black hat USA 2023

AUGUST 9-10, 2023

BRIEFINGS

MaginotDNS: Attacking the Boundary of DNS Caching Protection

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Contributor(s): Xiang Li and Qifan Zhang

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About Us

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PhD at UC Irvine

Attack Impact

Our MaginotDNS attack could poison a whole TLD, e.g., .com, at one round.

All domains under that TLD can be hijacked.

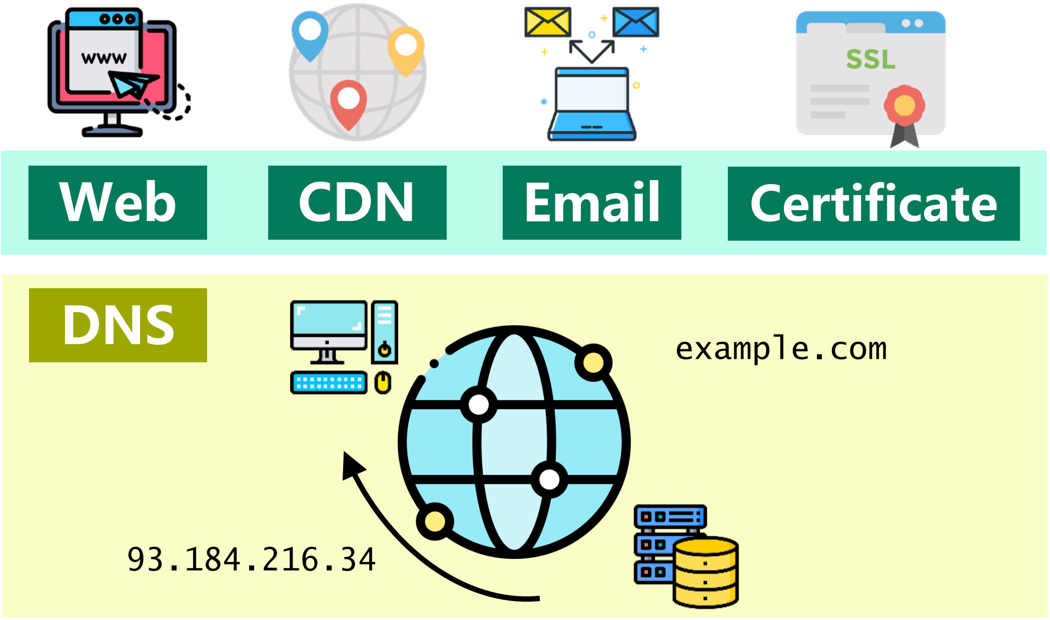
Outline

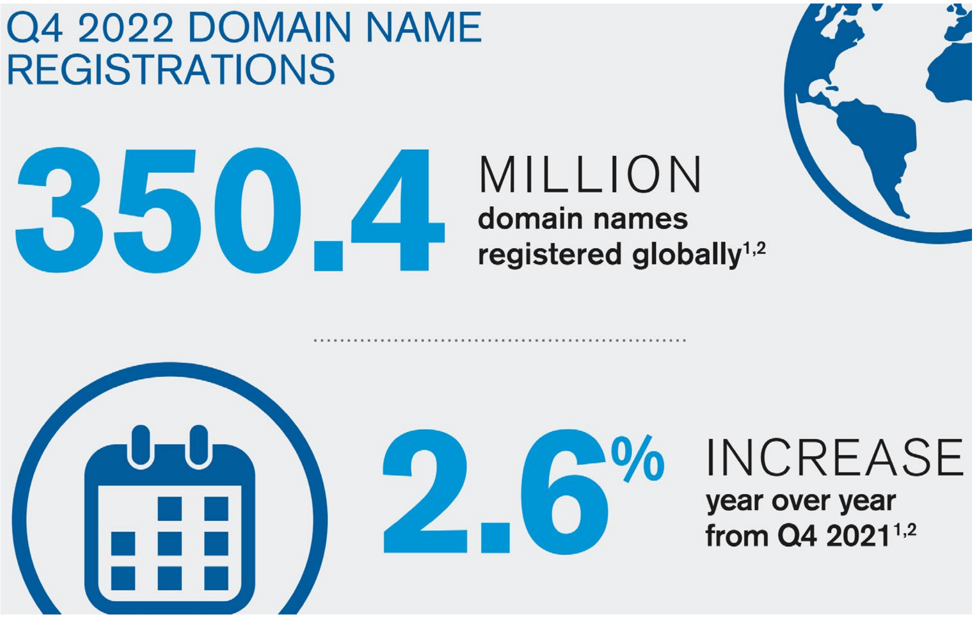
- DNS overview
- DNS cache poisoning
- MaginotDNS workflow
- Attack demo
- Large-scale scanning
- Discussion & conclusion

Domain Name System (DNS)

➢ **DNS Overview**

- ❑ Translating domain names to IP addresses
- ❑ Entry point of many Internet activities
- ❑ Domain names are widely registered



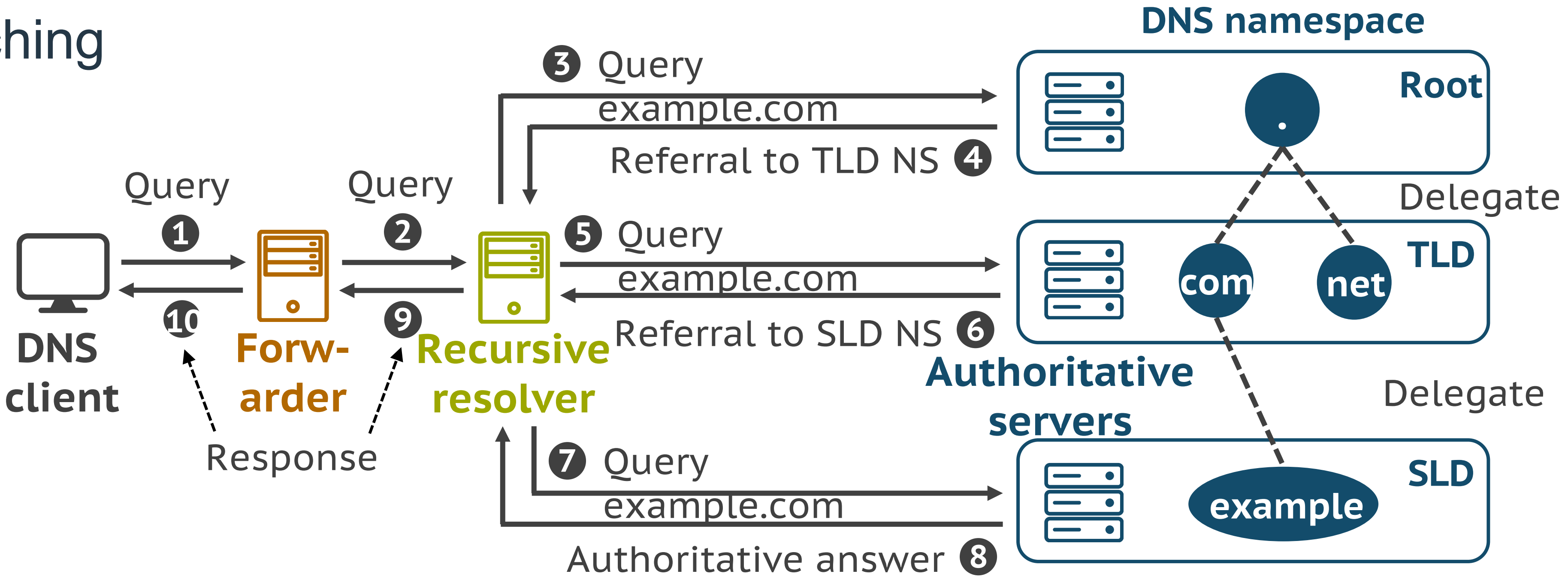


verisign.com/dnib

DNS Resolution

➢ Resolution Process

- ❑ Primarily over UDP
- ❑ Iterative and recursive
- ❑ Record caching



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- **DNS cache poisoning**
- MaginotDNS workflow
- Attack demo
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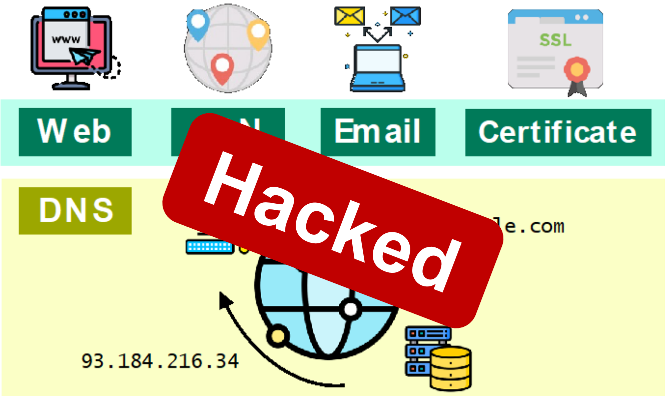
DNS Cache Poisoning

- **Target**
  - ❑ Injecting forged answers into resolvers' cache
- **Taxonomy**
  - ❑ On-path, off-path
- **Technique**
  - ❑ Cat-and-mouse game



1997 Birthday Attack

2002 Kashpureff Attack

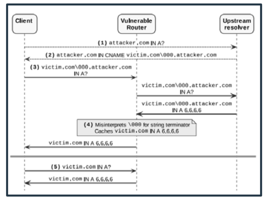
2008 Kaminsky Attack

2013 Fragmentation Attack

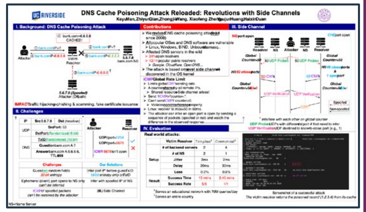
2020 Attack on Forwarders

2020 SADDNS Attack

2021 Attack via Escaped Chars



2021 SADDNS v2 Attack



2022 Attack via Escaped Chars v2

Massive DNS poisoning attacks in Brazil

INCIDENTS 07 NOV 2011 2 minute read

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

Help Net Security
October 26, 2021

Share

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

MASQUERADE PARTY —

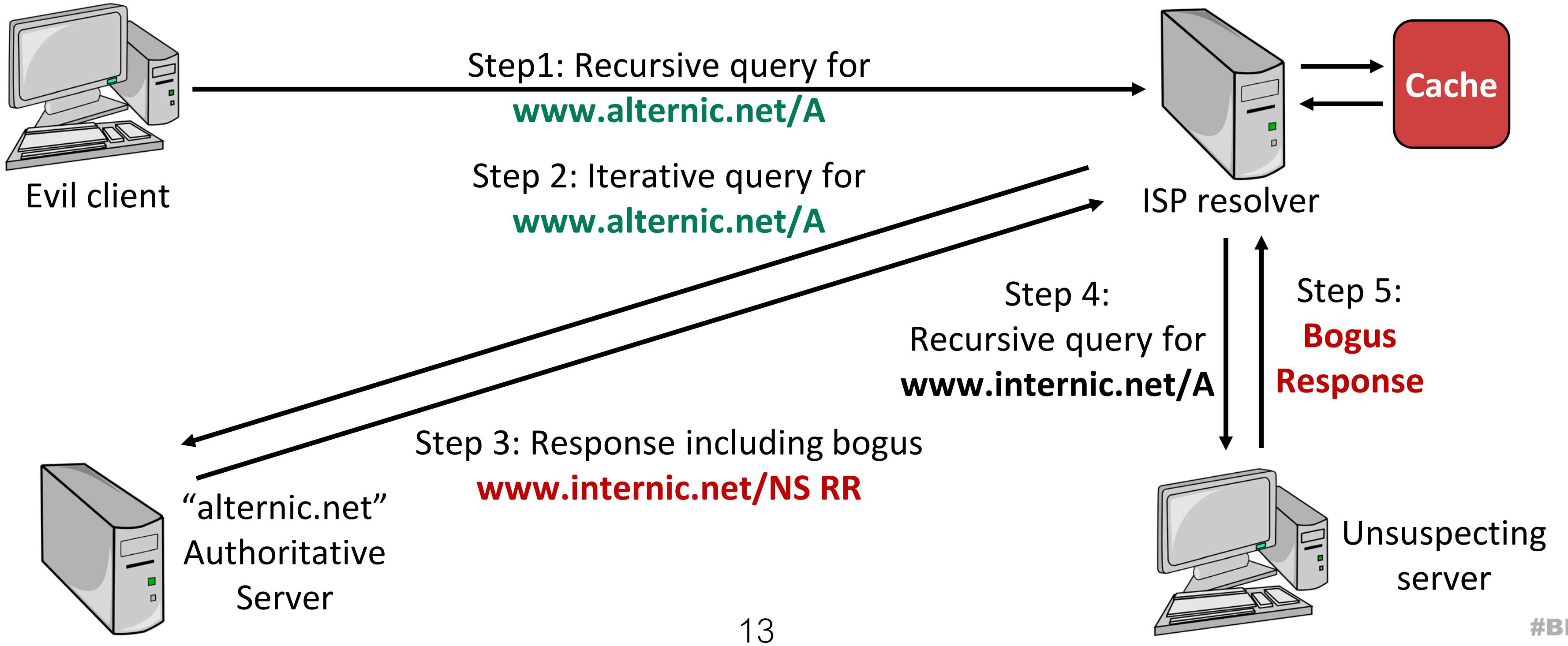
DNS cache poisoning, the Internet attack from 2008, is back from the dead

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

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

On-path DNS Cache Poisoning

- **Kashpureff Attack (on-path, 1997)**
  - ❑ Method: returning forged responses from the authoritative
  - ❑ Result: resolver accepting all records in the response
  - ❑ Cause: lacking data verification (**bailiwick rules**)



DNS Bailiwick Rules

- **Mitigating the Kashpureff Attack**
  - Record validation when storing cache entries
  - Checking for “**in bailiwick**” in response data: **answer records must be from the same domain as the requested name**

```
$ dig example.com

;; ANSWER SECTION:
example.com. 86400 IN A 93.184.216.34

;; AUTHORITY SECTION:
mybank.com. 86400 IN NS ns.mybank.com.

;; ADDITIONAL SECTION:
ns.mybank.com. 86400 IN A 1.2.3.4
```

Bailiwick

In-bailiwick
Can be trusted

Out-of-bailiwick
Should be removed

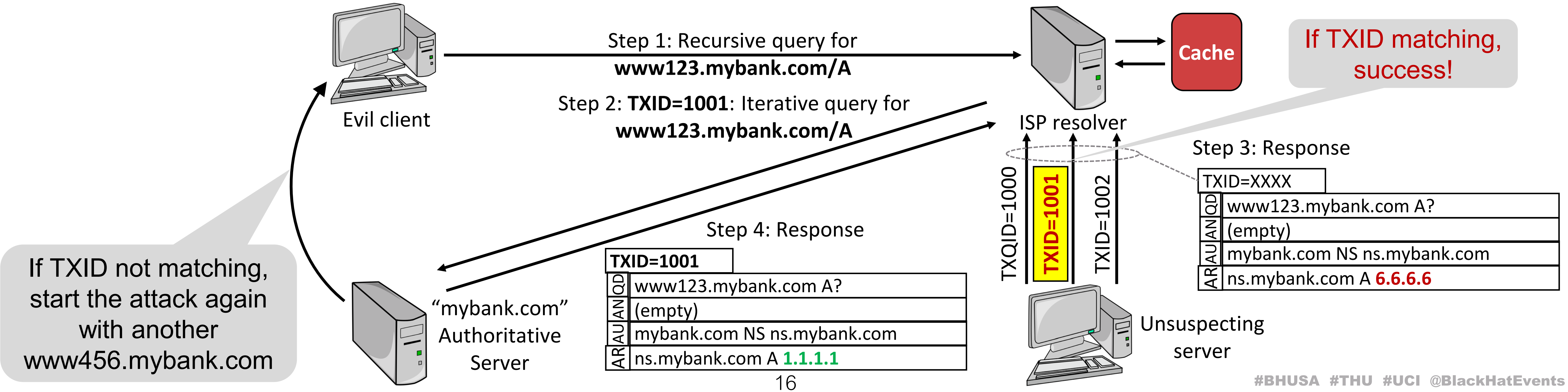
Takeaway

After the Kashpureff attack, bailiwick checking is integrated into the resolver's implementation,

DNS cache poisoning on recursives from the on-path seems **impossible** to conduct from 1997.

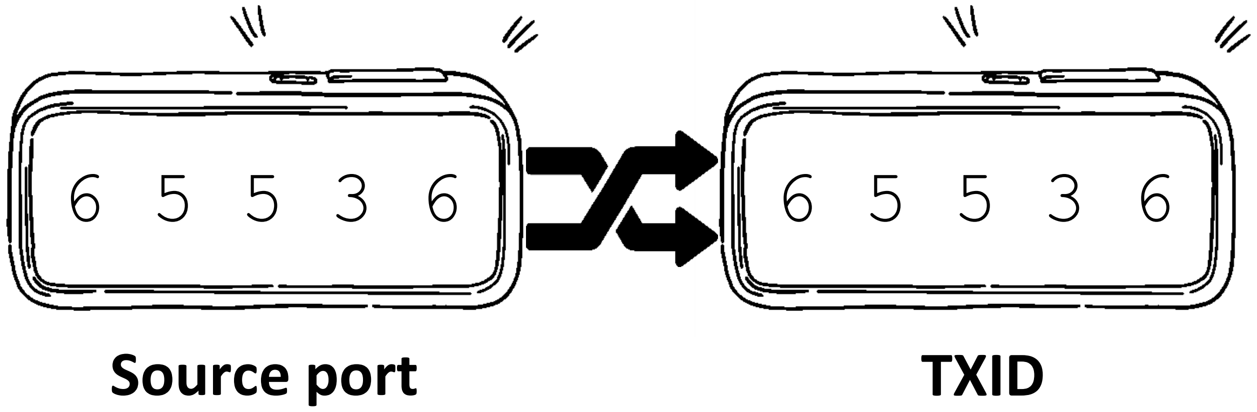
Off-path DNS Cache Poisoning

- **Kaminsky Attack (Off-path, 2008)**
  - ❑ Method: injecting forged responses with the birthday attack
  - ❑ Result: resolver accepting glue records in the response
  - ❑ Cause: lacking **source port randomization** (TXID only 16 bits)



DNS Source Port/TXID Randomization

- **Mitigating the Kaminsky Attack**
  - ❑ Increasing the query guessing entropy
  - ❑ 16-bit source port x 16-bit TXID = 32-bit space
  - ❑ **Hard to brute force**



Takeaway

After the Kaminsky attack, source port randomization is integrated into the resolver's implementation,

DNS cache poisoning on resolvers from the off-path became **difficult** to conduct from 2008.

Outline

- ➢DNS overview
- ➢DNS cache poisoning
- ➢**MaginotDNS workflow**
- ➢Attack demo
- ➢Large-scale scanning
- ➢Discussion & conclusion

Question

Are bailiwick checking and port randomization good enough?

No. **MaginotDNS** breaks this guarantee with a new powerful **cache poisoning vulnerability**.

MaginotDNS Attack

- **What is the MaginotDNS attack**
  - A new powerful DNS cache poisoning attack against **CDNS resolvers**
  - Can be launched from either **on-path** or **off-path**
  - Can poison **arbitrary domains** including **TLDs**, such as .com and .net
- **Name**
  - Exploiting **vulnerabilities** of bailiwick checking to bypass itself
  - Working like breaking the **Maginot Line** → **MaginotDNS**

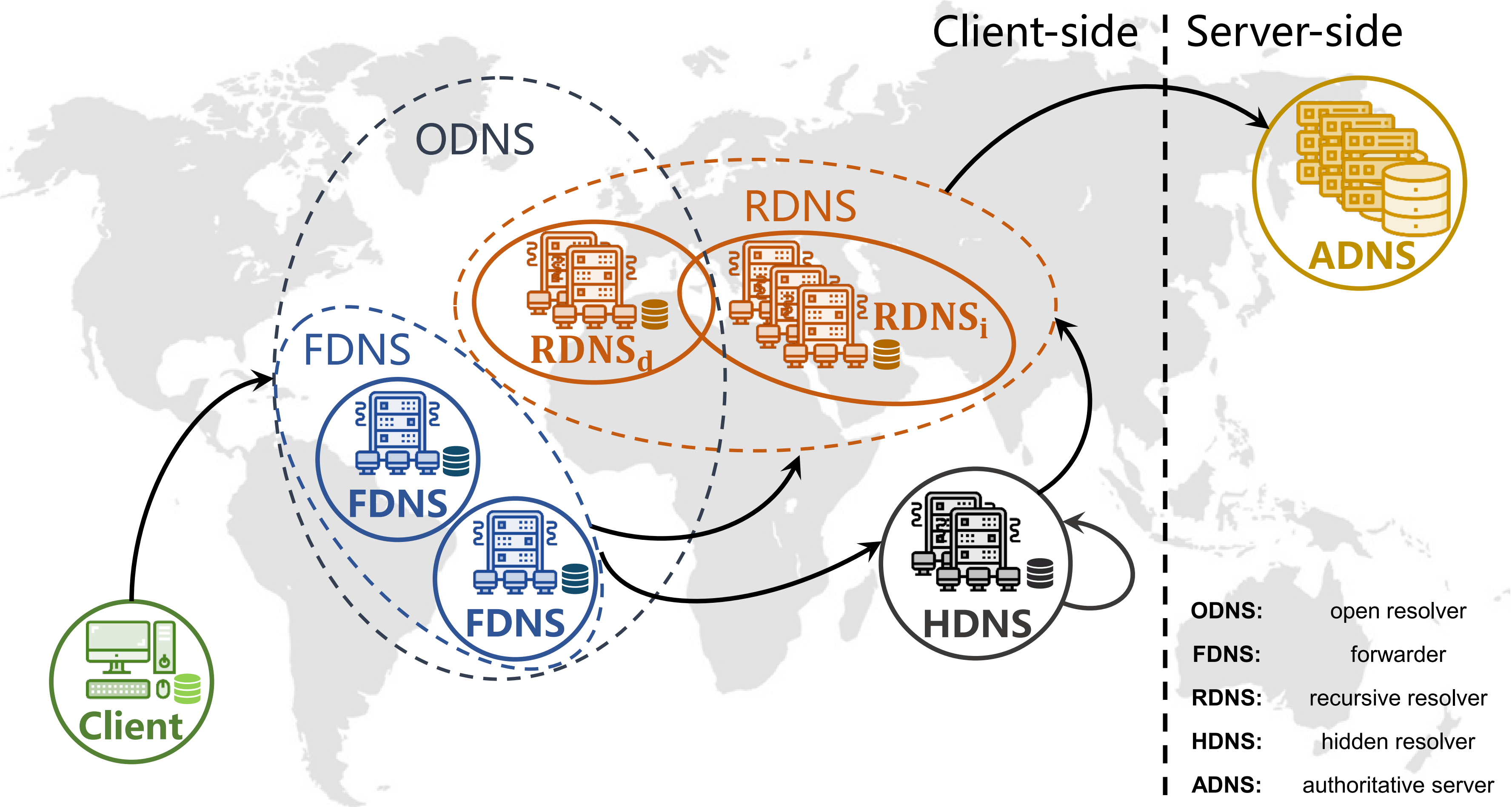
Question

What is the CDNS resolver?

A **conditional DNS resolver** with both **recursive** and **forwarding** query modes.

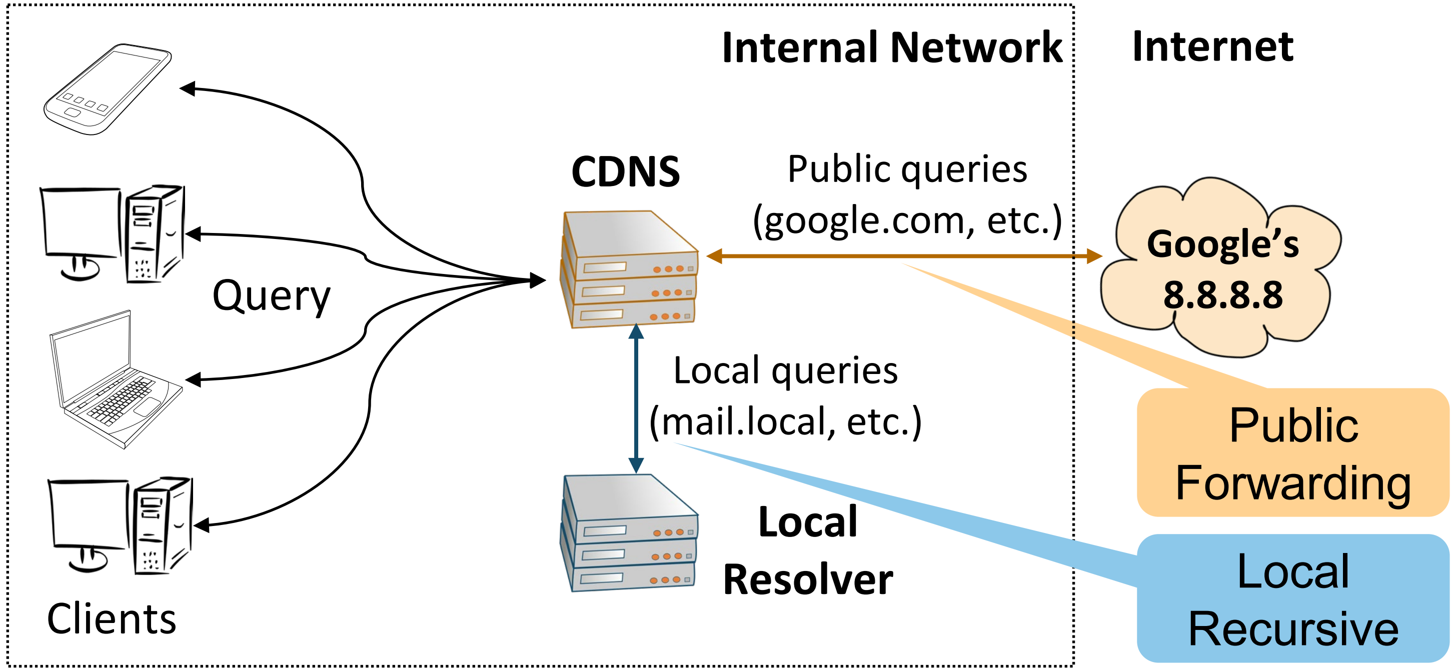
DNS Resolvers

- **Worldwide**
- **Multiple Roles**
  - Recursive, forwarder
  - Hidden DNS (HDNS)
- **Complex Interaction**
- **CDNS**
  - One of HDNSes
  - Never been studied



Attack Target: CDNS

- **Conditional DNS Resolver (CDNS)**
  - Forwarder + recursive resolver (shared cache)
  - 2 query zones used for different resolution
    - Z_F: domains for forwarding queries
    - Z_R: domains for recursive queries
- **Usage Scenarios**
  - Enterprise: splitting networks
  - ISP: reducing heavy traffic cost



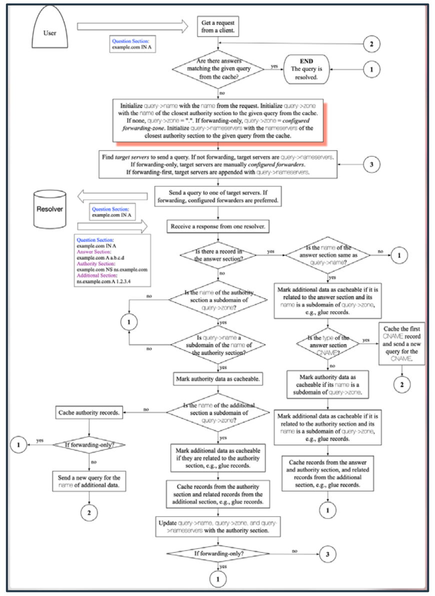
Attack Overview of MaginotDNS

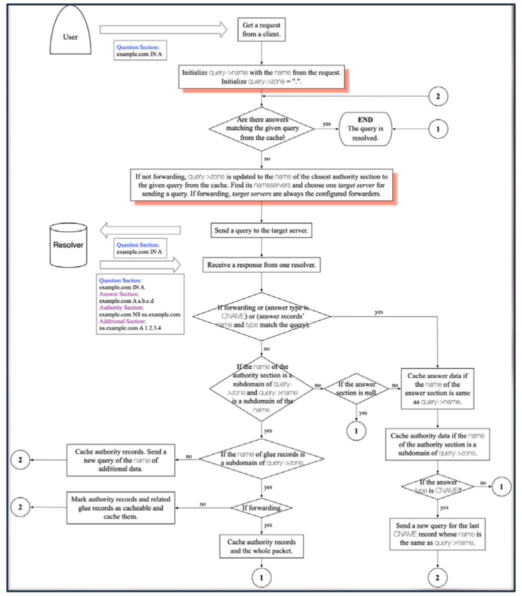
- **Threat Model**
  - Assuming we discovered a CDNS and inferred its Z_F & Z_R
  - Attacking the forwarding mode
- **Why forwarding mode?**
  - Bailiwick checking of the recursive mode is well enforced
  - But the forwarder mode is not
  - Since they share the same global DNS cache
  - We can exploit the weak forwarder mode to attack the well-protected recursive mode
    - → Breaking the boundary of DNS cache protection

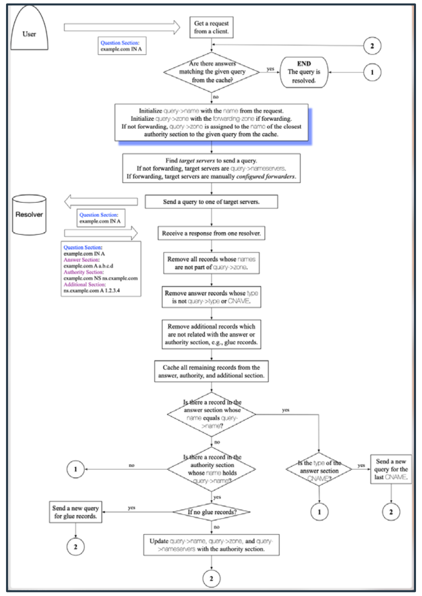
Software Analysis

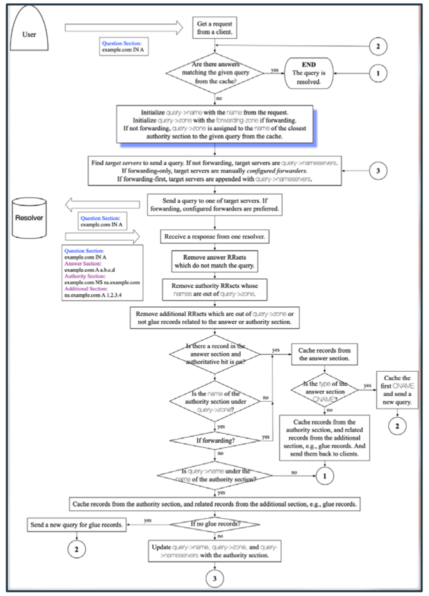
➢ Finding Vulnerable Software

- ❑ In depth **bailiwick checking implementation** analysis
- ❑ Via source code review, debugging, and testing
- ❑ 8 mainstream DNS software, e.g., BIND and Microsoft DNS


BIND


Knot


PowerDNS


Unbound

Inconsistent bailiwick checking implementations

Root Cause & Vulnerable Software

➢ General Bailiwick Checking Logic

- ❑ Summarized by us

➢ Root Cause

- ❑ In the `InitQuery` function:
  - o `Qry.zone` is set to root → all records is **in-bailiwick** (root's subdomains)

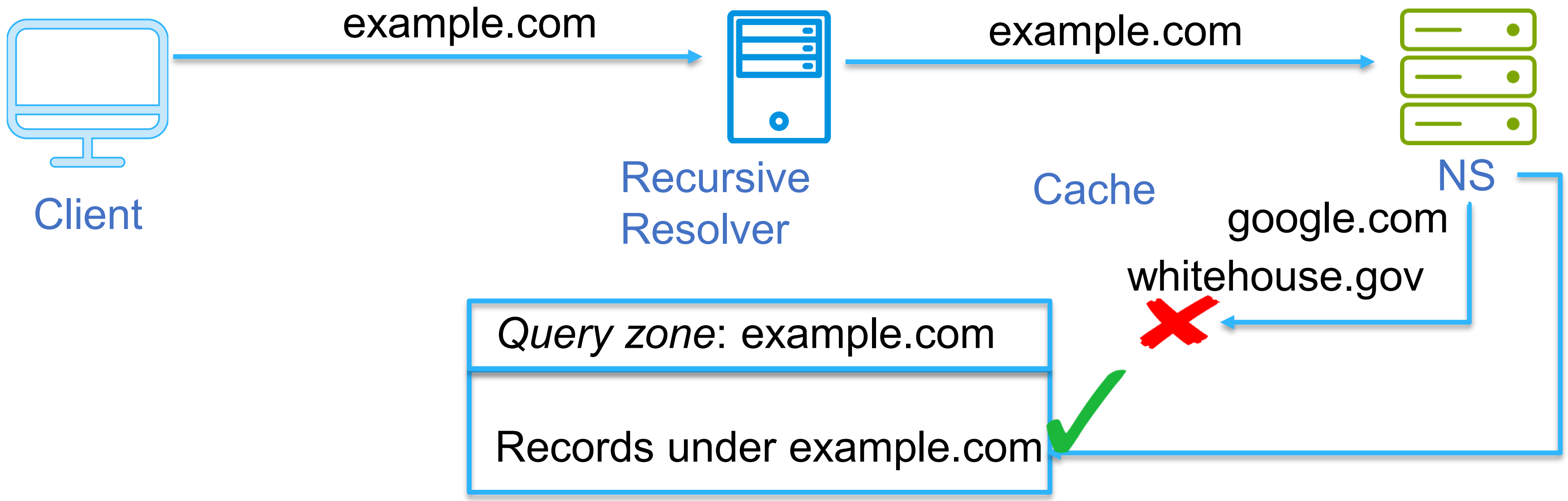
➢ Vulnerable Software

DNS Software	Forwarding	Recursive	Vulnerable
BIND9	Enabled	Enabled	Yes
Knot Resolver	Enabled	Enabled	Yes
Microsoft DNS	Enabled	Enabled	Yes
Technitium	Enabled	Enabled	Yes

Algorithm 1: DNS resolution process

```
input  : A DNS Request from clients
output : A DNS Reply to clients
main()
    step_0: InitQuery(Q, Request)
    step_1: if SeachCache(Q, Cache) then
        goto final
    step_2: FindServers(Q, TgtSvrs)
    step_3: SendQuery(Q, TgtSvrs)
    step_4: ProcessResponse(Q, R)
        if ServerIsError(Q, R) then
            goto step 3
        if not MatchQuery(Q, R) then
            goto final
        SanitizeRecords(Q, R)
        if IsReferral(Q, R) then
            if not IsFwding() then
                UpdateQuery(Q)
                goto step 2
        if IsCNAME(Q, R) then
            UpdateQuery(Q)
            goto step 1
        CacheRecords(R, Cache)
    final: ConstructReply(Reply)
    return Reply
InitQuery(Q, Request)
    initialize Q.name, Q.type, Q.zone
    if IsFwding() then
        ModifyFwdQuery(Q)
SanitizeRecords(Q, R)
    for RR ∈ R do
        if OutofBailiwick(RR) then
            remove RR from R
UpdateQuery(Q, R)
    update Q.name, Q.type, Q.zone
```

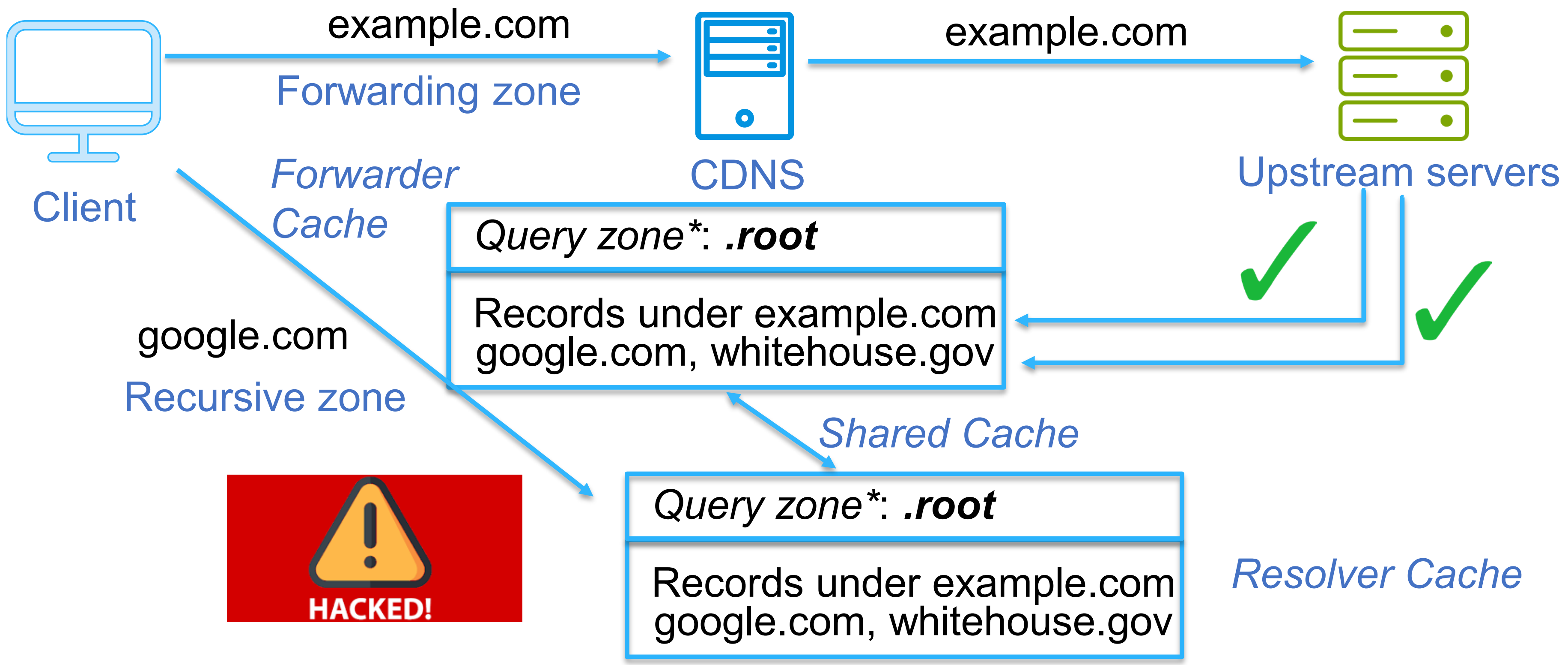
Bailiwick Checking (Done Right)



Bailiwick Checking (Done Wrong)

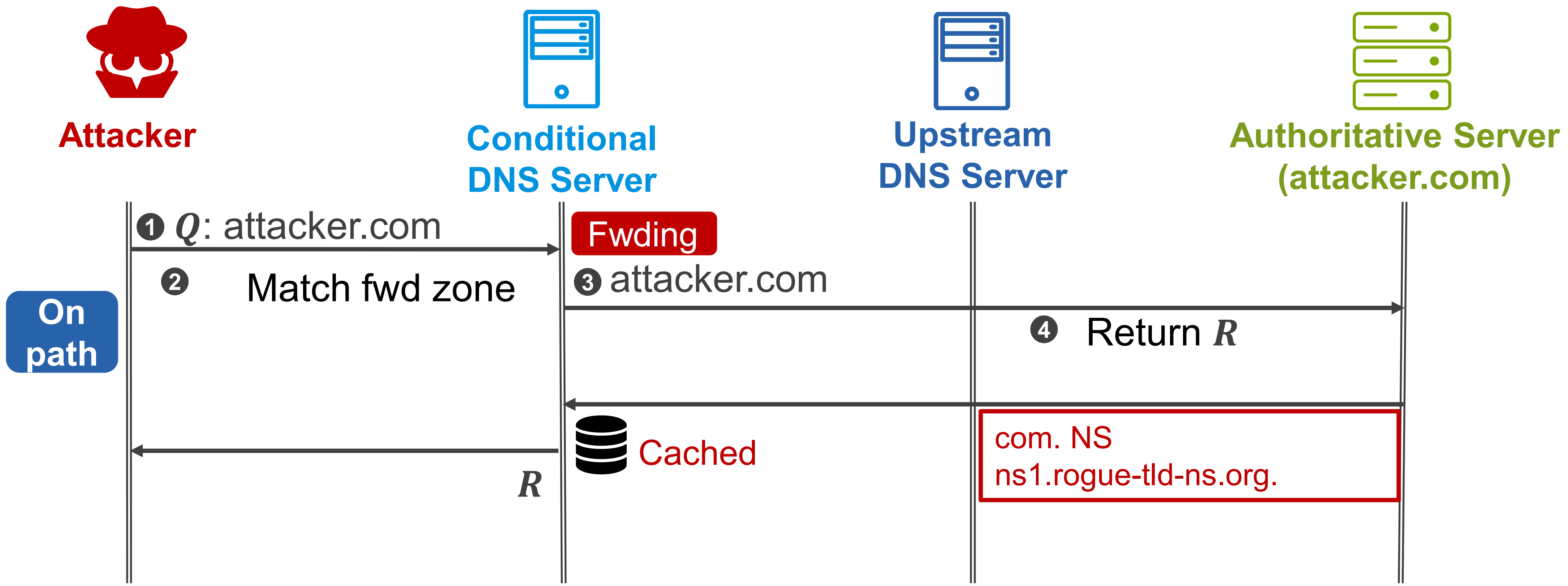
Forwarding zone: example.com

Recursive zone: {domains}-example.com



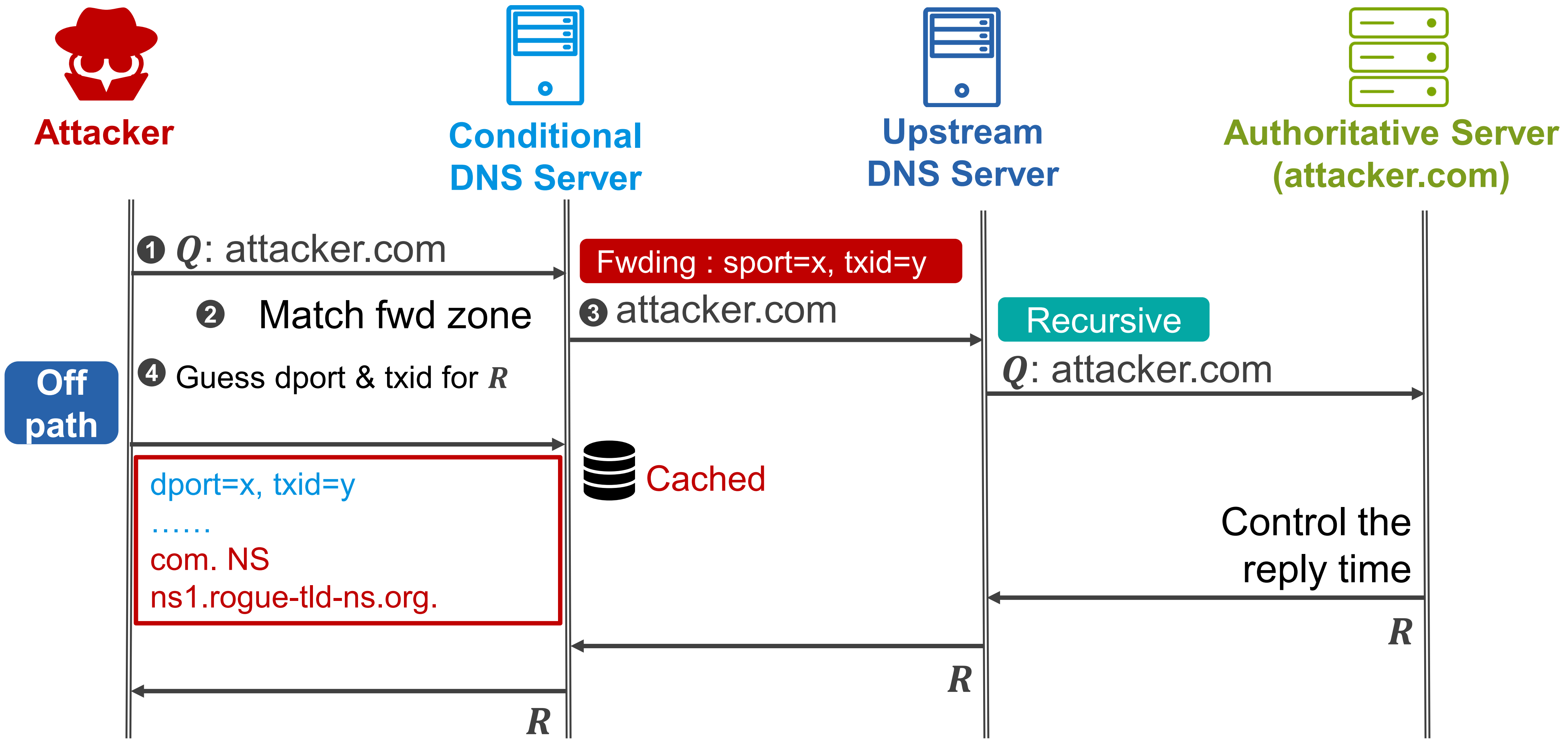
Attack Steps of MaginotDNS (On-path)

- Returning fake responses **directly**
- **BIND**, **Microsoft DNS**, **Knot**, and **Technitium**



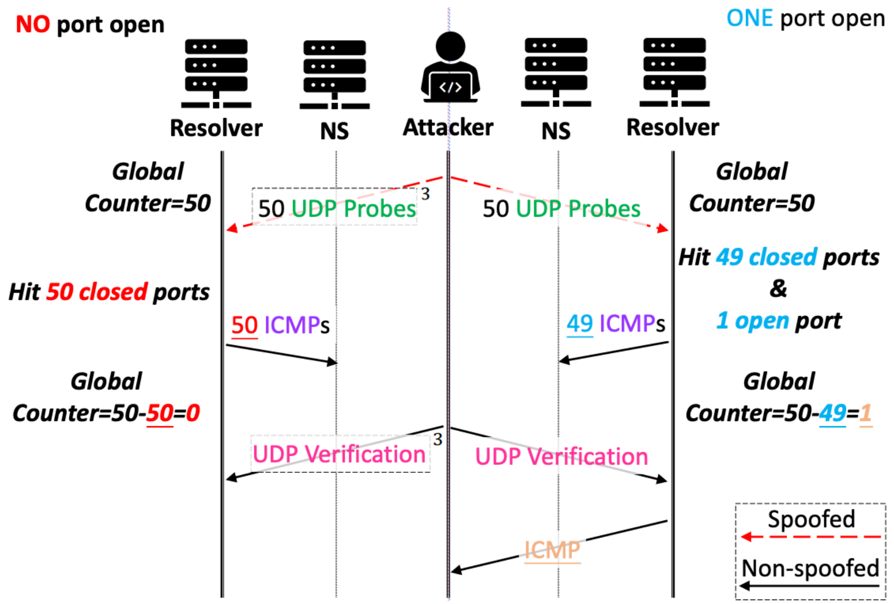
Attack Steps of MaginotDNS (Off-path)

- Guessing source port & TXID
- **Microsoft: new port vulnerability**
- **BIND9: using the SADDNS attack**



Off-path Attack on BIND9

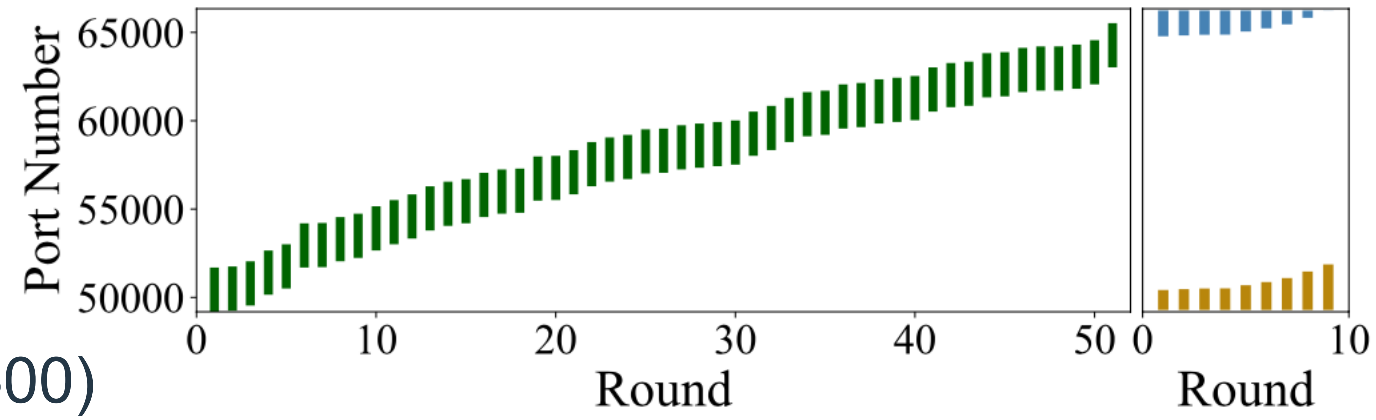
- ➢ **Guessing Source Port**
  - ❑ We use SADDNS to infer the source port
  - ❑ ICMP rate-limit side-channel (check the SADDNS paper for details)
- ➢ **Brute-forcing TXID**
- ➢ **Attack analysis**
  - ❑ Source port range: 32,768 - 60,999 (28,232)
  - ❑ Query timeout: 1.2s, guessing 50 ports each round
  - ❑ **Success rate** after 3,600 rounds:
    - ○ $1 - [(28{,}232 - 50)/28{,}232]^{3{,}600} = 99.8\%$



SADDNS https://www.saddns.net/

Off-path Attack on Microsoft DNS

- **Guessing Source Port**
  - We found MS DNS only uses **~2,500 source ports** for resolution
  - 2,500 ports are **all in the open state** (SADDNS not working)
  - **Brute-forcing** all 2,500 ports
- **Brute-forcing TXID**
- **Attack analysis**
  - Source port range: probing in advance (2,500)
  - Query timeout: 5s, guessing 20 ports each round
  - **Success rate** after 720 rounds:
    - $1 - [(2{,}500 - 20)/2{,}500]^{720} = 99.7\%$



Source Port Range Examples of Microsoft DNS

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- DNS overview
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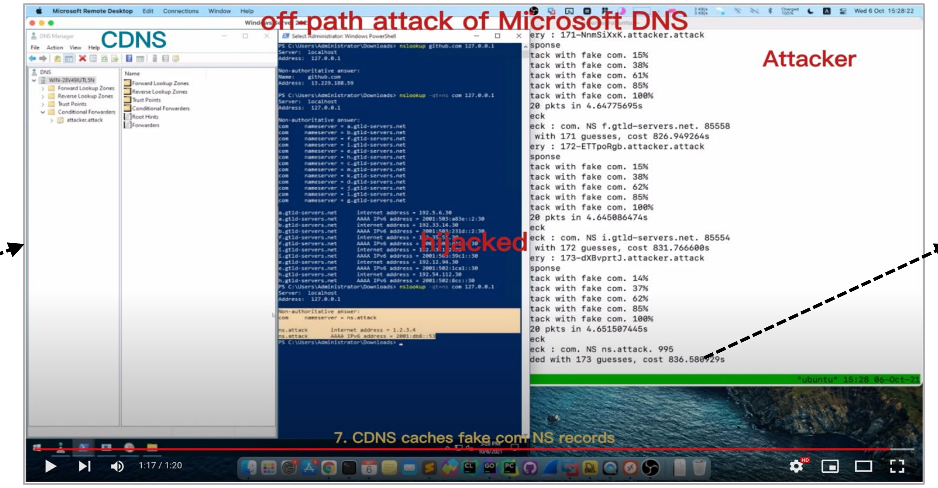
MaginotDNS Attack Demos

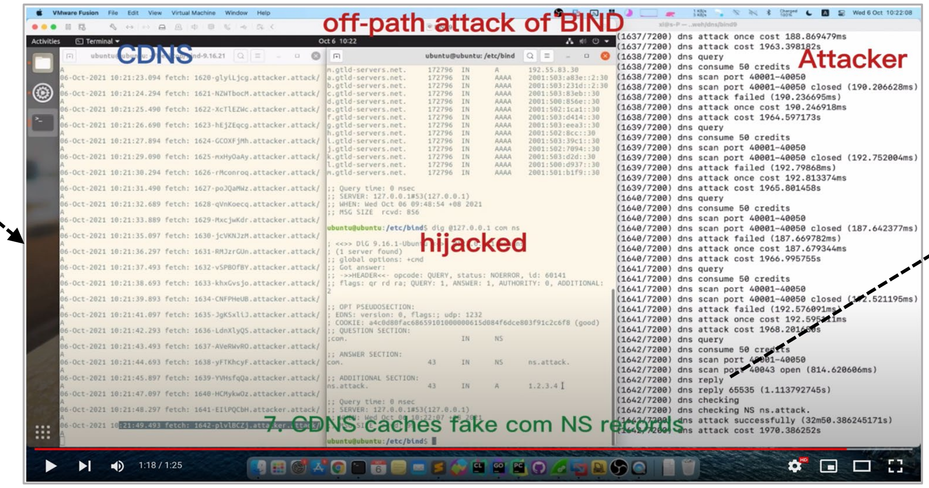
- **On-path Attack**
  - The result is determinative
- **Off-path Attack**
  - Microsoft: **avg. 802s**
  - BIND9: **avg. 790s**

Watch videos here.




```
Mon Aug  9 03:31:01 2021 : (2/360) dns query : 2-BatHkHSX.idealeer.com
Mon Aug  9 03:31:01 2021 : (2/360) dns response
Mon Aug  9 03:31:03 2021 : (2/360) dns attack with fake com. 15%
Mon Aug  9 03:31:04 2021 : (2/360) dns attack with fake com. 37%
Mon Aug  9 03:31:05 2021 : (2/360) dns attack with fake com. 60%
Mon Aug  9 03:31:06 2021 : (2/360) dns attack with fake com. 85%
Mon Aug  9 03:31:06 2021 : (2/360) dns attack with fake com. 100%
Mon Aug  9 03:31:06 2021 : to 202.112.238.57 : 1310720 pkts in 4.632276358s
Mon Aug  9 03:31:06 2021 : (2/360) dns check
Mon Aug  9 03:31:06 2021 : (2/360) dns check : com. NS gtld-servers.attack.
Mon Aug  9 03:31:06 2021 : dns attack succeeded with 2 guesses, cost 10.079395433s
```

Log of Attacking Microsoft

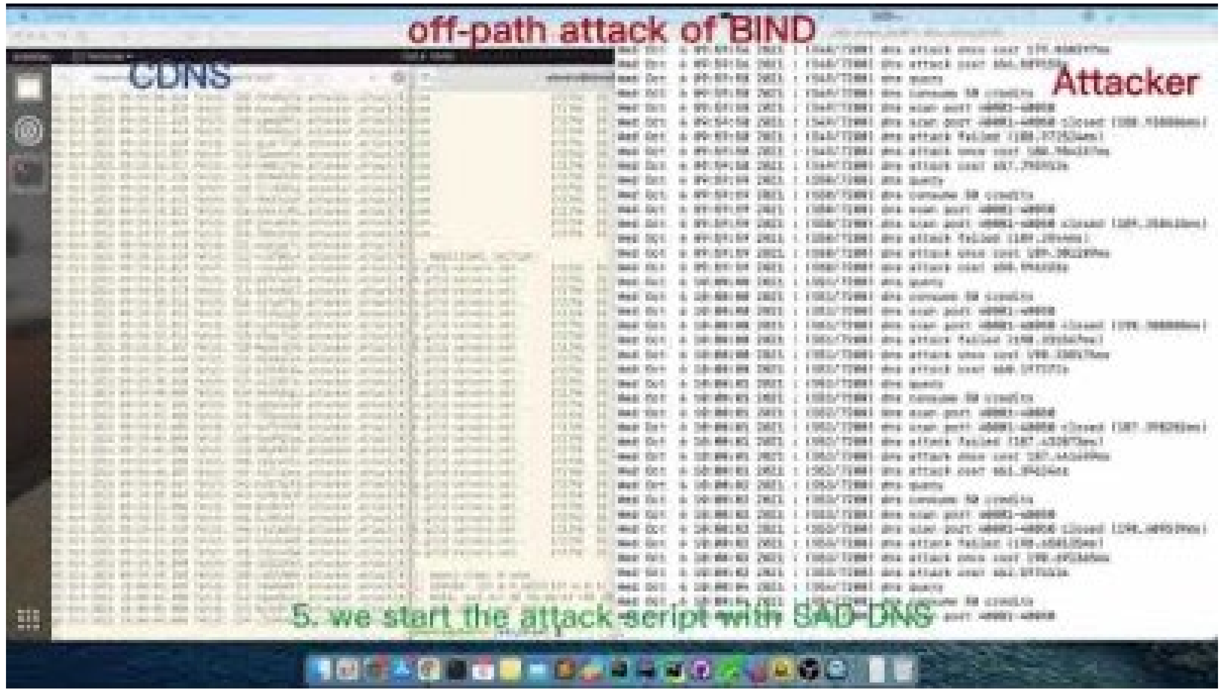



```
Thu Aug 26 23:10:53 2021 : (661/3600) dns querying
Thu Aug 26 23:10:53 2021 : (661/3600) dns consuming 50 credits
Thu Aug 26 23:10:53 2021 : (661/3600) dns scanning port 40001-40050
Thu Aug 26 23:10:54 2021 : (661/3600) dns scanning port 40020 open (651.902104ms)
Thu Aug 26 23:10:54 2021 : (661/3600) dns replying
Thu Aug 26 23:10:54 2021 : (661/3600) dns replying 65535 (928.938966ms)
Thu Aug 26 23:10:54 2021 : (661/3600) dns checking
Thu Aug 26 23:10:54 2021 : (661/3600) dns checking NS gtld-servers.attack.
Thu Aug 26 23:10:54 2021 : (661/3600) dns attack successfully (13m12.992182401s)
Thu Aug 26 23:10:54 2021 : (661/3600) dns attack cost (13m12.99219492s)
```

Log of Attacking BIND9

MaginotDNS Attack Demos

➢ **Off-path Attacks on BIND9 & Microsoft DNS**



BIND9

Microsoft DNS

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- DNS overview
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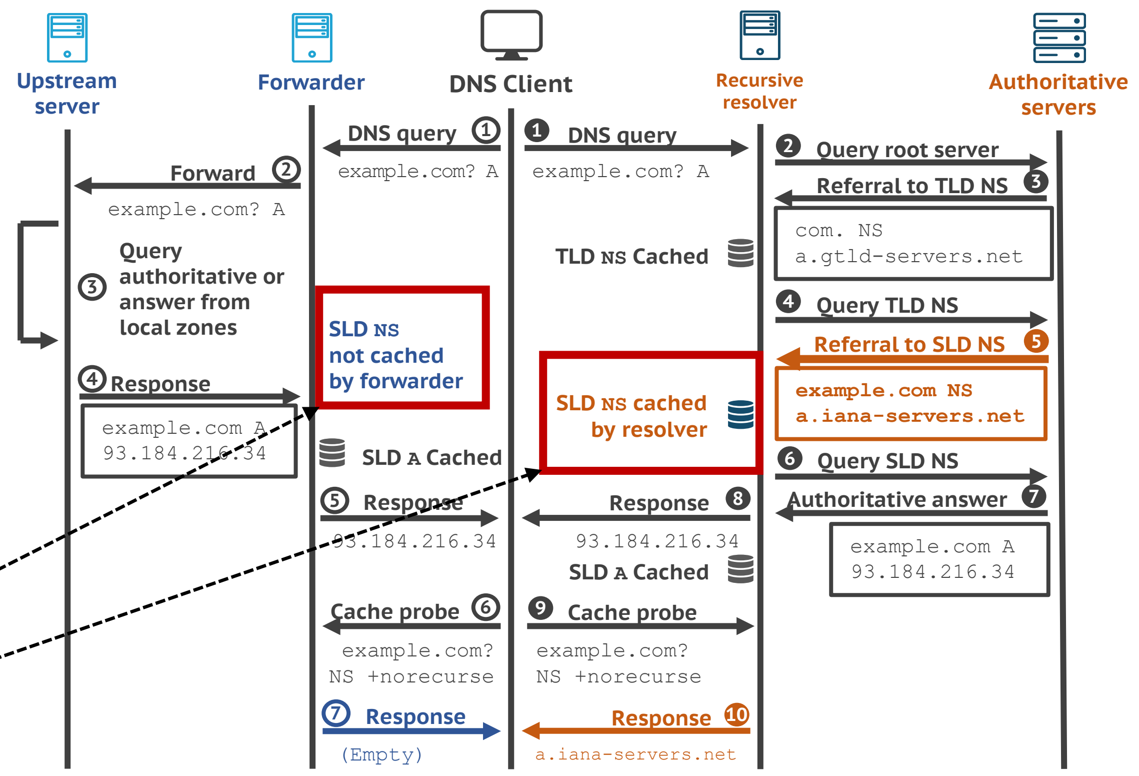
Finding Vulnerable CDNSes

- ➢ **Differentiating Forwarder & Recursive**
  - ❑ Based on the DNS resolution mechanism
  - ❑ **Forwarders** do not cache **intermediate NS records**
- ➢ **Finding CDNSes**
  - ❑ New methodology
    1. Targeting one resolver
    2. Testing a group of domains, sending **NS&NR** queries
    3. For some domains, no NS responses (**forwarding**)
    4. For others, we get NS responses (**recursive**)
    5. The resolver does **both forwarding & recursive resolution**
    6. → **CDNS identified**



Vulnerable CDNS Population

➢ Measurement

- ❑ We collected **1.2M resolvers**
- ❑ Removing not-applicable ones, such as violating NR or multiple caches
- ❑ Applying our method to identify **154,955 CDNSes**
- ❑ Using **software fingerprints** to locate **54,949 vulnerable CDNSes**
    - Resolvers with DNSSEC or 0x20 are filtered out

CDNSes identified by probing	**154,955**	**41.8%**
– Version identifiable (in CDNS)	117,306	31.7%
– by `version.bind`	59,419	16.0%
– by `fpdns`	57,887	15.6%
– OS identified for BIND (in CDNS)	19,995	5.4%
– DNSSEC validation (in CDNS)	34,424	9.3%
– 0x20 encoding (in CDNS)	1,119	0.3%

Vulnerable CDNSes	**54,949**	**14.8%**
– On-path attack possible*	**54,949**	**14.8%**
– BIND	24,287	6.6%
– Microsoft DNS	30,662	8.3%
– Off-path attack possible*	**48,539**	**13.1%**
– BIND (OS exploitable)	17,877	4.8%
– Microsoft DNS	30,662	8.3%
– Recursive-default	10,445	5.0%
– Forwarding-default	36,581	9.9%

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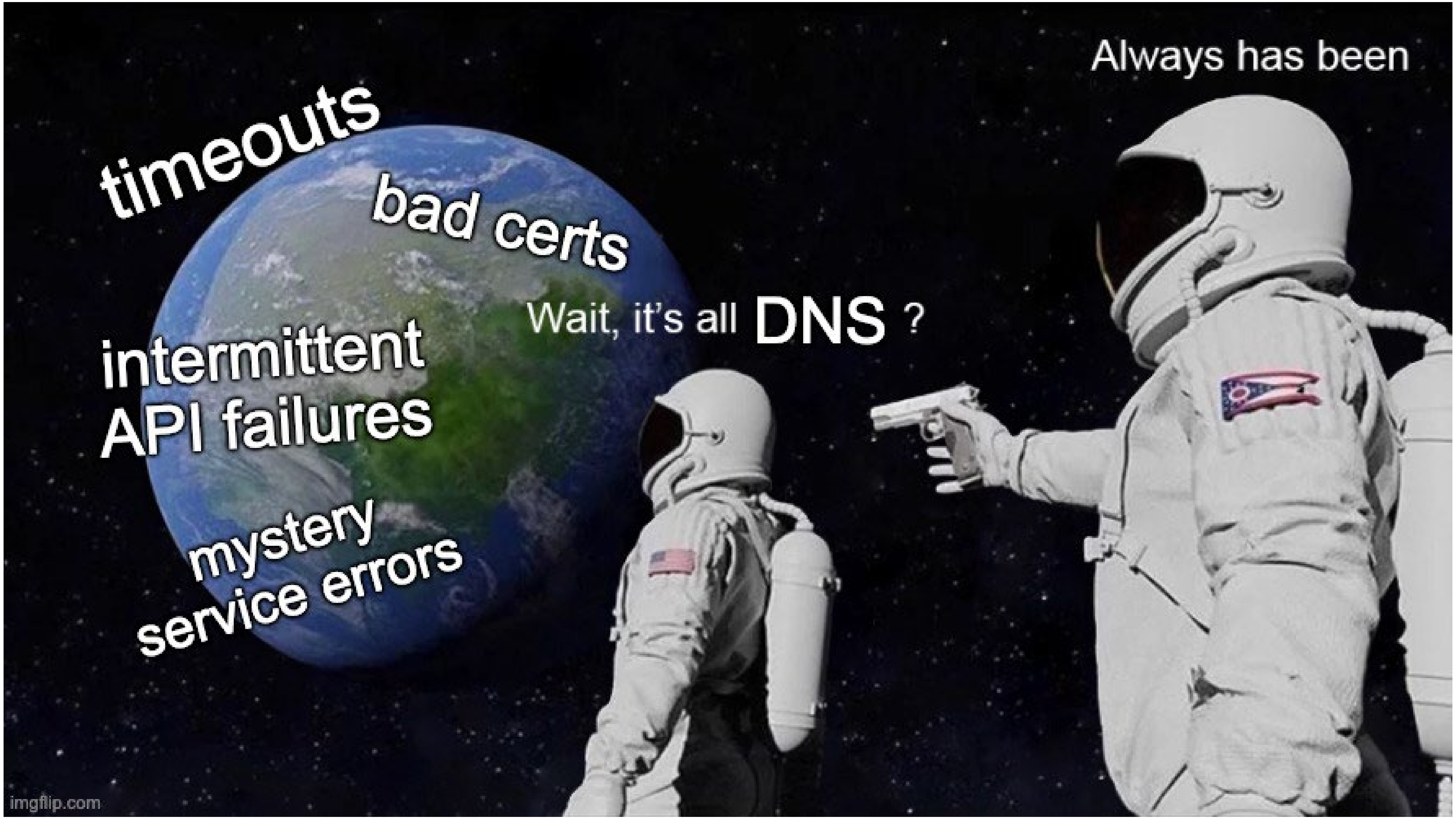
Discussion & Mitigation

- **Vulnerability Disclosure**
  - **Confirmed** and **fixed** by **all affected software**: BIND9, Knot, Microsoft, & Technitium
  - **4 CVE-ids** published & **Bounty** awarded by Microsoft
- **Root Cause**
  - Problematic forwarding bailiwick checking implementations (`Qry.zone` <- root)
    - **Why? Forwarder needs flexibility**
- **Mitigation Solution**
  - `Qry.zone` should be set to the forwarded domain in Z_F (query zone restriction)
  - Then only records under forwarded domain are acceptable (cache split)
  - Have been adopted by affected software

Black Hat Sound Bytes

- **Bailiwick checking is not bullet-proof!**
  - We thought it's perfect after **26 years** since it's born.
- **Inconsistent DNS implementations are common…**
  - Forwarder vs. resolver
  - BIND, Knot, Microsoft, ….
  - Partially caused by the vague RFCs
- **There might be more vulnerabilities we don't even know …**
  - We need **automated tools** (e.g., fuzzers) customized to analyze DNS software
  - My group is working on that ☺

MaginotDNS


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

Wrap-up

Thanks for listening!
Any questions?

Paper

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Qifan Zhang, qifan.zhang@uci.edu

Tool