ETH zürich

Demystifying Resolver Work: A Formal Perspective on DNS Resolver Performance Vulnerabilities

Liwen Xu, Doctoral Researcher, ETH Zürich (liwen.xu@inf.ethz.ch)

Joint work with: Huayi Duan (HKUST-GZ), Zechao Cai, and Adrian Perrig (ETH Zürich)

armasuisse

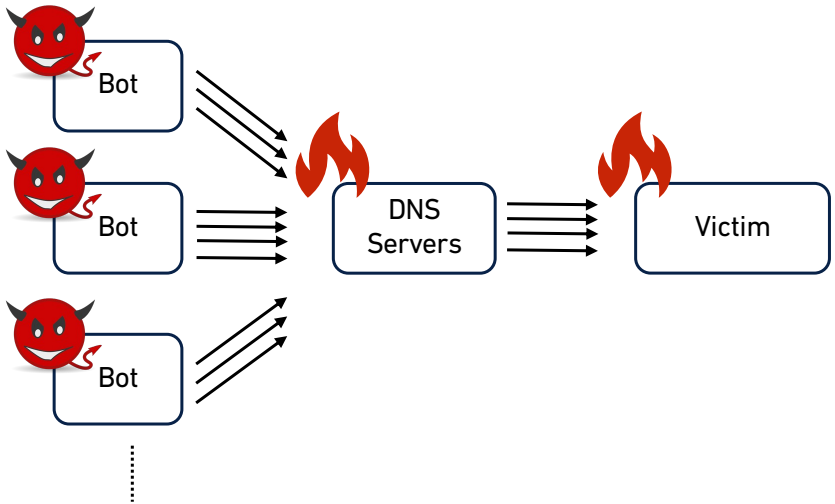
ZISC Zurich Information Security & Privacy Center

Swiss National Science Foundation

HASLERSTIFTUNG

Classes of DoS Attacks Targeting Resolvers

Traditional Volumetric DDoS



Many queries
Large traffic volume

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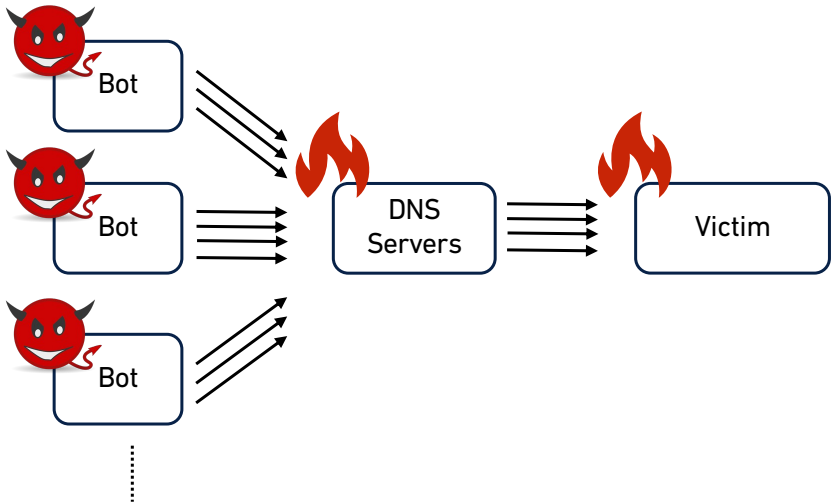

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Resolver Work Amplification

A few queries
Disproportionate work

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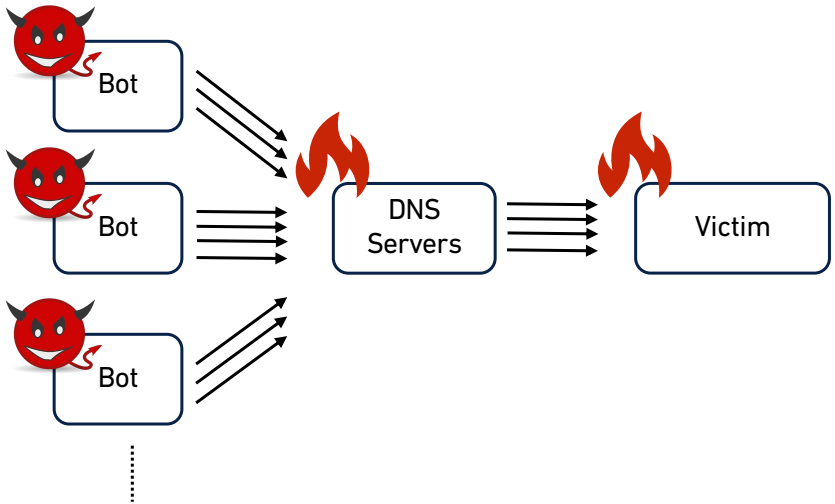

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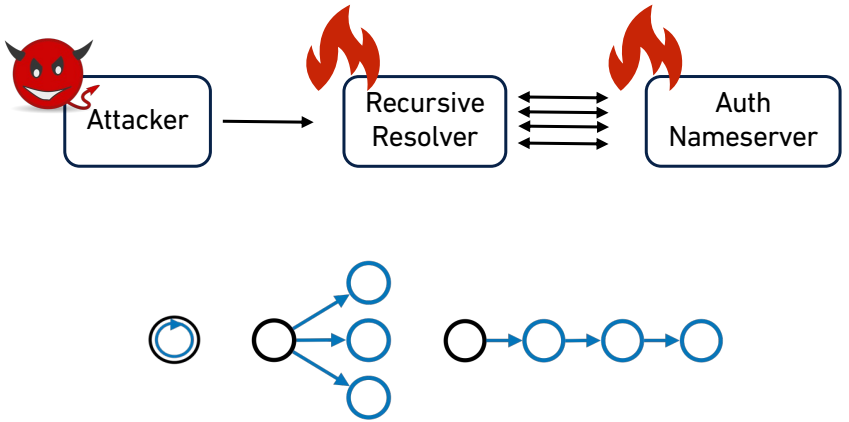
Resolver Work Amplification

(aka, Self-Amplification @ DNS-OARC'43)



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The Problem That Never Got Answered Explicitly To The Full

> The recommended priorities for the resolver designer are:
>
> 1. **Bound the amount of work** (packets sent, parallel processes started) so that a request can't get into an infinite loop or start off a chain reaction of requests or queries with other implementations EVEN IF SOMEONE HAS INCORRECTLY CONFIGURED SOME DATA.
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- Way to measure it
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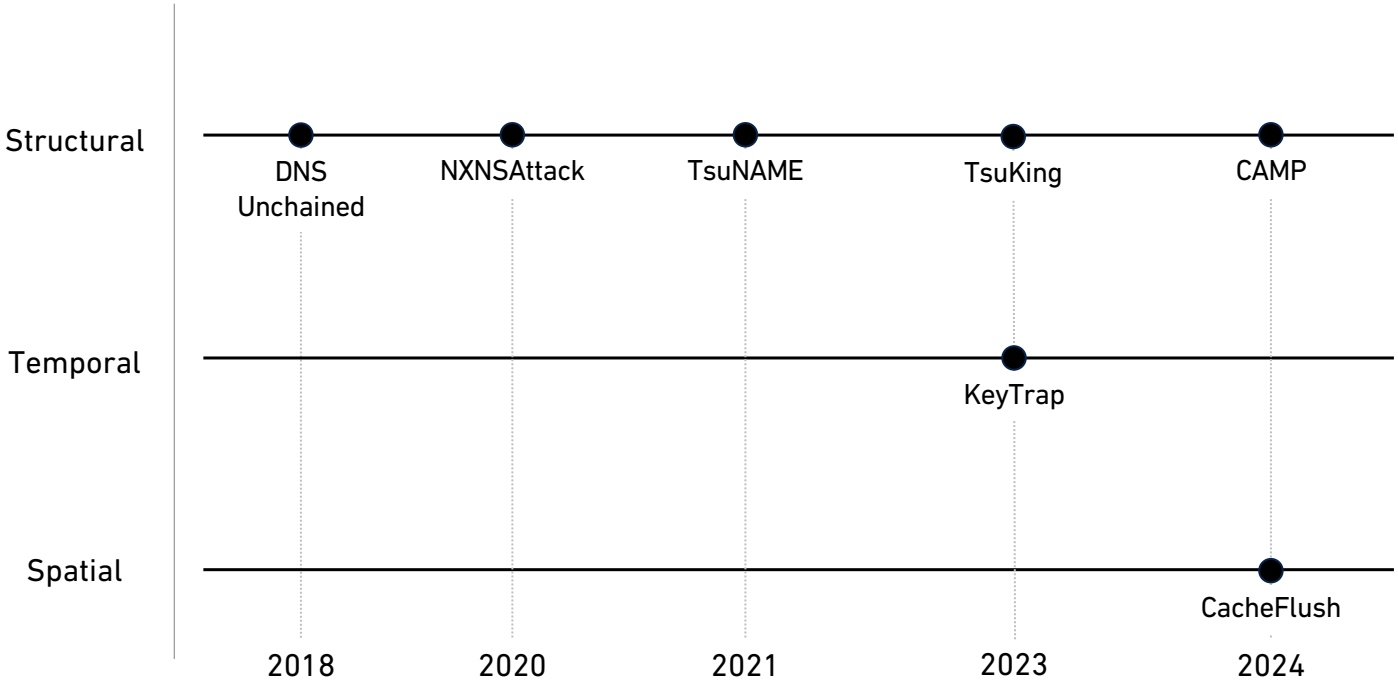
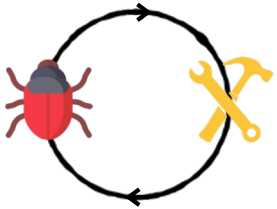
What is the maximum amount of work a resolver can perform for a single query?

We're Caught In A Break-and-Fix Cycle





* Taxonomy based on the primary source of introduced complexity

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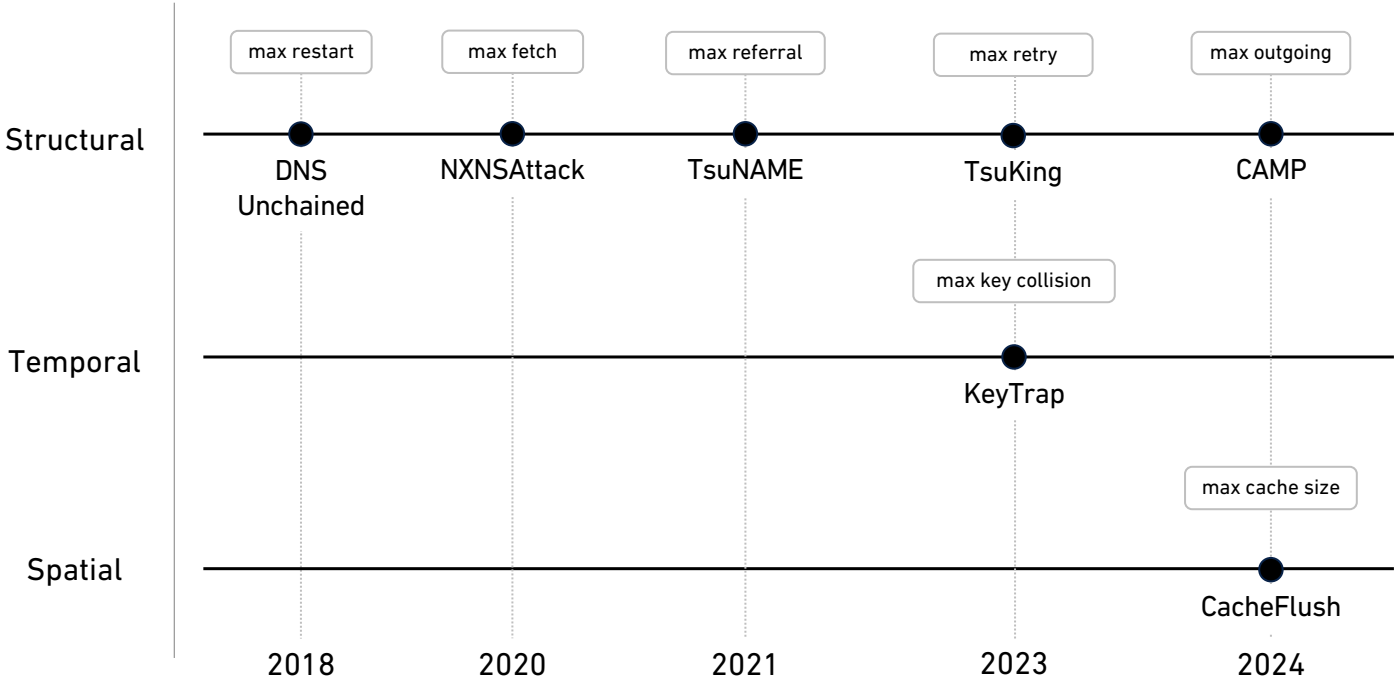

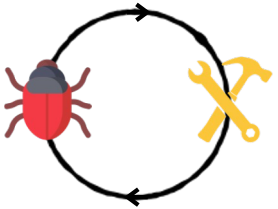

New attack vector

↓

New patch(es)

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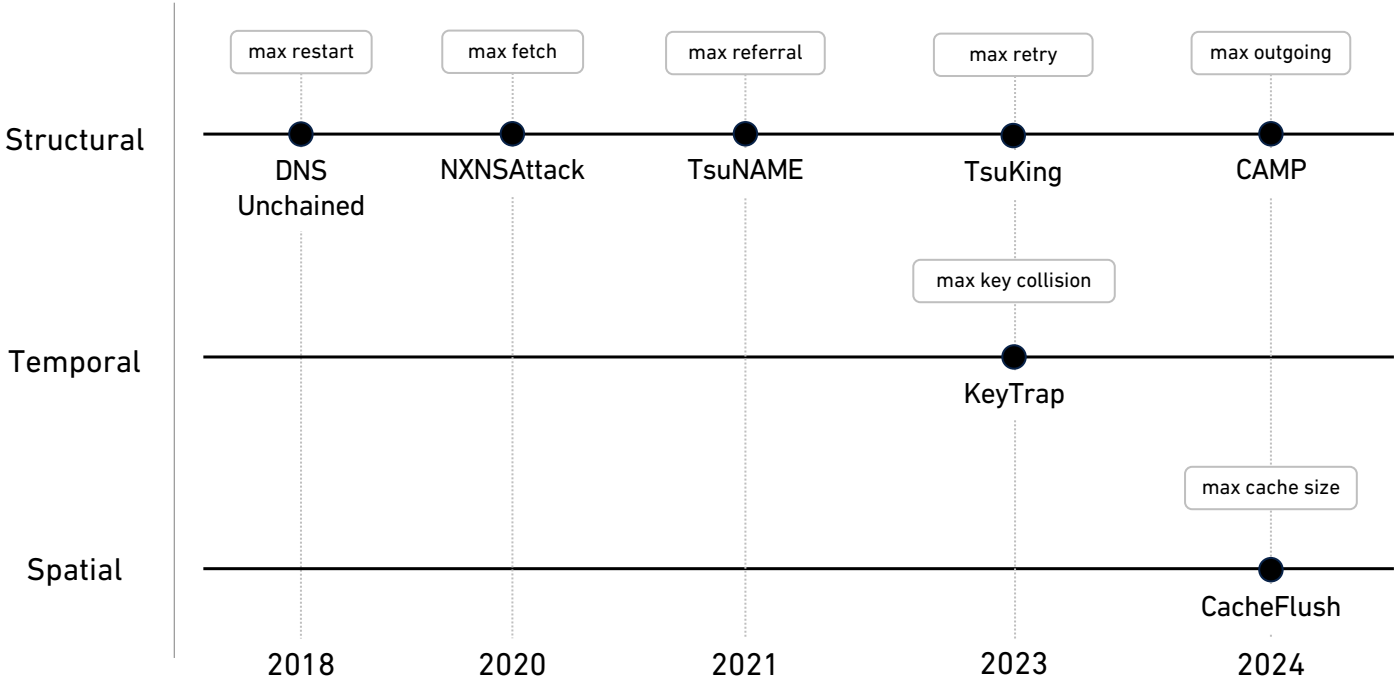

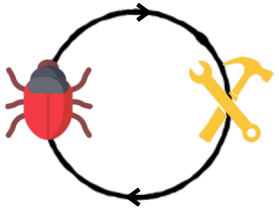

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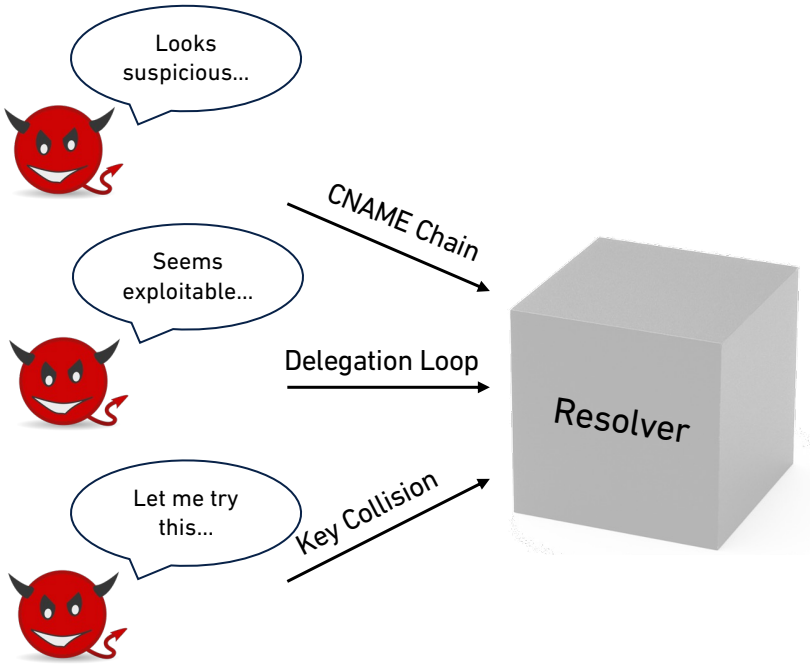
Are there more? How many more?

From Intuition to Formalization



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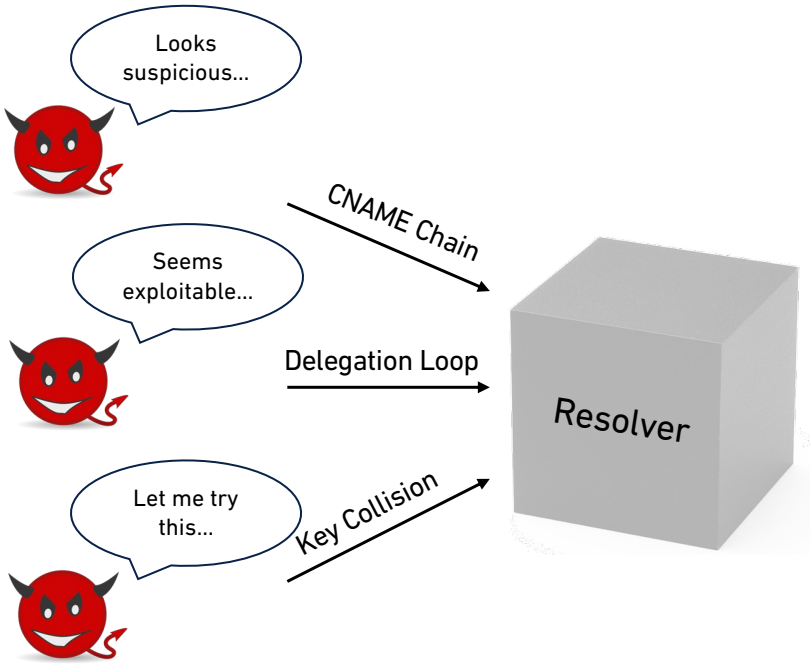

Let's go back to where it all started.

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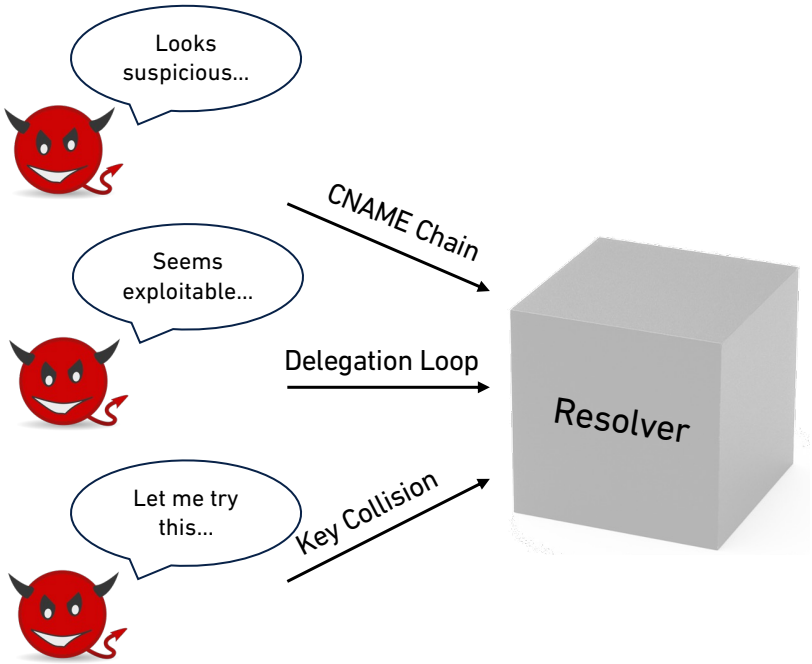

Let's go back to where it all started.

The top level algorithm has four steps:

1. See if the answer is in local information, and if so return it to the client.

2. Find the best servers to ask.

3. Send them queries until one returns a response.

4. Analyze the response, either:

   a. if the response answers the question or contains a name error, cache the data as well as returning it back to the client.

   b. if the response contains a better delegation to other servers, cache the delegation information, and go to step 2.

   c. if the response shows a CNAME and that is not the answer itself, cache the CNAME, change the SNAME to the canonical name in the CNAME RR and go to step 1.

   d. if the response shows a servers failure or other bizarre contents, delete the server from the SLIST and go back to step 3.

– RFC1034, §5.3.3

Resolution as a Transition System

Algorithm 1: Recursive Resolution Algorithm

Input: A query $Q = (SNAME, STYPE)$ from a client
Output: Resolved answer A or an error response $\perp$

```
   /* Step 1: Check local cache                          */
1  if ∃A = (SNAME, STYPE, RRs) ∈ CACHE then
2      return A to client ;
3      terminate ;
   /* Step 2: Find the best authoritative
      servers                                            */
4  SLIST ← FindBestServers(Q) ;
   /* Step 3: Send queries and wait for a
      response                                           */
5  repeat
6      foreach s ∈ SLIST do
7          Send query Q to server s ;
8      Collect all responses in R ;
9  until ∃R ∈ R such that R ≠ ∅;
   /* Step 4: Case A                                     */
10 if A = (SNAME, STYPE, RRs) ∈ R or R =⊥ (Name
     Error) then
11     CACHE ← CACHE ∪ {A} ;
12     return R to client ;
13     terminate ;
   /* Step 4: Case B                                     */
14 else if NS: D = (SNAME, S) ∈ R and D is valid then
15     CACHE ← CACHE ∪ {D} ;
16     SLIST ← SLIST ∪ {S} ;
17     goto step 2 ;
   /* Step 4: Case C                                     */
18 else if CNAME: C = (SNAME → SNAME′) ∈ R and
     STYPE ≠ CNAME then
19     CACHE ← CACHE ∪ {C} ;
20     Q ← (SNAME′, STYPE) ;
21     goto step 1 ;
   /* Step 4: Case D                                     */
22 else if R indicates a server failure or an invalid response then
23     SLIST ← SLIST \ {s} ;
24     goto step 3
25     or
26     return SERVFAIL to client;
27     terminate ;
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/* Step 4: Case A                                              */
if A = (SNAME, STYPE, RRs) ∈ R or R =⊥ (Name Error) then
    CACHE ← CACHE ∪ {A} ;
    return R to client ;
    terminate ;
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else if NS: D = (SNAME, S) ∈ R and D is valid then
    CACHE ← CACHE ∪ {D} ;
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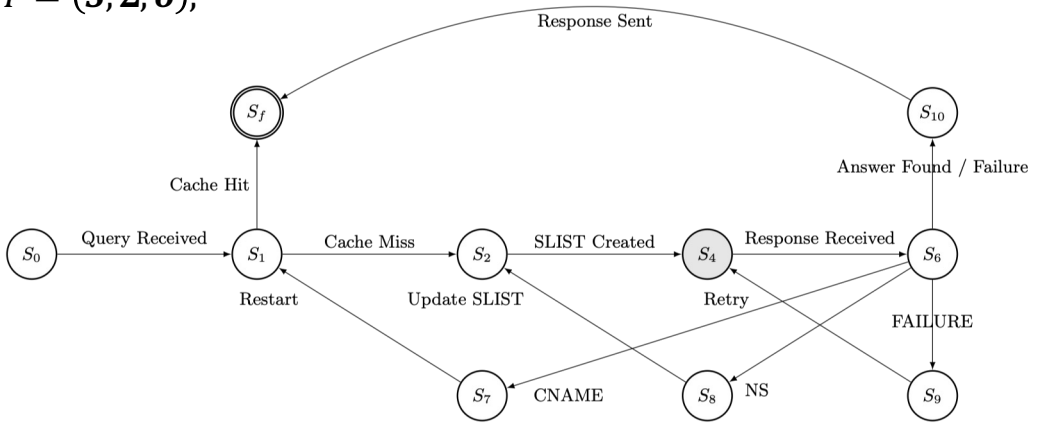
$$T = (\boldsymbol{S}, \boldsymbol{\Sigma}, \boldsymbol{\delta}),$$

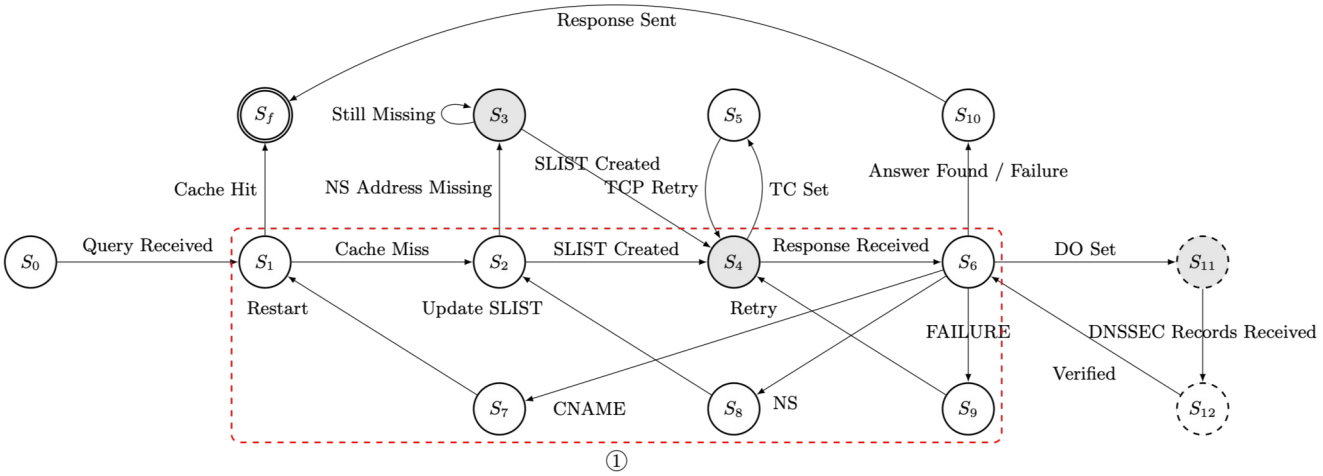


① Resolver Top Level Algorithm

Answer	$\delta(S_6, \sigma_{\text{ANSWER}}) \rightarrow (S_{10})$	Referral	$\delta(S_8, \sigma_{NS}) \rightarrow (S_2)$
Rewrite	$\delta(S_7, \sigma_{CNAME}) \rightarrow (S_1)$	Failover	$\delta(S_9, \sigma_{FAIL}) \rightarrow (S_4)$

State Transition

$T = (\boldsymbol{S}, \boldsymbol{\Sigma}, \boldsymbol{\delta})$,



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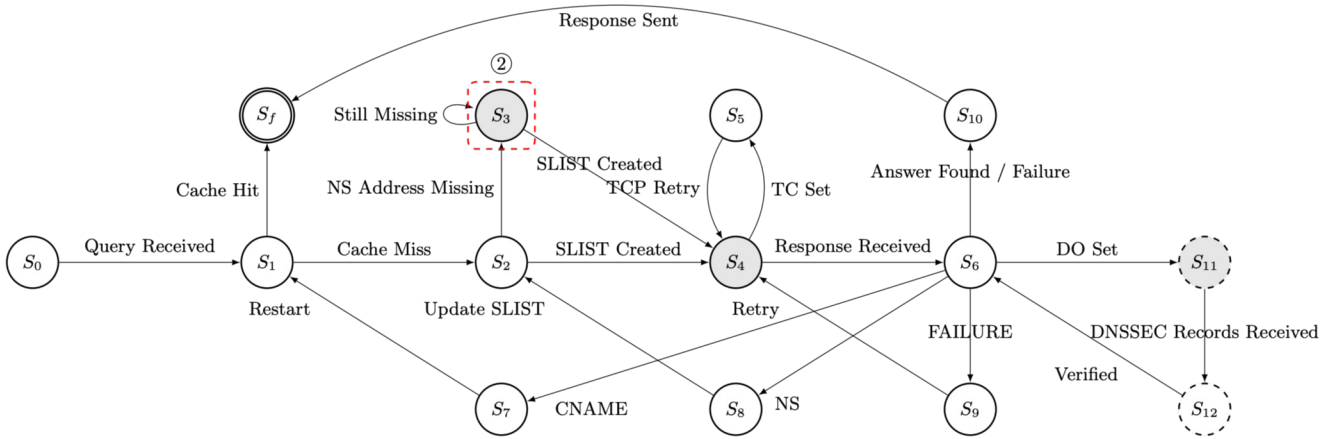

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② Missing Nameserver Addresses

$\delta(S_2, \sigma_{MISS}) \rightarrow (S_3)$

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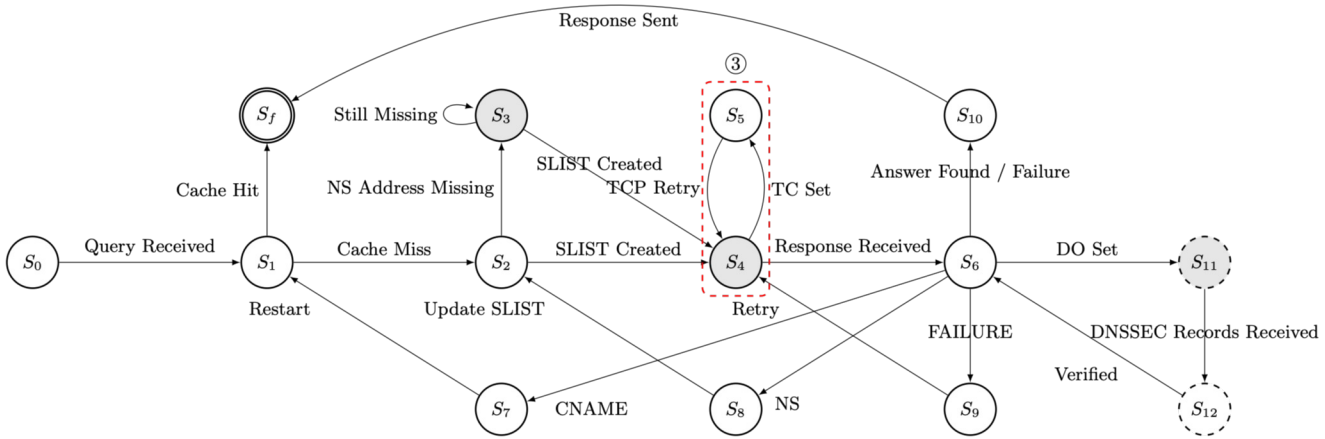

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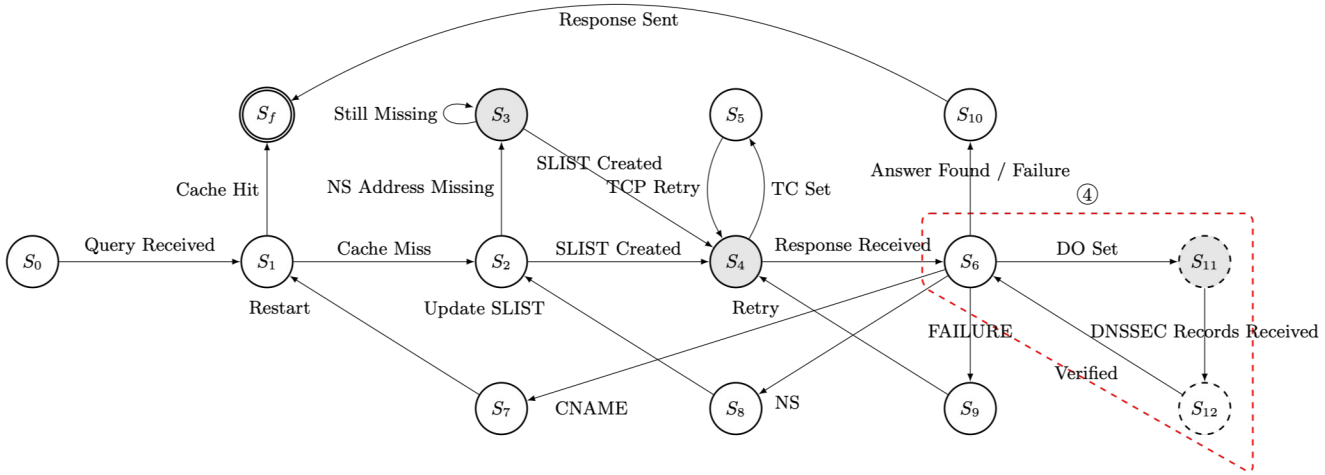

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$\delta(S_4, \sigma_{TC}) \rightarrow (S_5)$

④ DNSSEC Validation

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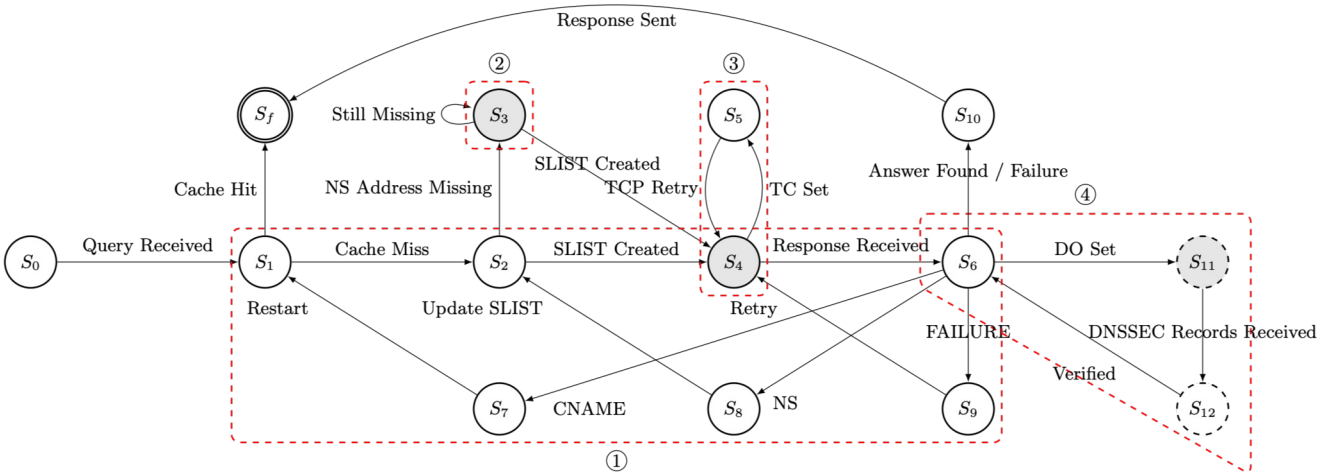
State Transition

$T = (\boldsymbol{S}, \boldsymbol{\Sigma}, \boldsymbol{\delta})$,



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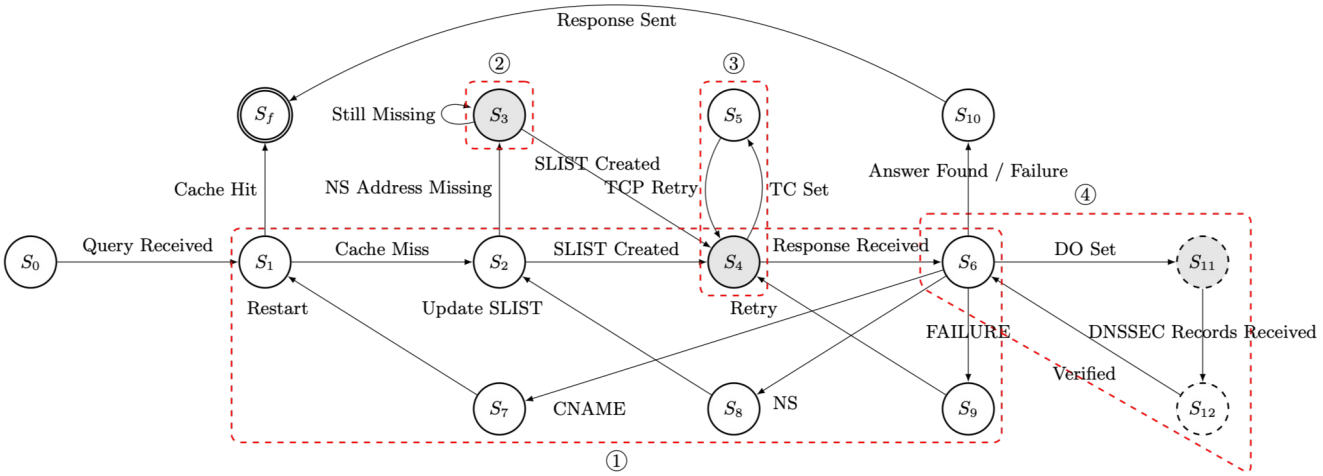

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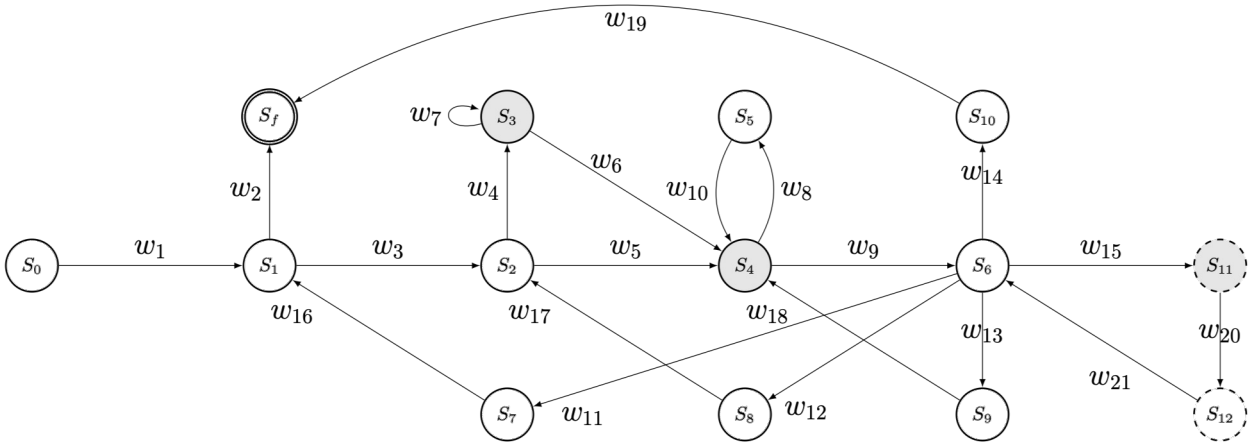
Modeling state transitions makes resolver behavior tractable.

Transition Cost

$T = (S, \Sigma, \delta, \boldsymbol{C})$,



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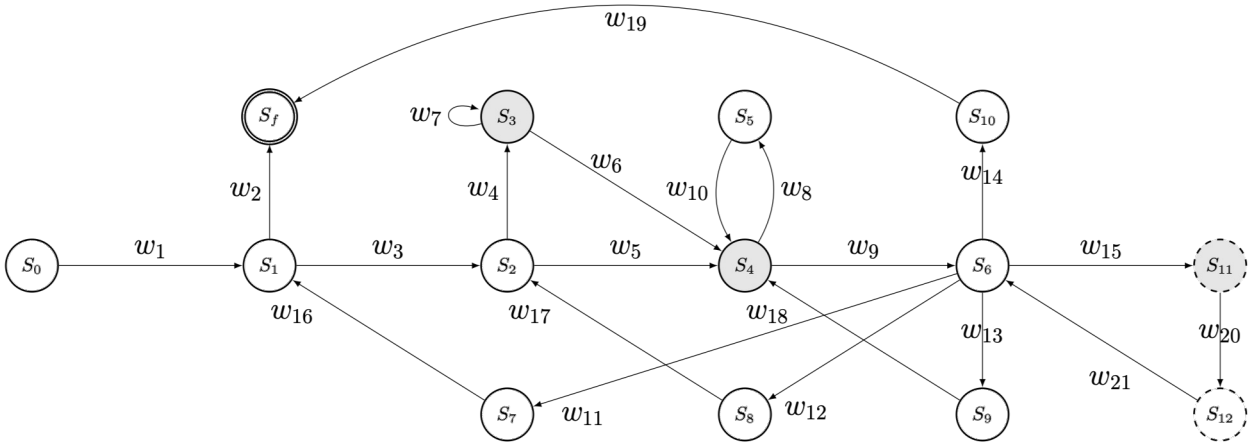

- Outgoing Query Processing Cost

Transport Protocol
TCP vs UDP

Data Transmission
- RR Size

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- RR Count

Caching
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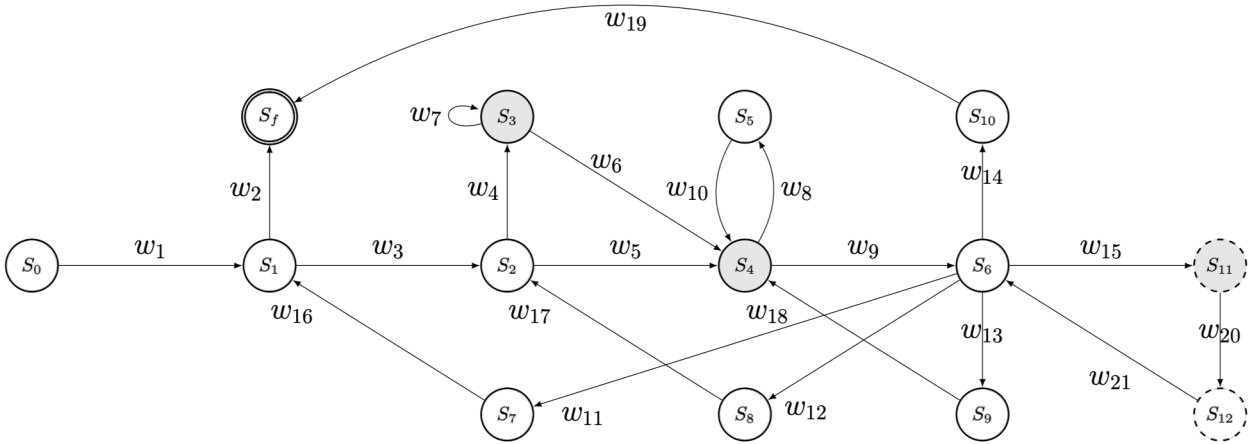

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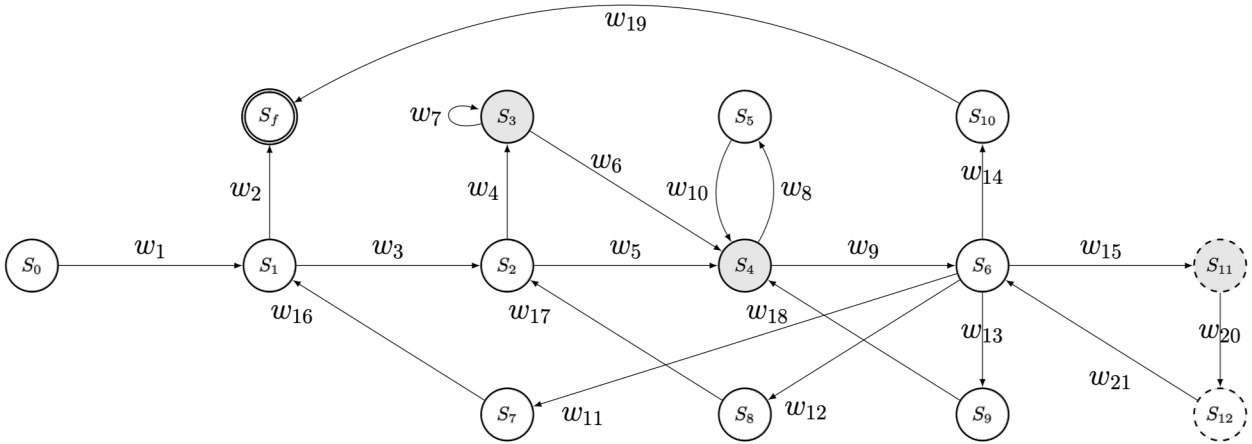

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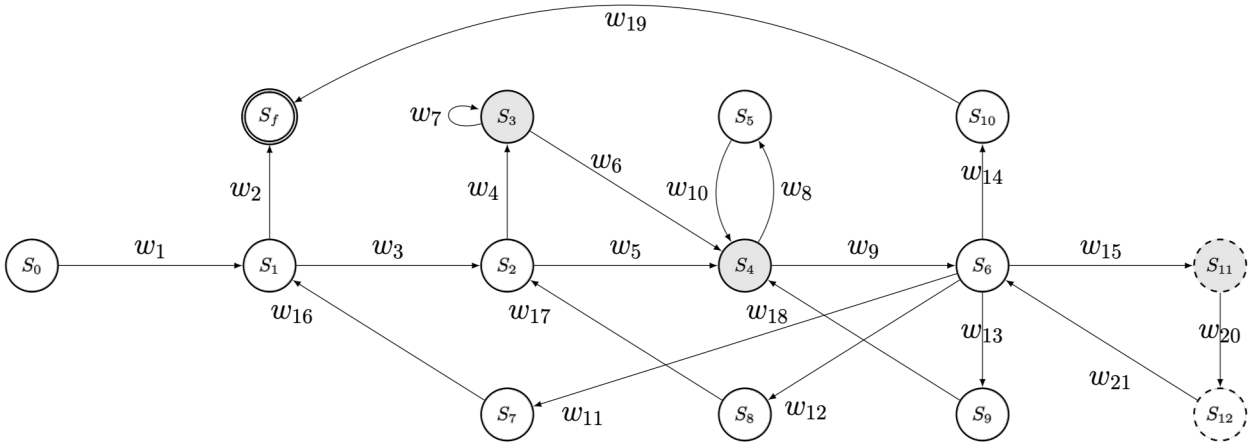

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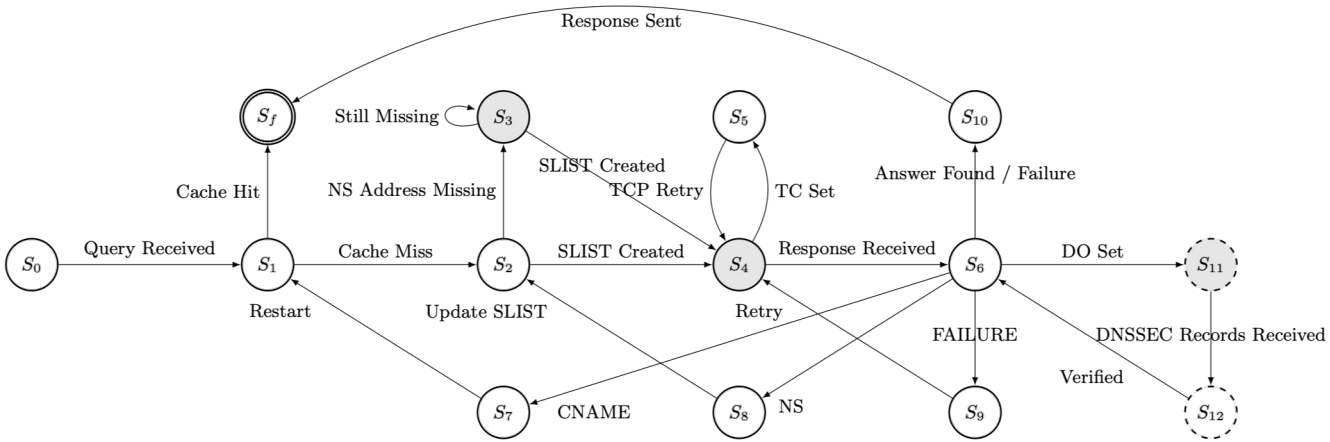
Annotating transitions with cost makes resolver work quantifiable.

Extended Transition System



S	states	stages of resolution	δ	transitions	state transition function
Σ	inputs	server responses	C	cost	resource consumption

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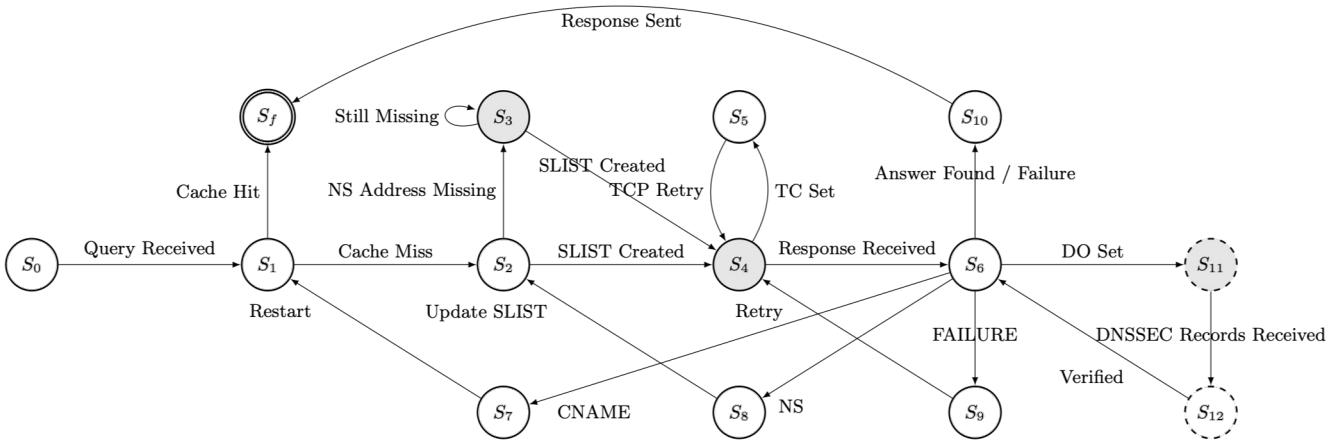

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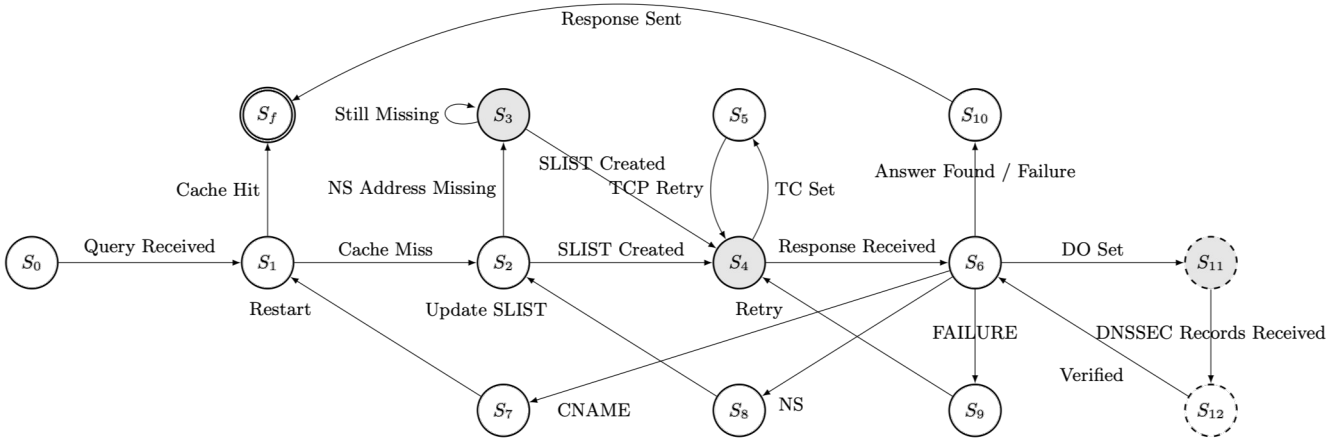
V **Counters**
track cycle traversal history

L **Constraints**
bound the feasible state space

Extended Transition System

$T = (S, \Sigma, \boldsymbol{V}, \delta, \boldsymbol{L}, C),$



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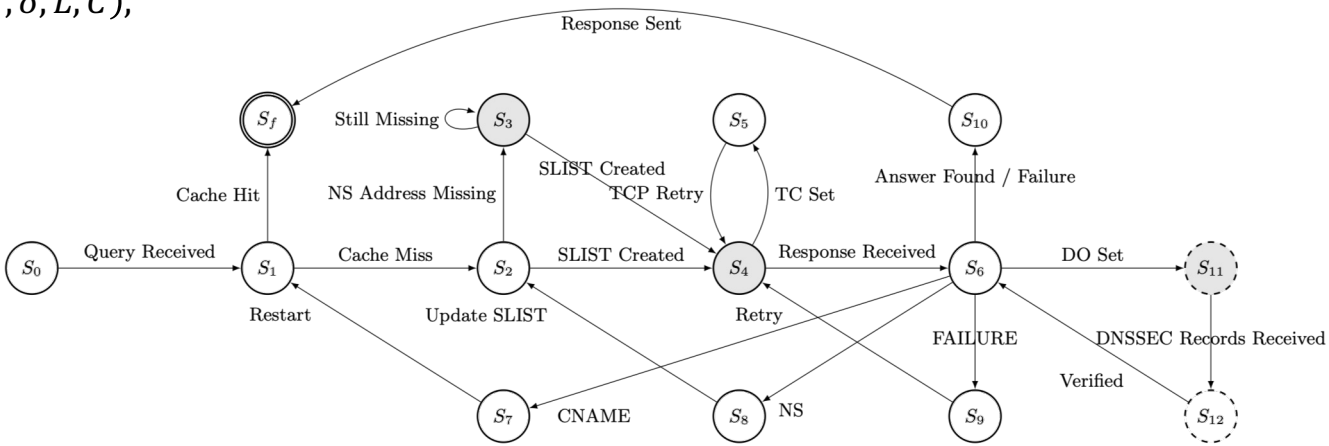

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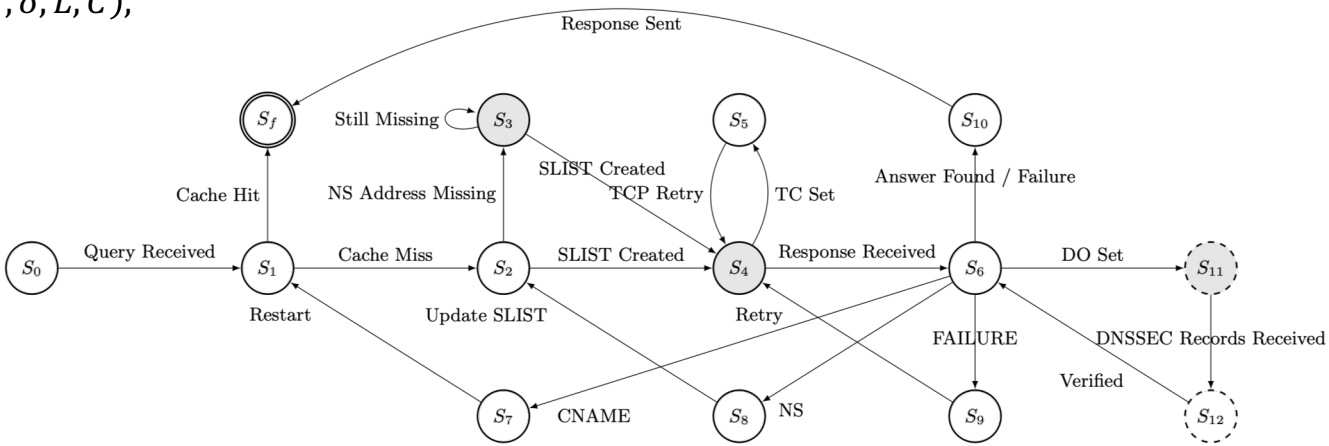


The total work of a resolution is the sum of costs along its state transition path.

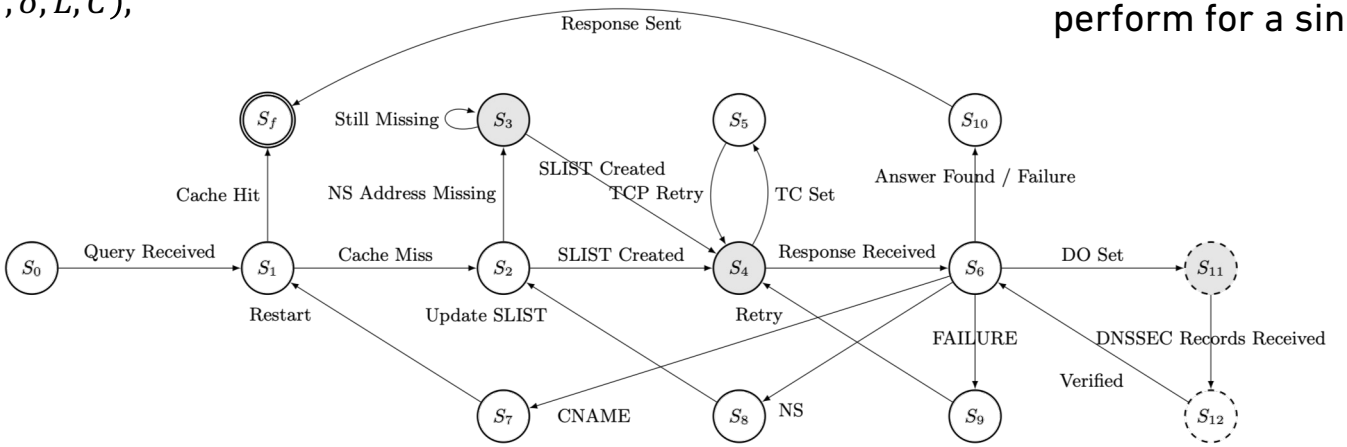
Work

$$W = \sum_{t=1}^{T} w_t$$

Problem Formulation

$T = (S, \Sigma, V, \delta, L, C),$

What is the maximum amount of work a resolver can perform for a single query?

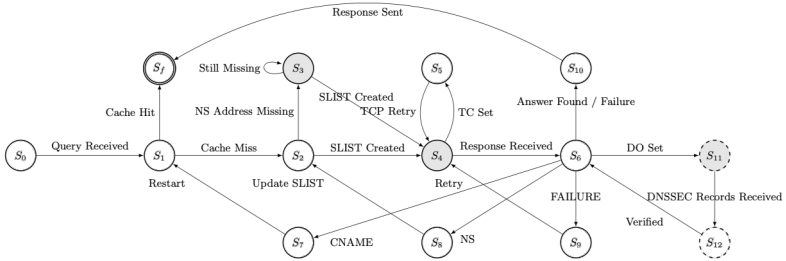


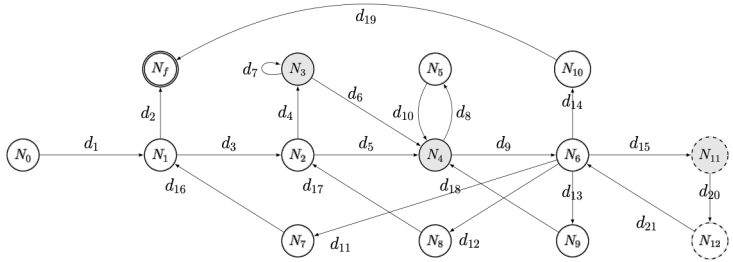
The total work of a resolution is the sum of costs along its state transition path.

Work **Upper Bound**

$$W = \sum_{t=1}^{T} w_t \longrightarrow W^* = \max_{S_0 \to S_f} W$$

Finding the Worst Case





States → Nodes Transitions → Directed Edges Cost → Distance Constraints → Feasibility Bounds

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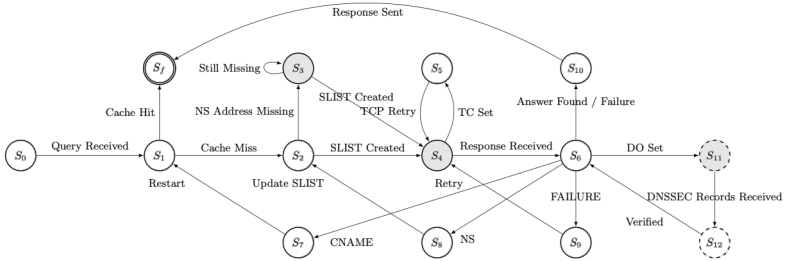

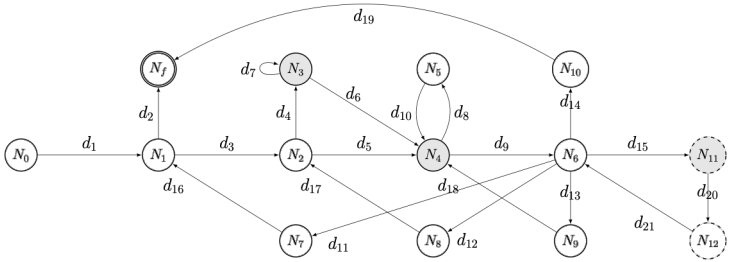

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Maximum Work → **Length of the Longest Path**

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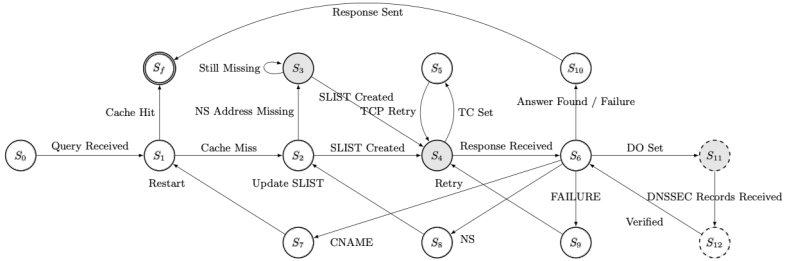

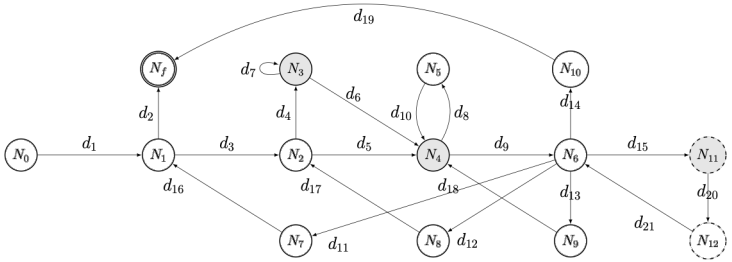

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Constrained Longest Path Search

- Priority search — favor high-cost paths
- Constraint checking — prune infeasible branches at every step
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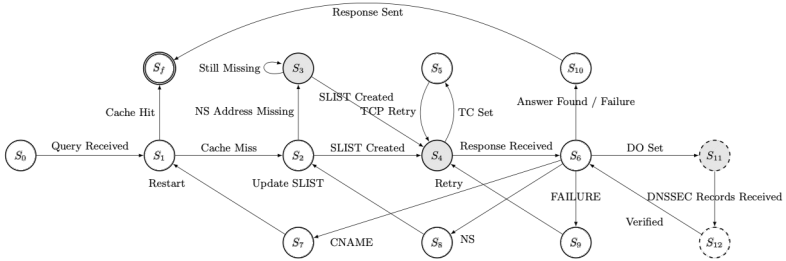

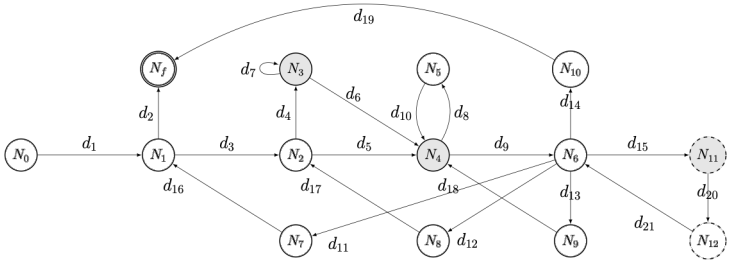

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Maximum Work → **Length of the Longest Path**

W, π*: $S_0 \rightarrow S_1 \rightarrow S_2 \rightarrow \ldots \rightarrow S_f$*
— provably optimal traces

Constrained Longest Path Search

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Correctness Guarantee

- State Completeness
- Additivity
- Boundedness/Termination

Instantiating Resolution Traces

```
> Init:
     S0 → S1 → S2

> for r = 1 to 11:
     > for d = 1 to 32:
          S2 → S4 → S5 → S4 → S6
          S6 → S11 → S12 → S6
          S6 → S8 → S2
          S2 → S4 → S5 → S4 → S6
          S6 → S11 → S12 → S6
          S6 → S7 → S1 → S2

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> Final Answer:
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A formal model and algorithm are necessary but insufficient
— standard nameservers cannot serve the traces they produce.

We need a system that can…

- Generates responses dynamically
- Session-aware across queries
- Full control over content, timing, ordering

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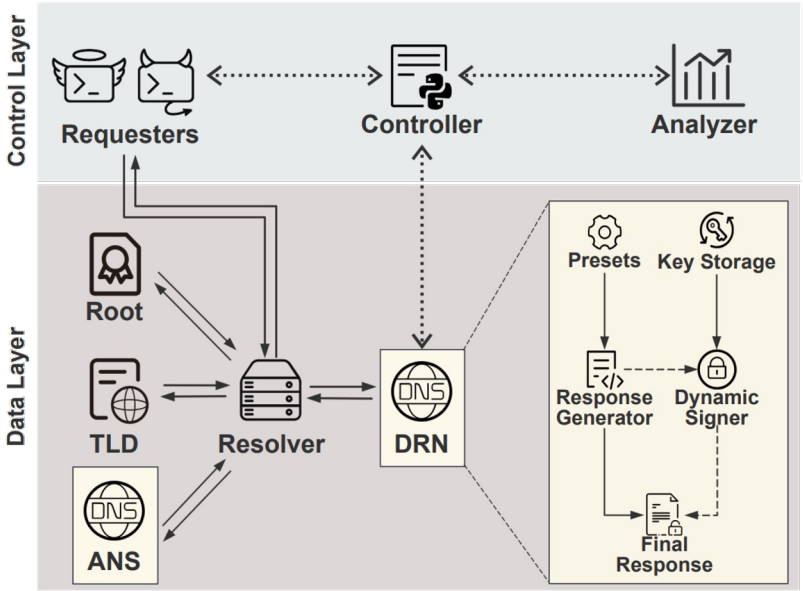

rProfiler

From Constraints to Measured Resolver Work

On State Transitions

Parameters	**BIND** 9.21.1	**Unbound** 1.21.1	**PowerDNS** 5.1.3
max_restart	11	11	10
max_depth	32	128	50
max_fetch	5	6	10
max_referral	7	4	16
cname_reset	True	True	False
max_outgoing_query	384	128	50
tcp_retry_included	False	False	True
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Response	Type	Bind9 9.21.1	Unbound 1.21.1	PowerDNS 5.1.3
Answer	QTYPE	✓	✓	✓, ↔, ↓
	RRSIG	○	○	○
Authoritative	NS	✓	✓	✓, ↔, ↓
	DS	○	○	○
	RRSIG	○	○	○
Additional	A	✓	✓	○
	AAAA	✓	✓	✓, ↔, ↓
	RRSIG	○	○	○

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Some constraints are implicit — only discoverable through probing.

Sample Traces

 # TRX = 1536

> Init:
> $S_0 \to S_1 \to S_2$
> for r = 1 to 11:
> > for d = 1 to 32:
> > $S_2 \to S_4 \to S_5 \to S_4 \to S_6$
> > $S_6 \to S_{11} \to S_{12} \to S_6$
> > $S_6 \to S_8 \to S_2$
> $S_2 \to S_4 \to S_5 \to S_4 \to S_6$
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> Final Answer:
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(a) Bind9

 # TRX = 512

> Init:
> $S_0 \to S_1 \to S_2$
> for d = 1 to 127:
> $S_2 \to S_4 \to S_5 \to S_4 \to S_6$
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(b) Unbound

 # TRX = 96 (with IPv6)

> Init:
> $S_0 \to S_1 \to S_2$
> for d = 1 to 15:
> $S_2 \to S_4 \to S_5 \to S_4 \to S_6$
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(c) PowerDNS

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(c) PowerDNS

One single query can trigger...

Resolver	Transactions	Packets	Volume	Validation	Cache
BIND	1459 / 1536	12369	38.84 M	377	35.57 M
Unbound	493 / 512	5381	13.12 M	132	14.28 M
PowerDNS†	80 / 96	363	2.13 M	30	3.84 M

30 QPS Is More Than Enough To Exhaust Resolvers

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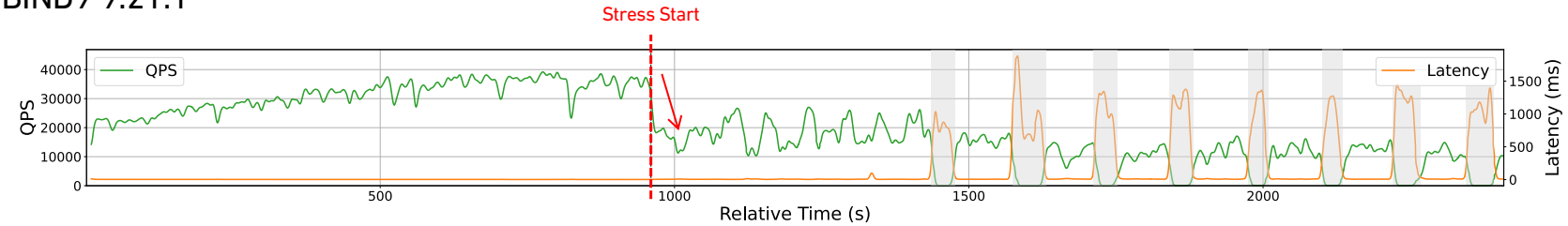
BIND9 9.21.1



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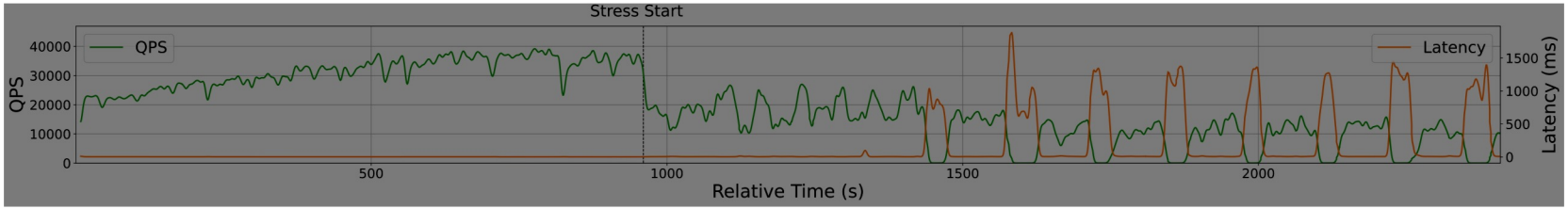
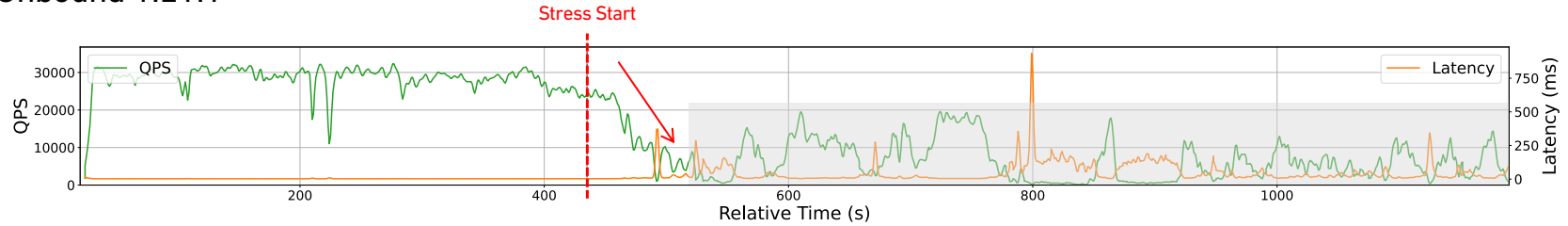


Unbound 1.21.1



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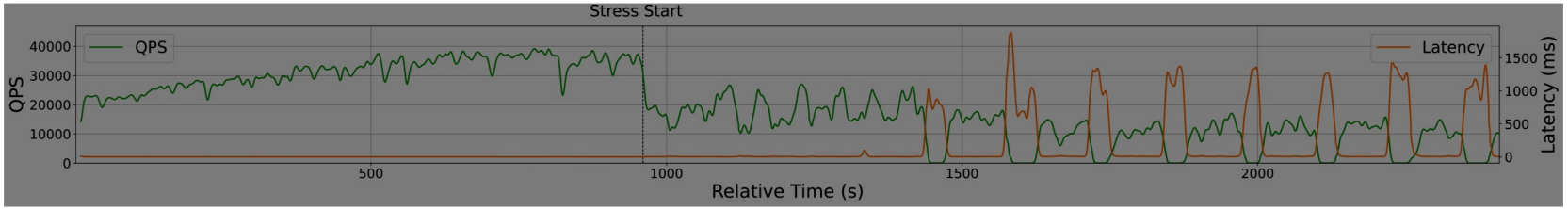

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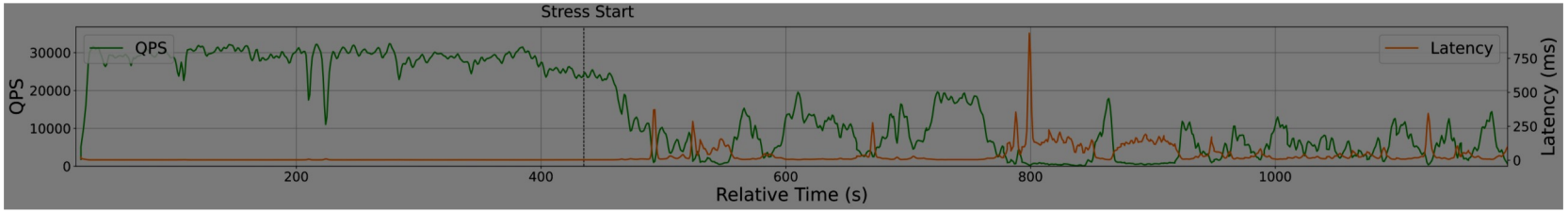

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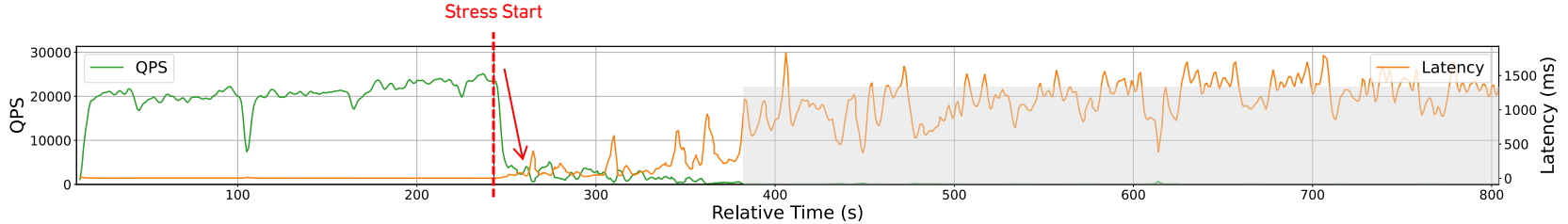

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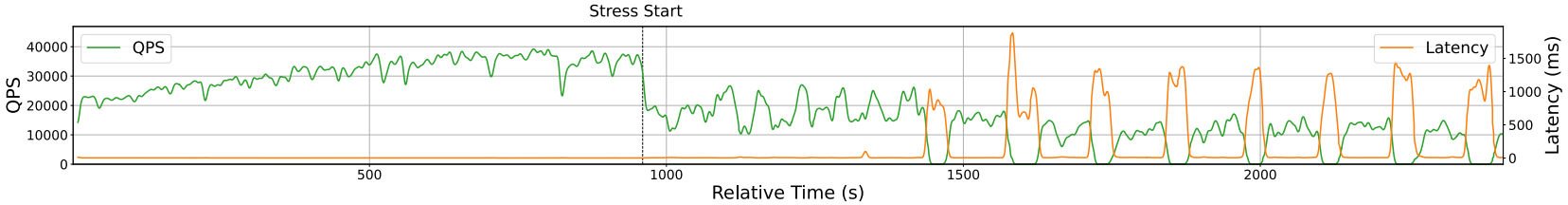

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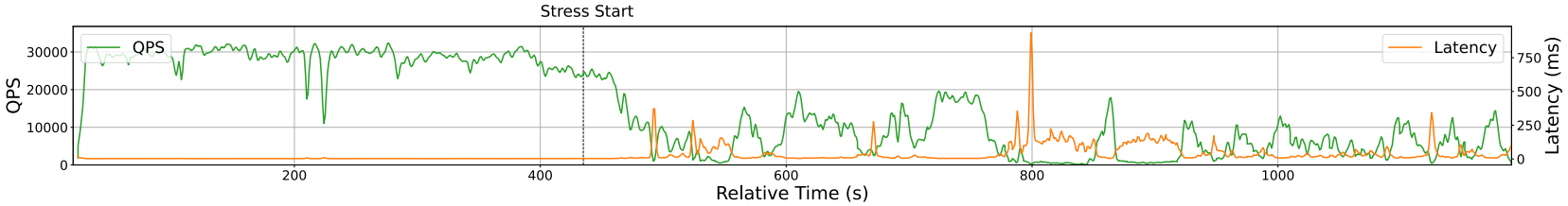

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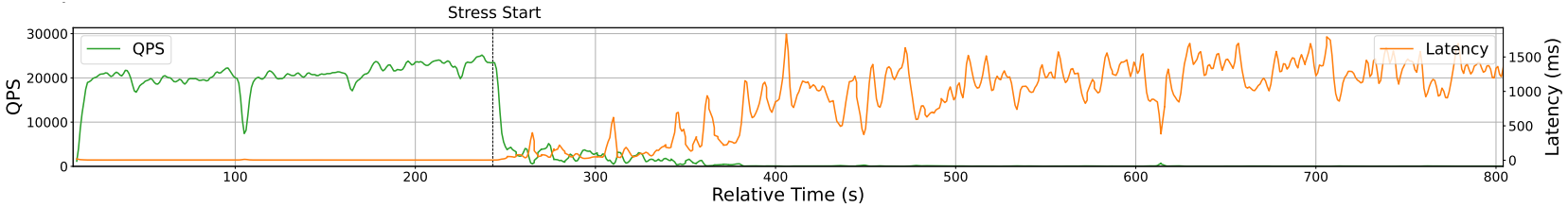

Takeaway

Resolver work can be and should be formally defined and computed

> The recommended priorities for the resolver designer are:
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SCAN ME

Resolve the Unresolved: Systematic Work Profiling for DNS Resolvers.

Contact: liwen.xu@inf.ethz.ch