Content Distribution Networks

COS 418: *Distributed Systems*
Lecture 24

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[Selected content adapted from M. Freedman, B. Maggs and S. Shenker]

Today

1. **Domain Name System (DNS) primer**
2. The Web: HTTP, hosting, and caching
3. Content distribution networks (CDNs)

DNS hostname versus IP address

- **DNS host name** (*e.g.* www.cs.princeton.edu)
  - **Mnemonic** name appreciated by humans
  - **Variable length**, full alphabet of characters
  - Provides **little** (if any) information about **location**
- **IP address** (*e.g.* 128.112.136.35)
  - Numerical address appreciated by **routers**
  - **Fixed length**, decimal number
  - **Hierarchical** address space, related to host **location**

Many uses of DNS

- Hostname to IP address translation
  - IP address to hostname translation (***reverse lookup***)
- Host name ***aliasing***: other DNS names for a host
  - ***Alias*** host names point to ***canonical*** hostname
- **Email:** Lookup domain's mail server by domain name

Original design of the DNS

- Per-host file named /etc/hosts
  - Flat namespace: each **line = IP address & DNS name**
  - SRI (Menlo Park, California) kept the master copy
  - Everyone else downloads regularly
- **But, a single server doesn't scale**
  - Traffic implosion (lookups and updates)
  - Single point of failure
- Need a distributed, hierarchical **collection** of servers

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DNS: Goals and non-goals

- A wide-area **distributed database**
- Goals:
  - **Scalability**; decentralized maintenance
  - **Robustness**
  - Global scope
    - Names mean the same thing everywhere
  - Distributed updates/queries
  - Good **performance**
- But **don't need** strong **consistency** properties

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Domain Name System (DNS)

- **Hierarchical name space** divided into contiguous sections called ***zones***
  - Zones are distributed over a collection of DNS servers
- **Hierarchy** of DNS **servers**:
  - ***Root*** servers (identity hardwired into other servers)
  - ***Top-level domain (TLD)*** servers
  - ***Authoritative*** DNS servers
- Performing the translations:
  - ***Local DNS servers*** located near clients
  - ***Resolver*** software running on clients

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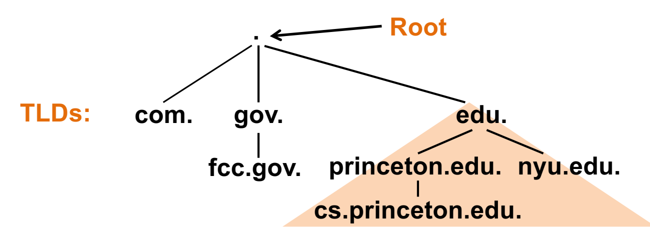
The DNS namespace is hierarchical



- **Hierarchy of namespace matches hierarchy of servers**
- Set of nameservers answers queries for names within zone
- Nameservers store names and links to other servers in tree

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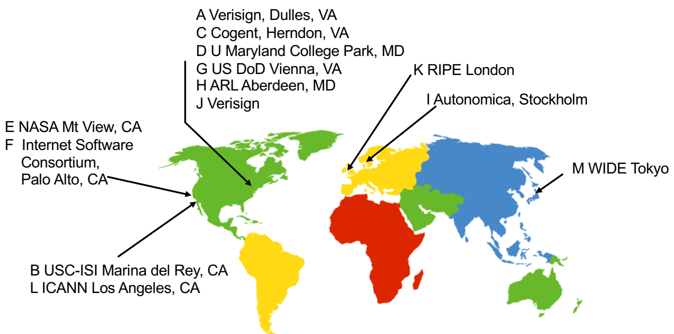
DNS root nameservers

- 13 root servers. *Does this scale?*



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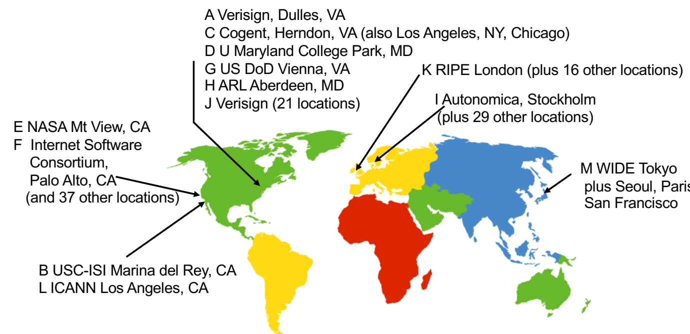
DNS root nameservers

- 13 root servers. *Does this scale?*
- Each server is really a **cluster** of servers (some geographically distributed), replicated via **IP anycast**



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TLD and Authoritative Servers

- ***Top-level domain (TLD)*** servers
  - Responsible for com, org, net, edu, etc, and all top-level country domains: uk, fr, ca, jp
  - *Network Solutions* maintains servers for com TLD
  - *Educause* non-profit for edu TLD
- ***Authoritative*** DNS servers
  - An organization's DNS servers, providing authoritative information for that organization
  - May be maintained by organization itself, or ISP

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Local name servers

- Do not strictly belong to hierarchy
- Each ISP (or company, or university) has one
  - Also called ***default*** or ***caching*** name server
- When host makes DNS query, query is sent to its local DNS server
  - Acts as proxy, forwards query into hierarchy
  - Does work for the client

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DNS resource records

- DNS is a distributed database storing **resource records**
- Resource record includes: (**name**, type, **value**, time-to-live)

Type = **A** (address)
- **name** = hostname
- **value** is IP address

Type = **CNAME**
- **name** = alias for some "canonical" (real) name
- **value** is canonical name

Type = **NS** (name server)
- **name** = domain (e.g. princeton.edu)
- **value** is hostname of authoritative name server for this domain

Type = **MX** (mail exchange)
- **name** = domain
- **value** is name of mail server for that domain

DNS in operation

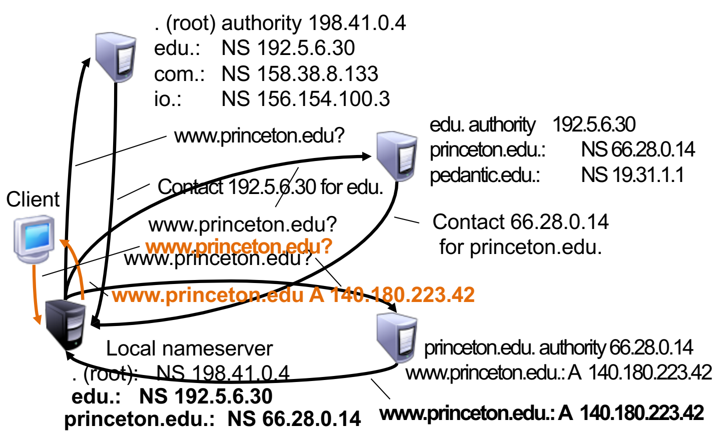
- Most queries and responses are UDP datagrams
  - Two types of queries:
- ***Recursive***: Nameserver responds with answer or error

Answer: www.princeton.edu A 140.180.223.42

- ***Iterative***: Nameserver may respond with a referral

Referral: .edu NS a.edu-servers.net.

A recursive DNS lookup



Recursive versus iterative queries

Recursive query

- Less burden on entity initiating the query
- **More burden on nameserver** (has to return an answer to the query)
- Most root and TLD servers won't answer (shed load)
  - Local name server answers recursive query

Iterative query

- **More burden on query initiator**
- Less burden on nameserver (simply refers the query to another server)

```
$ dig @a.root-servers.net www.freebsd.org +norecurse
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 57494
;; QUERY: 1, ANSWER: 0, AUTHORITY: 2, ADDITIONAL: 2

;; QUESTION SECTION:
;www.freebsd.org.        IN A

;; AUTHORITY SECTION:
org.          172800 IN  NS  b0.org.afilias-nst.org.
org.          172800 IN  NS  d0.org.afilias-nst.org.

;; ADDITIONAL SECTION:
b0.org.afilias-nst.org.   172800 IN  A   199.19.54.1
d0.org.afilias-nst.org.   172800 IN  A   199.19.57.1
```

Glue records

[Output edited for clarity]

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(authoritative for org.)

```
$ dig @199.19.54.1 www.freebsd.org +norecurse
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 39912
;; QUERY: 1, ANSWER: 0, AUTHORITY: 3, ADDITIONAL: 0

;; QUESTION SECTION:
;www.freebsd.org.        IN A

;; AUTHORITY SECTION:
freebsd.org.    86400  IN NS  ns1.isc-sns.net.
freebsd.org.    86400  IN NS  ns2.isc-sns.com.
freebsd.org.    86400  IN NS  ns3.isc-sns.info.
```

[Output edited for clarity]

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(authoritative for freebsd.org.)

```
$ dig @ns1.isc-sns.net www.freebsd.org +norecurse
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 17037
;; QUERY: 1, ANSWER: 1, AUTHORITY: 3, ADDITIONAL: 3

;; QUESTION SECTION:
;www.freebsd.org.        IN A

;; ANSWER SECTION:
www.freebsd.org.   3600   IN A   69.147.83.33

;; AUTHORITY SECTION:
freebsd.org.      3600   IN NS  ns2.isc-sns.com.
freebsd.org.      3600   IN NS  ns1.isc-sns.net.
freebsd.org.      3600   IN NS  ns3.isc-sns.info.

;; ADDITIONAL SECTION:
ns1.isc-sns.net.    3600   IN A   72.52.71.1
ns2.isc-sns.com.    3600   IN A   38.103.2.1
ns3.isc-sns.info.   3600   IN A   63.243.194.1
```

[Output edited for clarity]

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DNS caching

- Performing all these queries takes time
  - And all this **before actual communication** takes place
- Caching can **greatly reduce overhead**
  - The top-level servers very rarely change
    - Popular sites visited often
  - Local DNS server often has the information cached
- How DNS caching works
  - All DNS servers **cache responses to queries**
  - Responses include a time-to-live (TTL) field
    - Server deletes cached entry after TTL expires

Plays a key role in **CDN** (Akamai) **load balancing**

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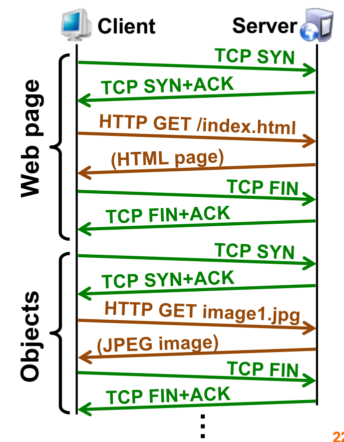
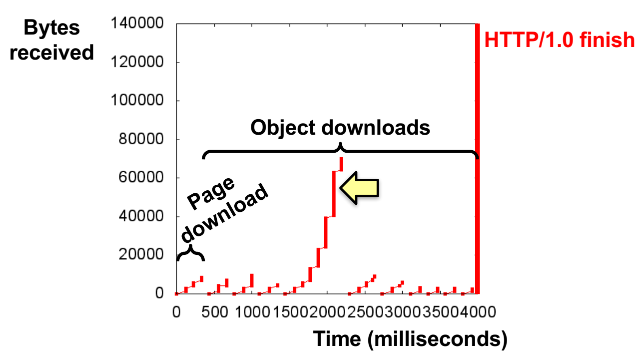
3. Content distribution networks (CDNs)

Anatomy of an HTTP/1.0 web page fetch

- Web page = HTML file + embedded images/objects
- ***Stop-and-wait*** at the granularity of objects:
  - Close then open new TCP connection for **each object**
    - Incurs a **TCP round-trip-time delay** each time
  - Each TCP connection may stay in "slow start"



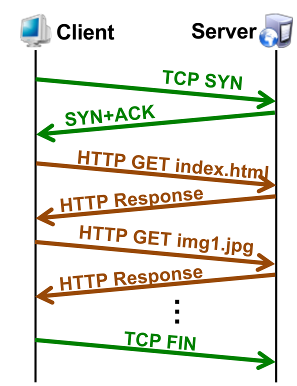
HTTP/1.0 webpage fetch: Timeline



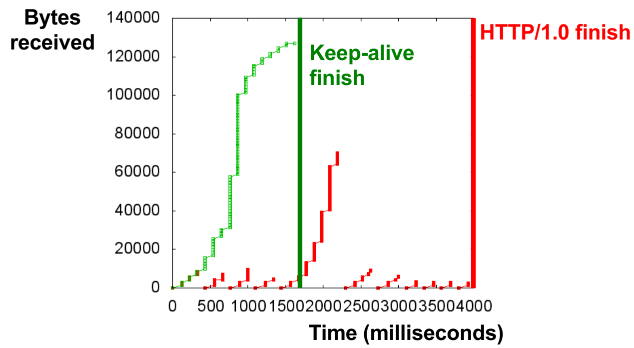
- Fetch 8.5 Kbyte page with 10 objects, most < 10 Kbyte

Letting the TCP connection persist

- Known as ***HTTP keepalive***
- **Still stop-and-wait** at the granularity of objects, at the application layer
  - HTTP response fully received before next HTTP GET dispatched
    - ≥ 1 RTT per object



HTTP Keepalive avoids TCP slow starts



Incur **one slow start**, **but stop-and-wait** to issue next request

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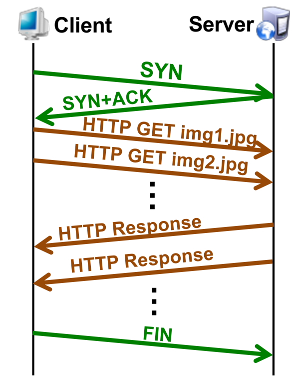
Pipelining within HTTP

- **Idea: Pipeline** HTTP GETs and their responses

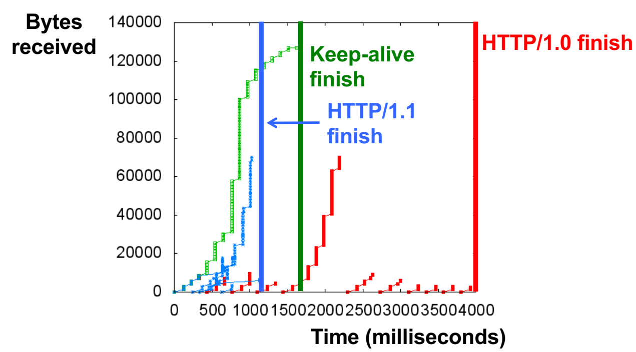


- Main benefits:

1. **Amortizes the RTT** across multiple objects retrieved
2. **Reduces overhead** of HTTP requests, packing multiple requests into one packet

- Implemented in HTTP/1.1

Pipelined HTTP requests overlap RTTs



- Many **HTTP requests** and **TCP connections** at once
- **Overlaps RTTs of all requests**

Today

1. Domain Name System (DNS) primer
2. The Web: HTTP, **hosting, and caching**
   - **Handling heavy loads**
3. Content distribution networks (CDNs)

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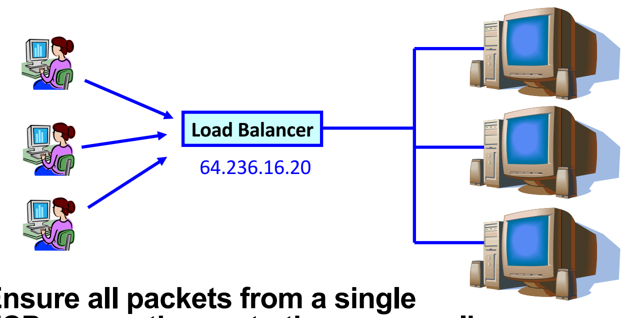
Hosting: Multiple machines per site

- **Problem:** **Overloaded** popular web site
  - **Replicate** the site across multiple machines
    - Helps to handle the load
- Want to direct client to a particular replica. Why?
  - **Balance load** across server replicas
- **Solution #1:** Manual selection by clients
  - Each replica has its own site name
  - Some Web page lists replicas (*e.g.*, by name, location), asks clients to click link to pick

Hosting: Load-balancer approach

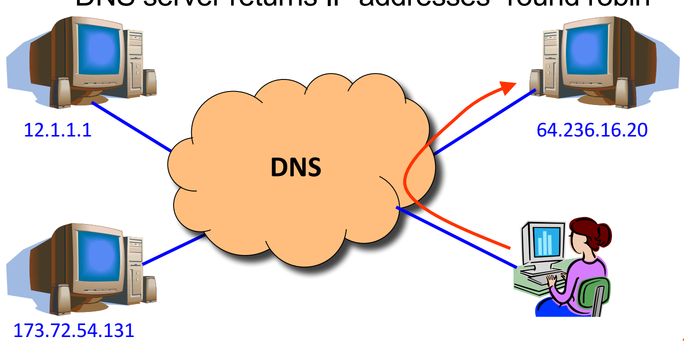
- **Solution #2:** Single IP address, multiple machines
  - Run multiple machines behind a single IP address



  - **Ensure all packets from a single TCP connection go to the same replica**

Hosting: DNS redirection approach

- **Solution #3:** Multiple IP addresses, multiple machines
  - Same DNS name but different IP for each replica
    - DNS server returns IP addresses “round robin”

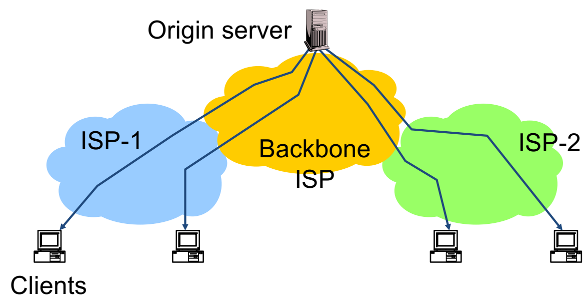


Hosting: Summary

- Load-balancer approach
  - No geographical diversity ✘
  - TCP connection issue ✘
  - Does not reduce network traffic ✘
- DNS redirection
  - No TCP connection issues ✔
  - Simple round-robin server selection
    - May be less responsive ✘
  - Does not reduce network traffic ✘

Web caching

- Many clients transfer the **same information**
  - Generates **redundant** server and network load
  - Also, clients may experience high **latency**

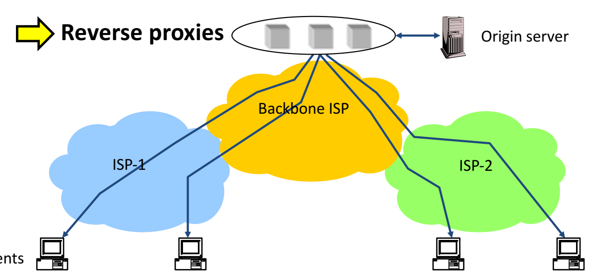


Why web caching?

- Motivation for **placing content closer to client**:
  - User gets **better response time**
    - Content providers get happier users
  - Network gets **reduced load**
- Why does caching work? Exploits locality of reference
- How well does caching work?
  - Very well, **up to a limit**
  - Large overlap in content
  - But many unique requests

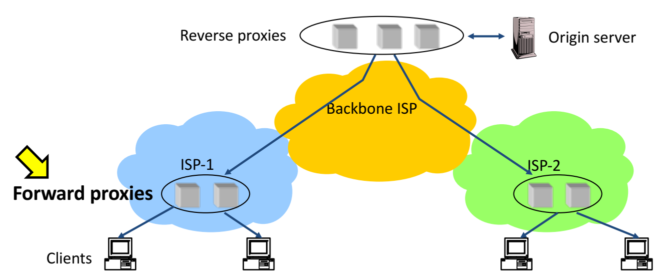
Caching with Reverse Proxies

- Cache data close to origin server → decrease server load
  - Typically done by content providers
  - Client thinks it is talking to the origin server (the server with content)
- Does not work for **dynamic content**



Caching with Forward Proxies

- Cache close to clients → less network traffic, less latency
  - Typically done by ISPs or corporate LANs
  - **Client configured** to send HTTP requests to forward proxy
- Reduces traffic on ISP-1's access link, origin server, and backbone ISP



Caching & Load-Balancing: Outstanding problems

- Problem *ca.* 2002: *How to reliably deliver large amounts of content to users worldwide?*
  - Popular event: **"Flash crowds" overwhelm** (replicated) web server, access link, or back-end database infrastructure
  - More rich content: audio, video, photos
- Web caching: Diversity causes **low cache hit rates (25−40%)**

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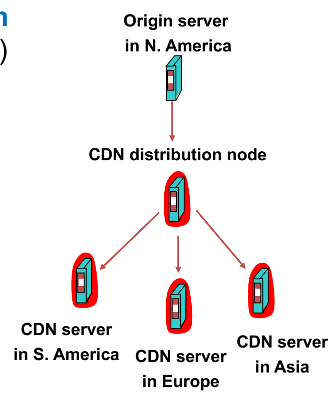
1. Domain Name System (DNS) primer
2. The Web: HTTP, hosting, and caching
3. **Content distribution networks (CDNs)**
   – Akamai case study

Content Distribution Networks

- **Proactive content replication**
  - Content provider (*e.g.* CNN) pushes content out from its own ***origin server***
- CDN **replicates** the content
  - On many servers spread throughout the Internet
- Updating the replicas
  - Updates **pushed to replicas** when the content changes



Replica selection: Goals

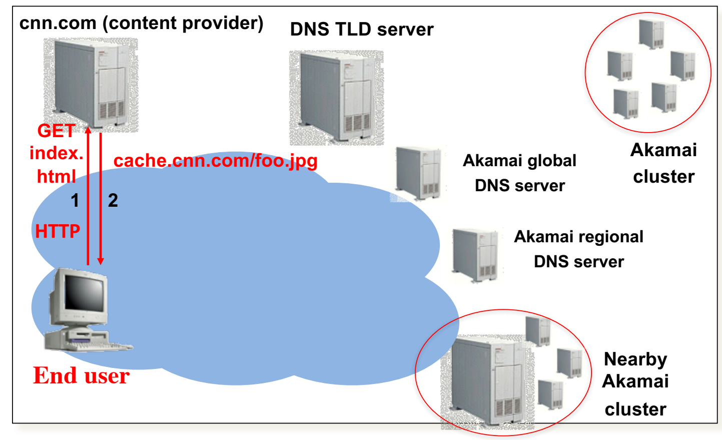
- **Live** server
  - For availability
- Lowest **load**
  - To balance load across the servers
- **Closest**
  - Nearest geographically, or in round-trip time
- Best **performance**
  - Throughput, latency, reliability…

Requires continuous monitoring of liveness, load, and performance

Akamai statistics

- Distributed servers
  - Servers: ~100,000
  - Networks: ~1,000
  - Countries: ~70
- Many customers
  - Apple, BBC, FOX, GM IBM, MTV, NASA, NBC, NFL, NPR, Puma, Red Bull, Rutgers, SAP, …
- Client requests
  - 20+M per second
  - Half in the top 45 networks
  - 20% of all Web traffic worldwide

How Akamai Uses DNS



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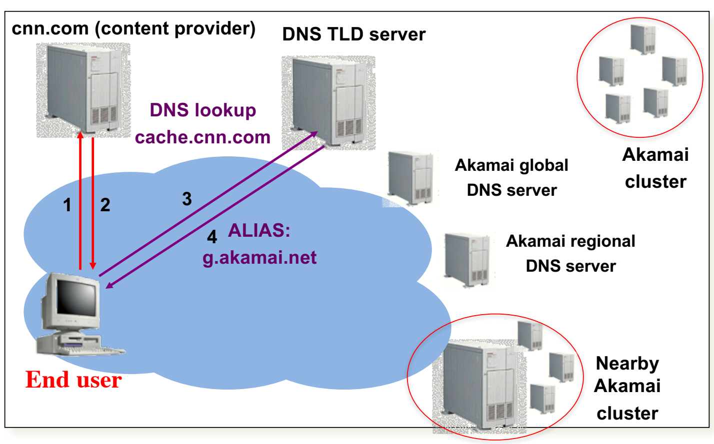

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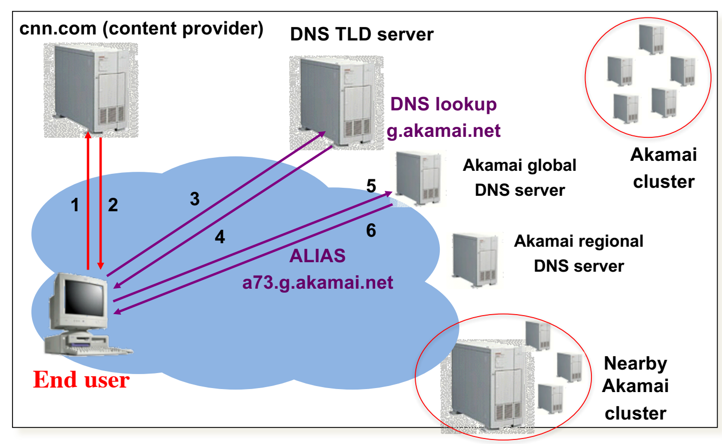

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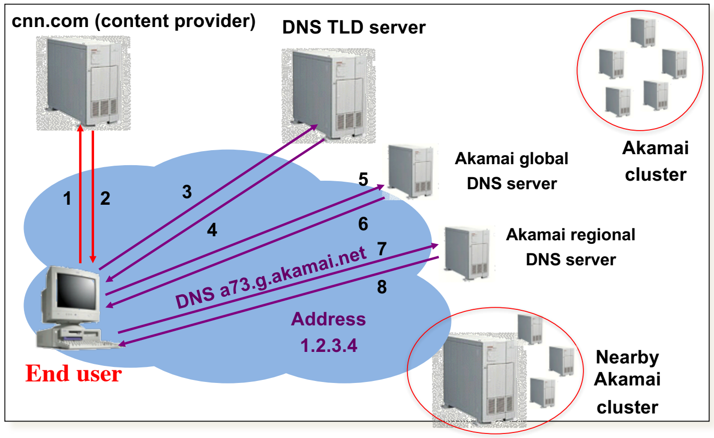

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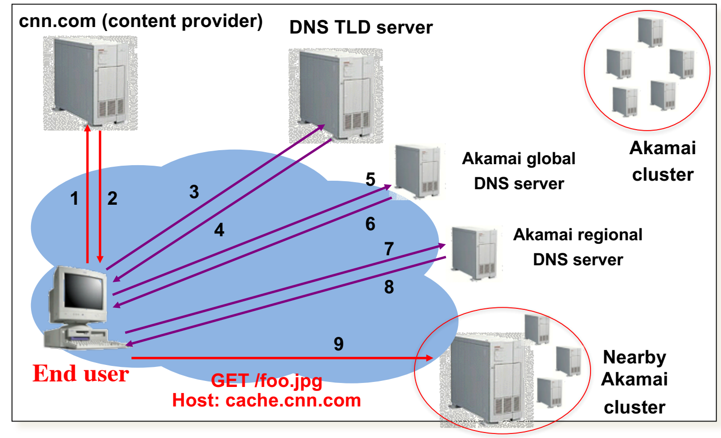

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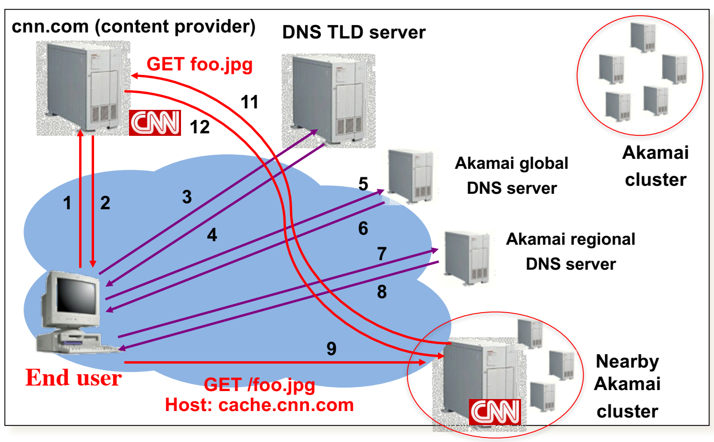

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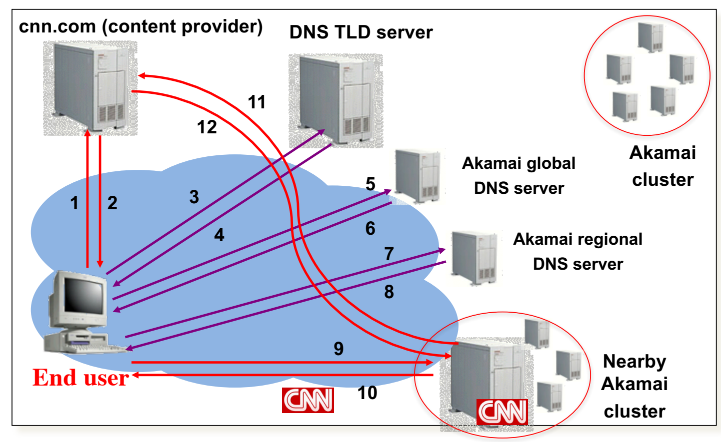
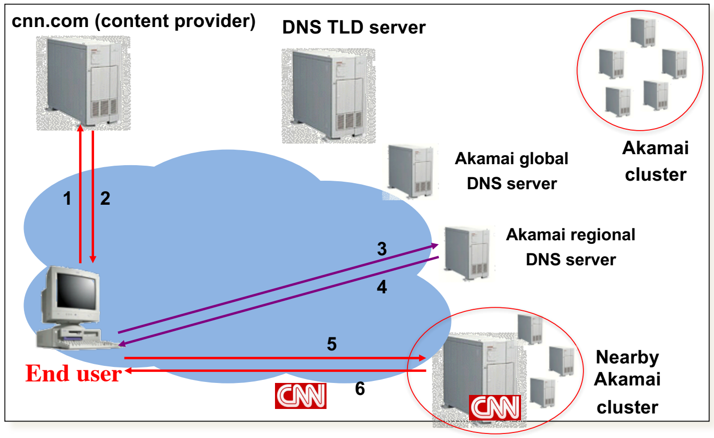


How Akamai Works: Cache Hit



Mapping System

- Equivalence classes of IP addresses
  - IP addresses experiencing similar performance
  - Quantify how well they connect to each other
- **Collect and combine** measurements
  - Ping, traceroute, BGP routes, server logs
    - *e.g.*, over 100 TB of logs per days
  - Network latency, loss, throughput, and connectivity

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Routing client requests with the map

- Map each **IP class** to a preferred **server cluster**
  - Based on performance, cluster health, etc.
  - Updated roughly every minute
    - **Short, 60-sec DNS TTLs** in Akamai regional DNS accomplish this
- Map client request to a server in the cluster
  - **Load balancer** selects a specific server
  - *e.g.*, to **maximize** the **cache hit rate**

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Adapting to failures

- Failing **hard drive** on a server
  - Suspends after finishing "in progress" requests
- Failed **server**
  - Another server takes over for the IP address
  - Low-level map updated **quickly** (load balancer)
- Failed **cluster**, or **network path**
  - High-level map updated **quickly** (ping/traceroute)

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Take-away points: CDNs

- Content distribution is hard
  - Many, diverse, changing objects
  - Clients distributed all over the world
- **Moving content to the client** is key
  - Reduces latency, improves throughput, reliability
- Content distribution solutions **evolved:**
  - Load balancing, reactive caching, to
  - Proactive content distribution networks

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Friday precept:
Extended office hours

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