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ResolverFuzz: Automated Discovery of DNS Resolver Vulnerabilities with Query-Response Fuzzing

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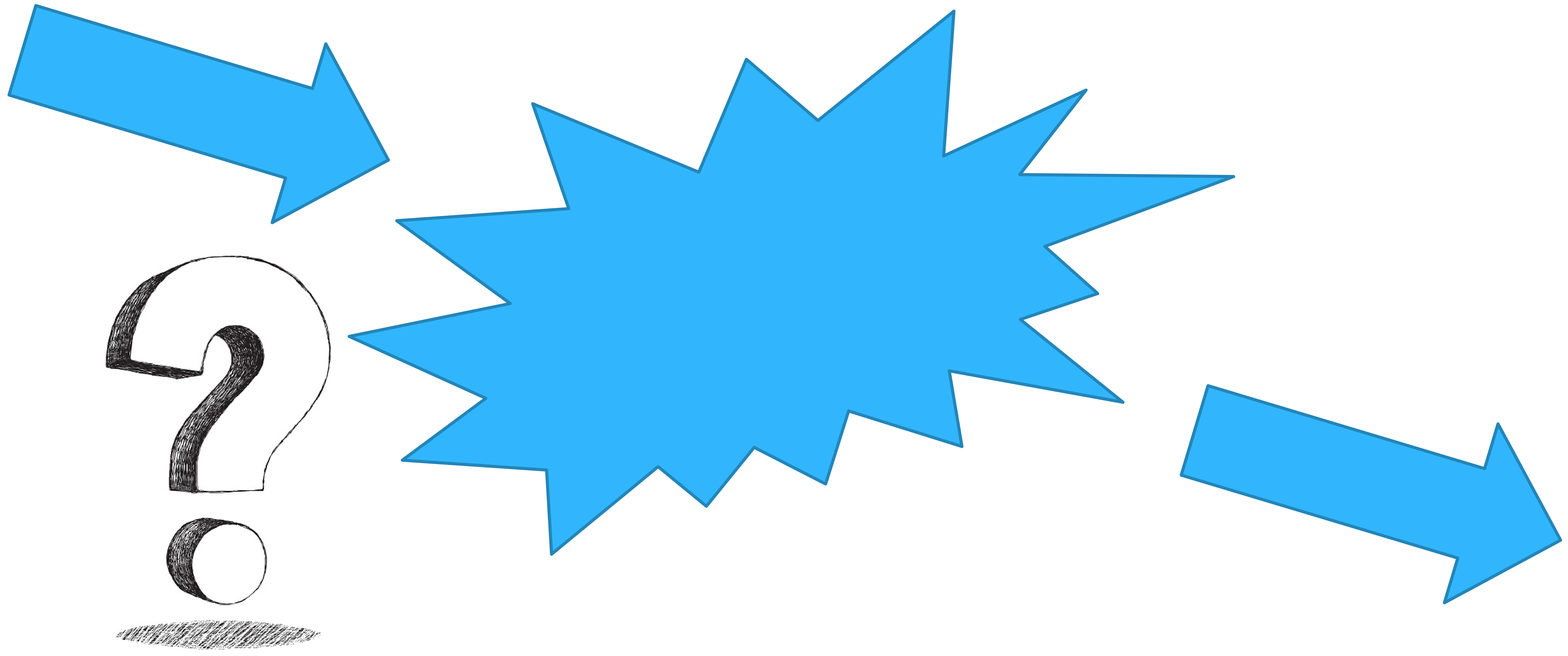
Domain Name System

What is the IP address of the domain uci.edu?

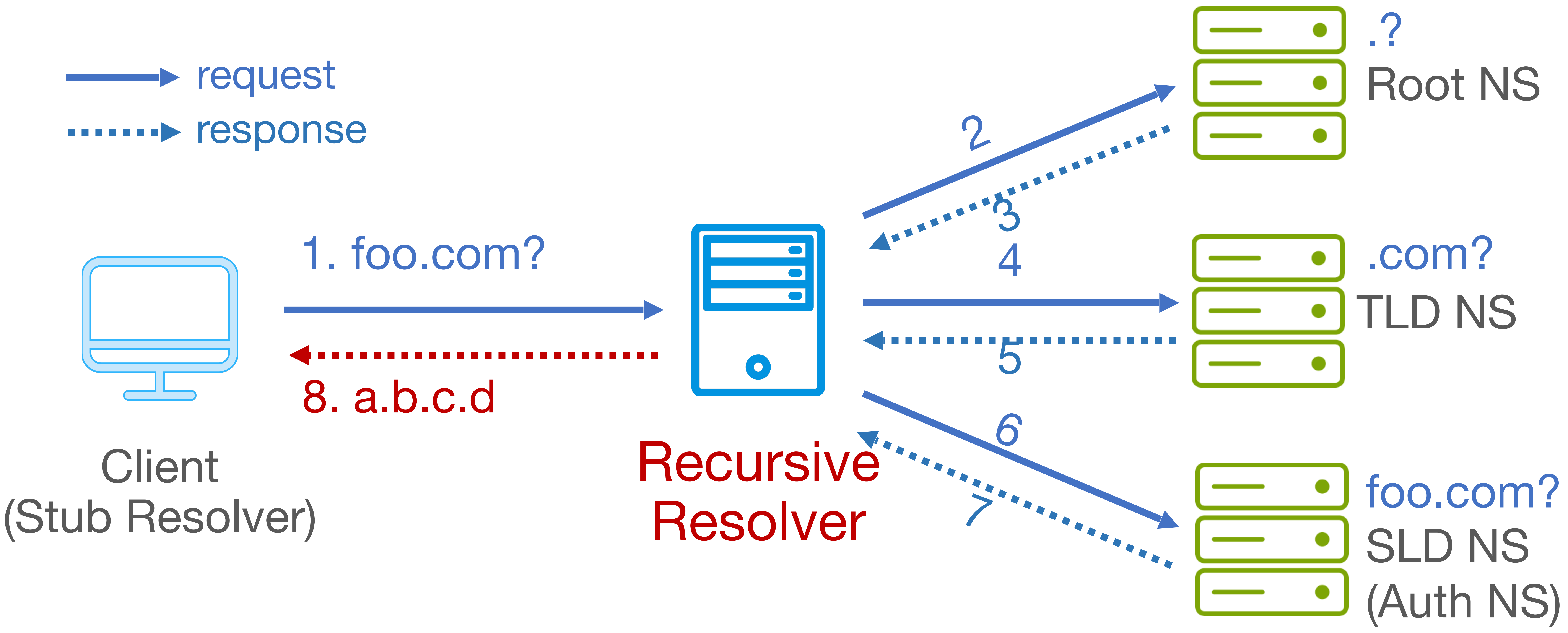


It’s 44.237.37.40!

Under the Hood

NS: Name Server

DNS Infrastructure



DNS Failures & Attacks Happened a Lot

Help Net Security
October 26, 2021
Share

72% of organizations hit by DNS attacks in the past year

Unpatched DNS Bug Puts Millions of Routers, IoT Devices at Risk

MASQUERADE PARTY —

DNS cache poisoning, the Internet attack from 2008, is back from the dead

A newly found side channel in a widely used protocol lets attackers spoof domains.

DAN GOODIN - 11/12/2020, 6:30 AM

Facebook outage was a series of unfortunate events

A badly written command, a buggy audit tool, a DNS system that hobbled efforts to restore the network, and tight data-center security all contributed to Facebook's seven-hour Dumpster fire.

By Tim Greene
Executive Editor, Network World | OCT 5, 2021 6:25 PM PDT

timeouts
bad certs
intermittent API failures
mystery service errors
Wait, it's all DNS ?
Always has been
imgflip.com

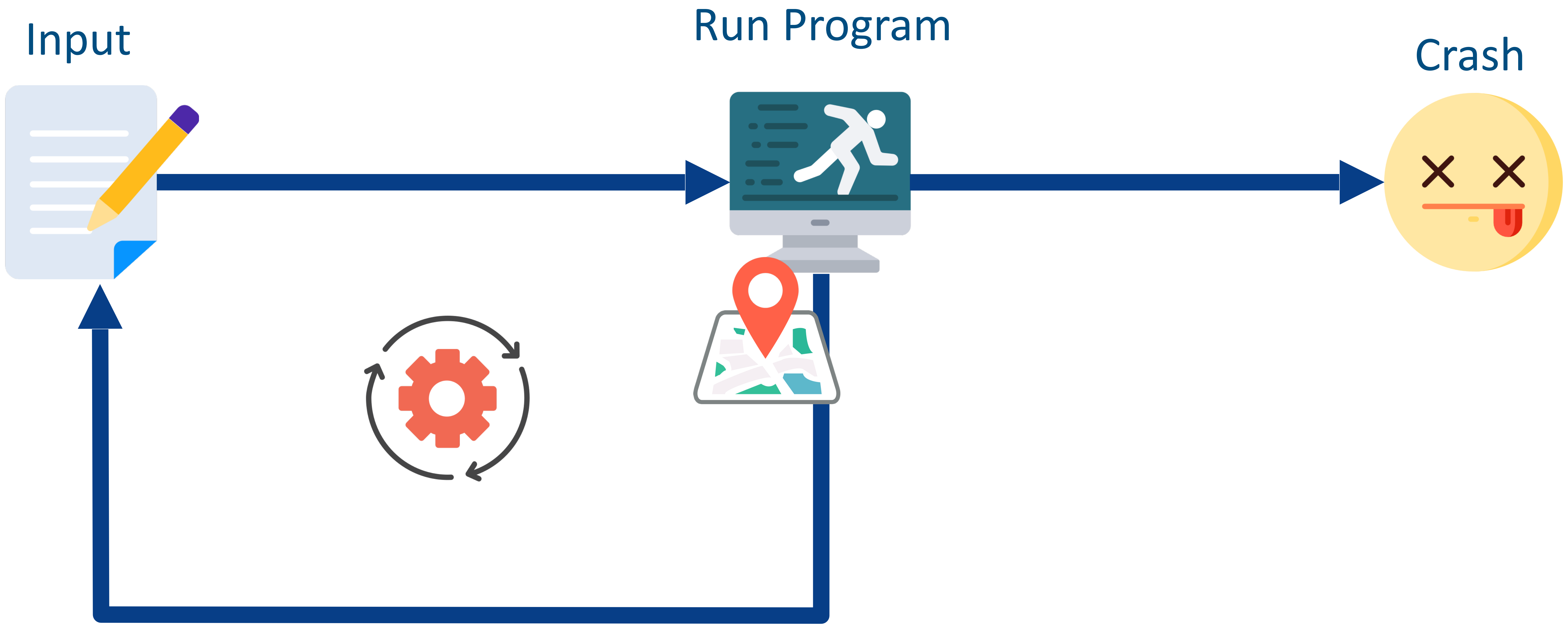
Previous Works

- Existing Attacks
  - SADDNS [CCS’21&20], Kashpureff Attack [1997]
    - Lack of **automated, large-scale** vulnerability analysis
- Automated vulnerability analysis
  - Formal Analysis: Liu and Duan et al. [SIGCOMM’23], SCALE [NDSI’22], GRoot [SIGCOMM’20]
  - Fuzzing: dns-fuzz-server (GitHub repo), DNS fuzzer (GitHub repo) and SnapFuzz [ISSTA’22]
    - Focus mostly on Auth NS, **no recursive resolver**
    - Lack of analysis on **real-world** DNS resolver implementations
    - Not specially tailored to DNS resolvers

No one has ever done
effective automated analysis on
DNS resolvers before!

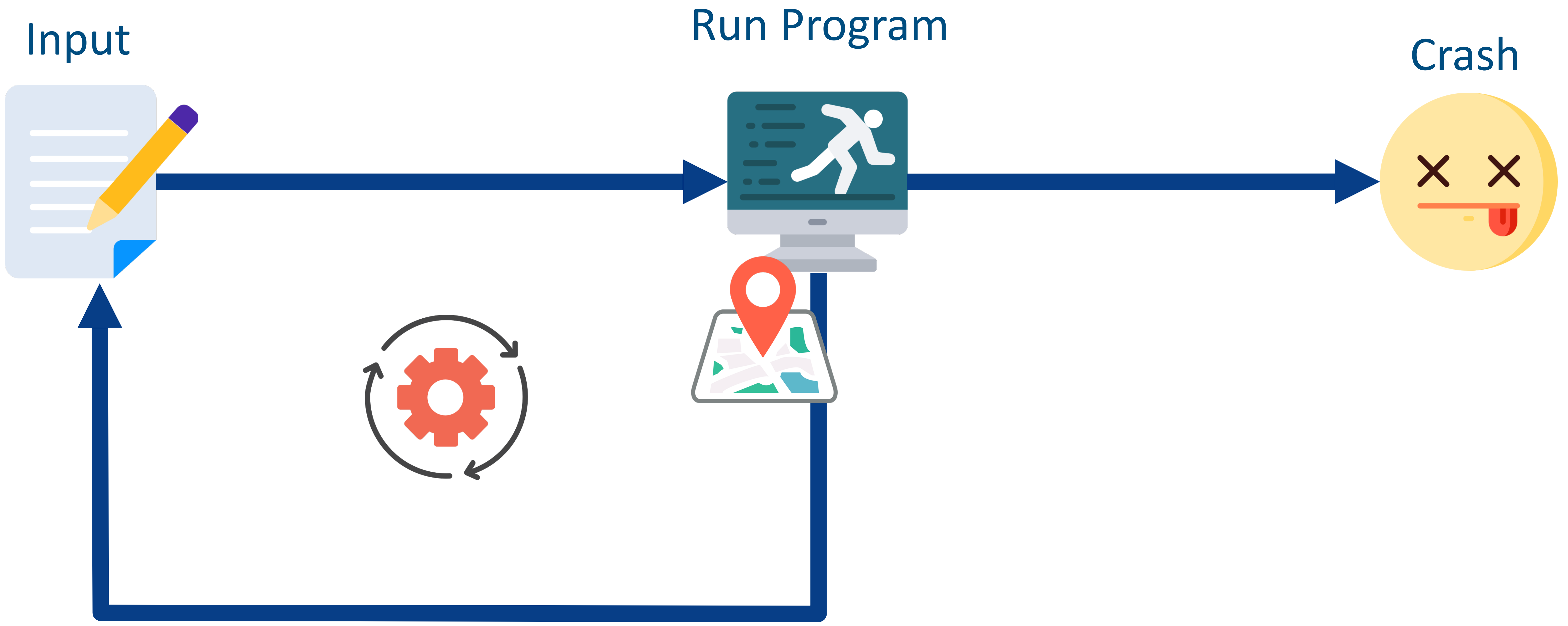
Fuzzing: Automated (Fuzz) Testing

- Coverage-based grey-box fuzzing, e.g., AFL



What are the challenges to fuzz DNS ?

Challenge 1: Non-crash Bugs



DNS Bugs:
- Cache poisoning
- Denial-of-service
- Access violation

Not always crash!

Which part is more vulnerable? Where should we focus on?

Check vulnerabilities which **have been** identified

Focus on where they were **most** spotted

DNS CVEs

- Manual analysis of *423* DNS CVEs from 1999-2023
  - *291* CVEs about 6 DNS software
    - *245* CVEs about DNS resolvers
      - *109* CVEs don't trigger any crash!
      - *93* crash CVEs are non-memory (e.g., assertion failures)

Software*	# CVE							
	Non-crash				Crash			Total
	Cache Poisoning	Resource Consum.[1]	Others[2]	Total	Non-memory	Memory	Total	
BIND	18	18	11	47	75	22	97	144
Unbound	4	5	4	13	5	8	13	26
Knot Resolver	6	4	0	10	2	0	2	12
PowerDNS Recursor	13	8	9	30	7	6	13	43
MaraDNS	2	3	0	5	4	7	11	16
Technitium	3	1	0	4	0	0	0	4
Total	46	39	24	109	93	43	136	245

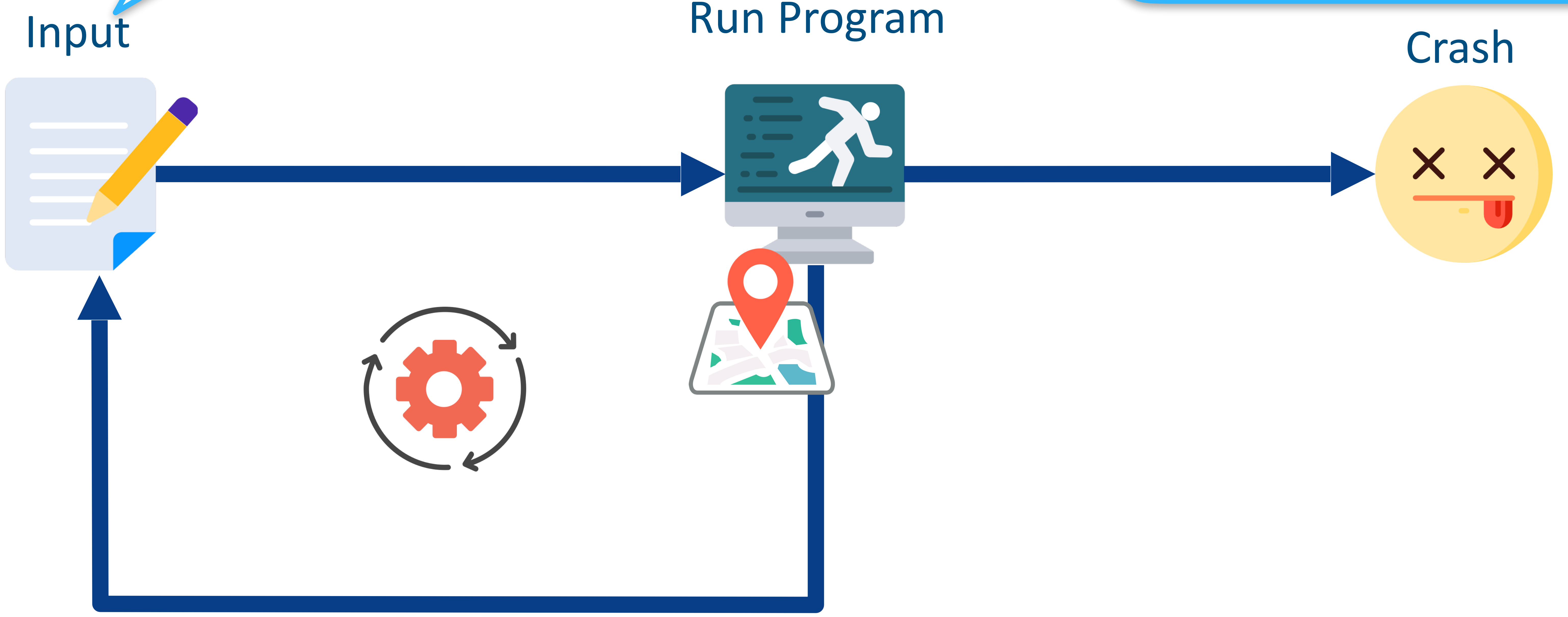
Challenge 2: Stateful Fuzzing

Standard fuzzing:

+ Stateless (1 input per round)

DNS:

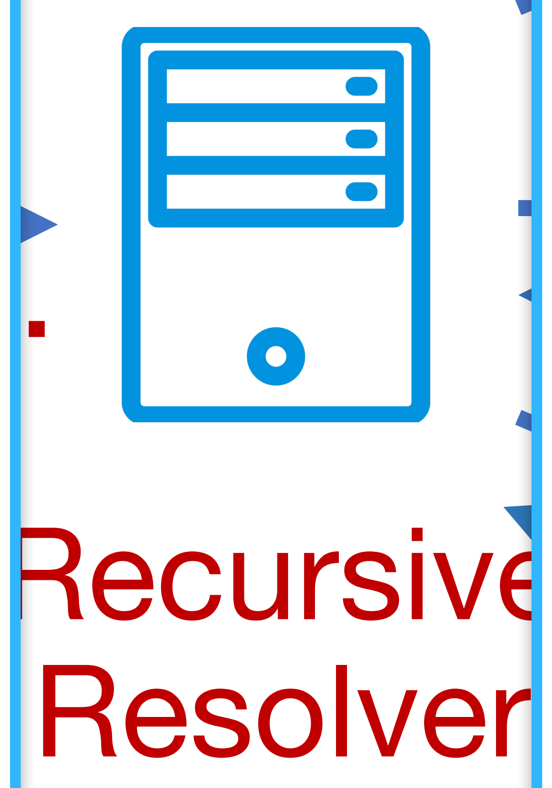
+ Stateful at resolver
+ Multi-party (client, resolver, name server)



Stateless Fuzzing v.s. Stateful Resolver

Response without query

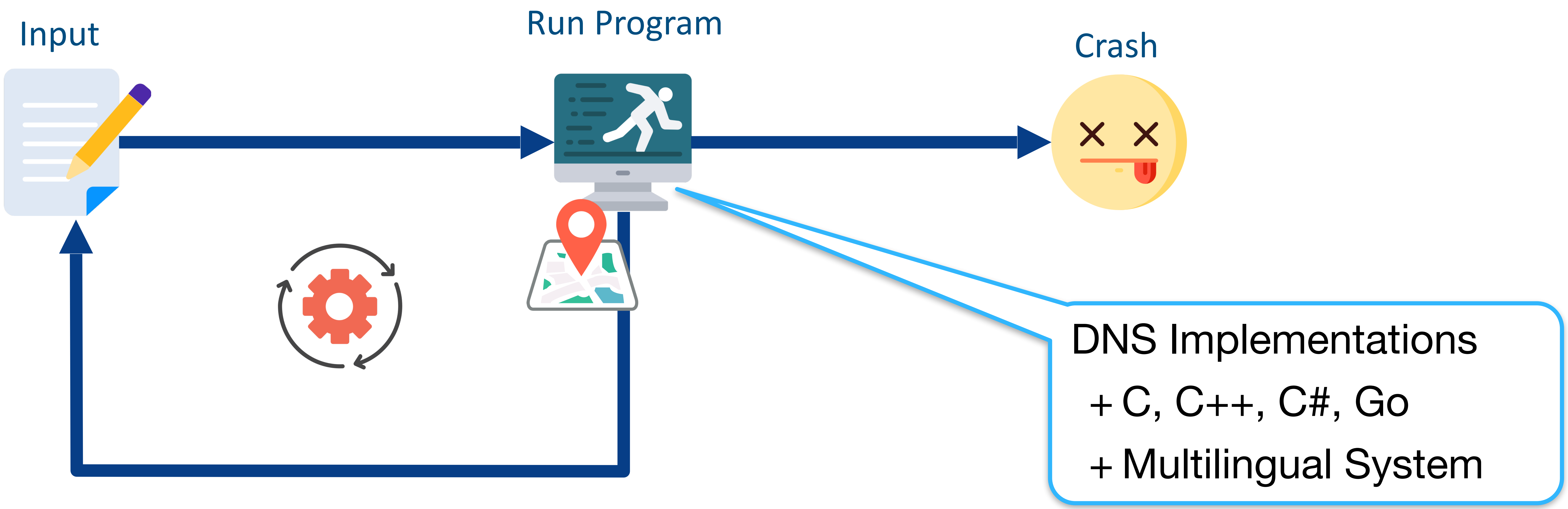
CVE-2021-25220:
+ Bogus NS response
+ Cache poisoning



Query without response

CVE-2022-3924:
+ Many recursive queries
+ Stale option enabled
+ Race condition & crash

Challenge 3: Multilingual System



How should we design ResolverFuzz?

Black-box, **Stateful** and **Grammar**-based fuzzing

Two input generators

Identify different vulnerabilities by different **oracles**

ResolverFuzz Workflow

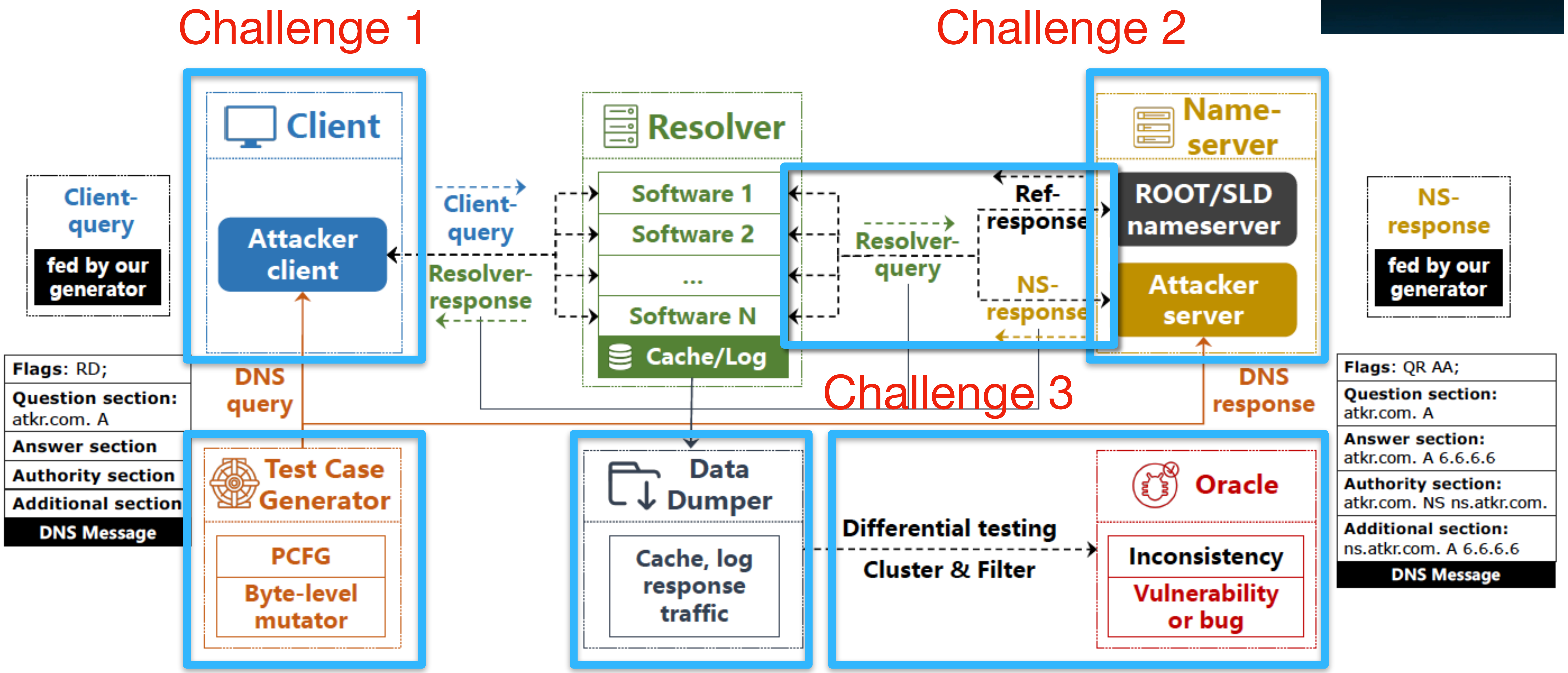


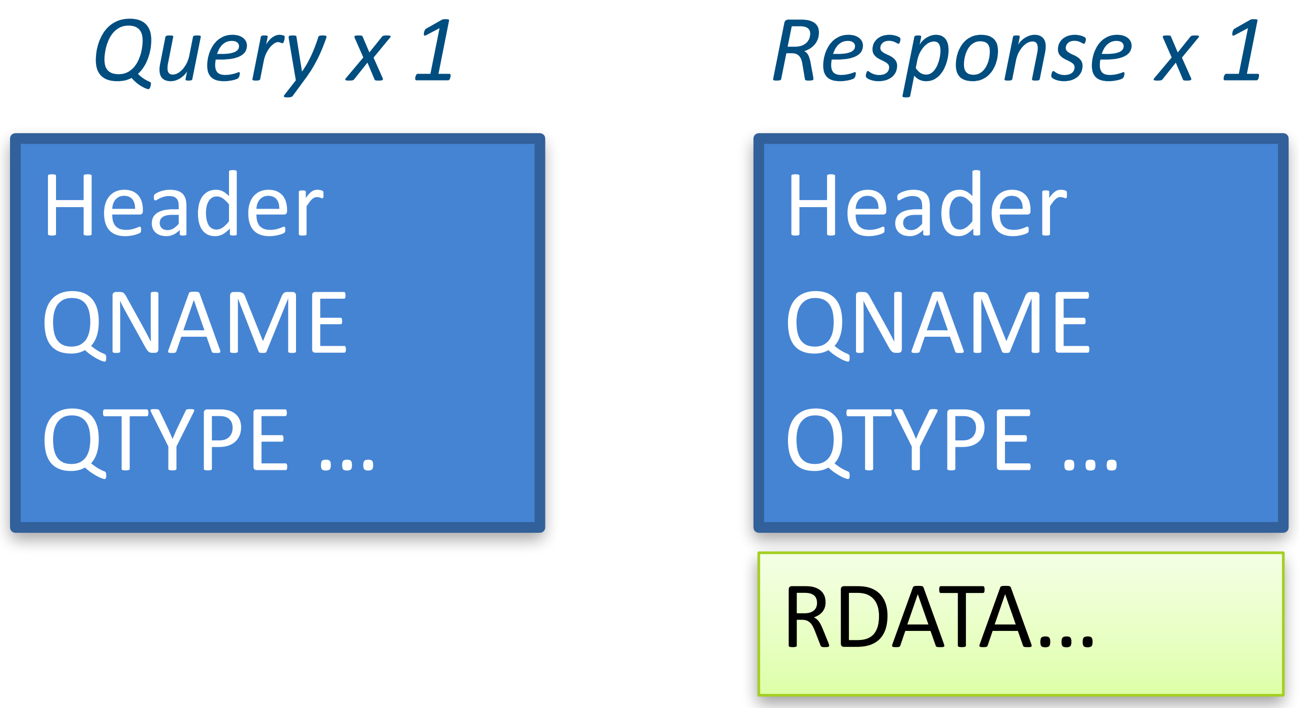
Figure 3: Workflow of RESOLVERFUZZ.

ResolverFuzz: Techniques

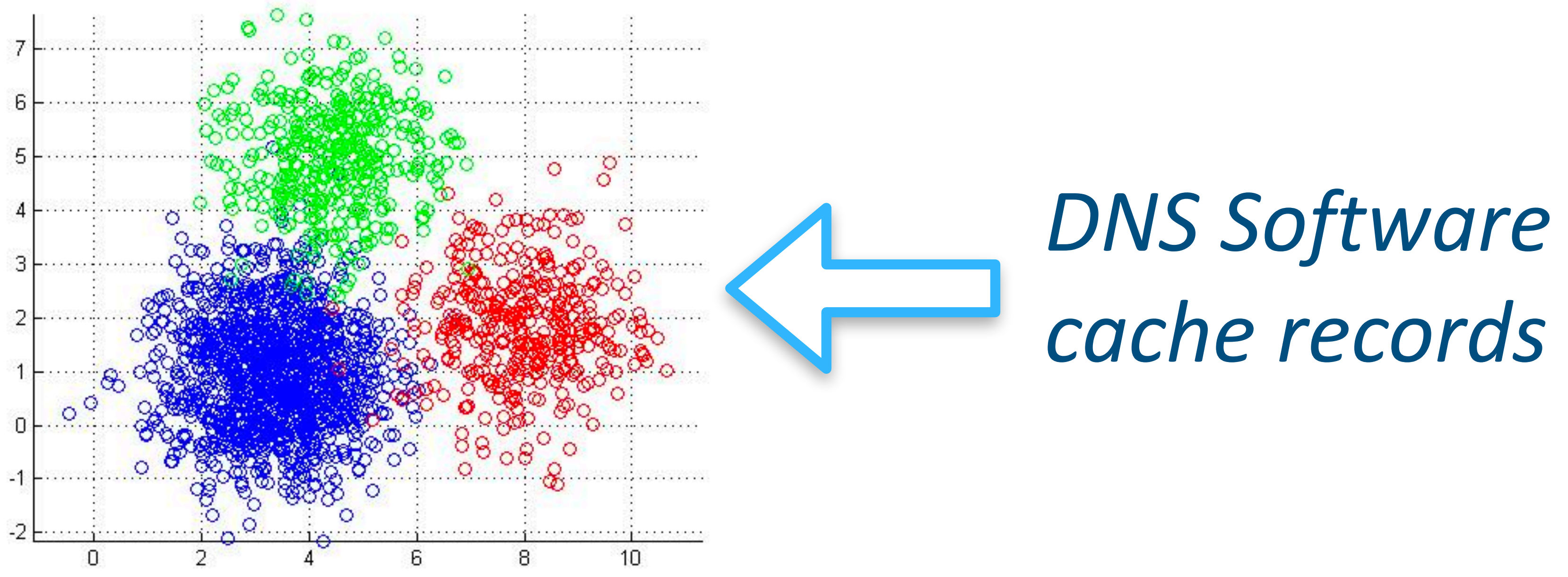
- PCFG (Probabilistic Context-Free Grammar) + byte mutation

```
⟨Record⟩ ::= ⟨NAME⟩⟨TYPE⟩⟨CLASS⟩⟨TTL⟩⟨RDLENGTH⟩⟨RDATA⟩
⟨NAME⟩ ::= (domain queried)[.2] |
           (sub-domain)[.2] |
           (same-level domain)[.2] |
           (parent domain)[.2] |
           (unrelated domain)[.2]
⟨TYPE⟩ ::= (TYPE queried)[.50] | A[.05] | CNAME[.05] | SOA
     [.05] | PTR[.05] | MX[.05] | TXT[.05] | AAAA[.05] |
     RRSIG[.05] | SPF[.05]
```

- Query-response fuzzing input



- Differential testing (cache poisoning)



Bisecting K-means

How does ResolverFuzz perform?

Tested in 4 popular modes
Good coverage of different field values
Efficient runtime performance
23 vulnerabilities identified
19 confirmed, 15 CVEs assigned
Categorized into 3 classes

Configuration Settings

- Tested in 4 popular modes

```
options {
	recursion yes;
	// includes the entire namespace
}
```

(a)

```
options {
	recursion no;
	// disables recursive resolution
	forwarders {
		x.x.x.x port 53;
	}
	// forward the entire zone "." to an upstream server
}
```

(b)

```
options {
	recursion yes;
}
// create a forward zone for test-cdns.example.com
zone "test-cdns.example.com" {
	type forward;
	forwarders { x.x.x.x port 53; };
	forward only; // fallback mode disabled
}
```

(c)

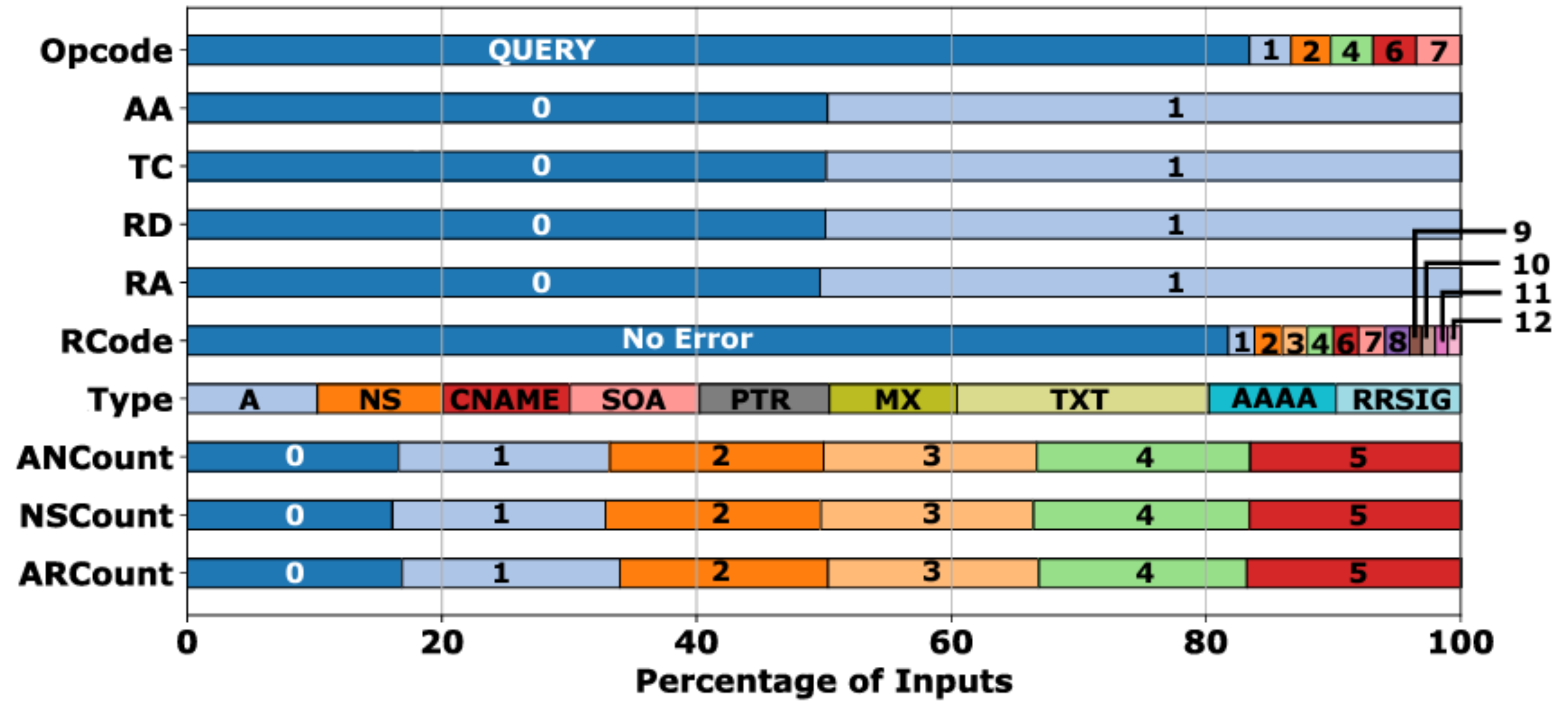
```
options {
	recursion yes;
}
// create a forward zone for test-cdns.example.com
zone "test-cdns.example.com" {
	type forward;
	forwarders { x.x.x.x port 53; };
	forward first; // fallback mode enabled
}
```

(d)

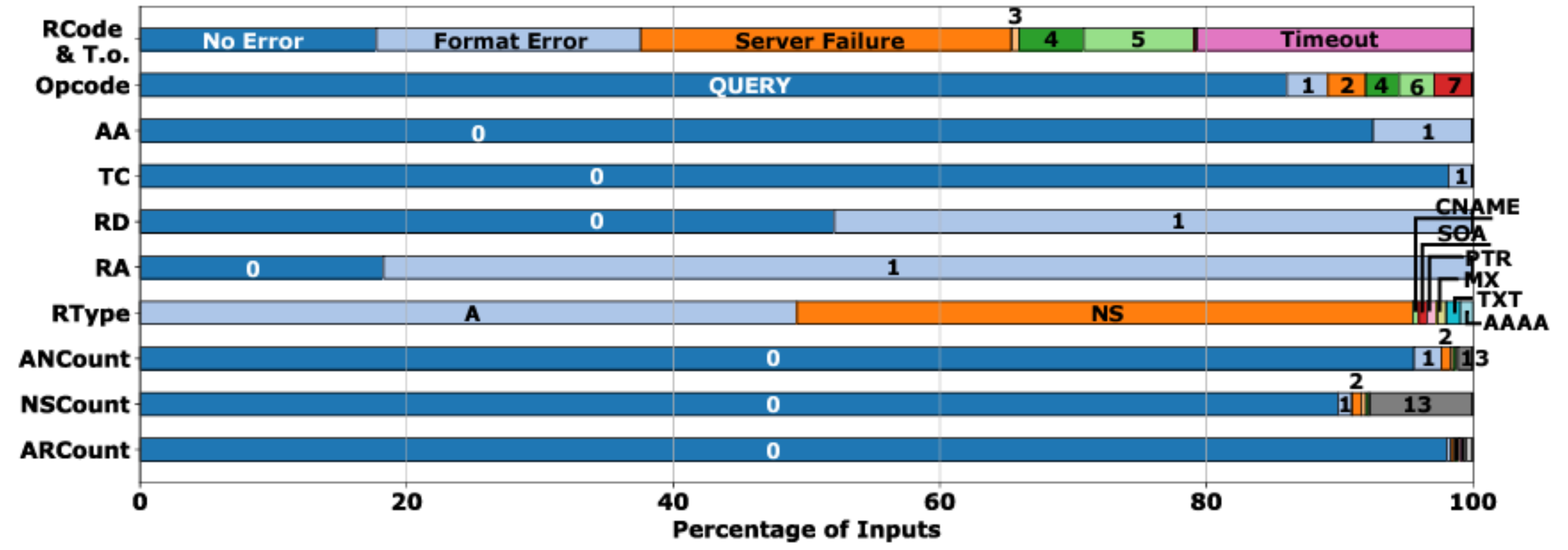
Figure 12: Example BIND configs of a) recursive-only, b) forward-only, c) CDNS without fallback, and d) CDNS with fallback.

Test Generation Analysis

- Rule probabilities of PCFG
  - Test certain code logic more intensively
- Good coverage of field values
- Test cases prone to trigger errors
  - Potentially bugs
  - Only 17.8% have RCODE=NOERROR



(a) Client-queries and NS-responses.



(b) Resolver-responses. "*RCode & T.o.*" refers to "RCODE and Timeouts".

Figure 4: Input coverage analysis on: a) client-queries and ns-responses; b) resolver-responses. The client-query and ns-response have the similar distribution for fields from `OPCODE` to `TYPE`. `AN`/`NS`/`ARCOUNT` applies to ns-responses. The values marked on bars are standard DNS values from [83].

Runtime Performance

- Use concurrency to speed up
  - 5.9 QPS (CDNS w/ f.b.)
    - BIND and Unbound only
  - 2.8 QPS (other modes)
    - MaraDNS, PowerDNS: low on efficiency
- Similar speed with real-world DNS resolution
  - Google DNS: 300-400 ms per query [1]
    - i.e., 2.5-3.3 QPS

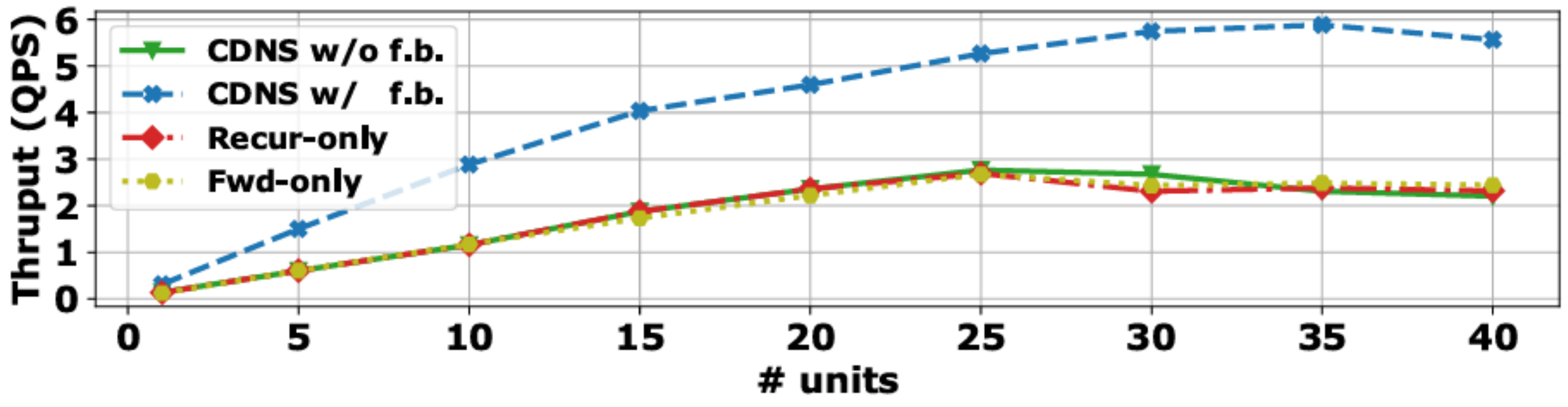
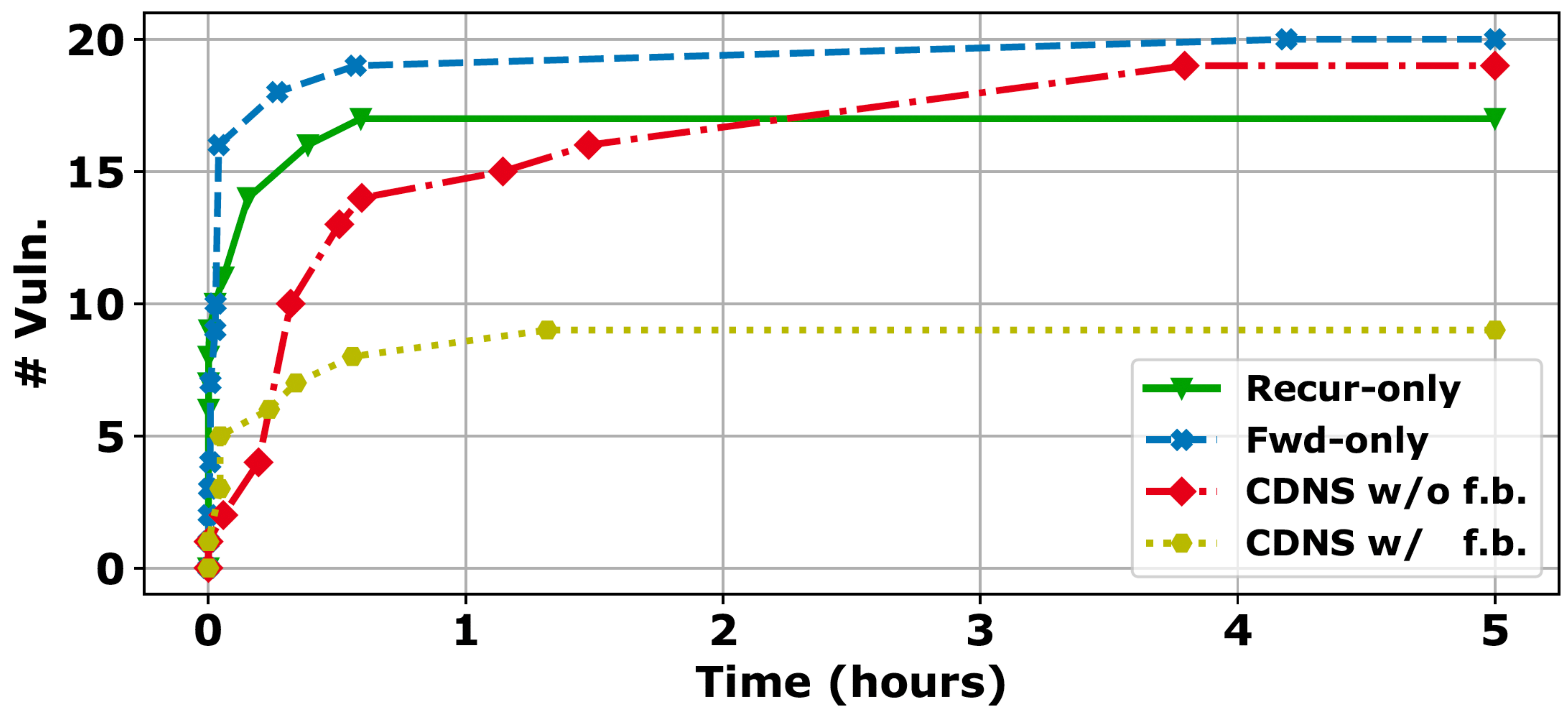


Figure 5: Throughput ("*Thruput*") of 4 modes with regard to the number of units. *CDNS w/o f.b.*, *CDNS w/ f.b.*, *Recur-only* and *Fwd-only* refers to *CDNS without fallback*, *CDNS with fallback*, *Recursive-only*, and *Forward-only*.

[1] https://developers.google.com/speed/public-dns/docs/performance

Discovered Vulnerabilities

- **23** bugs discovered
  - Cache poisoning, resource consumption, crash
  - **15** CVEs assigned
  - Outperform dns-fuzz-server, DNS fuzzer and SnapFuzz



(a) Recursive-only, forward-only and CDNS with/without fallback modes.

MaginotDNS Phoenix Domain TuDoor

Table 2: Identified bugs and test cases of six mainstream DNS software.

Software*	Cache poisoning					Resource consumption								Crash& Corruption	Total
	CP1	CP2	CP3	CP4[1]	Tot.[2]	RC1	RC2	RC3	RC4	RC5	RC6	RC7	Tot.	CC1	
BIND	✓†	✗	✓	✓	3	✗	✗	✗	✗	✗	✗	✗	0	✓	4
Unbound	✗	✗	✓	✓†	2	✗	✓	✓	✗	✓	✓	✗	4	-	6
Knot	✓†	✗	✓†	✓†	3	✗	✗	✗	✗	✗	✗	✓†	1	-	4
PowerDNS	✗	✓†	✗	✓†	2	✓†	✗	✓†	✗	✗	✗	✗	2	-	4
MaraDNS	✗	✗	-	✓†	1	✗	✗	✗	✓†	✗	✗	✗	1	-	2
Technitium	✓†	✗	-	✓†	2	✗	✗	✗	✓†	✗	✗	✗	1	-	3
Total	3	1	3	6	13	1	2	1	2	1	1	1	9	1	23

*: Recursive or forwarding modes. [1]: They are triggered by different responses and their cache are inconsistent. [2]: Total. ✓or ✓: Vulnerable.
✓: Discussed but no immediate action. ✓: Confirmed and/or fixed by vendors. ✗: Not vulnerable. †: CVEs assigned. '-': Not applicable.
Amount of test cases: *CP*1 (19), *CP*2 (1,422), *CP*3 (111,328), *CP*4 (7,856), *RC*1 (539,745), *RC*2 (112,126), *RC*3 (88,935), *RC*4 (132), *RC*5 (272) *RC*6 (6,264), *RC*7 (4,448), and *CC*1 (5).

Conclusion

- Conducted a comprehensive study on DNS CVEs
- Proposed ResolverFuzz, a fuzz system tailored to DNS resolvers
  - Constrained stateful fuzzing, differential testing, grammar-based fuzzing
- Identified **23** vulnerabilities, **19** confirmed, **15** CVEs assigned
  - 3 top-tier conferences published with extended study on 3 discovered vulnerabilities
- Limitations:
  - Only test a subset of DNS; Not fully automated; Fixed testing timeouts; Lack of long sequence testing; Survivorship bias on CVE study

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ARTIFACT EVALUATED usenix ASSOCIATION AVAILABLE

ARTIFACT EVALUATED usenix ASSOCIATION FUNCTIONAL

Thanks for listening!
Any questions?

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ResolverFuzz GitHub repo

ResolverFuzz

Qifan's Homepage