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

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Feel free to visit my homepage (qifanz.com) for slides

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Short Bio

- **4th-year Ph.D. student of Department of EECS**
  - Advisor: Prof. Dr. Zhou Li
- **Field of Research:**
  - **Domain Name System (DNS)**
    - [Security'24] **Zhang, Q.,** Bai, X., Li, X., Duan, H., Li, Q. and Li, Z., *ResolverFuzz: Automated Discovery of DNS Resolver Vulnerabilities with Query-Response Fuzzing.*
    - [NDSS'23] Li, X., Liu, B., Bai, X., Zhang, M., **Zhang, Q.,** Li, Z., Duan, H. and Li, Q., *Ghost Domain Reloaded: Vulnerable Links in Domain Name Delegation and Revocation.*
    - [Security'23] Li, X., Lu, C., Liu, B., **Zhang, Q.,** Li, Z., Duan, H. and Li, Q., *The Maginot Line: Attacking the Boundary of DNS Caching Protection.*
    - [IEEE Access'22] Liao, X., Xu, J., **Zhang, Q.** and Li, Z., *A Comprehensive Study of DNS Operational Issues by Mining DNS Forums.*

Short Bio

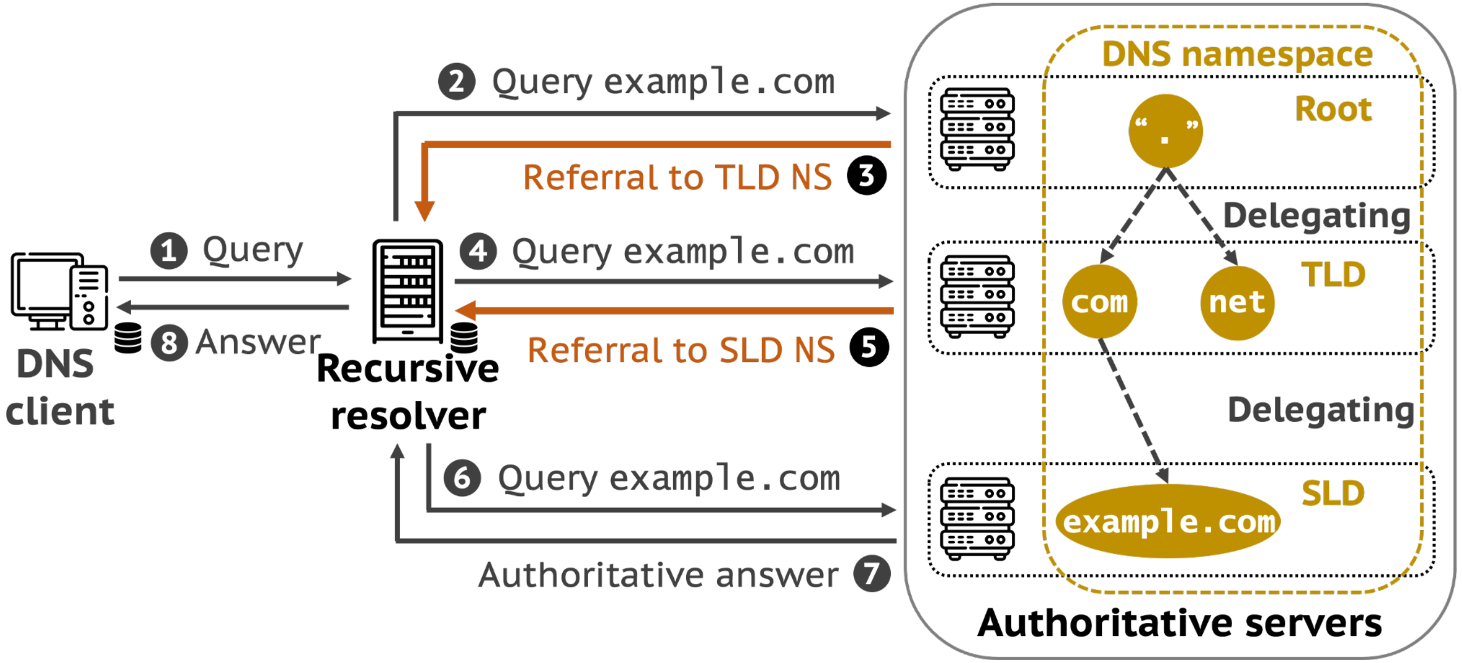
- **4th-year Ph.D. student of Department of EECS**
  - Advisor: Prof. Dr. Zhou Li
- **Field of Research:**
  - **Machine Learning and Security**
    - [ACSAC'22] **Zhang, Q.,** Shen, J., Tan, M., Zhou, Z., Li, Z., Chen, Q.A. and Zhang, H., *Play the Imitation Game: Model Extraction Attack against Autonomous Driving Localization.*
    - [Under review in ICLR'24] Han, S., Buyukates, B., Hu, Z., Jin, H., Jin, W., Sun, L., Wang, X., Xie, C., Zhang, K., **Zhang, Q.** and Zhang, Y., 2023. *FedMLSecurity: A Benchmark for Attacks and Defenses in Federated Learning and Federated LLMs.*
    - [Under review in ICLR'24] Han, S., Wu, W., Buyukates, B., Jin, W., Yao, Y., **Zhang, Q.**, Avestimehr, S. and He, C., 2023. *Kick Bad Guys Out! Zero-Knowledge-Proof-Based Anomaly Detection in Federated Learning.*

Domain Name System

- **Domain Name System (DNS)**
  - Entry point of many Internet activities
    - Interpret domain names into network addresses (IPs)
    - E.g., translate uci.edu into 128.200.151.40
  - Security guarantee of multiple application services
  - Domain names are widely registered
- **Fundamental for other apps**
  - Web, CDN, Email, Certificate Authentication, etc.

DNS Resolution

- **Recursive/Iterative process**
  - Multiple roles
  - Forwarder, recursive resolver, authoritative server



DNS Resolution

Cache Mechanism

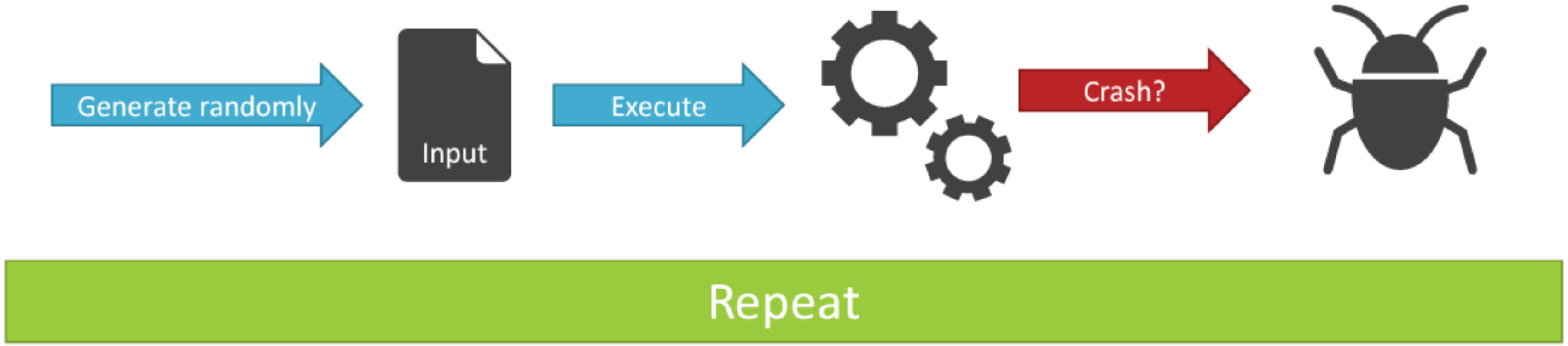
- Cache DNS recourse records (RRs) for future references
- One of the **most vulnerable** parts in DNS
  - Cache poisoning, e.g., MaginotDNS [Security’23], SAD DNS [CCS’20&21]
  - Domain delegation (Ghost Domain), e.g., Phoenix Domain [NDSS’23]
- Only involved for recursive resolvers
  - Focus on **recursive resolvers**

DNS Vulnerability Detection

- **How to find vulnerabilities <u>automatically</u>?**
  - Formal analysis
    - Already applied to nameservers: SCALE [SIGCOMM'22], G-Root [NSDI'20]
    - Lack **<u>rigorous specifications</u>** as references for vulnerability detection
  - **<u>Fuzzing</u>**

Fuzzing

- **Suitable for testing large-size software in large scale**
- **Flexible for multiple scenarios**
  - Lexical-based: Blackbox/Graybox/Whitebox fuzzing
  - Syntactic-based: (Probalistic) Grammar-based fuzzing
  - Semantic-based: Concolic/Symbolic fuzzing



Fuzzing on DNS

- **Previous works**
  - AFL++/AFLNet
  - SnapFuzz [ISSTA'22], DNS Fuzzer (a github repo)
  - Focus on **memory vulnerabilities**
    - Could **only** detect crashes
  - But cache poisoning is **semantic vulnerabilities**
    - Traditional memory-based fuzzers does not work
- **Need to design a fuzzer to detect semantic bugs in DNS**

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

Check vulnerabilities which **have been** identified
Focus on where they were **most** spotted

Comprehensive Study of CVEs

➢ **Understand the distribution and root causes of DNS-related vulnerabilities**

Table 1: Study results of DNS CVEs for mainstream DNS software.

Software*	# CVE								
	Semantic					Memory			Total
	Cache poison.[1]	Res. consumpt.[2]	Serv. crash[3]	Others	Total	Corrupt.[4]	Others	Total	
BIND	18	17	73	10	118	22	1	23	141
Unbound	4	5	5	3	17	8	1	9	26
Knot Resolver	6	3	2	0	11	0	0	0	11
PowerDNS Recursor	13	7	7	9	36	6	0	6	42
MaraDNS	2	3	3	0	8	7	0	7	15
Technitium	3	1	0	0	4	0	0	0	4
Total	46	36	90	22	194	43	2	45	239

*: Recursive or forwarding modes. [1]: Cache poisoning. [2]: Resource consumption. [3]: Service crash. [4]: Corruption.
CVE of the forwarding mode only: Total (7), BIND (5), Unbound (0), Knot (1), PowerDNS (0), MaraDNS (0), and Technitium (1).
CVE of the authoritative mode only: Total (45), BIND (19), Unbound (4), Knot (2), PowerDNS (19), MaraDNS (1), and Technitium (0).
CVE of other software: Total (131), Microsoft DNS (90), Simple DNS Plus (1), Dnsmasq (33), CoreDNS (1), NSD (4), Yadifa (1), and TrustDNS (1).

Comprehensive Study of CVEs

➢Findings:

- ➢Most of the CVEs are about resolvers
  - ➢284 CVEs, only 45 related to nameservers

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Comprehensive Study of CVEs

➢ Findings:

- ➢ Diversified CVEs among DNS software
  - ➢ BIND has the most CVEs
  - ➢ Only 13 out of 239 CVEs affect all software

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Comprehensive Study of CVEs

➢Findings:

- ➢Most of the CVEs are semantic bugs
  - ➢Cache poisoning, resource consumption and service crash

Table 1: Study results of DNS CVEs for mainstream DNS software.

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Comprehensive Study of CVEs

- **Findings:**
  - Nearly every field of a DNS message has related CVEs
    - Query name, query type, query flag, RCODE, RDATA, TTL, etc.
  - Most of the CVEs are triggered with short message sequence

Table 1: Study results of DNS CVEs for mainstream DNS software.

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How should we design ResolverFuzz?

Black box, **Stateful** and **Grammar**-based fuzzing
Two input generators
Identify diff. vuln. by adapting diff. **oracles**

ResolverFuzz Infrastructure

- **Input:**
  - Query Generator
  - Response Generator

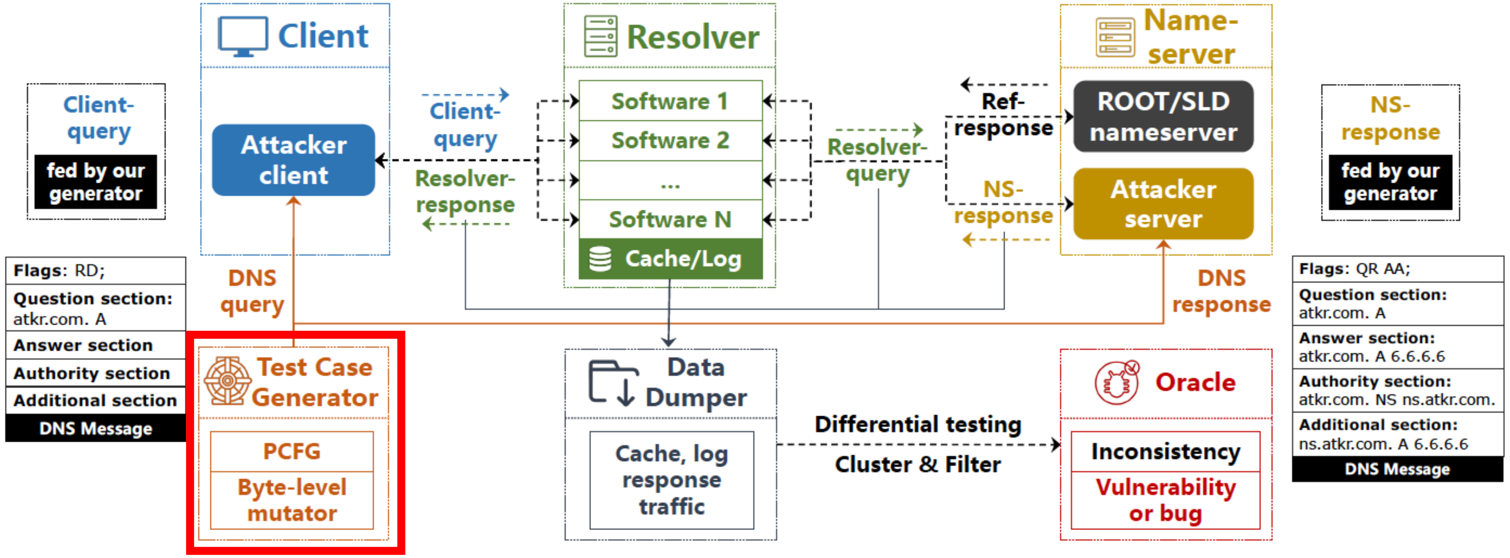


Figure 3: Workflow of RESOLVERFUZZ.

ResolverFuzz Infrastructure

- ➢ **Output:**
  - ➢ Response
  - ➢ Cache
  - ➢ System logs

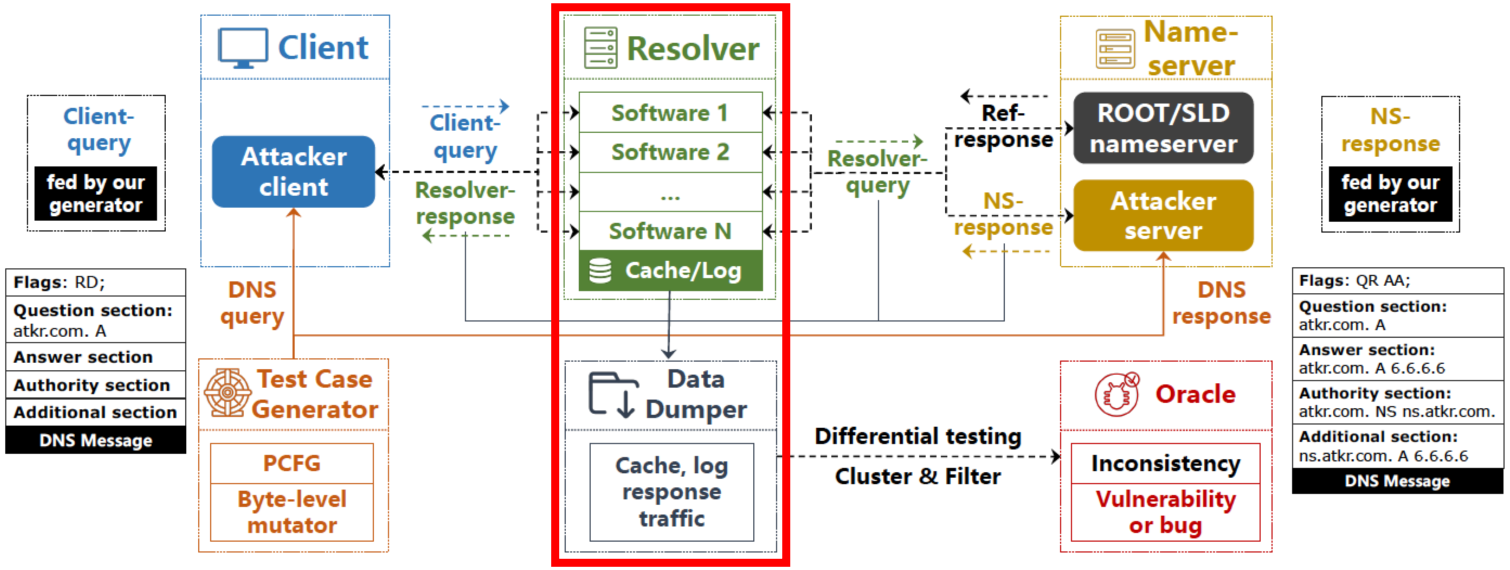


Figure 3: Workflow of RESOLVERFUZZ.

ResolverFuzz Infrastructure

➢Oracle:

- ➢Measure divergence
- ➢Bug/vuln. analysis

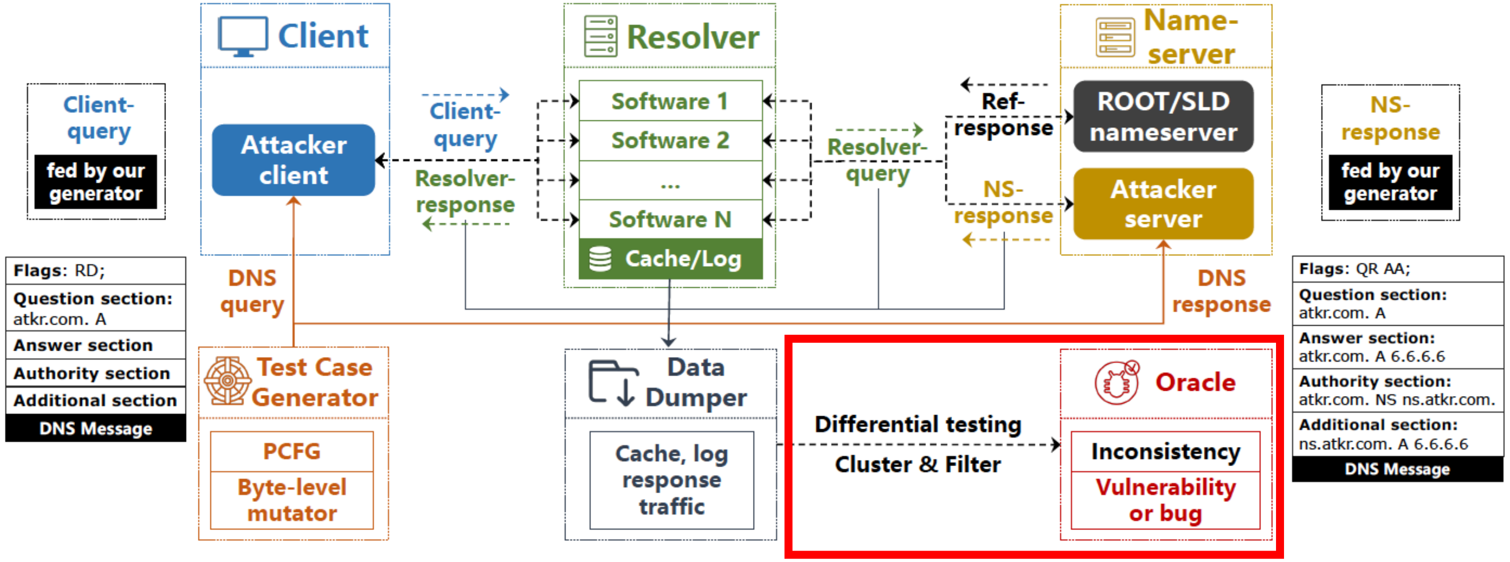


Figure 3: Workflow of RESOLVERFUZZ.

ResolverFuzz: Workflow

- Initialize DNS Resolvers
- Test case generation
  - Query & Responses
- Test case execution
  - Data dump
- Reset for next round
- Differential analysis

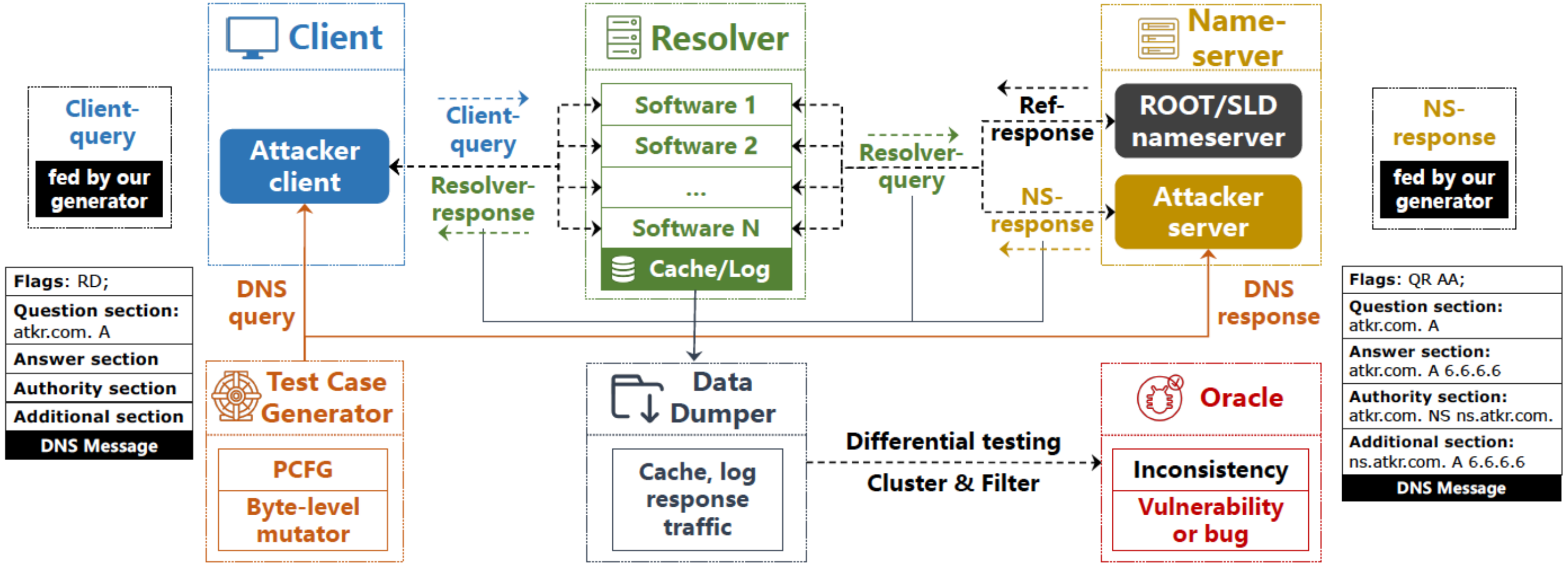


Figure 3: Workflow of ResolverFuzz.

What are the challenges for ResolverFuzz?

Efficiency
Mutation
Stateful Fuzzing
Oracle

Efficiency

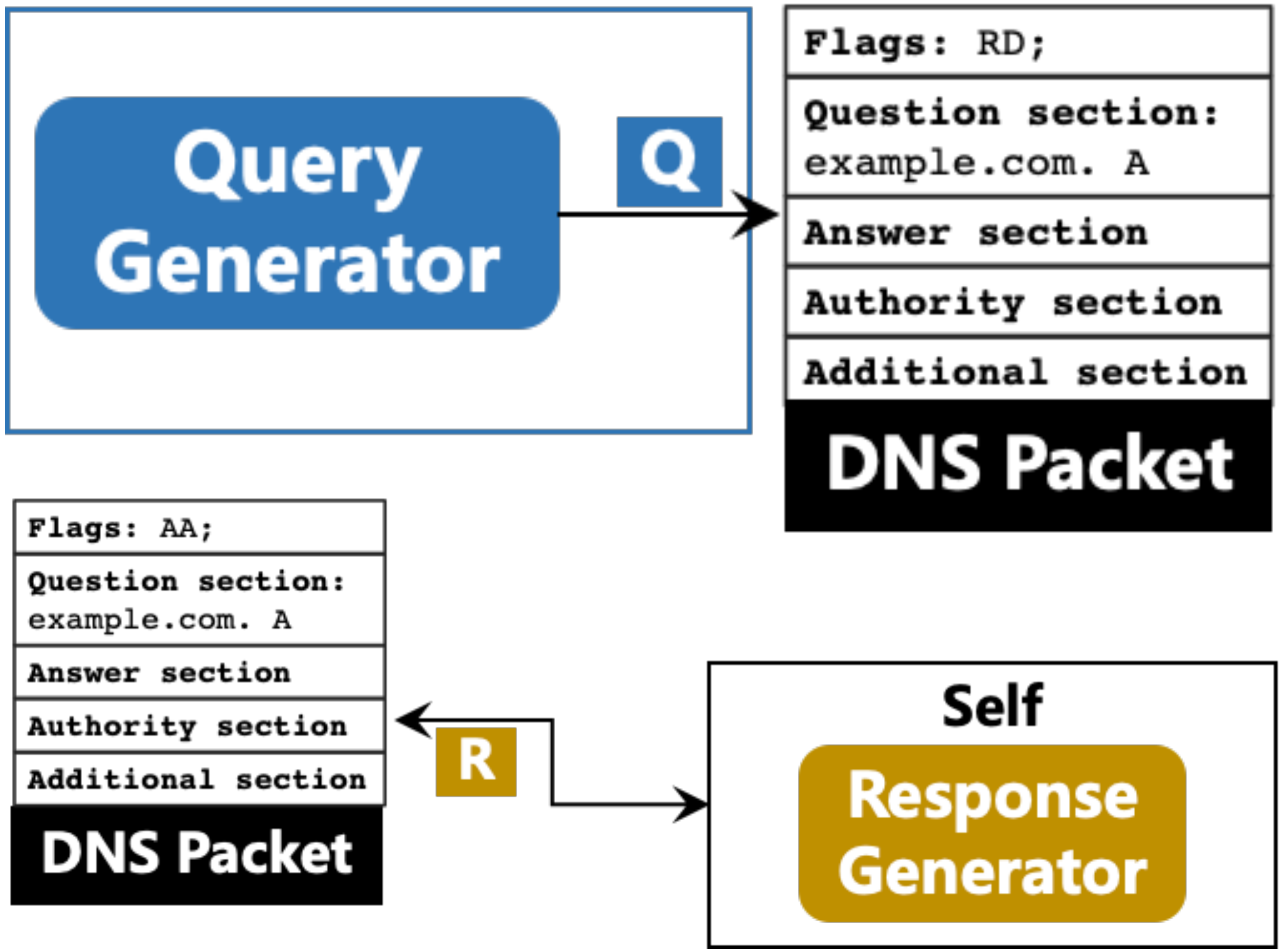
- **Some DNS software are slow**
  - E.g., BIND (~0.4s per query) v.s. PowerDNS (>1s per query)
- **Empty cache for each test**
- **Preset timeouts**
- **Pre- and post-processing**
  - NS initialization
  - Data collection
- **Solution: Run several test units in parallel**
  - "High efficiency via high **throughput**"

Mutation

- **Coverage-based fuzzers**
  - Fail to provide sufficient guidance
  - Poor on deciding which part should be mutated
  - **Reason**: no preliminary knowledge on DNS packets
- **Input dimension**
  - Only one dimension (query or NS response) leads to many invalid tests

Input Generation

- **Two dimensions**
  - Client-queries
    - For attacker clients
  - Nameserver (NS)-responses
    - For attacker NSes



Input Generation

- **Grammar-based Fuzzing**
  - Probabilistic context-free grammar (PCFG)
    - Queries and Responses
  - High prob. for certain fields
    - Guide fuzzing process

```
⟨start⟩ ::= ⟨query⟩
⟨query⟩ ::= ⟨Header⟩⟨Question⟩
⟨Header⟩ ::= ⟨TransactionID⟩⟨Flags⟩⟨RRs⟩
⟨TransactionID⟩ ::= (randomly generated 2-byte hex value)
⟨Flags⟩ ::= ⟨QR⟩⟨OPCODE⟩⟨AA⟩⟨TC⟩⟨RD⟩⟨RA⟩⟨Z⟩⟨AD⟩⟨CD⟩⟨RCODE⟩
⟨QR⟩ ::= 0
⟨OPCODE⟩ ::= QUERY[.80] | IQUERY[.04] | STATUS[.04] |
    NOTIFY[.04] | UPDATE[.04] | DSO[.04]
⟨AA⟩ ::= 0 | 1
⟨TC⟩ ::= 0 | 1
⟨RD⟩ ::= 0 | 1
⟨RA⟩ ::= 0 | 1
⟨Z⟩ ::= 0 | 1
⟨AD⟩ ::= 0 | 1
⟨CD⟩ ::= 0 | 1
⟨RCODE⟩ ::= NOERROR[.80] | FORMERR[.01] | SERVFAIL[.01] |
    NXDOMAIN[.01] | NOTIMP[.01] | REFUSED[.01] | YXDOMAIN
    [.01] | YXRRSET[.01] | NXRRSET[.01] | NOTAUTH[.01] |
    NOTZONE[.01] | DSOTYPENI[.01] | BADVERS[.01] | BADKEY
    [.01] | BADTIME[.01] | BADMODE[.01] | BADNAME[.01] |
    BADALG[.01] | BADTRUNC[.01] | BADCOOKIE[.01]
⟨RRs⟩ ::= ⟨QDCOUNT⟩⟨ANCOUNT⟩⟨NSCOUNT⟩⟨ARCOUNT⟩
⟨QDCOUNT⟩ ::= 1
⟨ANCOUNT⟩ ::= 0
⟨NSCOUNT⟩ ::= 0
⟨ARCOUNT⟩ ::= 0
⟨Question⟩ ::= ⟨QNAME⟩⟨QTYPE⟩⟨QCLASS⟩
⟨QNAME⟩ ::= (base domain)[.40] |
          (sub-domain)[.40] |
          (2-9th sub-domain)[.10] |
          (10-max sub-domain)[.10] |
⟨QTYPE⟩ ::= A | NS | CNAME | SOA | PTR | MX | TXT | AAAA |
     RRSIG | SPF | ANY
⟨QCLASS⟩ ::= IN
```

Listing 1: PCFG for DNS query.

Input Generation

- **Byte-level mutation**
  - Some DNS implementations fail to correctly decode strings with **special characters** embedded
    - E.g., \., \000, @, /, and \
    - Jeitner et al. [Security'21]
  - Addition, deletion, and replacement
    - After PCFG test generation

Stateful Fuzzing

- **DNS resolvers are stateful**
  - Depending on cache records, configurations, etc.
  - Major challenge for network fuzzing
    - Large search space of input sequences
- **Solution:**
  - Generate one pair of the query and (authoritative) response
    - Cover most vulnerable cases
  - Deploy the auth. response on the NS side
  - Start to test by sending the query
    - Communication between DNS resolvers and the NS
    - Preset timeout (5s) is deployed

Oracle

- **Lack an oracle to detect semantic bugs**
  - Memory bugs have their oracle
    - E.g., AddressSanitizer [USENIX ATC'12]
- **Differential testing**
  - Used for memory bugs, but none for DNS
- **How to connect inconsistency with vulnerabilities?**
  - Inconsistencies are common in DNS
  - Many of them do not indicate vulnerabilities

Differential Analysis

- **Runs multiple programs, comparing their outputs for the same input**
  - Detecting rendering regressions in browsers (e.g., R2Z2 [ICSE'22])
  - Comparing outputs from different versions
  - Efficient to find divergences

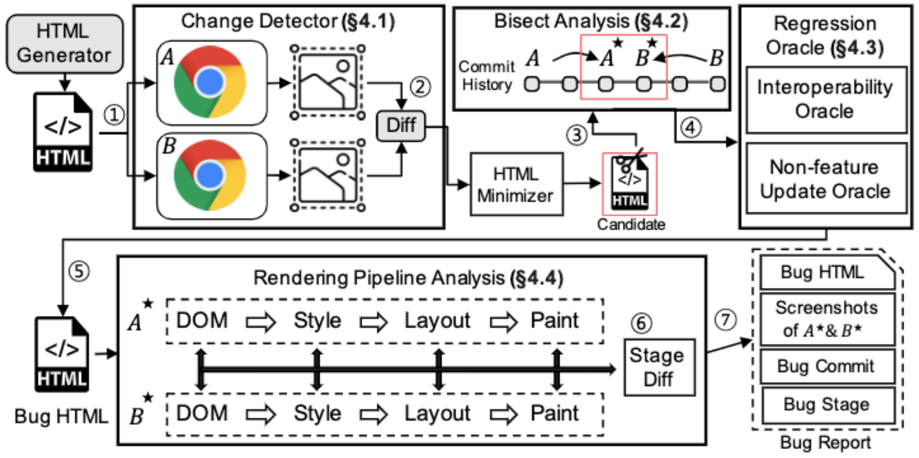
```
<html>
  <style>
  .class7 {
    backdrop-filter: hue-rotate(1deg);
    filter: brightness(0.32269068);
    padding: 66%;
  }
  </style>
  <body>
  THE EXAMPLE OF RENDERING BUG
    <span class="class7" ></span>
  </body>
</html>
```

(a) PoC HTML code

(b) Correct (Chrome 85)

(c) Incorrect (Chrome 86)

Figure 2: A rendering bug example (Chrome Issue #1122021).



Oracle

- **Different DNS software**
  - Objects of differential analysis
- **Three Oracles**
  - Cache poisoning oracle
    - Semi-automatic, differential-analysis based
    - Record the max # different records of one software from the others
    - Cluster by Bisecting K-Means
    - Manually check each cluster to identify possible vulnerabilities

Oracle

Three Oracles

- Resource consumption oracle
  - 4 metrics:
    - # queries
    - Sizes of responses
    - Resolution timeout
    - Frequency of internal operations (e.g., cache search)
  - Compare metrics with the value distribution in normal cases

Oracle

- **Three Oracles**
  - Crash & Corruption oracle
    - Monitor DNS software processes
    - Check if the process is running after each test case

How does ResolverFuzz perform?

Tested in **6** popular DNS software and **4** popular modes
Good coverage of different field values
Efficient runtime performance

Evaluation

- **6 DNS software**
  - BIND 9, Unbound, PowerDNS, Knot, Technitium and MaraDNS
  - Docker-based
  - Schedulers and oracles implemented in Python

Evaluation

➢4 configurations:

- ➢Recur.-only, Fwd-only, CDNS w/ fallback and CDNS w/o fallback

```
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
}
```

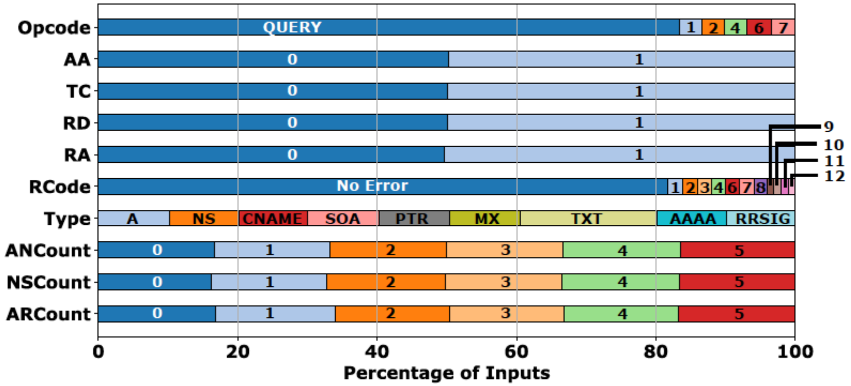
(d)

Figure 11: Example BIND configs of a) recursive-only, b) forward-only, c) CDNS without fallback, and d) CDNS with fallback.

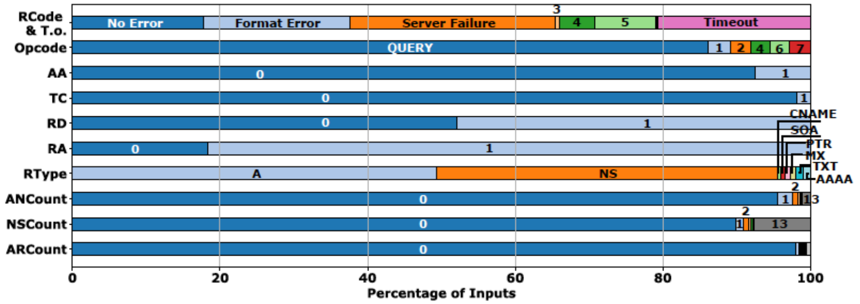
Evaluation

➢Analysis of tests generation

- ➢Good coverage of different field values
- ➢Rule probabilities of PCFG
  - ➢Test certain code logic more intensively
- ➢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 6: 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 [78].

Evaluation

➢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
    - ➢ i.e., 2.5-3.3 QPS

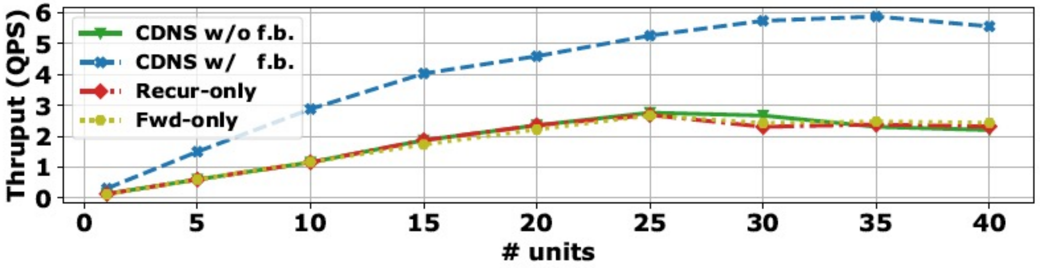


Figure 7: Throughput ("*Thruput*") of 4 modes with regard to the number of units. *CDNS w/o f.b.*, *CDNS w/ f.b.*, *Recur-only* and *Fwd-only* refers to *CDNS without fallback*, *CDNS with fallback*, *Recursive-only*, and *Forwarder-only*.

How many new vuln. are discovered?

23 vulnerabilities identified
19 confirmed, **15** CVEs assigned
Categorized into 3 classes

Discovered Vulnerabilities

- **23 vulnerabilities identified**
  - 19 vulnerabilities confirmed
  - 15 CVEs assigned
  - Details available in the paper

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. ✓: In discussion. ✓: Confirmed and/or fixed by vendors. ✗: Not vulnerable. [†]: CVEs are assigned. '-': Not applicable.
Amount of test case: *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).

CP1: Out-of-Bailiwick Cache Poisoning

➢Bailiwick rule

- ➢NS **should not** return RRs out of **their controlled zone**
- ➢E.g., RRs from .com server should not contain .org RRs

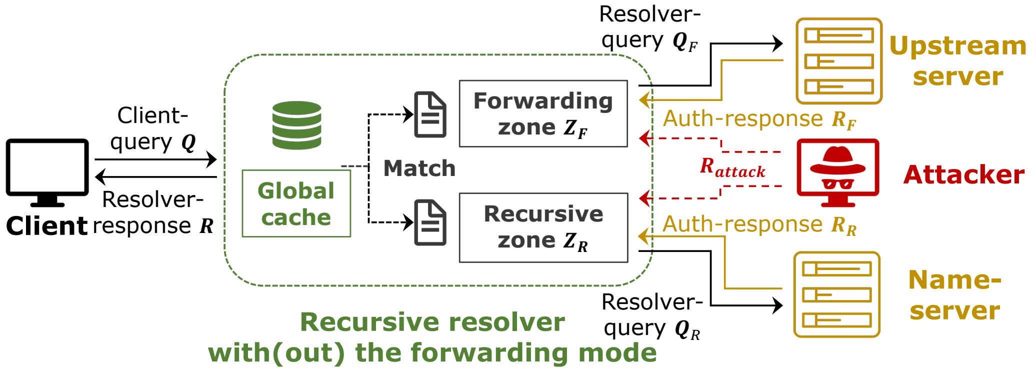
Header: TXID; QR AA;
Question section: atkr-fwd.com. A
Answer section: atkr-fwd.com. A x.x.x.x
Authority section: com. NS ns.atkr-fwd.com.
Additional section: ns.atkr-fwd.com. A **a.t.k.r**

CP1: Out-of-Bailiwick Cache Poisoning

➢Out-of-Bailiwick attack

- ➢First found in BIND under CDNS without fallback mode
  - ➢Also identified in Knot and Technitium
- ➢Forged NS records with AA Flag have **higher** trust level
- ➢Resolvers may overwrite cached records with the forged one
  - ➢Some DNS resolver do not check the response
- ➢Hijack the whole .com zone into ns.atkr-fwd.com
- ➢Details analyzed in MaginotDNS [Security'23]

Header: TXID; QR AA;
Question section: atkr-fwd.com. A
Answer section: atkr-fwd.com. A x.x.x.x
Authority section: com. NS ns.atkr-fwd.com.
Additional section: ns.atkr-fwd.com. A **a.t.k.r**



RC1: Excessive cache search operations

- **Forward-only mode, PowerDNS**
- **Looks up its local cache for trust anchors and NS records before sending it to a server**
  - E.g., s.atkr-fwd.com
    - Should be only one search only
  - PowerDNS: search records in the order of s.atkr-fwd.com, atkr-fwd.com, .com and root servers
    - Until an NS record is found
  - May cause resource consumption due to excessive cache search

Conclusion

- **Comprehensive study of published DNS CVEs**
- **Develop a blackbox fuzzing system for DNS resolvers**
- **Novel techniques**
  - Stateful fuzzing
  - Differential testing
  - Grammar-based fuzzing
- **12 types of vulnerabilities and 15 CVEs assigned**

Future Works

- **Fuzzing on DNS Security Extensions (DNSSEC)**
  - DNSSEC
    - Provides origin authentication and integrity protection for DNS data
    - A means of public key distribution in DNS
  - Built-in security protection protocol based on DNS records
  - Proposed in RFC 4033-4035 since 2005
  - Efficiently defend DNS against multiple kinds of vulnerabilities

Future Works

- **Challenges on Fuzzing on DNSSEC**
  - Not so many CVEs reported till now
  - Multiple records involved
    - DNSKEY, RRSIG, NSEC/NSEC3, DS
  - Multiple states and transitions
    - Zone signing, DNSKEY selection
  - Applied cryptography
    - Mutation on different crypto. algorithms (mnemonics) will be involved
    - May need extend PCFG support for mnemonics

Future Works

- **ResolverFuzz v2.0: Fuzzing DNS with multiple query-response**
  - Hard to trigger
    - Only 6% of CVEs are triggered by multiple query-response
  - Multiple states and state transitions
    - May require larger PCFGs
  - Cache state maintenance and reproduction
  - More metrics may be involved to improve fuzzing guidance
    - E.g., counters of variables related to cache

Acknowledgements

- **This work is not possible with them!**
  - **Xuesong Bai** from DSP Lab of UC Irvine
  - **Xiang Li** from Tsinghua University
  - **Prof. Zhou Li**, my advisor
  - **Prof. Qi Li** and **Prof. Haixin Duan** from Tsinghua University

Thanks for listening!

Any questions?

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Discovered Vulnerabilities

➢Cache poisoning (CP)

- ➢CP1: Out-of-bailiwick cache poisoning
- ➢CP2: In-bailiwick cache poisoning
- ➢CP3: Fragmentation-based cache poisoning
- ➢CP4: Iterative subdomain caching

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.
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Header: TXID; QR AA;
Question section:
atkr-fwd.com. A
Answer section:
atkr-fwd.com. A x.x.x.x
Authority section:
com. NS ns.atkr-fwd.com.
Additional section:
ns.atkr-fwd.com. A **a.t.k.r**

(a) Auth-response for *CP*1.

Header: TXID; QR AA;
Question section:
vctm-fwd.com. A
Answer section:
vctm-fwd.com. A x.x.x.x
Authority section:
s.vctm-fwd.com. NS ns.vctm-fwd.com.
Additional section:
ns.vctm-fwd.com. A **a.t.k.r**

(b) Auth-response for *CP*2.

Header: TXID; QR AA;
...
Answer section:
victim.com. A x.x.x.x
...
victim.com. RRSIG xxx...x

(c) 1st fragment for *CP*3.

Authority section:
victim.com. NS ns.victim.com.
Additional section:
ns.victim.com. A **a.t.k.r**

(d) spoofed 2rd fragment for *CP*3.

Header: TXID; QR AA;
Question section:
s.atkr-rev.com. A
Answer section:
s.atkr-rev.com. A **a.t.k.r**
Authority section:
s.atkr-rev.com. NS ns.atkr-rev.com.
Additional section:
ns.atkr-rev.com. A **a.t.k.r**

(e) Auth-response for *CP*4.

Header: TXID; QR AA;
Question section:
s.atkr-rev.com. A
Answer section:
(Empty)
Authority section:
s.atkr-rev.com. NS ns.atkr-rev.com.
Additional section:
ns.atkr-rev.com. A **a.t.k.r**

(f) Ref-response for *CP*4.

Figure 9: DNS responses utilized for cache poisoning attacks. Red parts carry the attacking payloads.

Discovered Vulnerabilities

➢Resource Consumption Bugs (RC)

- ➢RC1: Excessive cache search operations
- ➢RC2: Unlimited cache store operations
- ➢RC3: Ignoring the RD flag
- ➢RC4: Following a self-CNAME reference
- ➢RC5: Large responses to clients
- ➢RC6: Overlong waiting time over UDP
- ➢RC7: Excessive queries for resolution over TCP

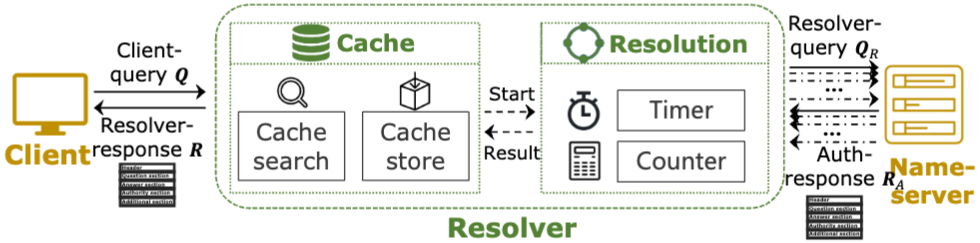

Figure 10: Threat model of resource consumption bugs.

Discovered Vulnerabilities

➢Crash & Corruption Bugs

- ➢Assertion failure when receiving queries

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

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Unbound	✗	✗	✓	✓[†]	2	✗	✓	✓	✗	✓	✓	✗	4	-	6
Knot	✓[†]	✗	✓	✓[†]	3	✗	✗	✗	✗	✗	✗	✓	1	-	4
PowerDNS	✗	✓	✗	✓[†]	2	✓	✗	✓	✗	✗	✗	✗	2	-	4
MaraDNS	✗	✗	-	✓[†]	1	✗	✗	✗	✓[†]	✗	✗	✗	1	-	2
Technitium	✓[†]	✗	-	✓[†]	2	✗	✗	✗	✓[†]	✗	✗	✗	1	-	3
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