Secure Nameserver Selection Algorithm for DNS Resolvers

`draft-zhang-dnsop-ns-selection-00`

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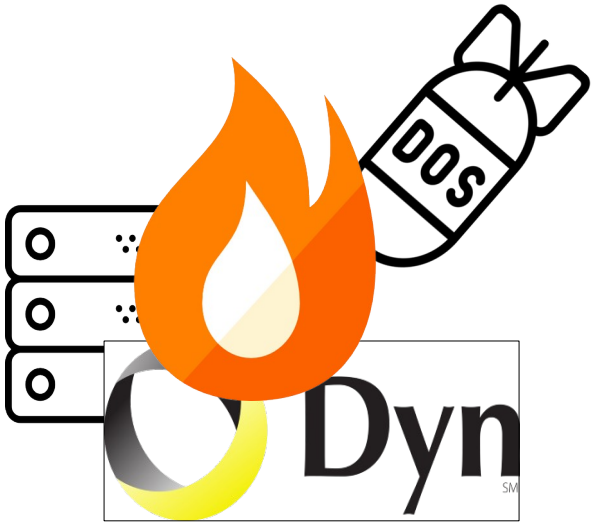
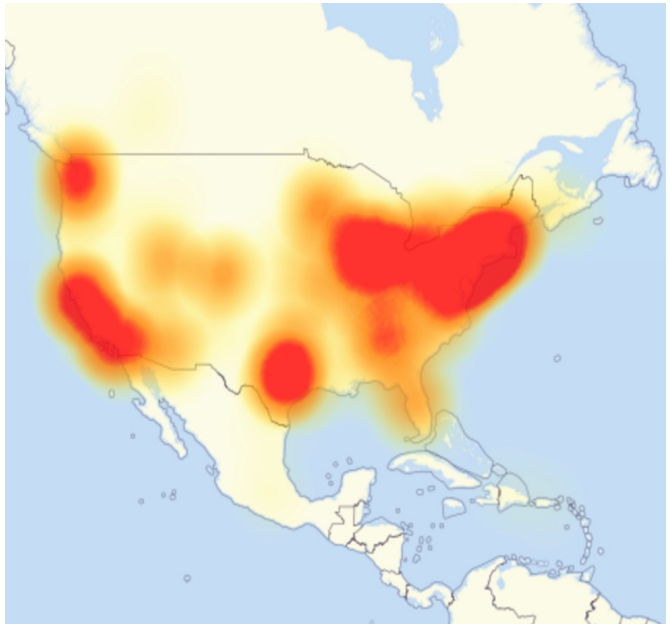
The security of DNS is critical to Internet operation

- Domain Name System (DNS) is a **cornerstone** of Internet infrastructure.
- The outage of DNS can cause **severe** influence.





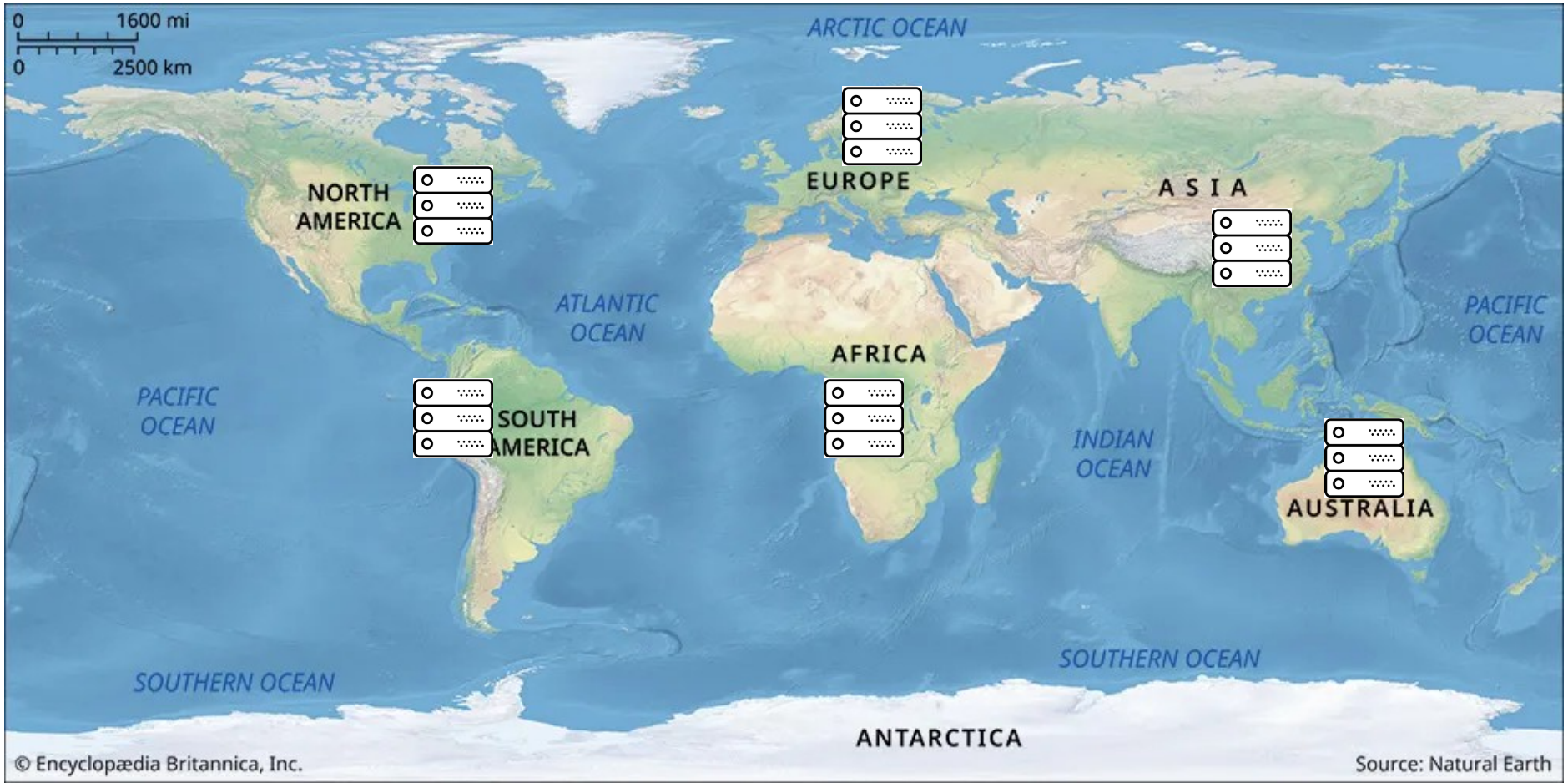
BBC CNN GitHub PayPal amazon.com

Several popular domains were unavailable in most regions
in the US during the DDoS attack on Dyn in Oct 2016

Load balancing from the view of nameservers

Nameservers support **load balancing mechanisms**

to ensure robustness and availability



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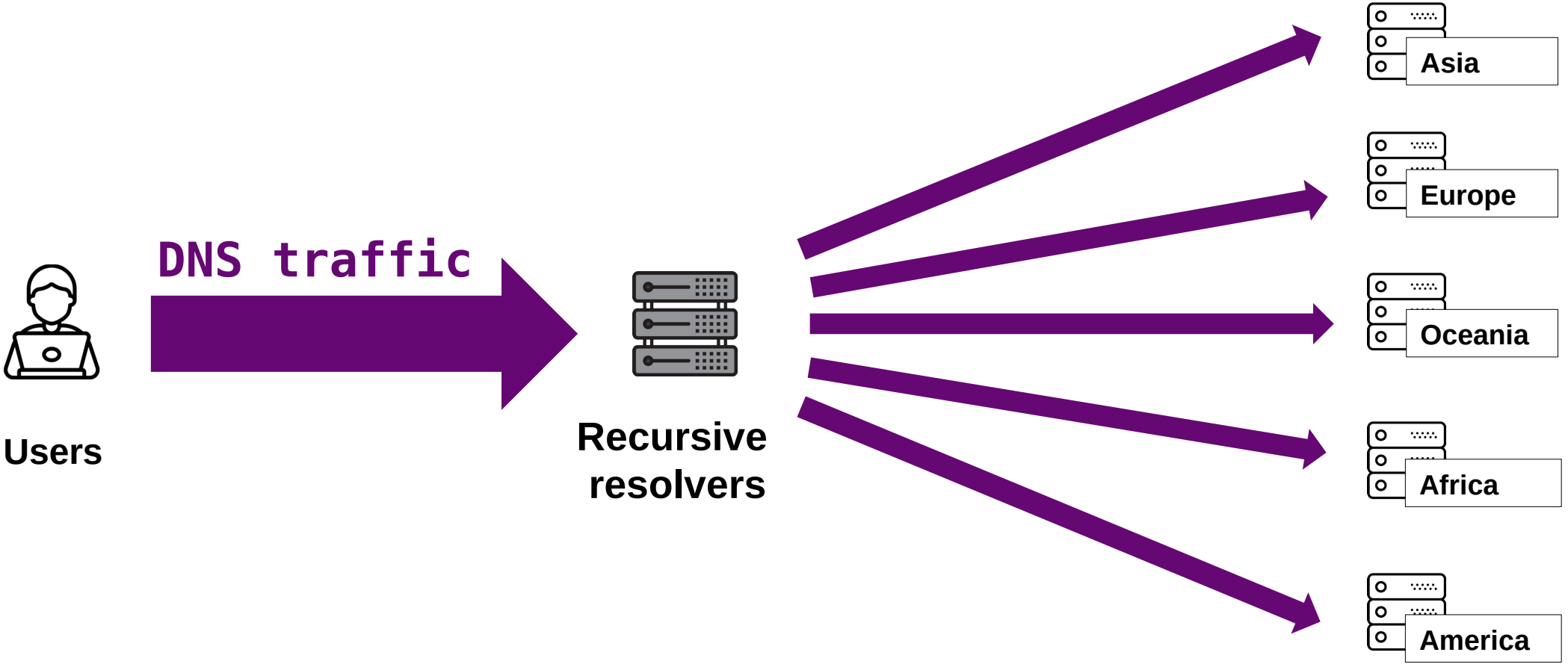
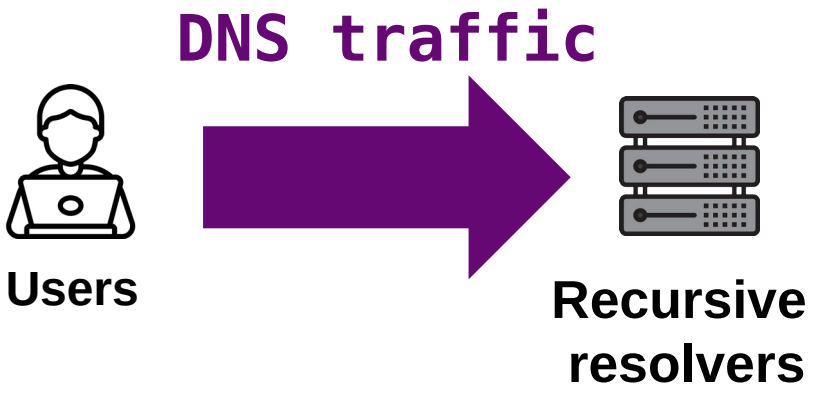


Load balancing from the view of resolvers

- Resolvers witness multiple candidates **with limited information**
- Resolvers rely on **nameserver selection algorithm** to pick the best candidate




```
;; AUTHORITY SECTION:
bilibili.com.           172800  IN      NS      ns3.dnsv5.com.
bilibili.com.           172800  IN      NS      ns4.dnsv5.com.

;; ADDITIONAL SECTION:
ns3.dnsv5.com.          172800  IN      A       1.12.0.17
ns3.dnsv5.com.          172800  IN      A       1.12.0.18
ns3.dnsv5.com.          172800  IN      A       1.12.0.20
ns3.dnsv5.com.          172800  IN      A       223.166.151.16
ns3.dnsv5.com.          172800  IN      AAAA    2402:4e00:1430:1102:0:9136:2b2b:ba61
ns3.dnsv5.com.          172800  IN      A       36.155.149.211
ns3.dnsv5.com.          172800  IN      A       49.234.175.103
ns3.dnsv5.com.          172800  IN      A       61.151.180.51
ns4.dnsv5.com.          172800  IN      A       1.12.0.16
ns4.dnsv5.com.          172800  IN      A       1.12.0.19
ns4.dnsv5.com.          172800  IN      A       106.55.82.76
ns4.dnsv5.com.          172800  IN      A       117.89.178.200
ns4.dnsv5.com.          172800  IN      A       183.192.164.119
ns4.dnsv5.com.          172800  IN      A       183.47.126.155
ns4.dnsv5.com.          172800  IN      A       223.166.151.126
ns4.dnsv5.com.          172800  IN      AAAA    2402:4e00:1020:1264:0:9136:29b6:fc32
```

Load balancing from the view of resolvers

- Resolvers witness multiple candidates **with limited information**
- Resolvers rely on **nameserver selection algorithm** to pick the best candidate

The NS load balancing will never function correctly if the NS selection algorithm works abnormally

Users

DN

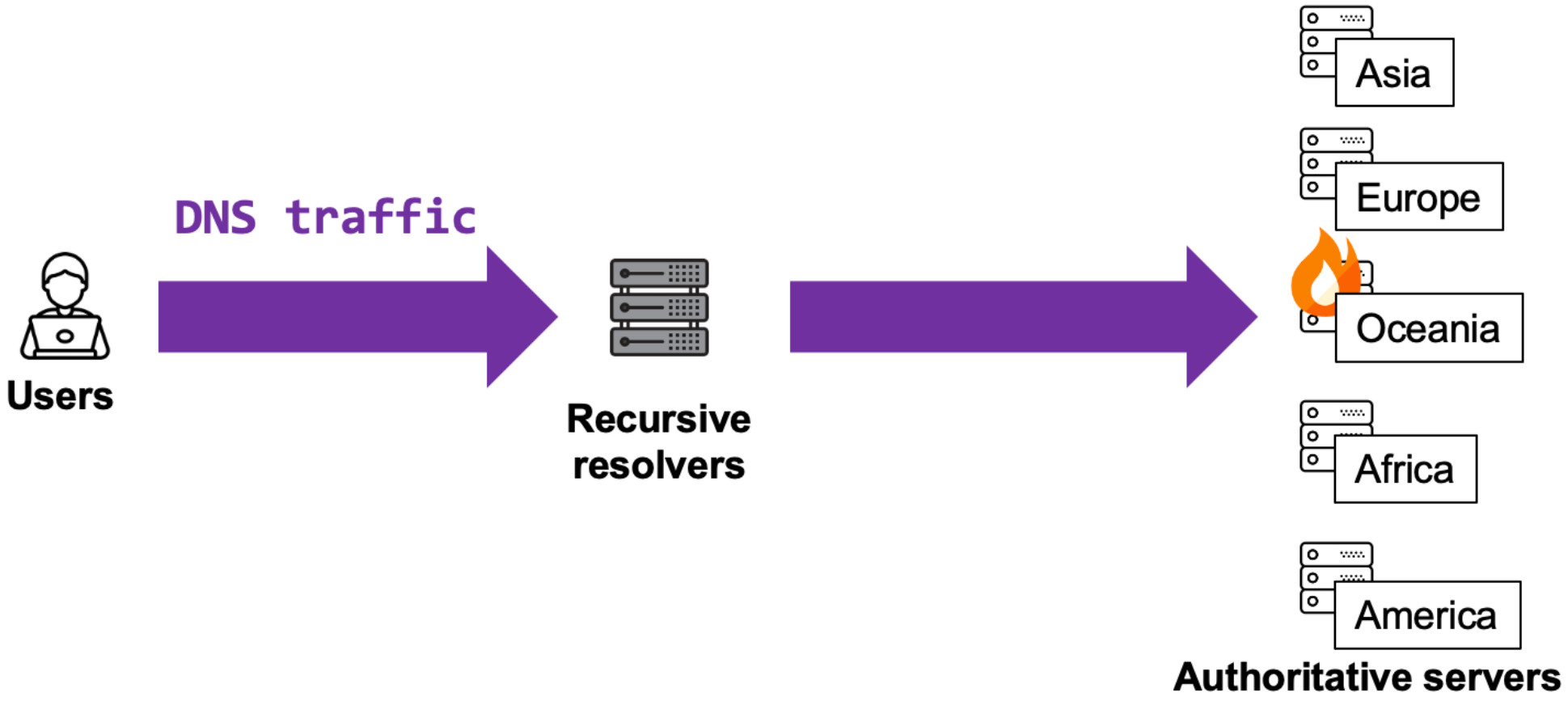
:0:9136:2b2b:ba61

```
ns4.dnsv5.com.          172800  IN      A       223.166.151.126
ns4.dnsv5.com.          172800  IN      AAAA    2402:4e00:1020:1264:0:9136:29b6:fc32
```

Security risks of vulnerable NS selection

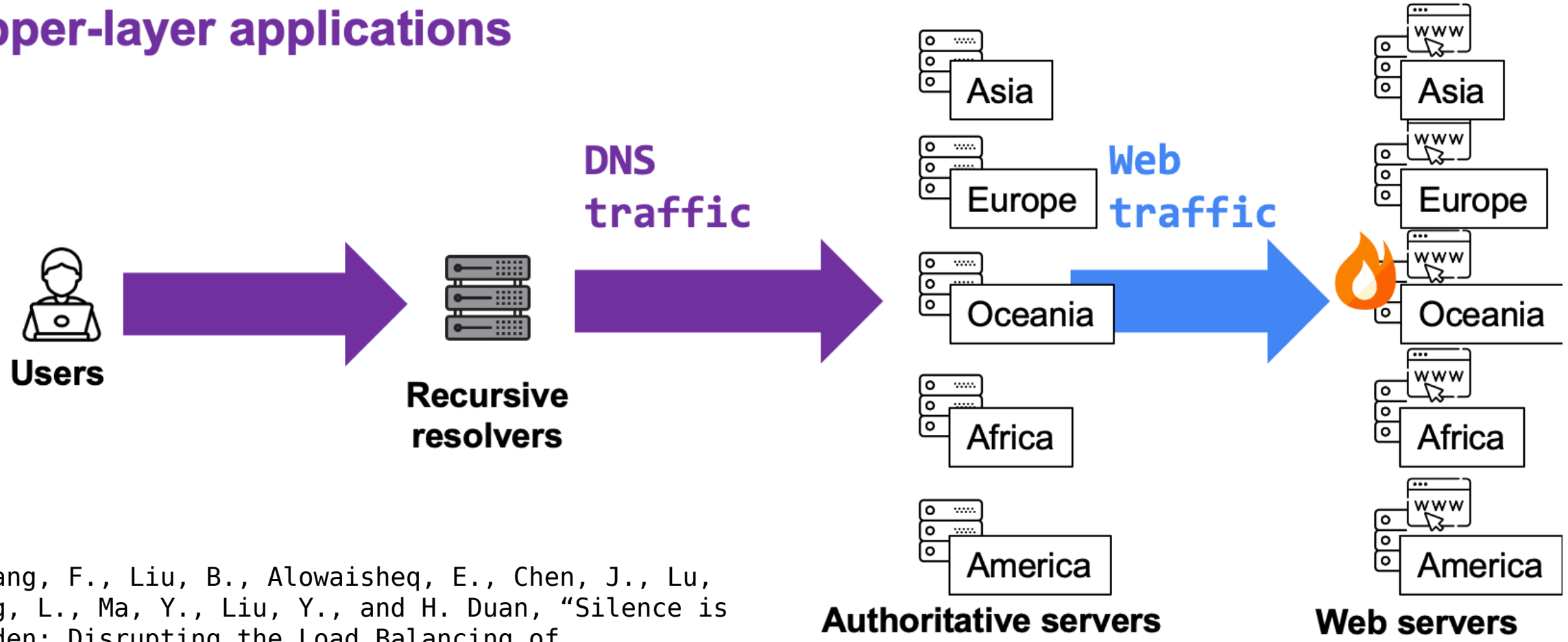
Security risks of vulnerable NS selection

Impact 1: overloading authoritative DNS servers with legitimate traffic



Security risks of vulnerable NS selection

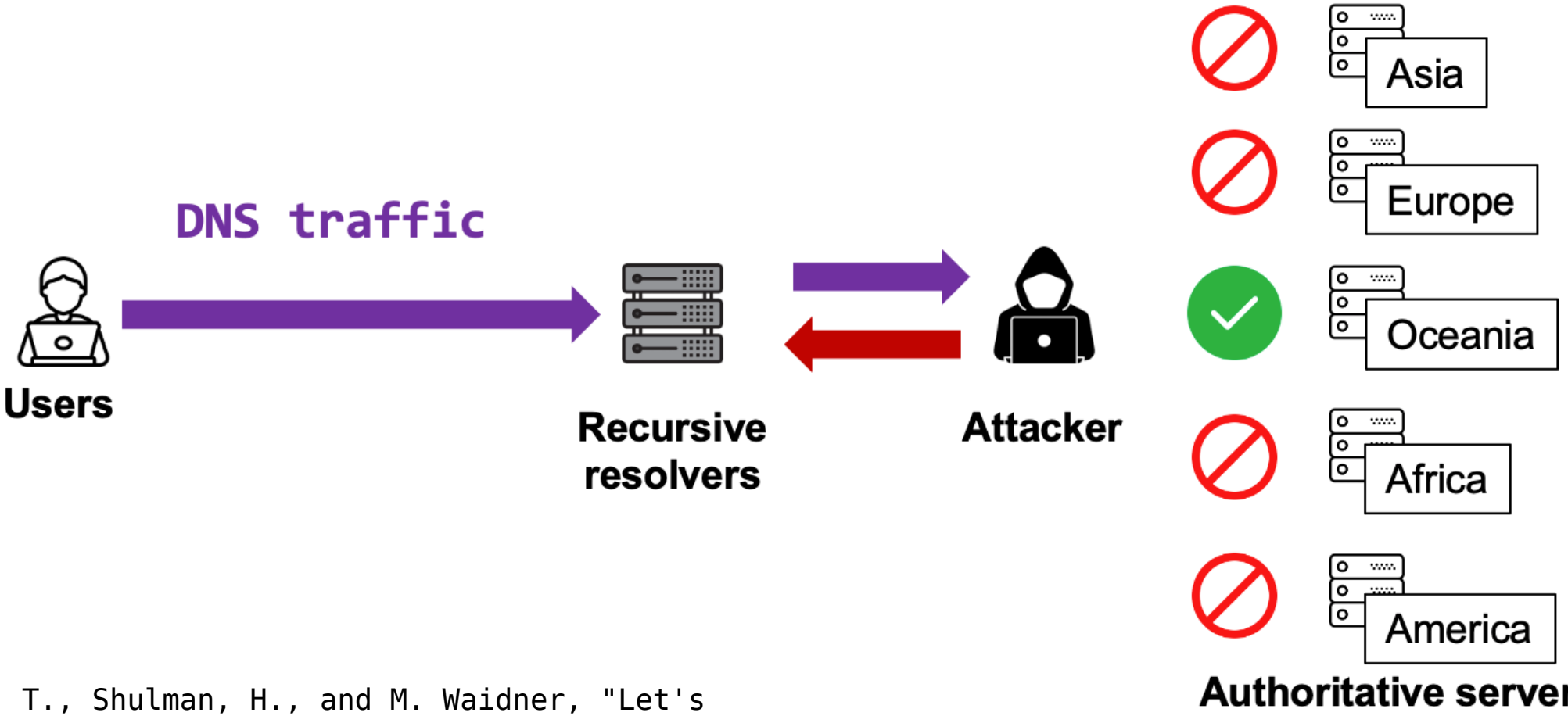
Impact 2: disrupting DNS-based load balancing of upper-layer applications



Ref: Zhang, F., Liu, B., Alowaisheq, E., Chen, J., Lu, C., Song, L., Ma, Y., Liu, Y., and H. Duan, “Silence is not Golden: Disrupting the Load Balancing of Authoritative DNS Servers”, DOI 10.1145/3576915.3616647,

Security risks of vulnerable NS selection

Impact 3: Lowering the bar of traffic hijacking and cache poisoning



Ref: Dai, T., Shulman, H., and M. Waidner, "Let's Downgrade Let's Encrypt", DOI 10.1145/3460120.3484815,

Summary of our draft

- **The risks are critical VS. The standardization of NS selection lack**
  - [RFC1034] vaguely suggests that resolvers should *“find the best server to ask.”*
- To fill the gap, we **summarize the published paper** and propose this draft to
  - **Reveal the mainstream nameserver selection algorithm**
    - Five mainstream DNS software and real-world resolvers
  - **Summarize the uncovered vulnerabilities abused NS selection**
    - Five vulnerabilities
  - **Provide recommendations to defend against the security risks**
    - Five recommendations

Mainstream NS selection algorithms

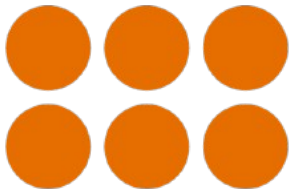
Methodology

- **Refer to four published research papers**
  1. Zhang, F., Liu, B., Alowaisheq, E., Chen, J., Lu, C., Song, L., Ma, Y., Liu, Y., and H. Duan, “Silence is not Golden: Disrupting the Load Balancing of Authoritative DNS Servers”, DOI 10.1145/3576915.3616647, 2023, ACM CCS
  2. Zhang, F., Lu, C., Liu, B., Duan, H., and Y. Liu, "Measuring the Practical Effect of DNS Root Server Instances: A China-Wide Case Study", 2022, PAM
  3. Yu, Y., Wessels, D., Larson, M., and L. Zhang, "Authority server selection in DNS caching resolvers", 2012,
  4. Müller, M., Moura, G.C.M., Schmidt, R. de O., and J.Heidemann, "Recursives in the Wild: Engineering Authoritative DNS Servers", DOI 10.1145/3131365.3131366, 2017
- **Include five recursive DNS software and open resolvers in the wild**
- **From white-box view and black-box view**

Result: the definition of the best server

- [RFC1034] vaguely suggests that resolvers should *"find the best server to ask."*
  - **What is the definition of the best server?**

BIND9



PowerDNS

Always pick the candidate with the highest priority

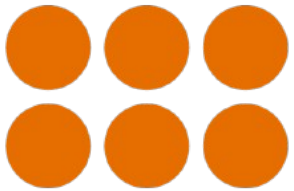
~95% chances: the highest priority,
~5% pick randomly

Knot

Unbound

Pick randomly in a range of priority

BIND9



PowerDNS

Unbound

Knot

1. The priority is the adjusted SRTT (Smoothed Round Trip Time)
2. Apply a penalty to the SRTT while detecting failure (e.g., DNSSEC failure)

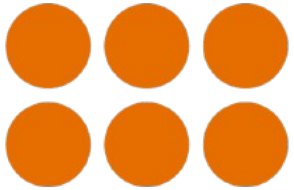
Result: store the status of the NS

BIND9

Knot

Share the status at the level of **IP address**

Share the status at the level of **NS record**



PowerDNS

Unbound

maintaining the status for each delegation individually

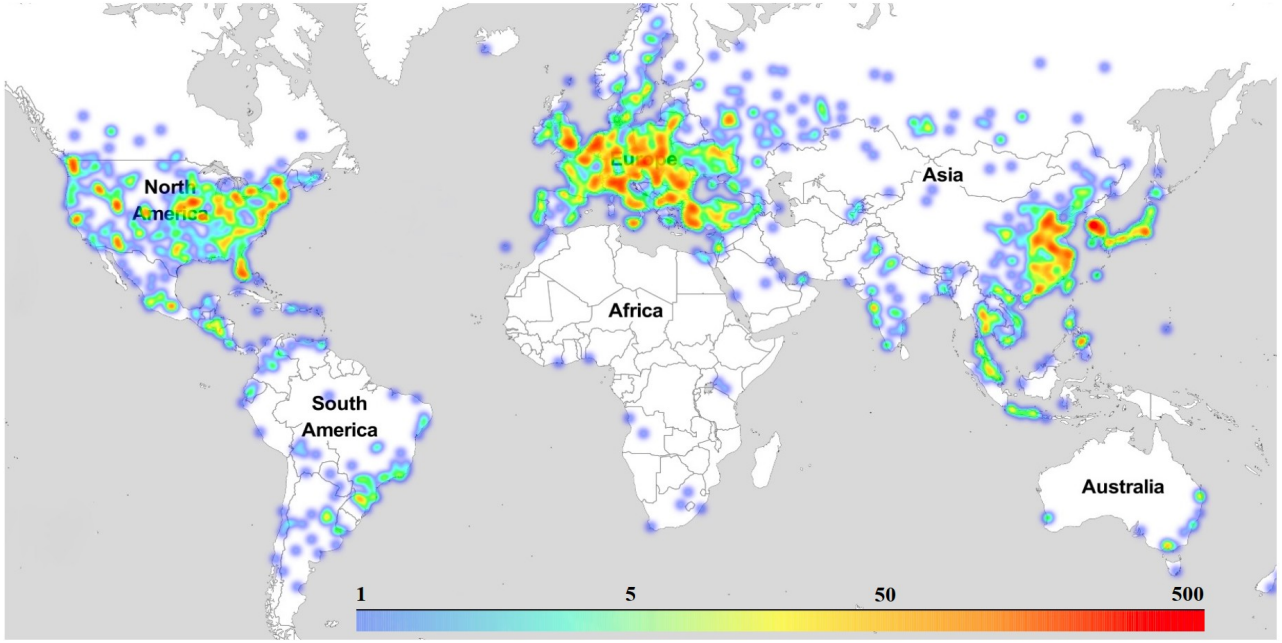
Vulnerabilities exploiting NS selection algorithm

Five vulnerabilities exploiting NS selection algorithm

- V1: Disablance Attack
- V2: Subverting SRTT Algorithm
- V3: Spoofed Fragment
- V4: Lame Cache
- V5: Cyclical Queries

Five vulnerabilities exploiting NS selection algorithm

- **V1: Disablance Attack**
  - allows disrupting load balancing of NS at a low cost
  - exploits shared status of NS + penalty mechanism
  - affects BIND9, PowerDNS, Microsoft DNS, and 37.88% of tested open resolvers
- V2: Subverting SRTT Algorithm
- V3: Spoofed Fragment
- V4: Lame Cache
- V5: Cyclical Queries



Five vulnerabilities exploiting NS selection algorithm

- V1: Disablance Attack
- **V2: Subverting SRTT Algorithm**
  - allows manipulating NS selections
  - exploits shared status of NS + penalty mechanism
  - affects BIND9
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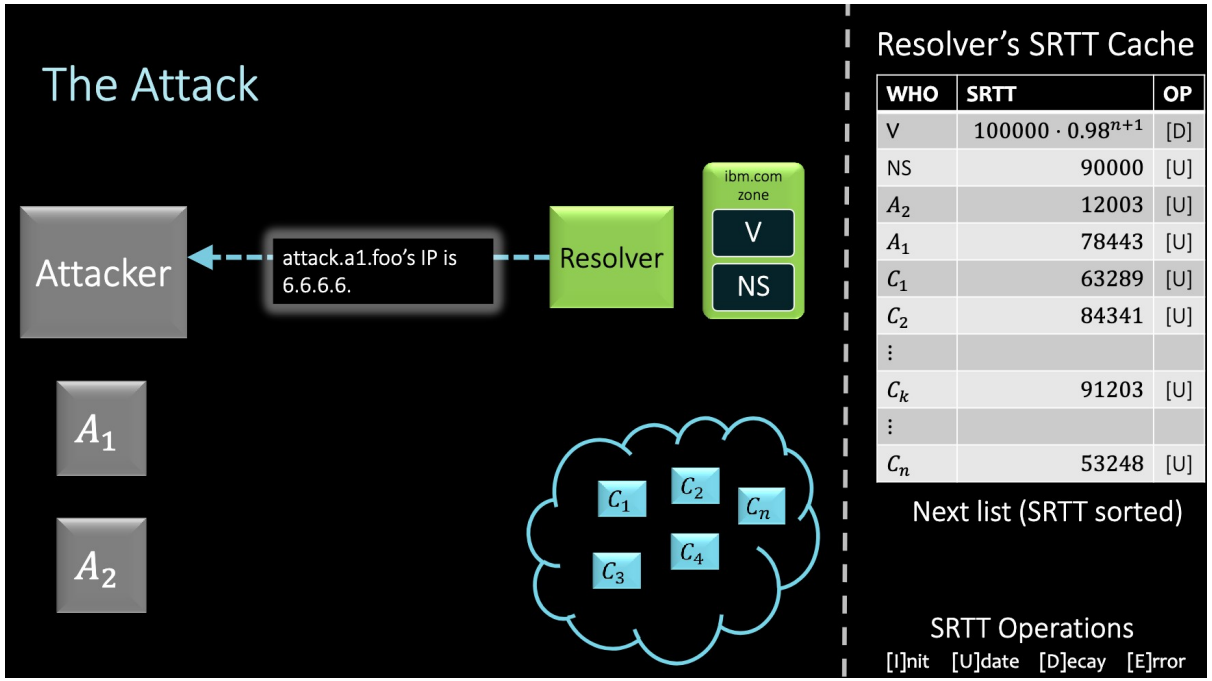


Five vulnerabilities exploiting NS selection algorithm

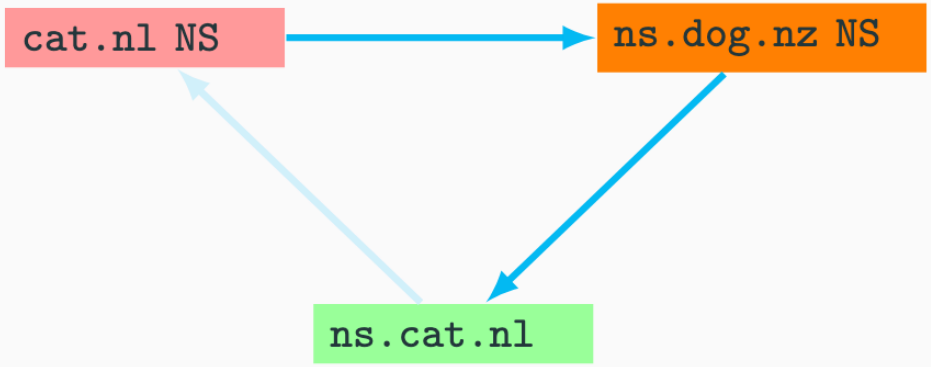
- V1: Disablance Attack
- V2: Subverting SRTT Algorithm
- **V3: Spoofed Fragment**
  - allows manipulating NS selections
  - exploits IP spoofing + fragment query + penalty mechanism
  - affects BIND9
- V4: Lame Cache
- V5: Cyclical Queries

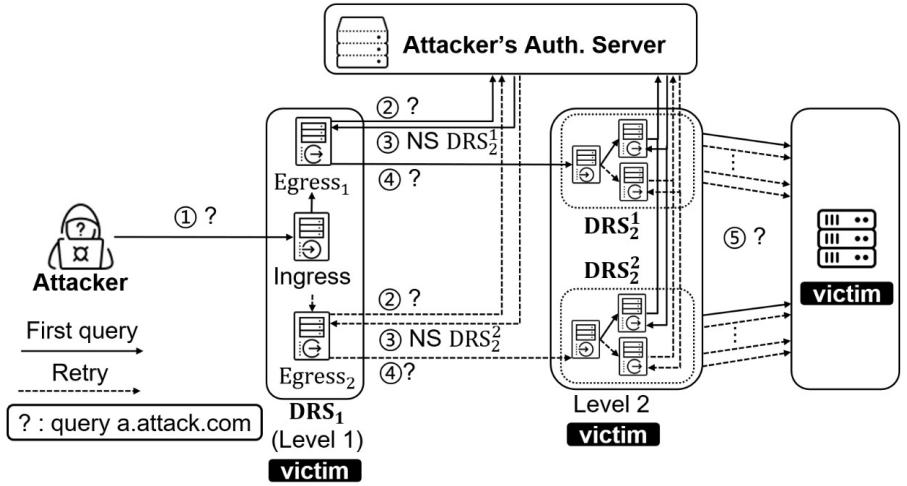
Five vulnerabilities exploiting NS selection algorithm

- V1: Disablance Attack
- V2: Subverting SRTT Algorithm
- V3: Spoofed Fragment
- **V4: Lame Cache**
  - causes the risk of DoS
  - exploits the data structure of NS status
  - affects BIND9
- V5: Cyclical Queries

Five vulnerabilities exploiting NS selection algorithm

- V1: Disablance Attack
- V2: Subverting SRTT Algorithm
- V3: Spoofed Fragment
- V4: Lame Cache
- **V5: Cyclical Queries**
  - allows traffic amplification and DoS attack
  - exploit the unbounded designs of NS selection
  - affects real-world resolvers and vendors





Recommendations

Five recommendations

- ❑ **R1: Balance between Optimization and Exploration**
- ❑ **R2: Independent Nameserver Status**
- ❑ **R3: Secure Cache of Nameserver Performance**
- ❑ **R4: Bounding Work**
- ❑ **R5: Proper Retry and Failover**

Five recommendations

- **R1: Balance between Optimization and Exploration**
  - Vulnerabilities (V1-V3) abuse the selection of the candidate with the best performance and manipulate the NS selection of resolvers
  - We recommend a balance between optimization and exploration (as Knot and Unbound)
- **R2: Independent Nameserver Status**
- **R3: Secure Cache of Nameserver Performance**
- **R4: Bounding Work**
- **R5: Proper Retry and Failover**

Five recommendations

- R1: Balance between Optimization and Exploration
- **R2: Independent Nameserver Status**
  - Vulnerabilities (V1-V2) abuse the shared status of NS and manipulate the NS selection of resolvers
  - We recommend maintaining independent status for each domain (as Unbound)
- R3: Secure Cache of Nameserver Performance
- R4: Bounding Work
- R5: Proper Retry and Failover

Five recommendations

- R1: Balance between Optimization and Exploration
- R2: Independent Nameserver Status
- **R3: Secure Cache of Nameserver Performance**
  - Vulnerable data structures of NS structure allow DoS attacks (V4)
  - We recommend avoiding inefficient data structures or unnecessary fine-grained information within the cache
- R4: Bounding Work
- R5: Proper Retry and Failover

Five recommendations

- R1: Balance between Optimization and Exploration
- R2: Independent Nameserver Status
- R3: Secure Cache of Nameserver Performance
- **R4: Bounding Work**
  - Cyclical queries (V5) abuse unbounded designs of resolvers and lead to the DoS attack
  - We recommend preventing cyclical queries and aborting with an error
- R5: Proper Retry and Failover

Five recommendations

- R1: Balance between Optimization and Exploration
- R2: Independent Nameserver Status
- R3: Secure Cache of Nameserver Performance
- R4: Bounding Work
- **R5: Proper Retry and Failover**
  - We clarify when resolvers should re-query other servers (upon non-response or error)
  - This should be balanced with the requirement to bound work (R4)

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Thanks for listening
Any questions and comments are welcome

zfl20@tsinghua.org.cn

https://github.com/zhangshanfen9/draft-zhang-dnsop-ns-selection