SCALE

# Automatically Finding RFC Compliance Bugs in DNS Nameservers


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Microsoft

Intentionet

# Website Domain Name → IP


DNS (Domain Name System)

usenix.org

↓

23.185.0.4

# Many DNS Implementations

## Open-Source

BIND 9

POWERDNS

NSD

CoreDNS

KNOT DNS

## Closed-Source

Akamai

CLOUDFLARE

DNS

Route53

# DNS Software needs to be absolutely Correct!

- Incorrect responses from DNS servers can cause service unavailability
- Attackers can exploit security vulnerabilities (code bugs) to mount DDoS attacks
- DNS outages have a “large blast radius”

## Bind DoS Bug

**ISC updates critical DoS bug in BIND DNS software**

The denial-of-service flaw in BIND can be triggered by specially crafted DNS packages and is capable of knocking critical servers offline

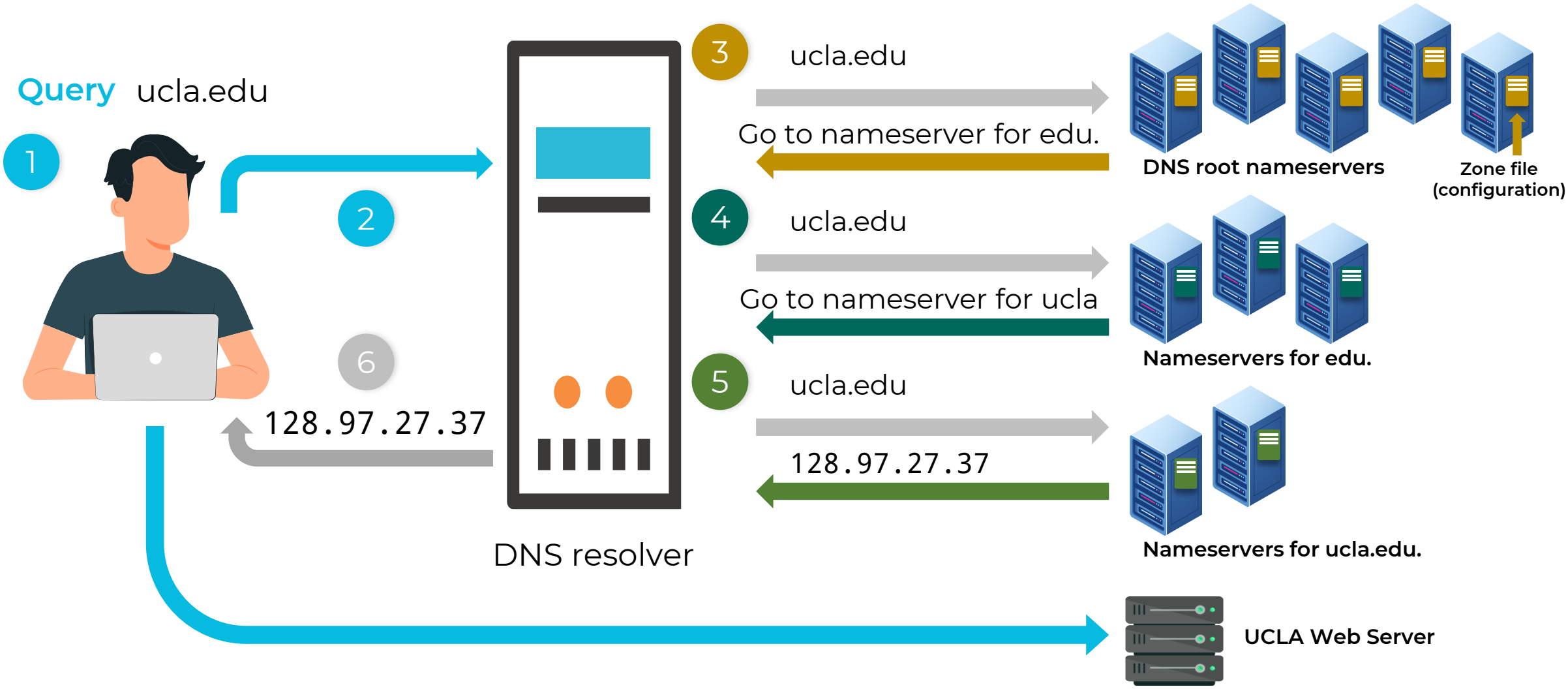
## Slack Outage due to Route 53 bug

**Slack is down for some people, and of course, the problem is DNS**

*If you've been having trouble contacting co-workers, this may be why*

By Mitchell Clark | Updated Sep 30, 2021, 4:18pm EDT

# How the Domain Name System Works



# DNS is way more complex than people think!

**Nondeterminism** in which nameserver to ask next

**Complex record types** each with unique semantics

- DNAME records: domain (partial) rewrite
- CNAME records: alias another domain name
- Wildcard records: match anything not otherwise matched
- NS records: nameserver redirection
- **56** other records types across **~30** RFCs

> The DNS is a lot like chess; it's a simple game in terms of the rules, but phenomenally complex in the way it can be played.

Geoff Huston (APNIC)

# Our Goal

Automatically generate test cases for DNS nameserver implementations covering as many RFC (specification) behaviors as possible

**Challenge – Need to generate config (zone file) and input (query) jointly**

# Previously Unknown BIND Crash Bug

**Tool Generated Test Case**

**1. Zone file**

| Domain Name | Type | Data |
|---|---|---|
| attack.com. | SOA | ns1.exm. … |
| foo.attack.com. | DNAME | com. |

⟨foo.attack.foo.attack.com.,DNAME⟩

**2. Query**

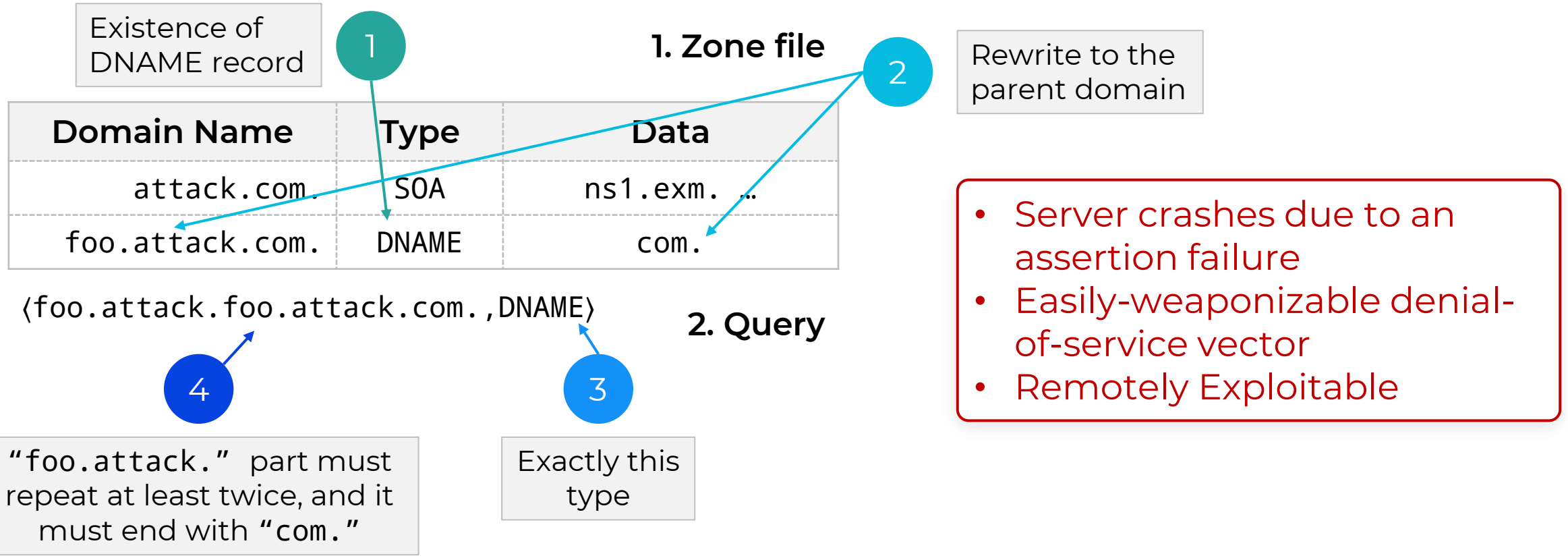
⟨foo.attack.foo.

attack.com.,DNAME⟩

**BIND Server**

# Previously Unknown BIND Crash Bug

**Tool Generated Test Case**




- Server crashes due to an assertion failure
- Easily-weaponizable denial-of-service vector
- Remotely Exploitable

# BIND Crash Remote Exploitation

**Scenario 1: Attack on a DNS hosting service that uses BIND**

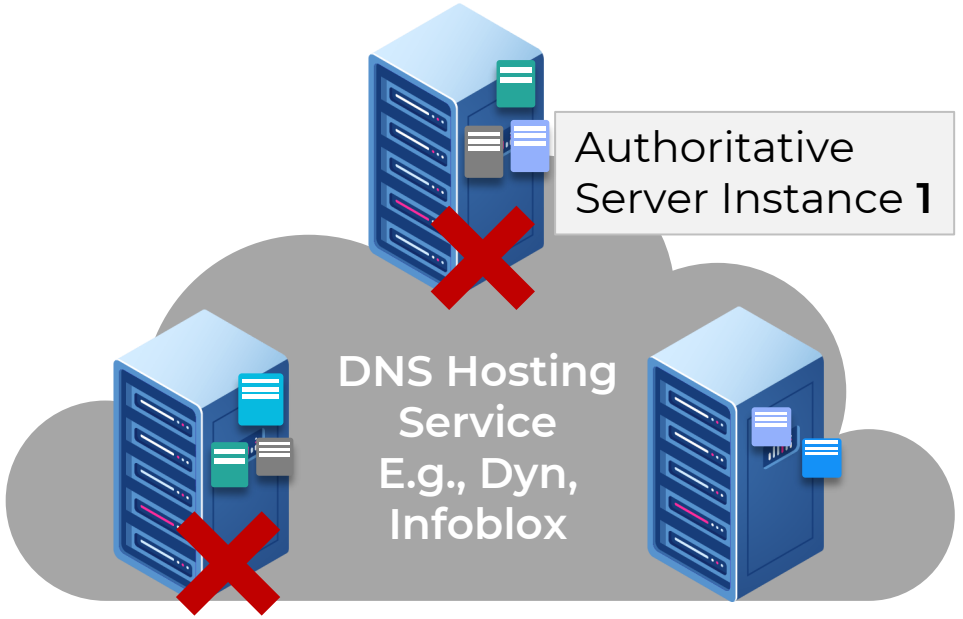
| Domain Name | Type | Data |
|---|---|---|
| attack.com. | SOA | ns1.exm. … |
| foo.attack.com. | DNAME | com. |

Attacker

1 Host `attack.com` zone file

2 Query for:

⟨`foo.attack.foo.attack.com.,DNAME`⟩




**Crashes and takes down other customer zone files – Remote DoS Attack**

# BIND Crash Remote Exploitation

**Scenario 1: Attack on a DNS hosting service that uses BIND**

**Scenario 2: Attack on a public BIND DNS Resolver**

# BIND Crash Disclosure

**Scenario 1: Attack on a DNS hosting service that uses Bind**

Initiated a responsible disclosure with BIND

**Scenario 2: Attack on a public BIND DNS Resolver**

Affected all maintained BIND versions affecting NetApp, Ubuntu, Infoblox, and Red Hat.

**CVE:** CVE-2021-25215

**Document version:** 2.0

**Posting date:** 28 April 2021

**Program impacted:** BIND

**Versions affected:** BIND 9.0.0 -> 9.11.2
BIND Supported Preview Edition, as well

**Severity:** High

**Exploitable:** Remotely

**Description:**

DNAME records, described in RFC 6672,

# Previously Unknown BIND Crash Bug

**Tool Generated Test Case**

**1. Zone file**

| Domain Name | Type | Data |
|---|---|---|
| attack.com. | SOA | ns1.exm. … |
| foo.attack.com. | DNAME | com. |

⟨foo.attack.foo.attack.com.,DNAME⟩

**2. Query**

⟨foo.attack.foo.

attack.com.,DNAME⟩

**BIND Server**

**Joint auto generation of query and zone file is required**

# Standard Automated Testers are Insufficient

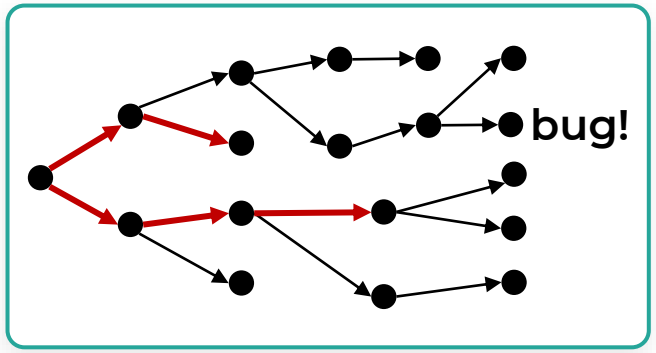
**Fuzz testing for DNS Implementations**

- ✓ Scalable to large codebases
- ✗ Can't navigate complex semantic requirements and dependencies to generate zone files
- ✗ **Generates queries only to check zone file parsers**
- ✗ No coverage guarantees

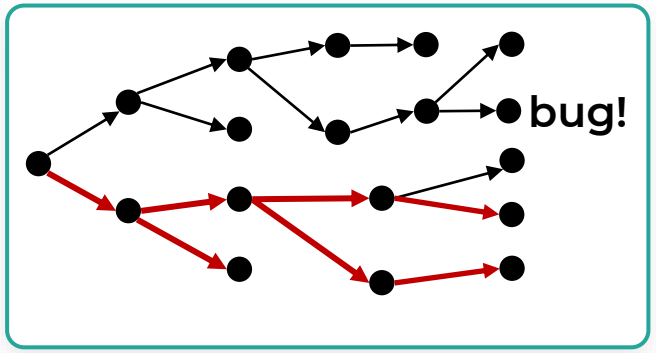
**Symbolic execution for DNS Implementations**

- ✓ Solves for path input conditions
- ✗ Path explosion and difficulty with complex data structures
- ✗ Explores a subset of implementation paths
- ✗ **Coverage guarantees in theory**

**Current automated testers for DNS do not generate zone files and hence do not find RFC violations**




**DNS Nameserver Implementation (BIND)**



# Our Approach

- **S** Small-scope
- **C** Constraint-driven
- **A** Automated
- **L** Logical
- **E** Execution

- **Jointly** generates zone files & queries
- Covers many **different** RFC behaviors
- Applicable to **black-box** implementations

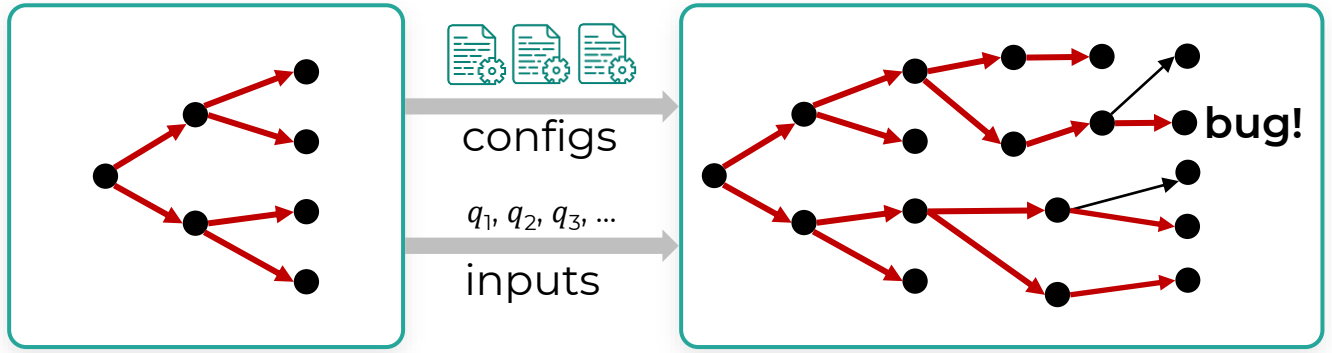
**Specification of DNS**
**RFCs 1034, 4592, 6672, ...**

# Our Insight

- **S** Small-scope
- **C** Constraint-driven
- **A** Automated
- **L** Logical
- **E** Execution

**Use DNS formal model to guide test generation**

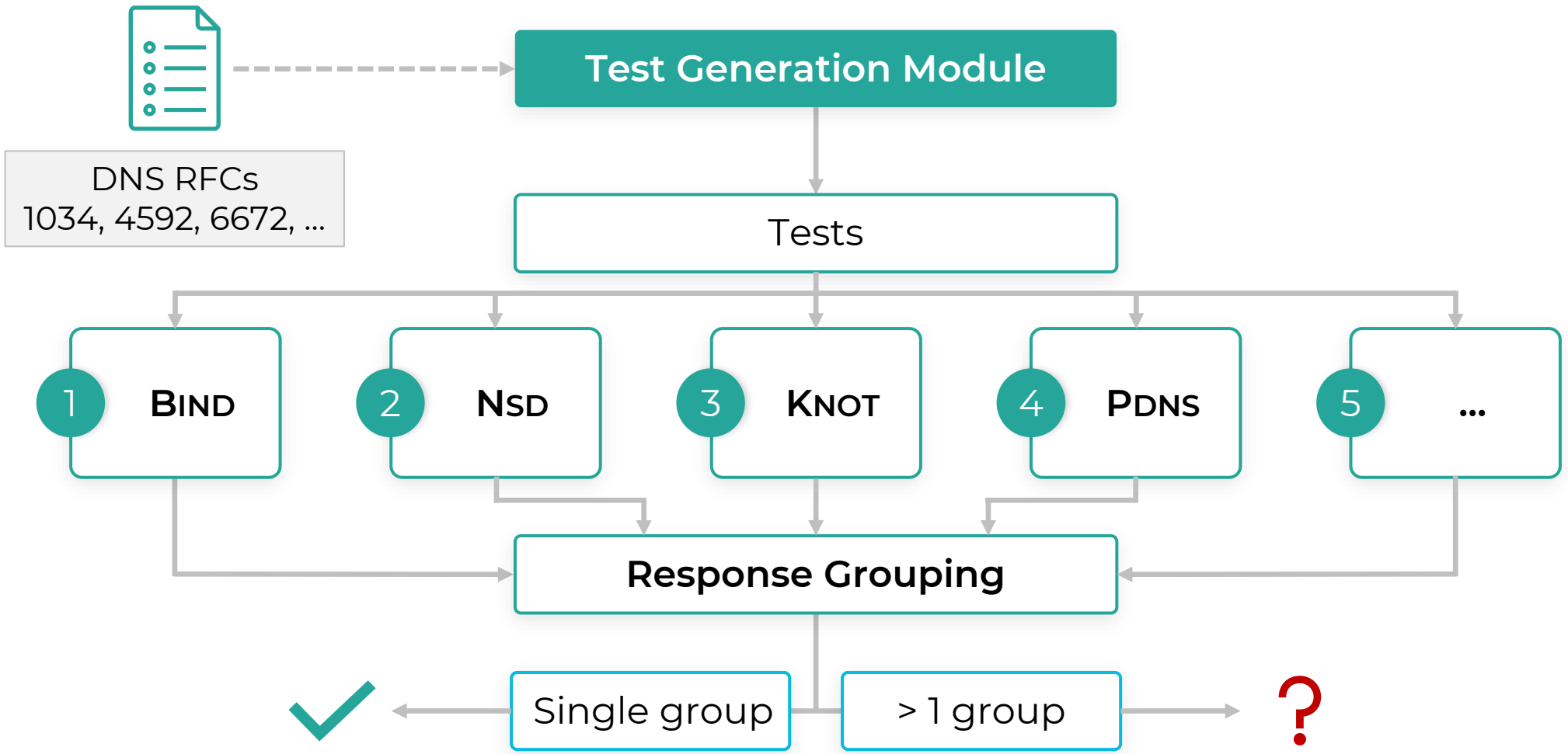
**High RFC behavior coverage – Tests cover all return points (different RFC scenarios) in the logical model**




**DNS logical model from RFCs**

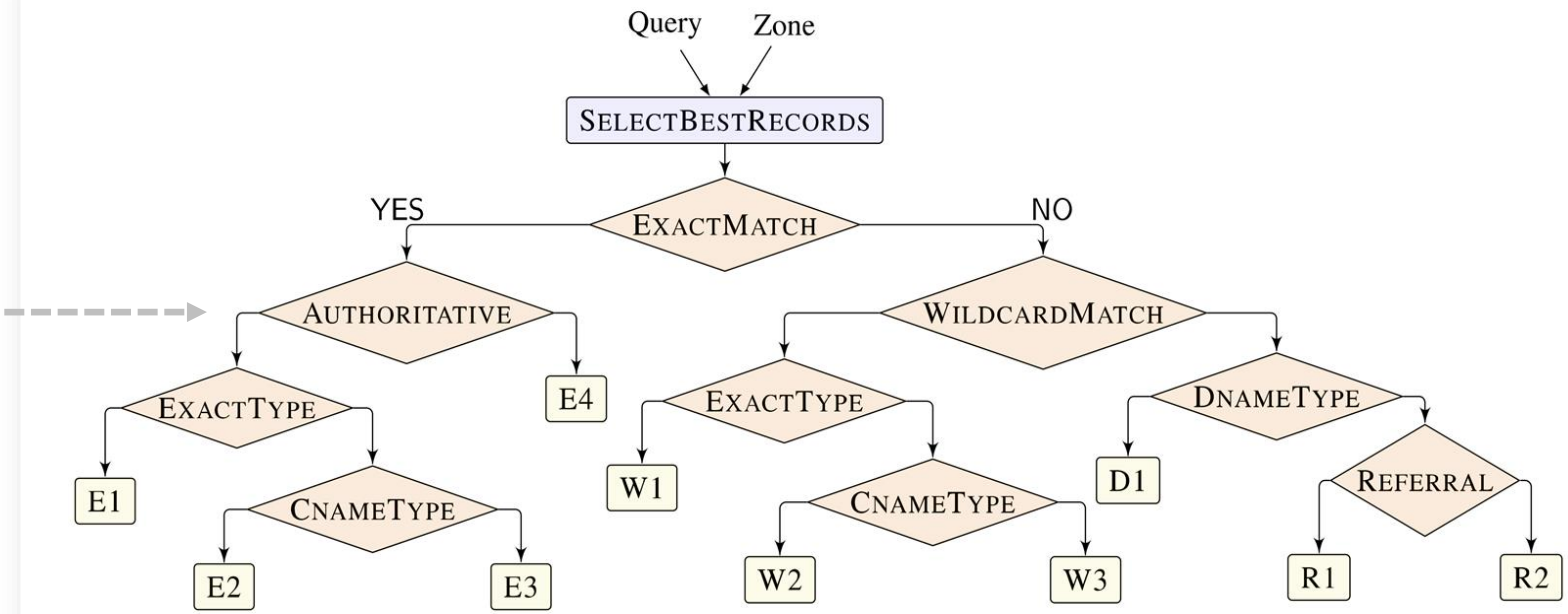
**DNS Nameserver Implementation (BIND)**

# FERRET: Tool based on SCALE for DNS



# Test Generation Module

Formal Model †




RFCs
1034, 4592, 6672, ...

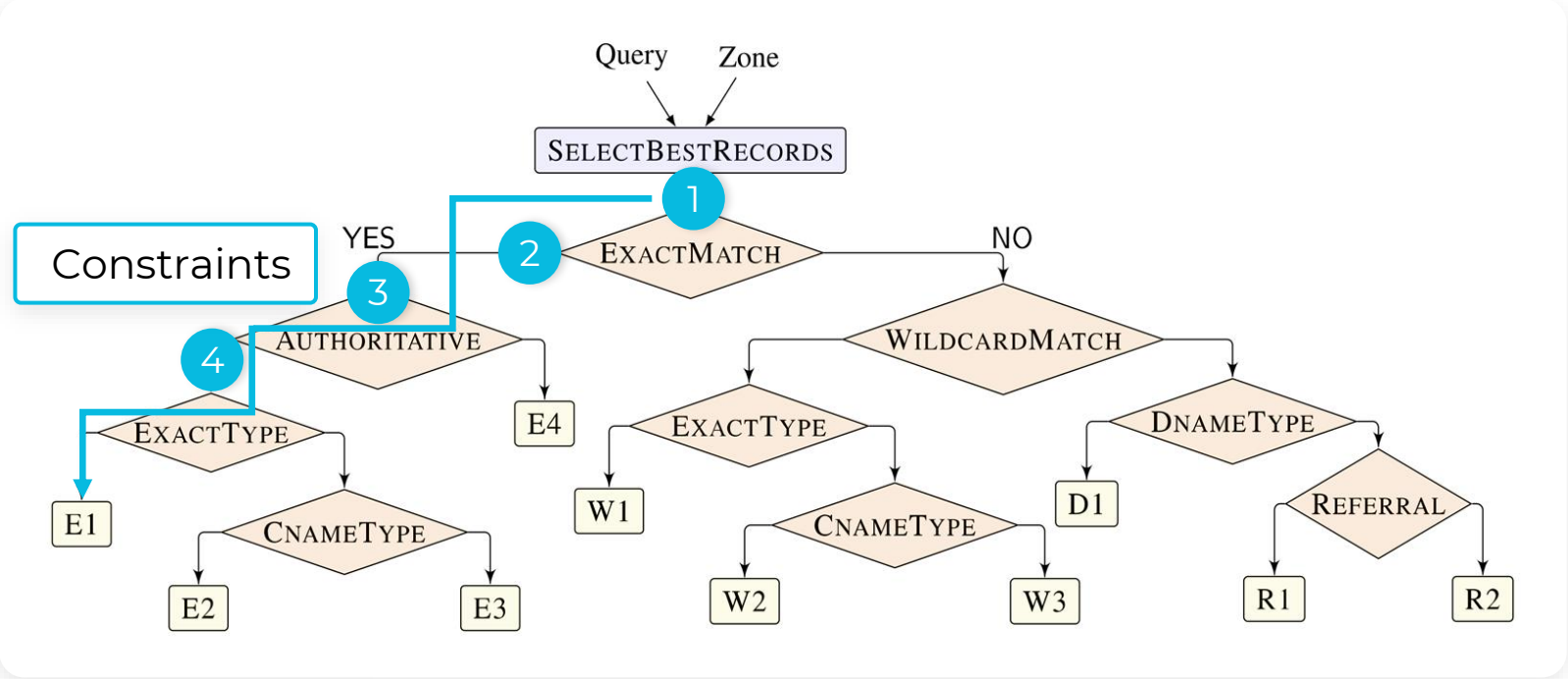
English

Declarative (Mathematical) specification of the nameserver logic

† GROOT: Proactive Verification of DNS Configurations – Siva Kakarla et al., SIGCOMM 2020

# Test Generation Module

Formal Model




Constraints

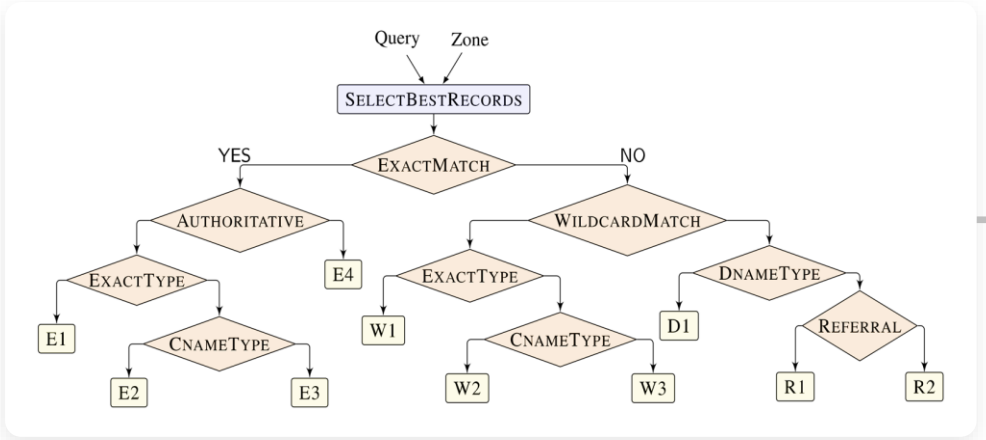
Symbolic Execution

Solve (1,2,3,4) for inputs → $(z, q)$

# Test Generation Module

Formal Model

Executable version in Zen




```
Zen<Response> QueryLookup(
  Zen<Query> q,
  Zen<Zone> z)
{
  var records = SelectBestRecords(q, z);
  var rname = records.At(0).Value().Name();
  var types = records.Select(r => r.Type());

  return If(
    rname == q.Name(),
    ExactMatch(records, q, z),
    If(
      IsWildcardMatch(q.Name(), rname),
      WildcardMatch(records, q, z),
      If(
        types.Any(t => t == RType.DNAME),
        Rewrite(records, q),
        If(
          And(types.Any(t => t == RType.NS),
              Not(types.Any(t => t == RType.SOA))),
          Response(Tag.R1,
            Delegation(records, z), Null<Query>()),
          Response(Tag.R2, empty, Null<Query>())
    ))));
}
```

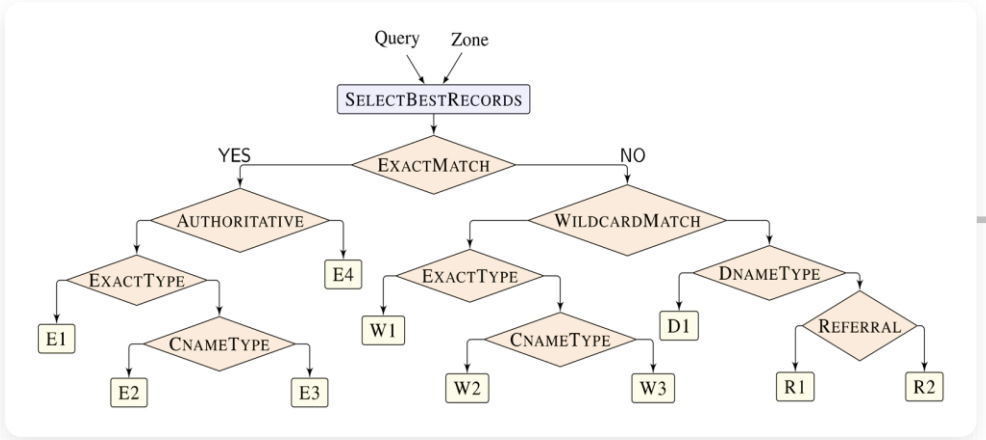
An **executable version** of formal model is implemented in **Zen**, a domain-specific modeling language embedded in **C#** with built-in support for **symbolic execution**

# Test Generation Module

Formal Model

Executable version in Zen

Tests

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    ))));
}
```

Symbolic Execution

$\langle$zone file$_1$, query$_1\rangle$

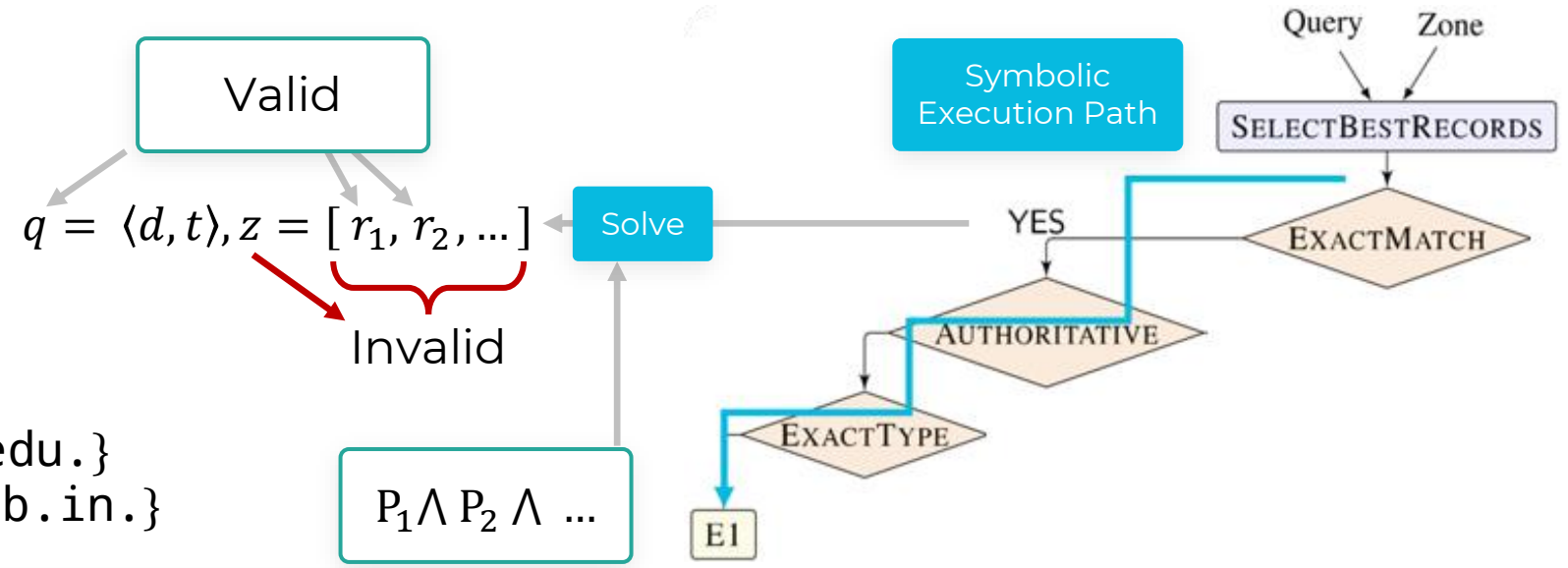
$\langle$zone file$_2$, query$_2\rangle$

...

$\langle$zone file$_n$, query$_n\rangle$

An **executable version** of formal model is implemented in **Zen**, a domain-specific modeling language embedded in **C#** with built-in support for **symbolic execution**

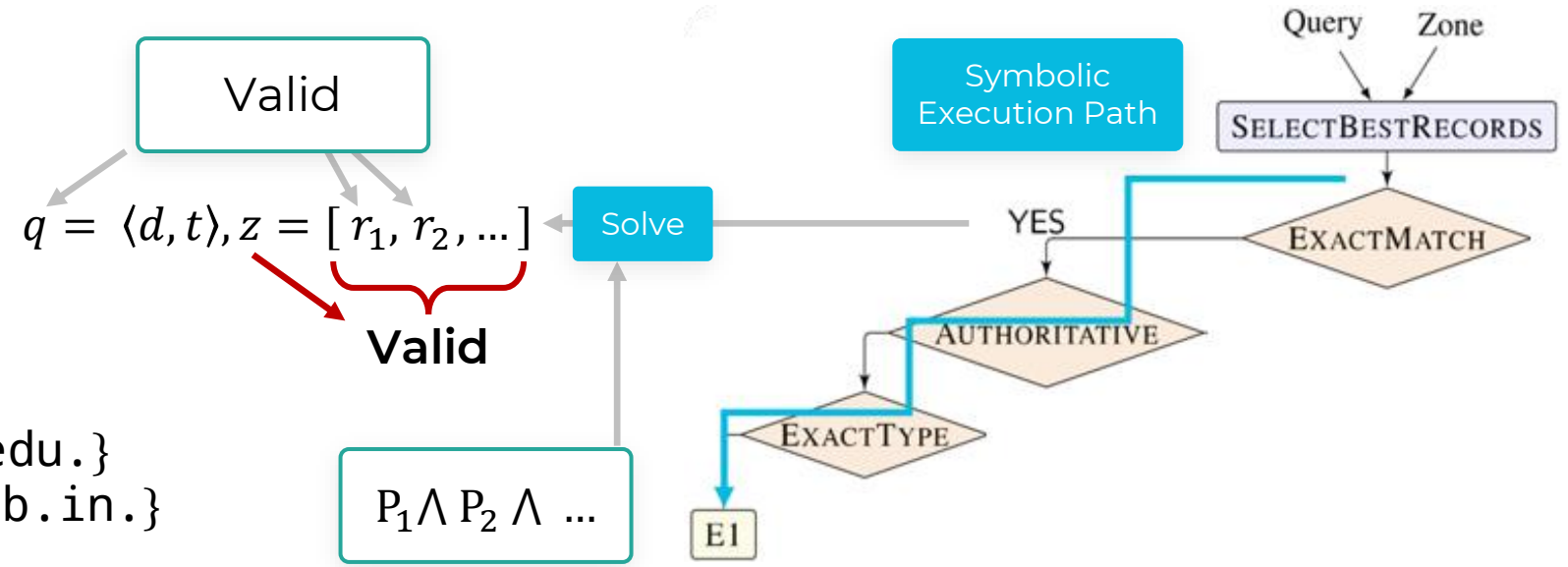
# Challenge – Generating Valid Zones




$r_1$ = {**foo.com.**,DNAME,bar.edu.}
$\Longrightarrow r_n \neq$ {**foo.com.**,DNAME,web.in.}

- Zone must satisfy several conditions to be valid
- Example condition $C_1$ - There can be only one DNAME record for a domain name
- Conditions $C_1$, $C_2$, … → Zen predicates $P_1$, $P_2$, …

# Challenge – Generating Valid Zones

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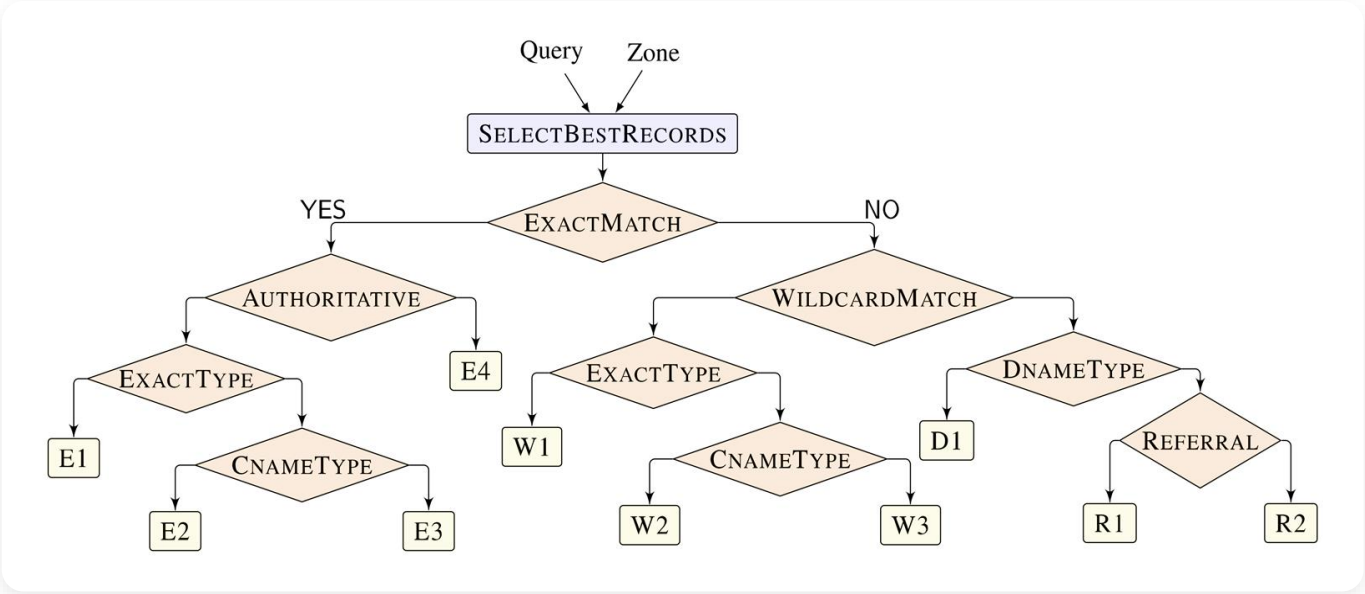
- Conditions $C_1$, $C_2$, … → Zen predicates $P_1$, $P_2$, …

We also generate invalid zone files using Zen predicates

# Exhaustive Model Coverage with Test Generation

All model leaves are covered




Using small-scope property of DNS we limit the length of each domain name & the number of records in the zone ≤ 4

| Model Case | Number of Tests |
|---|---|
| E1 | 3180 |
| E2 | 12 |
| E4 | 96 |
| W1 | 6036 |
| W2 | 60 |
| W3 | 24 |
| D1 | 18 |
| R1 | 230 |
| R2 | 2980 |
| **Total** | **12,673** |

# Bugs Found and Confirmed in Open-source DNS Implementations

| Implementation | Language | Description | Bugs found | Crashes |
|---|---|---|---|---|
| BIND | **C** | De facto standard | **4** | **1** |
| POWERDNS | **C++** | Popular in North Europe | **2** | **--** |
| NSD | **C** | Hosts several TLDs | **4** | **--** |
| KNOT | **C** | Hosts several TLDs | **5** | **--** |
| COREDNS | **Go** | Used in Kubernetes | **6** | **1** |
| YADIFA | **C** | Created by EURid (.eu) | **3** | **--** |
| TRUSTDNS | **Rust** | Security, safety focused | **4** | **1** |
| MARADNS | **C** | Lightweight server | **2** | **--** |

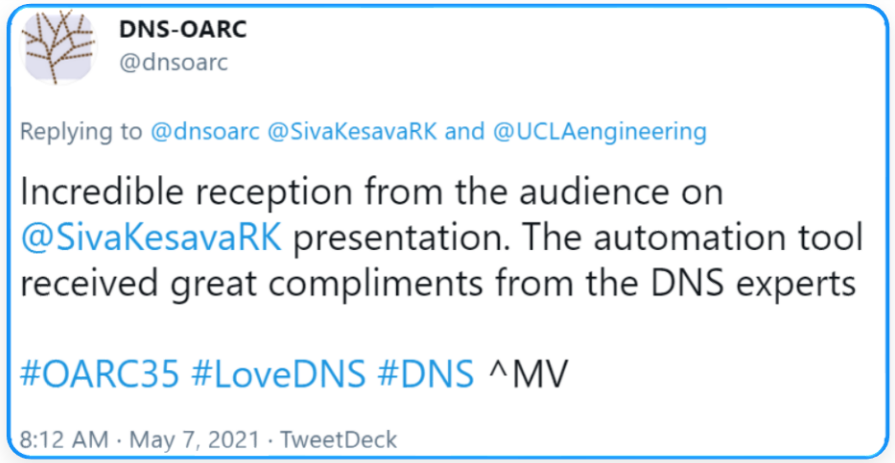
Tests part of CI/CD pipeline in **Amazon Route 53** DNS

# Comments from DNS Community

"**This is awesome**, thank you for this work, and thank you for your very clear bug reports, both to us (PowerDNS) and to other projects."

"I was not kidding about the **excellent** bug reports, by the way.."

**— Peter Van Dijik**
**(Senior PowerDNS Developer)**




"I was skeptical because I thought – why should I believe his tests, but **he proved them** by running against so many DNS servers through them"

"So, possibly new RFCs should come with their **own logic diagram** which can be used to generate the tests"

**— Vicky Risk**
**(Director of Marketing, ISC Bind)**
**And**
**Pauel Hauffman**
**(IETF & ICANN)**

# Summary

**Technical Challenge**

Must *jointly* generate structured zone files and queries in order to check RFC behavior compliance of DNS nameserver implementations

**Key Idea**

Leverages the small-scope property to build an executable model of DNS resolution and symbolically execute it to generate high-coverage tests that cover all paths in the model

**Impact**

Found dozens of bugs across 8 nameserver implementations, including 3 critical security vulnerabilities

FERRET: github.com/dns-groot/Ferret
Dataset: github.com/dns-groot/FerretDataset