.com/microsoft/restler-fuzzer
- Multiple teams are using it daily
  - Developer fuzzing
  - Specification correctness
  - Regression testing

[1] https://patricegodefroid.github.io/research-overview.html

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IvySyn: Automated Vulnerability Discovery in DL Frameworks

What

- Find memory safety errors in Deep Learning (DL) frameworks

Why

- Core of DL frameworks is implemented in C/C++
- Past approaches required manual effort and domain knowledge

How: A bottom-up approach

- Find a crash in the native part
- Synthesize python code reproducing the crash

Example

Native (*kernel*) implementation

```
class EditDistanceOp : public OpKernel {
  void Compute(OpKernelContext* ctx) override {
  // ...
  if (g_truth == g_hypothesis) {
  auto loc = std::inner_product(g_truth.begin(),
     g_truth.end(), output_strides.begin(),
     int64_t{0});
  OP_REQUIRES(
      loc < output_elements,
      errors::Internal("..."))
  output_t(loc) =
      gtl::LevenshteinDistance<T>(truth_seq,
        hypothesis_seq, cmp);
  // ...
```

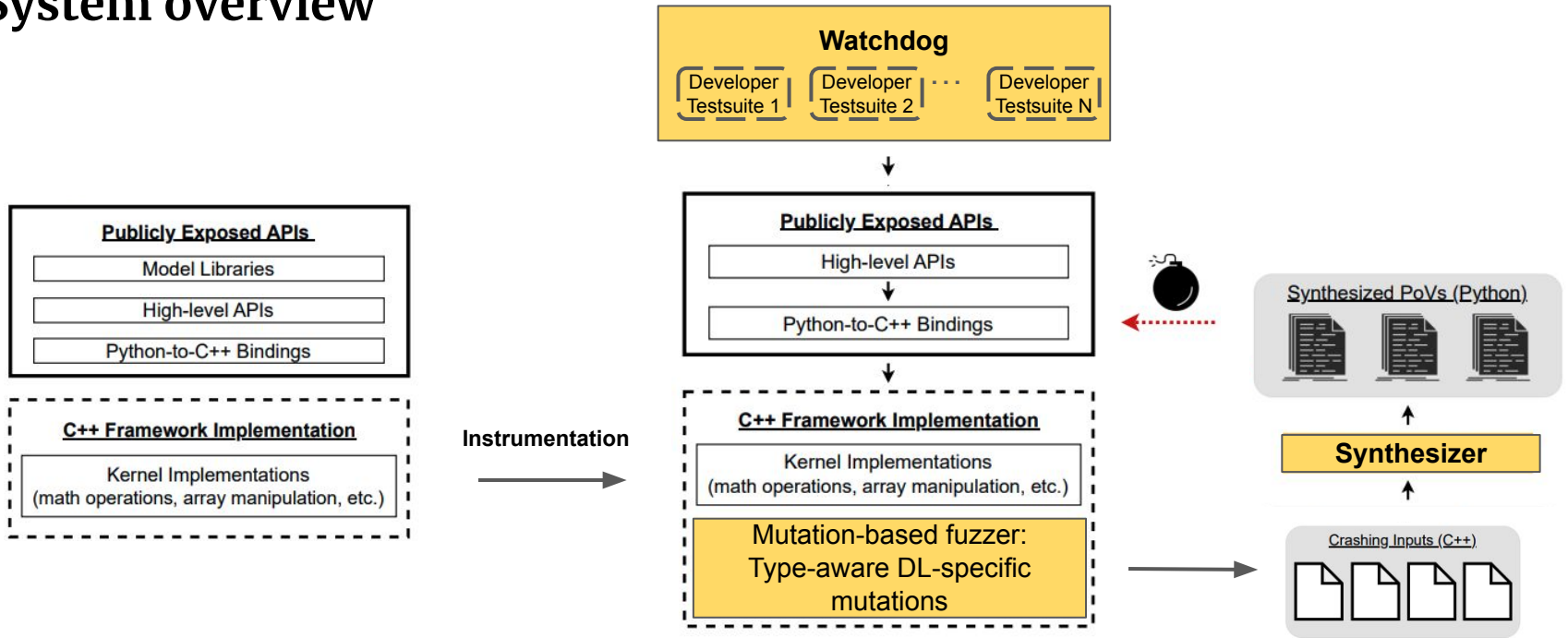
Triggers a crash

from public python APIs

Proof-of-Vulnerability (PoV)

```
hypothesis_indices = tf.constant(-125099896764,
                     shape=[3,3], dtype=tf.int64)
hypothesis_values  = tf.constant(0,
                     shape=[3], dtype=tf.int64)
hypothesis_shape   = tf.constant(0,
                     shape=[3], dtype=tf.int64)
truth_indices      = tf.constant(0,
                     shape=[2,3], dtype=tf.int64)
truth_values       = tf.constant(-1879048192,
                     shape=[2], dtype=tf.int64)
truth_shape        = tf.constant(2,
                     shape=[3], dtype=tf.int64)
tf.raw_ops.EditDistance(
    hypothesis_indices = hypothesis_indices,
    hypothesis_values  = hypothesis_values,
    hypothesis_shape   = hypothesis_shape,
    truth_indices      = truth_indices,
    truth_values       = truth_values,
    truth_shape        = truth_shape)
```

System overview



Selected evaluation results

- Q1: How quickly can IvySyn find crashes?
- Q2: How effective is IvySyn in synthesizing PoVs?

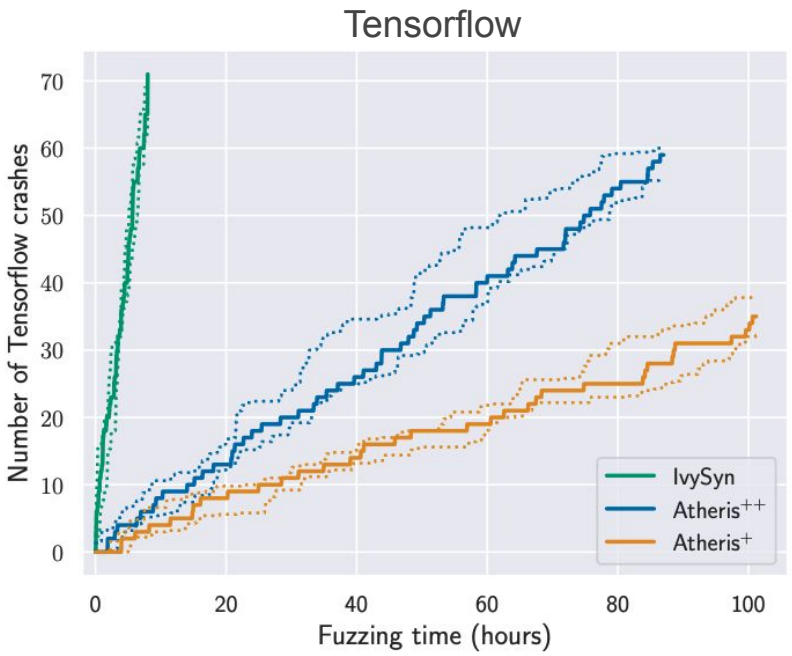
Target Frameworks: *Tensorflow*[1] and *Pytorch*[2]

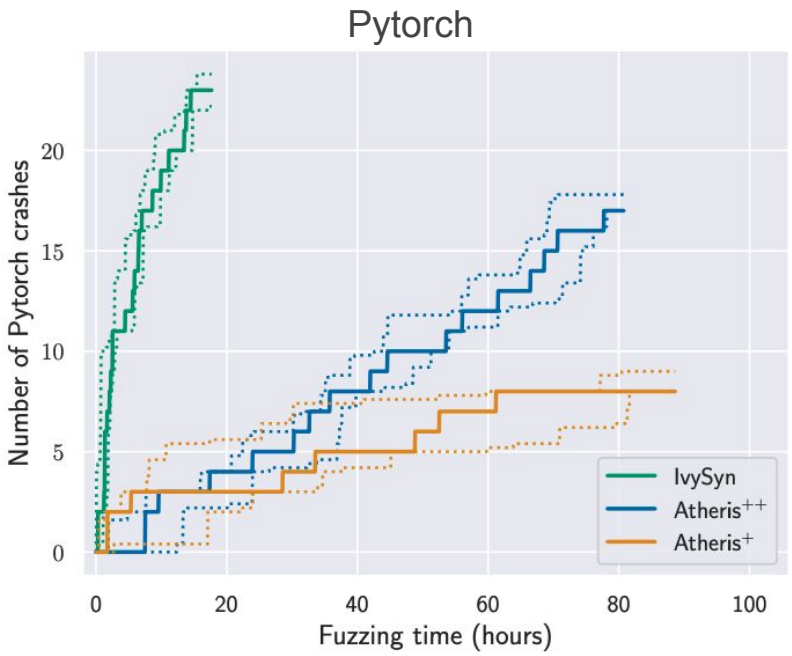
Against Google's *Atheris*[3]

- ***Atheris+***: Default *Atheris* + automation
- **Atheris++**: Default *Atheris* + automation + type-aware
- **IvySyn:** Type-aware + DL-specific mutations

[1] https://www.tensorflow.org/
[2] https://github.com/pytorch/pytorch
[3] https://github.com/google/atheris

Efficiency in finding crashing inputs (Q1)





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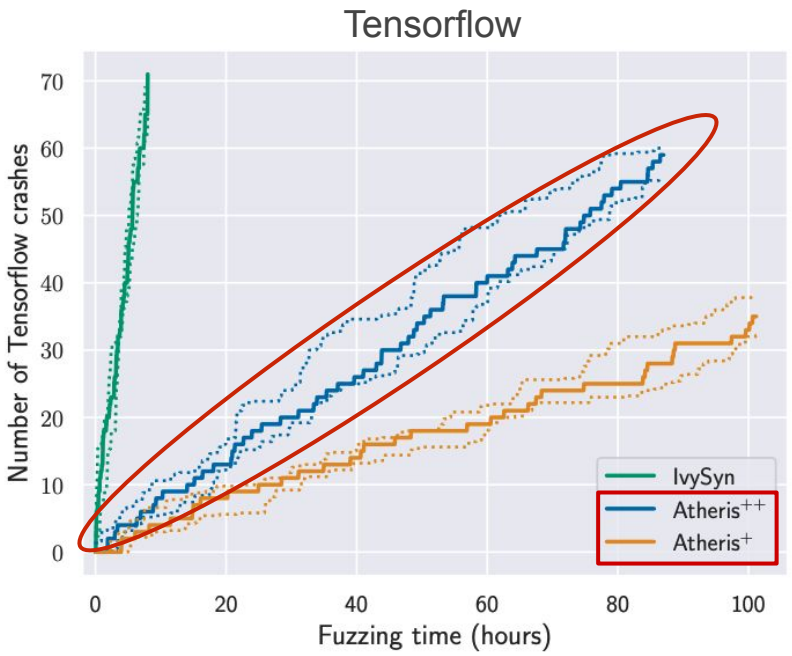

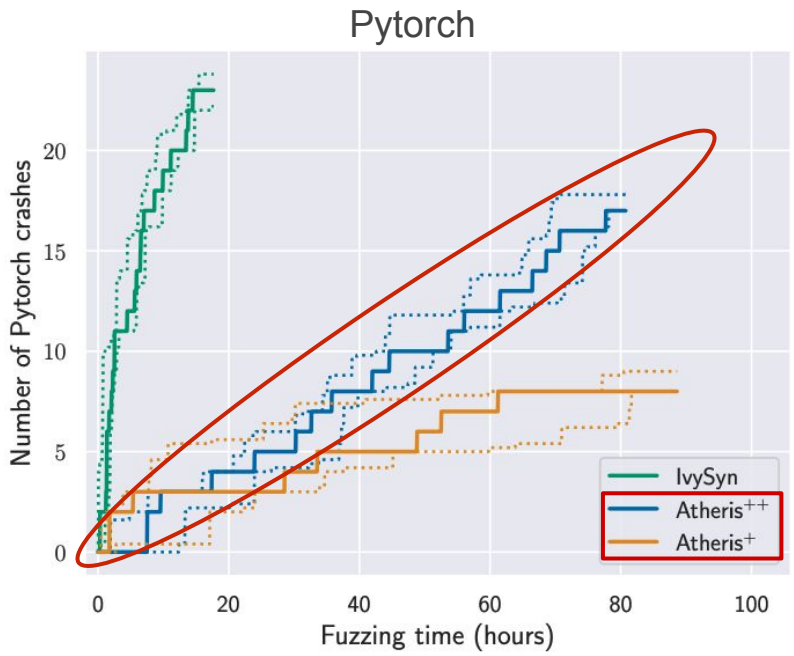

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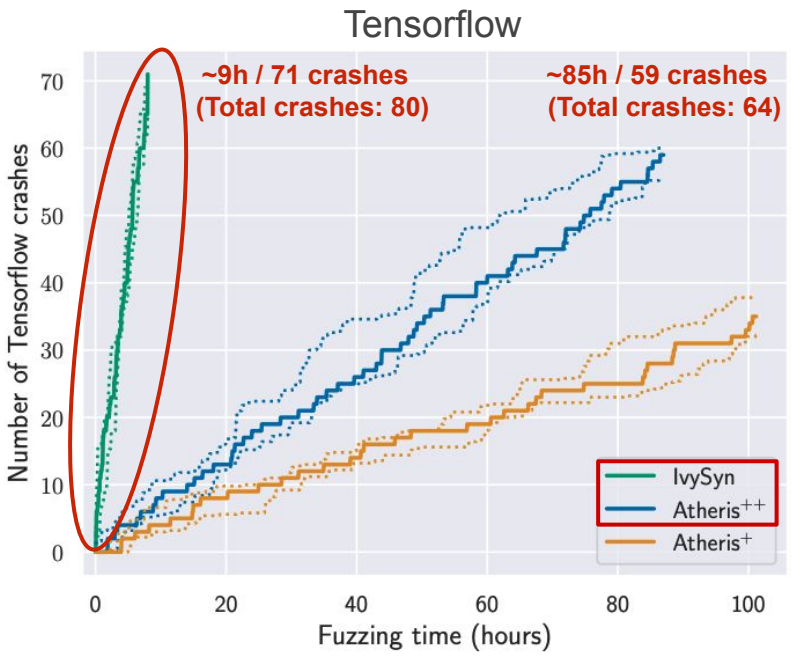

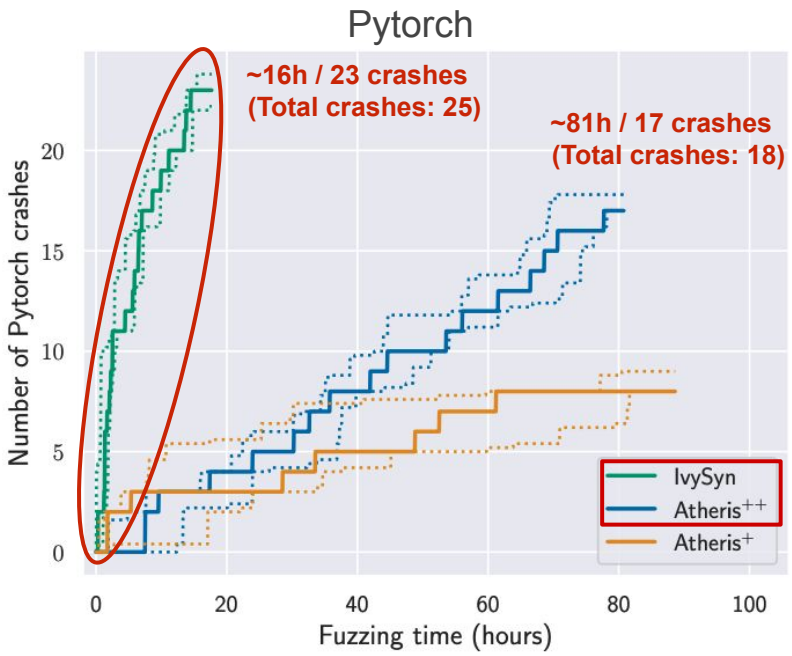

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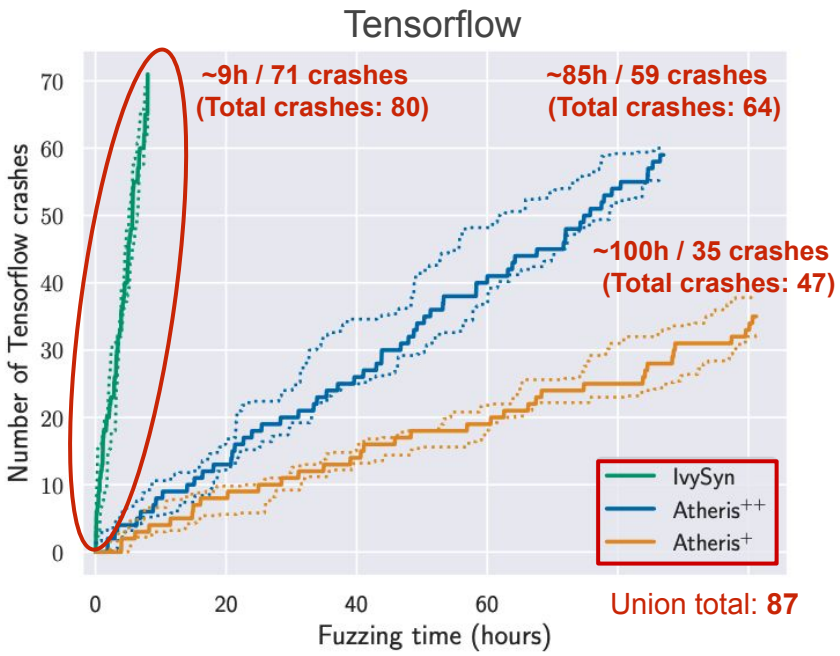

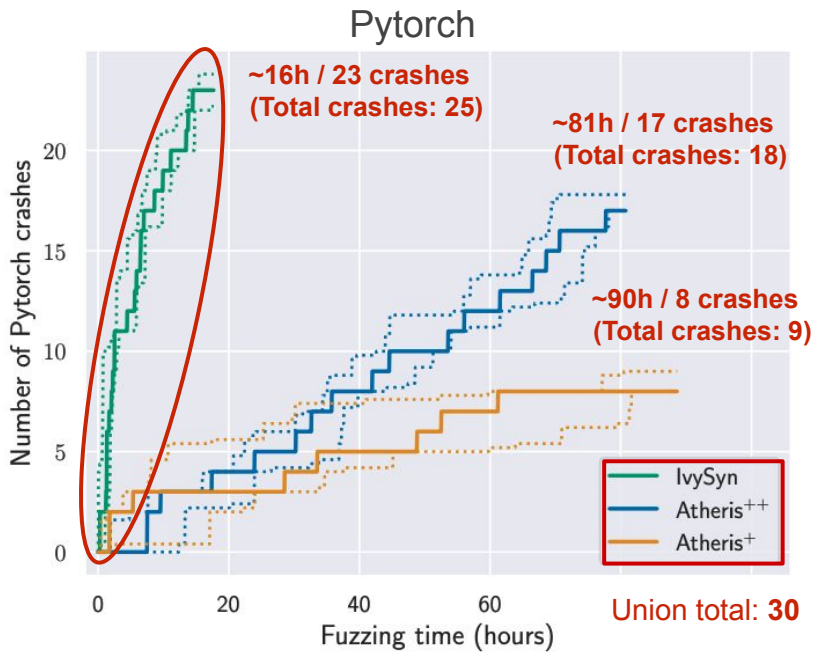

Effectiveness in synthesizing PoVs (Q2)

Framework	Fuzzed Kernels	Unique Crashes	Synthesized PoVs
Tensorflow	412	103	86 / 103 (83%)
Pytorch	747	81	49 / 81 (60%)
All	1159	184	135 / 184 (73%)

- Synthesized 135 PoVs
- Identified 61 previously-unknown vulnerabilities
- Assigned with **39** new CVEs

https://gitlab.com/brown-ssl/ivysyn

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  // ...
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  auto loc = std::inner_product(g_truth.begin(),
     g_truth.end(), output_strides.begin(),
     int64_t{0});
  OP_REQUIRES(
      ctx,
      0 <= loc &&
      loc < output_elements,
      errors::Internal("...")
  output_t(loc) =
      gtl::LevenshteinDistance<T>(truth_seq,
        hypothesis_seq, cmp);
  // ...
```

Automated software testing with blackbox fuzzing

- RESTler [ICSE '19]
  Top-down approach: Start from the APIs
- IvySyn [USENIX SEC '23]
  Bottom-up approach: Start from native implementations

RESTler team: Patrice Godefroid and Marina Polishchuk @ Microft Research

IvySyn team: Neophytos Chrisou, Di Jin, and Vasilions Kemerlis @ Brown University
Baishakhi Ray @ Columbia University