Computer Networks

EDA387/DIT663

Domain Name System (DNS)

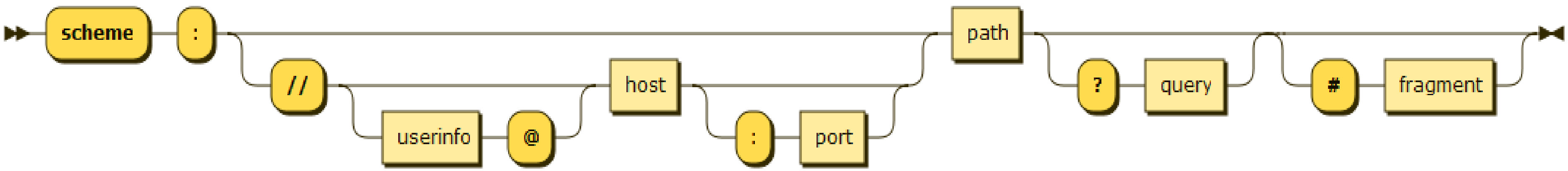
Many slides are barrowed from Philip Levis and David Mazieres and some slides are barrowed from Ali Salehson

Outline

- DNS architecture
- DNS protocol and resource records (RRs)
- Record types: A, NS, glue, MX, SOA, CNAME
- Reverse lookup
- Load balancing
- DNS security

Parsing a URL

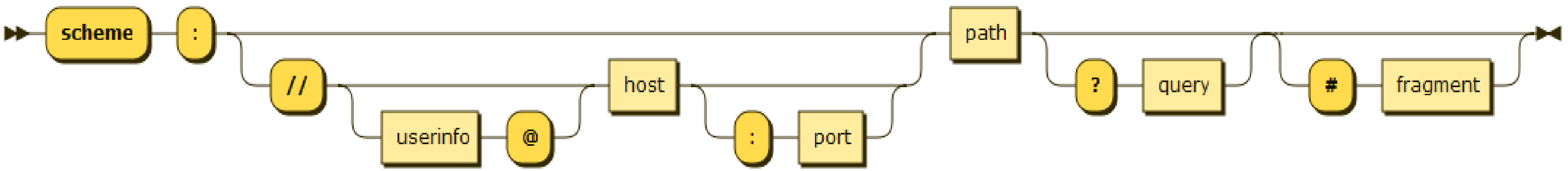
https://www.example.com/state/city.html



- Scheme: http, https, ftp, mailto, file, data, irc etc.
- Query: a string of non-hierarchical data
- The fragment identifier directs to a secondary resource, e.g., section heading in the page

Parsing a URL

https://www.93.184.216.34.com/state/city.html



- Scheme: http, https, ftp, mailto, file, data, irc etc.
- Query: a string of non-hierarchical data
- The fragment identifier directs to a secondary resource, e.g., section heading in the page

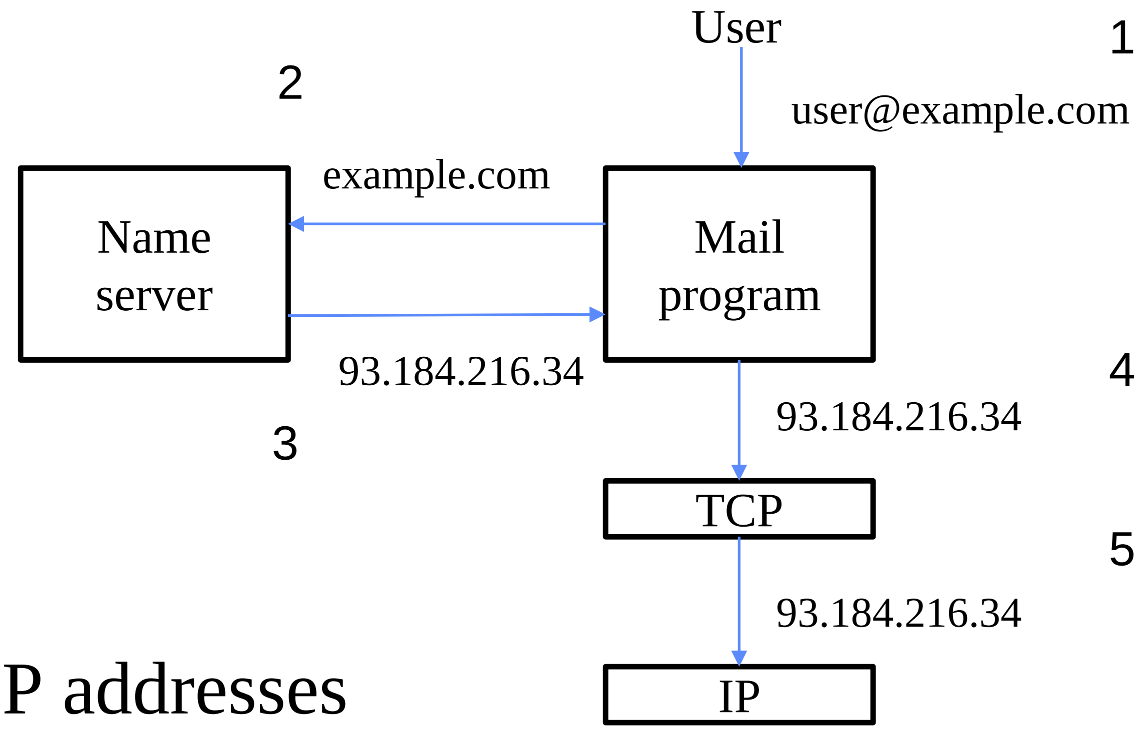
How do we find the address?

```
[elad@remote11 ~]$ nslookup www.example.com
Server:         127.0.0.1
Address:        127.0.0.1#53

Non-authoritative answer:
Name:   www.example.com
Address: 93.184.216.34
Name:   www.example.com
Address: 2606:2800:220:1:248:1893:25c8:1946

[elad@remote11 ~]$
```

Motivation



- Hard to remember IP addresses
  - Need to map symbolic names to IP addresses
- Implemented by library functions and servers
  - getaddrinfo() talks to server over UDP (or TCP)
- Actually, more generally, need to map symbolic names to values

hosts.txt system

- Originally, hosts were listed in a file, hosts.txt
  - Email global network administrator when you add a host
  - Administrator mails out new hosts.txt file every few days
  - Maintained at SR:SRI-NIC.ARPA, 26.0.0.73 (RFC952)
  - Hosts periodically used FTP for downloading updates
- Would be completely impractical today
  - hosts.txt today would be huge (Gigabytes)
  - What if two people wanted to add same name?
  - Who is authorized to change address of a name?
  - People need to change name mappings more often than every few days (e.g., Dynamic IP addresses)

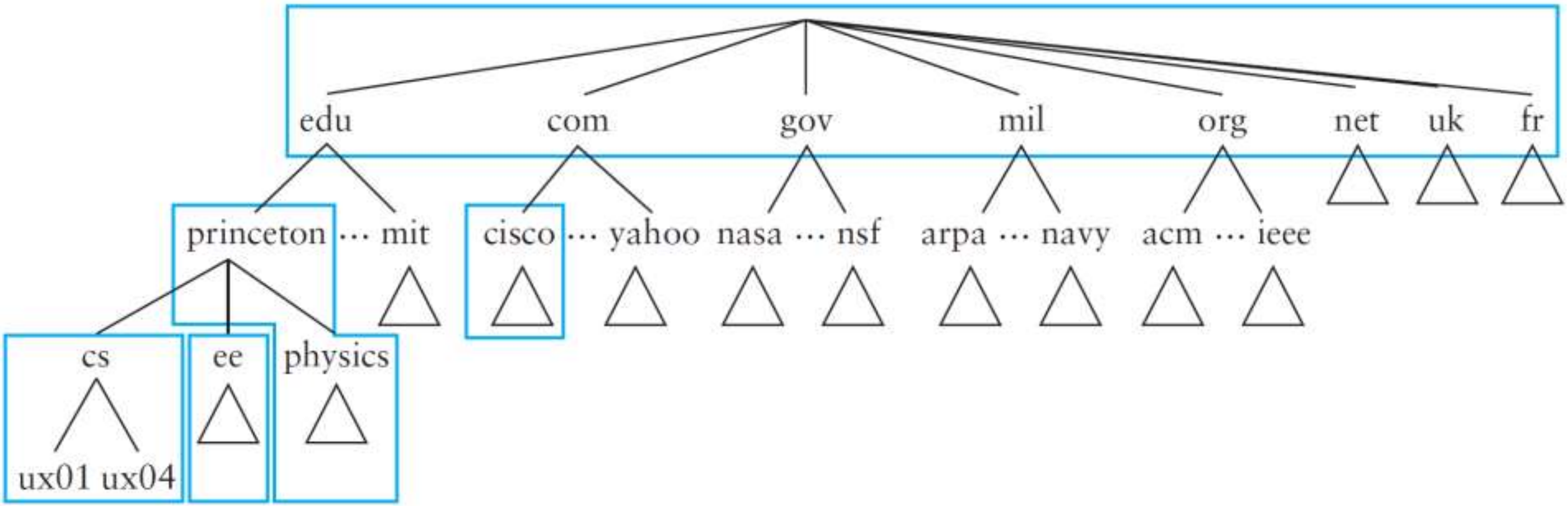
Goals of DNS

- Scalability
  - Must handle huge number of records
  - Potentially exponential in name size—because custom software may synthesize names on-the-fly
- Distributed control
  - Let people control their own names
- Fault-tolerance
  - Old software assumed hosts.txt always there
  - Bad potential failure modes when name lookups fail
  - Minimize lookup failures in the face of other network problems

The good news

- Properties that make DNS goals easier to achieve:
  1. Read-only or read-mostly database
  - People typically look up hostnames much more often than they are updated
  2. Loose consistency
  - When adding a machine, may be okay if info takes minutes or hours to propagate
- These suggest approach w. aggressive caching
  - Once you have looked up hostname, remember result
  - Don't need to look it up again in near future

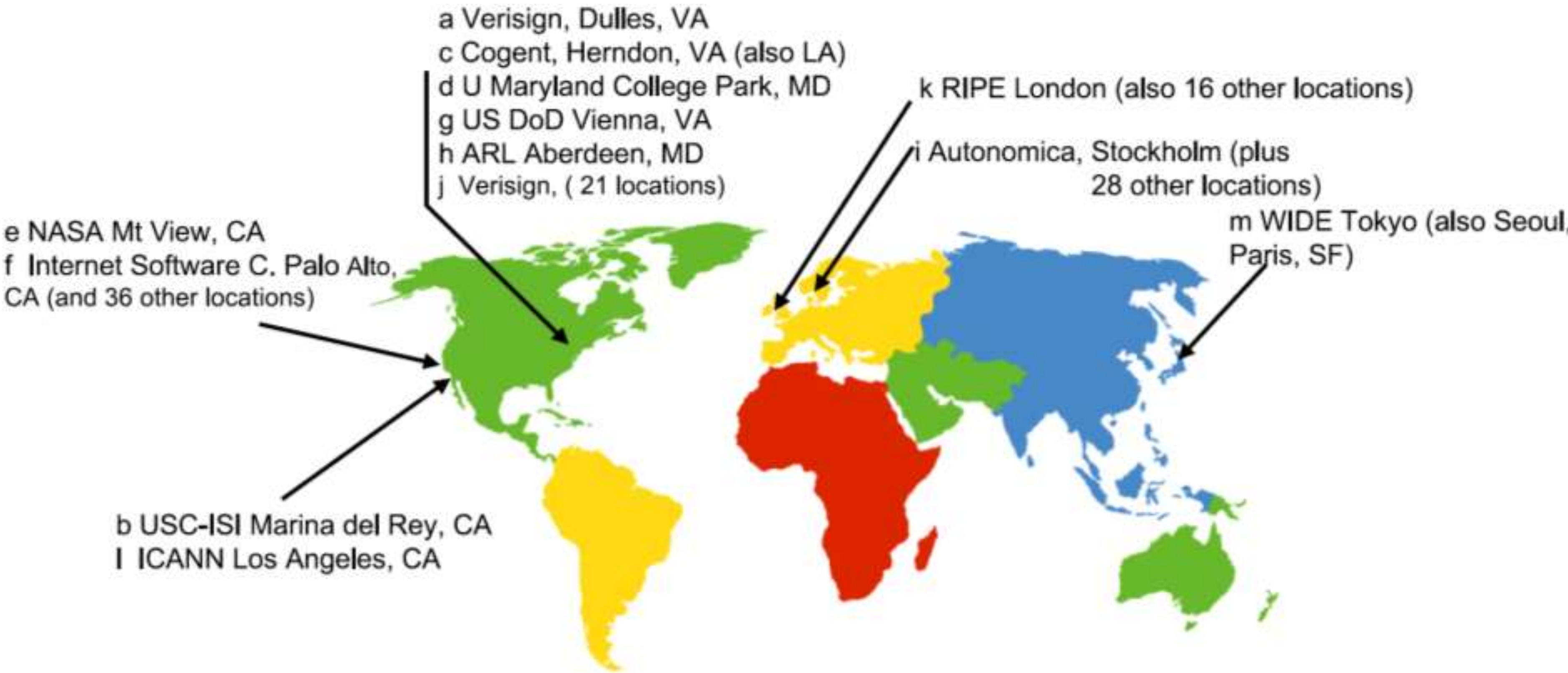
Domain Name System (DNS)



- **Break namespace into a bunch of zones**
  - . (“root”), .se, chalmers.se, ...
  - Zones separately administered => delegation
  - Parent zones tell you how to find servers for dubdomains.

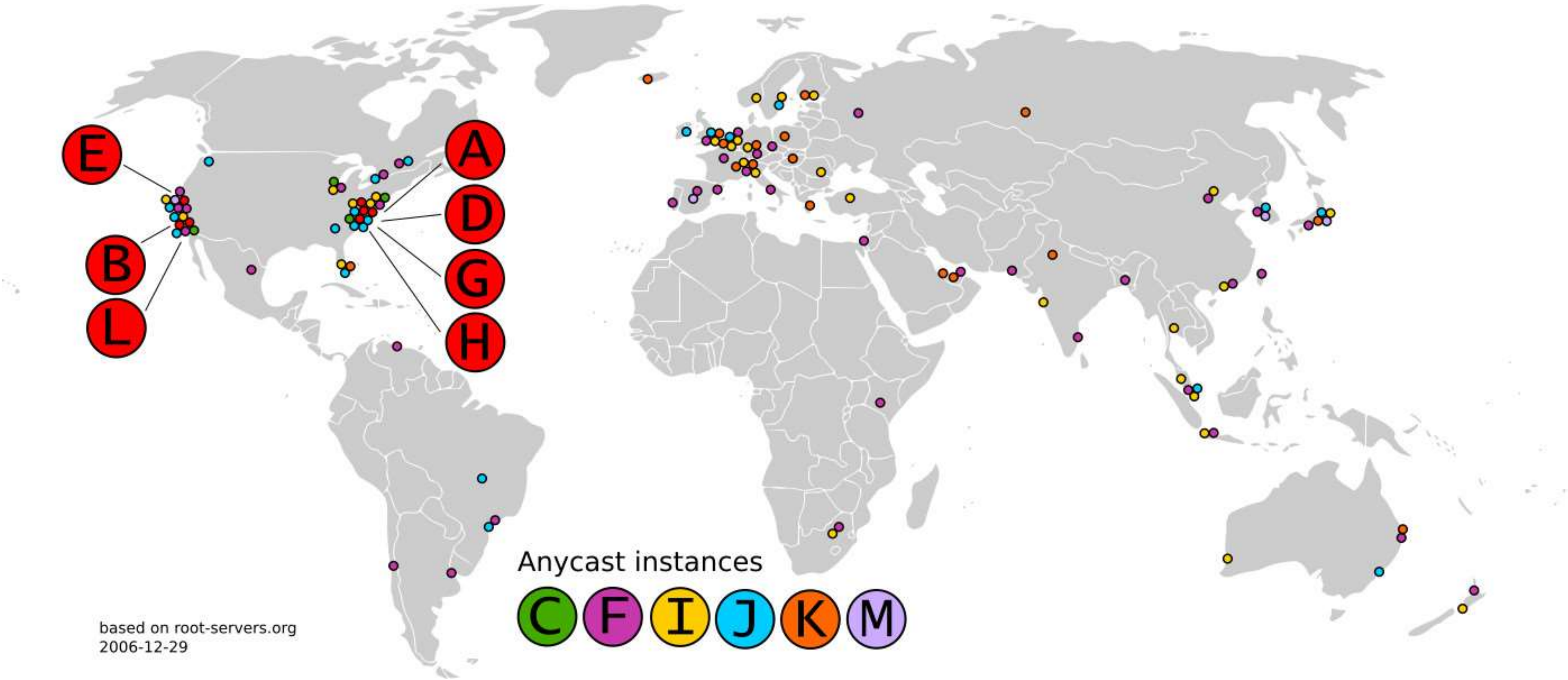
- **Each zone served from several replicated servers**

Root servers



- Root (and TLD) servers must be widely replicated
  - For some, use various tricks like IP anycast

Root servers

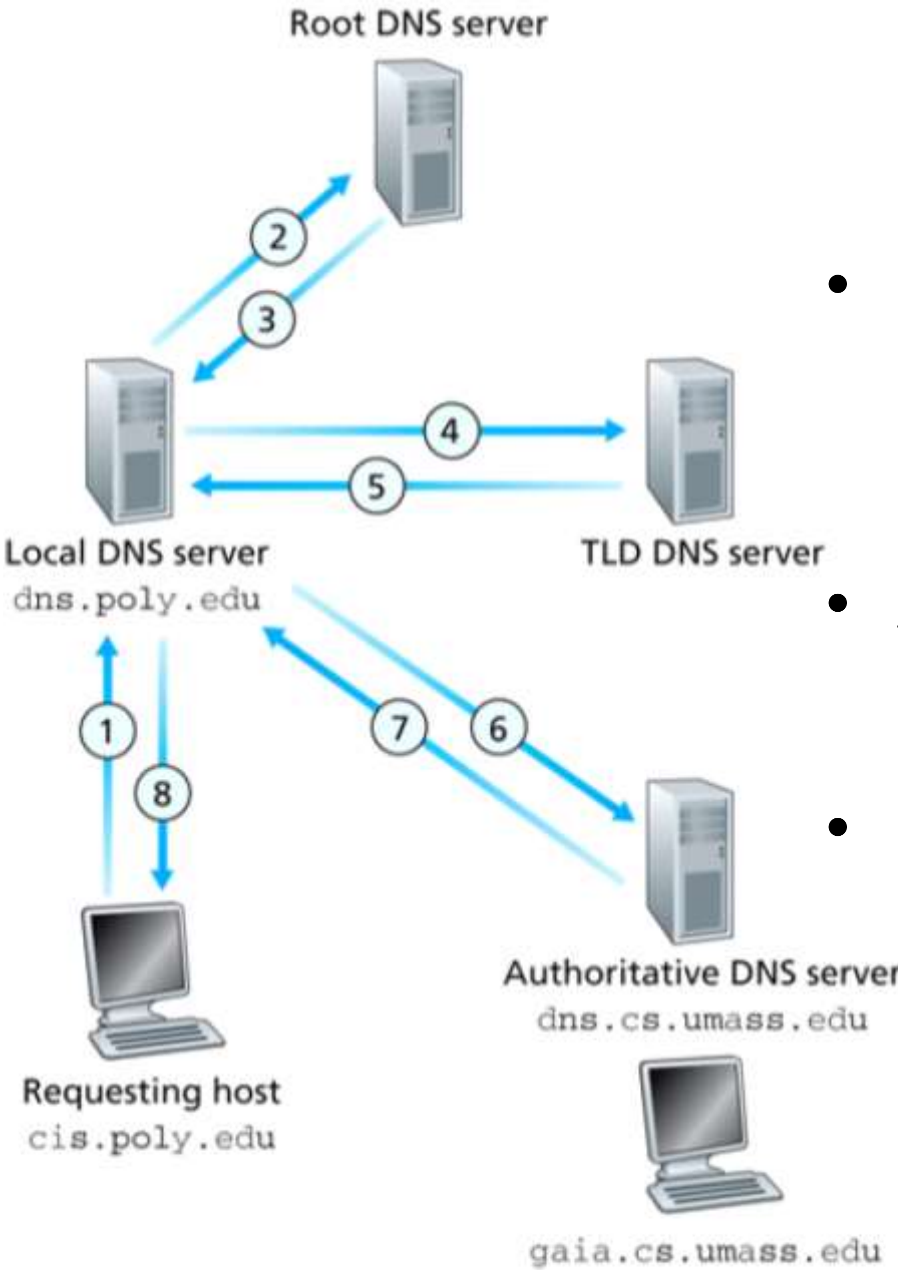


- Root (and TLD) servers must be widely replicated
  - For some, use various tricks like IP anycast

Root servers

```
;; QUESTION SECTION:
;.                          IN      NS
;; ANSWER SECTION:
.               139826      IN      NS      e.root-servers.net.
.               139826      IN      NS      k.root-servers.net.
.               139826      IN      NS      j.root-servers.net.
.               139826      IN      NS      a.root-servers.net.
.               139826      IN      NS      h.root-servers.net.
.               139826      IN      NS      i.root-servers.net.
.               139826      IN      NS      g.root-servers.net.
.               139826      IN      NS      m.root-servers.net.
.               139826      IN      NS      b.root-servers.net.
.               139826      IN      NS      l.root-servers.net.
.               139826      IN      NS      f.root-servers.net.
.               139826      IN      NS      c.root-servers.net.
.               139826      IN      NS      d.root-servers.net.
;; ADDITIONAL SECTION:
a.root-servers.net.   337865  IN   A      198.41.0.4
a.root-servers.net.   3717    IN   AAAA   2001:503:ba3e::2:30
b.root-servers.net.   350299  IN   A      192.228.79.201
c.root-servers.net.   350299  IN   A      192.33.4.12
d.root-servers.net.   350299  IN   A      128.8.10.90
d.root-servers.net.   3717    IN   AAAA   2001:500:2d::d
e.root-servers.net.   350299  IN   A      192.203.230.10
f.root-servers.net.   350299  IN   A      192.5.5.241
f.root-servers.net.   3717    IN   AAAA   2001:500:2f::f
g.root-servers.net.   350299  IN   A      192.112.36.4
h.root-servers.net.   350299  IN   A      128.63.2.53
h.root-servers.net.   3717    IN   AAAA   2001:500:1::803f:235
i.root-servers.net.   350299  IN   A      192.36.148.17
i.root-servers.net.   3717    IN   AAAA   2001:7fe::53
```

DNS architecture

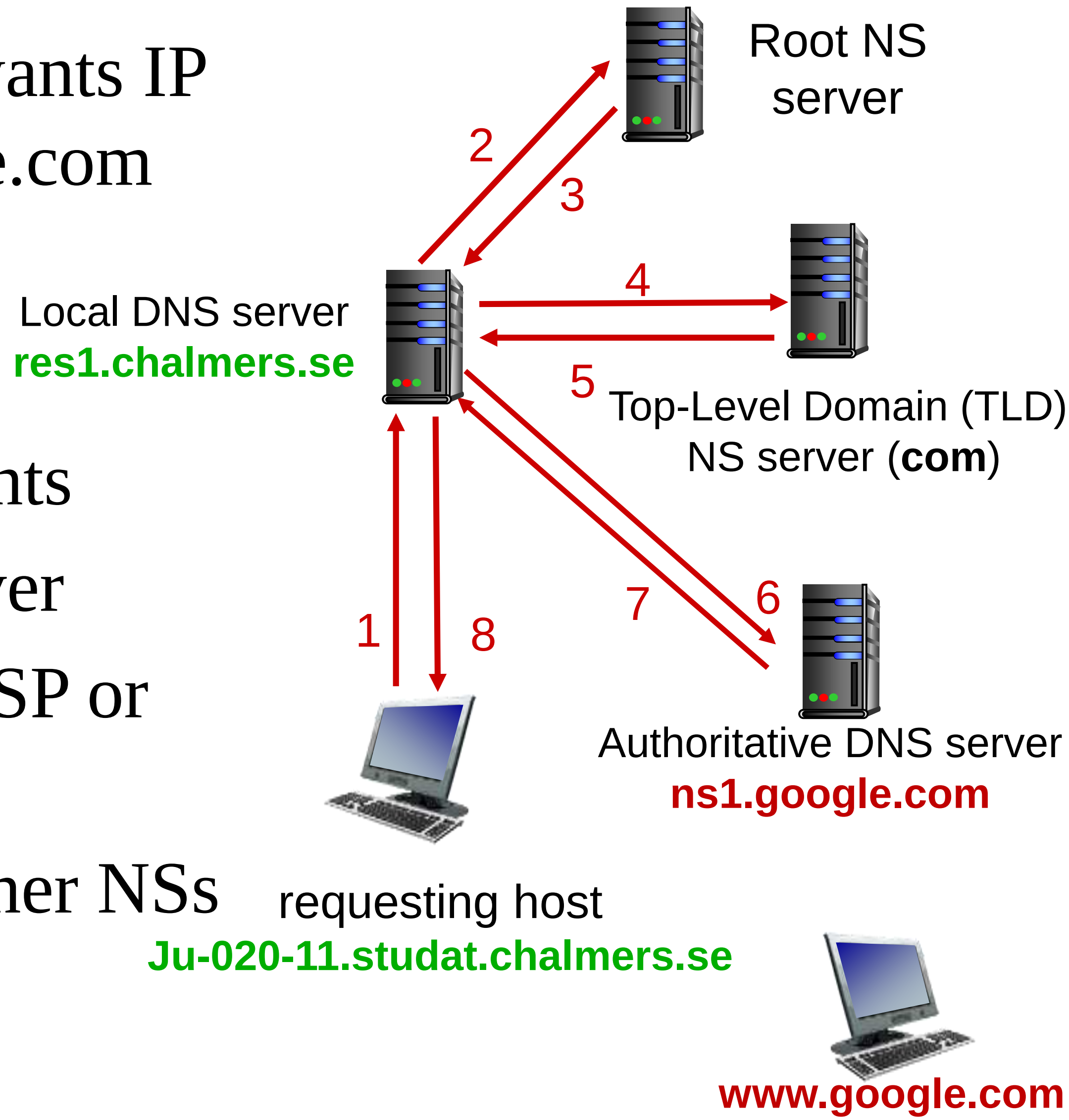


- Two types of query
  - Recursive
  - Non-Recursive
- Apps make recursive queries to local DNS server (1)
- Local server queries remote servers non-recursively (2, 4, 6)
  - Aggressively caches result
  - E.g., only contact root on first query ending .umass.edu

DNS Queries and Answers

- Host in “chalmers.se” wants IP address for www.google.com

- A local name server
  - acts as proxy for clients
  - often cache-only server
  - normally owned by ISP or organization
  - sends questions to other NSs in hierarchy



DNS protocol

- TCP/UDP port 53
- Most traffic uses UDP
  - Lightweight protocol has 512 byte UDP message limit
  - retry w. TCP if UDP fails (e.g., reply truncated)
- TCP requires message boundaries
  - Prefix all messages w. 16-bit length
- Bit in query determines if query is recursive

Resource records

- All DNS info represented as resource records (RR):

name [TTL] [*class*] *type rdata*

  - name – domain name (e.g., www.chalmers.se.)
  - TTL – time to live in seconds
  - class – for extensibility, usually IN (1) “Internet”
  - type – type of the record
  - rdata – resource data dependent on the type

- Two important DNS RR types:
  - A – Internet address (IPv4)
  - NS – name server

- Examples resource records:

dig chalmers.se:

```
chalmers.se.        6392   IN    A     129.16.71.10
```

dig res1.chalmers.se:

```
res1.chalmers.se.    5290   IN    A     129.16.1.53
```

Some implementation details

- How does local name server know root servers?
  - Need to configure name server with root cache file
  - Contains root name servers and their addresses

```
.                     3600000 NS A.ROOT-SERVERS.NET.
A.ROOT-SERVERS.NET. 3600000 A   198.41.0.4
.                     3600000 NS B.ROOT-SERVERS.NET.
B.ROOT-SERVERS.NET. 3600000 A  128.9.0.107
...
```

Some implementation details

- How do you get addresses of other name servers
  - To lookup names ending .chalmers.se., ask
  - res1.chalmers.se.
  - Chicken and egg problem:

  How to get res1.chalmers.se.'s address?
  - Solution: glue records – A records in parent zone
  - Name servers for se. have A record of res1.chalmers.se.

Glue Record Example

- Look up www.cse.chalmers.se assuming no cache

  dig +norec www.cse.chalmers.se @a.root-servers.net

  dig +norec www.cse.chalmers.se @a.ns.se

  dig +norec www.cse.chalmers.se @ns1.chalmers.se

- Get intermediary results for .se, chalmers.se, cse.chalmers.se, and www.cse.chalmers.se

- Where are the glue records?

  The Glue records can be seen **under the “Additional Section” of a DNS Response**. In the DNS Resolution process, the authoritative nameservers for yourdomain.com are ns1.yourdomain.com and ns2.yourdomain.com.
  referance: google.com

Structure of a DNS message [RFC 1035]

```
+---------------------+
|        Header       |
+---------------------+
|       Question      | the question for the name server
+---------------------+
|        Answer       | RRs answering the question
+---------------------+
|       Authority     | RRs pointing toward an authority
+---------------------+
|      Additional     | RRs holding additional information
+---------------------+
```

- Same message format for queries and replies
  - Query has zero RRs in Answer/Authority/Additional sections
  - Reply includes question, plus has RRs
- Authority allows for delegation
- Additional for glue + other RRs client might need

Header format

```
+---------------------+
|        Header       |
+---------------------+
|       Question      |
+---------------------+
|        Answer       |
+---------------------+
|      Authority      |
+---------------------+
|      Additional     |
+---------------------+
```

```
                                1  1  1  1  1  1
  0  1  2  3  4  5  6  7  8  9  0  1  2  3  4  5
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                      ID                       |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|QR|   Opcode  |AA|TC|RD|RA|   Z    |   RCODE   |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                    QDCOUNT                    |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                    ANCOUNT                    |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                    NSCOUNT                    |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                    ARCOUNT                    |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
```

- QR – 0=query, 1=response
- OPCODE - 0=standard query
- RCODE – error code
- AA=authoritative answer, TC=truncated,
- RD=recursion desired, RA=recursion available

Encoding of RRs

```
+---------------------+
|        Header       |
+---------------------+
|       Question      |
+---------------------+
|        Answer       |
+---------------------+
|      Authority      |
+---------------------+
|      Additional     |
+---------------------+
```

```
                                1  1  1  1  1  1
  0  1  2  3  4  5  6  7  8  9  0  1  2  3  4  5
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                                               |
/                                               /
/                      NAME                     /
|                                               |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                      TYPE                     |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                     CLASS                     |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                      TTL                      |
|                                               |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|                   RDLENGTH                    |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--|
/                     RDATA                     /
/                                               /
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
```

Encoding of domain names

- A DNS name consists of a series of labels
  - www.stanford.edu. has 3 labels: www, stanford, and edu
  - Labels can contain letters, digits, and “-”, but should not start or end with “-”
  - Maximum length 63 characters
  - Encoded as length byte followed by label
  - Last label always empty (zero-length) label
- Names are case insensitive
  - But server must preserve case of question in replies
  - Example: request www.sTANford.EDu, look at authority

Name compression

```
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
| 1  1|                OFFSET                   |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
```

- Observation: many common suffixes in DNS messages
  - Particularly because of case preservation rule
- Allow pointer labels to re-use suffixes
  - Recall label starts with length byte (0-63)
  - If value 0xc0 (192), subtract 0xc000 from first *two* bytes, and treat as pointer into message

Secondary servers

- Availability requires geographically disperate replicas
  - E.g., I ask MIT to serve scs.stanford.edu
- Typical setup: One master many slave servers
- How often to sync up servers? Trade-off
  - All the time => high overhead
  - Rarely => stale data
- Put trade-off under domain owner's control
  - Fields in SOA record control secondary's behavior
  - Primary can unilaterally change SOA
  - To speed propagation, primary can also notify secondary of change, providing a hint to refresh sooner [RFC 1996]

Other Records

- Start of Authority (SOA) record
  - States administrative information for a zone
  - dig stanford.edu soa
  - Tells you how long you can cache negative results
- Mail Exchange (MX) record
  - For historical reasons, mail does not have to use A records directly
  - Example: ping scs.stanford.edu
  - No such host, but you can still mail CS144 staff there
  - dig scs.stanford.edu mx

CNAME records

- CNAME record specifies an alias:

  name [TTL] [IN] CNAME *canonical-name*

  - As if any RR's associated w. canonical-name also for name
  - Can look up with AI_CANONNAME flag to getaddrinfo
- Examples, to save typing:

wb.scs.stanford.edu. CNAME williamsburg-bridge.scs.stanford.edu.

mb.scs.stanford.edu. CNAME manhattan-bridge.scs.stanford.edu.

CNAME records

- CNAME precludes any other RRs for name
  - E.g., might want: david.com CNAME david.stanford.edu
  - Illegal, because david.com would need NS records
- Note answer section can have CNAME for query name + other RR(s) for *canonical-name*
  - But don’t point MXes to CNAMEs, as no A recs in additional section (try bad-mx.scs.stanford.edu.)

Reverse Lookups

- Remember *traceroute*...
- Traceroute can learn names of hosts through *reverse lookup*
- 128.30.2.121 -> 121.2.30.128.in-addr.arpa
- PTR record points to canonical name
- Example:
  – tinyos.stanford.edu -> sing.stanford.edu
  – sing.stanford.edu -> 171.67.76.65
  – 65.76.67.171.in-addr.arpa -> sing.stanford.edu

Mapping addresses to names

- PTR records specify names

name [TTL] [IN] PTR "*ptrdname*"

  - *name* – somehow encode address… how?
  - *ptrdname* – domain name for this address
- IPv4 addrs stored under in-addr.arpa domain
  - Reverse name, append in-addr.arpa
  - To look up 171.66.3.9 => 9.3.66.171.in-addr.arpa.
  - Why reversed? Delegation!
- IPv6 under ip6.arpa
  - Historical note: ARPA funded original Internet
  - Acronym now re-purposed [RFC 3172]:
- Address and Routing Parameter Area

Using DNS for load-balancing

- Can have multiple RR of most types for one name
  - Required for NS records (for availability)
  - Useful for A records
  - (Not legal for CNAME records)
- Servers rotate order in which records returned
  - getaddrinfo returns a linked list of addrinfo structures
  - Most apps just use first address returned
  - Even if your name server caches results, clients will be spread amonst servers
- Example: dig cnn.com multiple times

SRV records

Self-study

- Service location records
- *_service._proto.name* [. . .] SRV *prio weight port target*
  - _service – E.g., sip for SIP (VOIP) protocol
  - _ proto – _tcp or _udp
  - name – domain name record applies to
  - prio – as with MX records, lower #! higher priority
  - weight – within priority, affects randomization of order
  - port – TCP or UDP port number (particularly useful for SIP)
  - target – Server name, for which client needs A record
- Like a generalization of MX records for arbitrary services

TXT records

Self-study

- Can place arbitrary text in DNS name

[TTL] [IN] TXT “text” . . .

  - text – whatever you want it to mean

- Great for prototyping new services
  - Don’t need to change DNS infrastructure

- Example: `dig gmail.com txt`
  - What’s this? SPF = “sender policy framework” (previously known as “sender permitted from”)
  - Much spam is forged email
  - SPF specifies IP addresses allowed to send mail from `@gmail.com`
  - Can have incremental deployment
  - Only mail servers must change, DNS can stay the same
  - Now SPF standardized (sort of), has RR type 99 [RFC 4408]

Editorial

Self-study

- SPF is based on envelope sender address
  - Nice because available earlier in SMTP protocol
  - So some users can reject forged mail while some accept
- Microsoft proposed competing standard, *Sender ID* [RFC 4406]
  - Instead of simple language, used XML monstrosity
  - Instead of envelope sender, extract address from message
- No agreement between camps, couldn't standardize
  - Compromise: kill XML, but use address in message
  - But Microsoft patented extracting address from message!

SPF vs. Sender ID (continued)

Self-study

- Compromise 2: Have two competing standards
  - After a few years, see which standard more widely used
- Use different formats for SPF vs. Sender ID
  - Start SPF records with string "`v=spf1`"
  - Start Sender ID records with string "`spf2.0/pra`"
- SPF had a head start—lots of sites had adopted it
- Dirty trick appeared in final draft of Sender ID
  - If no `spf2.0/pra` record present, but see `v=spf1, treat v=spf1` as if it were a sender ID record
  - Causes sender ID machines to reject mail from SPF sites

  (E.g., if you use SPF and post to mailing list, some recipients will reject)
  - Thwarts idea of independent experiment

DNS redirection for content distribution

Self-study

Play with akamai and www.microsoft.com

Classless `in-addr` delegation

Self-study

- How to delegate on non-byte boundary?
- Solution: Use CNAME records
  - So-called *classless* in-addr delegation
- Example:

```
1.3.66.171.in-addr.arpa. CNAME 1.ptr.your-domain.com.
2.3.66.171.in-addr.arpa. CNAME 2.ptr.your-domain.com.
3.3.66.171.in-addr.arpa. CNAME 3.ptr.your-domain.com.
```

DNS exploits

Self-study

- July 29, 2008, Bruce Scnheier:

  Despite the best efforts of the security community, the details of a critical internet vulnerability discovered by Dan Kaminsky about six months ago have leaked.

- One of the basic problems: DNS caching
  - \- If you can poison the cache, the damage stays
  - \- Who knows how far it spreads...

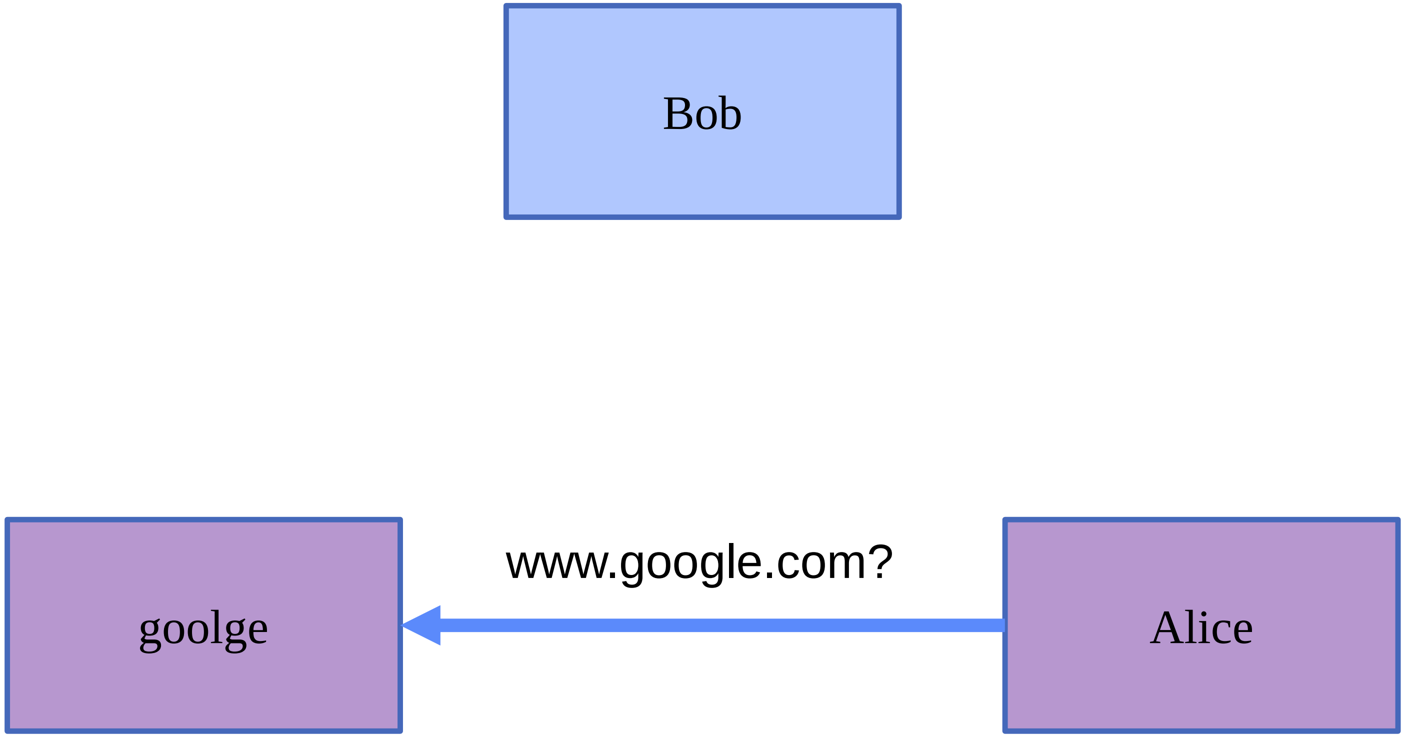
DNS exploit example

Self-study

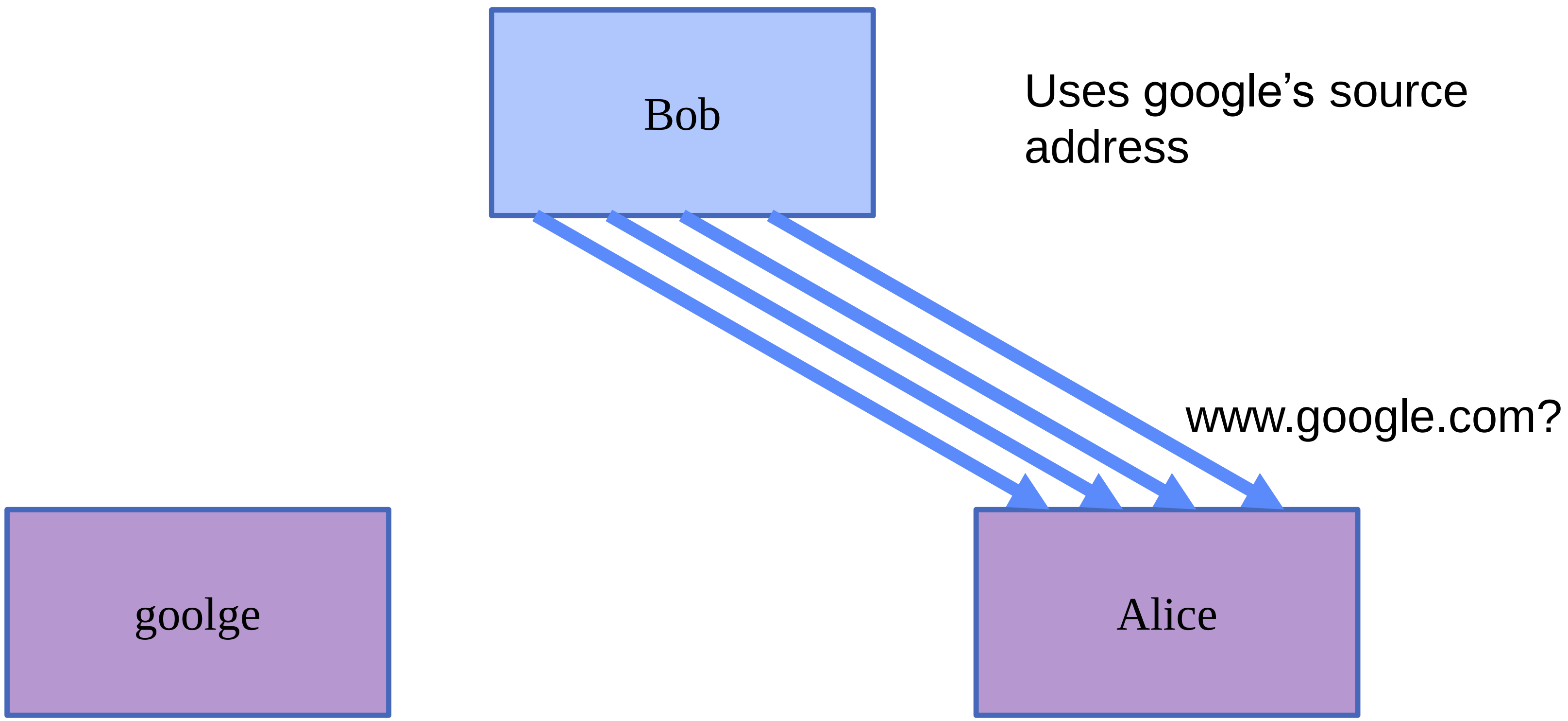
- Alice wants to look up `www.google.com`
- Bob the attacker knows
- Bob knows source address/port, destination address/port
- Bob generates a spoof response: `www.google.com` is `www.evil.com`
- Challenge: Bob has to guess Query ID
- If Bob guesses, RR can stay in Alice's cache a long time

Exploit Example

Self-study



Exploit Example



Countermeasures

Self-study

- Choose good QIDs (used to be incremented, now randomly generated), 16 bits
- Randomize source port, 16 bits
- Some protection, but only makes it take longer, networks are faster each day

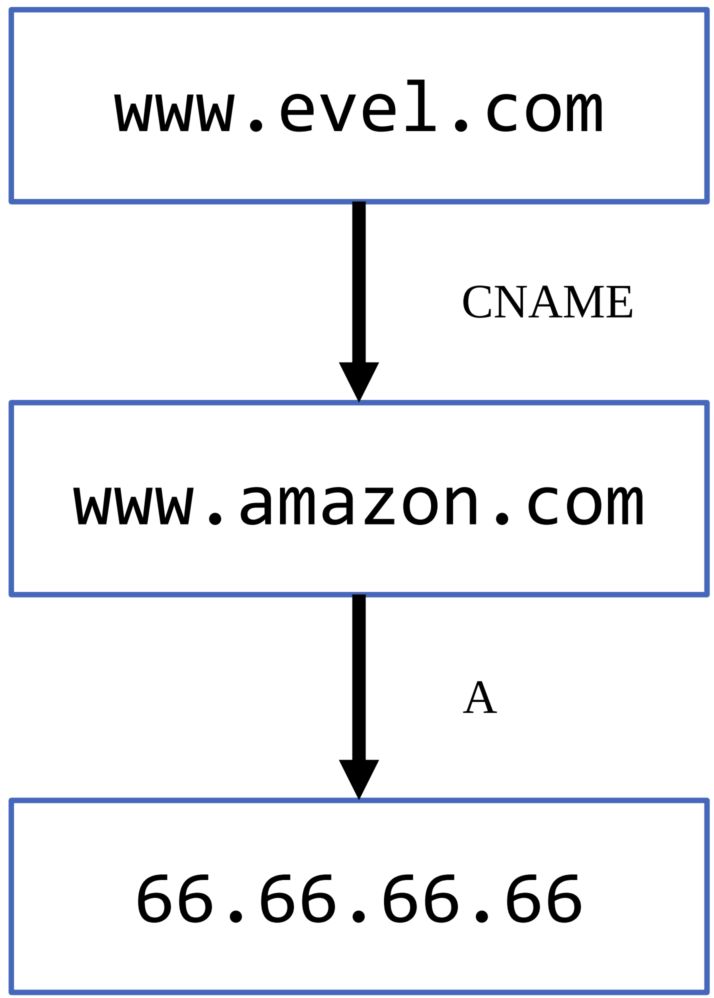
Another exploit

Self-study

- DNS clients used to trust all responses
- Problem: glue records and helpful A records
  - Ask NS of `evil.com` for `www.evil.com`
  - Says www.evil.com is a CNAME for www.amazon.com
  - Provides A record for `www.amazon.com`

Exploit Example

Self-study



It gets worse

Self-study

- Glue records can overwrite standard A records
- Even if you have a good A record for `www.amazon.com`, it's overwritten
- E.g., Server wants name of my IP address
  - Looks up `66.66.66.66.in-addr.arpa`
- I say nameserver for `66.66.66.66.in-addr.arpa` is `www.amazon.com`
  - Include glue A record for www.amazon.com in my reply

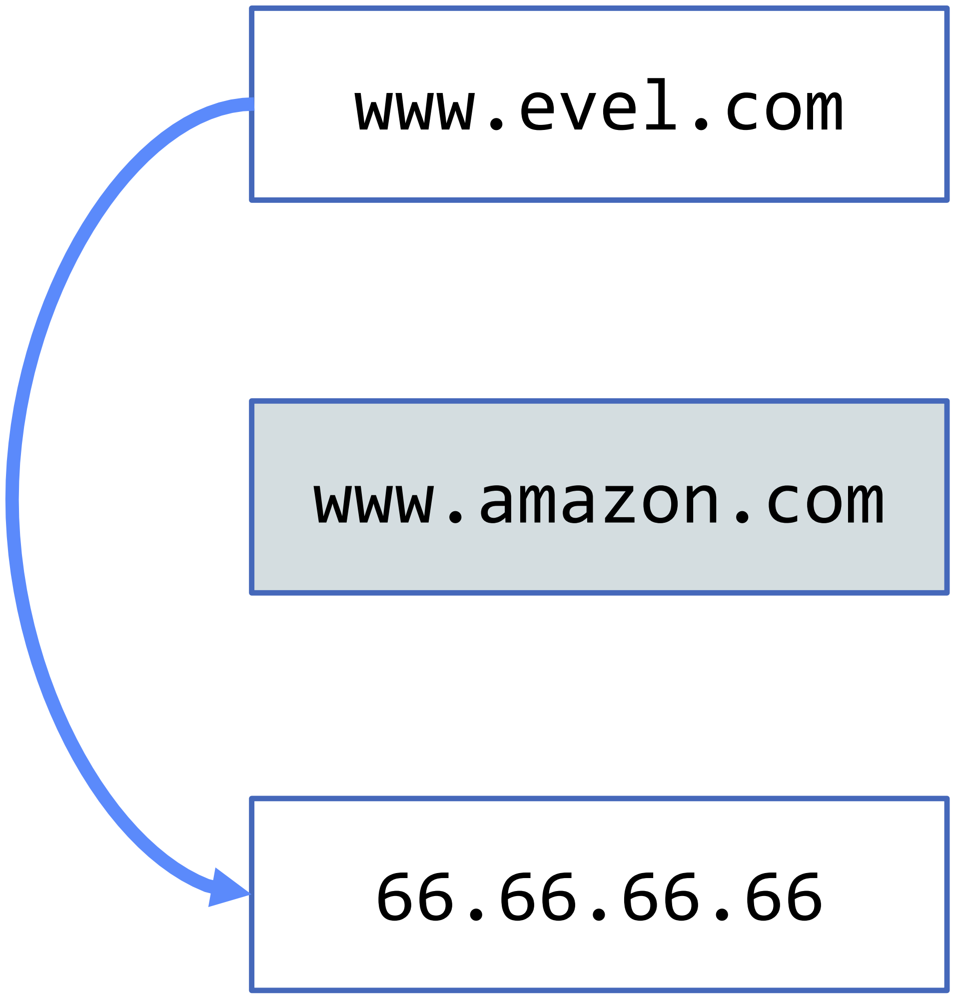
Solution 1

Self-study

- Only use glue records for duration of query
  - Cache only end-to-end traversal of pointers, not intermediate steps
- In CNAME example `www.evil.com` will point to evil server
  - `www.amazon.com` will not point to evil server
- In `in-addr.arpa` example, can lie about hostname
  - But I can lie anyway
  - Have to check reverse lookup result by doing forward lookup

Self-study

Example



Solution 2: bailiwick checking

Self-study

- Only pay attention to answers for the domain you've asked
- Response from `evil.com` can't tell you the A record for `google.com`
- Ask google.com for `www.google.com`
- Opponent can still race, but at least it's not deterministic

Kaminsky exploit

Self-study

- Make winning the race easier
- Brute force attack
- Force Alice to look up `AAAA.google.com`, `AAAB.google.com`, etc.
- Forge CNAME responses for each lookup, inserting A record for `www.google.com`
- Circumvents bailiwick checking

Solution: signatures

Self-study

- Signature: cryptographic way to prove a party is who they say they are (more later in quarter)
- Requires a chain of trust
- Whom do you trust to sign DNS?
- DNSSEC extensions may finally be deployed soon [RFC 4033]

DNS Summary

Self-study

- Distributed system for mapping names to values (e.g., IP addresses)
- Read-dominated workload allows caching
- Name structure allows distribution, independent administration
- Caching means bad data can stay a long time
- Standard protocol does not authenticate response is from server: DNSSec does