How It Works: DNS Fundamentals

ICANN 61

COMMUNITY FORUM

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Names and Numbers

- IP addresses easy for machines but hard for people
  - IPv4: 192.0.2.7
  - IPv6: 2001:db8::7
- People need to use names
- In the early days of the Internet, names were simple
  - No domain names yet
  - “Single-label names”, 24 characters maximum
  - Referred to as ***host names***

Name Resolution

- Mapping names to IP addresses to names is ***name resolution***
- Name resolution on the early Internet used a ***host file*** named HOSTS.TXT
  - Same function but slightly different format than the familiar */etc/hosts*
- Centrally maintained by the NIC (Network Information Center) at the Stanford Research Institute (SRI)
  - Network administrators sent updates via email
- Ideally everyone had the latest version of the file
  - Released once per week
  - Downloadable via FTP

Problems with HOSTS.TXT

- Naming contention
  - Edits made by hand to a text file (no database)
  - No good method to prevent duplicates
- Synchronization
  - No one ever had the same version of the file
- Traffic and load
  - Significant bandwidth required just to download the file
- A centrally maintained host file just didn’t scale

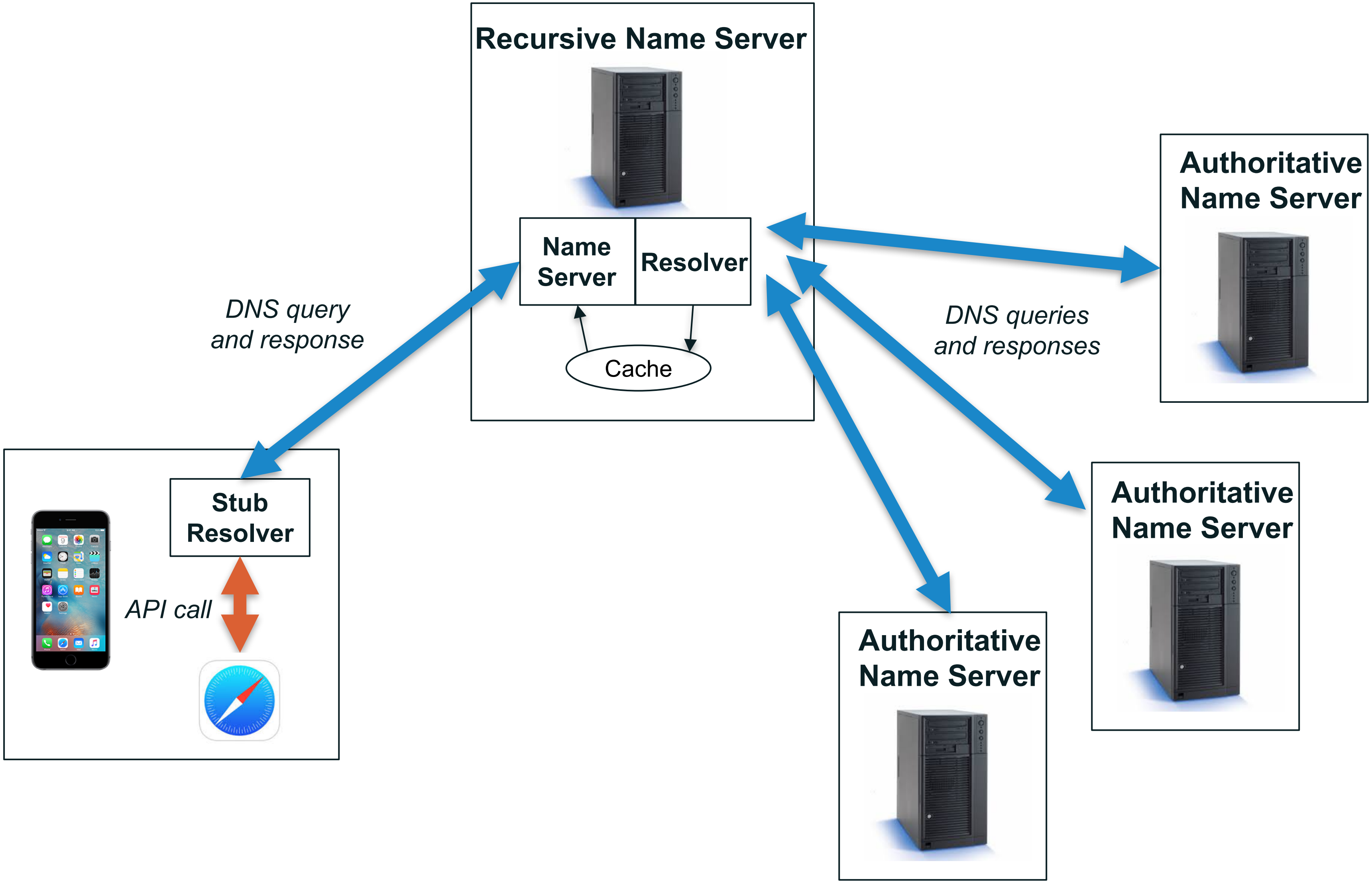
DNS to the Rescue

- Discussion started in the early 1980s on a replacement
- Goals:
  - Address HOST.TXT scaling issues
  - Simplify email routing
- Result was the ***Domain Name System***
- Requirements in multiple documents:
  - RFC 799, “Internet Name Domains”
  - RFC 819, “The Domain Naming Convention for Internet User Applications”

DNS in a nutshell

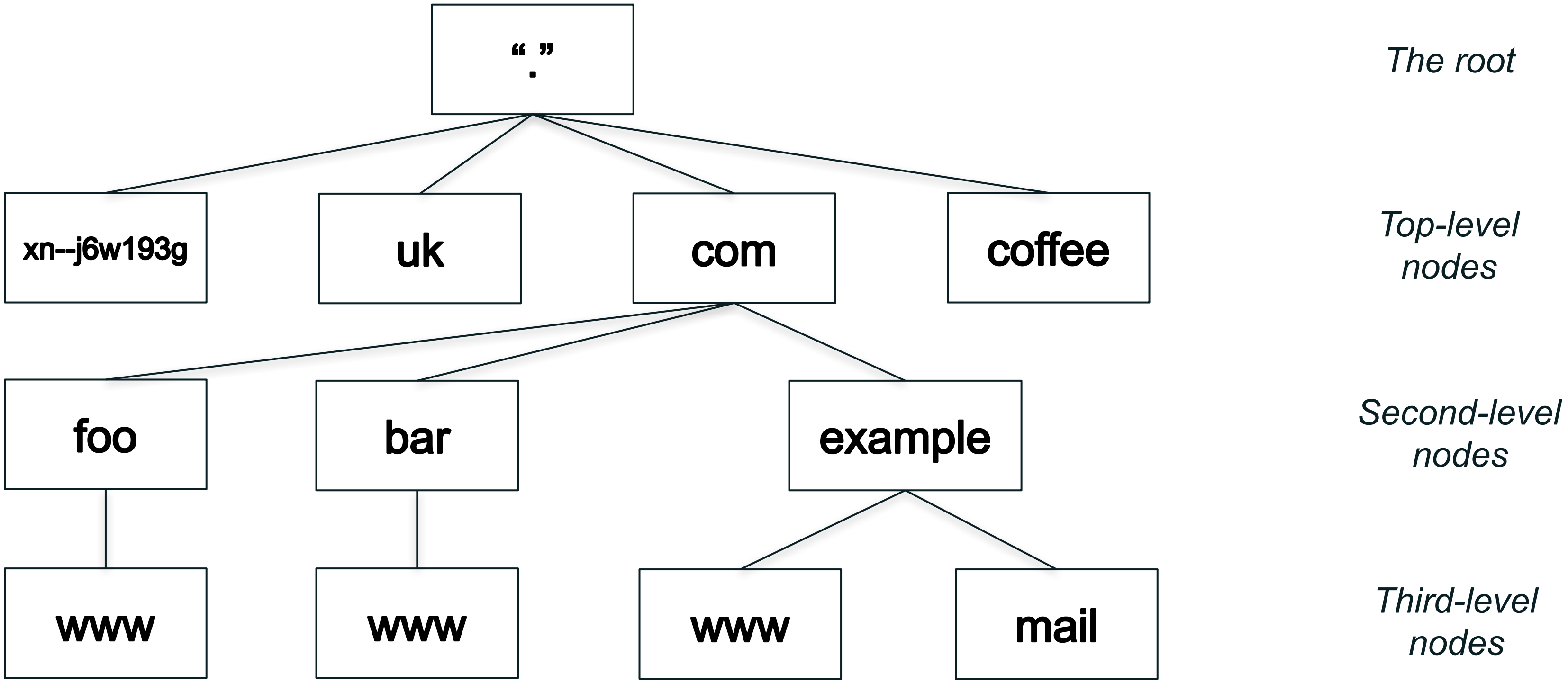
- DNS is a distributed database
  - Data is maintained locally but available globally
- ***Resolvers*** send queries
- ***Name servers*** answer queries
- Optimizations:
  - Caching to improve performance
  - Replication to provide redundancy and load distribution

DNS Components at a Glance



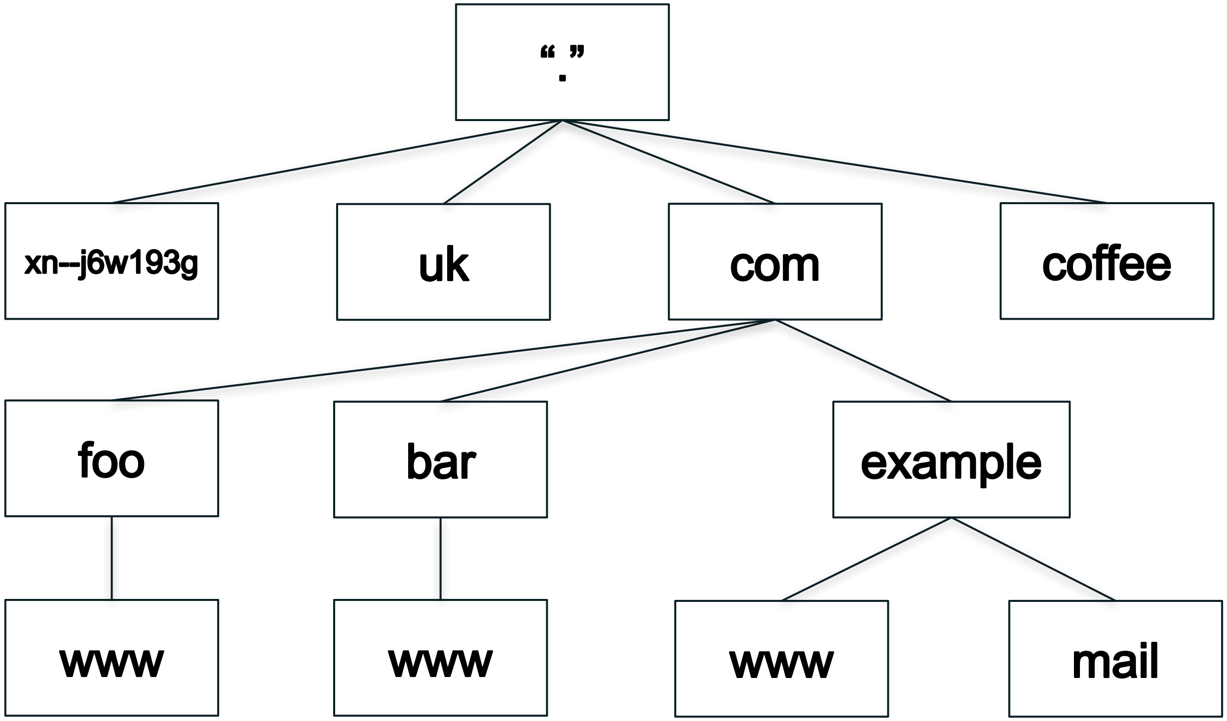
The Name Space

- DNS database structure is an inverted tree called the ***name space***
- Each node has a label
- The root node (and only the root node) has a null label



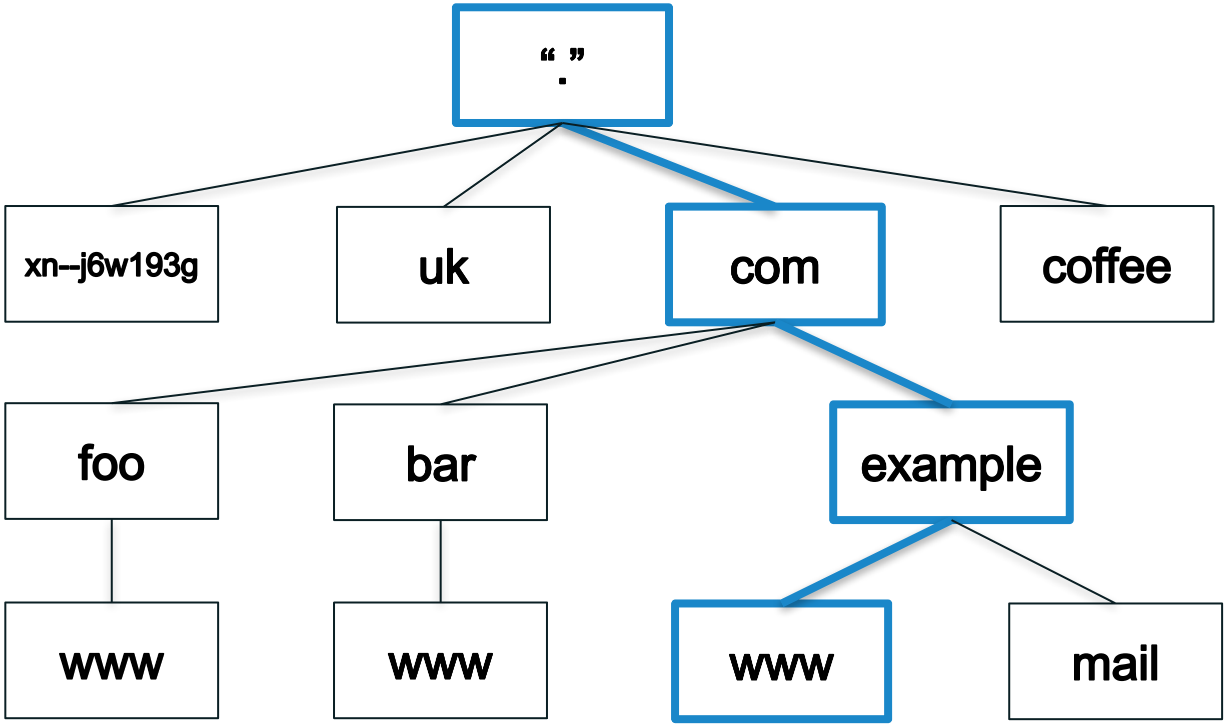
Label Syntax

- Legal characters for labels are “LDH” (letters, digits, hyphen)
- Maximum length 63 characters
- Comparisons of label names are not case sensitive



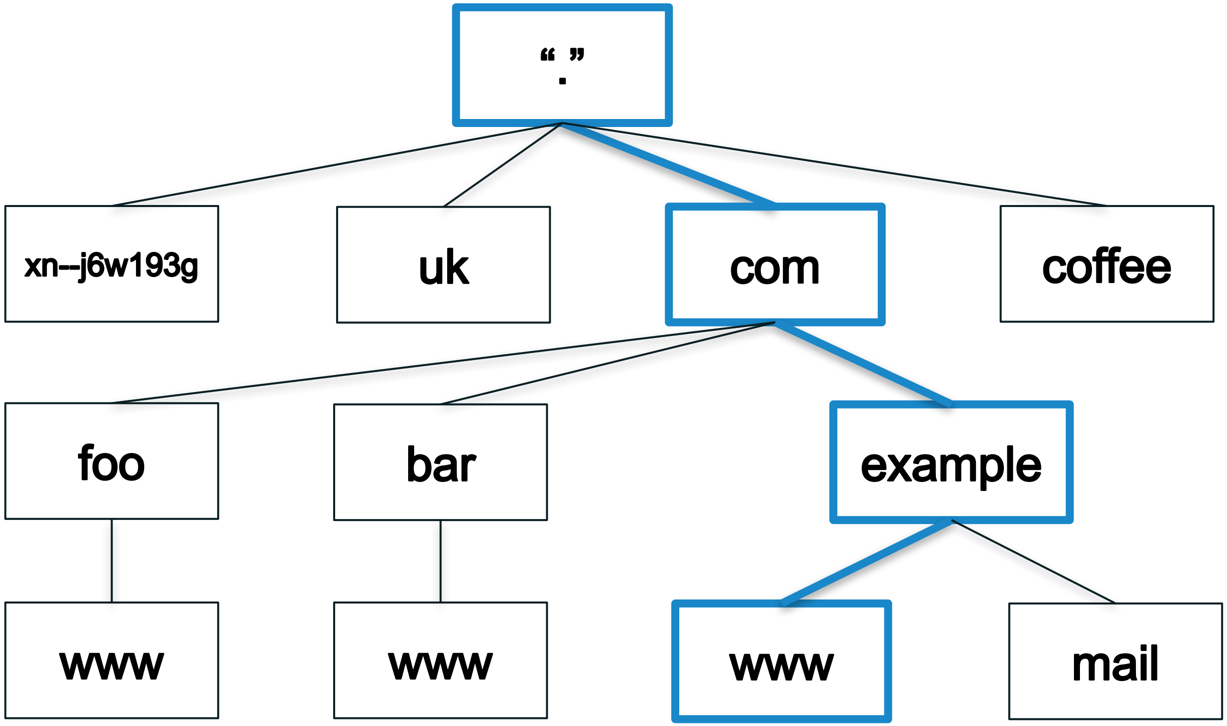
Domain Names

- Every node has a ***domain name***
- Sequence of labels from the node to the root separated by dots
- Highlighted: *www.example.com.*



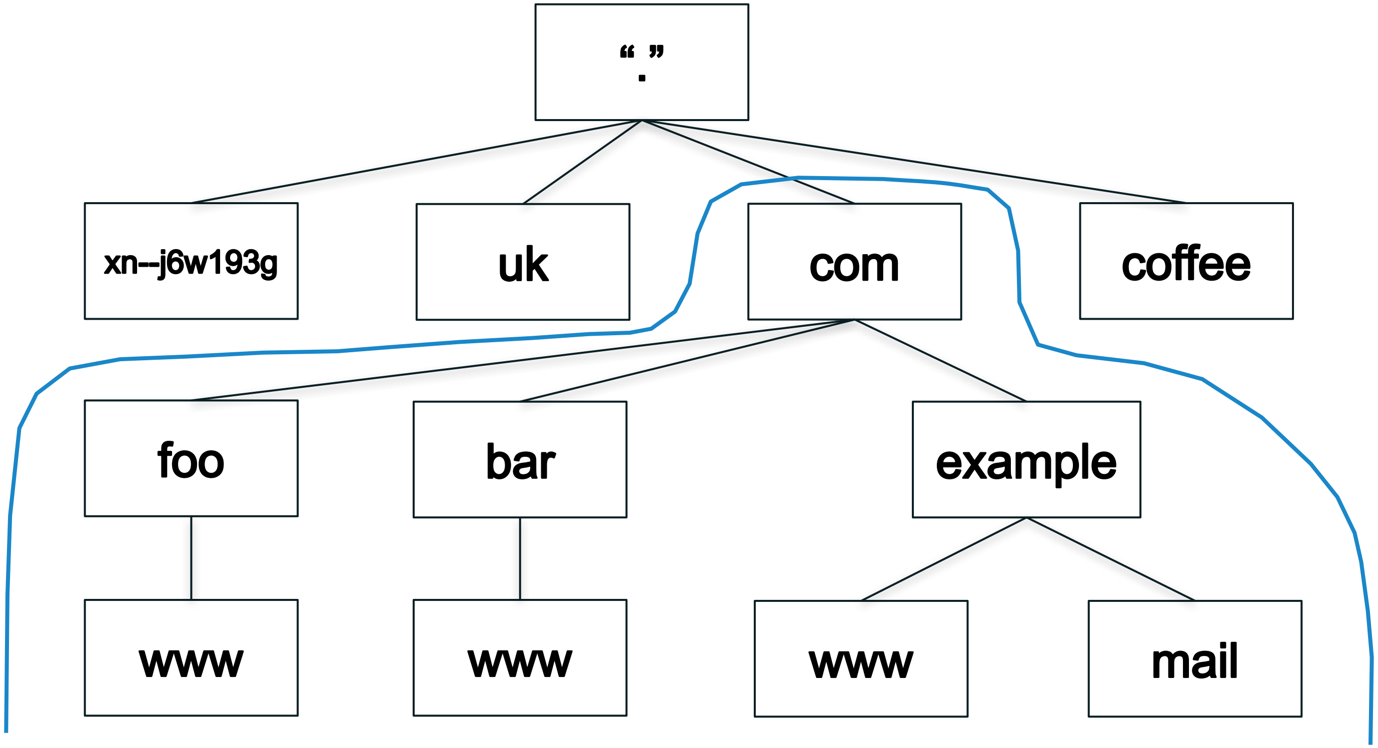
Fully Qualified Domain Names

- A ***fully qualified domain name (FQDN)*** unambiguously identifies a node
    - Not relative to any other domain name
- An FQDN ends in a dot
- Example FQDN: *www.example.com.*



Domains

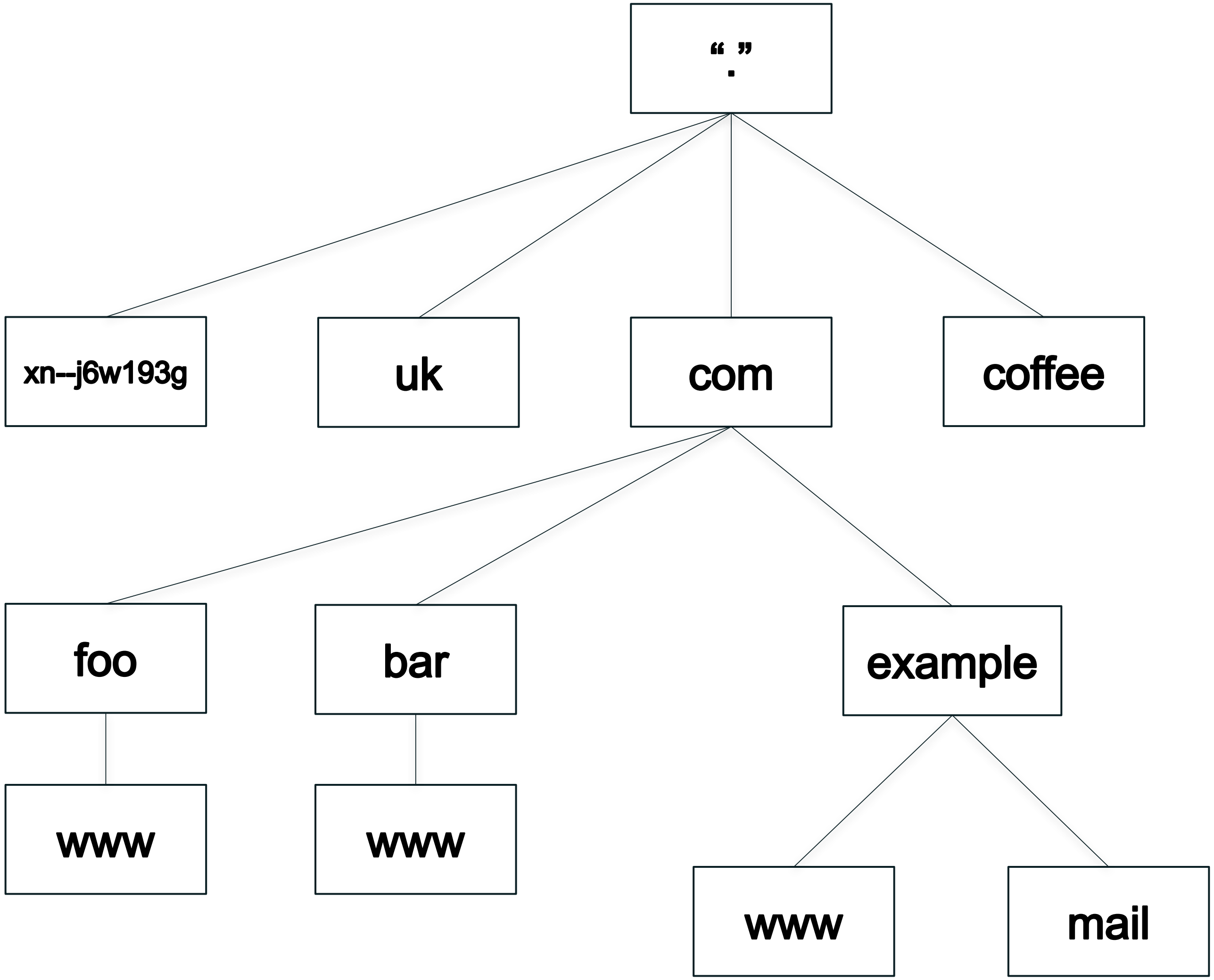
- A ***domain*** is a node and everything below it (its descendants)
- The top node of a domain is the ***apex*** of that domain
- Shown: the *com* domain



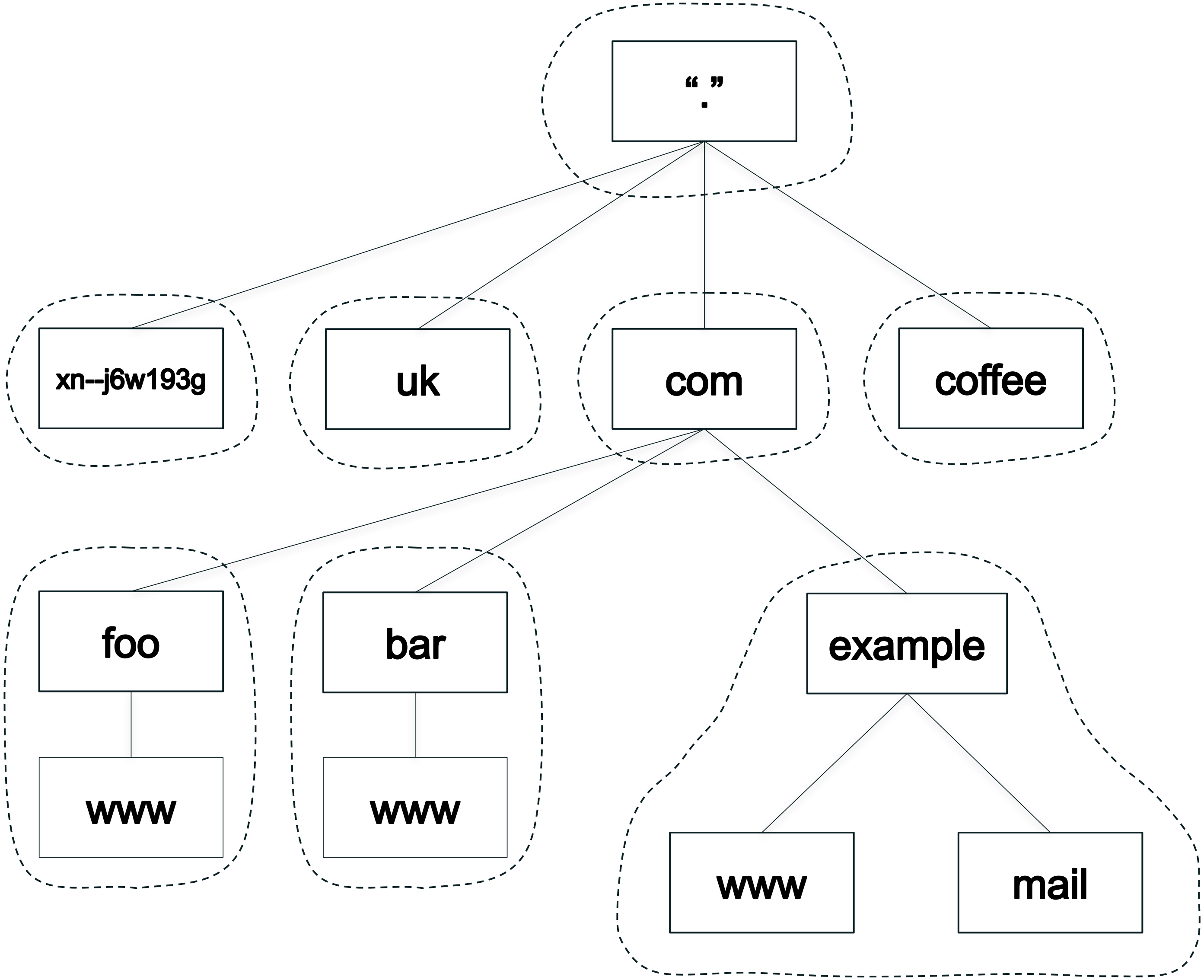
Zones

- The name space is divided up to allow distributed administration
- Administrative divisions are called ***zones***
- ***Delegation*** creates zones
  - Delegating zone is the ***parent***
  - Created zone is the ***child***

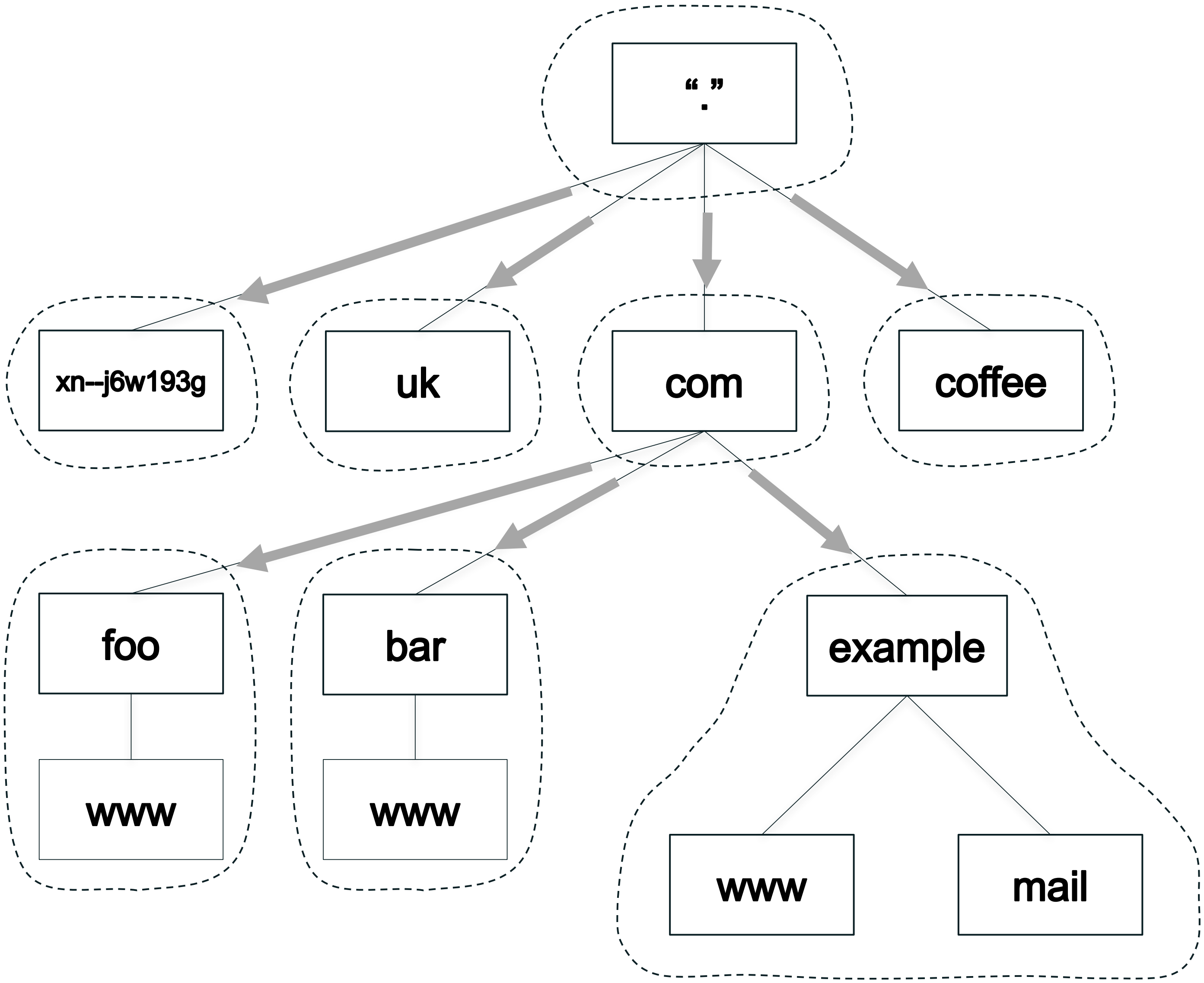
The Name Space



Zones are Administrative Boundaries



Delegation Creates Zones



Name Servers and Zones

- Name servers answer queries
- A name server ***authoritative*** for a zone has complete knowledge of that zone
  - Can provide a definitive answer to queries about the zone
- Zones should have multiple authoritative servers
  - Provides redundancy
  - Spreads the query load

Authoritative Server Synchronization

- How do you keep a zone's data in sync across multiple authoritative servers?
- Fortunately zone replication is built into the DNS protocol
- A zone's ***primary*** name server has the definitive zone data
  - Changes to the zone are made on the primary
- A zone's ***secondary*** or ***slave*** server retrieves the zone data from another authoritative server via a ***zone transfer***
  - The server it retrieves from is called the ***master server***
  - Master server is usually the primary but doesn't have to be
- Zone transfer is initiated by the secondary
  - Secondary polls the master periodically to check for changes
  - The master also notifies the primary of changes
    - RFC 1996, "A Mechanism for Prompt Notification of Zone Changes (DNS NOTIFY)"

DNS Data

- The DNS standard specifies the format of DNS packets sent over the network
  - Informally called “wire format”
- The standard also specifies a text-based representation for DNS data called ***master file format***
- A ***zone file*** contains all the data for a zone in master file format

DNS Resource Records

- Recall every node has a domain name
- A domain name can have different kinds of data associated with it
- That data is stored in ***resource records***
  - Sometimes abbreviated as ***RRs***
- Different record types for different kinds of data

Zone Files

- A zone consists of multiple resource records
- All the resource records for a zone are stored in a ***zone file***
- Every zone has (at least) one zone file
- Resource records from multiple zones are never mixed in the same file

Format of Resource Records

- Resource records have five fields:
  - ***Owner***: Domain name the resource record is associated with
  - ***Time to live (TTL)***: Time (in seconds) the record can be cached
  - ***Class***: A mechanism for extensibility that is largely unused
  - ***Type***: The type of data the record stores
  - ***RDATA***: The data (of the type specified) that the record carries

Master File Format

- Resource record syntax in master file format:

```
[owner]    [TTL]    [class]    type    RDATA
```

- Fields in brackets are optional
  - Shortcuts to make typing zone files easier on humans
- Type and RDATA always appear

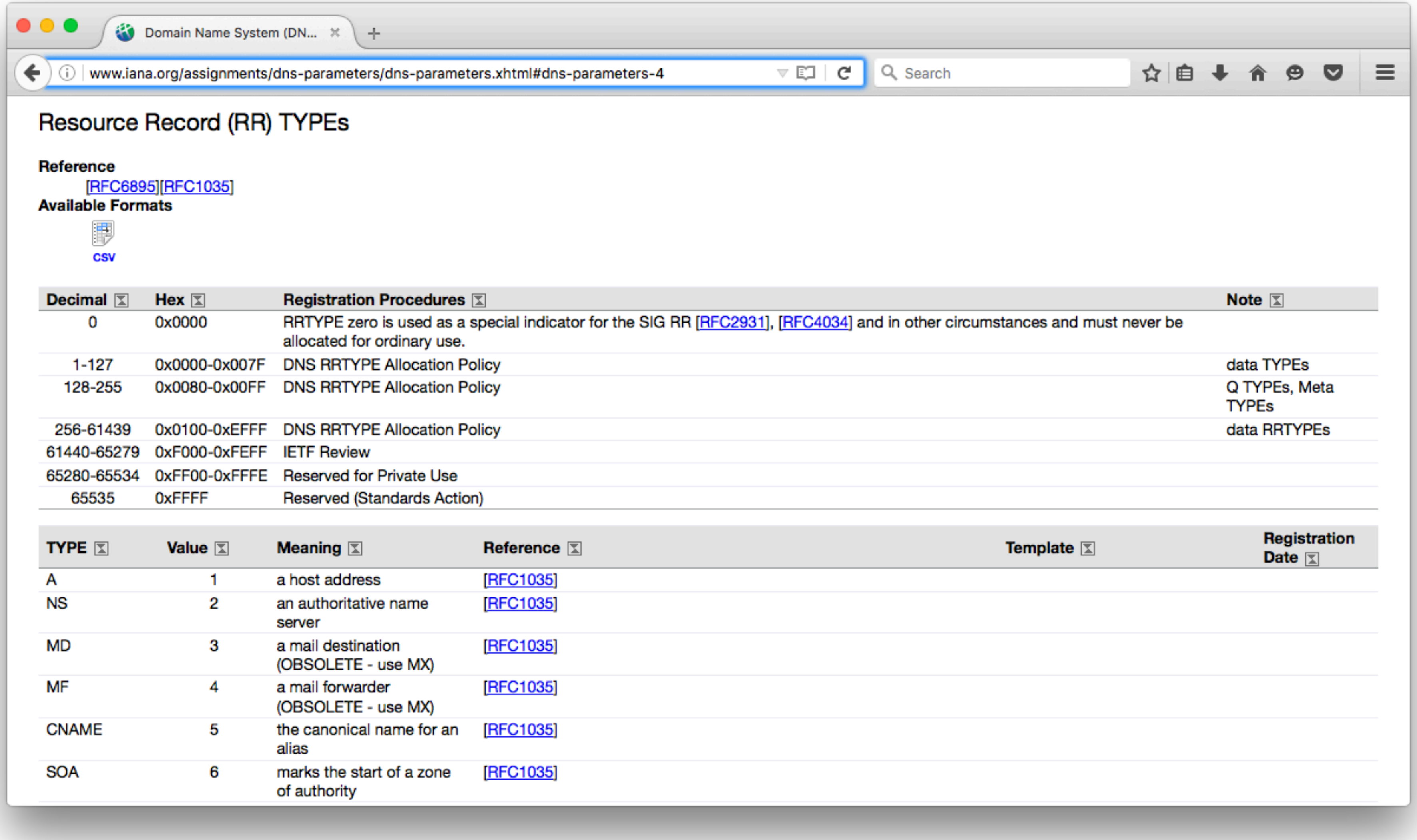
Common Resource Record Types

A	IPv4 address
AAAA	IPv6 address
NS	Name of an authoritative name server
SOA	“Start of authority”, appears at zone apex
CNAME	Name of an alias to another domain name
MX	Name of a “mail exchange server”
PTR	IP address encoded as a domain name (for reverse mapping)

Lots of Resource Records

- There are many other resource record types
- 84 types allocated as of December, 2017
- IANA “DNS Resource Record (RR) TYPE Registry” under “Domain Name System (DNS) Parameters”
  - *http://www.iana.org/assignments/dns-parameters/dns-parameters.xhtml#dns-parameters-4*

IANA DNS Resource Record (RR) TYPE Registry


Domain Name System (DN...
www.iana.org/assignments/dns-parameters/dns-parameters.xhtml#dns-parameters-4
Search

Resource Record (RR) TYPEs

Reference

[RFC6895][RFC1035]

Available Formats

CSV

Decimal	Hex	Registration Procedures	Note
0	0x0000	RRTYPE zero is used as a special indicator for the SIG RR [RFC2931], [RFC4034] and in other circumstances and must never be allocated for ordinary use.	
1-127	0x0000-0x007F	DNS RRTYPE Allocation Policy	data TYPEs
128-255	0x0080-0x00FF	DNS RRTYPE Allocation Policy	Q TYPEs, Meta TYPEs
256-61439	0x0100-0xEFFF	DNS RRTYPE Allocation Policy	data RRTYPEs
61440-65279	0xF000-0xFEFF	IETF Review	
65280-65534	0xFF00-0xFFFE	Reserved for Private Use	
65535	0xFFFF	Reserved (Standards Action)	

TYPE	Value	Meaning	Reference	Template	Registration Date
A	1	a host address	[RFC1035]		
NS	2	an authoritative name server	[RFC1035]		
MD	3	a mail destination (OBSOLETE - use MX)	[RFC1035]		
MF	4	a mail forwarder (OBSOLETE - use MX)	[RFC1035]		
CNAME	5	the canonical name for an alias	[RFC1035]		
SOA	6	marks the start of a zone of authority	[RFC1035]		

Address Records

- Most common use of DNS is mapping domain names to IP addresses
- Two most common types of resource records are:
  - Address (A) record stores an IPv4 address

```
example.com.          A        192.0.2.7
```

  - “Quad A” (AAAA) record stores an IPv6 address

```
example.com.          AAAA     2001:db8::7
```

Warehouse Analogy

- Most types are used by consumers of DNS
  - A, AAAA and almost everything else
- Some types are used mostly by DNS itself
  - NS, SOA
- DNS is like a warehouse
  - NS and SOA are the shelves you build…
  - ...so you can store stuff you care about (A, AAAA, etc.) in the warehouse

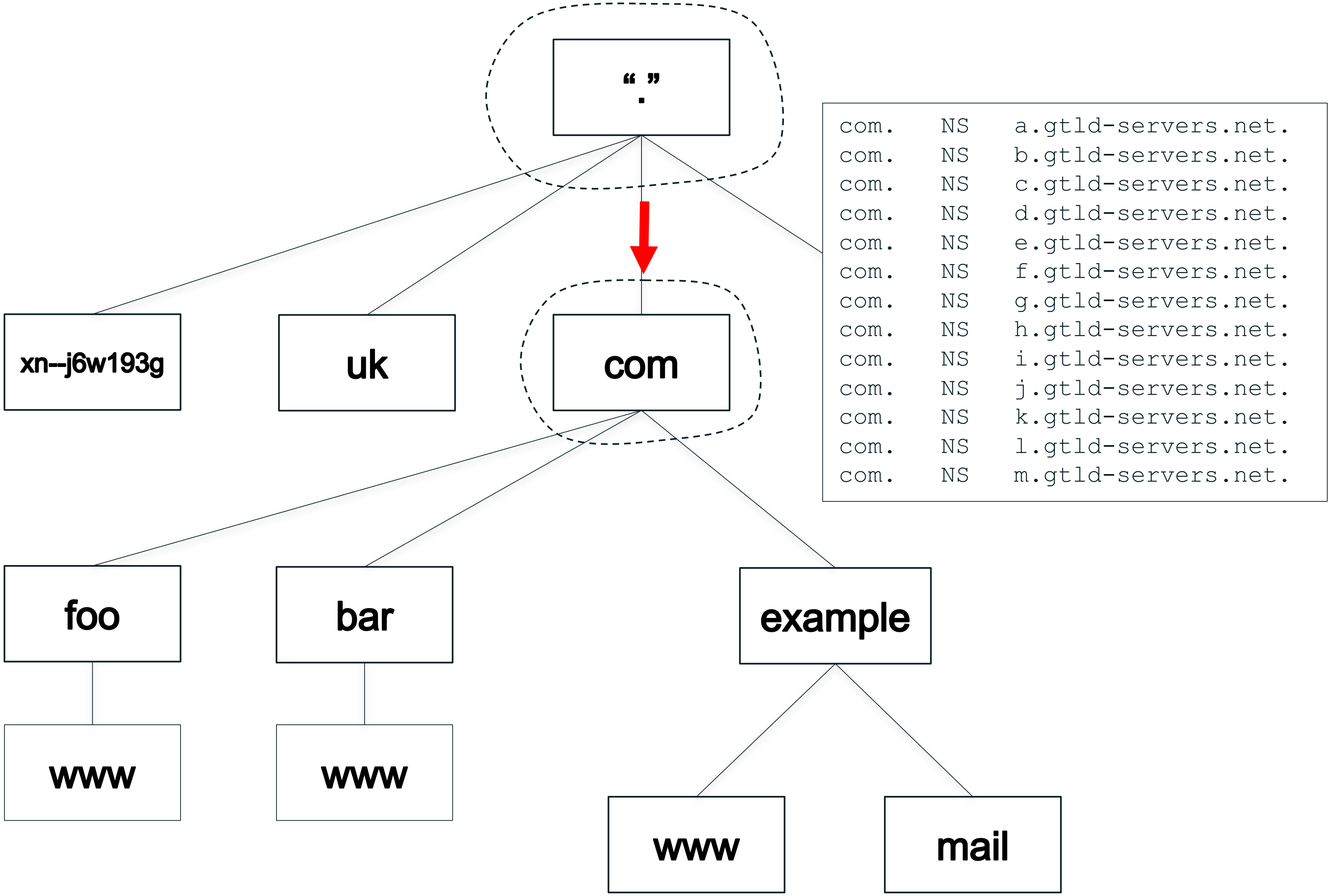
Name Server (NS)

- Specifies an authoritative name server for a zone
- The only record type to appear in two places
  - “Parent” and “child” zones

```
example.com.    NS    ns1.example.com.
example.com.    NS    ns2.example.com.
```

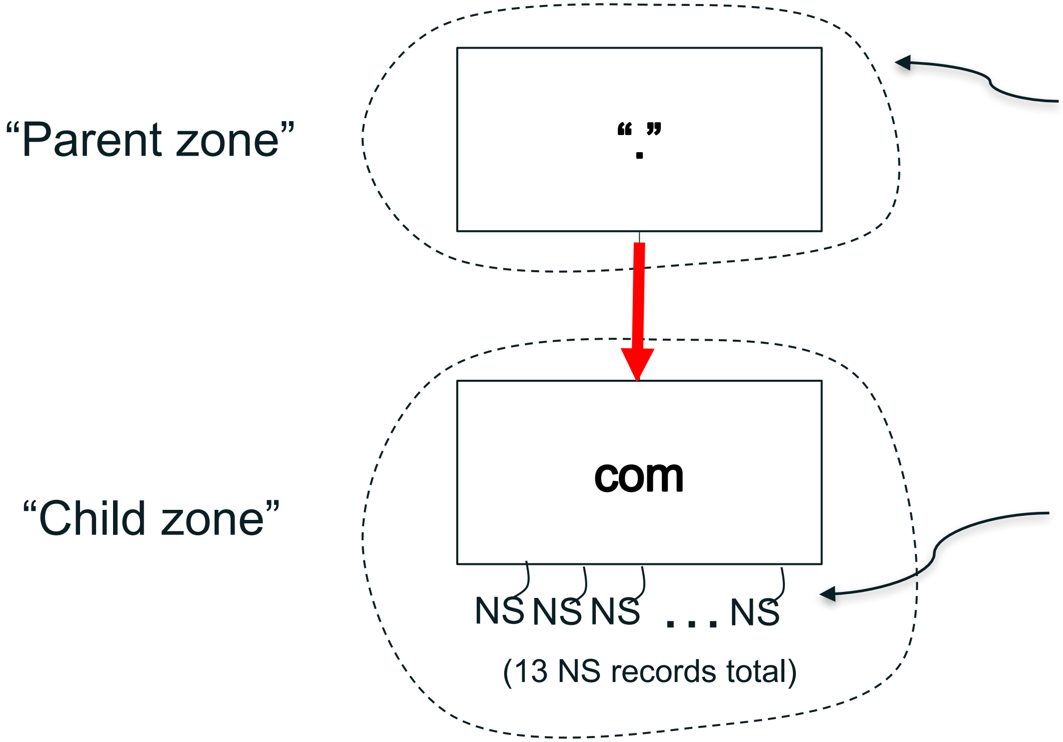
- Left hand side is the name of a zone
- Right hand side is the name of a name server
  - Not an IP address!

NS Records Mark Delegations



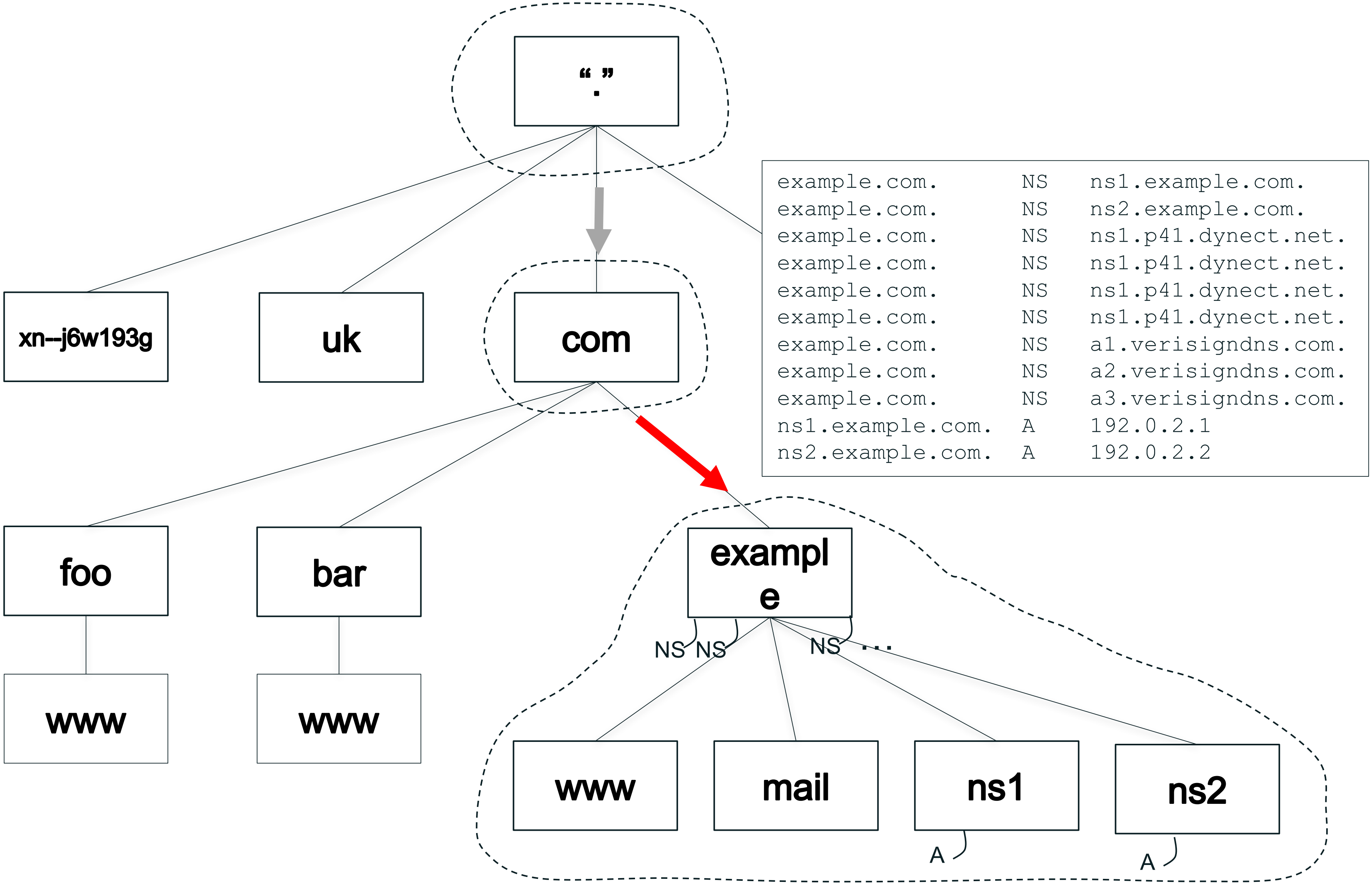
```
com.   NS   a.gtld-servers.net.
com.   NS   b.gtld-servers.net.
com.   NS   c.gtld-servers.net.
com.   NS   d.gtld-servers.net.
com.   NS   e.gtld-servers.net.
com.   NS   f.gtld-servers.net.
com.   NS   g.gtld-servers.net.
com.   NS   h.gtld-servers.net.
com.   NS   i.gtld-servers.net.
com.   NS   j.gtld-servers.net.
com.   NS   k.gtld-servers.net.
com.   NS   l.gtld-servers.net.
com.   NS   m.gtld-servers.net.
```

NS Records Appear in Two Places



```
com.    NS    a.gtld-servers.net.
com.    NS    b.gtld-servers.net.
com.    NS    c.gtld-servers.net.
com.    NS    d.gtld-servers.net.
com.    NS    e.gtld-servers.net.
com.    NS    f.gtld-servers.net.
com.    NS    g.gtld-servers.net.
com.    NS    h.gtld-servers.net.
com.    NS    i.gtld-servers.net.
com.    NS    j.gtld-servers.net.
com.    NS    k.gtld-servers.net.
com.    NS    l.gtld-servers.net.
com.    NS    m.gtld-servers.net.
```

More Delegation, Including Glue



```
example.com.        NS    ns1.example.com.
example.com.        NS    ns2.example.com.
example.com.        NS    ns1.p41.dynect.net.
example.com.        NS    ns1.p41.dynect.net.
example.com.        NS    ns1.p41.dynect.net.
example.com.        NS    ns1.p41.dynect.net.
example.com.        NS    a1.verisigndns.com.
example.com.        NS    a2.verisigndns.com.
example.com.        NS    a3.verisigndns.com.
ns1.example.com.    A     192.0.2.1
ns2.example.com.    A     192.0.2.2
```

Glue Records

- A glue record is:
  - An A or AAAA record
  - Included in the parent zone as part of the delegation information
- Glue is needed to break a circular dependency
  - When the name of the name server ends in the name of the zone being delegated

```
example.com.    NS    ns1.example.com.
```

- Also for breaking for complicated dependencies not described here

Start of Authority (SOA)

- One and only one SOA record per zone
- At the zone apex
- Most values control zone transfers

```
example.com.  SOA ns1.example.com. hostmaster.example.com. (
               2016050100 ; serial
               3600       ; refresh (1 hour)
               600        ; retry (10 minutes)
               2592000    ; expire (4 weeks 2 days)
               300        ; minimum (5 minutes)
               )
```

Alias (CNAME)

- The CNAME record creates an alias from one domain name to another
  - Left side is the alias
  - Right side is a canonical name, the “target” of the alias

```
mail.example.com.  CNAME  some-host.example.com.
```

- Remember: a CNAME creates an alias and points to a canonical name
  - Any other record type creates a canonical name
- Don’t use aliases on the right side of other records (e.g., NS, MX)
- A CNAME can point to another CNAME
  - But avoid long chains and loops

Mail Routing

- The problem: where does mail for *user@example.com* go?
- In the old days: look up the address of *example.com*, deliver via SMTP to that address
    - No flexibility: domain name in email address must be a mail server
    - Not a problem in HOST.TXT days: email address meant *user@host*
    - But what if email address is a host not on the Internet?
        - E.g., UUCP
- DNS offered more flexibility
- MX (Mail Exchange) records de-couple the mail server from the email address

Mail Exchange (MX)

- Specifies a mail server and a preference for a mail destination

```
example.com.   MX  10 mail.example.com.
example.com.   MX  20 mail-backup.example.com.
```

- Owner name corresponds to the domain name in an email address, i.e., to the right of the “@”
- The number is a preference, lower is more desirable
- Rightmost field is the domain name of a mail server that accepts mail for the domain in the owner name

Reverse Mapping

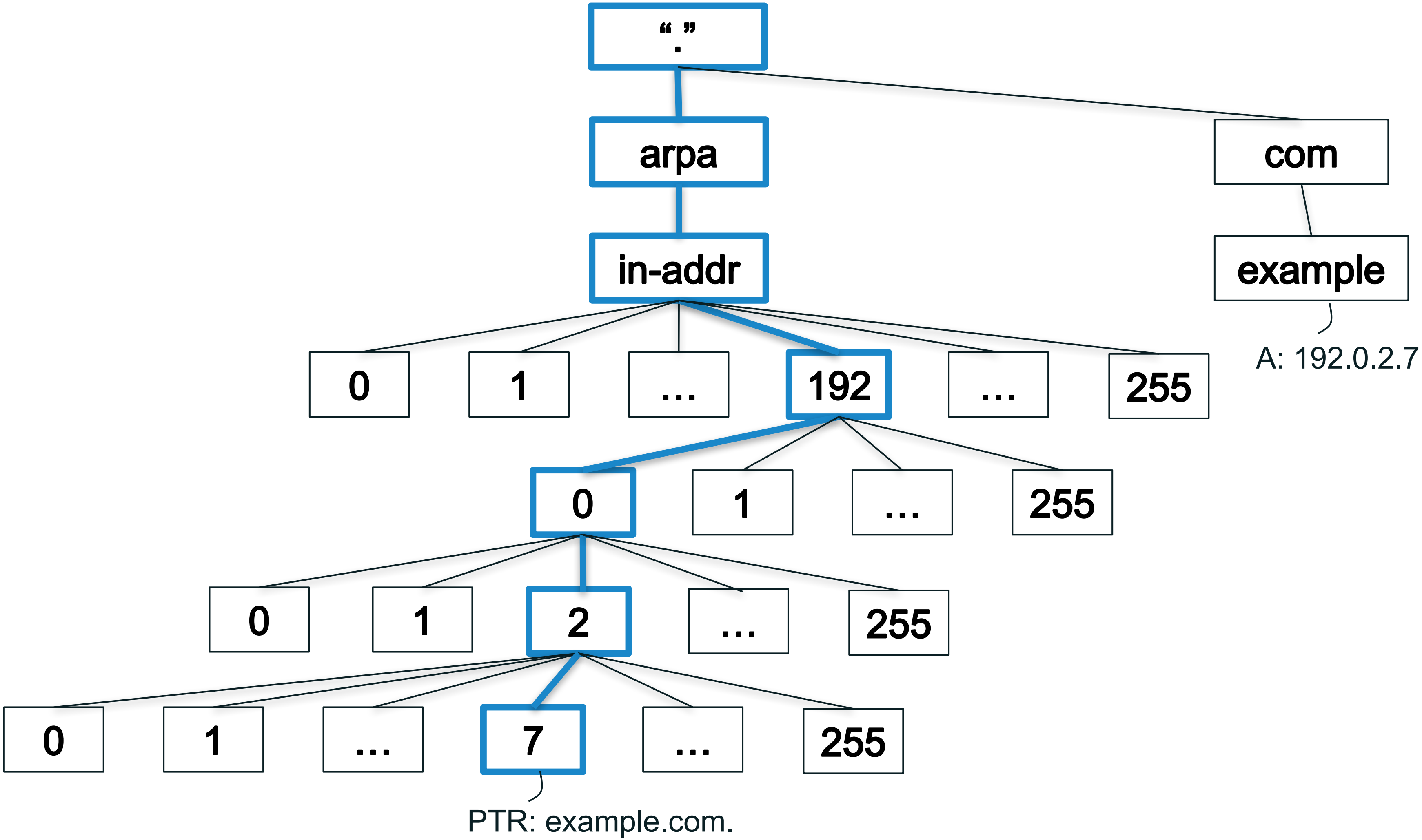
- Name-to-IP is “forward” mapping
- IP-to-name is “reverse” mapping
- Reverse mapping accomplished by mapping IP address space to the DNS name space
  - IPv4 addresses under *in-addr.arpa*
  - IPv6 addresses under *ip6.arpa*
- Uses PTR (pointer) records

```
7.2.0.192.in-addr.arpa.   PTR      example.com.
```

- Corresponds to this A record:

```
example.com.                A      192.0.2.7
```

Reverse Mapping



DNSSEC (DNS Security Extensions)

- DNS data can be digitally signed for authentication
  - Origin authentication and data integrity
- Each zone has a public/private key pair
  - No certificate authorities: a parent zone vouches for its child’s public key
- Several record types:
  - **DNSKEY**: public key for a zone
  - **RRSIG**: digital signature for a resource record set (RRset)
  - **NSEC/NSEC3**: pointer to the “next” name in a zone (provides authenticated denial of existence)
  - **DS**: delegation signer, resides in a parent zone and stores the hash of a child zone’s public key

A Sample of More Resource Record Types

- **TXT**
  - Arbitrary text
- **URI**, **NAPTR**
  - Map domain names to URIs
- **TLSA**
  - Used by DANE (DNSSEC Authentication of Named Entities) to associate X.509 certificates with a domain name
- **CDS**, **CDNSKEY**, **CSYNC**
  - Child-parent synchronization
- **X25**, **ISDN**, **ATMA**
  - Addresses for non-IP networking protocols
- **LOC**, **GPOS**
  - Location information
- …and many more, either obsolete or little-used

Unknown Types

- The type space is 16 bits, i.e., 65535 possible resource record types
  - A portion is reserved for private use
- New types are added regularly
- How does a server handle types it doesn’t recognize?
  - The old days: it didn’t. You lose.
  - Since 2003: RFC 3597, “Handling of Unknown DNS Resource Record (RR) Types” specifies treating unknown types as opaque blobs of data

Sample Zone File: *example.com*

```
example.com.      SOA   ns1.example.com. hostmaster.example.com. (
                         2016050100 ; serial
                         3600       ; refresh (1 hour)
                         600        ; retry (10 minutes)
                         2592000    ; expire (4 weeks 2 days)
                         300 )      ; minimum (5 minutes)
example.com.      NS    ns1.example.com.
example.com.      NS    ns2.example.com.
example.com.      NS    ns1.p41.dynect.net.
example.com.      NS    ns1.p41.dynect.net.
example.com.      NS    ns1.p41.dynect.net.
example.com.      NS    ns1.p41.dynect.net.
example.com.      NS    a1.verisigndns.com.
example.com.      NS    a2.verisigndns.com.
example.com.      NS    a3.verisigndns.com.
example.com.      A     192.0.2.7
example.com.      AAAA  2001:db8::7
example.com.      MX    10 mail.example.com.
example.com.      MX    20 mail-backup.example.com.
www.example.com.  CNAME example.com.
ns1.example.com.  A     192.0.2.1
ns2.example.com.  A     192.0.2.2
```

The Resolution Process

- Stub resolvers, recursive name servers and authoritative name servers cooperate to look up DNS data in the name space
- A DNS query always comprises three parameters:
  - Domain name, class, type
    - E.g., *www.example.com*, IN, A
- Two kinds of queries:
  - Stub resolvers send ***recursive*** queries
    - "I need the complete answer or an error."
  - Recursive name servers send ***non-recursive*** or ***iterative*** queries
    - "I can do some of the lookup work myself and will accept a ***referral***."

The Resolution Process

- High-level algorithm for processing a query:
  - Answer exact match from local data (authoritative or cache), if possible
  - If no exact answer possible, walk up the name space tree in local data from the queried name to find the best match, the closest enclosing zone
  - Is it a recursive query?
    - Send the query to a name server for the ***closest enclosing zone***
    - Keep following referrals down the tree until the zone with the answer (which could be “doesn’t exist”)
  - Is it a non-recursive query?
    - Return a referral to the closest enclosing zone

The Resolution Process

- How do you start the resolution process if there’s no local data?
  - Empty cache, or
  - Not authoritative for any zones
- No choice but to start at the root zone
  - The ***root name servers*** are the servers authoritative for the root zone
- How does a name server find the root name servers?
  - They must be configured
  - No way to discover them
- The ***root hints file*** contains the names and IP addresses of the root name servers
  - *http://www.internic.net/domain/named.root*

List of Root Name Servers and Root Hints File

```
.                      NS      a.root-servers.net.
.                      NS      b.root-servers.net.
.                      NS      c.root-servers.net.
.                      NS      d.root-servers.net.
.                      NS      e.root-servers.net.
.                      NS      f.root-servers.net.
.                      NS      g.root-servers.net.
.                      NS      h.root-servers.net.
.                      NS      i.root-servers.net.
.                      NS      j.root-servers.net.
.                      NS      k.root-servers.net.
.                      NS      l.root-servers.net.
.                      NS      m.root-servers.net.
a.root-servers.net.    A       198.41.0.4
b.root-servers.net.    A       192.228.79.201
c.root-servers.net.    A       192.33.4.12
d.root-servers.net.    A       199.7.91.13
e.root-servers.net.    A       192.203.230.10
f.root-servers.net.    A       192.5.5.241
g.root-servers.net.    A       192.112.36.4
h.root-servers.net.    A       198.97.190.53
i.root-servers.net.    A       192.36.148.17
j.root-servers.net.    A       192.58.128.30
k.root-servers.net.    A       193.0.14.129
l.root-servers.net.    A       199.7.83.42
m.root-servers.net.    A       202.12.27.33
a.root-servers.net.    AAAA    2001:503:ba3e::2:30
b.root-servers.net.    AAAA    2001:500:84::b
c.root-servers.net.    AAAA    2001:500:2::c
d.root-servers.net.    AAAA    2001:500:2d::d
e.root-servers.net.    AAAA    2001:500:a8::e
f.root-servers.net.    AAAA    2001:500:2f::f
h.root-servers.net.    AAAA    2001:500:1::53
i.root-servers.net.    AAAA    2001:7fe::53
j.root-servers.net.    AAAA    2001:503:c27::2:30
k.root-servers.net.    AAAA    2001:7fd::1
l.root-servers.net.    AAAA    2001:500:9f::42
m.root-servers.net.    AAAA    2001:dc3::35
```

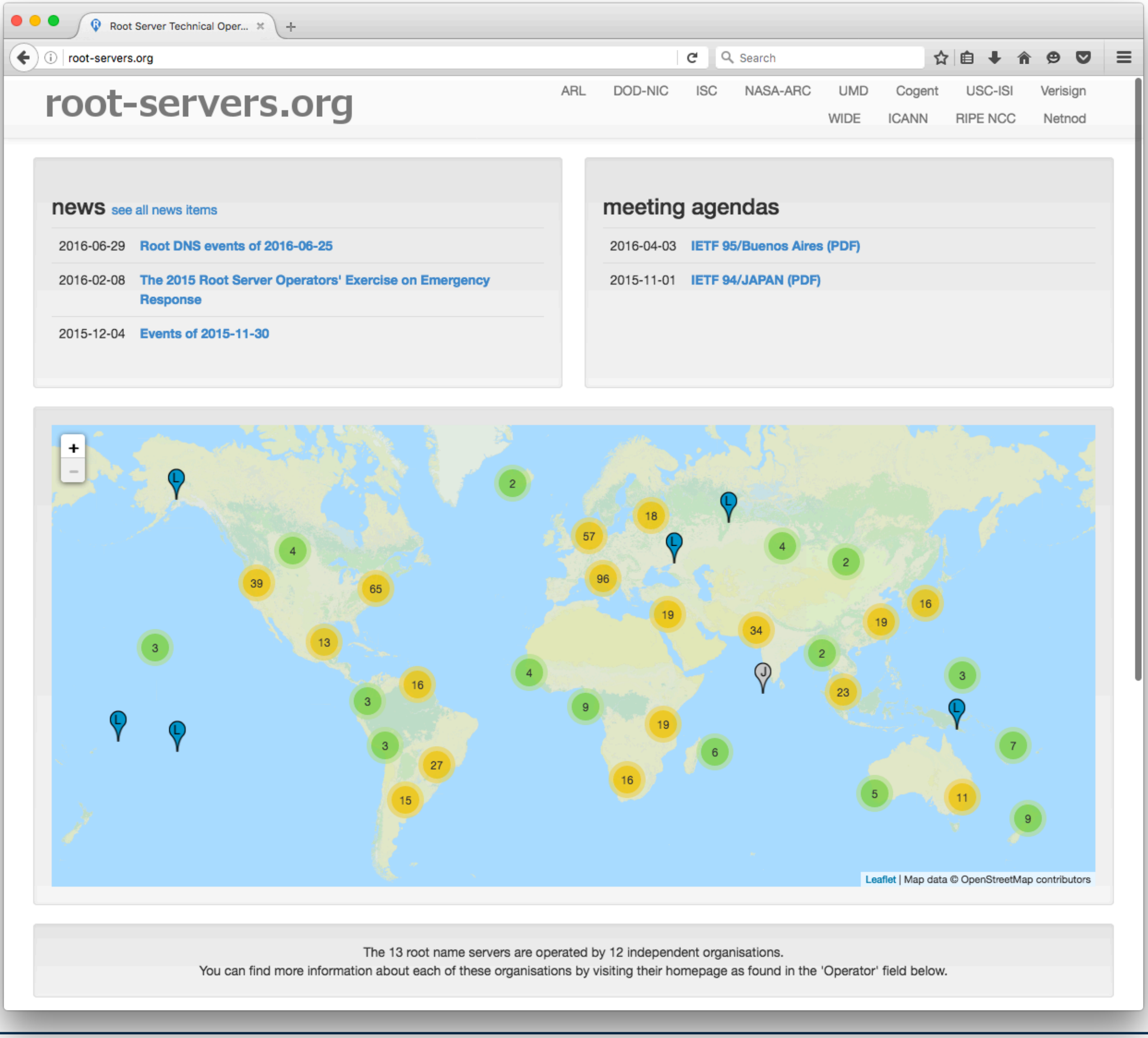
Root Zone Administration

- Administration of the root zone is complicated
- Two organizations cooperate to administer the zone’s contents
  - ICANN (IANA Functions Operator)
  - Verisign (Root Zone Maintainer)
- Twelve organizations operate authoritative name servers for the root zone

The Root Servers and Operators

A	Verisign
B	University of Southern California Information Sciences Institute
C	Cogent Communications, Inc.
D	University of Maryland
E	United States National Aeronautics and Space Administration (NASA) Ames Research Center
F	Information Systems Consortium (ISC)
G	United States Department of Defense (US DoD) Defense Information Systems Agency (DISA)
H	United States Army (Aberdeen Proving Ground)
I	Netnod Internet Exchange i Sverige
J	Verisign
K	Réseaux IP Européens Network Coordination Centre (RIPE NCC)
L	Internet Corporation For Assigned Names and Numbers (ICANN)
M	WIDE Project (Widely Integrated Distributed Environment)

The *root-servers.org* Web Site



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ARL DOD-NIC ISC NASA-ARC UMD Cogent USC-ISI Verisign
WIDE ICANN RIPE NCC Netnod

news see all news items

2016-06-29	Root DNS events of 2016-06-25
2016-02-08	The 2015 Root Server Operators' Exercise on Emergency Response
2015-12-04	Events of 2015-11-30

meeting agendas

2016-04-03	IETF 95/Buenos Aires (PDF)
2015-11-01	IETF 94/JAPAN (PDF)

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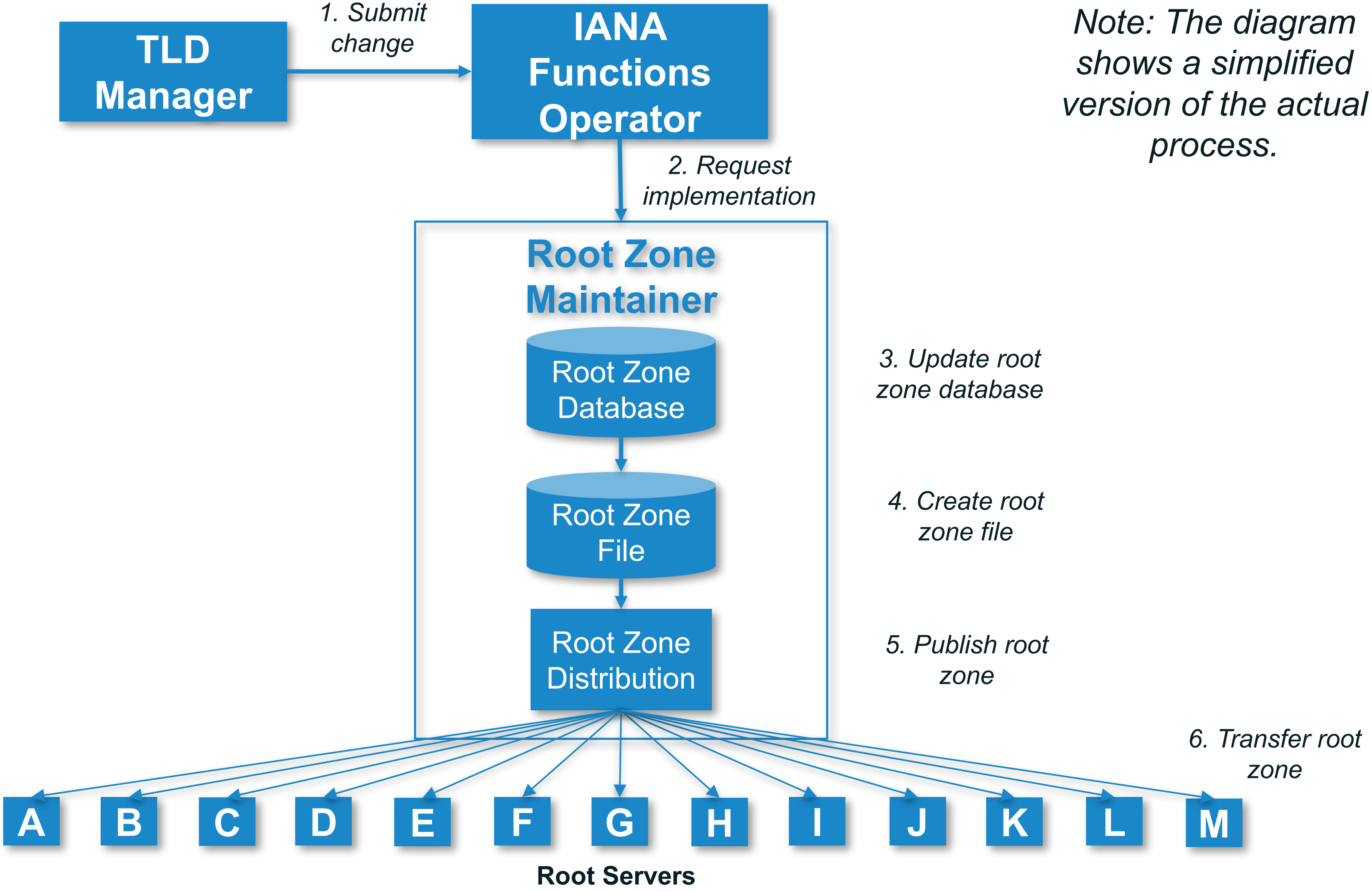
The 13 root name servers are operated by 12 independent organisations.
You can find more information about each of these organisations by visiting their homepage as found in the 'Operator' field below.

Root Zone Change Process

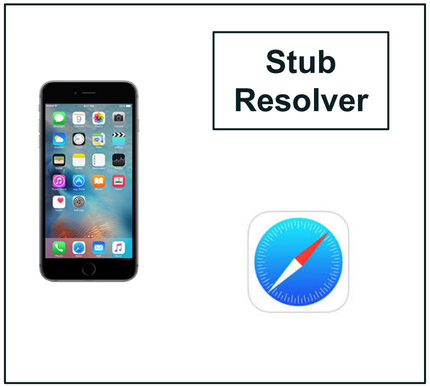


Note: The diagram shows a simplified version of the actual process.

Resolution Process

The phone is configured to send queries to the recursive name server with IP address 4.2.2.2

Recursive Name Server
4.2.2.2



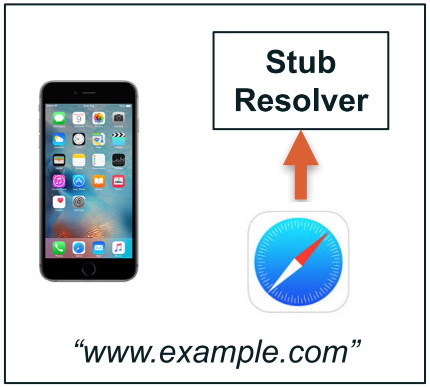
Stub Resolver

4.2.2.2 is a recursive server run by Level 3 Communications

Resolution Process

A user types *www.example.com* into Safari on her phone
Safari calls the stub resolver function to resolve the name

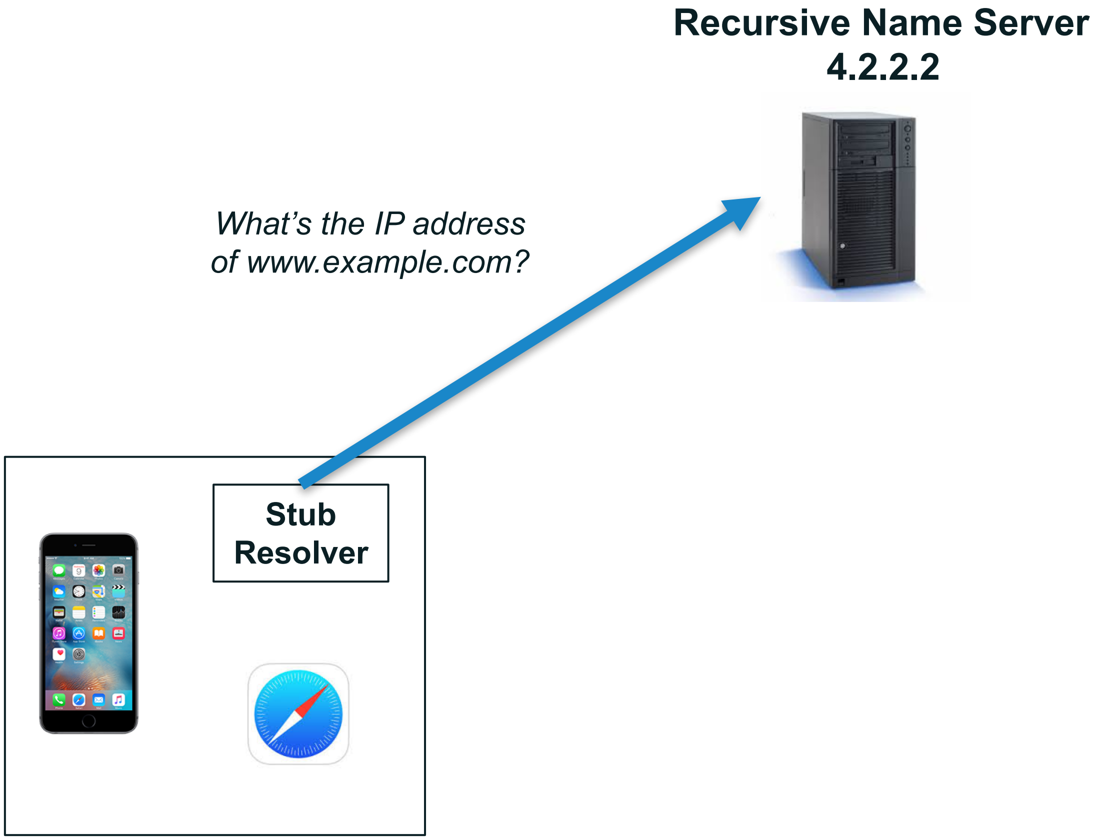
Recursive Name Server
4.2.2.2



“www.example.com”

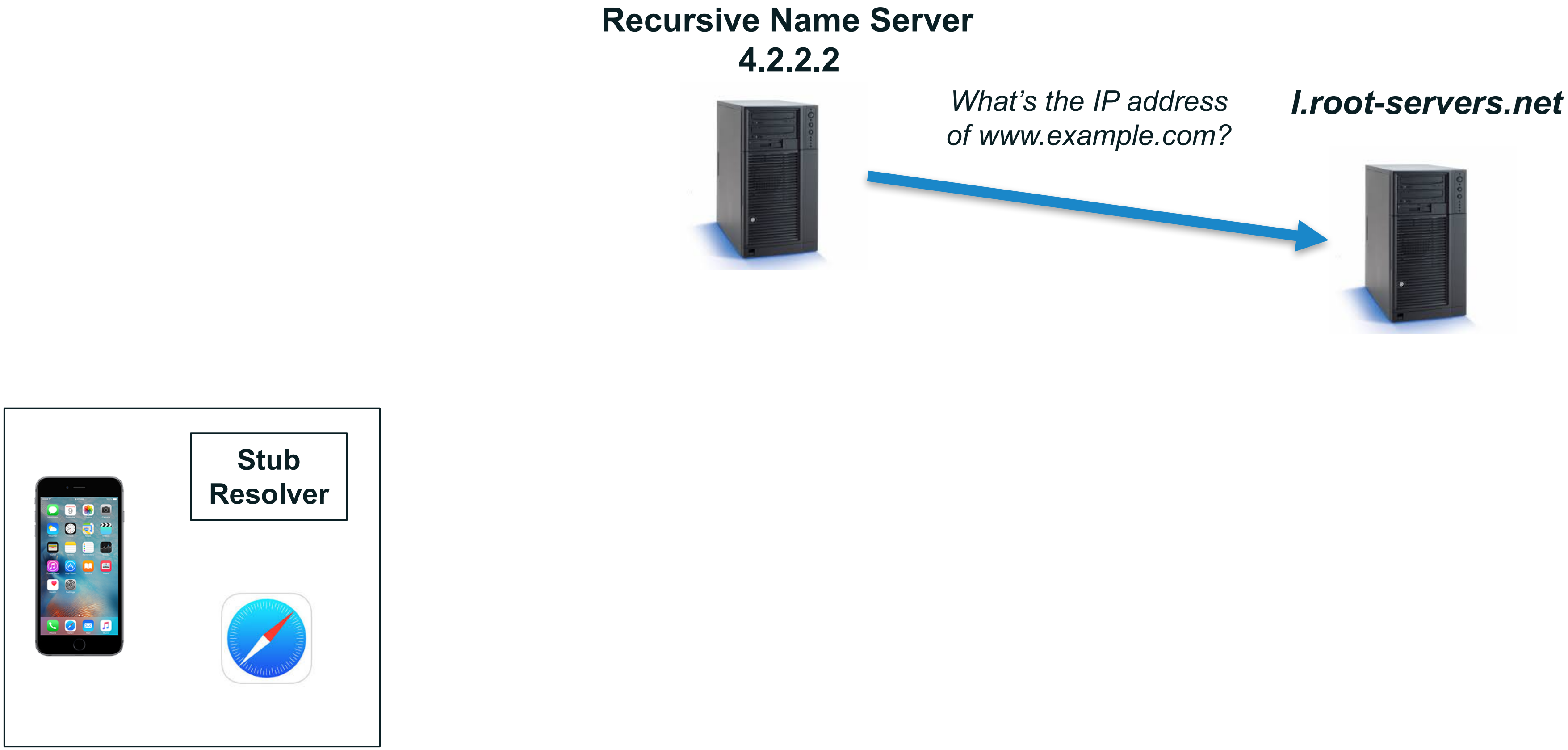
Resolution Process

The phone's stub resolver sends a query for *www.example.com*, IN, A to 4.2.2.2



Resolution Process

Empty cache, so recursive server queries a root server



Recursive Name Server
4.2.2.2

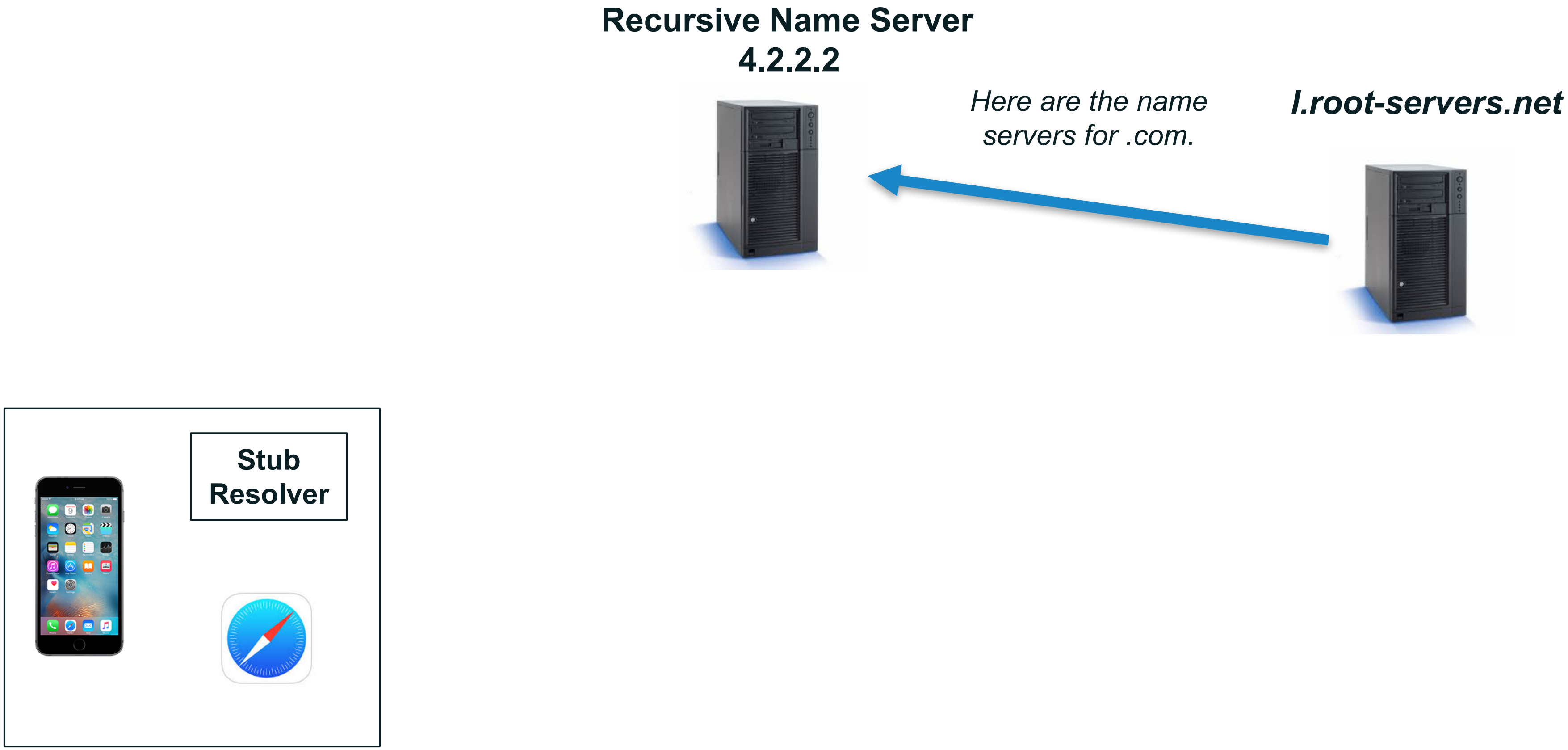
What's the IP address of www.example.com?

l.root-servers.net

Stub Resolver

Resolution Process

Root server returns a referral to *.com*



Recursive Name Server
4.2.2.2

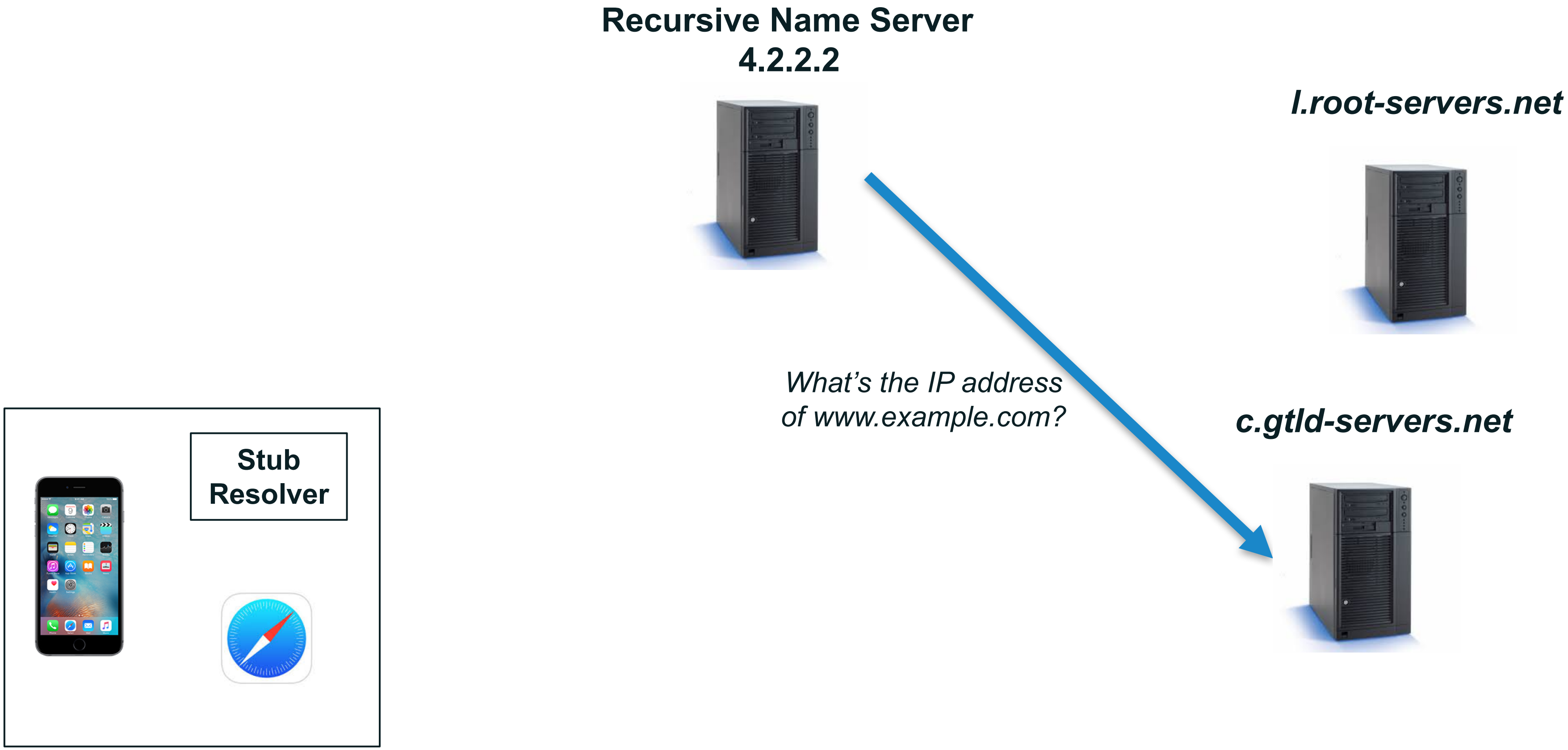
Here are the name servers for .com.

l.root-servers.net

Stub Resolver

Resolution Process

Recursive server queries a *.com* server



Recursive Name Server
4.2.2.2

l.root-servers.net

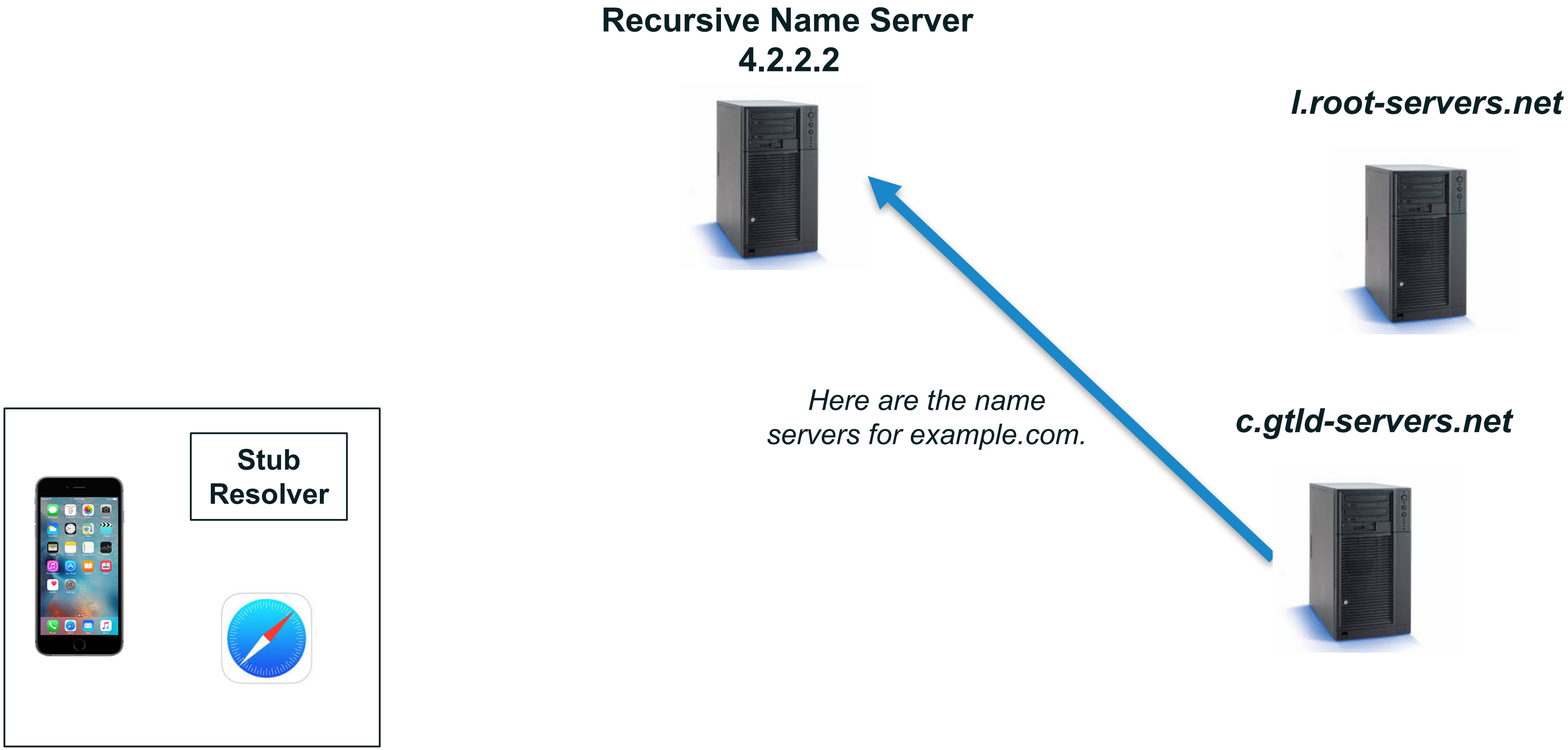
What's the IP address of www.example.com?

c.gtld-servers.net

Stub Resolver

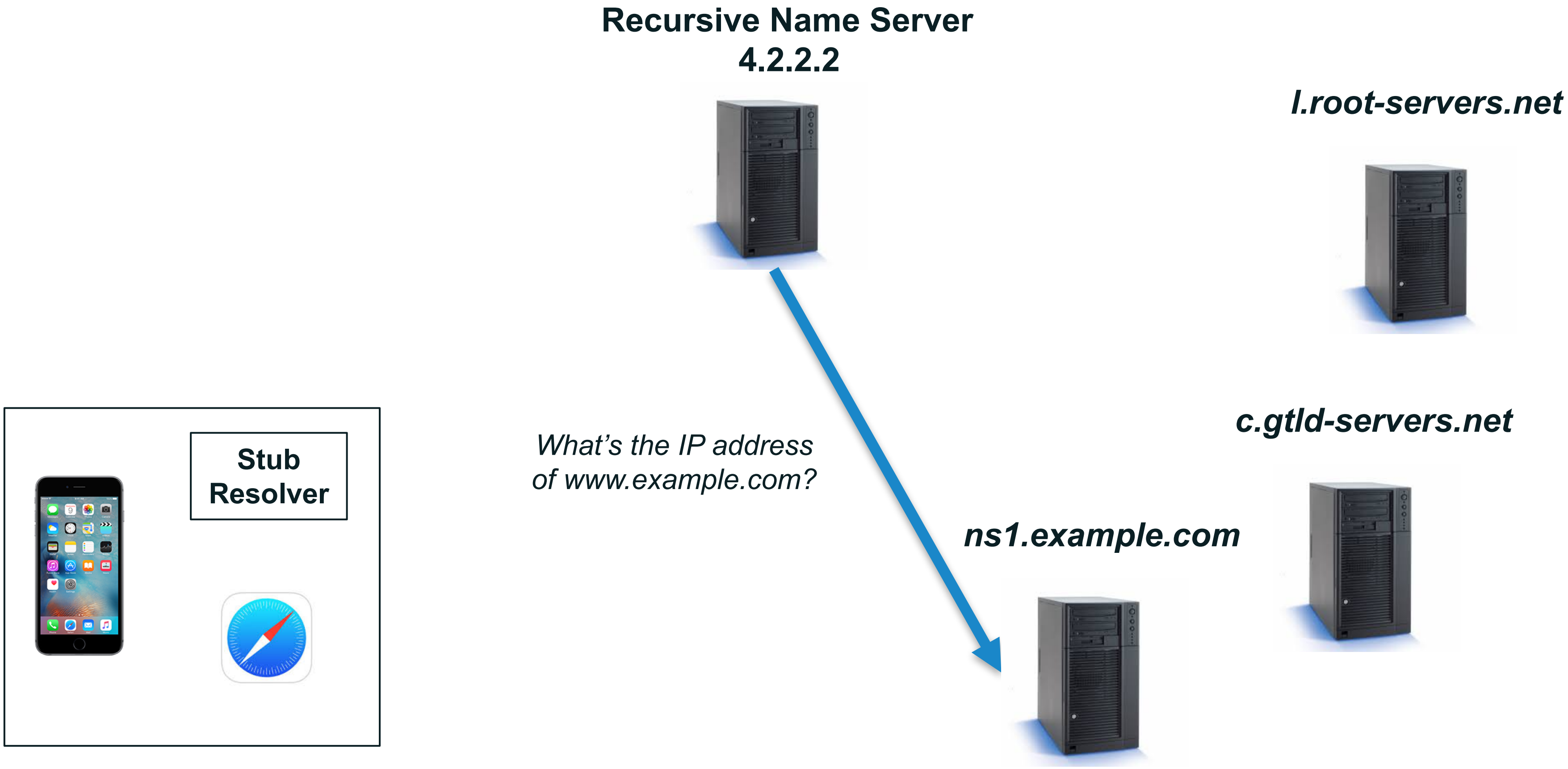
Resolution Process

.com server returns a referral to *example.com*



Resolution Process

Recursive server queries an *example.com* server



Recursive Name Server
4.2.2.2

l.root-servers.net

c.gtld-servers.net

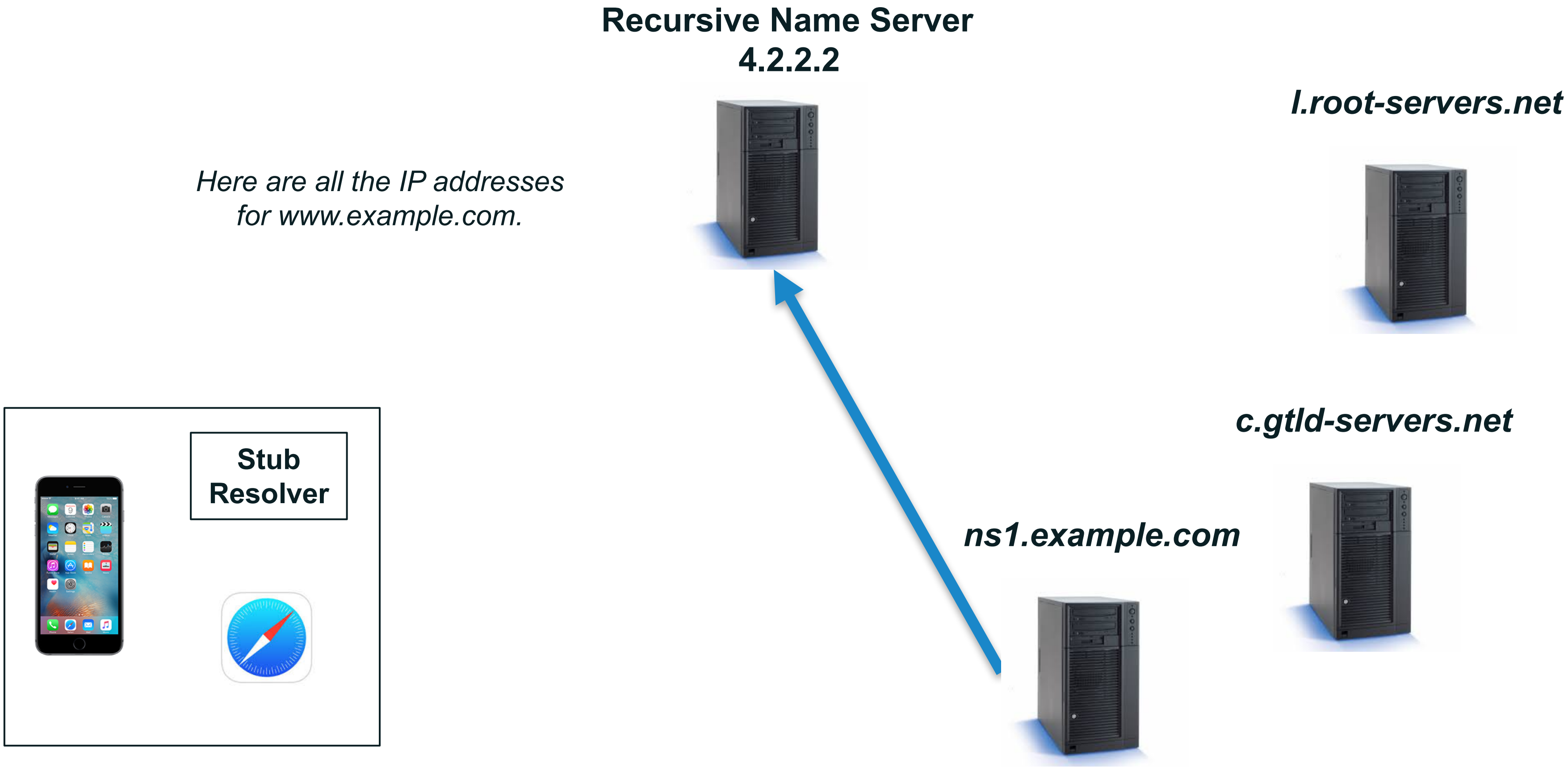
ns1.example.com

What’s the IP address of www.example.com?

Stub Resolver

Resolution Process

example.com server returns the answer to the query



Recursive Name Server
4.2.2.2

l.root-servers.net

Here are all the IP addresses
for www.example.com.

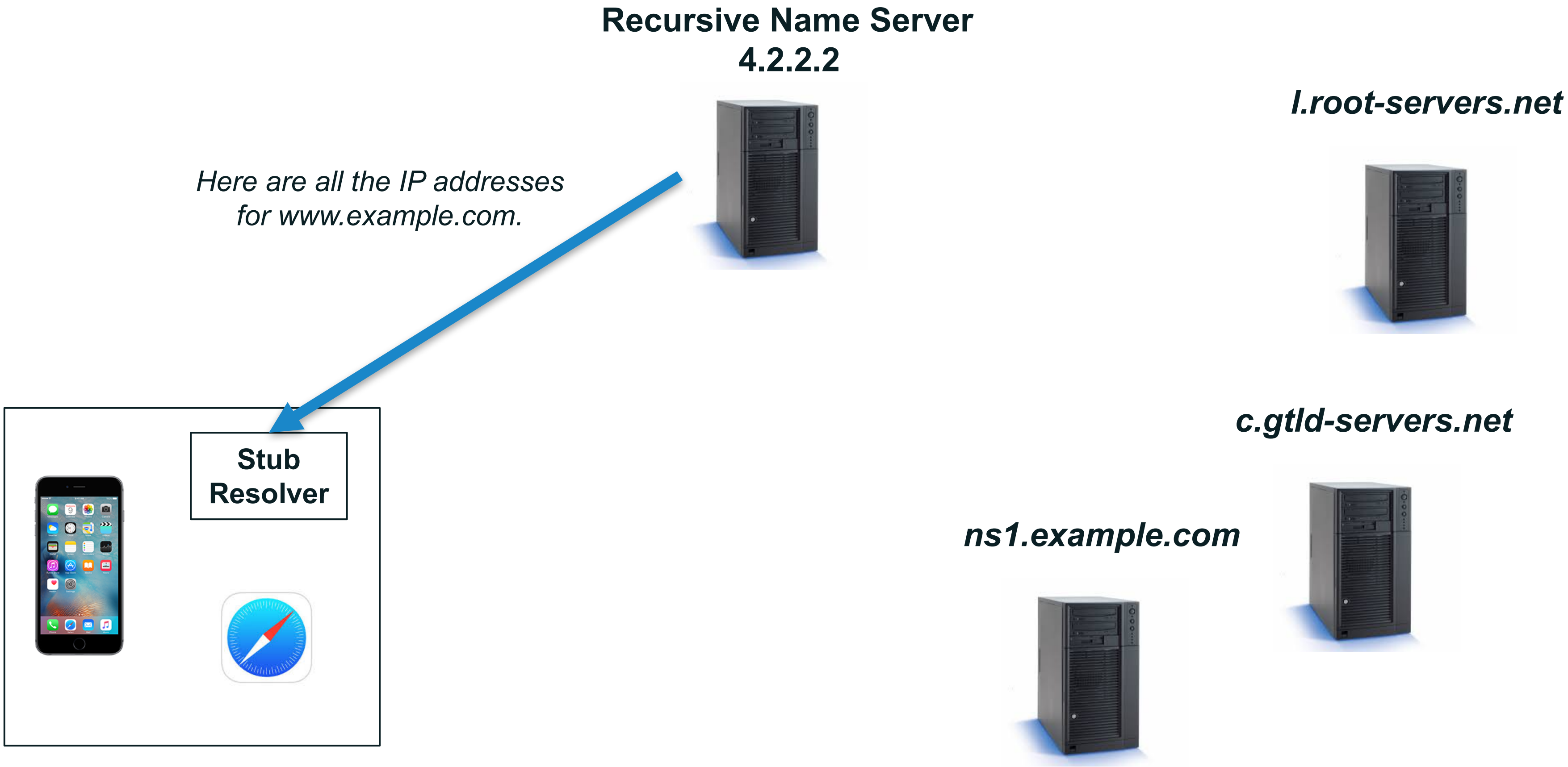
c.gtld-servers.net

Stub
Resolver

ns1.example.com

Resolution Process

Recursive server returns the answer to the query to the stub resolver



Recursive Name Server
4.2.2.2

l.root-servers.net

Here are all the IP addresses
for www.example.com.

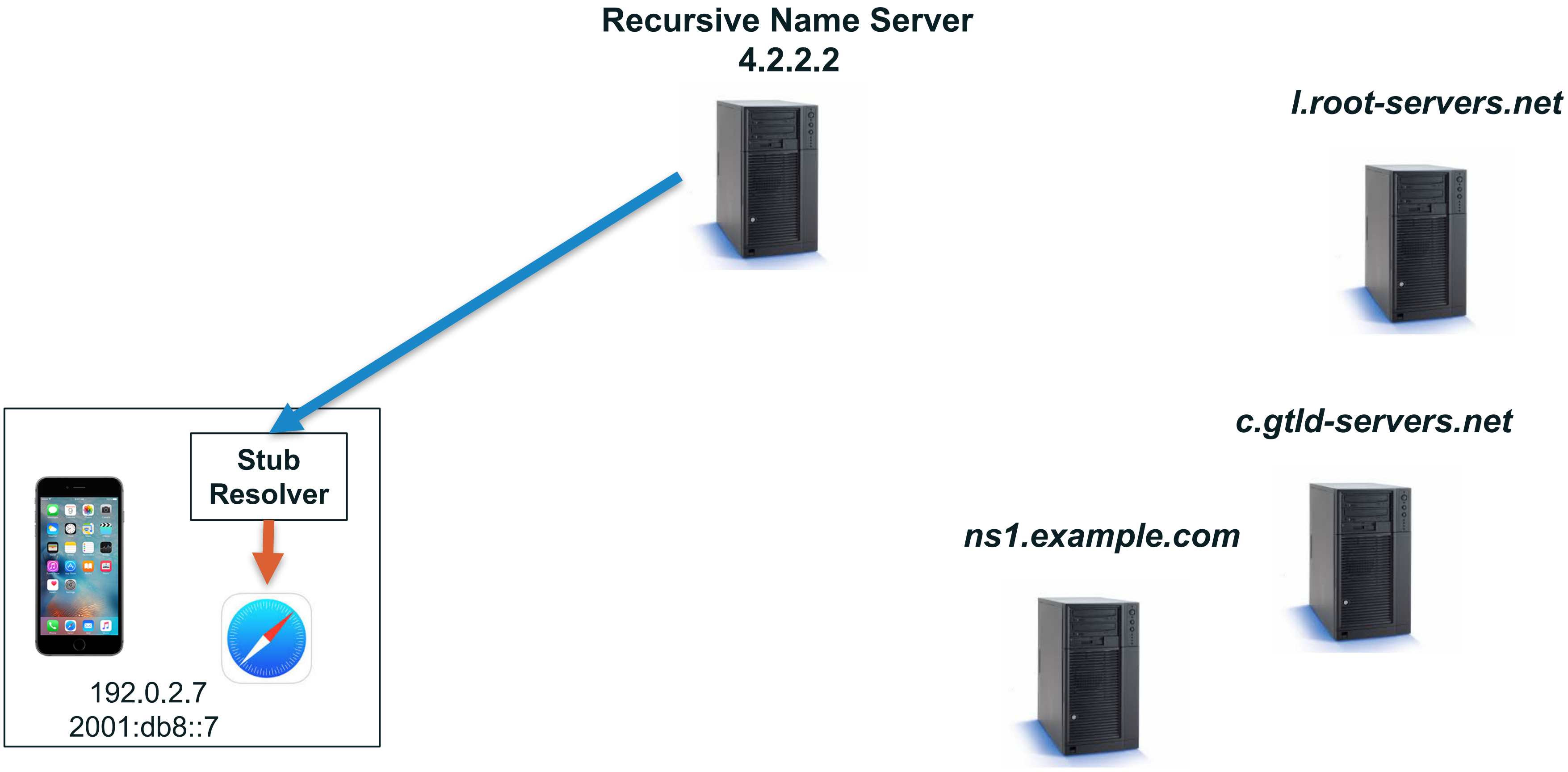
c.gtld-servers.net

ns1.example.com

Stub Resolver

Resolution Process

Stub resolver returns the IP addresses to Safari

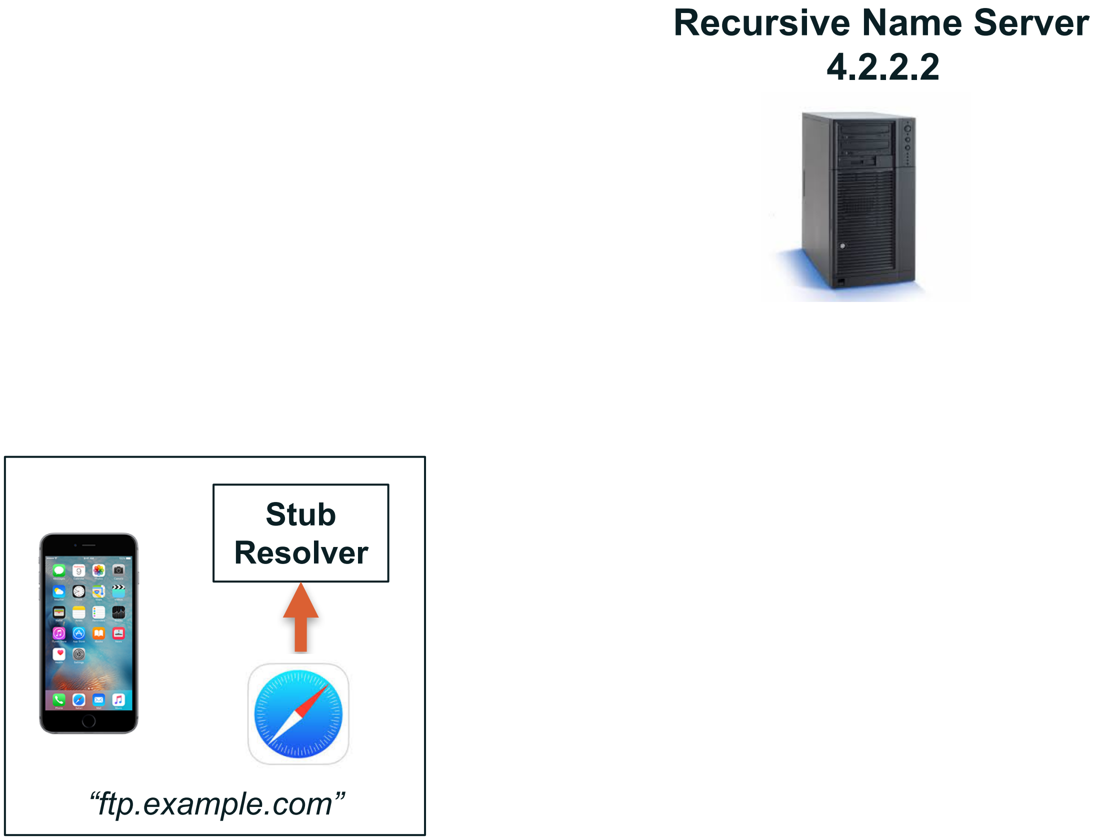


Caching

- Caching speeds up the resolution process
- After the previous query, the recursive server at 4.2.2.2 now knows:
  - Names and IP addresses of the .com servers
  - Names and IP addresses of the example.com servers
  - IP addresses for www.example.com
- Let’s look at another query following immediately the first

Resolution Process

A user types *ftp.example.com* into Safari on her phone
Safari calls the stub resolver function to resolve the name



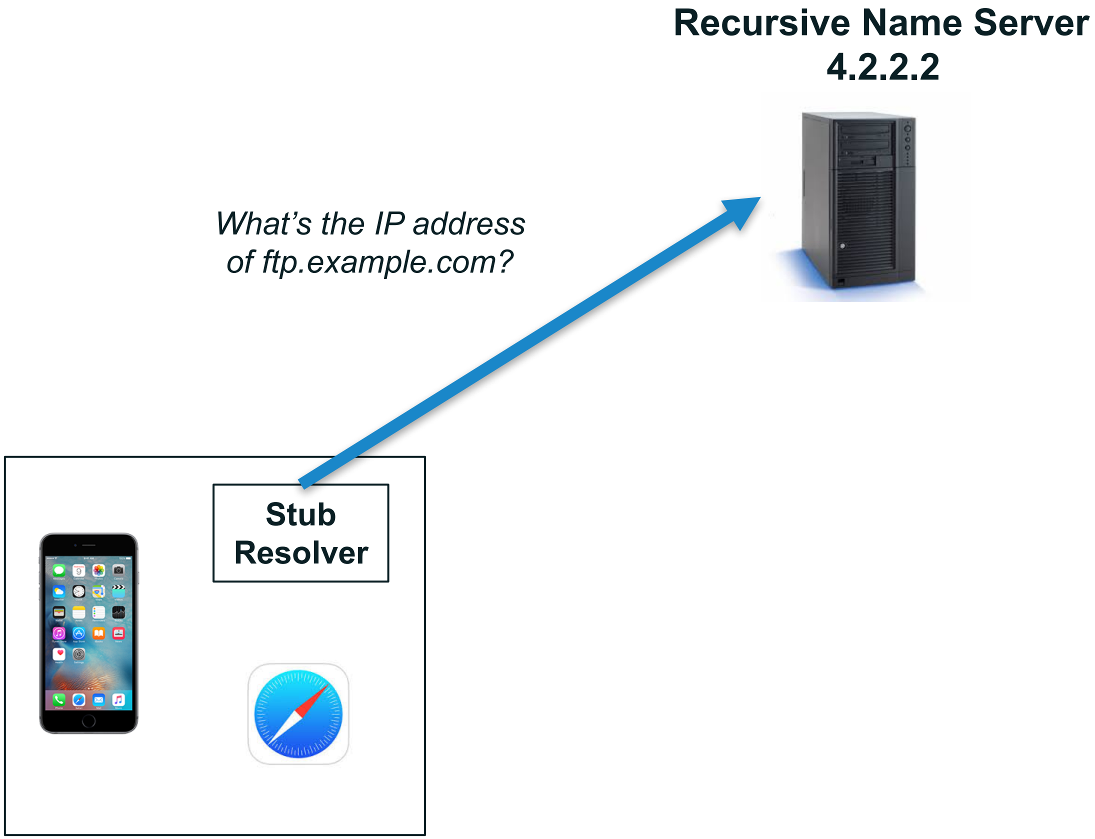
Recursive Name Server
4.2.2.2

Stub Resolver

"ftp.example.com"

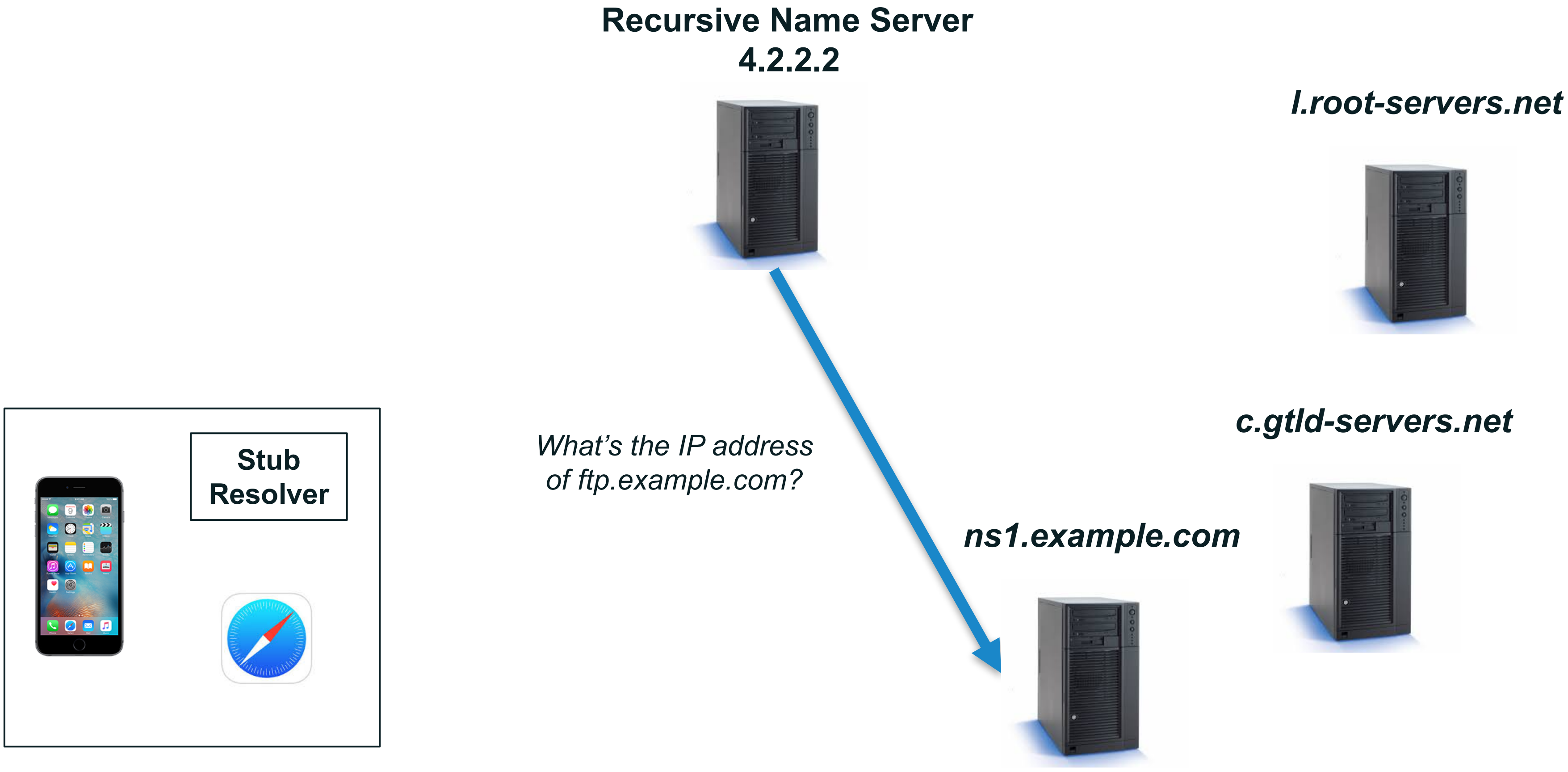
Resolution Process

The phone's stub resolver sends a query for *ftp.example.com*/IN/A to 4.2.2.2



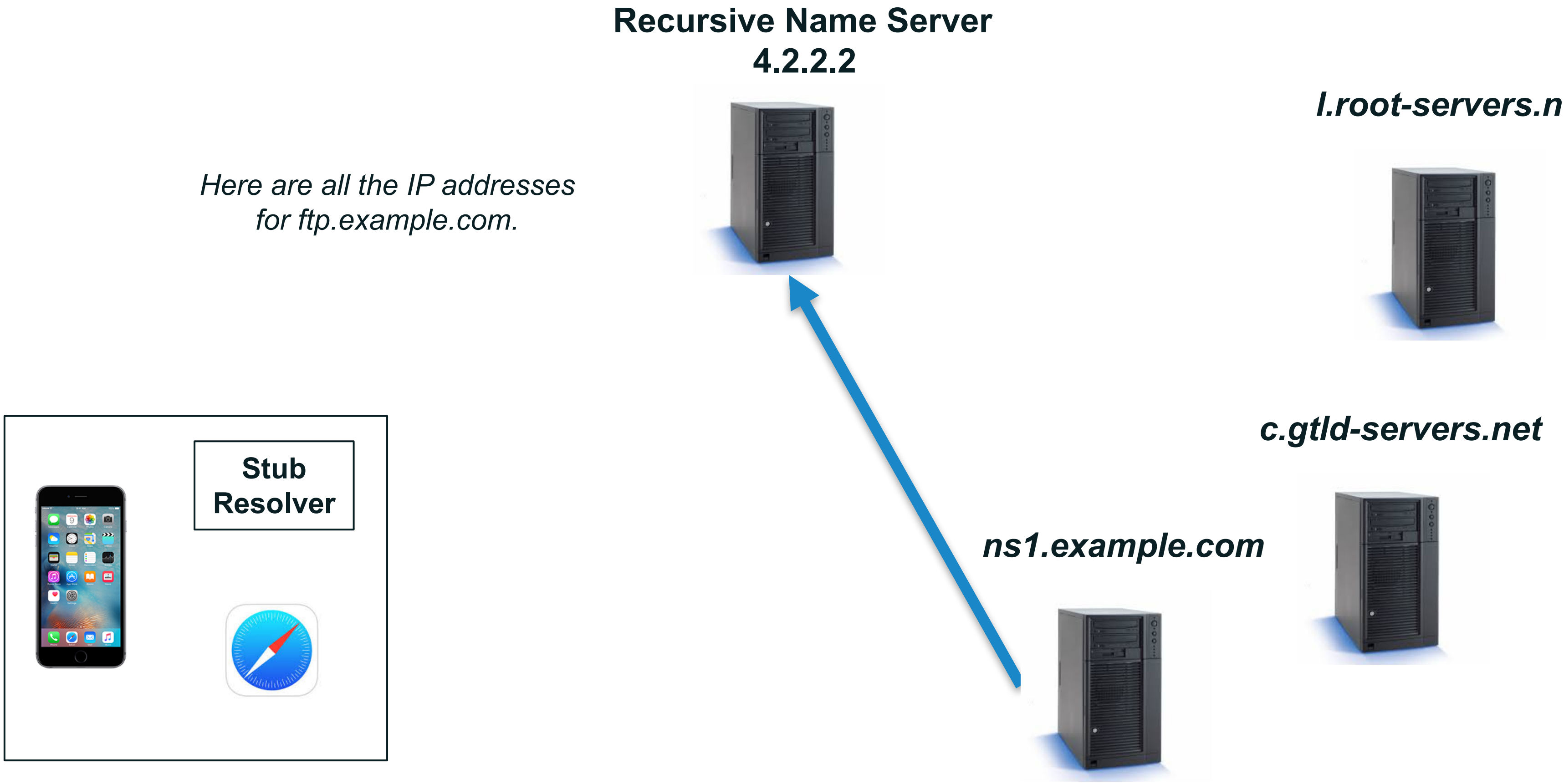
Resolution Process

Recursive server queries an *example.com* server



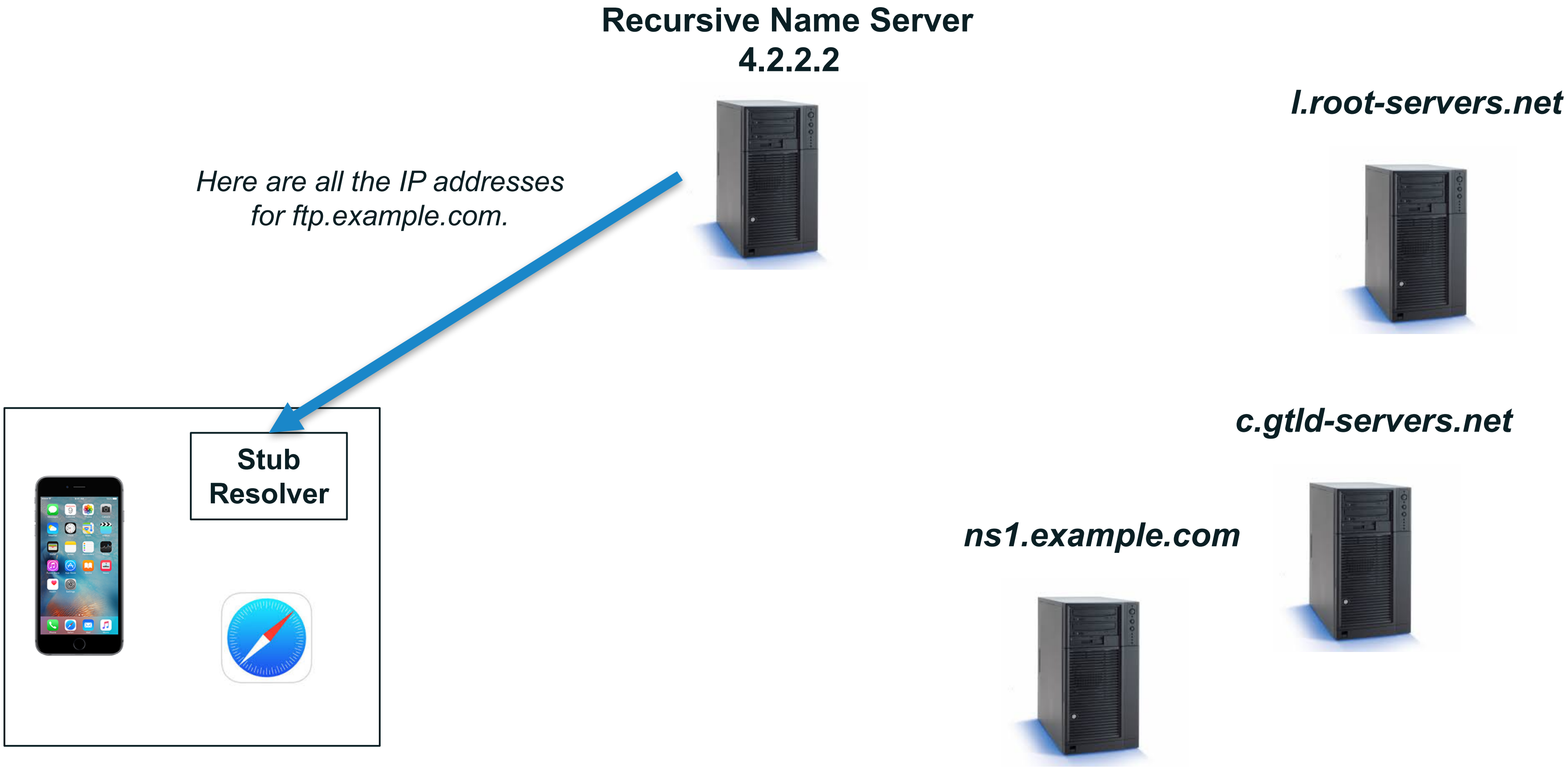
Resolution Process

example.com server returns the answer to the query



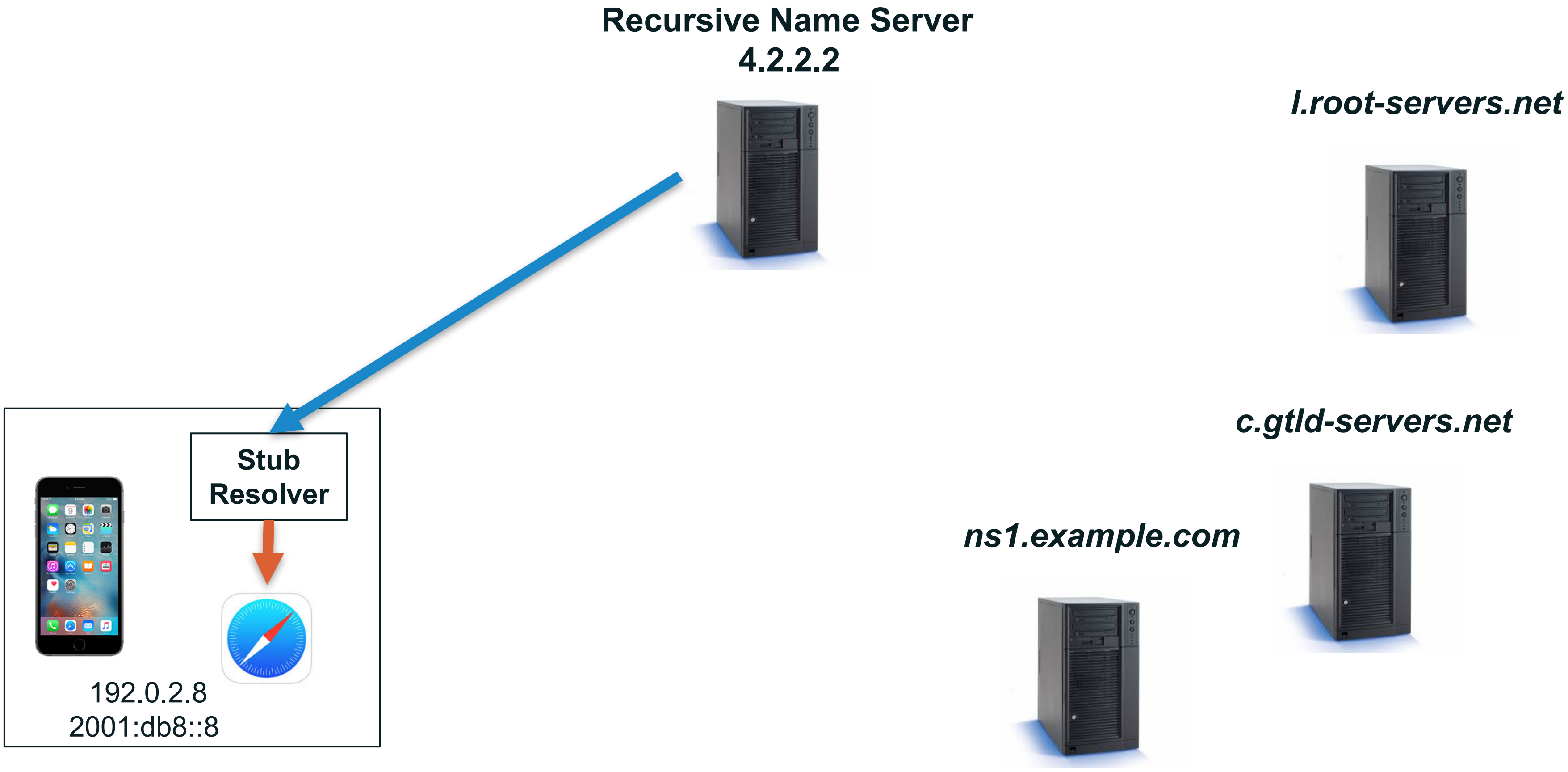
Resolution Process

Recursive server returns the answer to the query to the stub resolver



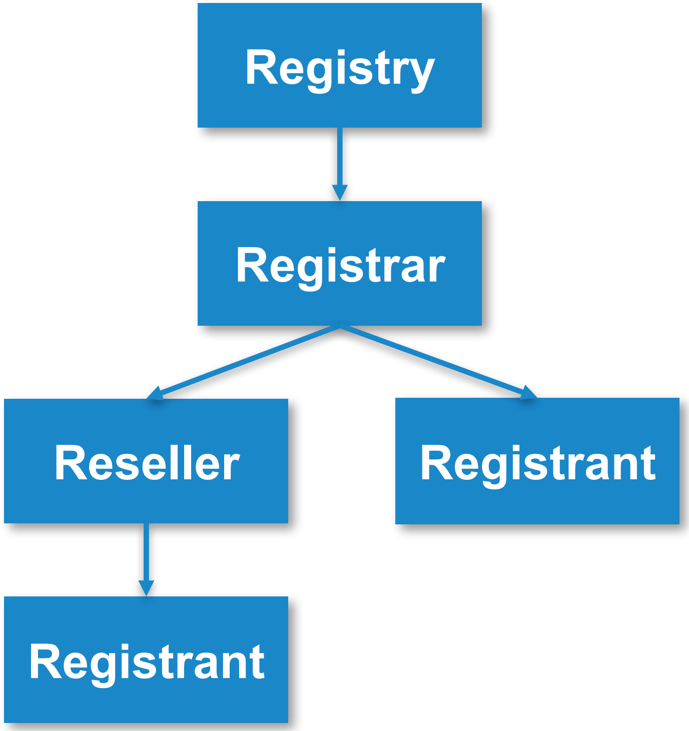
Resolution Process

Stub resolver returns the IP addresses to Safari

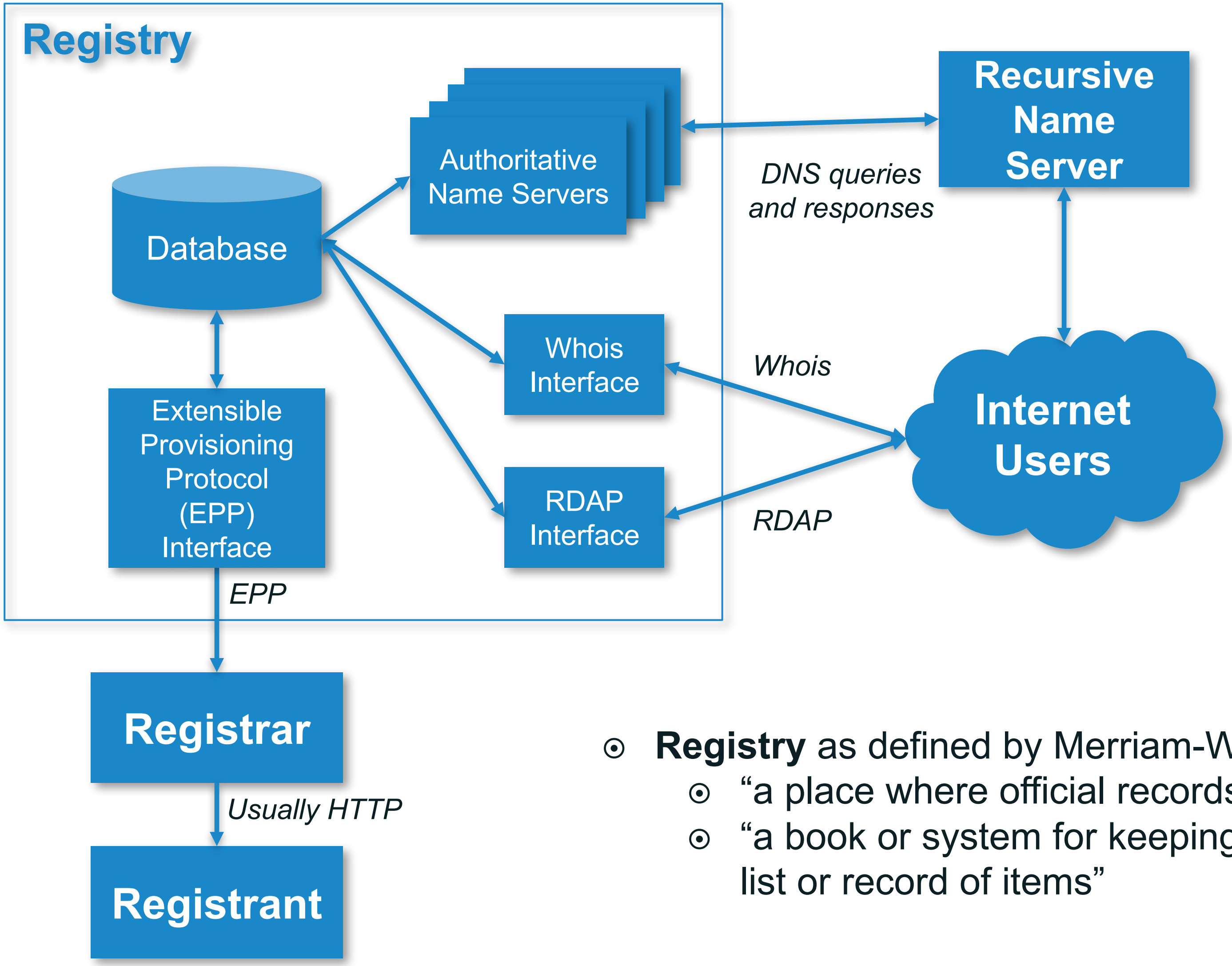


Domain Name Industry Ecosystem Players

- **Registry**: Database of domain names and registrants
- **Registrar**: Primary agent between registrant and registry
- **Registrant**: A holder of a domain name registration



Domain Name Registries



- **Registry** as defined by Merriam-Webster:
  - "a place where official records are kept"
  - "a book or system for keeping an official list or record of items"

Thank You and Questions

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