EECS 489
Computer Networks

Winter 2025

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Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.

Agenda

- CDN: Content Distribution Network
- DNS: Domain Name System

Caching

- Exploits locality of reference
- Works well for popular content
  - Not so much for unique requests
    - Effectiveness of caching grows logarithmically with size

Caching: How

- Modifier to GET requests:
  - `If-modified-since` – returns "not modified" if resource not modified since specified time

```
GET /somedir/page.html HTTP/1.1
Host: www.someschool.edu
User-agent: Mozilla/4.0
If-modified-since: Wed, 18 Jan 2017 10:25:50 GMT
(blank line)
```

Caching: How

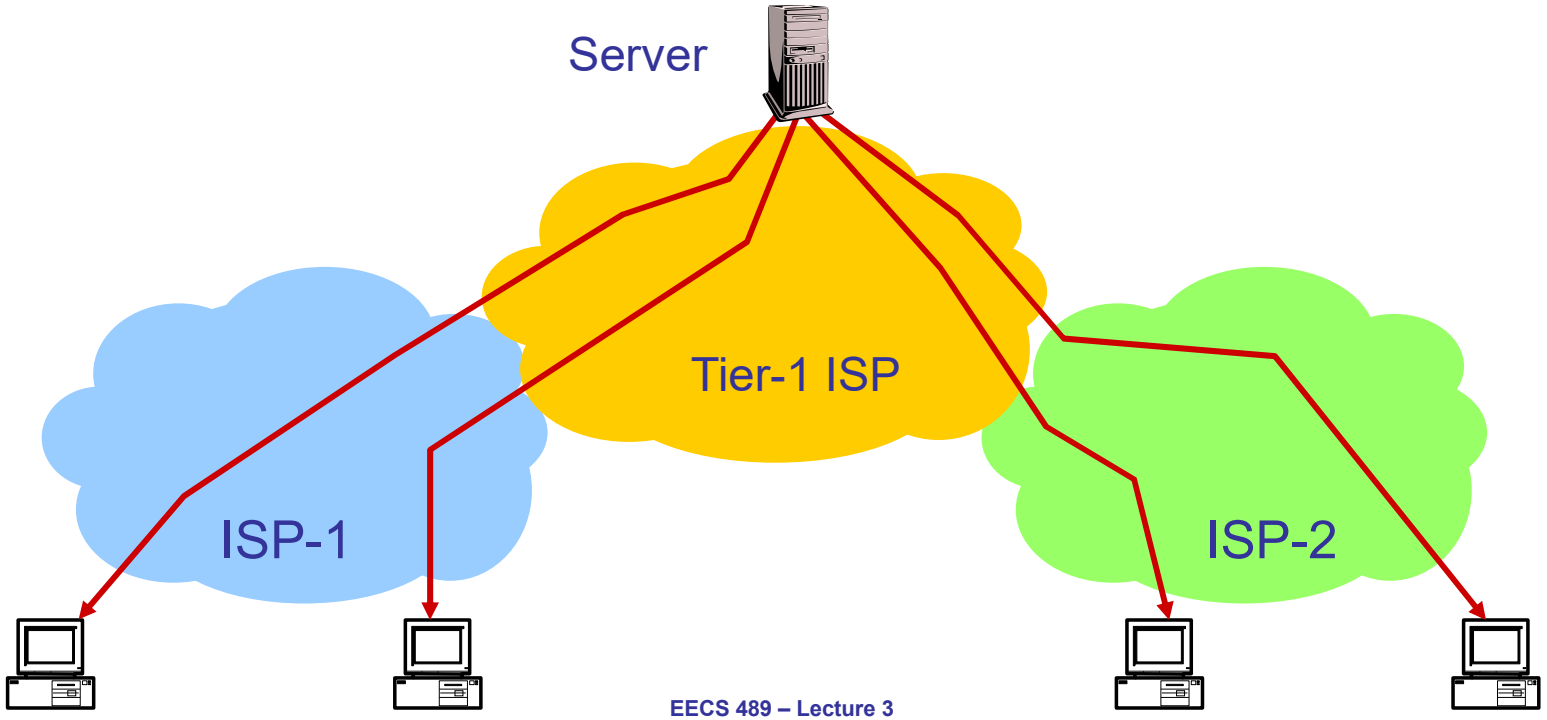
- Modifier to GET requests:
  - `If-modified-since` – returns "not modified" if resource not modified since specified time
- Response header:
  - `Expires` – how long it's safe to cache the resource
  - `No-cache` – ignore all caches; always get resource directly from server

Caching: Where?

- Options
  - Client (browser)
  - Forward proxies
  - Reverse proxies
  - Content Distribution Network

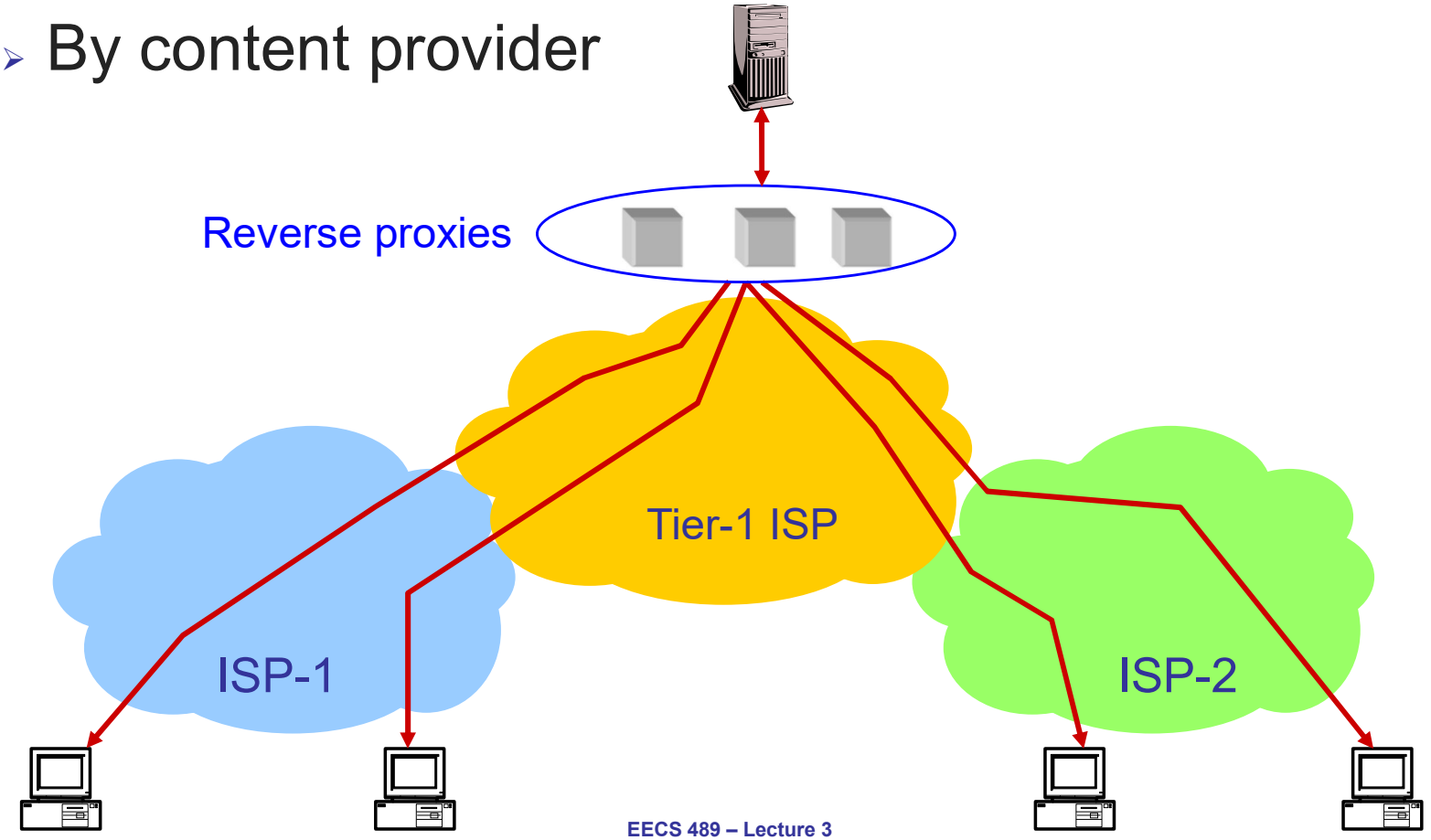
Caching: Where?

- Many clients transfer same information
  - Generate unnecessary server and network load
  - Clients experience unnecessary latency



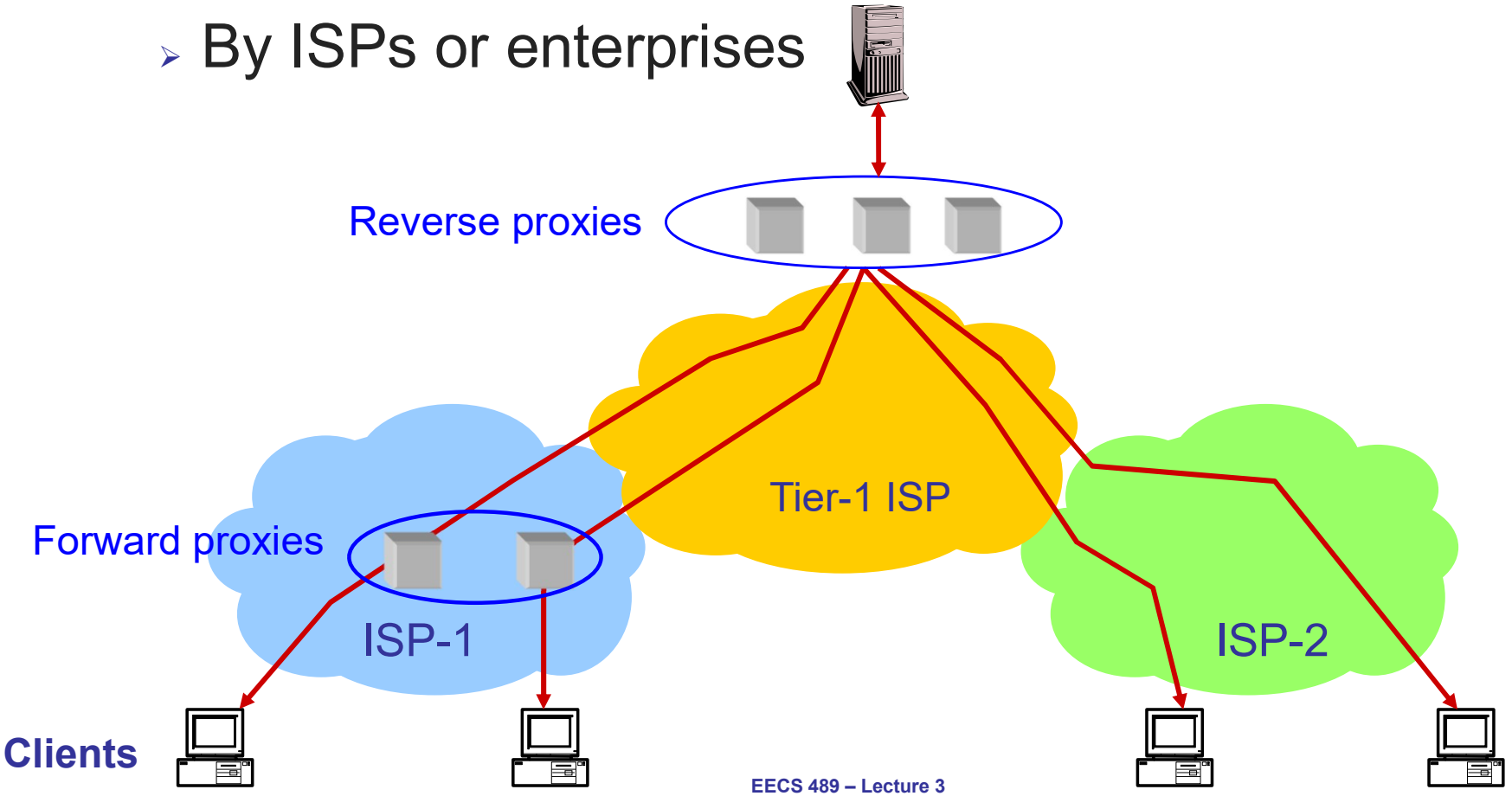
Caching with Reverse Proxies

- Cache documents close to server
  - Decrease server load
  - By content provider



Caching with Forward Proxies

- Cache documents close to clients
  - Reduce network traffic and decrease latency
  - By ISPs or enterprises



Replication

- Replicate popular Websites across many machines
  - Balance load across servers
  - Pairing clients with nearby servers to decrease latency and overall bandwidth usage
  - Helps when content isn't cacheable

Content Distribution Networks (CDN)

- Caching and replication as a service
  - Pull: Direct result of clients' requests (caching)
  - Push: Expectation of high access rate (replication)

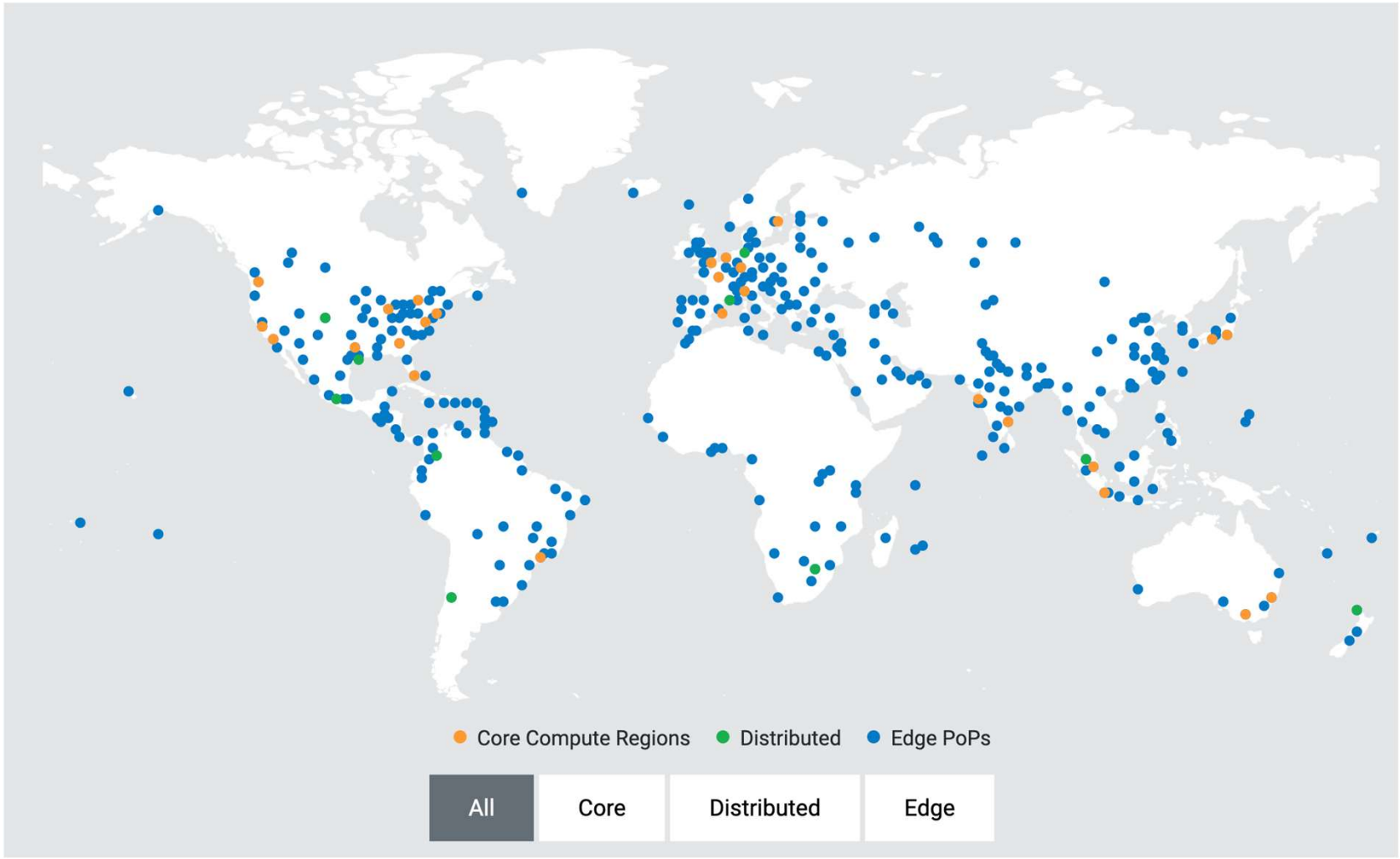
- Large-scale distributed storage infrastructure (usually) administered by one entity
  - e.g., Akamai is in 130 countries and 1200+ networks

- Economies of scale → Statistical multiplexing

CDN example – Akamai

- Akamai creates new domain names for each client
  - e.g., a128.g.akamai.net for cnn.com
- The client content provider modifies content so that embedded URLs reference new domains
  - "Akamaize" content
  - e.g., http://www.cnn.com/image-of-the-day.gif becomes http://a128.g.akamai.net/image-of-the-day.gif
- Requests now sent to CDN's infrastructure

CDN example – Akamai



Retrieved on Jan 18, 2025 from https://www.akamai.com/why-akamai/global-infrastructure

DNS: DOMAIN NAME SYSTEM

Internet names & addresses

- Machine addresses: e.g., 141.212.113.143
  - Router-usable labels for machines
  - Conforms to network structure (the "where")
- Machine names: e.g., cse.umich.edu
  - Human-usable labels for machines
  - Conforms to organizational structure (the "who")
- The Domain Name System (DNS) is how we map from one to the other
  - A directory service

Why?

- Convenience
  - Easier to remember
- Provides a level of indirection!
  - Decoupled names from addresses
  - Many uses beyond just naming a specific host

DNS: History

- Initially all host-address mappings were in a `hosts.txt` file (in `/etc/hosts`):
  - Maintained by the Stanford Research Institute (SRI)
  - Changes were submitted by email and updates downloaded periodically from SRI
- As the Internet grew SRI could not handle load
  - Names were not unique anymore
  - Hosts had inaccurate copies of `hosts.txt`

DNS: History

- In 1983, the first stable operational DNS implementation included
  - The associated query protocol;
  - A server implementation; and
  - Initial root servers.

- Since inception, DNS scaled from 1000s of queries/day to 10s of billions queries/day

AWARDS & RECOGNITION

Mockapetris Honored for Developing Domain Name System

ACM named Paul Mockapetris recipient of the 2019 ACM Software System Award for developing the Domain Name System (DNS), which provides the worldwide distributed directory service that is an essential component of the functionality of the global internet. In 1983, Mockapetris designed and built the DNS, creating the associated query protocol, a server implementation, and initial root servers. Taken together, these components provided the first stable operational DNS system.

Goals

- Uniqueness: no naming conflicts
- Scalable
  - Many names and frequent updates (secondary)
- Distributed, autonomous administration
  - Ability to update my own (machines') names
  - Don't have to track everybody's updates
- Highly available
- Lookups are fast
- Perfect consistency is a non-goal

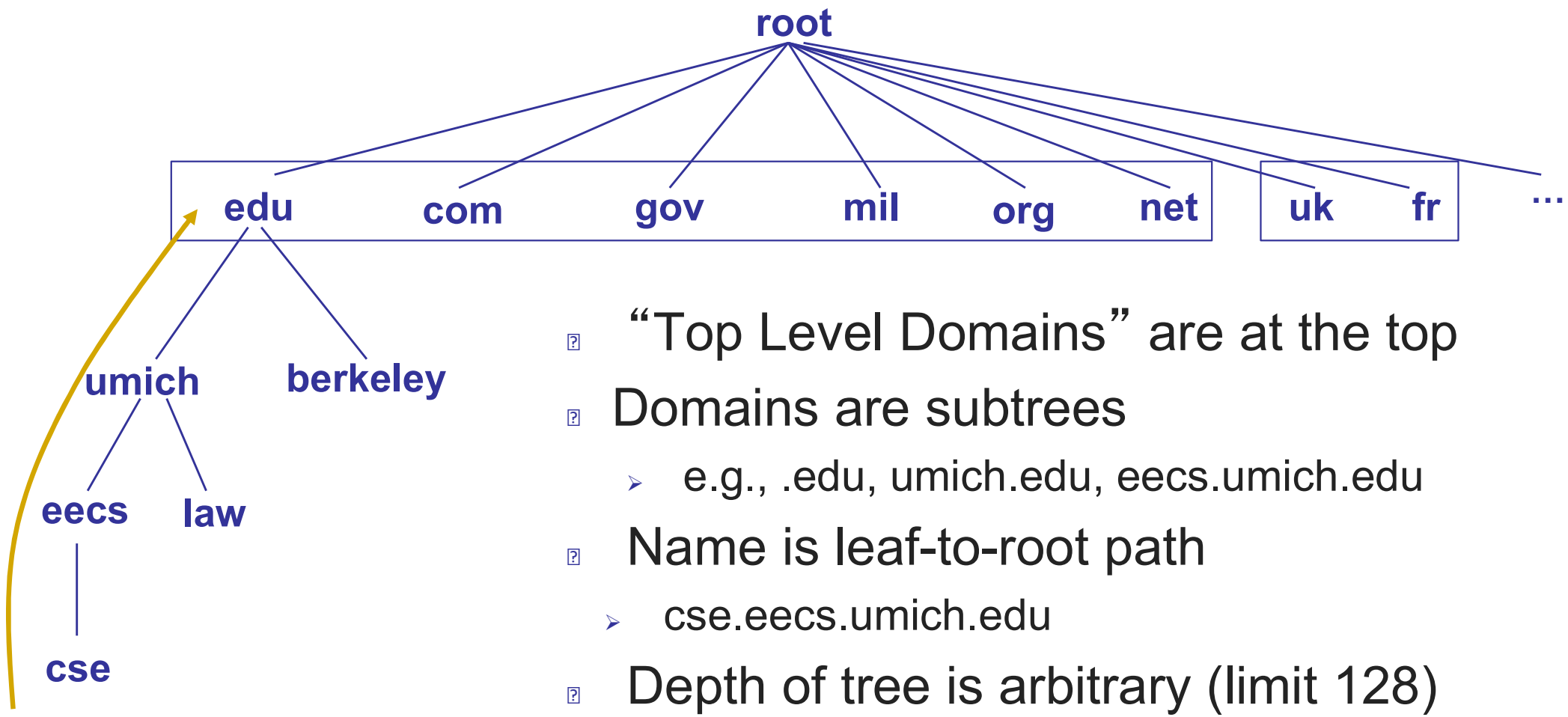
How?

- Partition the namespace
- Distribute administration of each partition
  - Autonomy to update my own (machines') names
  - Don't have to track everybody's updates
- Distribute name resolution for each partition
- How should we partition things?

Key idea: Hierarchy

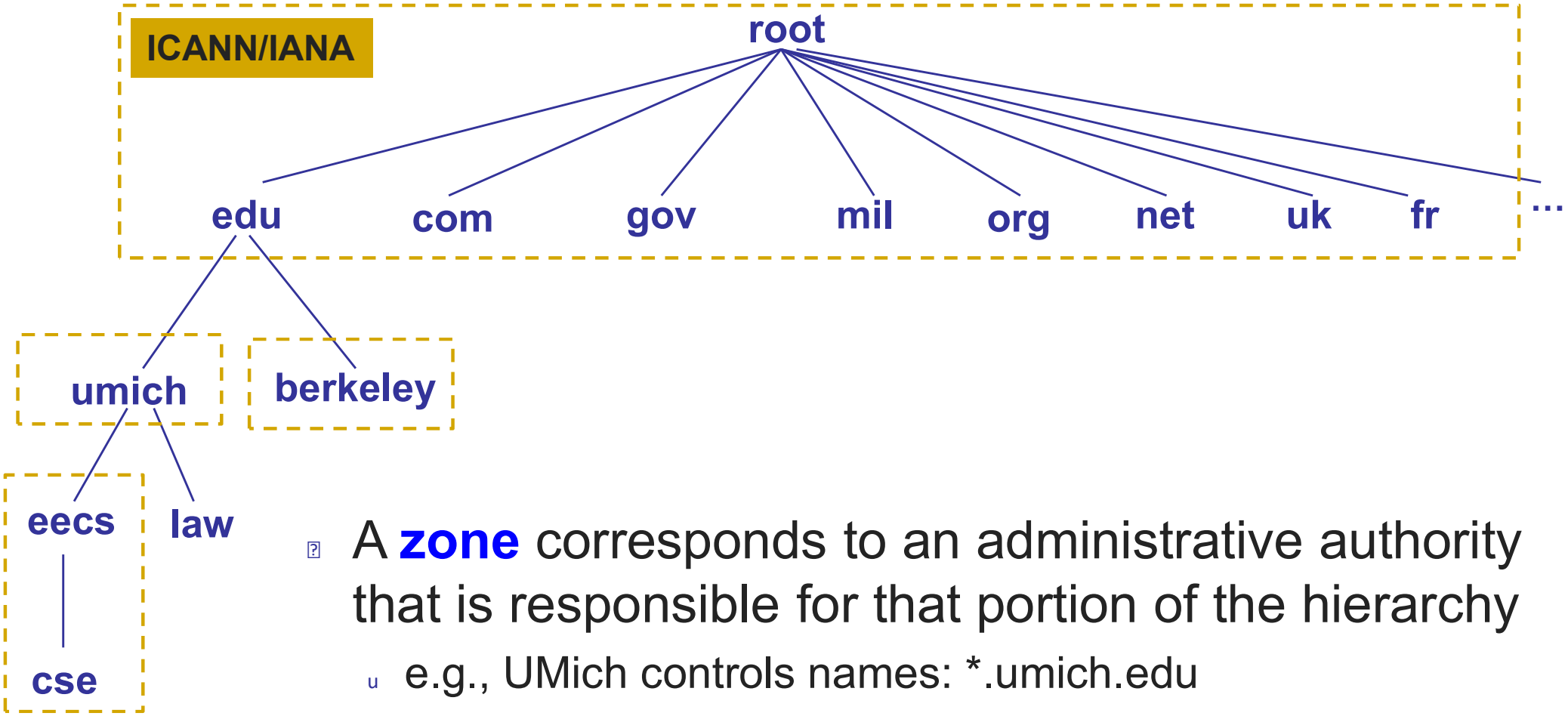
- Three intertwined hierarchies
  - Hierarchical namespace
    - »As opposed to original flat namespace
  - Hierarchically administered
    - »As opposed to centralized
  - (Distributed) hierarchy of servers
    - »As opposed to centralized storage

Hierarchical namespace



- "Top Level Domains" are at the top
- Domains are subtrees
  - e.g., .edu, umich.edu, eecs.umich.edu
- Name is leaf-to-root path
  - cse.eecs.umich.edu
- Depth of tree is arbitrary (limit 128)
- Name collisions trivially avoided
  - Each domain is responsible

Hierarchical administration



- A **zone** corresponds to an administrative authority that is responsible for that portion of the hierarchy
  - e.g., UMich controls names: *.umich.edu
  - e.g., EECS controls names: *.eecs.umich.edu

Server hierarchy

- Top of hierarchy: Root servers
  - Location hardwired into other servers
- Next Level: Top-level domain (TLD) servers
  - .com, .edu, etc.
  - Managed professionally
- Bottom Level: Authoritative DNS servers
  - Actually store the name-to-address mapping
  - Maintained by the corresponding administrative authority

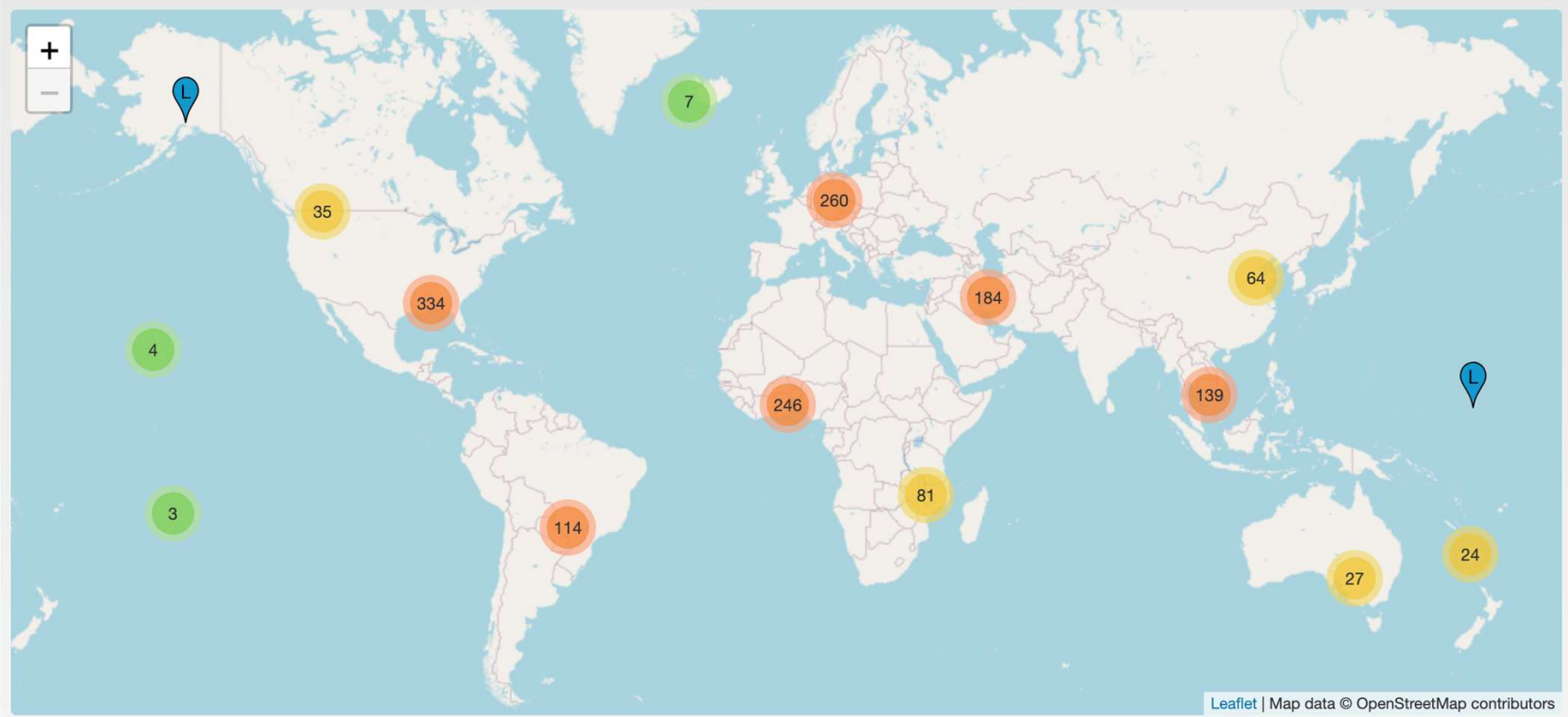
Server hierarchy

- Each server stores a (small!) subset of the total DNS database
- An authoritative DNS server stores "resource records" for all DNS names in the domain that it has authority for
- Each server needs to know other servers responsible for other portions of the hierarchy
  - Every server knows the root
  - Root server knows about all top-level domains

DNS root

- Located in Virginia, USA
- How do we make the root scale?
  - Replicate (https://www.iana.org/domains/root/servers)

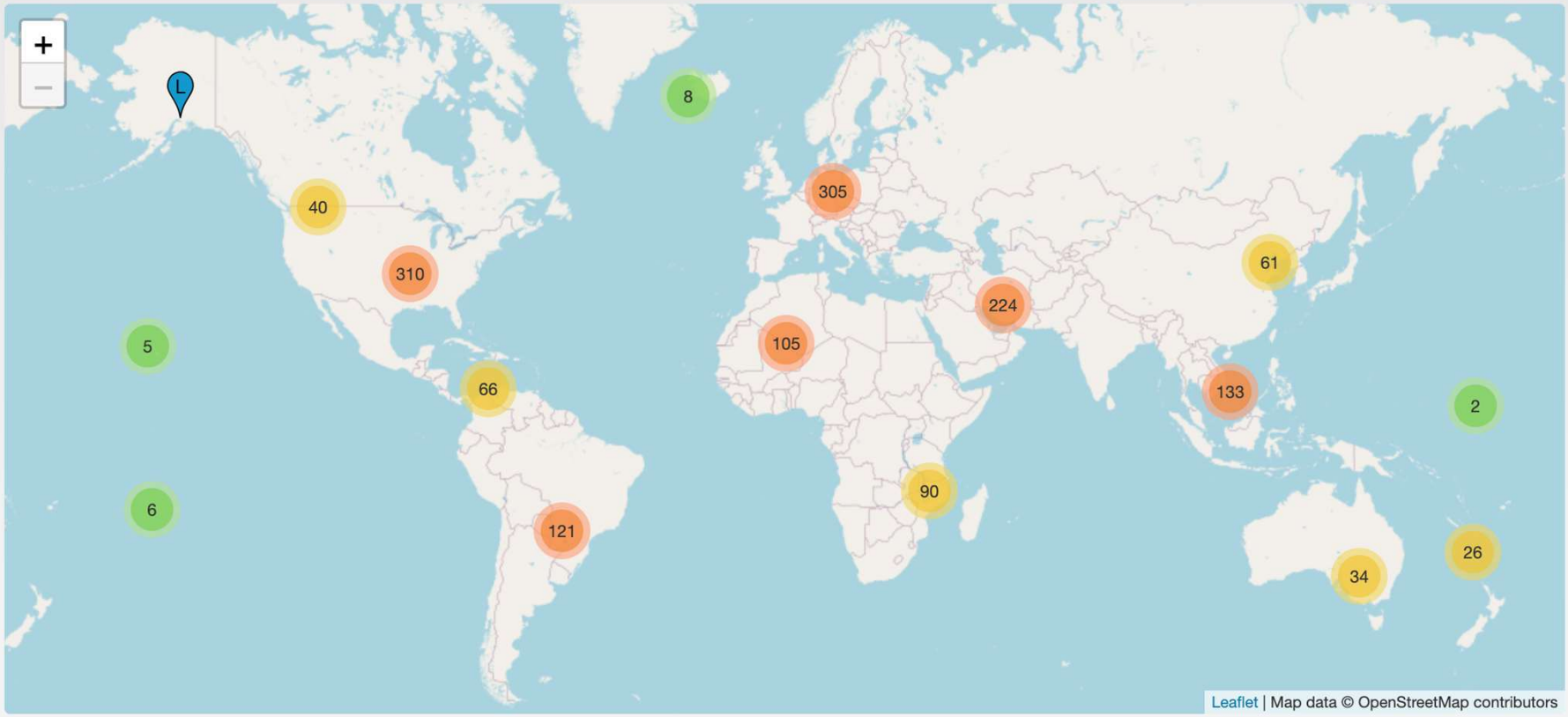
13 DNS root servers



As of 2025-01-19T03:06:00Z, the root server system consists of 1921 instances operated by the 12 independent root server operators.

https://root-servers.org/

13 DNS root servers (in 2024)



As of 2024-01-19T16:02:17Z, the root server system consists of 1756 instances operated by the 12 independent root server operators.

https://root-servers.org/

5-MINUTE BREAK!

Announcements

- Midterm: **Feb 21 7-9PM in Chrys**

- Sign up for midterm accommodations here: **https://forms.gle/htu8cw5g6nYenkCa7**

DNS records

- DNS servers store resource records (RRs)
  - RR is (name, value, type, TTL)
- Type = A: (→ Address)
  - name = hostname
  - value = IP address
- Type = NS: (→ Name Server)
  - name = domain
  - value = name of DNS server for domain

DNS records (cont'd)

- Type = CNAME: (→ Canonical Name)
  - name = alias name for some "canonical" (real) name
    - e.g., cse.umich.edu is really cse.eecs.umich.edu
  - value = canonical name
- Type = MX: (→ Mail eXchanger)
  - name = domain in email address
  - value = name(s) of mail server(s)

Inserting Resource Records into DNS

- Register foobar.com at registrar
  - Provide registrar with names and IP addresses of your authoritative name server(s)
  - Registrar inserts RR pairs into the .com TLD server:
    - (foobar.com, dns1.foobar.com, NS)
    - (dns1.foobar.com, 212.44.9.129, A)
- Store resource records in your server dns1.foobar.com
  - e.g., type A record for www.foobar.com
  - e.g., type MX record for foobar.com

Using DNS (Client/App View)

- Two components
  - Local DNS servers
  - Resolver software on hosts
- Local DNS server ("default name server")
  - Clients configured with default server's address OR learn it via a host configuration protocol (e.g., DHCP)
- Client application
  - Obtain DNS name (e.g., from URL)
  - Do `getnameinfo()` to trigger DNS request to its local DNS server

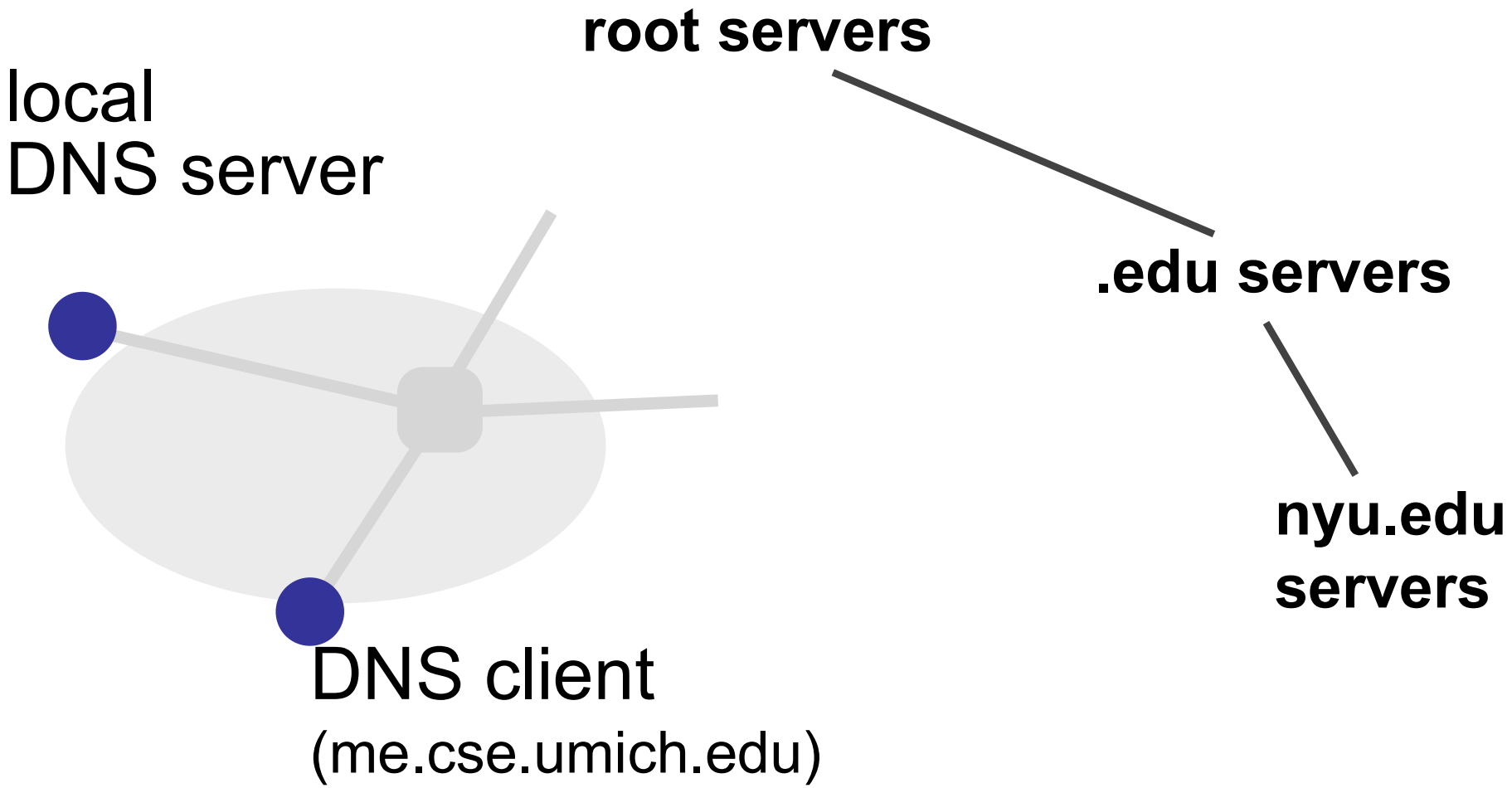
dig

```
dig nyu.edu

; <<>> DiG 9.10.6 <<>> nyu.edu
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 64269
;; flags: qr rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 512
;; QUESTION SECTION:
;nyu.edu.                       IN      A

;; ANSWER SECTION:
nyu.edu.                60      IN      A       216.165.61.24

;; Query time: 79 msec
;; SERVER: 8.8.8.8#53(8.8.8.8)
;; WHEN: Fri Jan 18 11:07:26 EST 2025
;; MSG SIZE  rcvd: 52
```

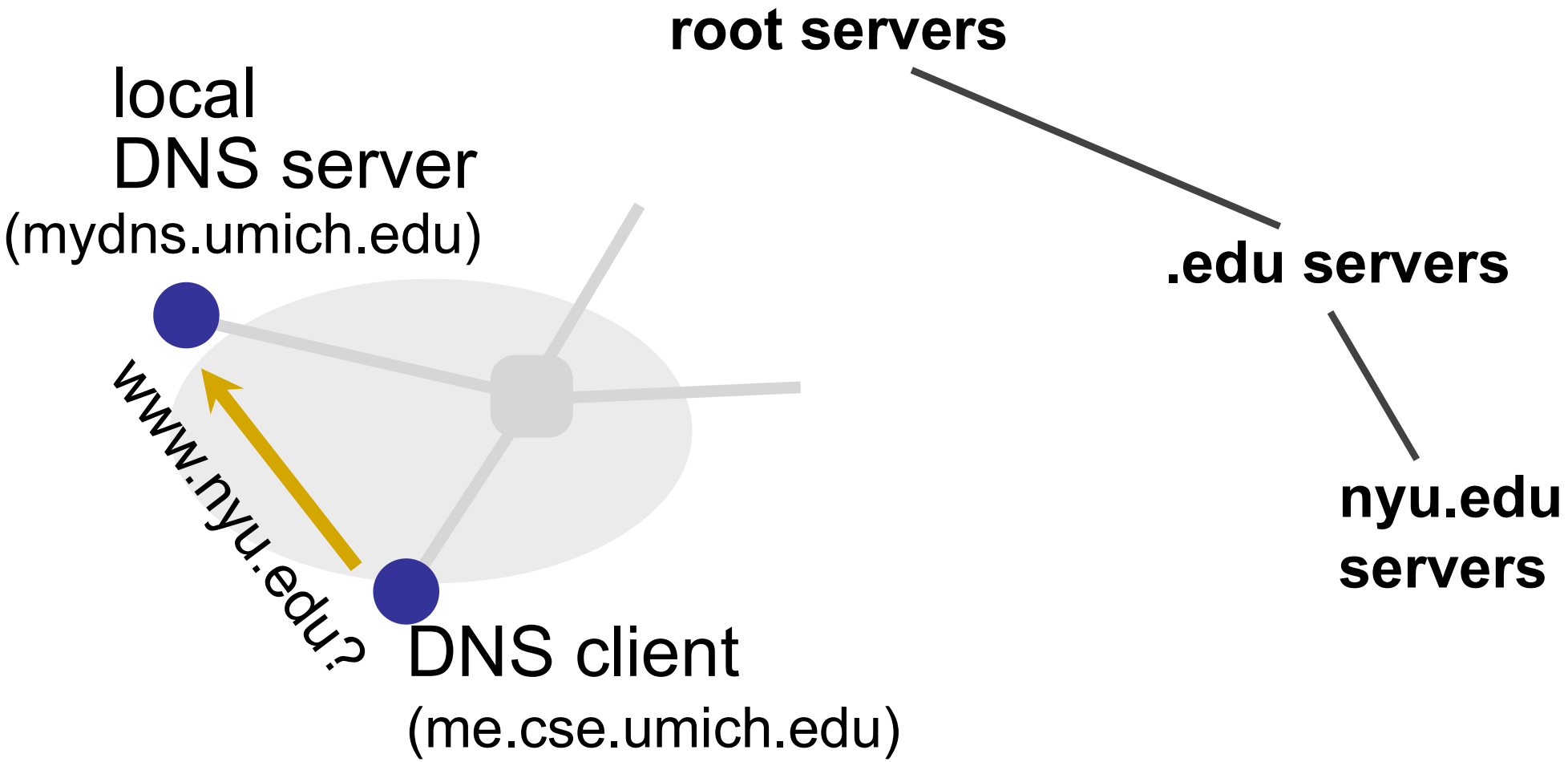
dig (in 2021)

```
dig nyu.edu

; <<>> DiG 9.10.6 <<>> nyu.edu
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 47443
;; flags: qr rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 512
;; QUESTION SECTION:
;nyu.edu.                       IN      A

;; ANSWER SECTION:
nyu.edu.                60      IN      A       216.165.47.10

;; Query time: 39 msec
;; SERVER: 192.168.1.1#53(192.168.1.1)
;; WHEN: Fri Sep 10 08:21:43 EDT 2021
;; MSG SIZE  rcvd: 52
```

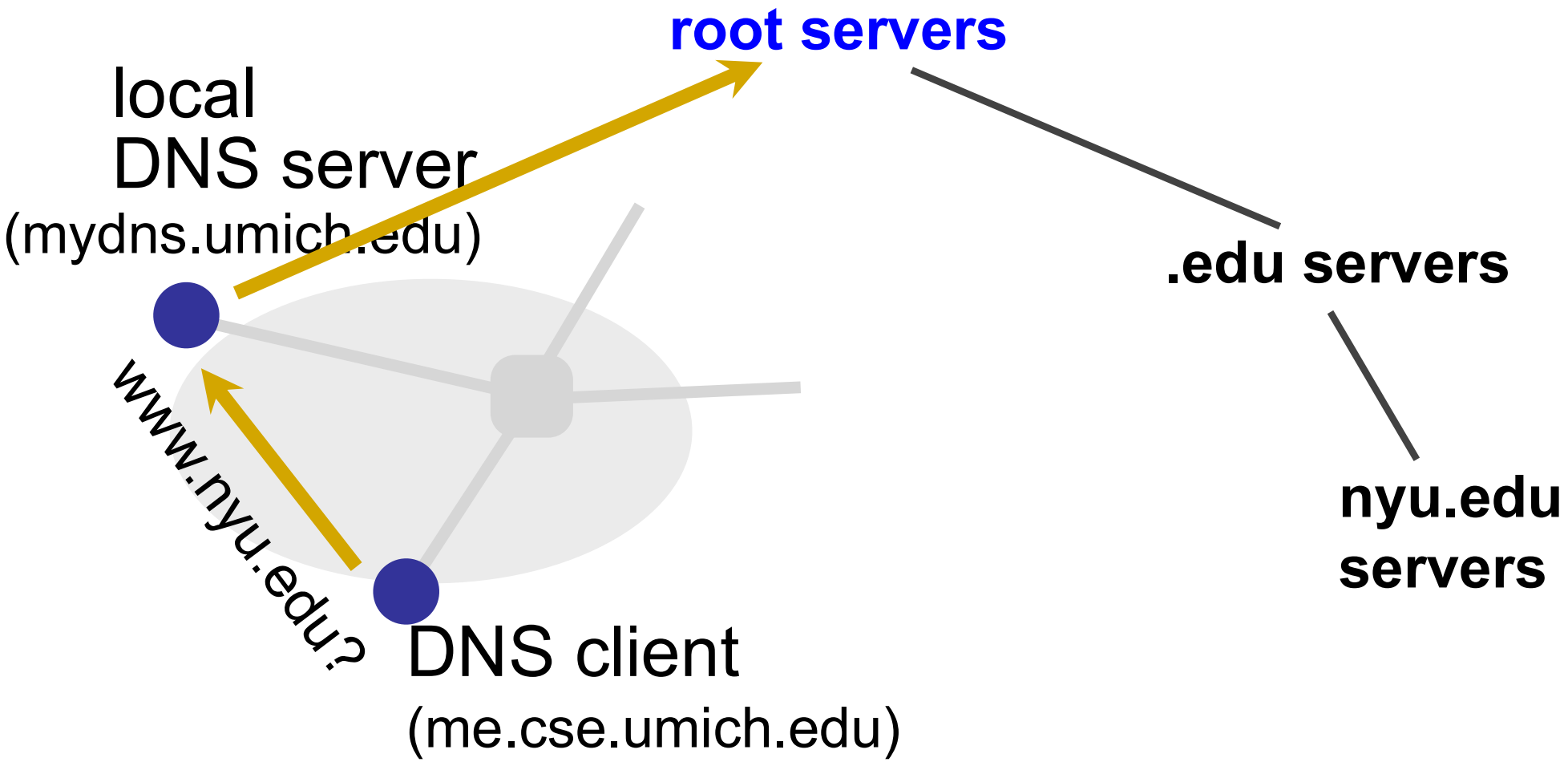
Name resolution



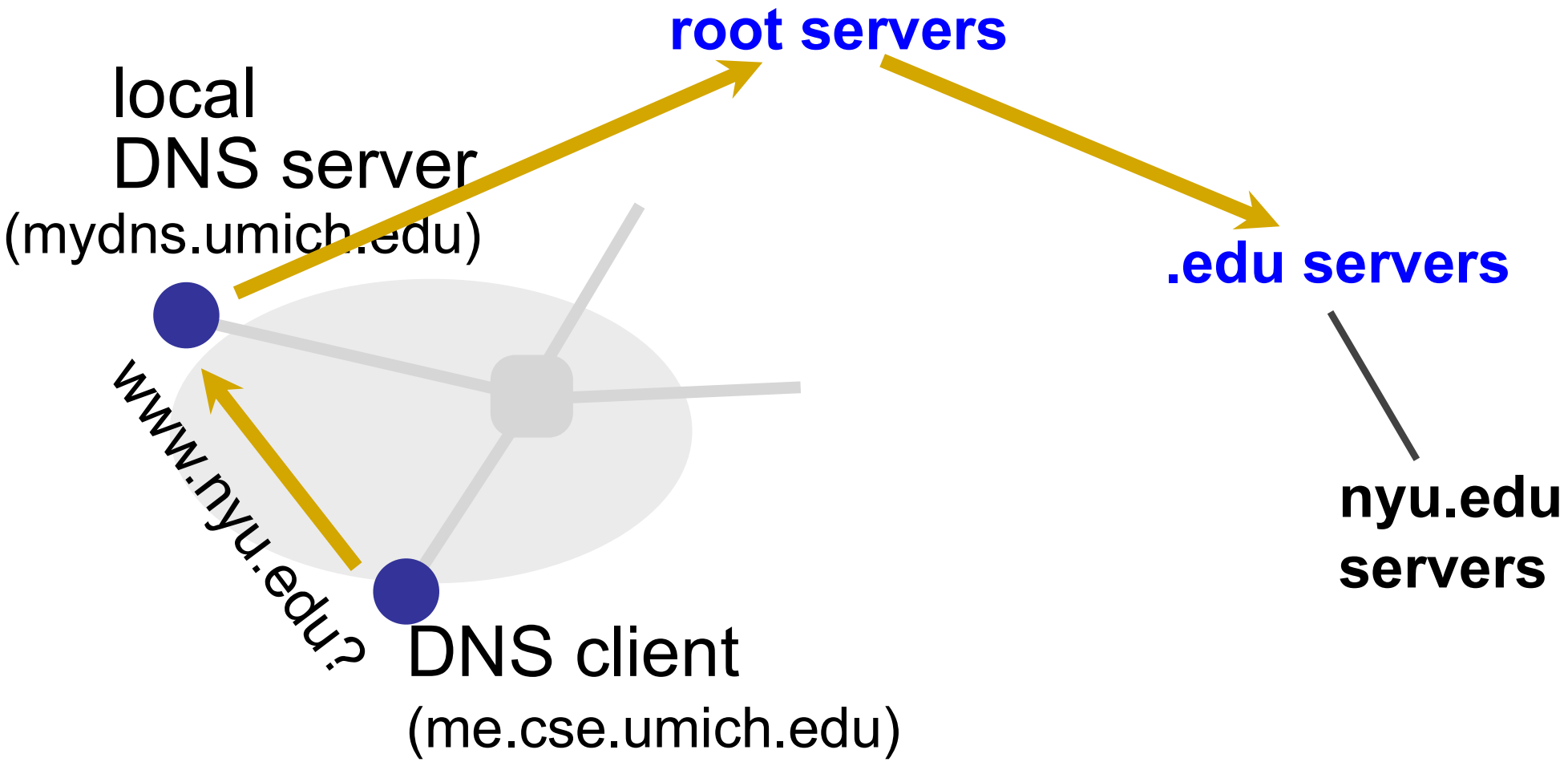
Name resolution



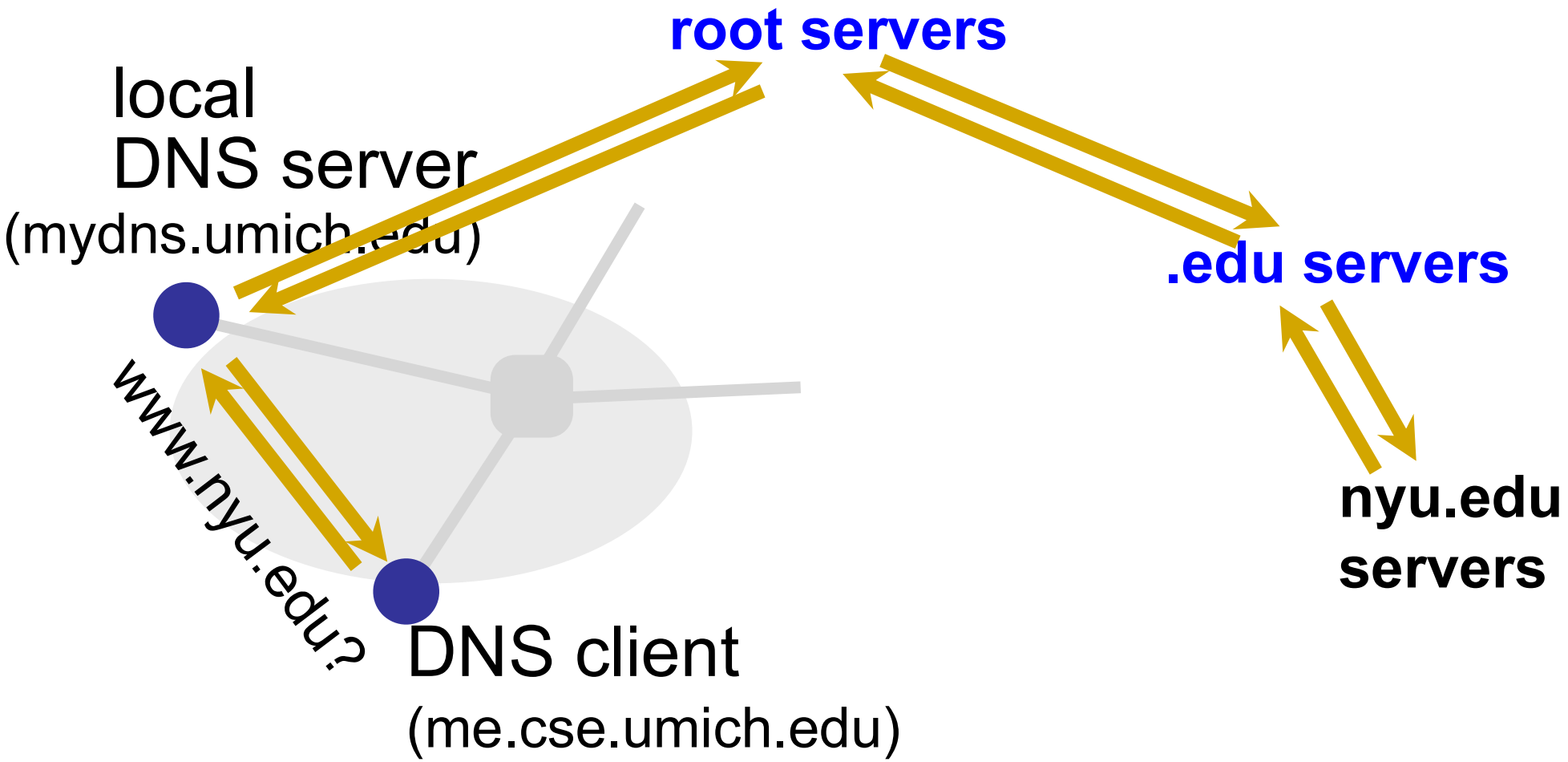
Name resolution



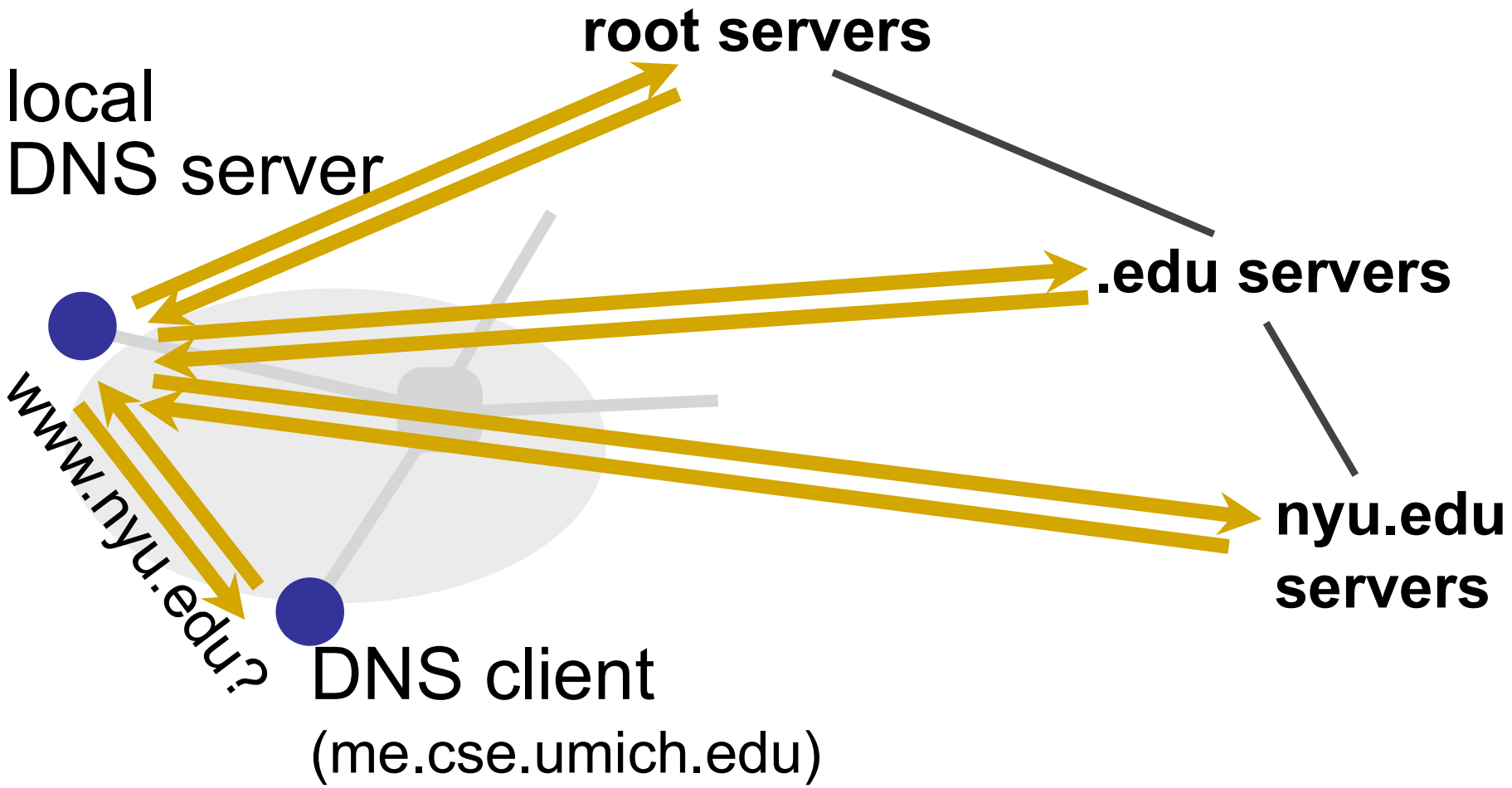
Name resolution



Name resolution: Recursive



Name resolution: Iterative



Two ways to resolve a name

- Recursive name resolution
  - Ask server to do it for you
- Iterative name resolution
  - Ask server who to ask next
- The iterative example we saw is a mix of both!

DNS protocol

- Query and Reply messages; both with the same message format
  - Header: identifier, flags, etc.
  - Plus, resource records
- Client–server interaction on UDP Port 53
  - Spec supports TCP too, but not always implemented

Goals: Are we there yet?

- Uniqueness: No naming conflicts
- Scalable
- Distributed, autonomous administration
- Highly available?

Reliability

- Replicated DNS servers (primary/secondary)
  - Name service available if at least one replica is up
  - Queries can be load-balanced between replicas
- Usually, UDP used for queries
  - Reliability, if needed, must be implemented on UDP
- Try alternate servers on timeout
  - Exponential backoff when retrying same server
- Same identifier for all queries
  - Don’t care which server responds

Goals: Are we there yet?

- Uniqueness: No naming conflicts
- Scalable
- Distributed, autonomous administration
- Highly available
- Fast lookups?

DNS caching

- Performing all these queries takes time
  - Up to 1-second latency before starting download
- Caching can greatly reduce overhead
  - The top-level servers very rarely change
  - Popular sites (e.g., www.google.com) visited often
  - Local DNS server often has the information cached
- How DNS caching works
  - DNS servers cache responses to queries
  - Responses include a "time to live" (TTL) field
  - Server deletes cached entry after TTL expires

TTL in dig output

```
dig nyu.edu

; <<>> DiG 9.10.6 <<>> nyu.edu
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 64269
;; flags: qr rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 512
;; QUESTION SECTION:
;nyu.edu.                       IN      A

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nyu.edu.                60      IN      A       216.165.61.24

;; Query time: 79 msec
;; SERVER: 8.8.8.8#53(8.8.8.8)
;; WHEN: Fri Jan 18 11:07:26 EST 2025
;; MSG SIZE  rcvd: 52
```

TTL (seconds)

Important properties of DNS

- Administrative delegation and hierarchy enables:
  - Easy unique naming
  - “Fate sharing” for network failures
  - Reasonable trust model
  - Caching increases scalability and performance

DNS provides indirection

- Addresses can change underneath
  - Move www.cnn.com to 4.125.91.21
- Name could map to multiple IP addresses
  - Load-balancing (CDN)
  - Reducing latency by picking nearby servers (CDN)
  - Try out: `dig google.com` a few times
- Multiple names for the same address
  - E.g., many services (mail, www) on same machine
  - E.g., aliases like www.cnn.com and cnn.com

Summary

- CDNs improve web performance
  - Via replication and caching
  - Good server selection
- DNS allows us to go to webpages without having to memorize IP addresses
  - Allows a level of indirection that enables many functionalities including CDN server selection

Negative caching

- Remember things that do not work
  - Misspellings like www.google.comm
  - These can take a long time to fail the first time
  - Good to remember that they do not work so the failure takes less time the next time around
- Negative caching is optional
  - Not widely implemented