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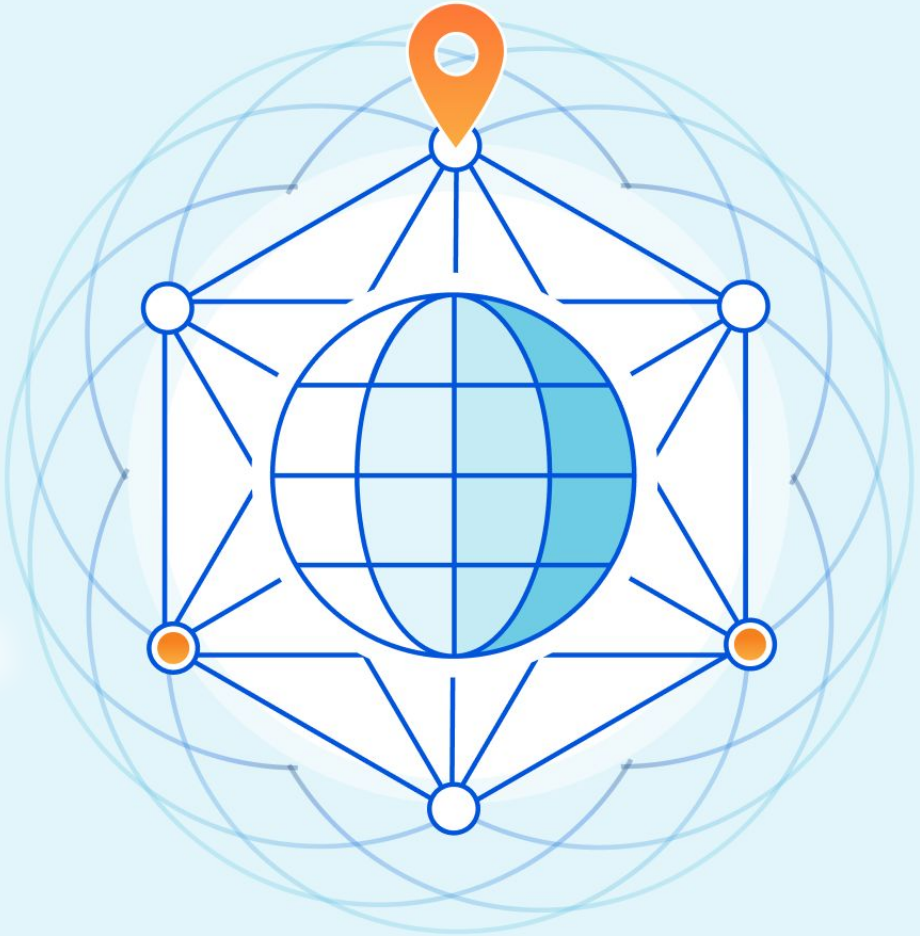

Exploring

DNS Essentials

Carlos Rodrigues
Systems Engineer @ Cloudflare

About

Cloudflare leverages its large global network to provide security, reliability, and speed to a big part of the Internet. It's best known for content distribution, attack protection, and the serverless Workers* platform.

335 cities in **125 countries**

13,000 interconnects with other networks

348 terabits/s of network capacity

71 million HTTP requests per second → **6.1 trillion** per day

44 million DNS queries per second → **3.8 trillion** per day

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* *workers.cloudflare.com*

When you browse to **www.example.com**, how does your computer figure out which IP address it should connect to?

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When Dinosaurs Roamed the Earth

«The Stanford Research Institute [...] maintained a text file named **HOSTS.TXT** that mapped host names to the numerical addresses of computers on the ARPANET.

[...] **Computers**, including their hostnames and addresses, **were added** to the primary file by contacting the SRI Network Information Center [...] **via telephone during business hours**.»

— from Wikipedia (DNS)

```
HOST : 46.0.0.12 : UCBCALDER : VAX-11/750 : UNIX : TCP/TELNET,TCP/FTP,UDP :
HOST : 46.0.0.13 : UCBDALI : VAX-11/750 : UNIX : TCP/TELNET,TCP/FTP,UDP :
HOST : 46.0.0.14 : UCBMATISSE : VAX-11/750 : UNIX : TCP/TELNET,TCP/FTP,UDP :
HOST : 46.0.0.15 : UCBMEDEA : VAX-11/750 : UNIX : TCP/TELNET,TCP/FTP,UDP :
HOST : 46.0.0.19 : UCBINGRES : VAX-11/780 : UNIX : TCP/TELNET,TCP/FTP,UDP :
HOST : 47.0.32.3 : SAC-VAX,SRI-SPUD,SPUD : VAX-11/780 : UNIX : TCP/TELNET,TCP/FTP,TCP/SMTP,UDP,…
HOST : 48.3.1.41 : NDRE1,NDRE : LSI-11/23 : FUZZ : TCP/TELNET,TCP/SMTP,TCP/FTP,UDP :
```

— excerpt from HOSTS.TXT, May 1983

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When Dinosaurs Roamed the Earth

Maintaining a **centralized** hosts database obviously **didn't scale**, and DNS was invented in **1983** as a **distributed** solution to that problem. The first RFCs describing it date from November of that year:

- RFC 882 — "*Domain names: Concepts and facilities*"
- RFC 883 — "*Domain names: Implementation specification*"

Although it's been 40 years, you still have a descendant of HOSTS.TXT on your computer, in the form of **/etc/hosts** in Unix-like operating systems and **C:\Windows\System32\drivers\etc\hosts** on Windows.

```
127.0.0.1 localhost
255.255.255.255 broadcasthost
::1 localhost
127.0.0.1 kubernetes.docker.internal
```

— excerpt from the /etc/hosts file on my laptop, November 2023

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The Domain Name System (DNS)

The DNS is a **distributed system** both **technically** (made up of many different servers around the globe) and **administratively** (separate organizations managing different parts of it independently of each other).

In the DNS, fully-qualified names are made of **domain components** glued together with dots. The leftmost component is the **host name**, and the rest is the **domain name** (*i.e.* the path to the host).

www.example.com.

There's always an **invisible dot** at the end. The nameless domain to its right is called the **root**.

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The Domain Name System (DNS)

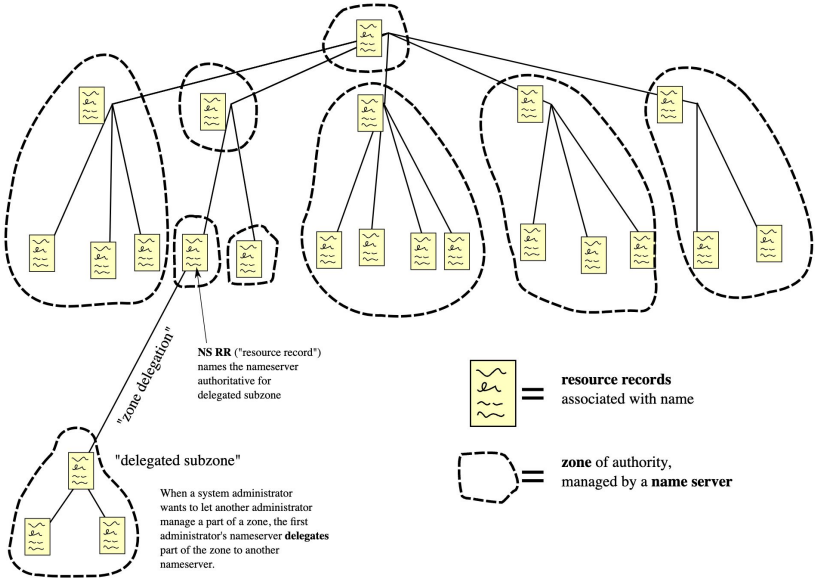
The DNS is a tree and each branch is called a **zone**.

- "**.**" (the root) is a zone
- "**.com**" is a zone under the root
- "**.example.com**" is a zone under ".com"

www.example.com is not a zone, because "www" is just the name of a particular host. But **example.com** can be both a zone *and* the name of a host.

Confused?

You can call zones "**domains**" if that makes it easier.



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Discovering Which DNS Servers to Use

To avoid a **chicken-and-egg** problem, your system needs to be bootstrapped with the **IP address** of **at least one** DNS server… somehow.

In the most common case, your computer **gets an IP address automatically** when it connects to the network and, along with it, **also gets the IP address(es) of one or more DNS servers**.

You can also configure DNS servers manually in your operating system, in which case those are used instead — *e.g.* using **1.1.1.1** instead of your ISP's servers for added performance, privacy, etc.

Some applications (*i.e.* web browsers) also have set of DNS servers pre-configured, which they may use instead of the servers configured in the operating system.

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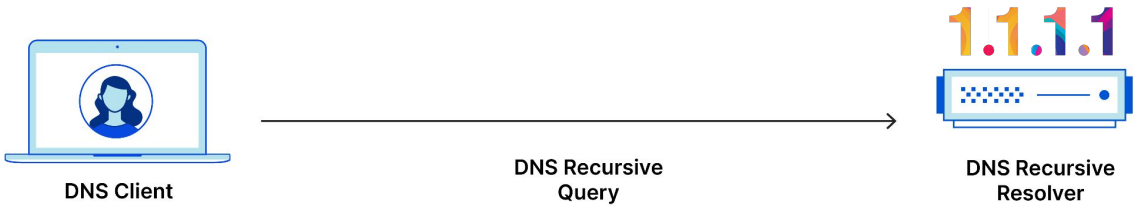
The Different Flavors of DNS Servers

The DNS servers your operating system uses to look up names are called **recursive resolvers**.

Why "recursive" in the name? We'll get to that soon...



In turn, **recursive resolvers** reach out to third-party DNS servers in order to answer client queries. These other DNS servers are called **nameservers** or, more often, **authoritative nameservers**.

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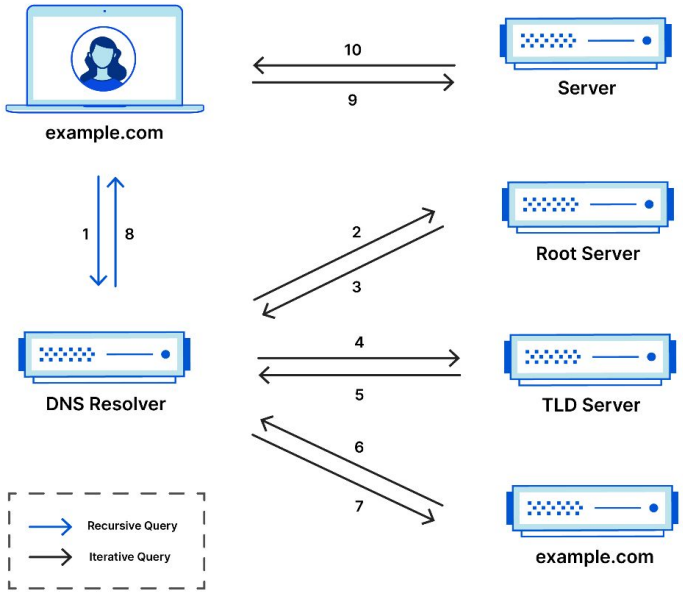
Looking up Names in DNS

Querying DNS means going down from the root until the **authoritative nameserver** holding the answer we want is found.

The **recursive resolver** does this on the client's behalf. It then **caches** the answer(s) and any intermediate steps to speed up subsequent queries.

How long things stay in cache is defined by the **time-to-live** (TTL) attached to each DNS record.

More on caching later…



Nothing stops you from running your own recursive resolver at home, if you want.

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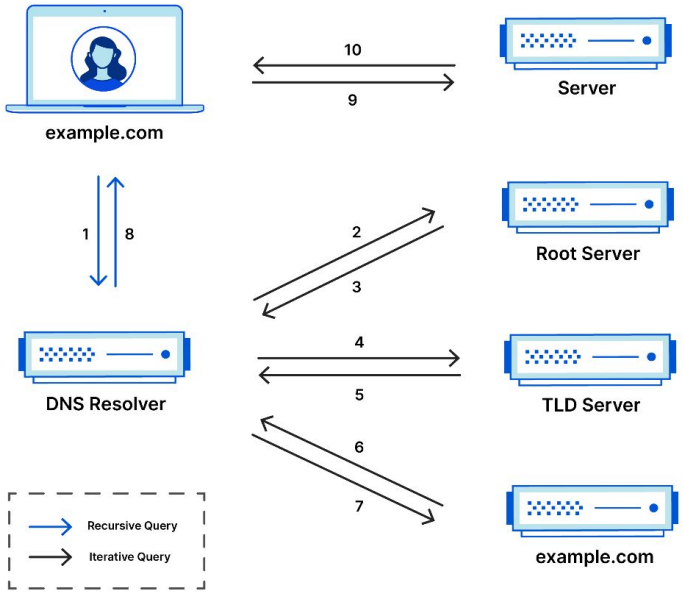
Looking up Names in DNS

DNS queries must specify the **type** of answer they're looking for. These are some common query types:

- **A** — IPv4 address for a name
- **AAAA** — IPv6 address for a name
- **NS** — names of the nameservers for the domain
- **MX** — names of the email servers for the domain
- **TXT** — text associated with the name (*e.g.* email policies)
- **PTR** — name for an IP address (reverse lookup)

DNS responses often contain additional (related) records of types that don't match the requested type (*e.g.* CNAME, DNAME, SOA).

The most important of these extra answers are the **glue records**.



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The Transport Protocols Used in DNS

DNS mostly* still uses **unencrypted UDP**. The query is a single UDP packet, and the response is also a single UDP packet. It's fast, but has some limitations.

When the **response is too big** to fit a single UDP packet (uncommon), the server will return a truncated response. The client must query again using **unencrypted TCP** to get a full response.

DNS-over-TLS (**DoT**) and DNS-over-HTTPS (**DoH**) provide encryption. DoT and DoH have their own specific advantages and disadvantages. Which one is better depends on the situation.

For traffic between **recursive resolvers** and **authoritative nameservers** there is no standard for encrypted communications (yet). Unencrypted **UDP** and **TCP** are the **only options****.

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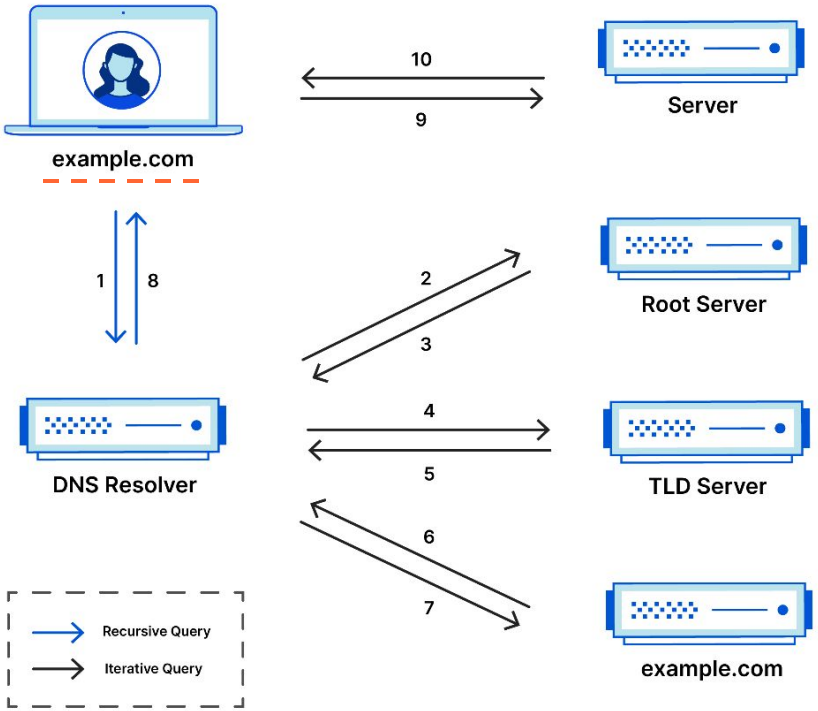
** More than **80%** of the time.*
*** DNSSEC is used to prevent tampering by signing responses (but adoption is still lacking).*

The Recursive Lookup Process



***TLD** means a top-level domain.*

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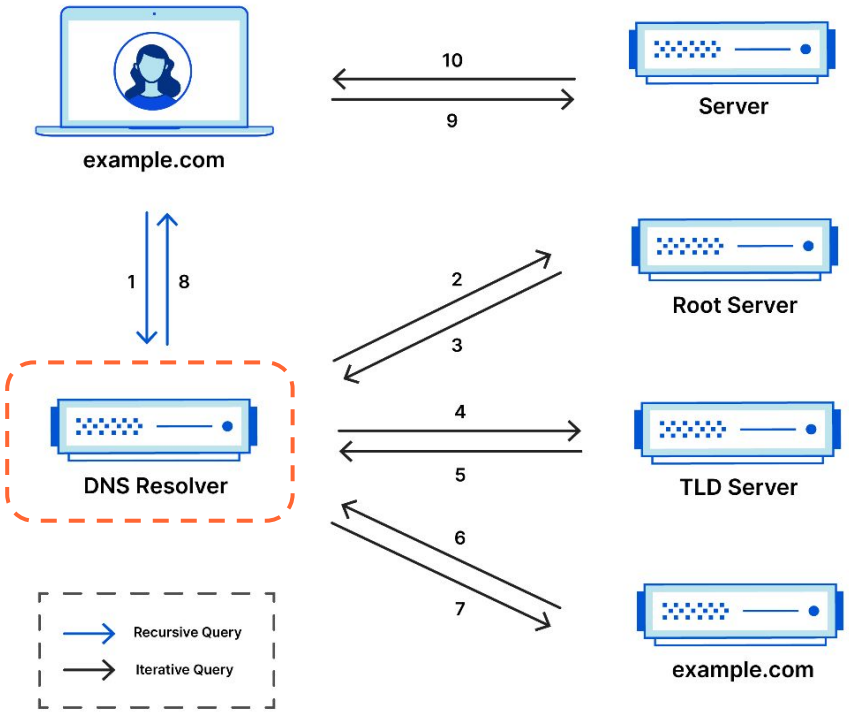
The Recursive Lookup Process



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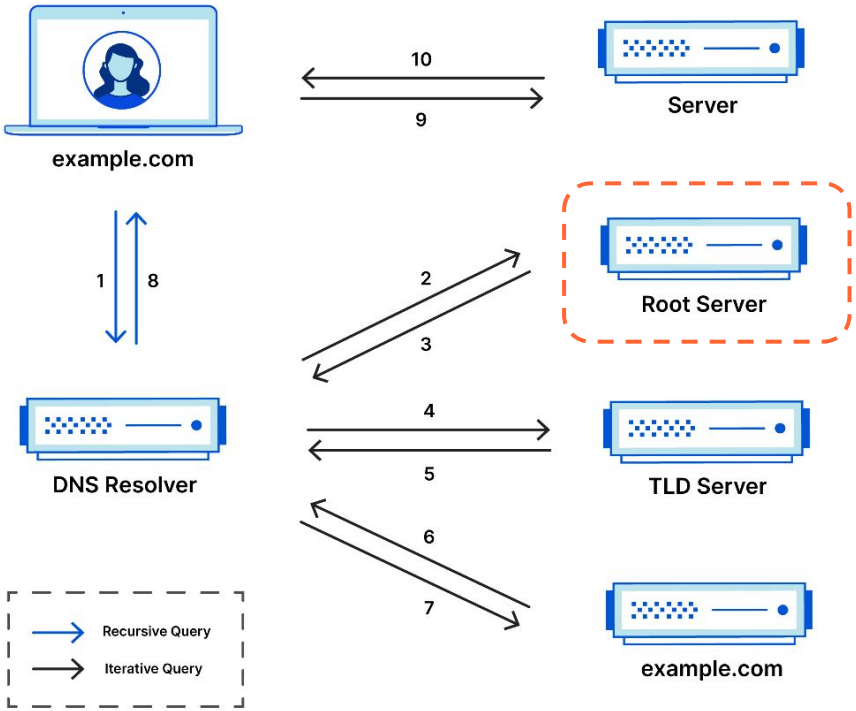
TLD means a top-level domain.

The Recursive Lookup Process



***TLD** means a top-level domain.*

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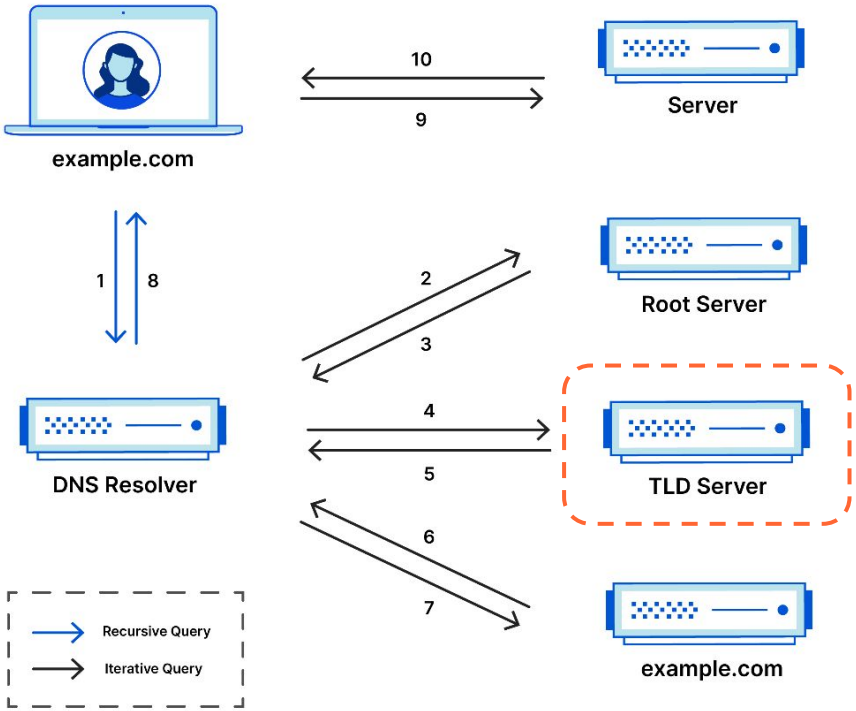
The Recursive Lookup Process



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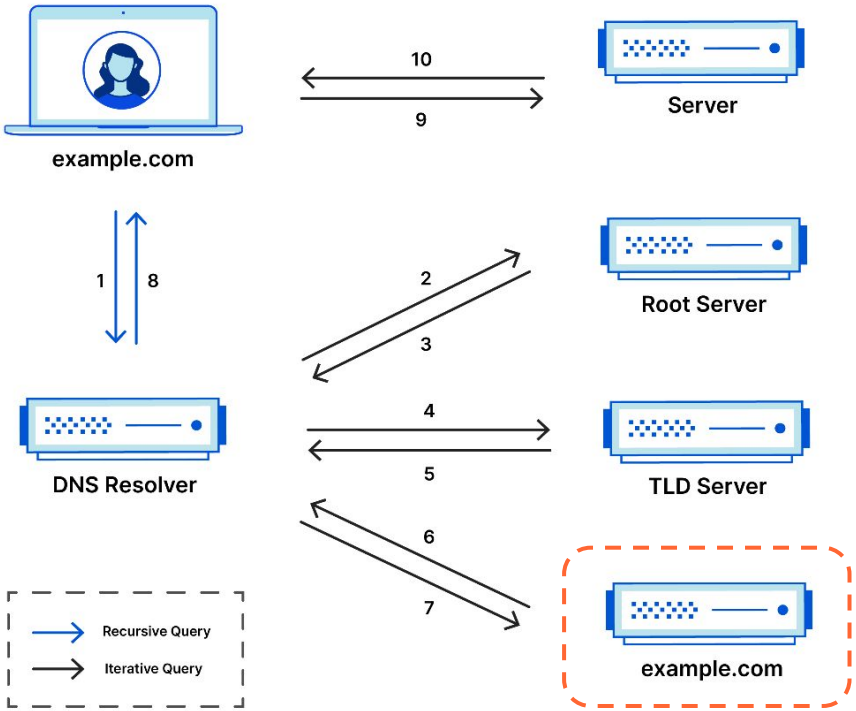
CLOUDFLARE

The Recursive Lookup Process



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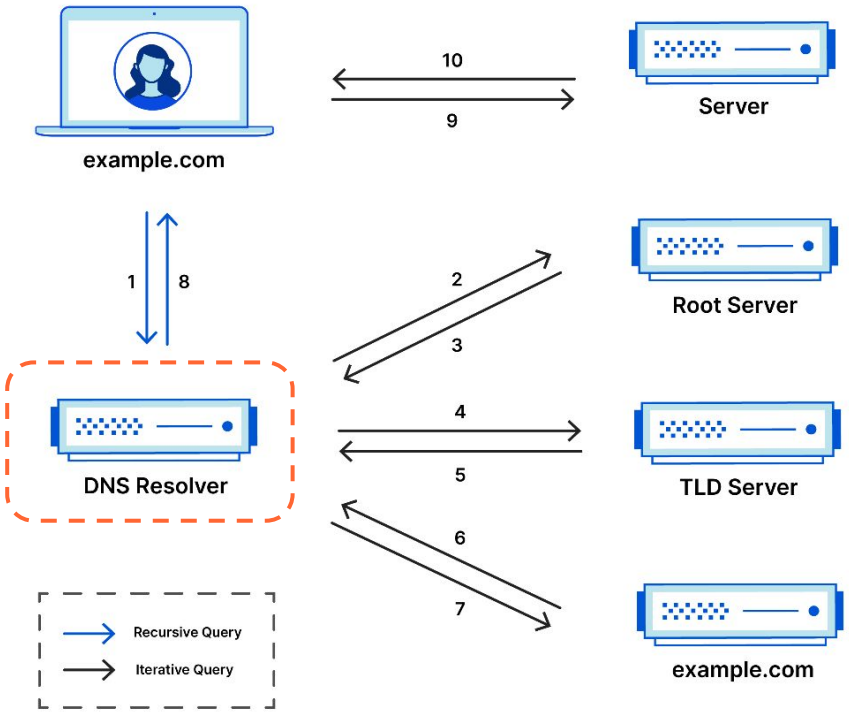
The Recursive Lookup Process



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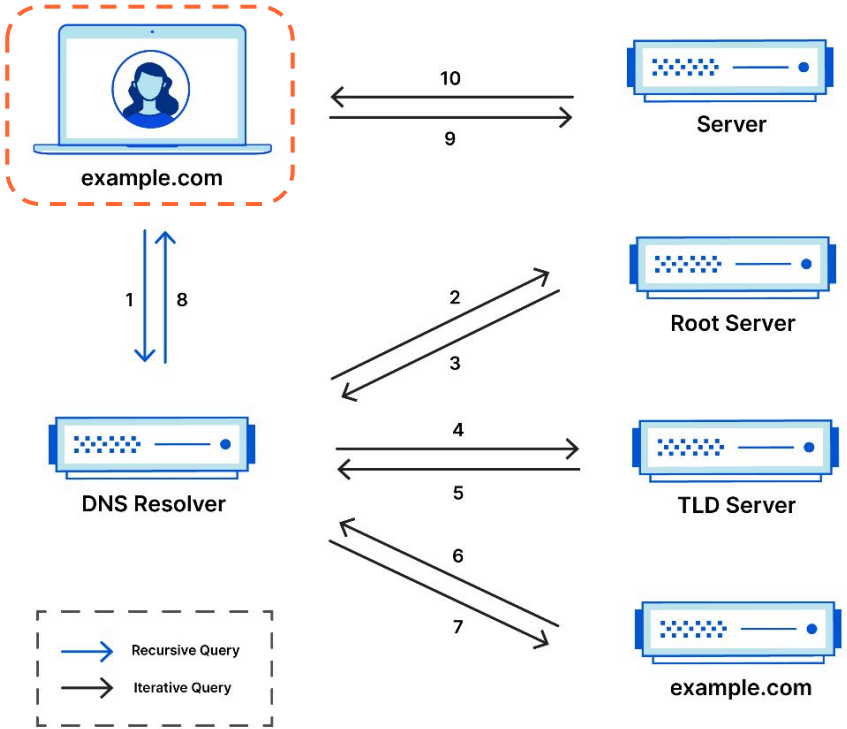
TLD means a top-level domain.

The Recursive Lookup Process



***TLD** means a top-level domain.*

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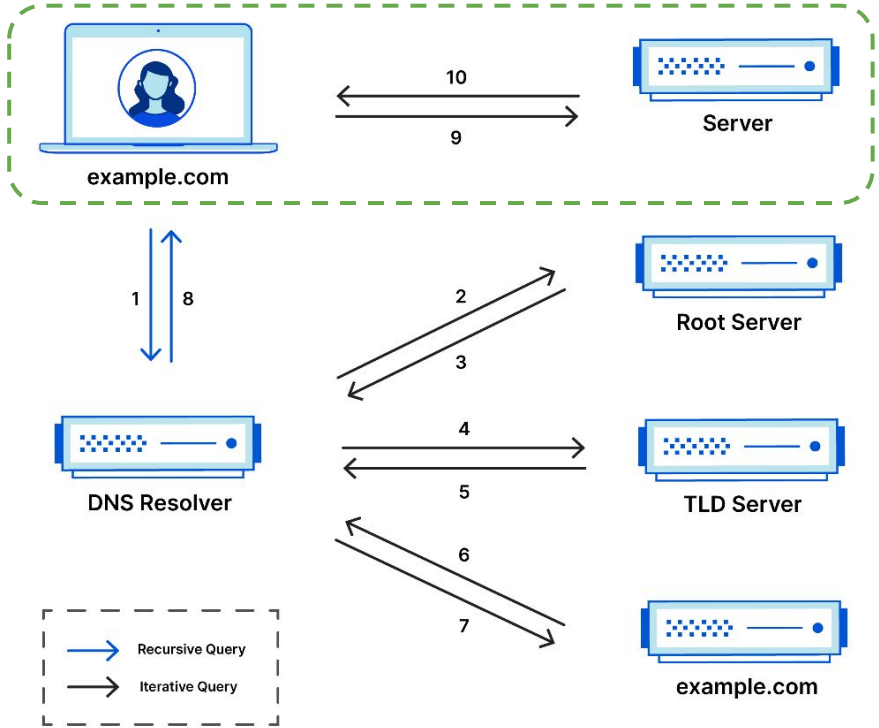
The Recursive Lookup Process



***TLD** means a top-level domain.*

f.root-servers.net

```
$ dig +nord A www.cloudflare.com @192.5.5.241
```

1

```
; <<>> DiG 9.10.6 <<>> A +nord www.cloudflare.com @192.5.5.241
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 35635
;; flags: qr; QUERY: 1, ANSWER: 0, AUTHORITY: 13, ADDITIONAL: 27

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 1472
;; QUESTION SECTION:
;www.cloudflare.com.            IN      A

;; AUTHORITY SECTION:
com.                    172800  IN      NS      i.gtld-servers.net.
[...]

;; ADDITIONAL SECTION:
i.gtld-servers.net.     172800  IN      A       192.43.172.30
i.gtld-servers.net.     172800  IN      AAAA    2001:503:39c1::30
[...]

;; Query time: 22 msec
[...]
```

i.gtld-servers.net

```
$ dig +nord A www.cloudflare.com @192.43.172.30
```

2

```
; <<>> DiG 9.10.6 <<>> A +nord www.cloudflare.com @192.43.172.30
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 56977
;; flags: qr; QUERY: 1, ANSWER: 0, AUTHORITY: 5, ADDITIONAL: 21

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 4096
;; QUESTION SECTION:
;www.cloudflare.com.            IN      A

;; AUTHORITY SECTION:
cloudflare.com.         172800  IN      NS      ns3.cloudflare.com.
[...]

;; ADDITIONAL SECTION:
ns3.cloudflare.com.     172800  IN      A       162.159.0.33
ns3.cloudflare.com.     172800  IN      A       162.159.7.226
ns3.cloudflare.com.     172800  IN      AAAA    2400:cb00:2049:1::a29f:21
ns3.cloudflare.com.     172800  IN      AAAA    2400:cb00:2049:1::a29f:7e2
[...]

;; Query time: 147 msec
[...]
```

ns3.cloudflare.com

```
$ dig +nord A www.cloudflare.com @162.159.0.33

; <<>> DiG 9.10.6 <<>> A +nord www.cloudflare.com @162.159.0.33
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 51039
;; flags: qr aa; QUERY: 1, ANSWER: 2, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 1232
;; QUESTION SECTION:
;www.cloudflare.com.            IN      A

;; ANSWER SECTION:
www.cloudflare.com.  300    IN      A       104.16.123.96
www.cloudflare.com.  300    IN      A       104.16.124.96

;; Query time: 114 msec
[...]
```

time-to-live (TTL)

3

```
$ dig +nord A www.cloudflare.com @162.159.0.33

; <<>> DiG 9.10.6 <<>> A +nord www.cloudflare.com @162.159.0.33
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 51039
;; flags: qr aa; QUERY: 1, ANSWER: 2, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 1232
;; QUESTION SECTION:
;www.cloudflare.com.            IN      A

;; ANSWER SECTION:
www.cloudflare.com.  300    IN      A       104.16.123.96
www.cloudflare.com.  300    IN      A       104.16.124.96

;; Query time: 114 msec
[...]
```

3

4

```
$ curl --head --resolve www.cloudflare.com:443:104.16.123.96 \
                                https://www.cloudflare.com/cdn-cgi/trace

HTTP/2 200
date: Mon, 10 Mar 2025 16:46:00 GMT
content-type: text/plain
server: cloudflare
cf-ray: 91e449244b77e3b0-LIS
[...]
```

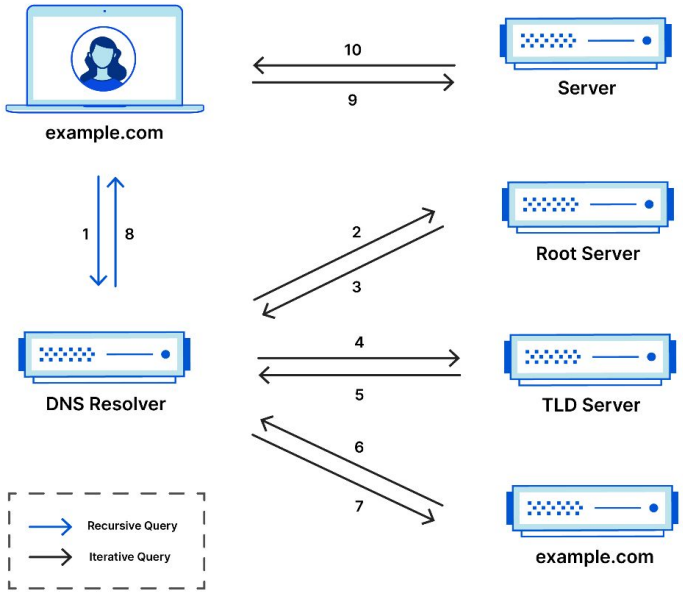
About Caching...

Caching in DNS is present **at every level**, not only in recursive resolvers: your operating system also caches DNS responses, and your home router* does too.

The authoritative nameservers return a **canonical TTL** on each record. Other levels return **adjusted TTLs** by subtracting the amount of time they've had the record in their caches.

This multi-level caching gives the **illusion of propagation**. For a DNS record to be present in a cache, it must have been requested by a client at some point.

When a response comes back empty (*e.g.* an AAAA query for a name that exists but doesn't have an IPv6 address), that can still be cached using the minimum TTL defined in the SOA record.



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* *Clients at home usually get the local router as their DNS resolver, which forwards queries to the recursive resolvers.*

Less Obvious Uses of DNS

It's easy to think of DNS as a static database, but there are plenty of things it can do if you choose DNS server software with fully-programmable backends (*e.g.* PowerDNS*****).

Returning different answers based on the client's location is the most common, but far from the most imaginative.

It's also easy to think of DNS as an Internet-centric service, but there are some less known use-cases out there, such as call routing in 4G/5G mobile networks******.

When your phone does a call using VoLTE ("HD" icon on Android), there are good chances that DNS with ENUM/NAPTR records was involved.

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***** *doc.powerdns.com/authoritative/backends/pipe.html*
****** *wikipedia.org/wiki/telephone_number_mapping*

Learn more about DNS:

cloudflare.com/learning/dns/what-is-dns

radar.cloudflare.com/dns

Experiment with DNS:

messwithdns.net

Thank You

cloudflare.com/careers/jobs

Carlos Rodrigues
crodrigues@cloudflare.com

Coimbra, March 11, 2025