DY Fuzzing:
Putting a Dolev-Yao attacker in the fuzzing loop

Steve Kremer, Inria Nancy, France

Journées du GT MFS 2024

joint work with
Max Ammann (Trail of Bits) & Lucca Hirschi & Tom Gouville & Michaël Mera (Inria)

Secure Cryptographic Protocols

Cryptographic Protocols

Informal definition

concurrent program relying on cryptography to secure communications

Security goals: confidentiality, integrity/authentication, etc.

Examples: TLS, EMV (credit cards), RFID, e-voting, mobile com., etc.

- Notoriously difficult to design and deploy securely
- Loads of failure stories: attacks, fixes, attacks, fixes, attacks, etc.

☞ What can we do today to avoid such failures in the future?

Retrospective of TLS Failures https:// 2014-2022

1: Formally Verifying Cryptographic Protocols Designs

Dolev-Yao Formal **Model**

☞ Formal model for analyzing cryptographic protocols amenable to automation

Threat model 👺:

- active adversary controls the network: **intercept, modify, inject messages**
- is able to **use cryptography**
- cryptography considered **black-box** (attacker's interface = functionality)

  Attacker can use encryption and decryption but does not see the internals (e.g., AES S-box) and cannot exploit potential leaks/biasis

« Messages as formal terms » paradigm: messages model = term algebra

1. Set of function symbols: e.g. $\mathsf{senc}(\,\cdot\,,\cdot\,), \mathsf{sdec}(\,\cdot\,,\cdot\,)$
2. Equivalence relation: e.g. $\mathsf{sdec}(\mathsf{senc}(m, k), k) = m$

Dolev-Yao Formal **Model**

✓ Sweet spot between precision (of results) and automation (verification algorithms)
Excel at finding logical attacks: protocol vulnerabilities at the design-level

Proverif

Tamarin

✗ Limited to specifications, *existing* implementations are out of scope (e.g., OpenSSL)

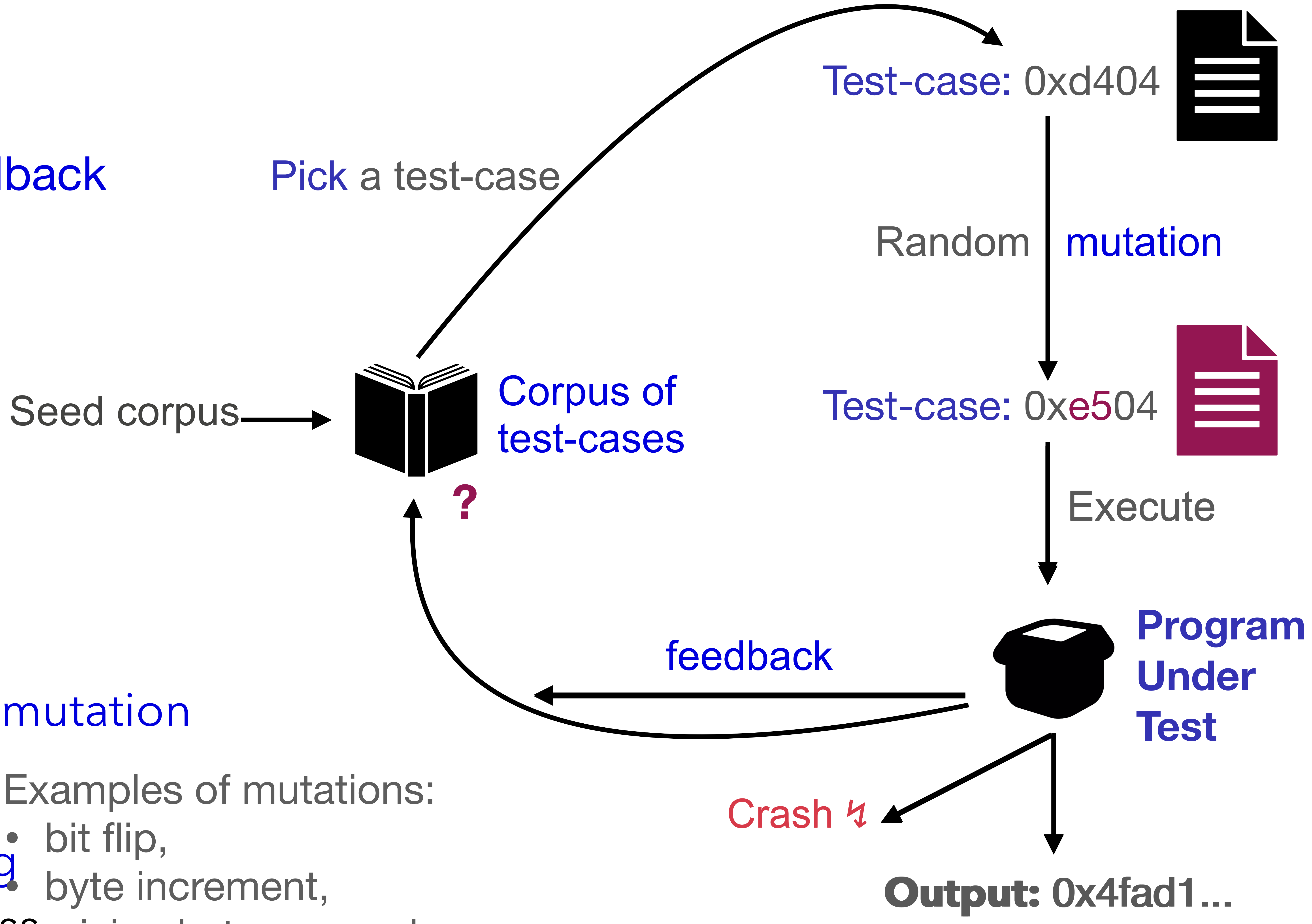
Retrospective of TLS Failures https:// 2014-2022

2: Fuzzing Cryptographic Protocols Implementations —State-of-the-Art

Bit-level fuzzing (AFL-like)

What is fuzzing?

- Instrument the PUT to record feedback (e.g. code coverage)
- Store a corpus of test-cases



- Fuzzing loop: while true do
  - Pick a test-case
  - Apply random transformation = mutation
  - Execute + collect feedback
  - Add it to the corpus if interesting according to feedback = progress (e.g. new coverage)

Examples of mutations:
- bit flip,
- byte increment,
- mixing bytes around

Bit-level fuzzing (AFL-like)

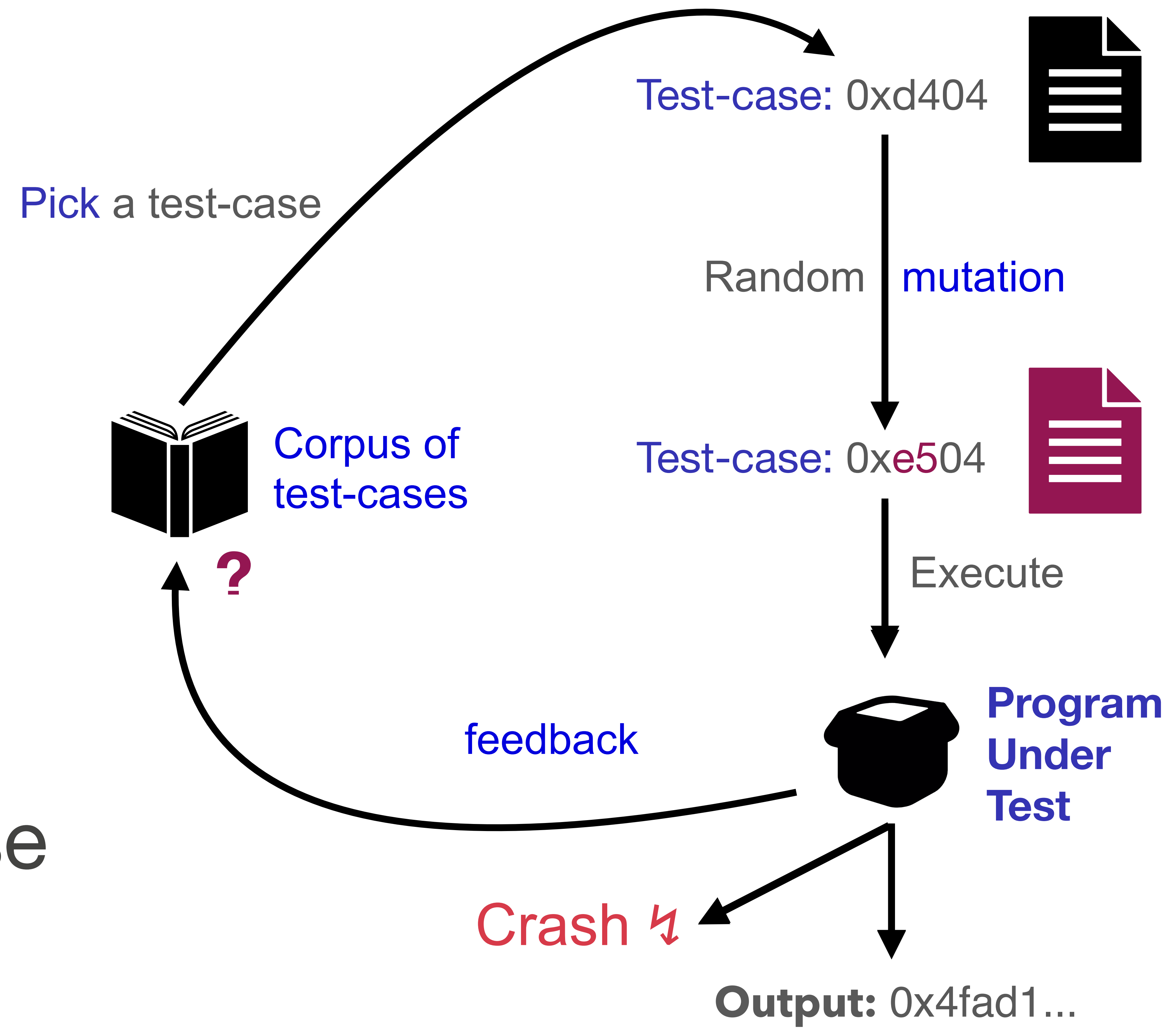
✓ Finds memory/crash vulnerabilities in implementations
E.g. buffer-overflow, use after free, RCE, etc.

✗ Bitstring-level mutations only

- No structural message modification
  e.g. negligible probability of computing a valid signature through bit-level mutations
- No message flow modification
  e.g. protocol executions != one bitstring

☞ logical attack states are **not reached**

☞ + miss some memory vulnerabilities requiring those



✗ Detect crashes only

☞ Protocol vulnerabilities are **not detected**
e.g. authentication bypass (no crash)

Retrospective of TLS Failures https:// 2014-2022

Retrospective of TLS Failures https:// 2014-2022

3: Our proposal: Dolev-Yao Fuzzing

tlspuffin

DY Fuzzing: Formal Dolev-Yao Models Meet Protocol Fuzz Testing

Max Ammann*
Independent Researcher & Trail of Bits
max@maxammann.org

Lucca Hirschi
Inria Nancy Grand-Est
Université de Lorraine, LORIA, France
lucca.hirschi@inria.fr

Steve Kremer
Inria Nancy Grand-Est
Université de Lorraine, LORIA, France
steve.kremer@inria.fr

Paper accepted at IEEE Security and Privacy 2024
Preprint IACR 2023/057

DY Fuzzing Design

DY Fuzzing: Big Picture

DY Fuzzer = DY attacker in a fuzzing loop

- We build on « messages as formal terms »: and assume a term algebra

- Test cases = symbolic traces expressing DY attacker 's actions

tr := out(r, w).tr : r is a role (client/server) and w is a variable (attacker knows)
| in(r, R).tr : R is a term in the term algebra (computed by attacker)
| 0

Example: tr_a=out(cl,w_1).in(serv,w_1).out(serv,w_2).in(cl, senc(sdec(w_2,k_a), k_b)).0

Attacker only relays the message w_1 to serv

Attacker computes a new term R out of w_2 and sends it to cl

DY Fuzzing: Big Picture

DY Fuzzer = MITM DY attacker

Symbolic traces (tr) are « concretized » with the PUT (or any ref. implem.)

1. out(r, w) ☞ call PUT role function to read bitstring b_w from output buffer of r
2. in(r, R) ☞
   a. call ref/PUT crypto functions to evaluate R into a bitstring b_R

      E.g. eval(sign(R',sk)) = RSA_{PUT}(eval(R'),b_{sk})

      eval(w) = b_w

      b_{sk} is obtained by calling $genKey_{PUT}()$

   b. call PUT role function to write b_R onto input buffer of r + make r progress

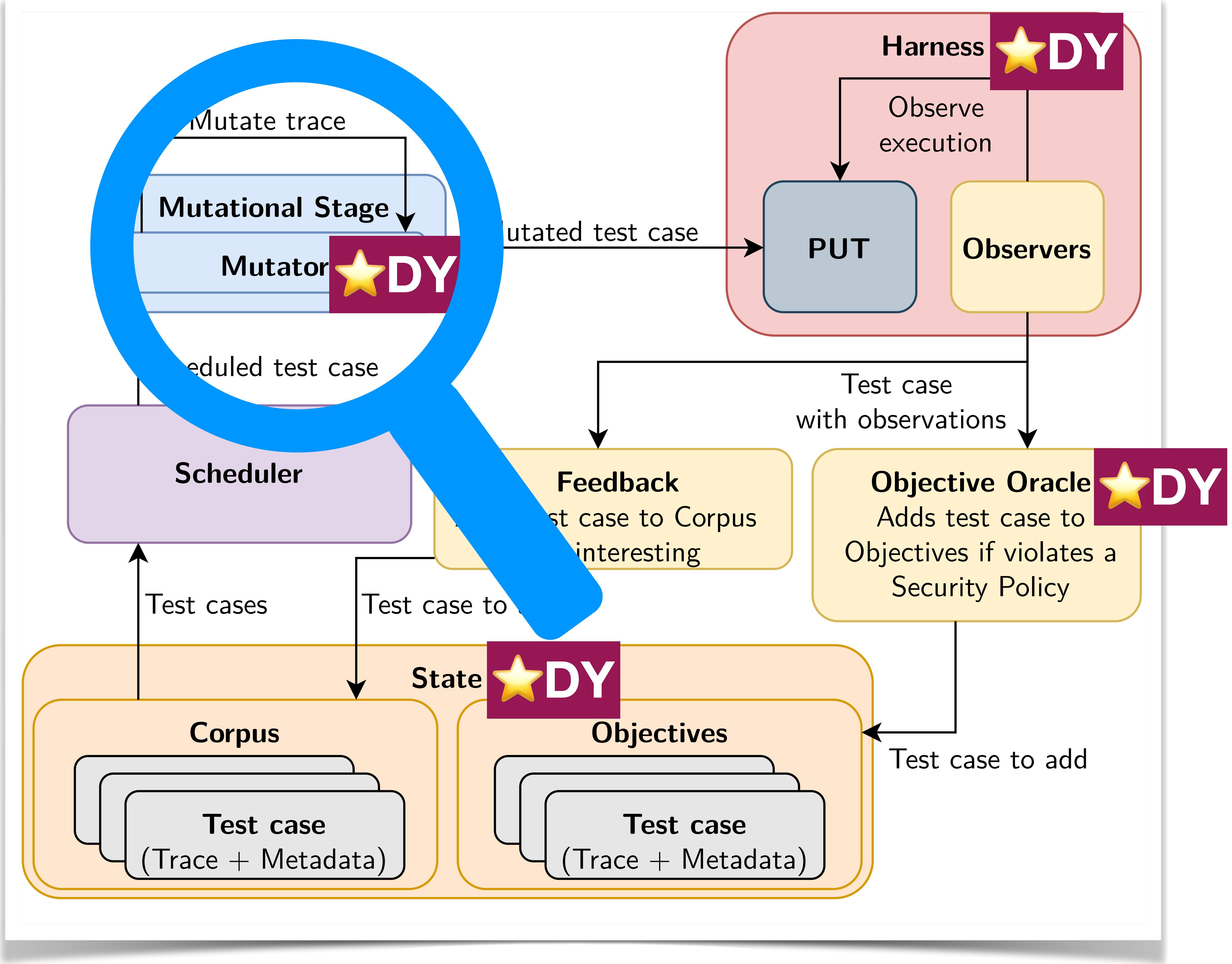
tr := out(r, w).tr
| in(r, R).tr
| 0

Executor (1 + 2.b): require a lightweight instrumentation of the PUT
Mapper (2.a): requires a per-protocol « executable term-algebra »

☞ Do **not** require a protocol DY model but only a DY attacker model (*i.e.*, term algebra)

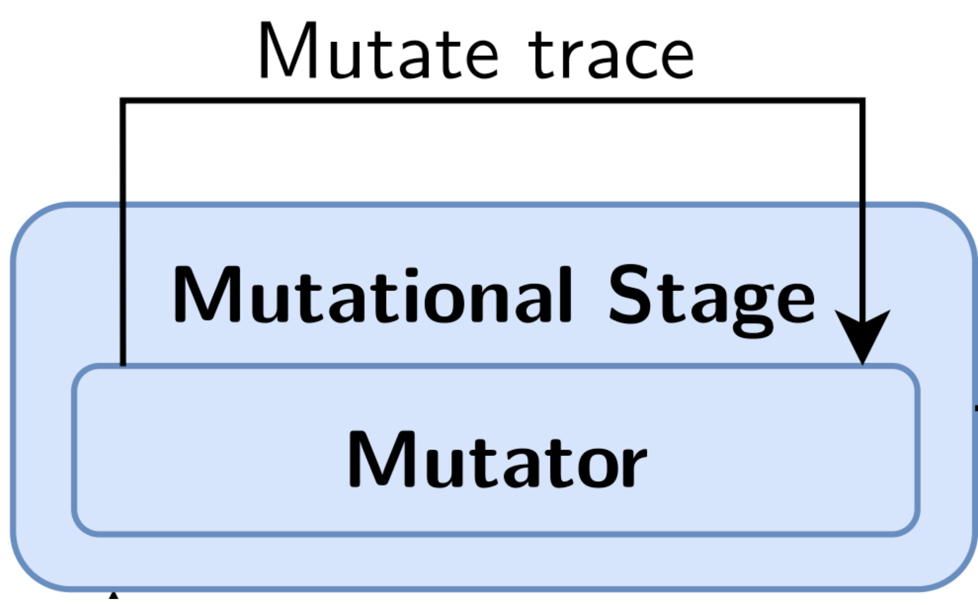
DY Fuzzer components

- State⭐: test-cases = DY traces,
  seeds corpus = happy flows
- Scheduler: FIFO
- Mutator⭐: custom trace mutations
- Harness⭐: Mapper + Executor + Claims
- Obj. Oracle⭐: DY security properties⭐ (e.g. agreement) + ASAN (memory vulns.)
- Feedback: PUT code-coverage



LibAFL components (we build on)

DY mutations



$$
\begin{aligned}
tr :=\ & out(r, w).tr \\
|\ & in(r, R).tr \\
|\ & 0
\end{aligned}
$$

Action-level Mutations

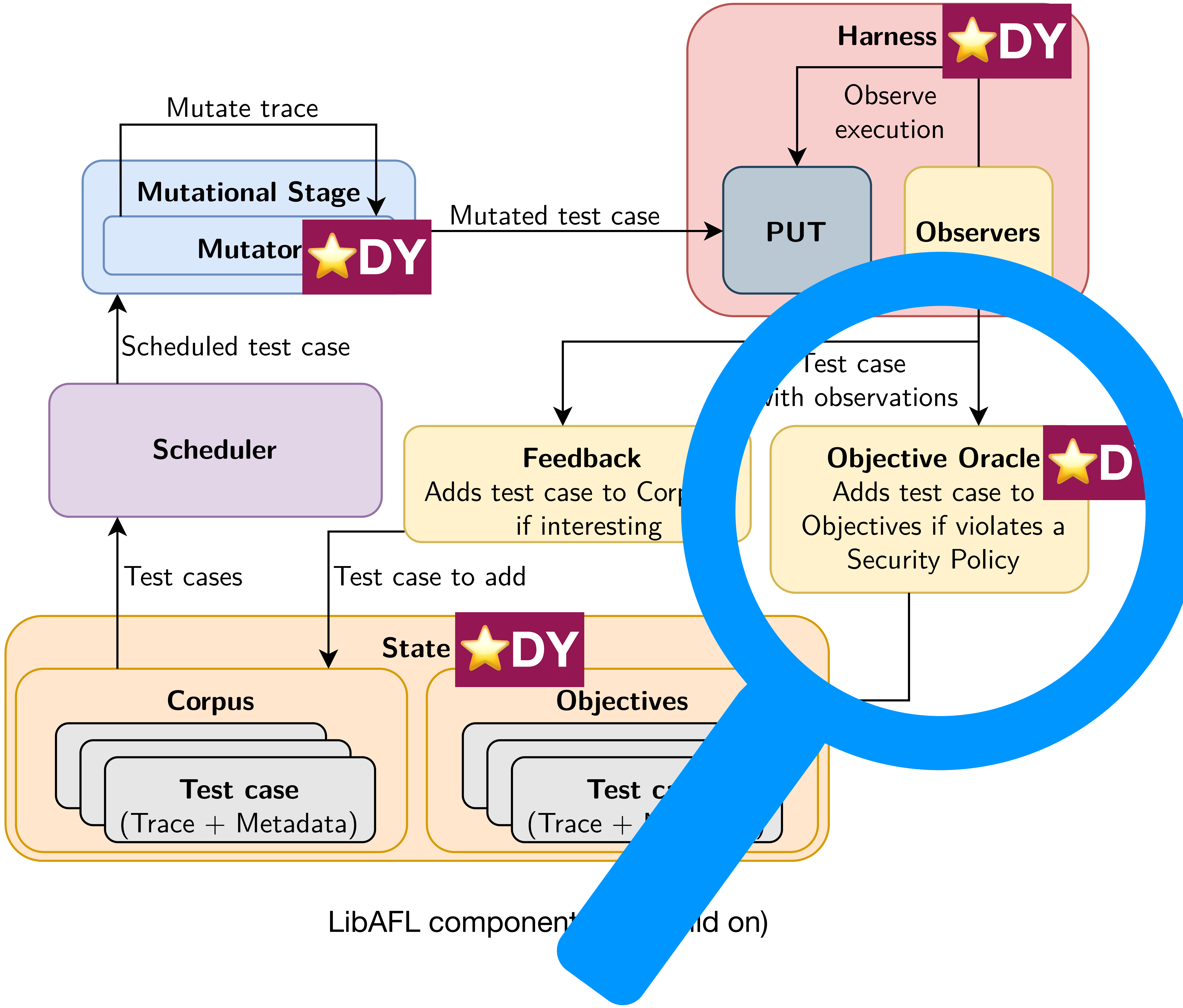
- Skip: remove random action (in/out)
- Repeat: randomly copy and insert an action

Term-level Mutations⭐

- Swap: Swap two (sub-)terms in the trace
- Generate: Replace a term by a random one
- Replace-Match: Swap two function symbols in the trace (e.g. SHA2 <-> SHA3)
- Replace-Reuse: Replace a (sub-)term by another (sub-)term in the trace
- Replace-and-Lift: Replace a (sub-)term by one of its sub-terms

DY Fuzzer components

- State⭐: test-cases = DY traces,
  seeds corpus = happy flows
- Scheduler: FIFO
- Mutator⭐: custom trace mutations
- Harness⭐: Mapper + Executor + Claims
- Obj. Oracle⭐: DY security properties⭐ (e.g. agreement) + ASAN (memory vulns.)
- Feedback: PUT code-coverage



DY Objective Oracle

Objective Oracle
Adds test case to Objectives if violates a Security Policy

Memory-related objective oracle

- Classical with bit-level fuzzing: code instrumentation with AddressSanitizer (*ASan*)

+

DY Security properties ⭐

- Introduce claims triggered by roles executing the PUT (part of Harness/Executor)
  E.g. agreement claims: Agr(client, pk, m)@i client believes to have agreed with server with pk on m @ i^{th} action
- Classical in DY models: security properties expressed as 1^{st}-order formula
  E.g. agreement property $\forall pk, m$: Agr(client, pk, m)@i $\Rightarrow$ Run(server, pk, m)@j $\wedge$ j<i
- DY Objective oracle also checks DY security properties
  - Gather all the claims throughout traces executions at the PUT
  - Check all the DY security properties (where terms are concretized into bitstrings)

tlspuffin Implementation

tlspuffin: a full-fledge DY fuzzer

- Open-source project written in Rust (16k LoC) (tlspuffin on Github)
- Built on LibAFL, a modular library to build fuzzers (+ new/custom components⭐)
- In-memory buffers, delightfully parallel, fast (700 execs/s/core)
- Modular: new protocol and new PUTs can be added
- For TLS: 189 function symbols, harnessed PUTs: OpenSSL, WolfSSL, BoringSSL, LibreSSL

tlspuffin Results

tlspuffin findings 👺

- We selected a small benchmark suite: recent logical attacks found on OpenSSL (most used) and WolfSSL (IoT)
- Found by tlspuffin in hours or seconds (SKIP), systematic reproducibility!
- We ran fuzzing campaigns on the harnessed PUTs and found 5 new CVEs
  ☞Not found by other fuzzers

CVE ID	AKA	CVSS	Type	New	Version	TLS
2021-3449	**SDOS1**	5.9	Server DoS, M	✗	1.1.1j	1.2
2022-25638	**SIG**	6.5	Auth. Bypass, P	✗	5.1.0	1.3
2022-25640	**SKIP**	7.5	Auth. Bypass, P	✗	5.1.0	1.3
2022-38152	**SDOS2**	7.5	Client DoS, M	✓	5.4.0	1.3
2022-38153	**CDOS**	5.9	Server DoS, M	✓	5.3.0	1.2
`2022-39173	**BUF**	7.5	Server DoS, M	✓	5.5.0	1.3
2022-42905	**HEAP**	9.1	Info. Leak, M	✓	5.5.0	1.3
2023-6936	**HEAP2**	N/A	Info. Leak, M	✓	5.6.5	1.3

Root causes of CVE-2022-39173 (WolfSSL, CVSS high)

1. Attacker acting as client performs a full TLS handshake, establishing a Pre-Shared-Key (PSK)
2. Forges a malicious ClientHello([c;..;c]) message such that
   (a) it **resumes previous session with PSK** (**needs to apply decrypt, hash, signature)** and
   (b) It has as list of supported cipher suites with **duplicates of** c (say n times)

☞ Server calls refineSuites to update suitesS (ciphers offered both by client and server) bc. of **resumption**

☞ **Flaw 1**: **actually** computes « multiset-intersection » so suitesS will contain **duplicates of** c (say k times)

Root causes of CVE-2022-39173 (WolfSSL, CVSS high)

1. Attacker acting as client performs a full TLS handshake, establishing a Pre-Shared-Key (PSK)
2. Forges a malicious ClientHello([c;..;c]) message such that
   (a) it **resumes previous session with PSK (needs to apply decrypt, hash, signature)** and
   (b) It has as list of supported cipher suites with **duplicates of** c (say n times)

☞ Server calls refineSuites to update suitesS (ciphers offered both by client and server) bc. of **resumption**

☞ **Flaw 1**: **actually** computes « multiset-intersection » so suitesS will contain **duplicates of** c (say k times)

How WolfSSL implements ∩ with refineSuites(suitesC)@tls13.c:4355

```
// suitesS initially with offered suites, MAX_SZ allocated
byte suites[MAX_SZ]; int suiteSz = 0; // supposed to compute suitesS ∩ suitesC

for (i = 0; i < suitesS.size; i += 1) {
      for (j = 0; j < suitesC.size; j += 1) {    // suitesC.size <= MAX_SZ
            if (suitesS->suites[i] == suitesC->suites[j]) {
                suites[suiteSz++] = suitesC->suites[j]; } } }
XMEMCPY(suitesS, &suites, sizeof(suites));
```

Root causes of CVE-2022-39173 (WolfSSL, CVSS high)

1. Attacker acting as client performs a full TLS handshake, establishing a Pre-Shared-Key (PSK)
2. Forges a malicious ClientHello([c;..;c]) message such that

   (a) it **resumes previous session with PSK (needs to apply decrypt, hash, signature)** and

   (b) It has as list of supported cipher suites with **duplicates of** c (say n times)

☞ Server calls refineSuites to update suitesS (ciphers offered both by client and server) bc. of **resumption**

☞ **Flaw 1**: **actually** computes « multiset-intersection » so suitesS will contain **duplicates of** c (say k times)

☞ No big deal because suitesS initially had no duplicate so: $k = n \leq |suitesC| \leq MAX\_SZ = 150$

   (c) Is **ill-formed** and **will be rejected but *late*** (after call to refineSuites), mess with supportGroupExtension

☞ Server rejects it and sends a HelloRetryRequest but

☞ **Flaw 2**: **side-effects** of refineSuites **are not reverted**

☞ **From now on,** refineSuites invariant is broken: suitesS contains n duplicates of c

3. Send ClientHello([c;..;c]) again, refineSuites is called again, the resulting buffer suites that contains $k^2 = n^2$ ciphers c is copied into suitesS

☞ For n = 13, we already overwrite the suitesS buffer allocated on MAX_ciphers_list_length = 150

Root causes of CVE-2022-39173 (WolfSSL, CVSS high)

An overflow on the stack of max 44700 bytes (controlled by n so is attacker 👺-controlled).

- ☞ **Therefore, large portions of the stack can get overwritten, including return addresses (confirmed)**
- ☞ **Potential RCE (unconfirmed)**
- ☞ **Potential for negotiating ciphers that server should reject (downgrade)**

(c) is **ill-formed** and **will be rejected but *late*** (after call to refineSuites), mess with supportGroupExtension

☞ Server rejects it and sends a HelloRetryRequest but

☞ **Flaw 2: side-effects** of refineSuites **are not reverted**

☞ **From now on,** refineSuites invariant is broken: suitesS contains n duplicates of c

3. Send ClientHello([c;..;c]) again, refineSuites is called again, the resulting buffer suites that contains $k^2 = n^2$ ciphers c is copied into suitesS

☞ For n = 13, we already overwrite the suitesS buffer allocated on MAX_ciphers_list_length = 150

DY Fuzzing Future Work

Future Work - Evaluation

- tlspuffin always found the new CVEs
- state-of-the art competitive fuzzers never found any of them

We can explain this with qualitative evidences but quantitative evidences are hard to obtain

- **Code-coverage** is a poor metric and prone to exhaustion

A statement reached from an attack state is similarly counted as if reached from the happy flow

E.g. client accepting a legitimate server's certificate $\sim_{coverage}$ *accepting illegitimate cert.*

☞ Need for a domain-specific DY-based notion of coverage + balance with code-cov.

Future Work (cont.)

Improved objective oracle

- Differential fuzzing: save t as objective when WolfSSL(t) ≉ OpenSSL(t)
- Or extend the oracle: +properties & +compromise scenarios

[WIP] Combine DY fuzzing with bit-level fuzzing (WIP): reach « deep states » with DY attacker and then smash the PUT with some bit-level mutations

Apply DY fuzzing to more protocols (e.g. WPA2, TelCo) and PUTs

Long-Term :

- (Partially) Automate Mapper and Harness → PUT-agnostic DY fuzzer
- Connect further with DY verifiers (ProVerif, Tamarin)

Summary of Contributions

1. A new approach to fuzzing cryptographic protocols
   connecting the DY formal approach with fuzzing
   → captures for the first time the class of logical attacks / DY attacker

2. DY Fuzzing design specification

3. tlspuffin: full-fledged, modular, efficient DY fuzzer implementation for TLS

4. Evaluate tlspuffin on TLS libraries:

   - (re)found 8 vulnerabilities
   - including 5 new ones (incl. 1 critical & 2 high)

Paper will appear at IEEE S&P 2024
Preprint IACR 2023/057

DY Fuzzing: Formal Dolev-Yao Models Meet Protocol Fuzz Testing

Max Ammann[*]
Independent Researcher &
Trail of Bits
max@maxammann.org

Lucca Hirschi
Inria Nancy Grand-Est
Université de Lorraine, LORIA, France
lucca.hirschi@inria.fr

Steve Kremer
Inria Nancy Grand-Est
Université de Lorraine, LORIA, France
steve.kremer@inria.fr

v1.0[†] — January 18, 2023

Project ANR JCJC
→ Looking for students/postdocs/engineers

AAPG2022	PROTOFUZZ		JCJC
Coordinated by	Lucca Hirschi	36 months	280 805€
Axe E.1 : Fondements du numérique : informatique, automatique, traitement du signal			

PROTOFUZZ: Cryptographic Protocol Logic Fuzz Testing
Formal Verification Meets Fuzz Testing
Consortium: PESTO (Inria Nancy)