CompSci 356: Computer Network Architectures

Lecture 23: Domain Name System (DNS) and Content distribution networks

Chapter 9.3.1

Xiaowei Yang

xwy@cs.duke.edu

Overview

- Domain Name System
- Content Distribution Networks
- DNS attacks

Domain Name System (DNS)

Outline

- Functions of DNS
- Design goals of DNS
- History of DNS
- DNS architecture: hierarchy is the key
    - Name space and resource records
    - Name servers
    - Name resolvers

Functions of DNS

- Map an easy-to-remember name to an IP address
  - Without DNS, to send an IP packet, we'd have to remember
    - 66.102.7.99
    - 64.236.24.28
  - With DNS
    - **www.google.com**→ 66.102.7.99
    - **www.cnn.com**→ 64.236.24.28
- DNS also provides inverse look up that maps an IP address to an easy-to-remember name

Design goals of DNS

- The primary goal is a consistent name space which will be used for referring to resources.
  - Consistent: same names should refer to same resources
  - Resources: IP addresses, mail servers
- Enable Distributed management
  - The size of the name database will be large
  - The updates will be frequent
- Design goals determine its structure
  - A hierarchical name space
  - A distributed directory service

Before there was DNS ….

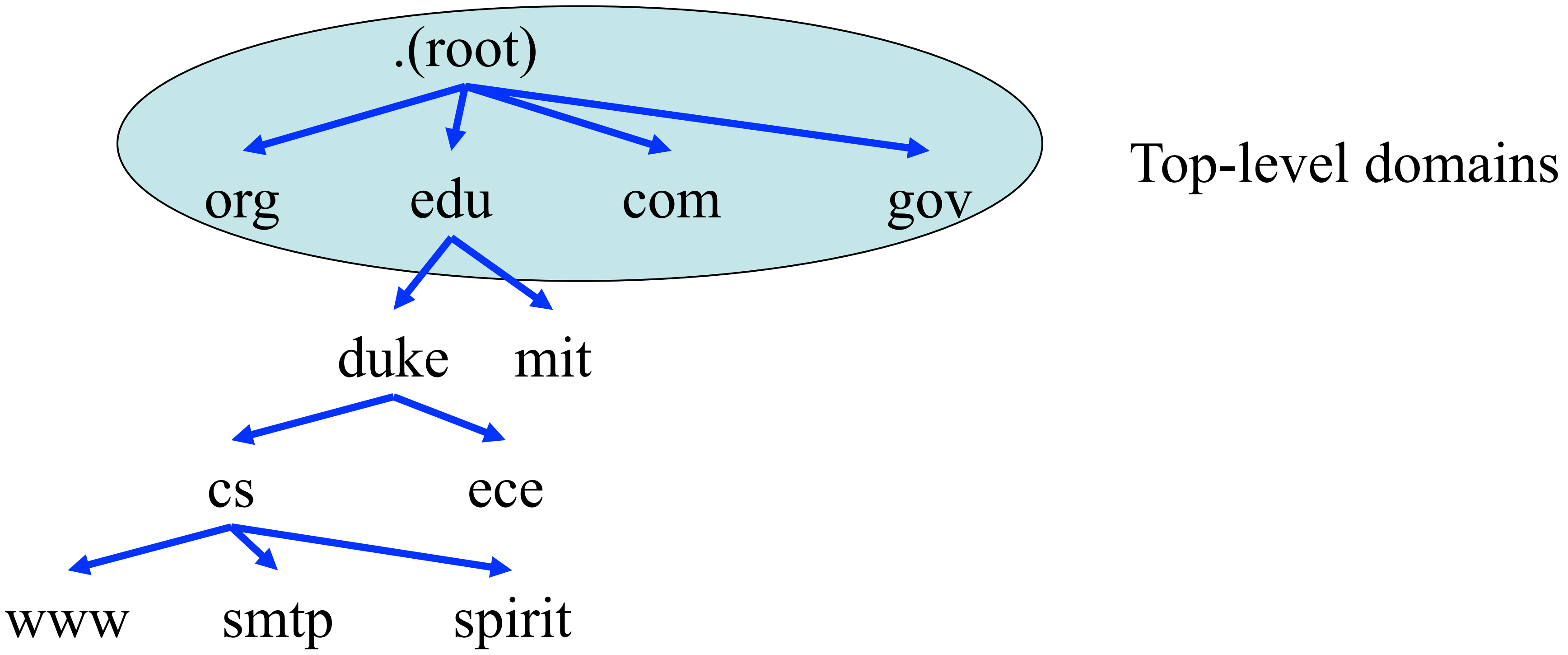
…. there was the HOSTS.TXT file maintained on a host at SRI Network Information Center (NIC)

- Before DNS (until 1985), the name-to-IP address was done by downloading a single file (hosts.txt) from a central server with FTP
  - Names in hosts.txt are not structured
  - The hosts.txt file still works on most operating systems. It can be used to define local names

Key components in DNS Architecture

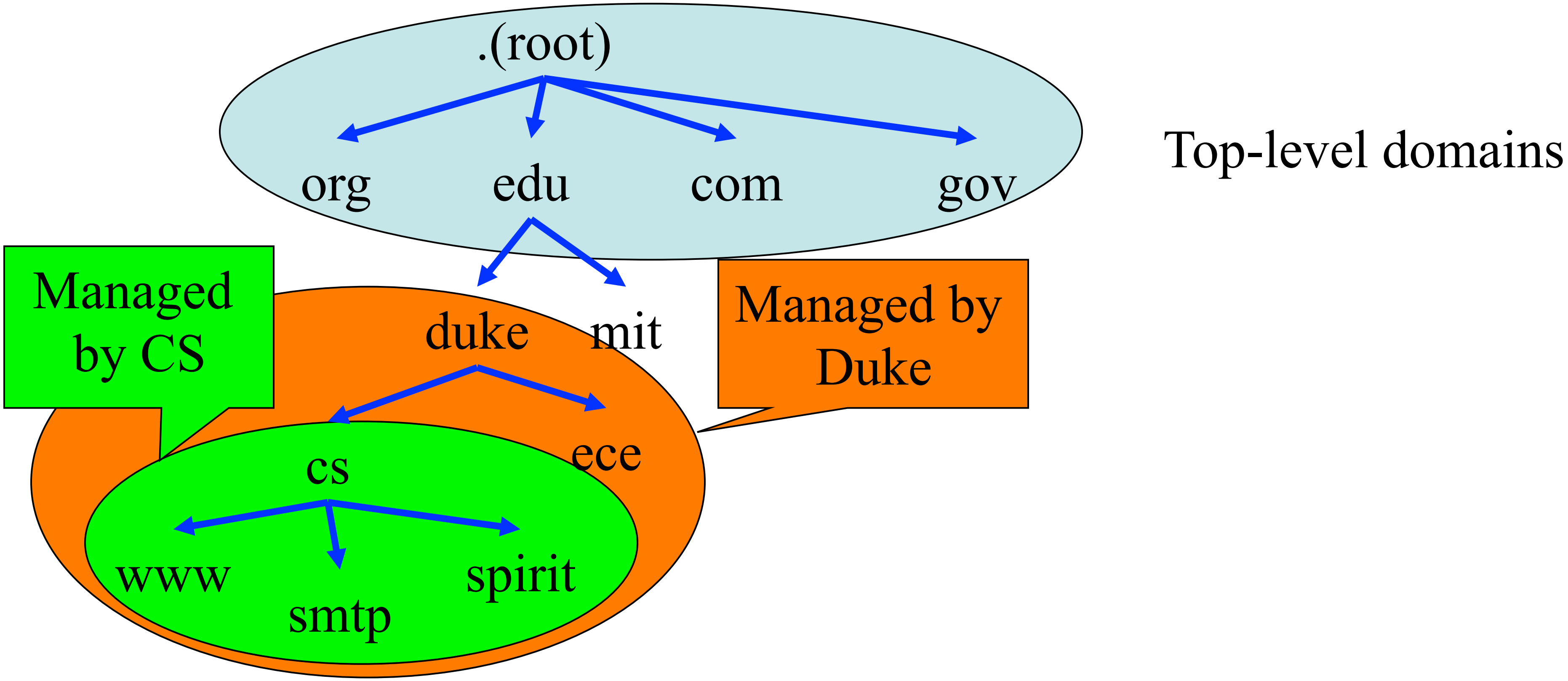
- Domain name space and resource records (RRs)
- Name servers
- Name resolution

Domain Namespace



- Domain namespace is a hierarchical and logical tree structure
- The label from a node to root in the DNS tree represents a DNS name
- Each subtree below a node is a DNS domain.
  - DNS domain can contain hosts or other domains (subdomains)
- Examples of DNS domains: .edu, duke.edu, cs.duke.edu

Distributed Management

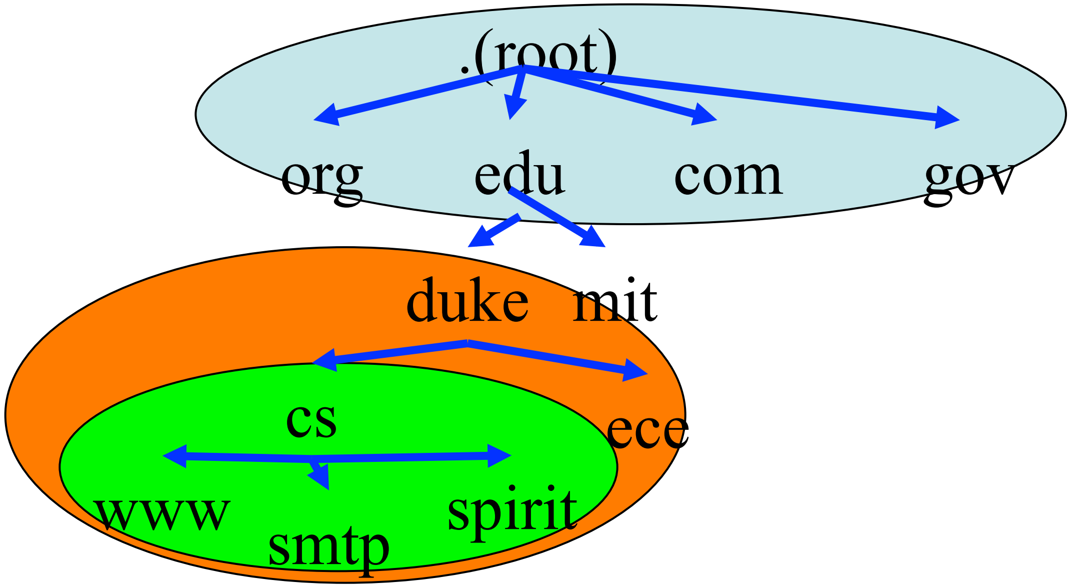


- Below top-level domain, administration of name space is delegated to organizations
- Each organization can delegate further

Domain names

- Names of hosts can be assigned independent of host locations on a link layer network, IP network or autonomous system
  - My computer’s DNS name *xiaowei.net* need not change even if my computer’s IP address has changed

Fully Qualified Domain Names



- Every node in the DNS domain tree can be identified by a unique Fully Qualified Domain Name (FQDN)

- A FQDN (from right to left) consists of labels (“cs”,“duke”,”edu”) separated by a period (“.”) from root to the node

- Each label can be up to 63 characters long. The total number of characters of a DNS name is limited to 255.
- FQDN contains characters, numerals, and dash character (“-”)
- FQDNs are not case-sensitive

Top-level domains

- Three types of top-level domains:
  - Generic Top Level Domains (gTLD): 3-character code indicates the function of the organization
    - Used primarily within the US
    - Examples: gov, mil, edu, org, com, net
  - Country Code Top Level Domain (ccTLD): 2-character country or region code
    - Examples: us, va, jp, de
  - Infrastructure top level domains: A special domain (in-addr.arpa) used for IP address-to-name mapping

There are more than 1000+ top-level domains.

Who “owns” DNS?

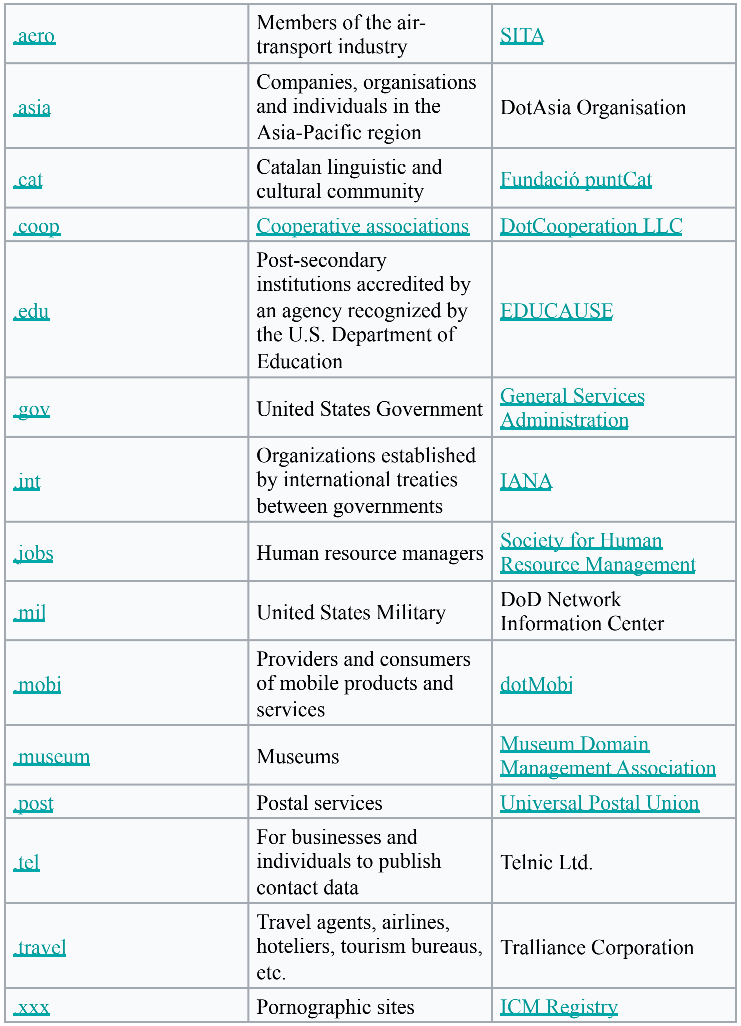
- The Internet needs governance
  - IP addresses, AS numbers, DNS, and other Internet names/numbers
  - Internet Assigned Numbers Authority (IANA) has the authority to manage the numbers
- Who implements IANA?
  - Originally by Jon Postel till 1998
  - By Internet Corporation of Assigned Names and Numbers (ICANN) formed in 1998
    - Used to be under the oversight of US government
    - By Oct 1, 2016, free of it

Generic Top Level Domains (gTLD)

- Sponsored top level domains
  - Has a sponsor representing the community
  - Sponsor in charge of policies
  - .aero sponsored by the company SITA

- Unsponsored top level domains
  - ICANN
  - .com, .net, .info

Sponsored top level domains



.aero	Members of the air-transport industry	SITA
.asia	Companies, organisations and individuals in the Asia-Pacific region	DotAsia Organisation
.cat	Catalan linguistic and cultural community	Fundació puntCat
.coop	Cooperative associations	DotCooperation LLC
.edu	Post-secondary institutions accredited by an agency recognized by the U.S. Department of Education	EDUCAUSE
.gov	United States Government	General Services Administration
.int	Organizations established by international treaties between governments	IANA
.jobs	Human resource managers	Society for Human Resource Management
.mil	United States Military	DoD Network Information Center
.mobi	Providers and consumers of mobile products and services	dotMobi
.museum	Museums	Museum Domain Management Association
.post	Postal services	Universal Postal Union
.tel	For businesses and individuals to publish contact data	Telnic Ltd.
.travel	Travel agents, airlines, hoteliers, tourism bureaus, etc.	Tralliance Corporation
.xxx	Pornographic sites	ICM Registry

Unsponsored top-level domains

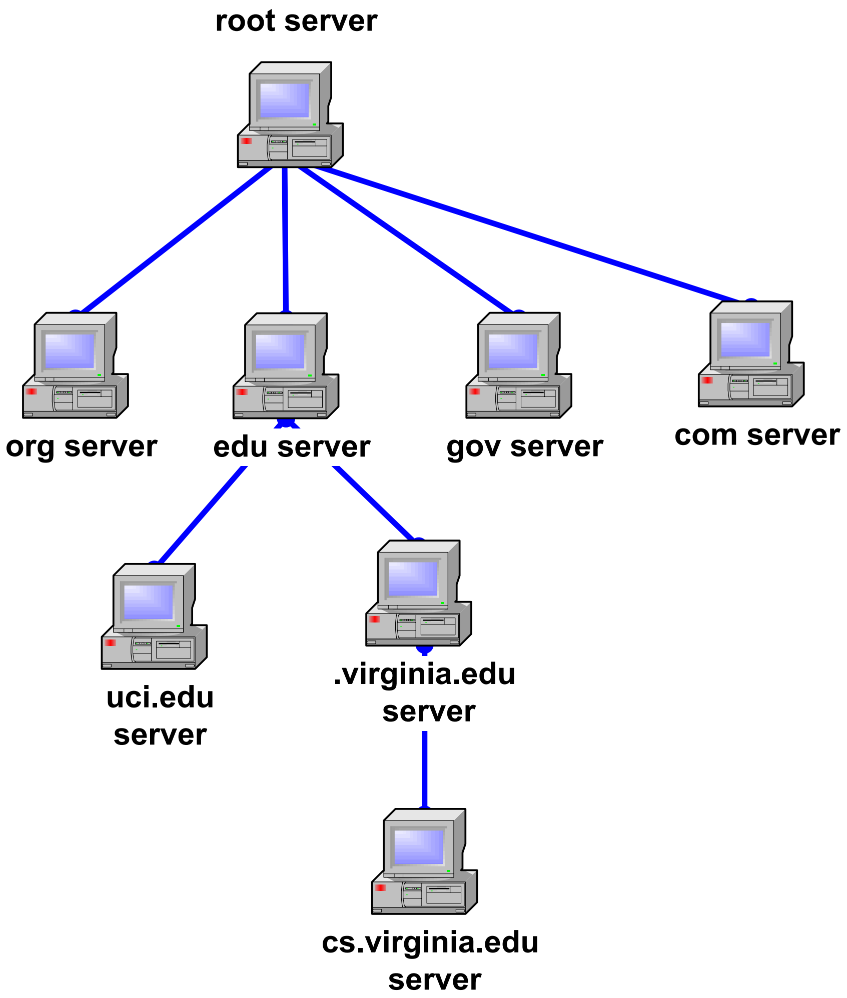
- .com
- .org
- .net
- .biz
- .info
- .name

DNS (technical) architecture

- Domain name space
  - A hierarchical tree structure
  - A domain can be delegated to an organization
- Resource records
  - Records domain name related information
- Name servers
  - Doman name hierarchy exists only in the abstract
  - Name servers implement the hierarchy
  - Maintains RRs
  - A host’s name servers are specified in /etc/resolv.conf
- Name resolution

Hierarchy of name servers

- The resolution of the hierarchical name space is done by a hierarchy of name servers
- Namespace is partitioned into zones. A zone is a contiguous portion of the DNS name space
- Each server is responsible (authoritative) for a zone.
- DNS server answers queries about host names in its zone



DNS domain and zones

- Each zone is anchored at a specific domain node, but zones are not domains.

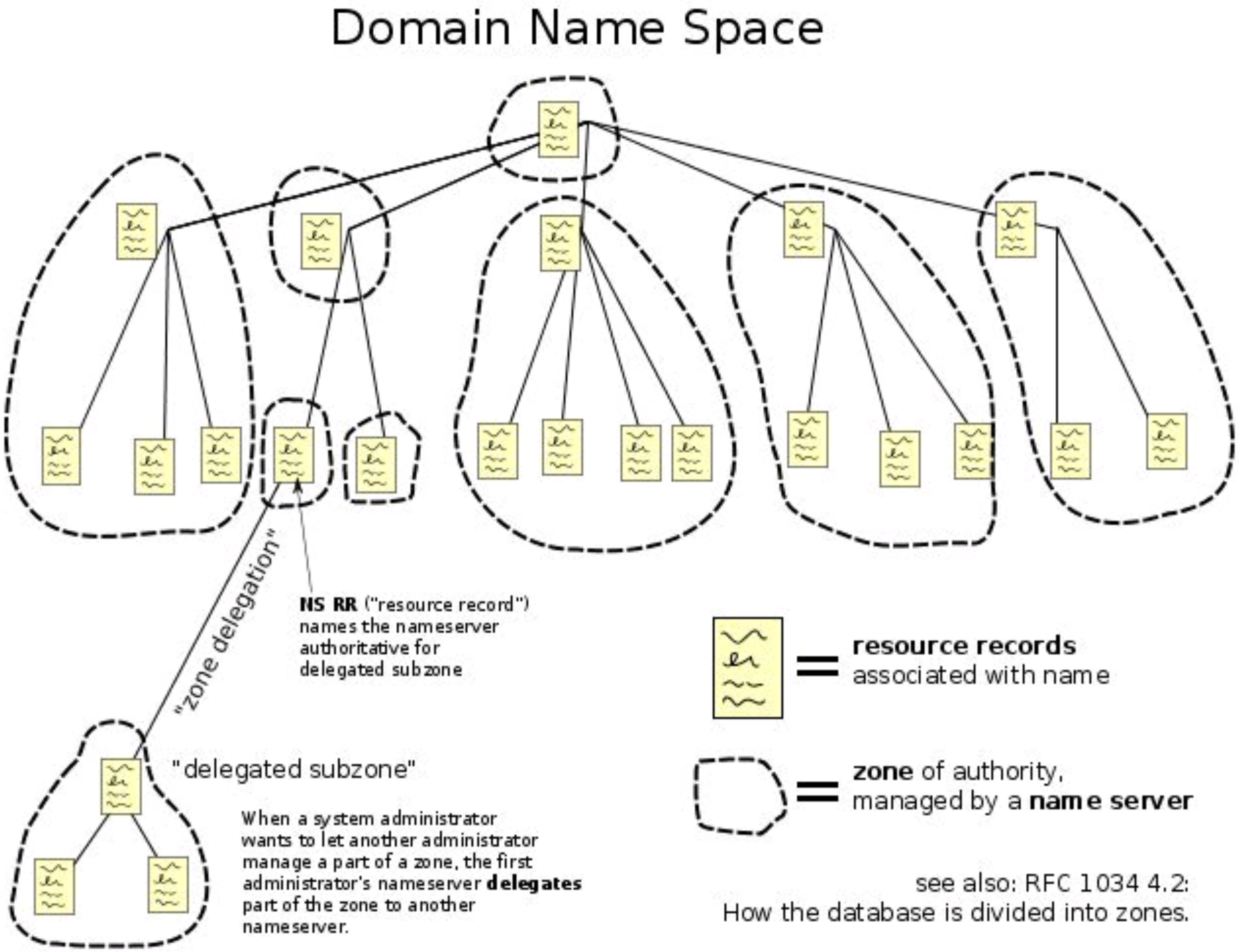
- *A DNS domain* is a subtree of the namespace

- A zone is a portion of the DNS namespace generally stored in a file (It could consists of multiple nodes)

- A server can divide part of its zone and delegate it to other servers

- A name server implements the zone information as a collection of resource records

Zone and sub-domain



Domain Name Space

NS RR ("resource record") names the nameserver authoritative for delegated subzone

When a system administrator wants to let another administrator manage a part of a zone, the first administrator's nameserver **delegates** part of the zone to another nameserver.

resource records associated with name

zone of authority, managed by a **name server**

see also: RFC 1034 4.2:
How the database is divided into zones.

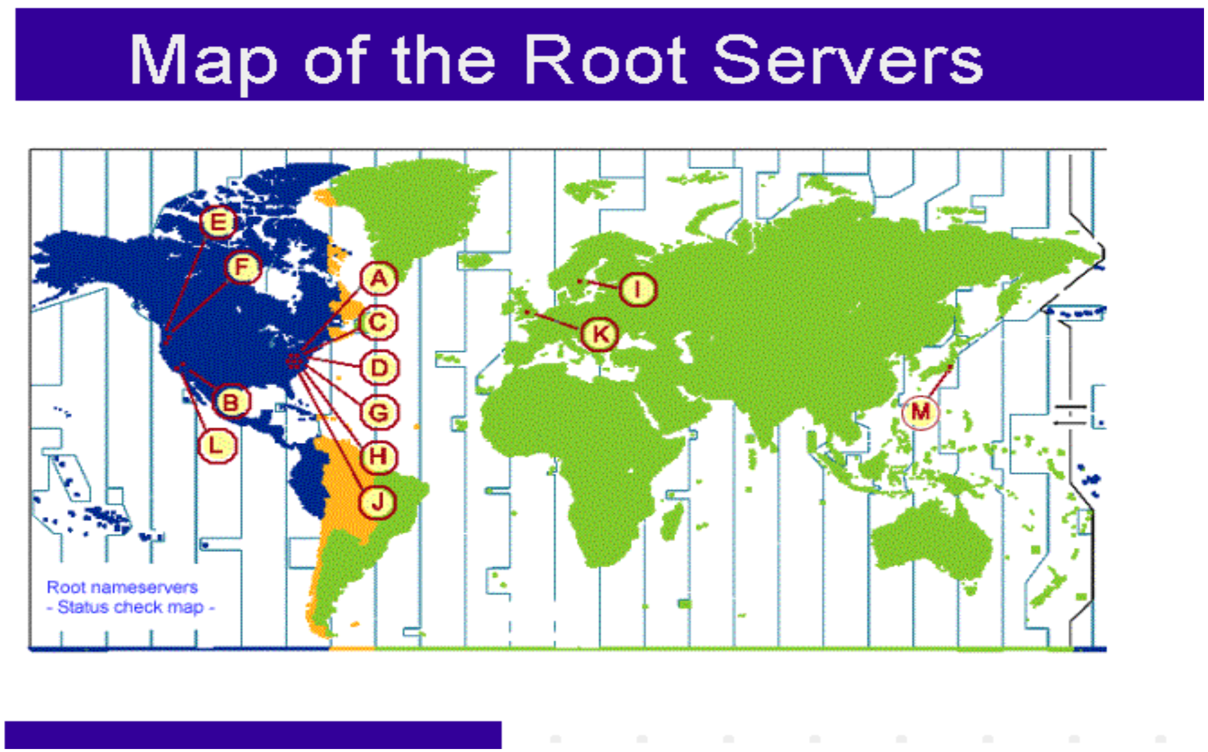
Primary and secondary name servers

- For each zone, there must be a primary name server and a secondary name server for reliability reason
  - The primary server (master server) maintains a zone file which has information about the zone. Updates are made to the primary server
  - The secondary server copies data stored at the primary server

Adding a host:

- When a new host is added (“spirit.cs.duke.edu”) to a zone, the administrator adds the IP information on the host (IP address and name) to a configuration file on the primary server

Root name servers



- The root name servers know how to find the authoritative name servers for all top-level zones.
- There are 13 (virtual) root name servers
- Root servers are critical for the proper functioning of name resolution

Addresses of root servers

A.ROOT-SERVERS.NET.	(VeriSign, Dulles, VA) 198.41.0.4
B.ROOT-SERVERS.NET.	(ISI, Marina Del Rey CA) 192.228.79.201
C.ROOT-SERVERS.NET.	(Cogent Communications) 192.33.4.12
D.ROOT-SERVERS.NET.	(University of Maryland) 128.8.10.90
E.ROOT-SERVERS.NET.	(Nasa Ames Research Center) 192.203.230.10
F.ROOT-SERVERS.NET.	(Internet Systems Consortium) 192.5.5.241
G.ROOT-SERVERS.NET.	(US Department of Defense) 192.112.36.4
H.ROOT-SERVERS.NET.	(US Army Research Lab) 128.63.2.53
I.ROOT-SERVERS.NET.	(Stockholm, Sweden) 192.36.148.17
J.ROOT-SERVERS.NET.	(Herndon, VA) 192.58.128.30
K.ROOT-SERVERS.NET.	(London, United Kingdom)

Resource Records

- A zone file includes a collection of resource records (RRs)

- (Name, Value, Type, Class, TTL)
  - Name and value are exactly what you expect
  - Type specifies how the Value should be interpreted
    - A, NS, CNAME, MX, AAAA
  - Class: allows other entities to define record types; IN is the widely used one to date
  - TTL: how long the record should be cached

Resource Records

- The database records of the DNS distributed database are called resource records (RR)

- Resource records are stored in configuration files (zone files) at name servers.

Resource records for a zone→

db.mylab.com

```
$TTL 86400
mylab.com. IN SOA PC4.mylab.com.
            hostmaster.mylab.com. (
            1 ; serial
            28800 ; refresh
            7200 ; retry
            604800 ; expire
            86400 ; minimum ttl
            )

;
mylab.com.  IN  NS  PC4.mylab.com.
;
localhost       A      127.0.0.1
PC4.mylab.com.  A      10.0.1.41
PC3.mylab.com.  A      10.0.1.31
PC2.mylab.com.  A      10.0.1.21
PC1.mylab.com.  A      10.0.1.11
```

Resource Records

```
$TTL 86400
mylab.com. IN SOA PC4.mylab.com.
Hostmaster.mylab.com. (
                          1 ; serial
                          28800 ; refresh
                          7200 ; retry
                          604800 ; expire
                          86400 ; minimum ttl
                          )
;
mylab.com.        IN      NS      PC4.mylab.com.
;
localhost                 A       127.0.0.1
PC4.mylab.com.    A       10.0.1.41
PC3.mylab.com.    A       10.0.1.31
PC2.mylab.com.    A       10.0.1.21
PC1.mylab.com.    A       10.0.1.11
```

Max. age of cached data
in seconds

•Start of authority (SOA) record. Means: “This name server is authoritative for the zone Mylab.com”

•PC4.mylab.com is the name server

•hostmaster@mylab.com is the email address of the person in charge

Name server (NS) record.
One entry for each authoritative name server

Address (A) records.
One entry for each host address

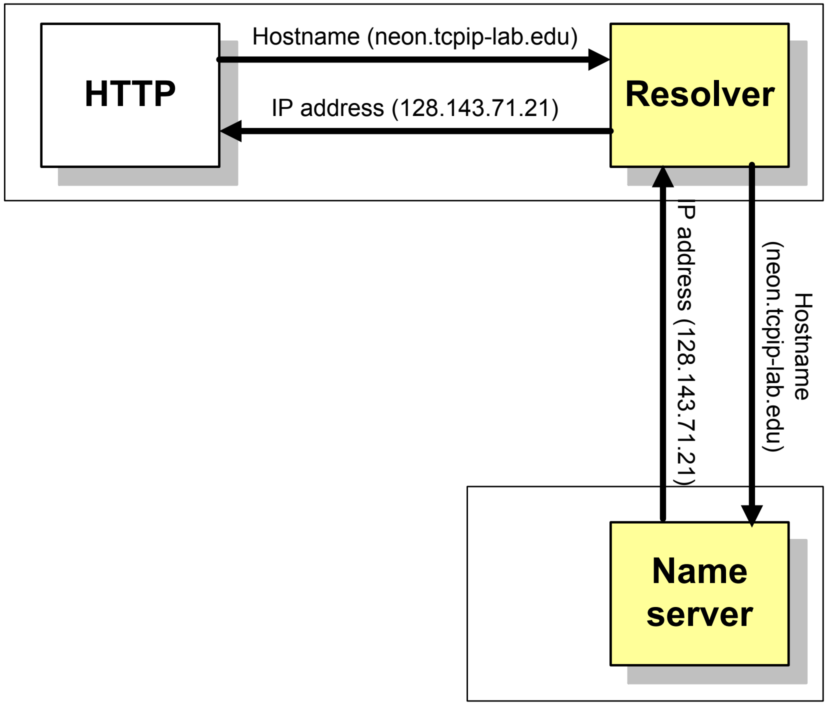
Domain name resolution

1. User program issues a request for the IP address of a hostname gethostbyname()

2. Local resolver formulates a DNS query to the name server of the host

3. Name server checks if it is authorized to answer the query.
   a) If yes, it responds.
   b) Otherwise, it will query other name servers, starting at the root tree

4. When the name server has the answer it sends it to the resolver.


HTTP
Hostname (neon.tcpip-lab.edu)
IP address (128.143.71.21)
Resolver
IP address (128.143.71.21)
Hostname
(neon.tcpip-lab.edu)
Name
server

Recursive and Iterative Queries

- There are two types of queries:
  - Recursive queries
  - Iterative (non-recursive) queries

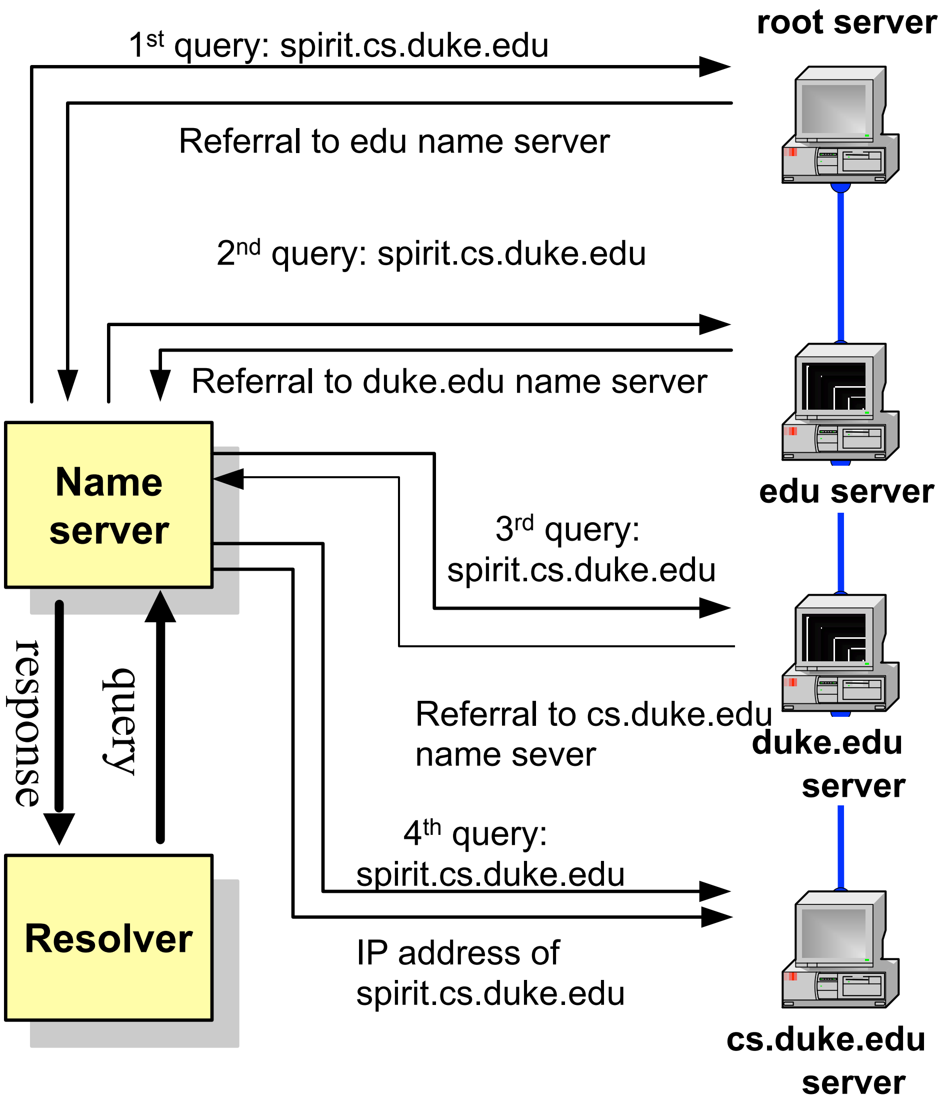
- The type of query is determined by a bit in the DNS query

- Recursive query: When the name server of a host cannot resolve a query, the server issues a query to resolve the query

- Iterative queries: When the name server of a host cannot resolve a query, it sends a referral to another server to the resolver

Recursive/iterative queries

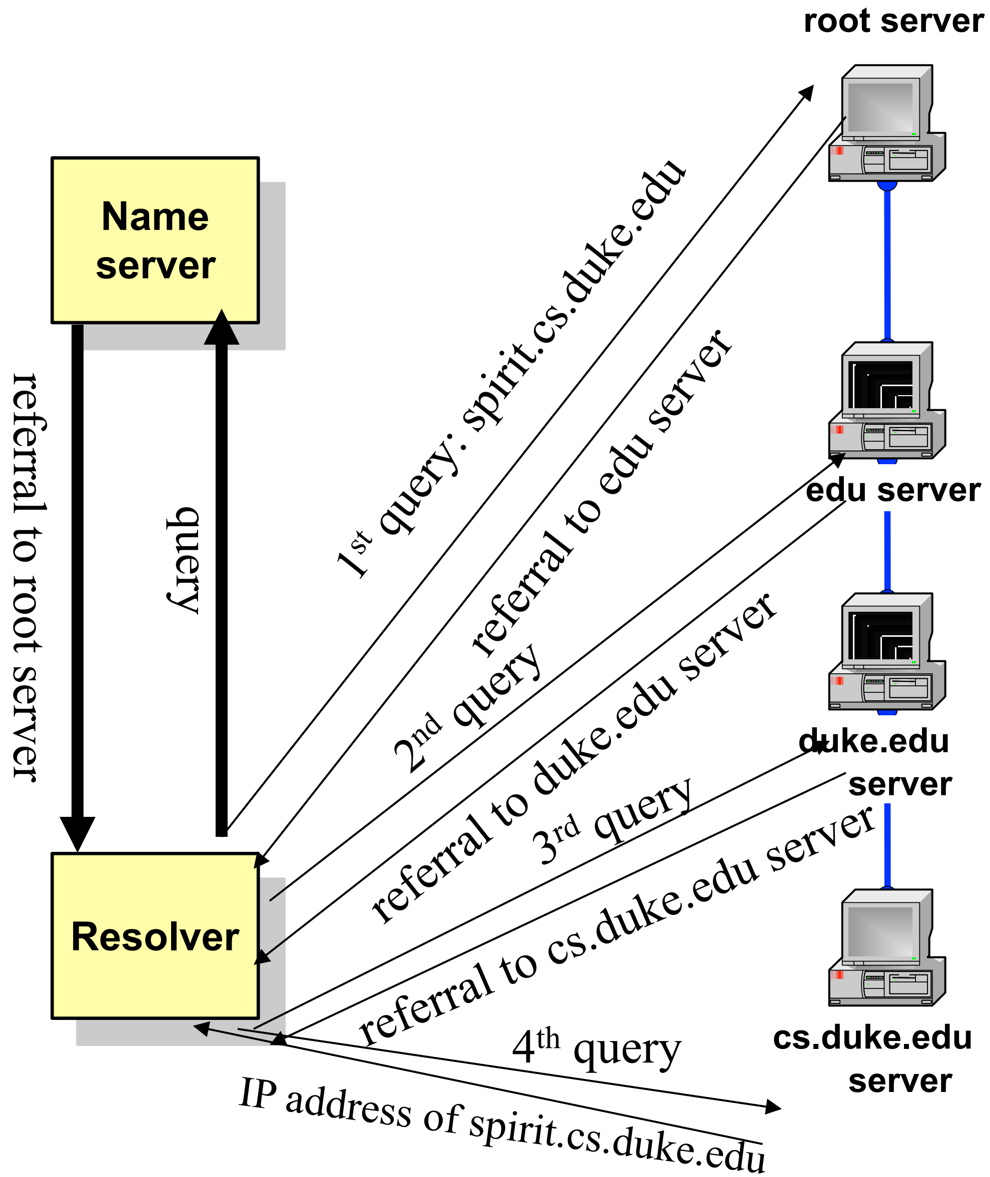
- In a recursive query, the resolver expects the response from the name server
- If the server cannot supply the answer, it will send the query to the “closest known” authoritative name server (here: In the worst case, the closest known server is the root server)
- The root sever sends a referral to the “edu” server. Querying this server yields a referral to the server of “duke.edu”
  - A “referral” is IP address to an intermediate name server
- … and so on
- First: recursive
- Subsequent: iterative



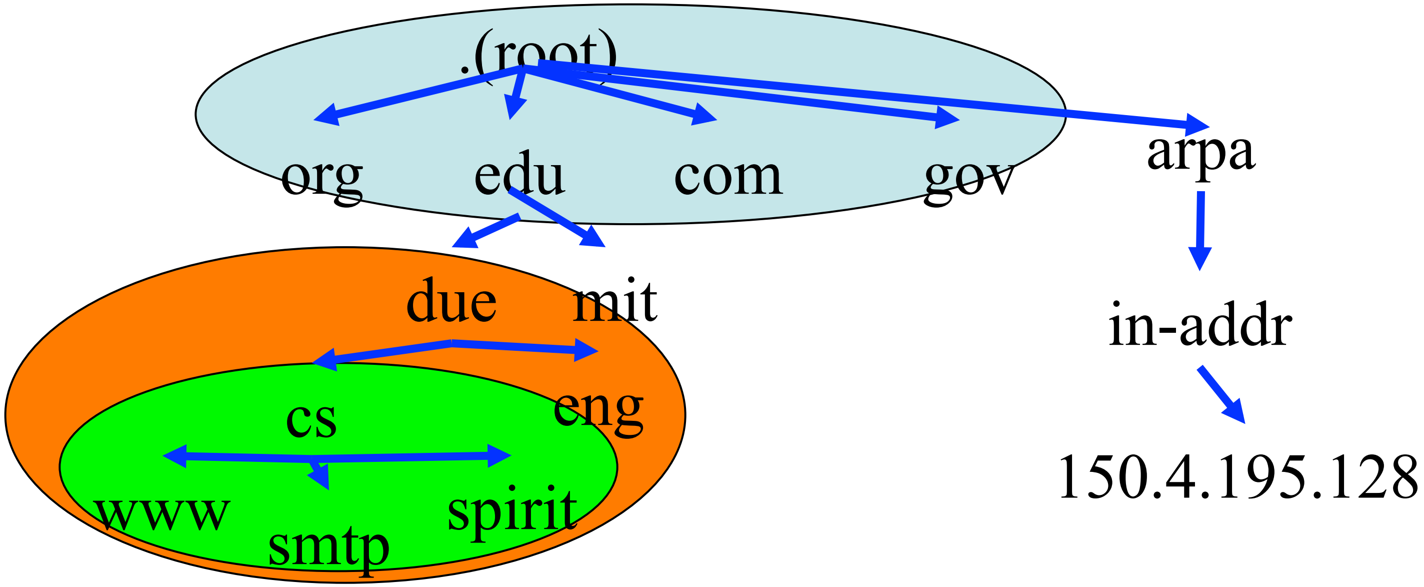
root server
1st query: spirit.cs.duke.edu
Referral to edu name server
2nd query: spirit.cs.duke.edu
Referral to duke.edu name server
edu server
Name server
3rd query: spirit.cs.duke.edu
Referral to cs.duke.edu name sever
duke.edu server
response
query
4th query: spirit.cs.duke.edu
IP address of spirit.cs.duke.edu
Resolver
cs.duke.edu server

Iterative name servers

- In an iterative query, the name server sends a closest known authoritative name server, if it does not know the answer to the query.
- The resolver queries the referral.
- This involves more work for the resolver



Inverse query



- What’s the host name for IP address 128.195.4.150
  - IP address is converted to domain name: 150.4.195.128.in-addr.arpa
  - Resolver sends query for this address

Canonical names and aliases

```
;; ANSWER SECTION:
www.cs.duke.edu.       86400  IN CNAME prophet.cs.duke.edu.
prophet.cs.duke.edu.   86400  IN      A        152.3.140.5
```

- Hosts can have several names.
- One is called canonical names and others are called aliases

Caching

- To reduce DNS traffic, name servers caches information on domain name/IP address mappings

- When an entry for a query is in the cache, the server does not contact other servers
- Note: If an entry is sent from a cache, the reply from the server is marked as “unauthoritative”
- Caching-only servers

Negative caching

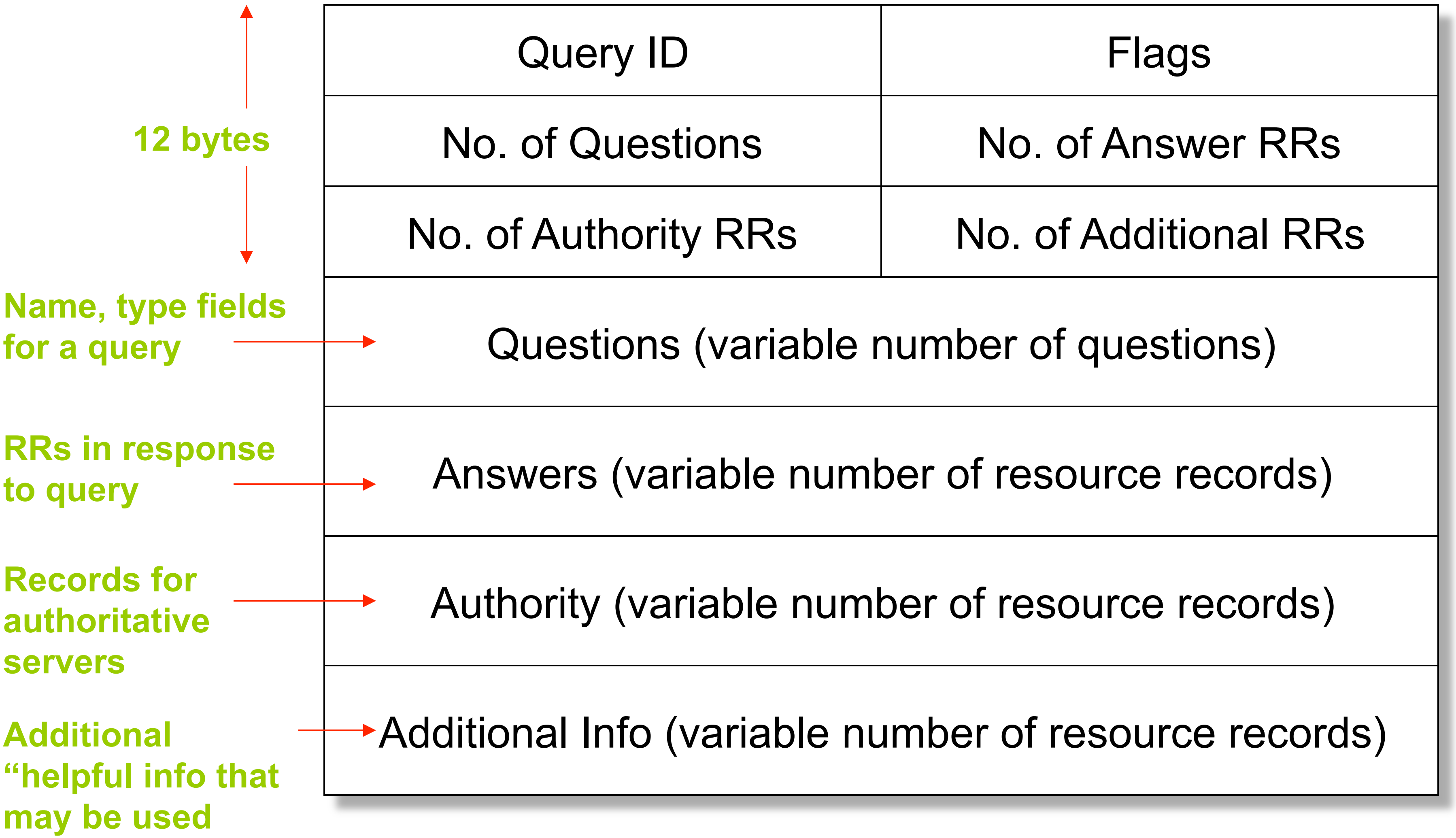
- Two negative responses
  - Name in question does not exist
  - The name in record exists, but the requested data do not

- Negative responses will be cached too

Dig

```
•   DNS lookup utility

•   xwy@liberty:~$ dig  +norecurse @a.root-servers.net NS www.cs.duke.edu

•   …..

•   ;; QUESTION SECTION:
•   ;www.cs.duke.edu.              IN          NS

•   ;; AUTHORITY SECTION:
•   edu.                           172800      IN          NS          L.GTLD-SERVERS.NET.
•   edu.                           172800      IN          NS          G.GTLD-SERVERS.NET.
•   edu.                           172800      IN          NS          C.GTLD-SERVERS.NET.
•   edu.                           172800      IN          NS          D.GTLD-SERVERS.NET.
•   edu.                           172800      IN          NS          A.GTLD-SERVERS.NET.
•   edu.                           172800      IN          NS          F.GTLD-SERVERS.NET.
•   edu.                           172800      IN          NS          E.GTLD-SERVERS.NET.

•   ;; ADDITIONAL SECTION:
•   A.GTLD-SERVERS.NET.    172800  IN    A       192.5.6.30
•   A.GTLD-SERVERS.NET.    172800  IN    AAAA    2001:503:a83e::2:30
•   C.GTLD-SERVERS.NET.    172800  IN    A       192.26.92.30
•   D.GTLD-SERVERS.NET.    172800  IN    A       192.31.80.30
•   E.GTLD-SERVERS.NET.    172800  IN    A       192.12.94.30
•   F.GTLD-SERVERS.NET.    172800  IN    A       192.35.51.30
•   G.GTLD-SERVERS.NET.    172800  IN    A       192.42.93.30
•   L.GTLD-SERVERS.NET.    172800  IN    A       192.41.162.30
```

DNS Message Format



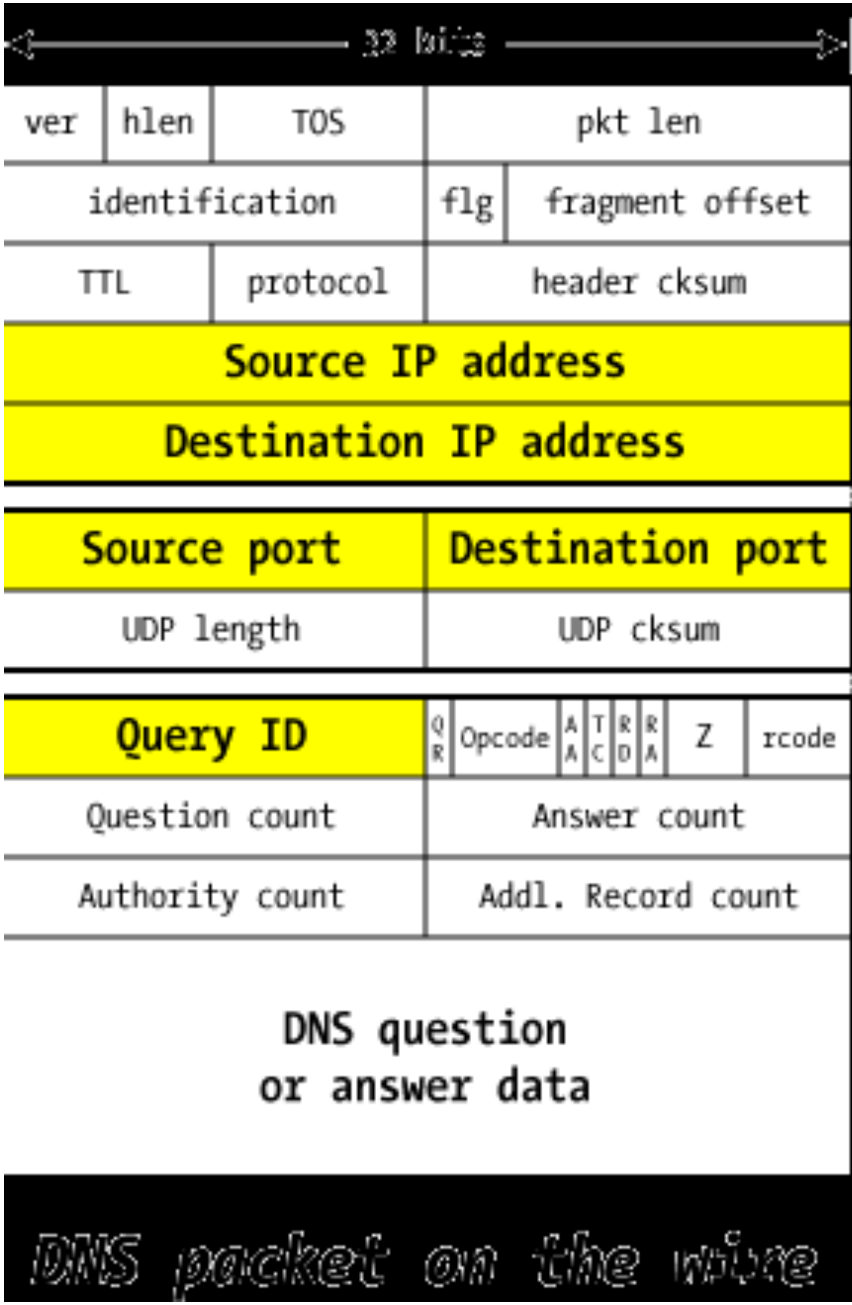
Query ID	Flags
No. of Questions	No. of Answer RRs
No. of Authority RRs	No. of Additional RRs
Questions (variable number of questions)	
Answers (variable number of resource records)	
Authority (variable number of resource records)	
Additional Info (variable number of resource records)	

12 bytes
Name, type fields for a query
RRs in response to query
Records for authoritative servers
Additional “helpful info that may be used

DNS Header Fields

- Identification
  - Used to match up request/response
  - DNS cache poisoning attacks exploit this field
- Flags
  - 1-bit to mark query or response
  - 1-bit to mark authoritative or not
  - 1-bit to request recursive resolution
  - 1-bit to indicate support for recursive resolution

- Port 53
- Question repeated in answer
- Query ID
  - Used to match up request/response
  - DNS cache poisoning attacks exploit this field
- Flags
  - 1-bit to mark query or response
  - 1-bit to mark authoritative or not
  - 1-bit to request recursive resolution
  - 1-bit to indicate support for recursive resolution



32 bits

ver | hlen | TOS | pkt len

identification | flg | fragment offset

TTL | protocol | header cksum

Source IP address

Destination IP address

Source port | Destination port

UDP length | UDP cksum

Query ID | QR | Opcode | AA | TC | RD | RA | Z | rcode

Question count | Answer count

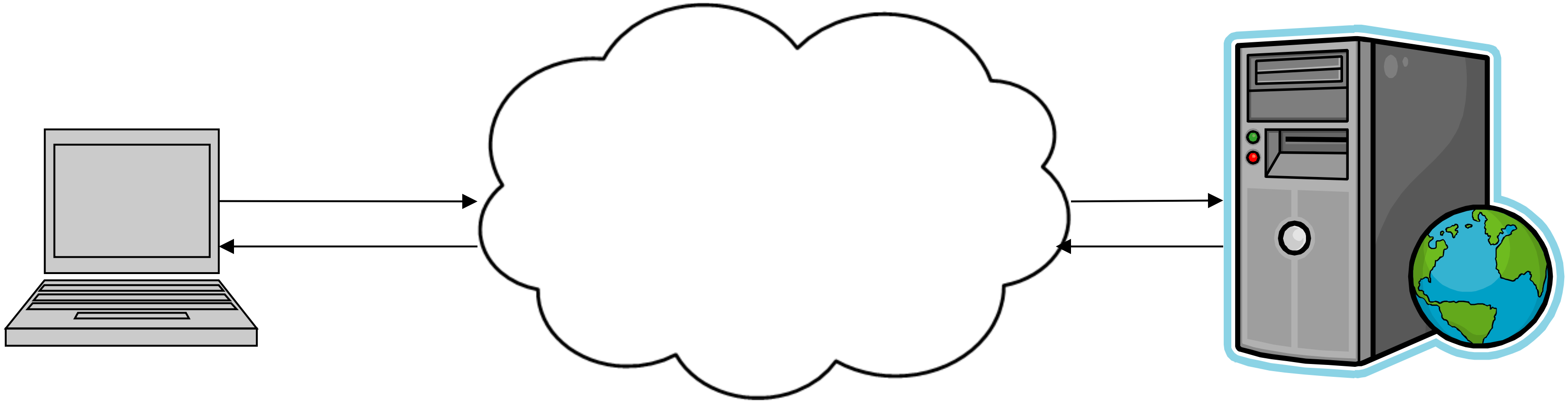
Authority count | Addl. Record count

DNS question
or answer data

DNS packet on the wire

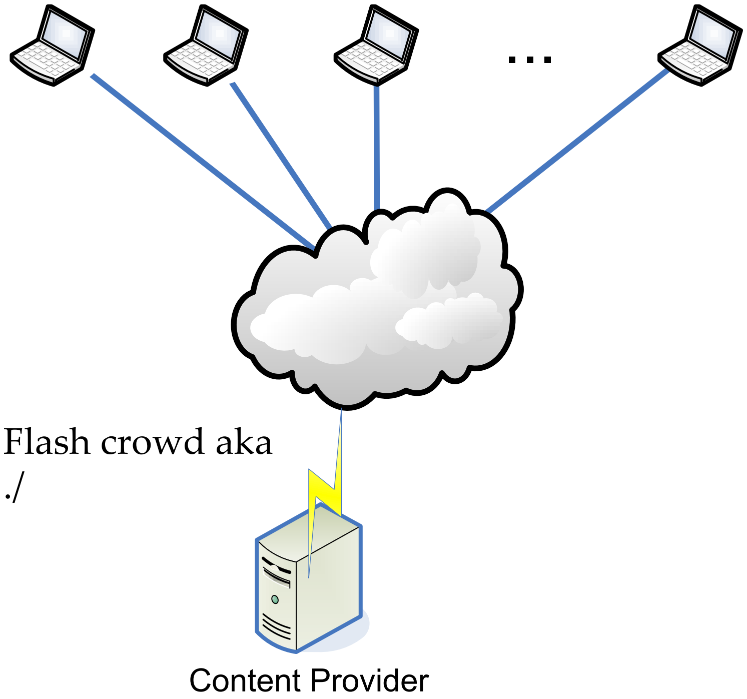
Server Selections and CDNs

A traditional web application



- HTTP request http://www.cs.duke.edu
- A DNS lookup on www.cs.duke.edu returns the IP address of the web server
- Requests are sent to the web site

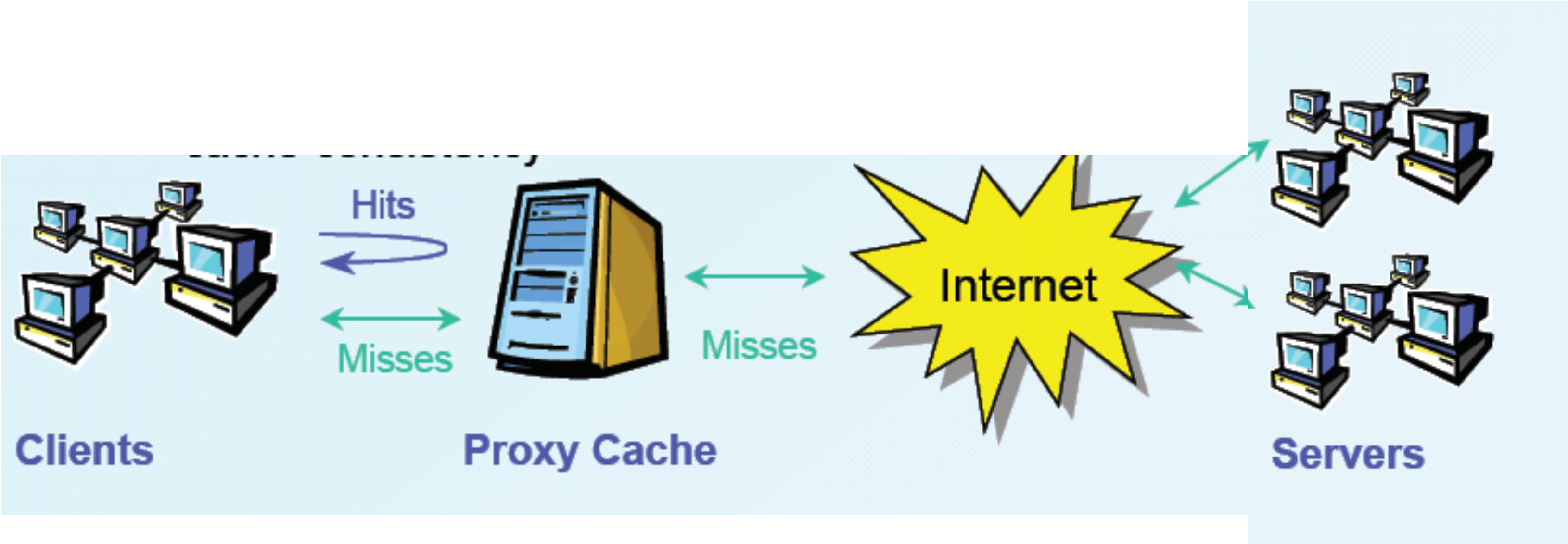
What problem does CDN solve?



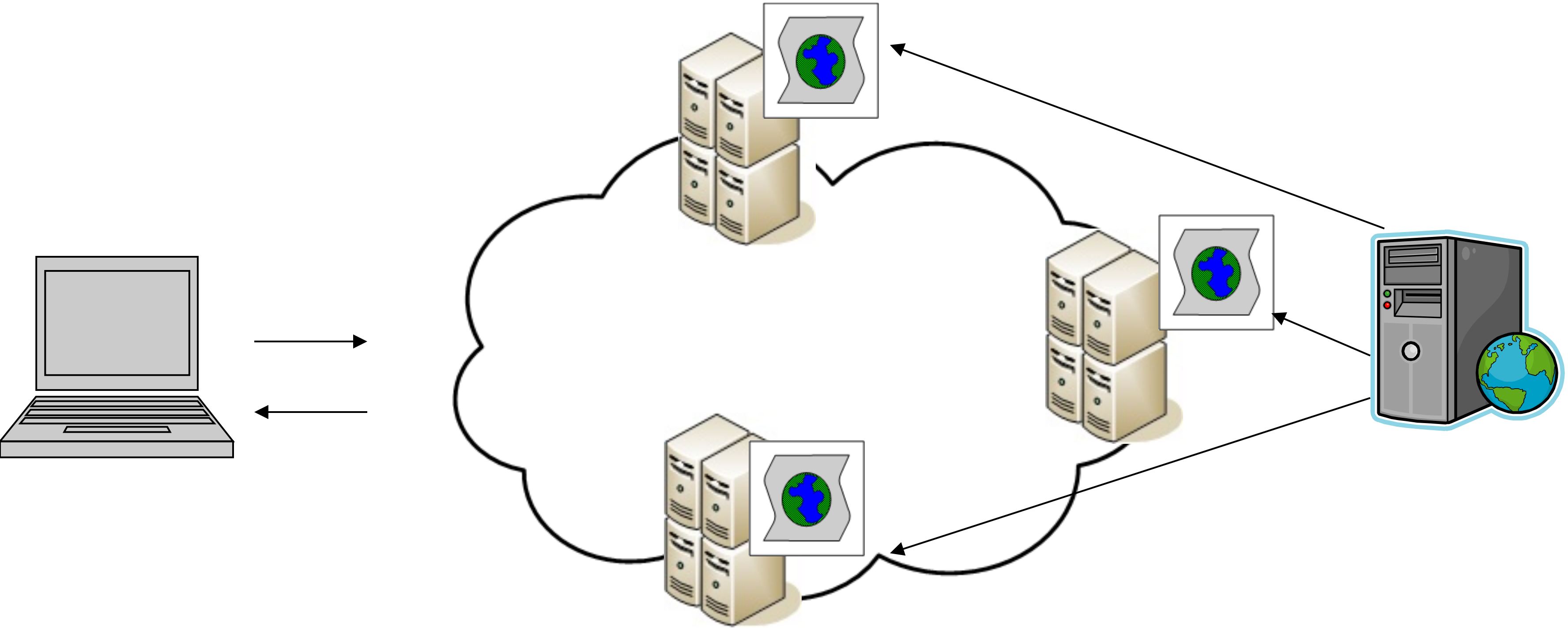
- Flash crowd may overwhelm a server and the access network
- Reduce latency, and network load

Proxy caching

- Enhance web performance
  - Cache content
  - Reduce server load, latency, network utilization



A content distribution network



- A single provider that manages multiple replicas
- A client obtains content from a close replica

Pros and cons of CDN

- Pros
  - + Multiple content providers may use the same CDN → economy of scale
  - + All other advantages of proxy caching
  - + Fault tolerance
  - + Load balancing across multiple CDN nodes
- Cons
  - - Expensive

CDN challenges

- Balancing load among multiple caches
- Fault tolerant
- Low latency
- Cache consistency
- DDoS resistance

How a CDN works

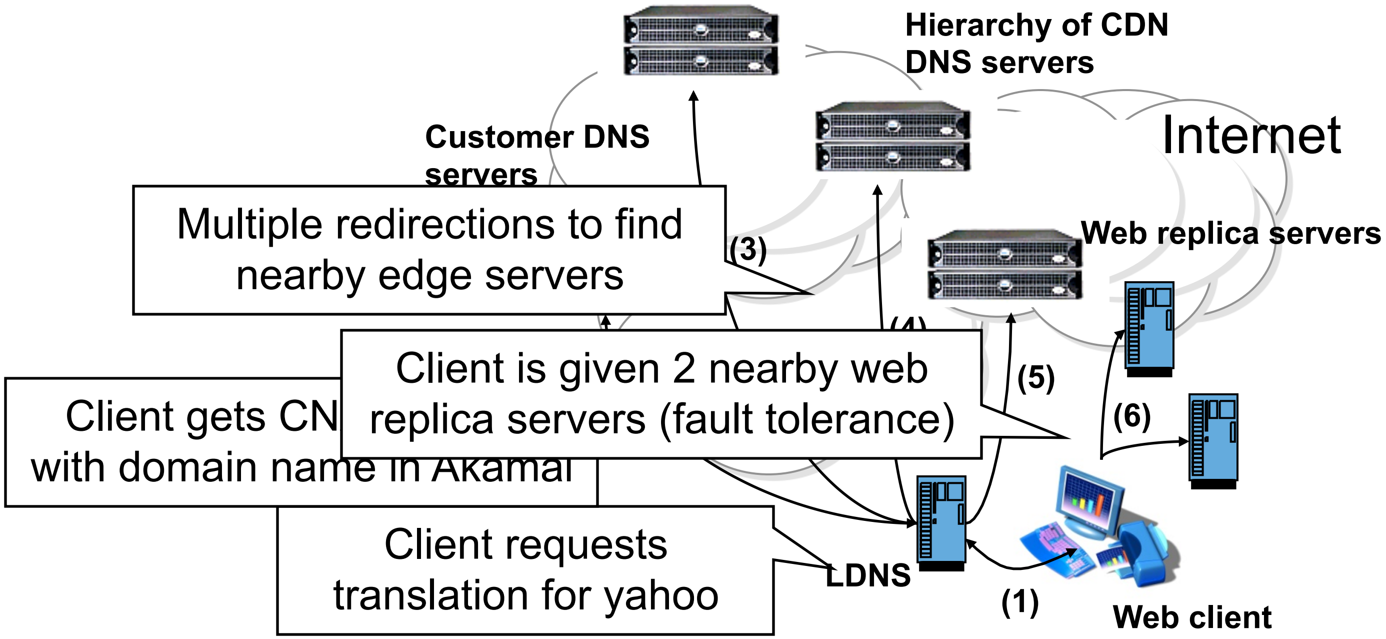
- One key technology:
  - DNS-based redirection: load balancing, latency

- Static content
  - Partial content

DNS redirection

- Using a hierarchy of DNS servers that translate a client’s web request to a nearby Akamai server
  - A client requests a DNS resolution (www.yahoo.com)
  - Akamai’s customer’s DNS name server uses a canonical name entry redirecting it to a DNS server in akamai’s network
  - A hierarchy of DNS name servers responds to the DNS name-translation request
  - Name of the Akamai customer and the name of the requested content as a guide to determine the best two Akamai edge servers

CDNs Basics



Multiple redirections to find nearby edge servers

Client is given 2 nearby web replica servers (fault tolerance)

Client gets CN with domain name in Akamai

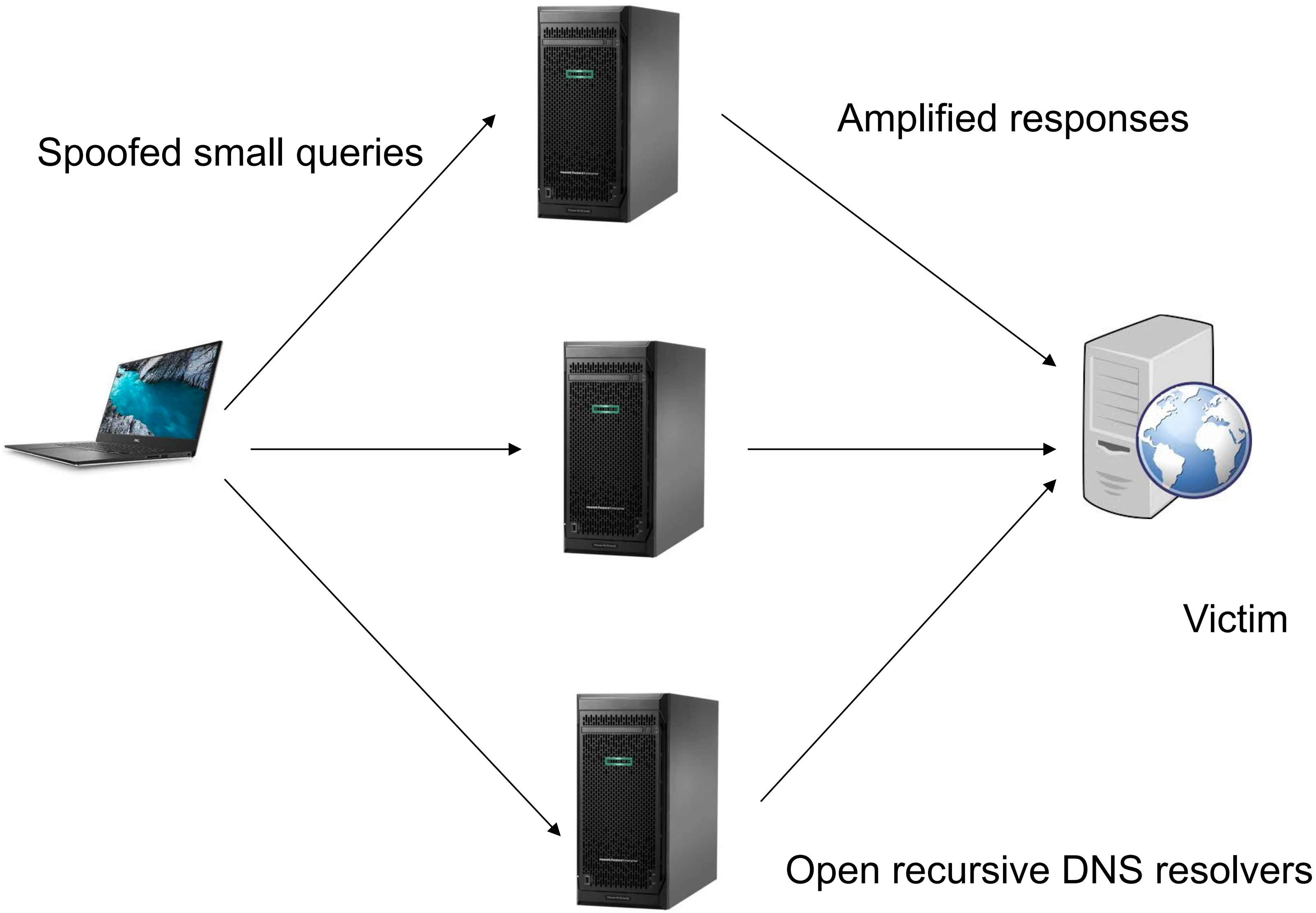
Client requests translation for yahoo

- Web client's request redirected to 'close' by server
  - Client gets web site's DNS CNAME entry with domain name in CDN network
  - Hierarchy of CDN's DNS servers direct client to 2 nearby servers

```
; <<>> DiG 9.4.2-P2 <<>> images.pcworld.com
;; global options:  printcmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 29098
;; flags: qr rd ra; QUERY: 1, ANSWER: 4, AUTHORITY: 9, ADDITIONAL: 2

;; QUESTION SECTION:
;images.pcworld.com.                  IN          A

;; ANSWER SECTION:
images.pcworld.com.         885       IN          CNAME       images.pcworld.com.edgesuite.net.
images.pcworld.com.edgesuite.net. 21585    IN CNAME a1694.g.akamai.net.
a1694.g.akamai.net.         5         IN          A           128.109.34.38
a1694.g.akamai.net.         5         IN          A           128.109.34.45

;; AUTHORITY SECTION:
g.akamai.net.               973       IN          NS          n1g.akamai.net.
g.akamai.net.               973       IN          NS          n2g.akamai.net.
g.akamai.net.               973       IN          NS          n3g.akamai.net.
g.akamai.net.               973       IN          NS          n4g.akamai.net.
g.akamai.net.               973       IN          NS          n5g.akamai.net.
g.akamai.net.               973       IN          NS          n6g.akamai.net.
g.akamai.net.               973       IN          NS          n7g.akamai.net.
g.akamai.net.               973       IN          NS          n8g.akamai.net.
g.akamai.net.               973       IN          NS          n0g.akamai.net.

;; ADDITIONAL SECTION:
n1g.akamai.net.                       1663        IN          A           97.65.135.156
n5g.akamai.net.                       889         IN          A           128.109.247.10

;; Query time: 1 msec
;; SERVER: 152.3.140.1#53(152.3.140.1)
;; WHEN: Mon Feb 23 18:05:12 2009
;; MSG SIZE  rcvd: 337
```

DNS attacks

DNS reflection attacks



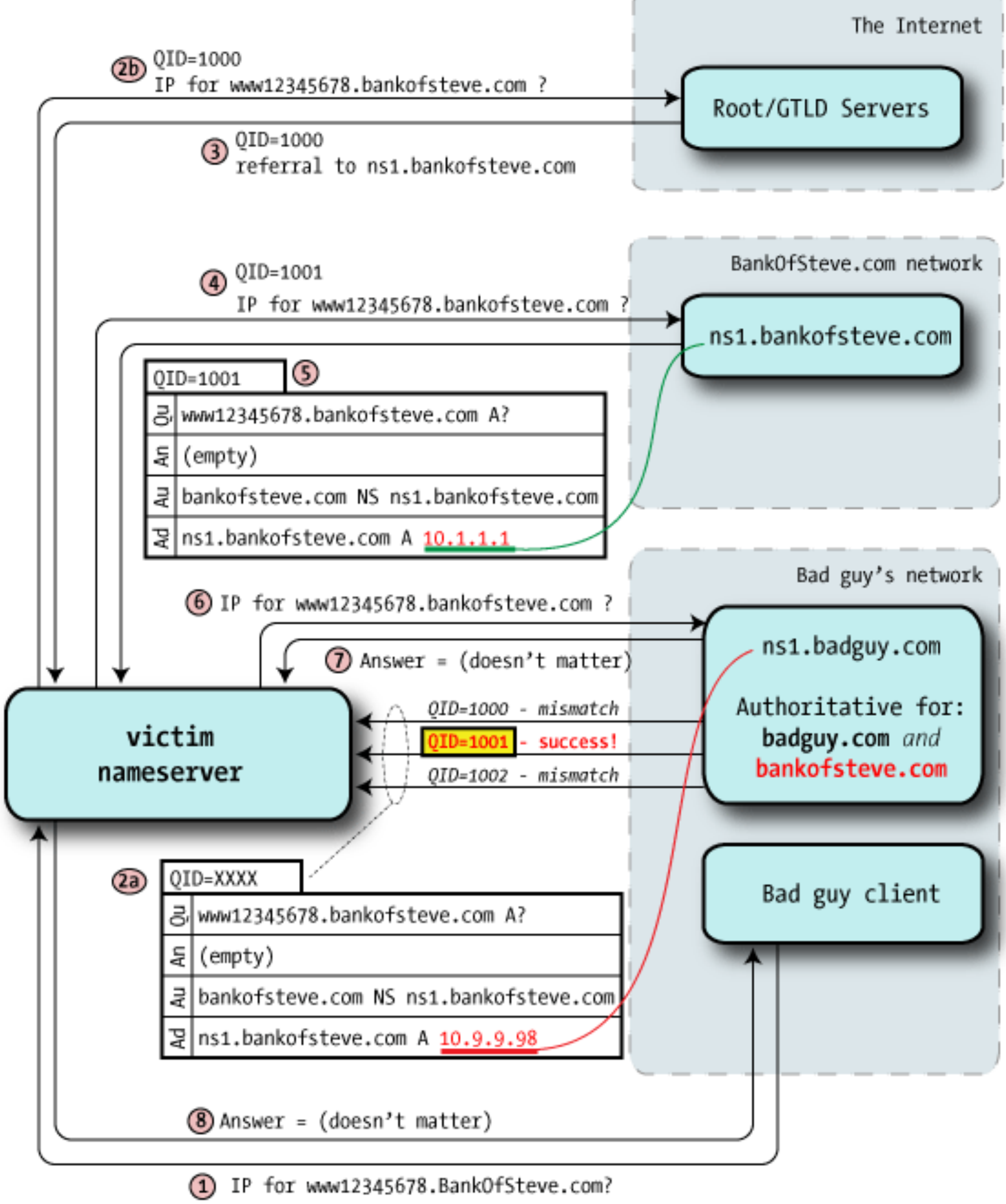
Spoofed small queries

Amplified responses

Victim

Open recursive DNS resolvers

- DNS Cache Poisoning Attacks



The Internet

Root/GTLD Servers

2b QID=1000
IP for www12345678.bankofsteve.com ?

3 QID=1000
referral to ns1.bankofsteve.com

BankOfSteve.com network

ns1.bankofsteve.com

4 QID=1001
IP for www12345678.bankofsteve.com ?

5 QID=1001

Qu	www12345678.bankofsteve.com A?
An	(empty)
Au	bankofsteve.com NS ns1.bankofsteve.com
Ad	ns1.bankofsteve.com A 10.1.1.1

Bad guy's network

6 IP for www12345678.bankofsteve.com ?

7 Answer = (doesn't matter)

ns1.badguy.com

Authoritative for:
badguy.com *and*
bankofsteve.com

QID=1000 - mismatch

QID=1001 - success!

QID=1002 - mismatch

victim
nameserver

Bad guy client

2a QID=XXXX

Qu	www12345678.bankofsteve.com A?
An	(empty)
Au	bankofsteve.com NS ns1.bankofsteve.com
Ad	ns1.bankofsteve.com A 10.9.9.98

8 Answer = (doesn't matter)

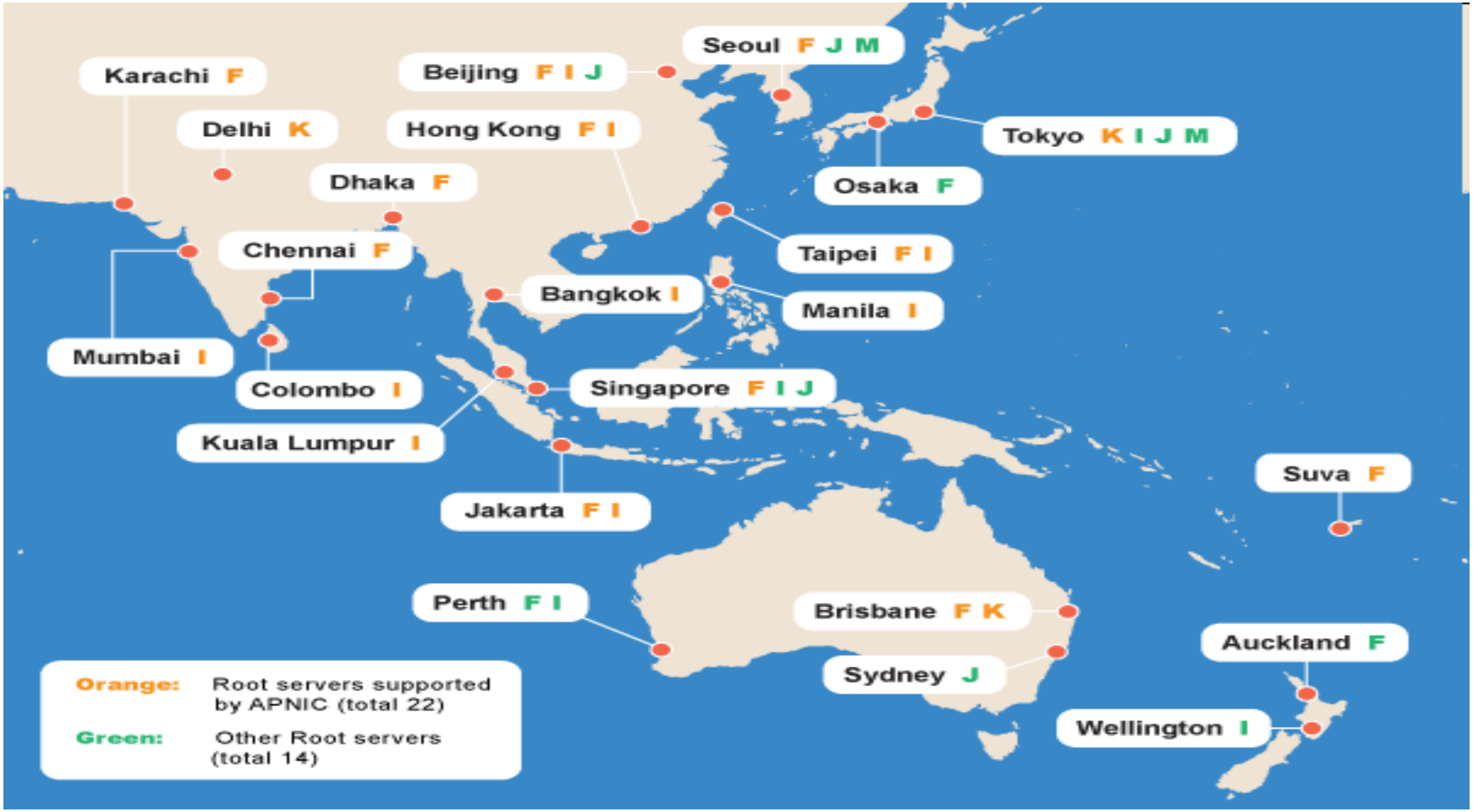
1 IP for www12345678.BankOfSteve.com?

Recent DNS news

When DNS goes bad

- China’s firewall goes global
  - http://www.computersolutions.cn/blog/2010/03/when-dns-goes-bad-chinas-firewall-goes-global-crossing/#more-416

- One of the I root servers is operated in China
- I root servers are announced via anycast
  - Swedish company NetNod (aka Autonomica) has a DNS root server in China – I.ROOT-SERVERS.NET / 192.36.148.17
  - China’s server is announced via BGP
  - Other ISPs used it


Karachi F
Beijing F I J
Seoul F J M
Delhi K
Hong Kong F I
Tokyo K I J M
Osaka F
Dhaka F
Taipei F I
Chennai F
Bangkok I
Manila I
Mumbai I
Colombo I
Singapore F I J
Kuala Lumpur I
Jakarta F I
Suva F
Perth F I
Brisbane F K
Auckland F
Sydney J
Wellington I
Orange: Root servers supported by APNIC (total 22)
Green: Other Root servers (total 14)

Conclusion

- DNS

- DNS and Content Distribution Networks

- DNS attacks