Computer Networking

Michaelmas/Lent Term
M/W/F 11:00-12:00
LT1 in Gates Building

Slide Set 6

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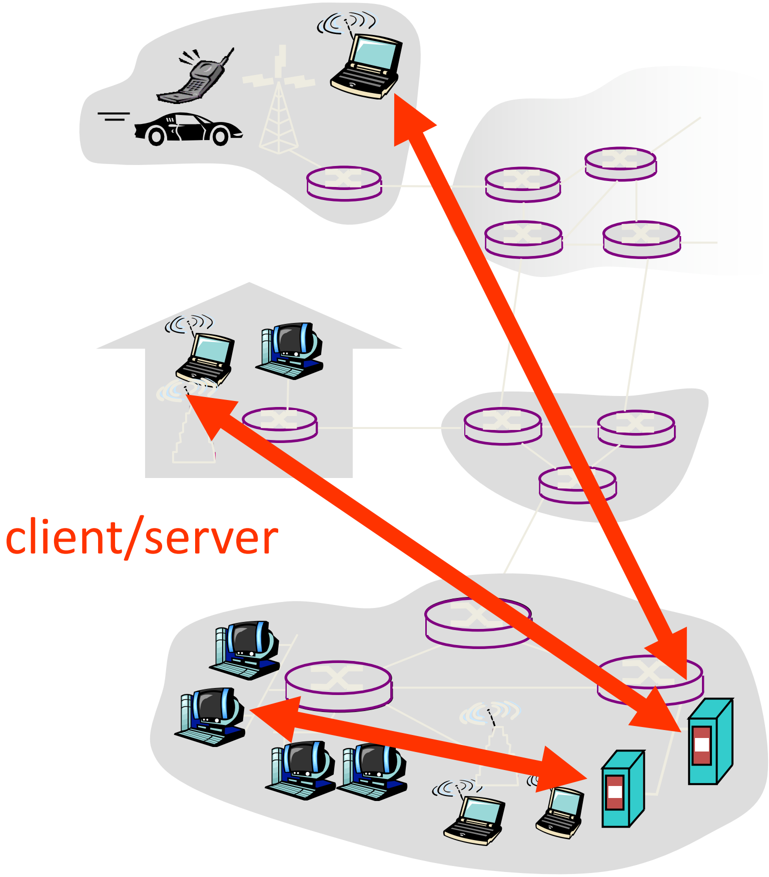
Topic 6 – Applications

- Overview
- Infrastructure Services (DNS)
- Traditional Applications (web)
- Multimedia Applications (SIP)
- P2P Networks

Client-server architecture



server:

- always-on host
- permanent IP address
- server farms for scaling

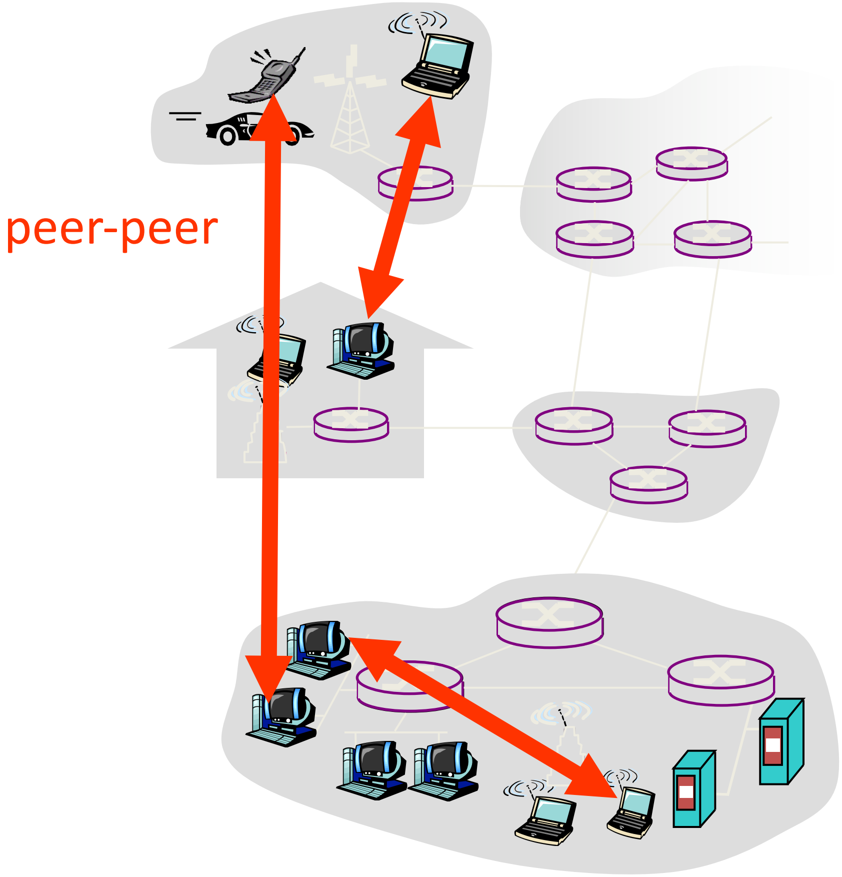
clients:

- communicate with server
- may be intermittently connected
- may have dynamic IP addresses
- do not communicate directly with each other

Pure P2P architecture

- *no* always-on server
- arbitrary end systems directly communicate
- peers are intermittently connected and change IP addresses

Highly scalable but difficult to manage



Hybrid of client-server and P2P

Skype

- voice-over-IP P2P application
- centralized server: finding address of remote party:
- client-client connection: direct (not through server)

Instant messaging

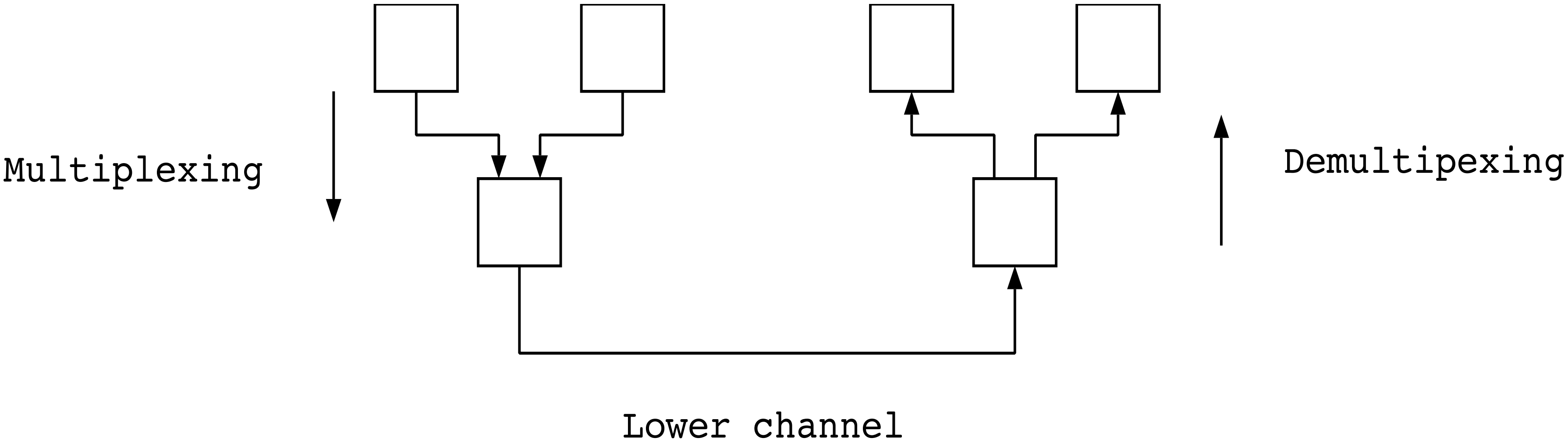
- chatting between two users is P2P
- centralized service: client presence detection/location
  - user registers its IP address with central server when it comes online
  - user contacts central server to find IP addresses of buddies

Addressing processes

- to receive messages, process must have *identifier*
- host device has unique 32-bit IP address
- Q: does IP address of host on which process runs suffice for identifying the process?
  - A: No, *many* processes can be running on same host

- *identifier* includes both IP address and port numbers associated with process on host.
- Example port numbers:
  - HTTP server: 80
  - Mail server: 25
- to send HTTP message to yuba.stanford.edu web server:
  - IP address: 171.64.74.58
  - Port number: 80
- more shortly…

Recall: Multiplexing is a service provided by (each) layer too!



Application: one web-server multiple sets of content

Host: one machine multiple services

Network: one physical box multiple addresses (like vns.cl.cam.ac.uk)

….

UNIX: /etc/protocols = examples of different transport-protocols on top of IP

UNIX: /etc/services = examples of different (TCP/UDP) services – by port

(These files are an example of a (static) approach to name services)

App-layer protocol defines

- Types of messages exchanged,
  - e.g., request, response
- Message syntax:
  - what fields in messages & how fields are delineated
- Message semantics
  - meaning of information in fields
- Rules for when and how processes send & respond to messages

Public-domain protocols:

- defined in RFCs
- allows for interoperability
- e.g., HTTP, SMTP

Proprietary protocols:

- e.g., Skype

What transport service does an app need?

Data loss

- some apps (e.g., audio) can tolerate some loss
- other apps (e.g., file transfer, telnet) require 100% reliable data transfer

Timing

- some apps (e.g., Internet telephony, interactive games) require low delay to be "effective"

Throughput

- ❒ some apps (e.g., multimedia) require minimum amount of throughput to be "effective"
- ❒ other apps ("elastic apps") make use of whatever throughput they get

Security

- ❒ Encryption, data integrity, …

Mysterious secret of *Transport*

- There is more than sort of *transport* layer

Shocked?

I seriously doubt it…

Recall the two most common TCP and UDP

Naming

- Internet has one global system of addressing: IP
  - By explicit design
- And one global system of naming: DNS
  - Almost by accident
- At the time, only items worth naming were hosts
  - A mistake that causes many painful workarounds
- Everything is now named relative to a host
  - Content is most notable example (URL structure)

Logical Steps in Using Internet

- Human has name of entity she wants to access
  - Content, host, etc.

- Invokes an application to perform relevant task
  - Using that name

- App invokes DNS to translate name to address

- App invokes transport protocol to contact host
  - Using address as destination

Addresses vs Names

- Scope of relevance:
  - App/user is primarily concerned with names
  - Network is primarily concerned with addresses
- Timescales:
  - Name lookup once (or get from cache)
  - Address lookup on each packet
- When moving a host to a different subnet:
  - The address changes
  - The name does not change
- When moving content to a differently named host
  - Name and address both change!

Relationship Between Names&Addresses

- Addresses can change underneath
  - Move www.bbc.co.uk to 212.58.246.92
  - Humans/Apps should be unaffected

- Name could map to multiple IP addresses
  - www.bbc.co.uk to multiple replicas of the Web site
  - Enables
    - Load-balancing
    - Reducing latency by picking nearby servers

- Multiple names for the same address
  - E.g., aliases like www.bbc.co.uk and bbc.co.uk
  - Mnemonic stable name, and dynamic canonical name
    - Canonical name = actual name of host

Mapping from Names to Addresses

- Originally: per-host file /etc/hosts
  - SRI (Menlo Park) kept master copy
  - Downloaded regularly
  - Flat namespace

- Single server not resilient, doesn’t scale
  - Adopted a distributed hierarchical system

- Two intertwined hierarchies:
  - Infrastructure: hierarchy of DNS servers
  - Naming structure: www.bbc.co.uk

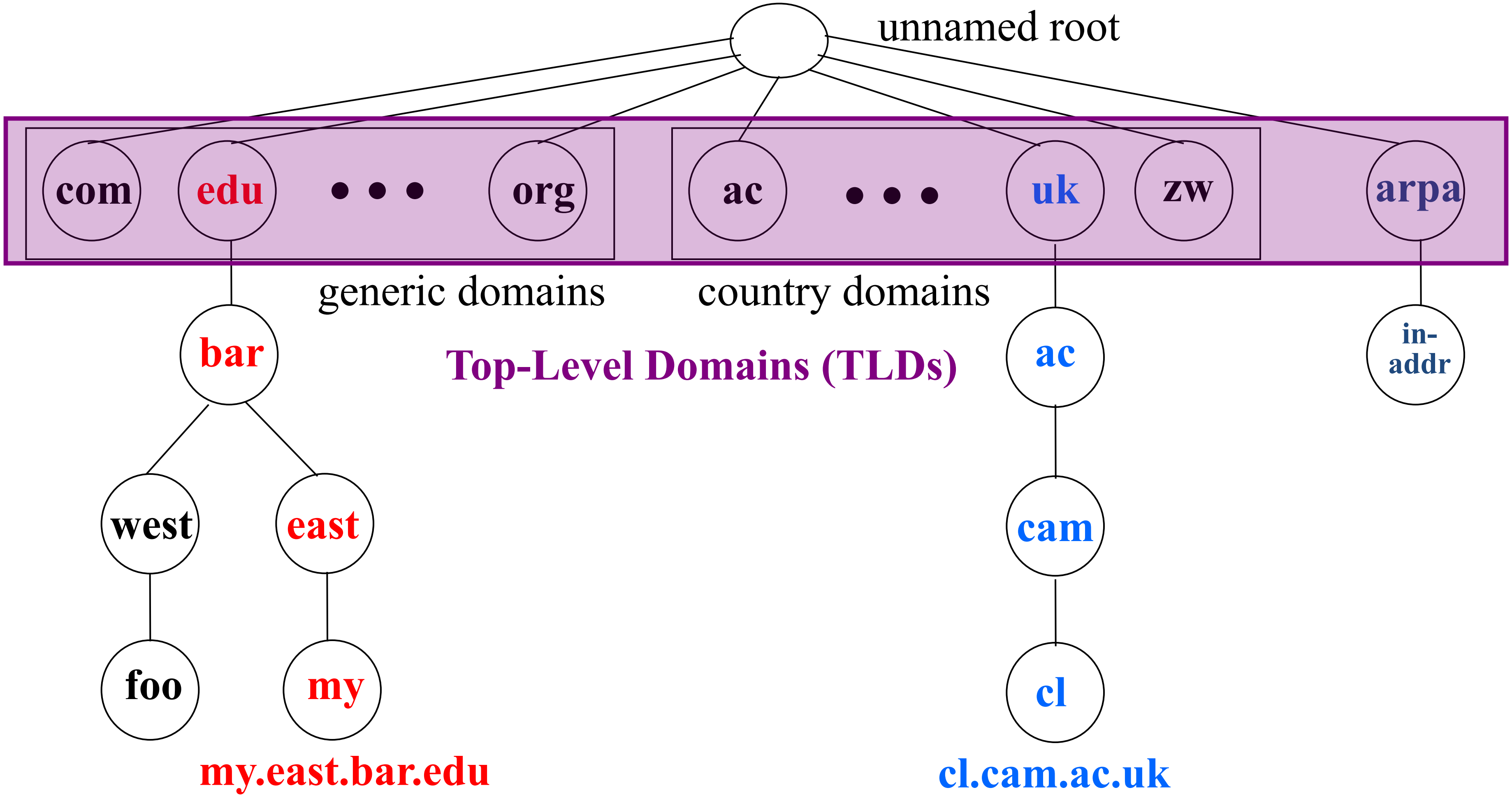
Domain Name System (DNS)

- Top of hierarchy: Root
  - Location hardwired into other servers

- Next Level: Top-level domain (TLD) servers
  - .com, .edu, etc.
  - .uk, .au, .to, etc.
  - Managed professionally

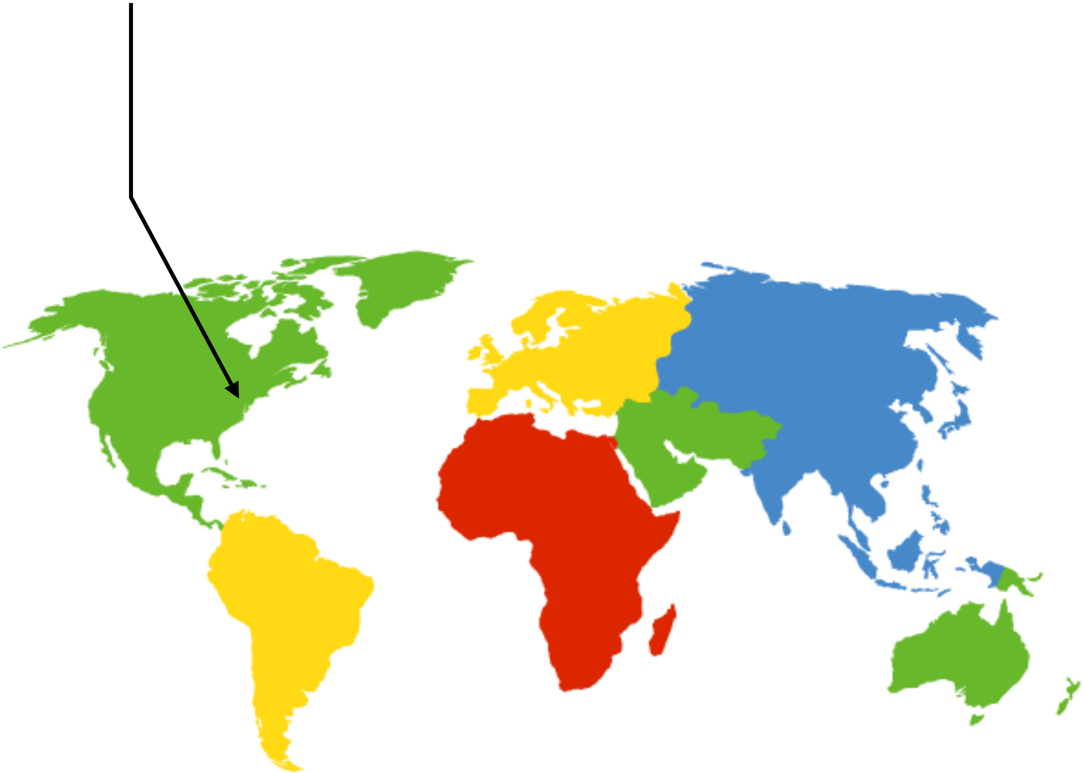
- Bottom Level: Authoritative DNS servers
  - Actually do the mapping
  - Can be maintained locally or by a service provider

Distributed Hierarchical Database



DNS Root

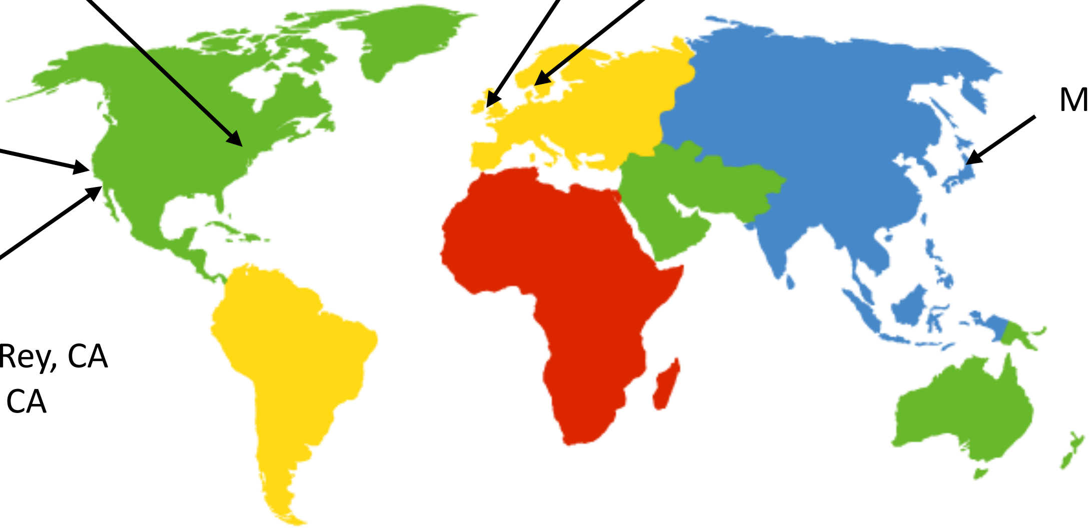
- Located in Virginia, USA
- How do we make the root scale?



Verisign, Dulles, VA

DNS Root Servers

- 13 root servers (see http://www.root-servers.org/)
  - Labeled A through M
- Does this scale?



A Verisign, Dulles, VA
C Cogent, Herndon, VA
D U Maryland College Park, MD
G US DoD Vienna, VA
H ARL Aberdeen, MD
J Verisign

K RIPE London

I Autonomica, Stockholm

E NASA Mt View, CA
F Internet Software Consortium Palo Alto, CA

M WIDE Tokyo

B USC-ISI Marina del Rey, CA
L ICANN Los Angeles, CA

DNS Root Servers

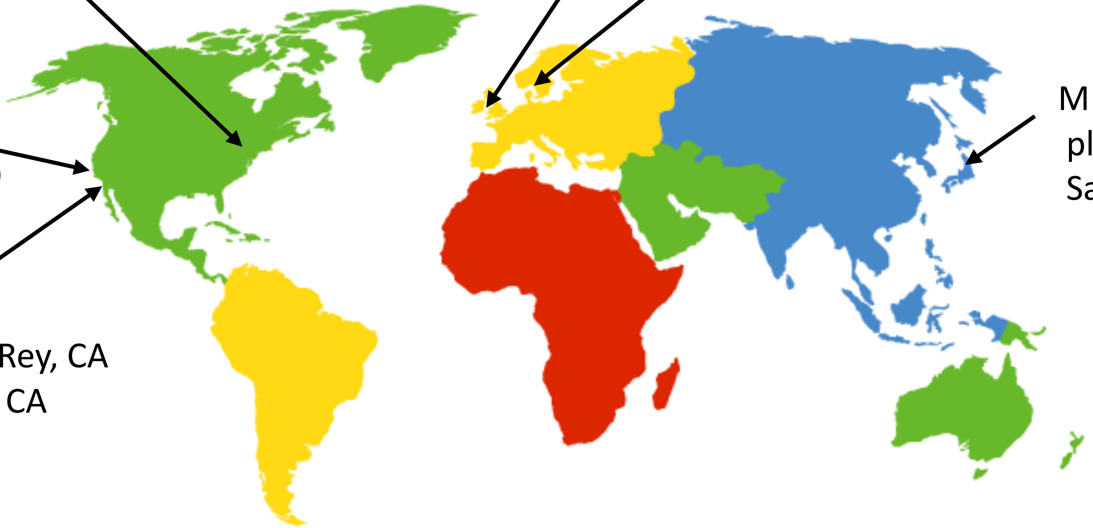
- 13 root servers (see http://www.root-servers.org/)
  - Labeled A through M
- Replication via any-casting (localized routing for addresses)

A Verisign, Dulles, VA
C Cogent, Herndon, VA (also Los Angeles, NY, Chicago)
D U Maryland College Park, MD
G US DoD Vienna, VA
H ARL Aberdeen, MD
J Verisign (21 locations)

K RIPE London (plus 16 other locations)

I Autonomica, Stockholm (plus 29 other locations)

E NASA Mt View, CA
F Internet Software Consortium, Palo Alto, CA (and 37 other locations)



M WIDE Tokyo plus Seoul, Paris, San Francisco

B USC-ISI Marina del Rey, CA
L ICANN Los Angeles, CA

Using DNS

- Two components
  - Local DNS servers
  - Resolver software on hosts

- Local DNS server ("default name server")
  - Usually near the endhosts that use it
  - Local hosts configured with local server (e.g., /etc/resolv.conf) or learn server via DHCP

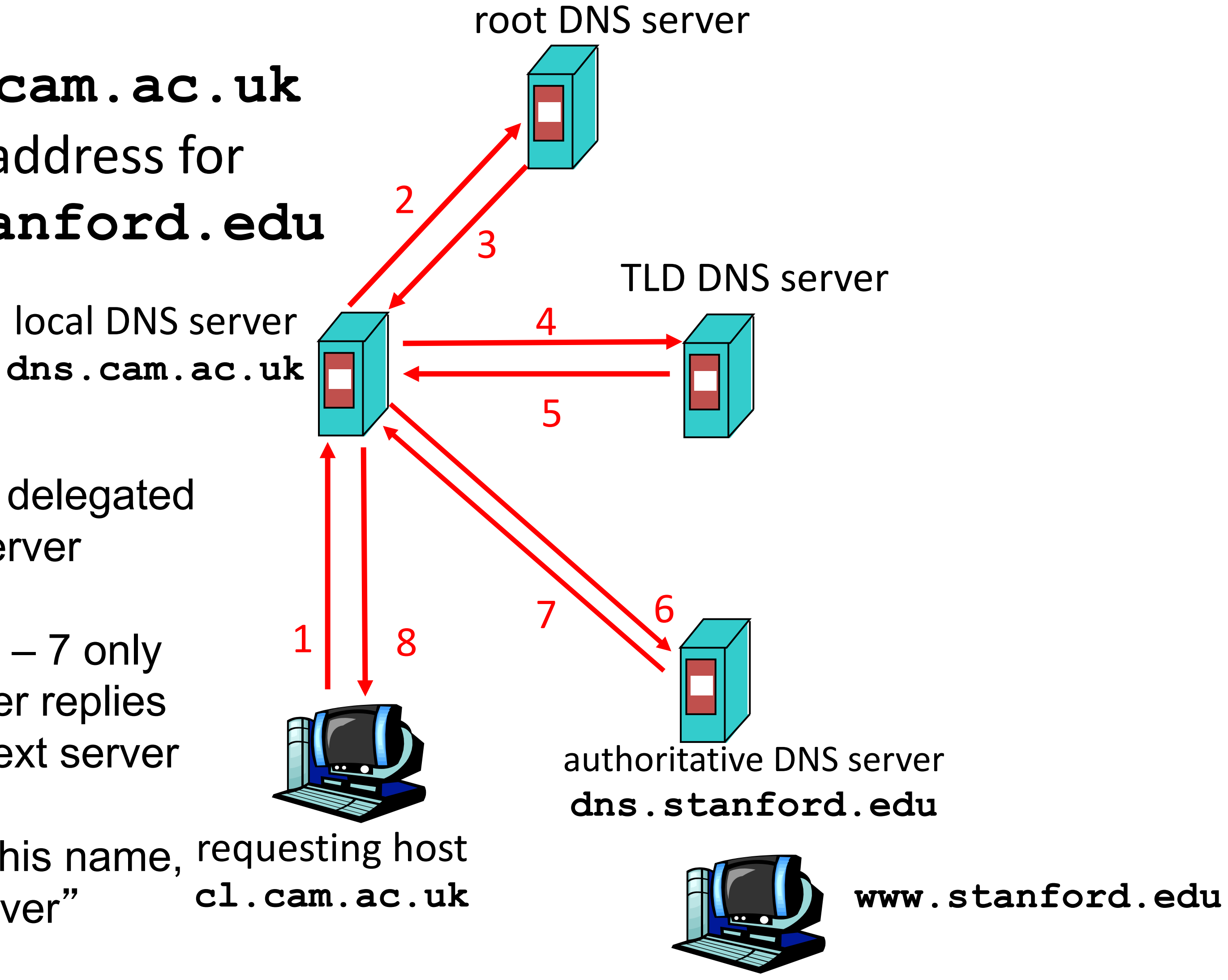
- Client application
  - Extract server name (e.g., from the URL)
  - Do gethostbyname() to trigger resolver code

How Does Resolution Happen?
(**Iterative** example)

Host at **`cl.cam.ac.uk`**

wants IP address for

`www.stanford.edu`



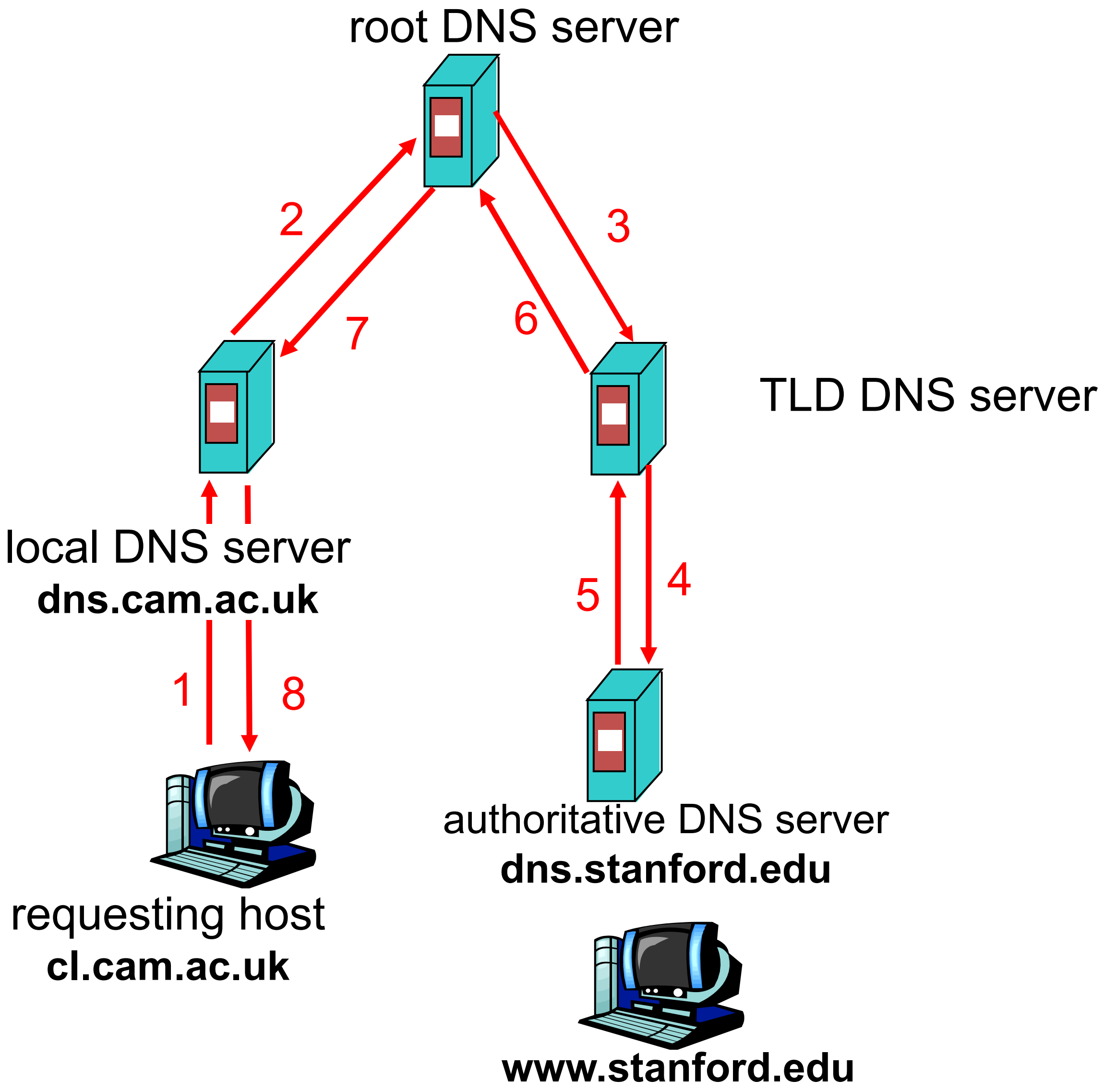
iterated query:

- Host enquiry is delegated to local DNS server
- Consider transactions 2 – 7 only
- contacted server replies with name of next server to contact
- “I don’t know this name, but ask this server”

DNS name resolution **recursive** example

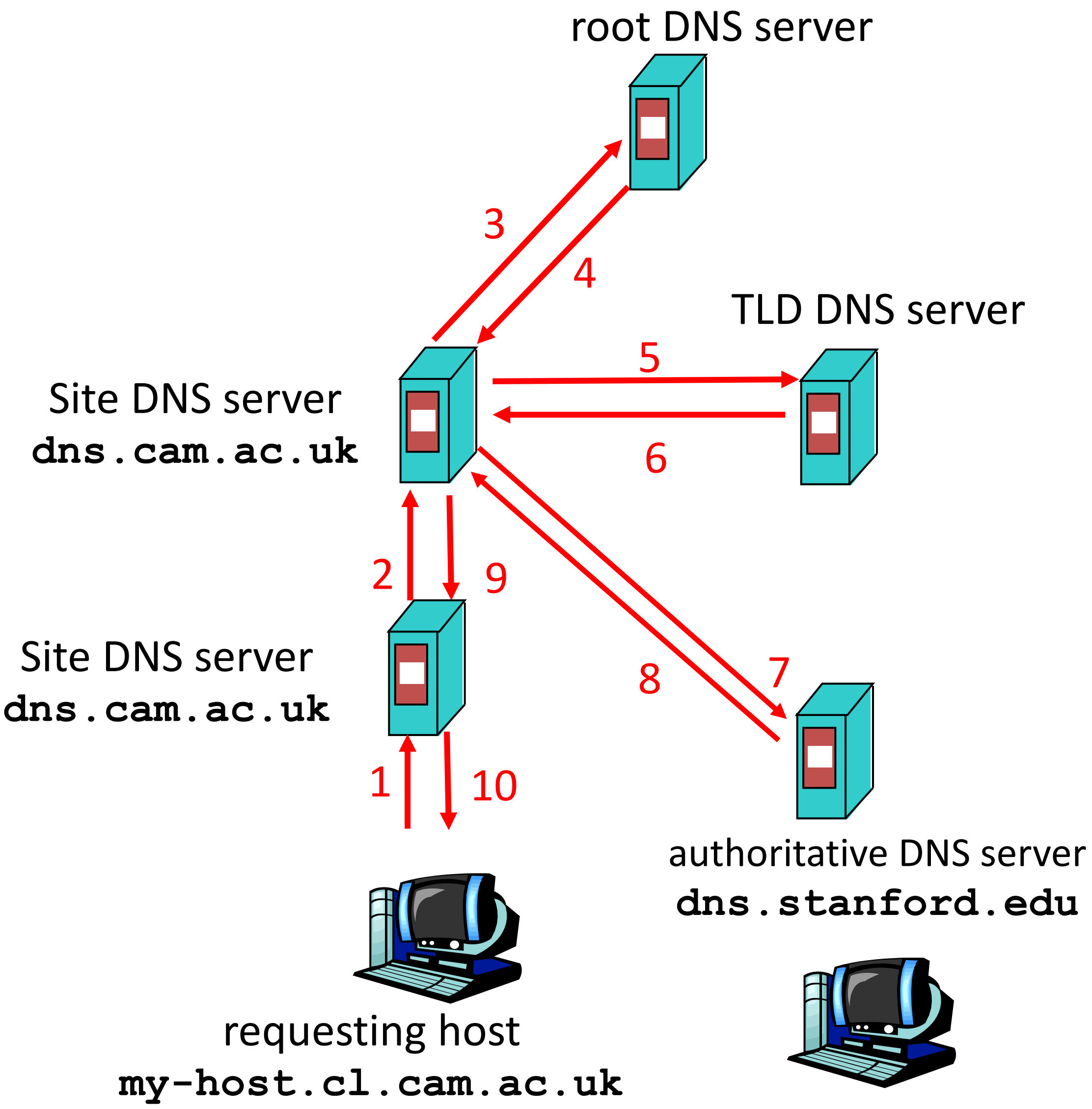
recursive query:

- ❒ puts burden of name resolution on contacted name server
- ❒ heavy load?



Recursive and Iterative Queries - **Hybrid** case

- Recursive query
  - Ask server to get answer for you
  - E.g., requests 1,2 and responses 9,10
- Iterative query
  - Ask server who to ask next
  - E.g., all other request-response pairs



DNS Caching

- Performing all these queries takes time
  - And all this before actual communication takes place
  - E.g., 1-second latency before starting Web download
- Caching can greatly reduce overhead
  - The top-level servers very rarely change
  - Popular sites (e.g., www.bbc.co.uk) 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

Negative Caching

- Remember things that don' t work
  - Misspellings like *bbcc.co.uk* and *www.bbc.com.uk*
  - These can take a long time to fail the first time
  - Good to remember that they don't work
  - … so the failure takes less time the next time around

- But: negative caching is optional
  - And not widely implemented

Reliability

- DNS servers are replicated (primary/secondary)
  - Name service available if at least one replica is up
  - Queries can be load-balanced between replicas
- Usually, UDP used for queries
  - Need reliability: must implement this on top of UDP
  - Spec supports TCP too, but not always implemented
- Try alternate servers on timeout
  - Exponential backoff when retrying same server
- Same identifier for all queries
  - Don’t care which server responds

DNS and Security

- No way to verify answers
  - Opens up DNS to many potential attacks
  - DNSSEC fixes this

- Most obvious vulnerability: recursive resolution
  - Using recursive resolution, host must trust DNS server
  - When at Starbucks, server is under their control
  - And can return whatever values it wants

- More subtle attack: Cache poisoning
  - Those “additional” records can be anything!

Why is the web so successful?

- What do the web, youtube, facebook, tumblr, twitter, flickr, ….. have in common?
  - The ability to self-publish
- Self-publishing that is easy, independent, *free*
- No interest in collaborative and idealistic endeavor
  - People aren’t looking for Nirvana (or even Xanadu)
  - People also aren’t looking for technical perfection
- Want to make their mark, and find something neat
  - Two sides of the same coin, creates synergy
  - “Performance” more important than dialogue….

Web Components

- Infrastructure:
  - Clients
  - Servers
  - Proxies

- Content:
  - Individual objects (files, etc.)
  - Web sites (coherent collection of objects)

- Implementation
  - HTML: formatting content
  - URL: naming content
  - HTTP: protocol for exchanging content

Any content not just HTML!

HTML: HyperText Markup Language

- A *Web page* has:
  - – Base HTML file
  - – Referenced objects (*e.g.*, images)

- HTML has several functions:
  - – Format text
  - – Reference images
  - – Embed *hyperlinks* (HREF)

URL Syntax

protocol : / /hostname[:port] /directorypath /resource

protocol	http, ftp, https, smtp, rtsp, *etc*.
hostname	DNS name, IP address
port	Defaults to protocol’s standard port *e.g.* http: 80 https: 443
directory path	Hierarchical, reflecting file system
resource	Identifies the desired resource

Can also extend to program executions:

```
http://us.f413.mail.yahoo.com/ym/ShowLetter?box=%4
0B%40Bulk&MsgId=2604_1744106_29699_1123_1261_0_289
17_3552_1289957100&Search=&Nhead=f&YY=31454&order=
down&sort=date&pos=0&view=a&head=b
```

HyperText Transfer Protocol (HTTP)

- Request-response protocol
- Reliance on a global namespace
- Resource *metadata*
- *Stateless*
- ASCII format

```
$ telnet www.cl.cam.ac.uk 80
GET /~awm22/win HTTP/1.0
<blank line, i.e., CRLF>
```

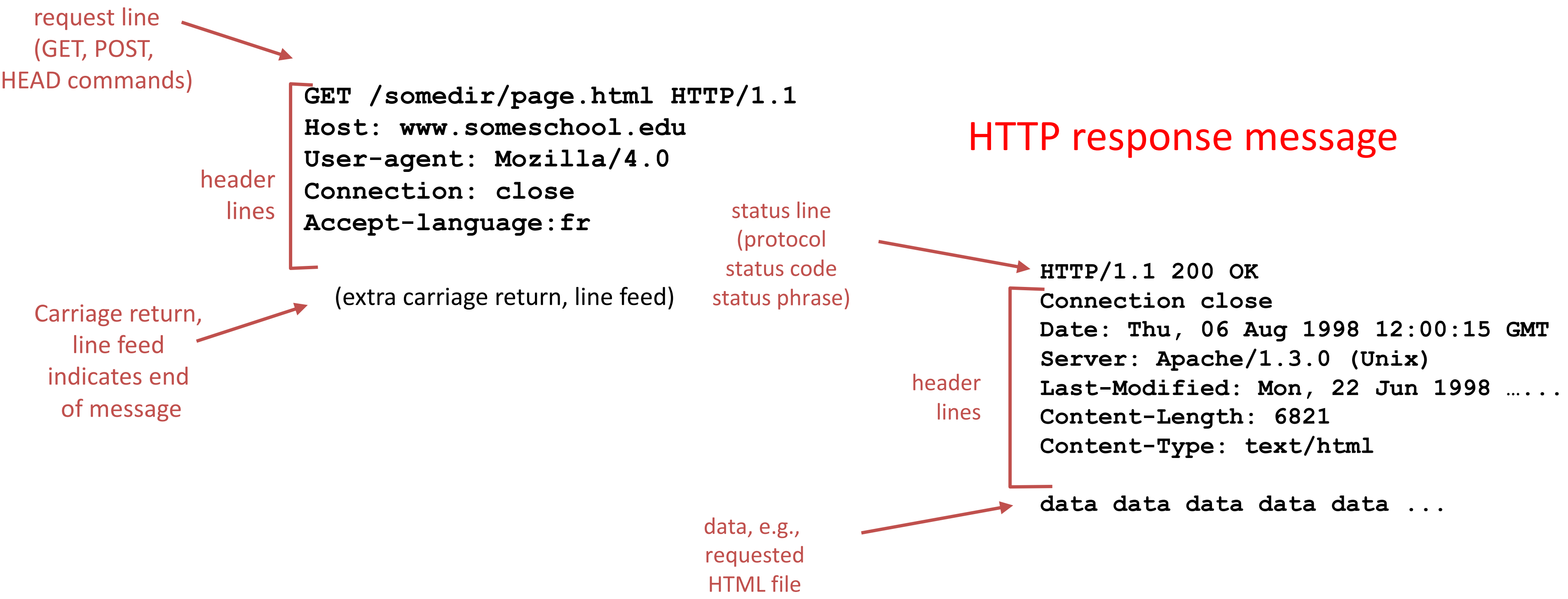
Steps in HTTP Request

- HTTP Client initiates TCP connection to server
  - SYN
  - SYNACK
  - ACK
- Client sends HTTP request to server
  - Can be piggybacked on TCP's ACK
- HTTP Server responds to request
- Client receives the request, terminates connection
- TCP connection termination exchange

How many RTTs for a single request?

Client-Server Communication

- two types of HTTP messages: *request, response*
- HTTP request message: (GET POST HEAD ….)



request line (GET, POST, HEAD commands)

header lines

```
GET /somedir/page.html HTTP/1.1
Host: www.someschool.edu
User-agent: Mozilla/4.0
Connection: close
Accept-language:fr
```

(extra carriage return, line feed)

Carriage return, line feed indicates end of message

HTTP response message

status line (protocol status code status phrase)

header lines

```
HTTP/1.1 200 OK
Connection close
Date: Thu, 06 Aug 1998 12:00:15 GMT
Server: Apache/1.3.0 (Unix)
Last-Modified: Mon, 22 Jun 1998 …...
Content-Length: 6821
Content-Type: text/html

data data data data data ...
```

data, e.g., requested HTML file

Different Forms of Server Response

- Return a file
  - URL matches a file (*e.g.,* `/www/index.html`)
  - Server returns file as the response
  - Server generates appropriate response header

- Generate response dynamically
  - URL triggers a program on the server
  - Server runs program and sends output to client

- Return meta-data with no body

HTTP Resource Meta-Data

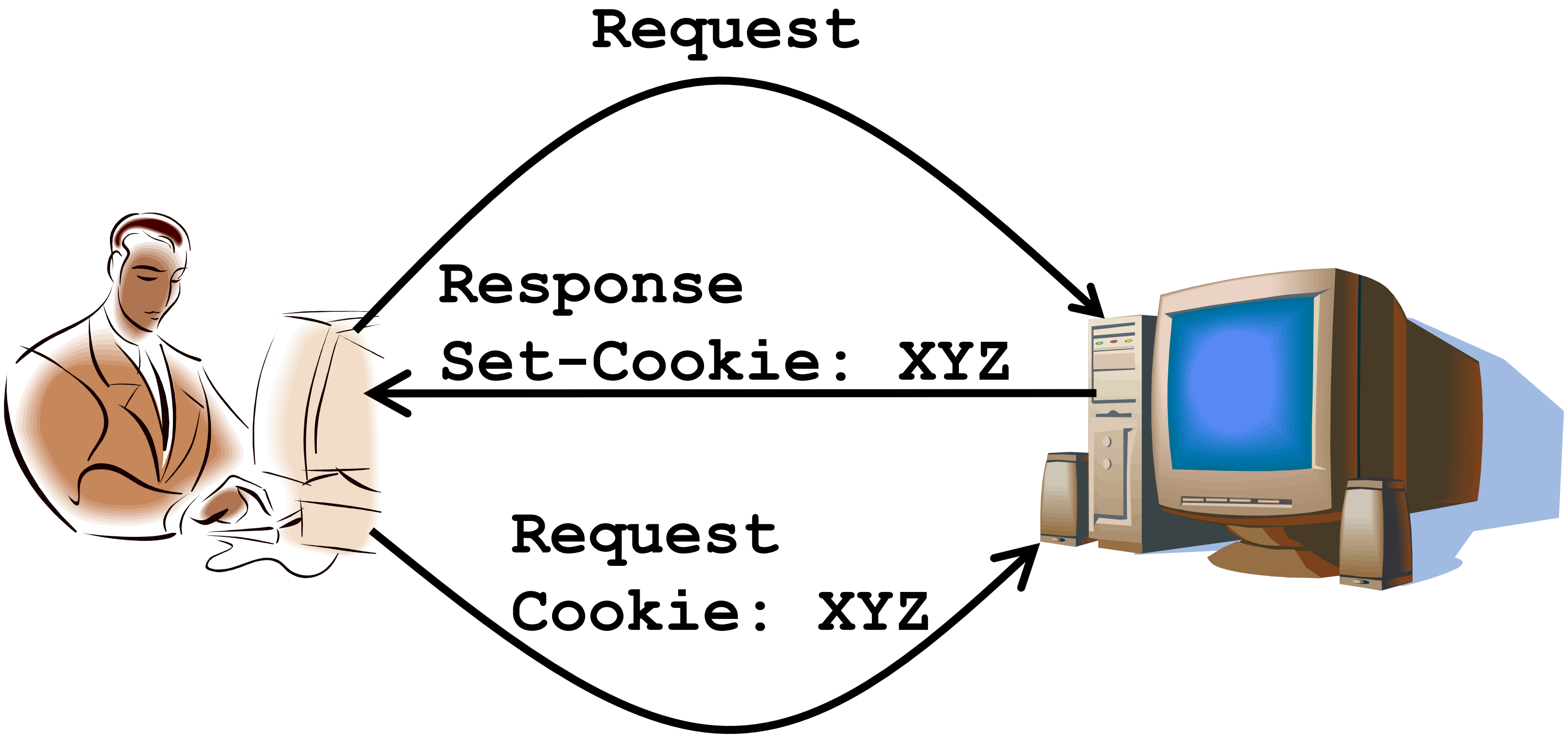
- Meta-data
  - Info *about* a resource, stored as a separate entity
- Examples:
  - Size of resource, last modification time, type of content
- Usage example: Conditional GET Request
  - Client requests object "**`If-modified-since`**"
  - If unchanged, "**`HTTP/1.1 304 Not Modified`**"
  - No body in the server's response, only a header

HTTP is *Stateless*

- Each request-response treated independently
  - Servers *not* required to retain state
- **Good**: Improves scalability on the server-side
  - Failure handling is easier
  - Can handle higher rate of requests
  - Order of requests doesn‘t matter
- **Bad**: Some applications need persistent state
  - Need to uniquely identify user or store temporary info
  - *e.g.,* Shopping cart, user profiles, usage tracking, …

State in a Stateless Protocol:
Cookies

- *Client-side* state maintenance
  - Client stores small(?) state on behalf of server
  - Client sends state in future requests to the server
- Can provide authentication



Request

Response
Set-Cookie: XYZ

Request
Cookie: XYZ

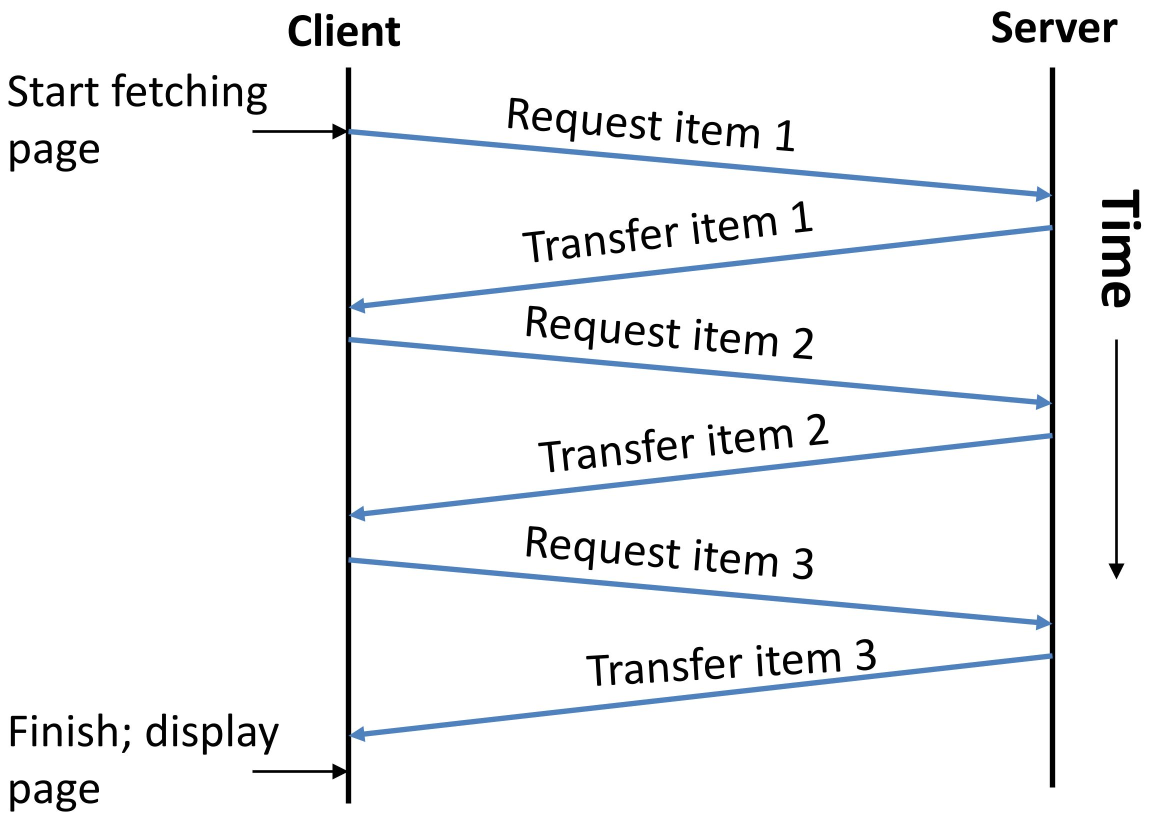
HTTP Performance

- Most Web pages have multiple objects
  - *e.g.,* HTML file and a bunch of embedded images

- How do you retrieve those objects (naively)?
  - *One item at a time*

- Put stuff in the optimal place?
  - *Where is that precisely?*
    - ***Enter the Web cache and the CDN***

Fetch HTTP Items: Stop & Wait

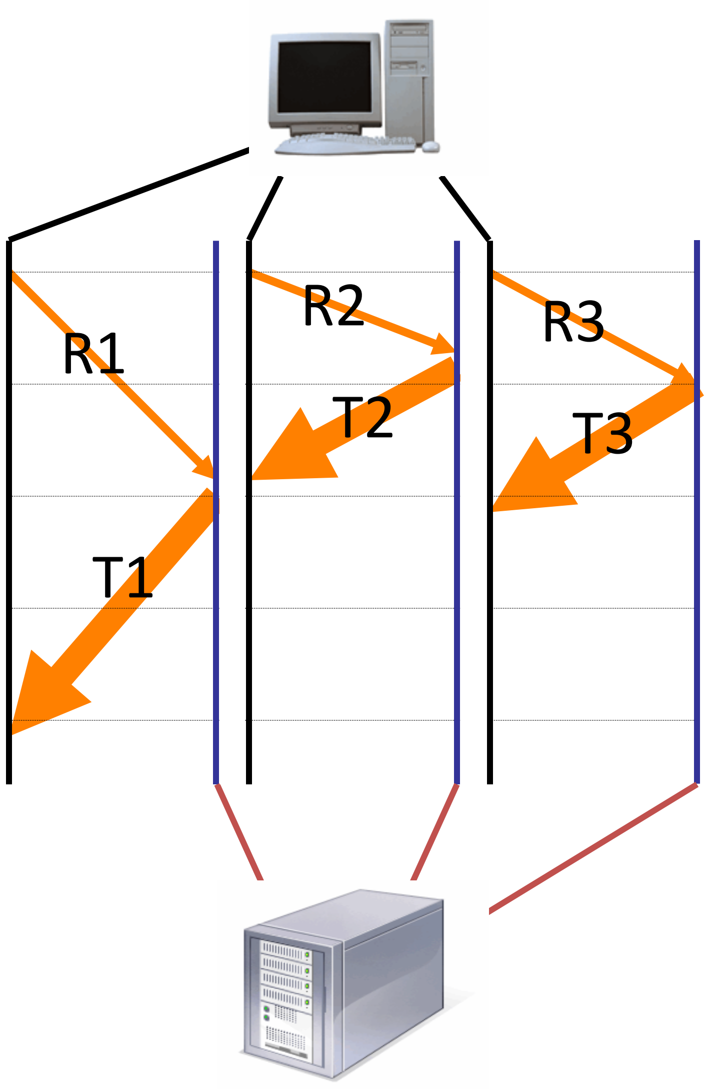


≥2 RTTs per object

Improving HTTP Performance:

Concurrent Requests & Responses

- Use multiple connections *in parallel*
- Does not necessarily maintain order of responses

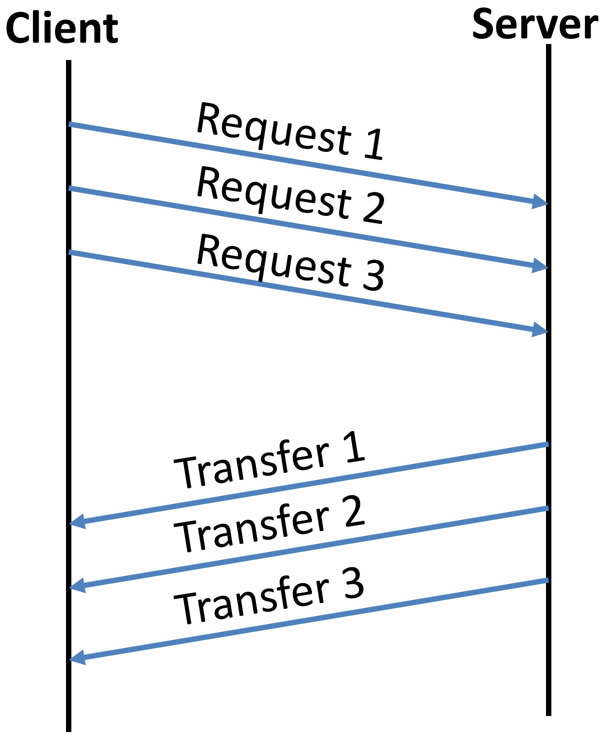


- Client = ☺
- Server = ☺
- Network = ☹ Why?

Improving HTTP Performance:

Pipelined Requests & Responses

- *Batch* requests and responses
  - Reduce connection overhead
  - Multiple requests sent in a single batch
  - Maintains order of responses
  - Item 1 always arrives before item 2
- How is this different from concurrent requests/responses?
  - Single TCP connection



Improving HTTP Performance:

Persistent Connections

- Enables multiple transfers per connection
  - Maintain TCP connection across multiple requests
  - Including transfers subsequent to current page
  - Client or server can tear down connection
- Performance advantages:
  - Avoid overhead of connection set-up and tear-down
  - Allow TCP to learn more accurate RTT estimate
  - Allow TCP congestion window to increase
  - i.e., leverage previously discovered bandwidth
- Default in HTTP/1.1

HTTP *evolution*

- 1.0 – one object per TCP: simple but slow
- Parallel connections - multiple TCP, one object each: wastes b/w, may be svr limited, out of order
- 1.1 pipelining – aggregate retrieval time: ordered, multiple objects sharing single TCP
- 1.1 persistent – aggregate TCP overhead: lower overhead in time, increase overhead at ends (e.g., when should/do you close the connection?)

Scorecard: Getting n Small Objects

Time dominated by latency

- One-at-a-time: ~2n RTT
- Persistent: ~ (n+1)RTT
- M concurrent: ~2[n/m] RTT
- Pipelined: ~2 RTT
- Pipelined/Persistent: ~2 RTT first time, RTT later

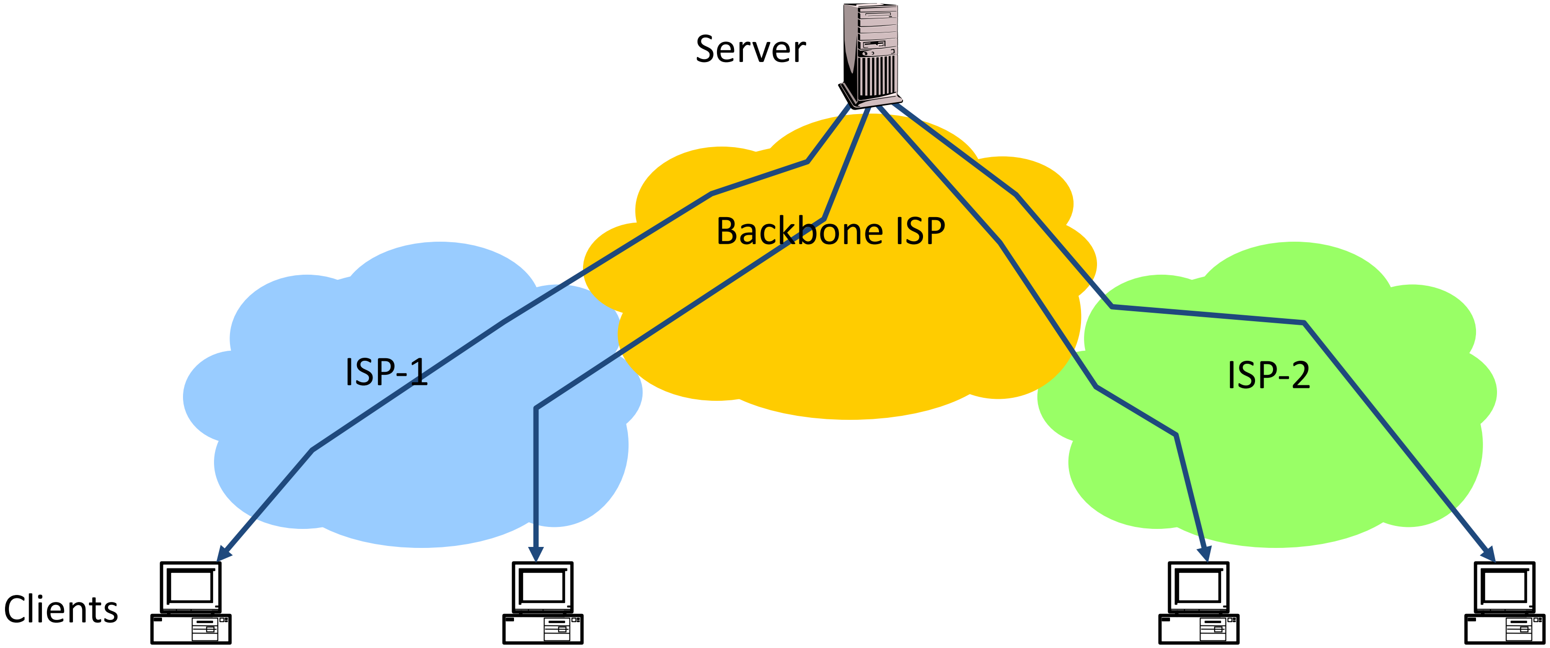
Scorecard: Getting n Large Objects

Time dominated by bandwidth

- One-at-a-time: ~ nF/B
- M concurrent: ~ [n/m] F/B
  - assuming shared with large population of users
- Pipelined and/or persistent: ~ nF/B
  - The only thing that helps is getting more bandwidth..

Improving HTTP Performance: Caching

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



Improving HTTP Performance:
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

Improving HTTP Performance:
Caching: Why

- Motive for placing content closer to client:
  - User gets better response time
  - Content providers get happier users
    - Time is money, really!
  - 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

Improving HTTP Performance:

Caching on the Client

Example: Conditional GET Request

- Return resource only if it has changed at the server
  - Save server resources!

Request from client to server:

```
GET /~awm22/win HTTP/1.1
Host: www.cl.cam.ac.uk
User-Agent: Mozilla/4.03
If-Modified-Since: Sun, 27 Aug 2006 22:25:50 GMT
<CRLF>
```

- How?
  - Client specifies “if-modified-since” time in request
  - Server compares this against “last modified” time of desired resource
  - Server returns “304 Not Modified” if resource has not changed
  - …. or a “200 OK” with the latest version otherwise

Improving HTTP Performance:

Caching with Reverse Proxies

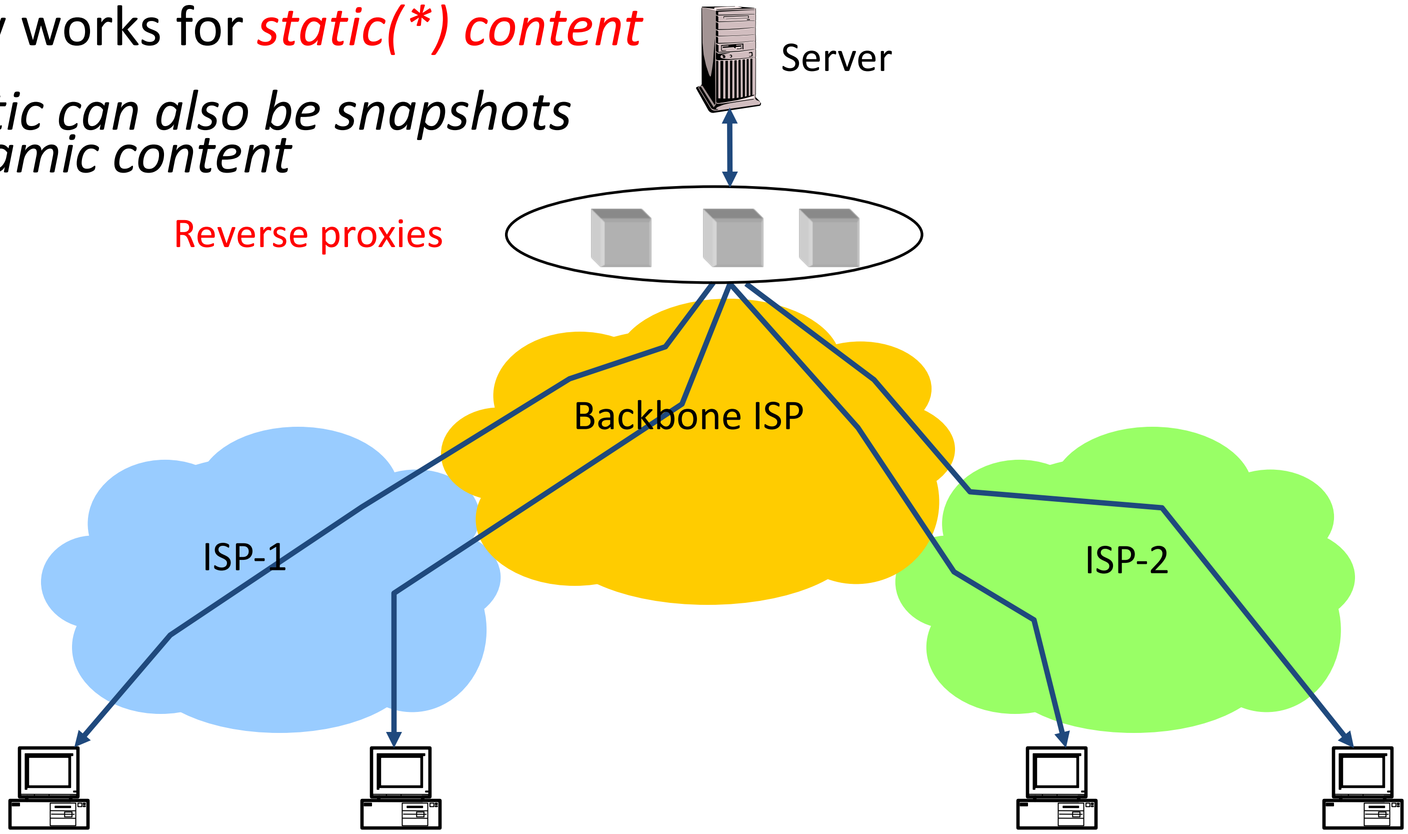
Cache documents close to **server**

→ decrease server load

- Typically done by content providers

- Only works for *static(*) content*

(*) static can also be snapshots of dynamic content

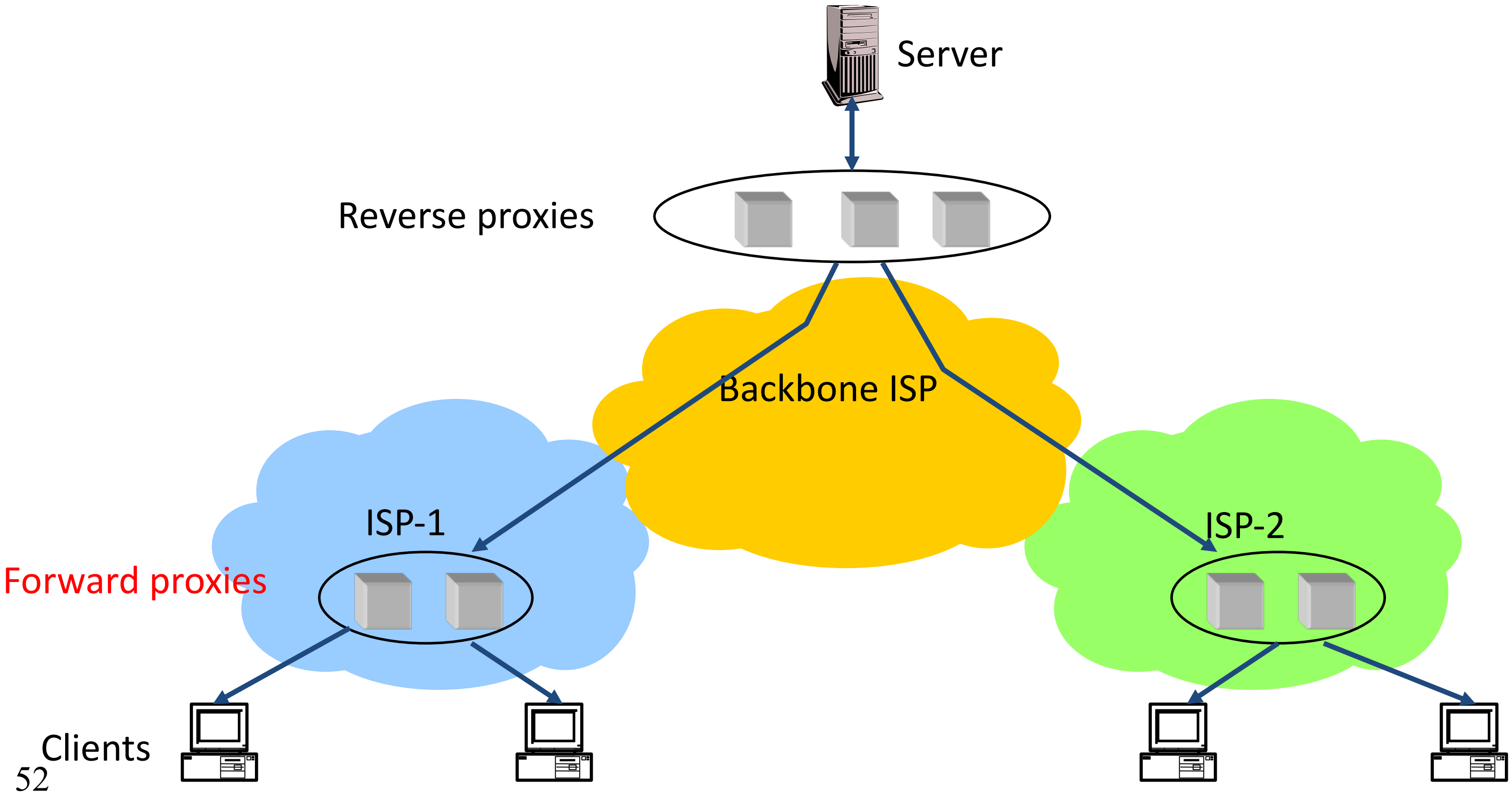


Improving HTTP Performance:

Caching with Forward Proxies

Cache documents close to **clients**
→ reduce network traffic and decrease latency

- Typically done by ISPs or corporate LANs



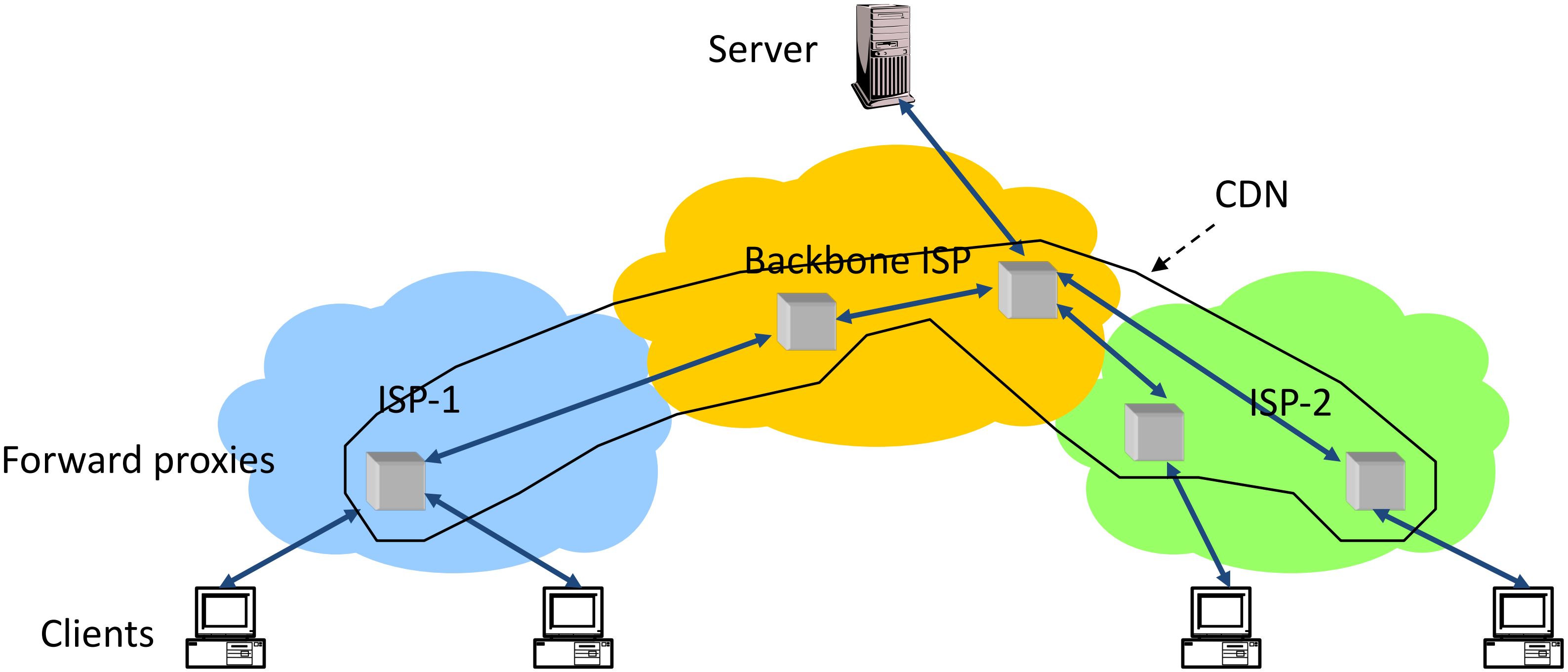
Improving HTTP Performance:

Caching w/ Content Distribution Networks

- Integrate forward and reverse caching functionality
  - One overlay network (usually) administered by one entity
  - *e.g.,* Akamai
- Provide document caching
  - **Pull:** Direct result of clients' requests
  - **Push:** Expectation of high access rate
- Also do some processing
  - Handle *dynamic* web pages
  - *Transcoding*
  - *Maybe do some security function – watermark IP*

Improving HTTP Performance:

Caching with CDNs (cont.)



Improving HTTP Performance:

CDN Example – Akamai

- Akamai creates new domain names for each client content provider.
  - e.g., *a128.g.akamai.net*
- The CDN's DNS servers are authoritative for the new domains
- The client content provider modifies its content so that embedded URLs reference the new domains.
  - "Akamaize" content
  - e.g.: *http://www.bbc.co.uk/popular-image.jpg* becomes *http://a128.g.akamai.net/popular-image.jpg*
- *Requests now sent to CDN's infrastructure…*

Hosting: Multiple Sites Per Machine

- Multiple Web sites on a single machine
  - Hosting company runs the Web server on behalf of multiple sites (*e.g.*, www.foo.com and www.bar.com)
- Problem: `GET /index.html`
  - `www.foo.com/index.html` or `www.bar.com/index.html`?
- Solutions:
  - Multiple server processes on the same machine
    - Have a separate IP address (or port) for each server
  - Include site name in HTTP request
    - Single Web server process with a single IP address
    - Client includes "Host" header (*e.g.,* `Host: www.foo.com`)
    - *Required header* with HTTP/1.1

Hosting: Multiple Machines Per Site

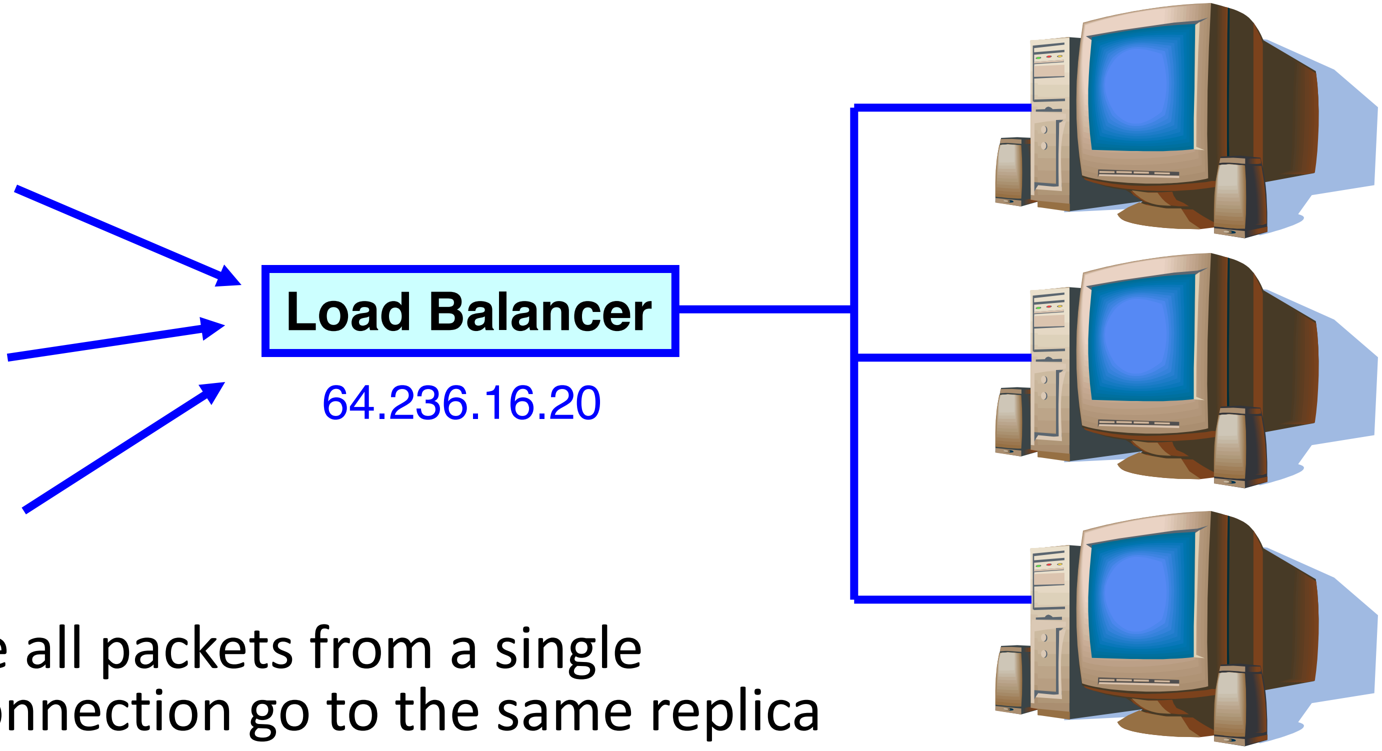
- Replicate popular Web site across many machines
  - Helps to handle the load
  - Places content closer to clients

- Helps when content isn’t cacheable

- Problem: Want to direct client to particular replica
  - Balance load across server replicas
  - Pair clients with nearby servers

Multi-Hosting at Single Location

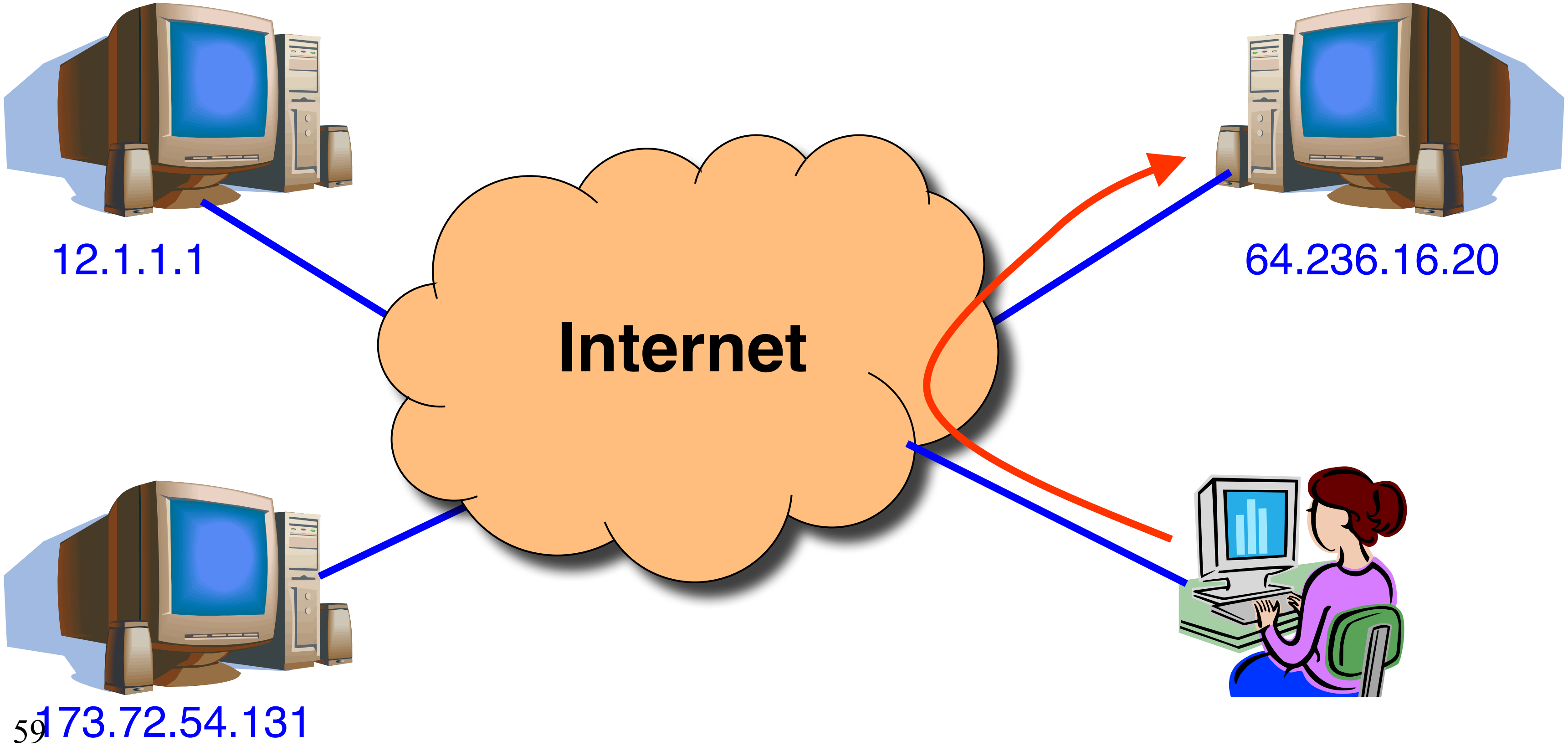
- Single IP address, multiple machines
  - Run multiple machines behind a single IP address



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

Multi-Hosting at Several Locations

- Multiple addresses, multiple machines
  - Same name but different addresses for all of the replicas
  - Configure DNS server to return *closest* address



CDN examples round-up

- CDN using DNS

  DNS has information on loading/distribution/location

- CDN using anycast

  same address from DNS name but local routes

- CDN based on rewriting HTML URLs

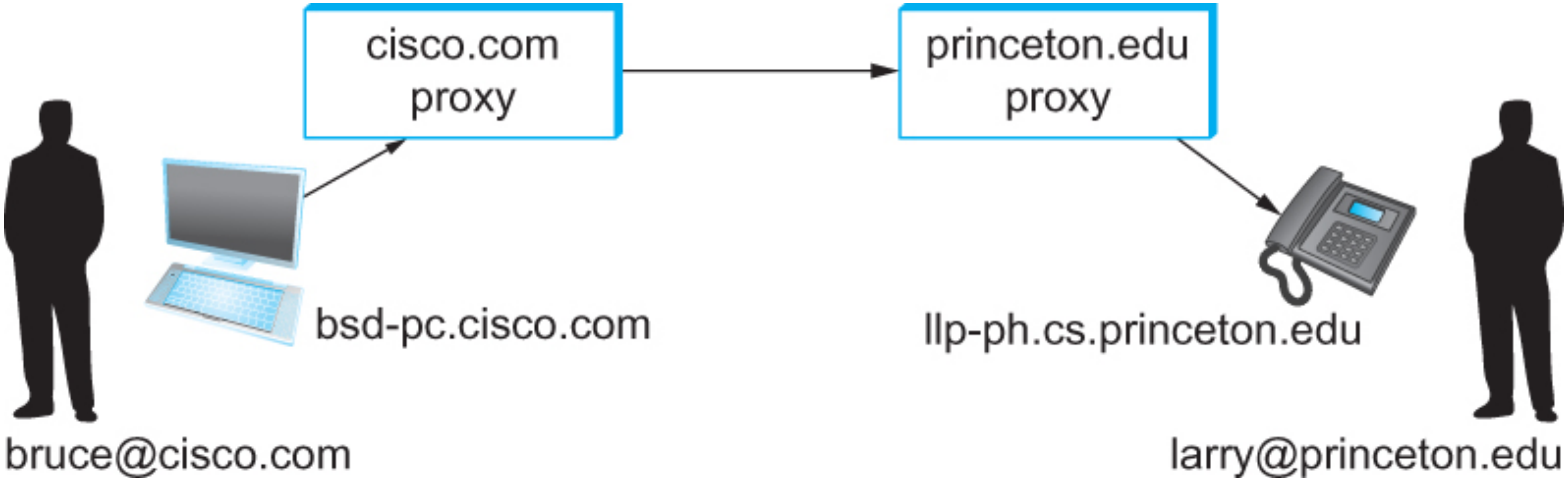
  (akami example just covered – akami uses DNS too)

SIP – Session Initiation Protocol

Session?

Anyone smell an OSI / ISO standards document burning?

SIP - VoIP



Establishing communication through SIP proxies.

SIP?

- SIP – bringing the fun/complexity of telephony to the Internet
  - User location
  - User availability
  - User capabilities
  - Session setup
  - Session management
    - (e.g. “call forwarding”)

H.323 – ITU

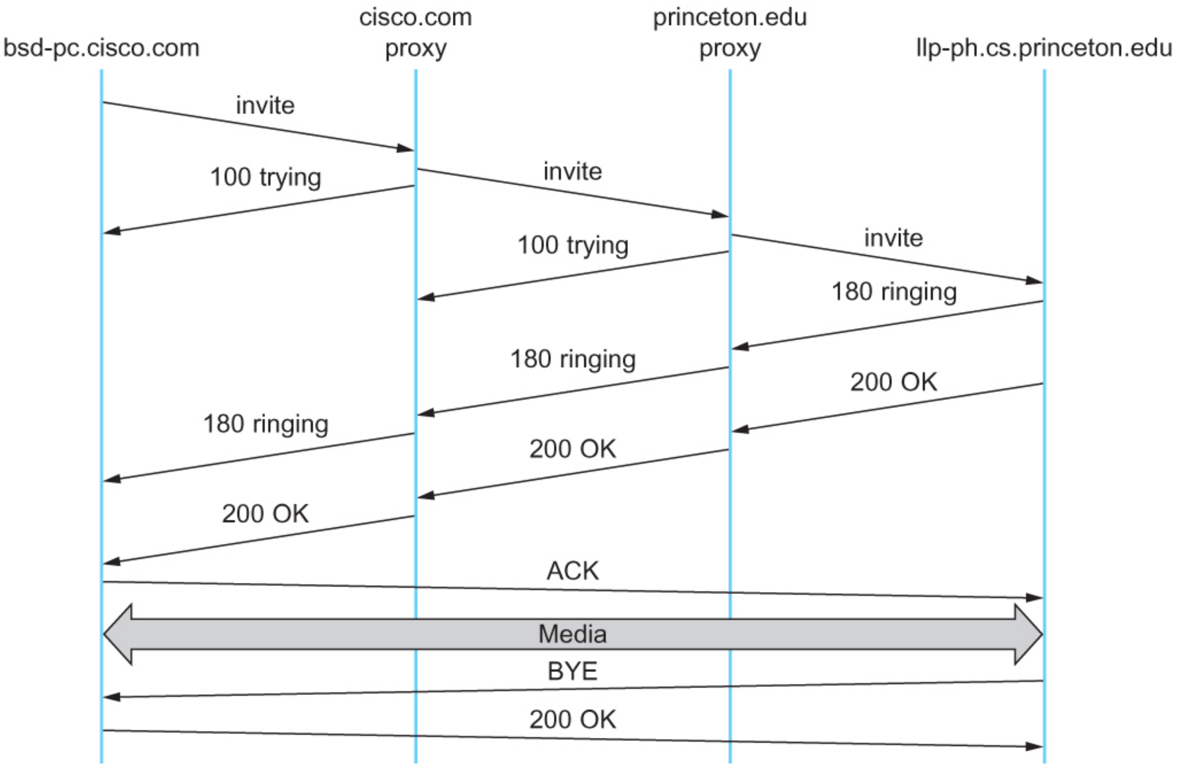
- Why have one standard when there are at least two….

- The full H.323 is hundreds of pages
  - The protocol is known for its complexity – an ITU hallmark

- SIP is not much better

  - IETF grew up and became the ITU….

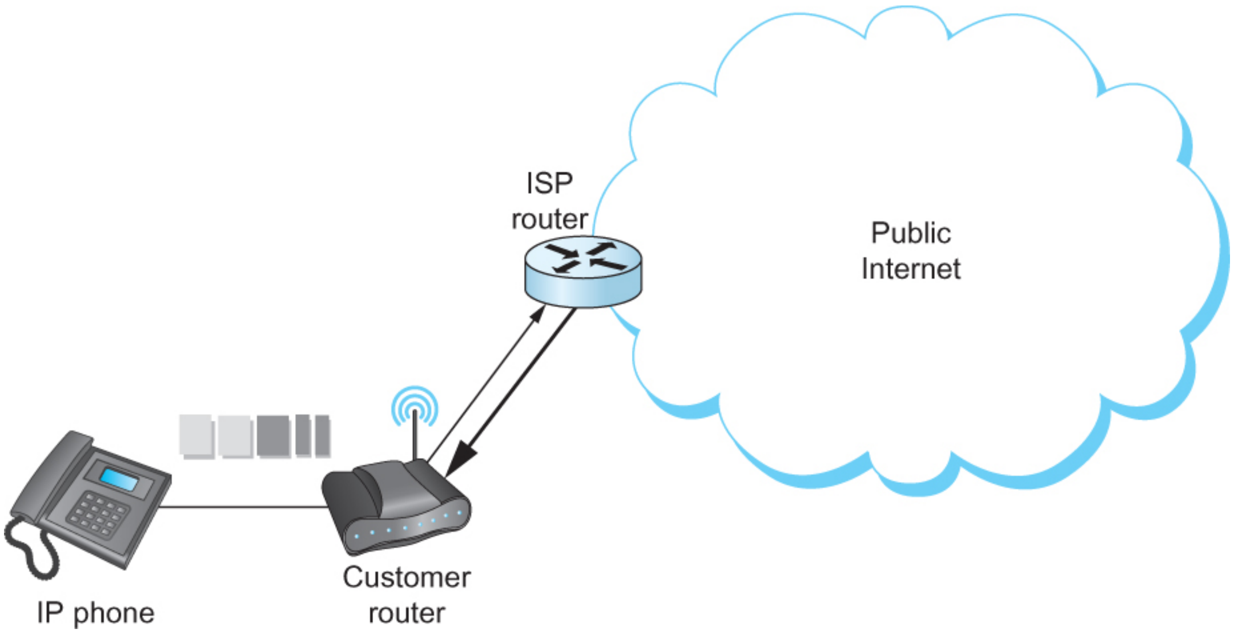
Multimedia Applications



Message flow for a basic SIP session

The (still?) missing piece:

Resource Allocation for Multimedia Applications

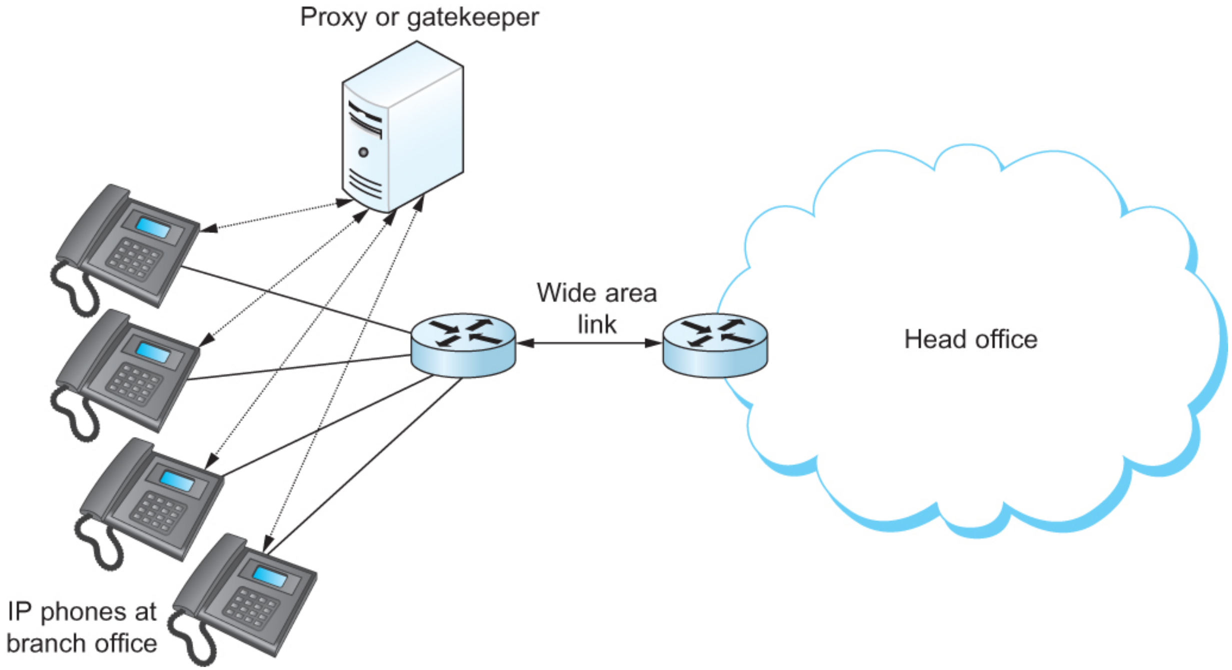


I can 'differentiate' VoIP from data but…

I can only control data going into the Internet

Multimedia Applications

- Resource Allocation for Multimedia Applications



Admission control using session control protocol.

Resource Allocation for Multimedia Applications

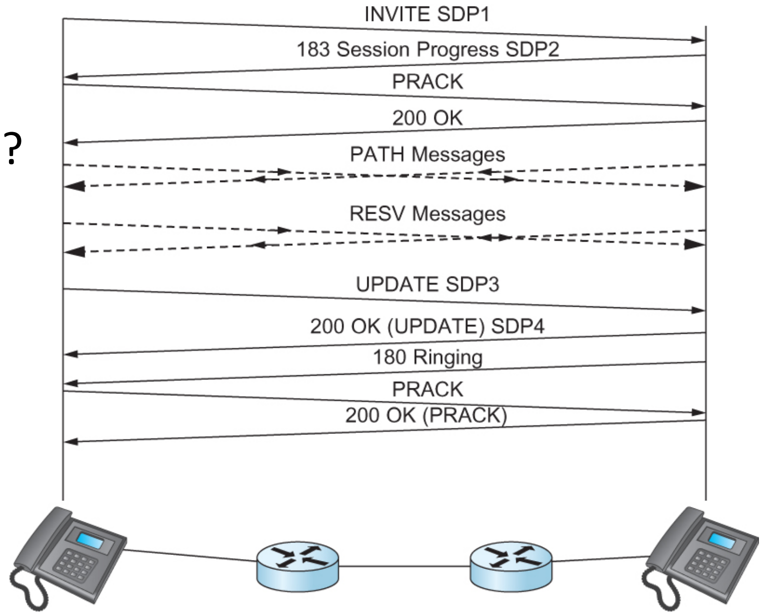
Coming soon… ~~1995~~

~~2000~~

~~2010~~

who are we kidding??

Co-ordination of SIP signaling and resource reservation.



So where does it happen?

Inside single institutions or *domains of control…..*

(Universities, Hospitals, big corp…)

What about my aDSL/CABLE/etc it combines voice and data?

Phone company **controls** the multiplexing on the line

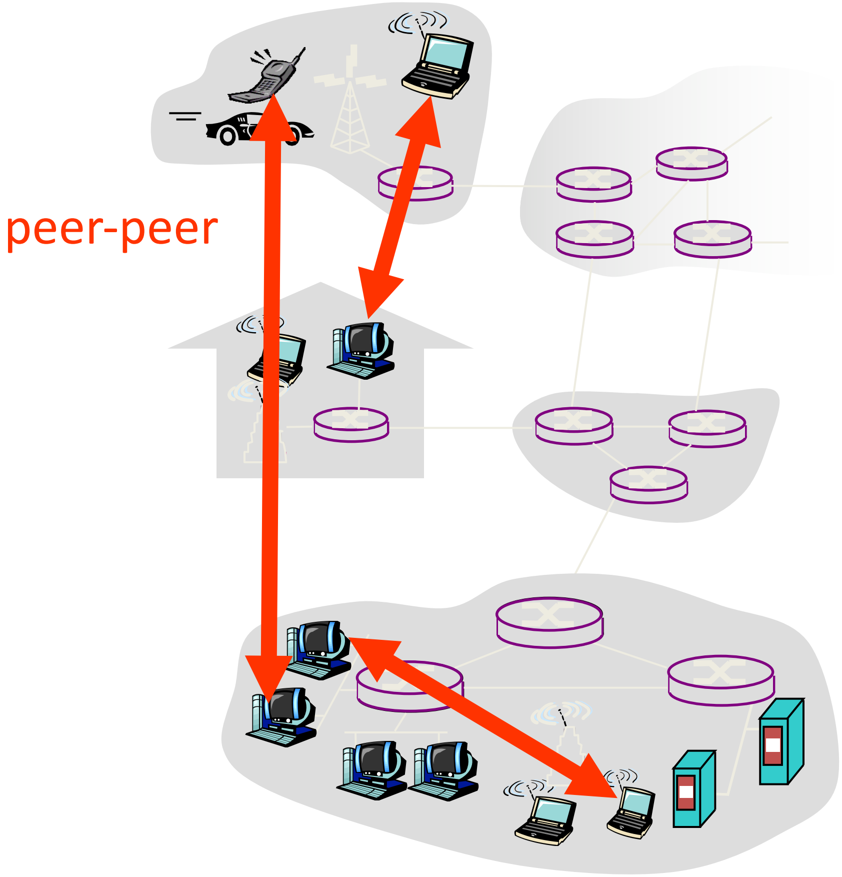
and throughout their own network too……

P2P – efficient network use that annoys the ISP

Pure P2P architecture

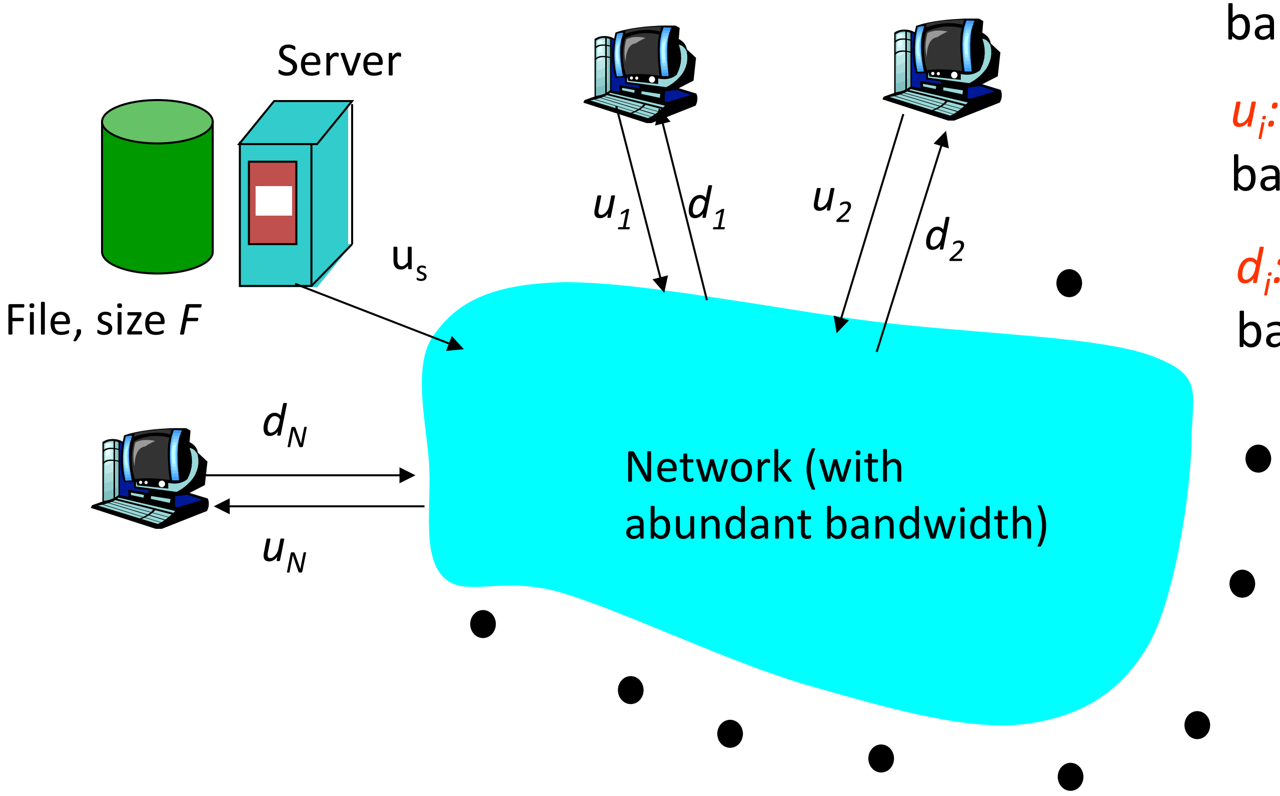
- *no* always-on server
- arbitrary end systems directly communicate
- peers are intermittently connected and change IP addresses

- Three topics:
  - File distribution
  - Searching for information
  - Case Study: Skype



File Distribution: Server-Client vs P2P

Question : How much time to distribute file from one server to *N peers*?



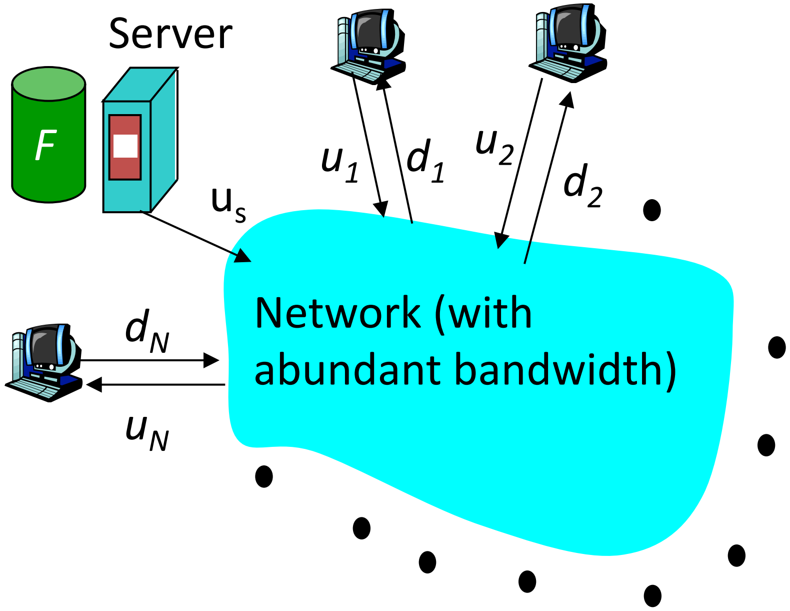
u_s: server upload bandwidth

u_i: peer i upload bandwidth

d_i: peer i download bandwidth

File distribution time: server-client

- server sequentially sends N copies:
  - *NF/u_s* time
- client i takes F/d_i time to download

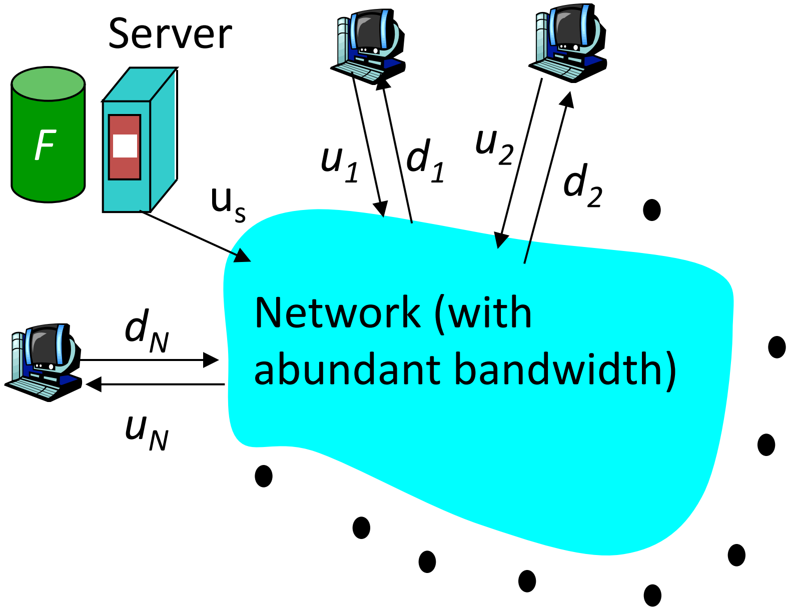


Time to distribute *F* to *N* clients using client/server approach $= d_{cs} = \max \{ NF/u_s, F/\min_i(d_i) \}$

increases linearly in N
(for large N)

File distribution time: P2P

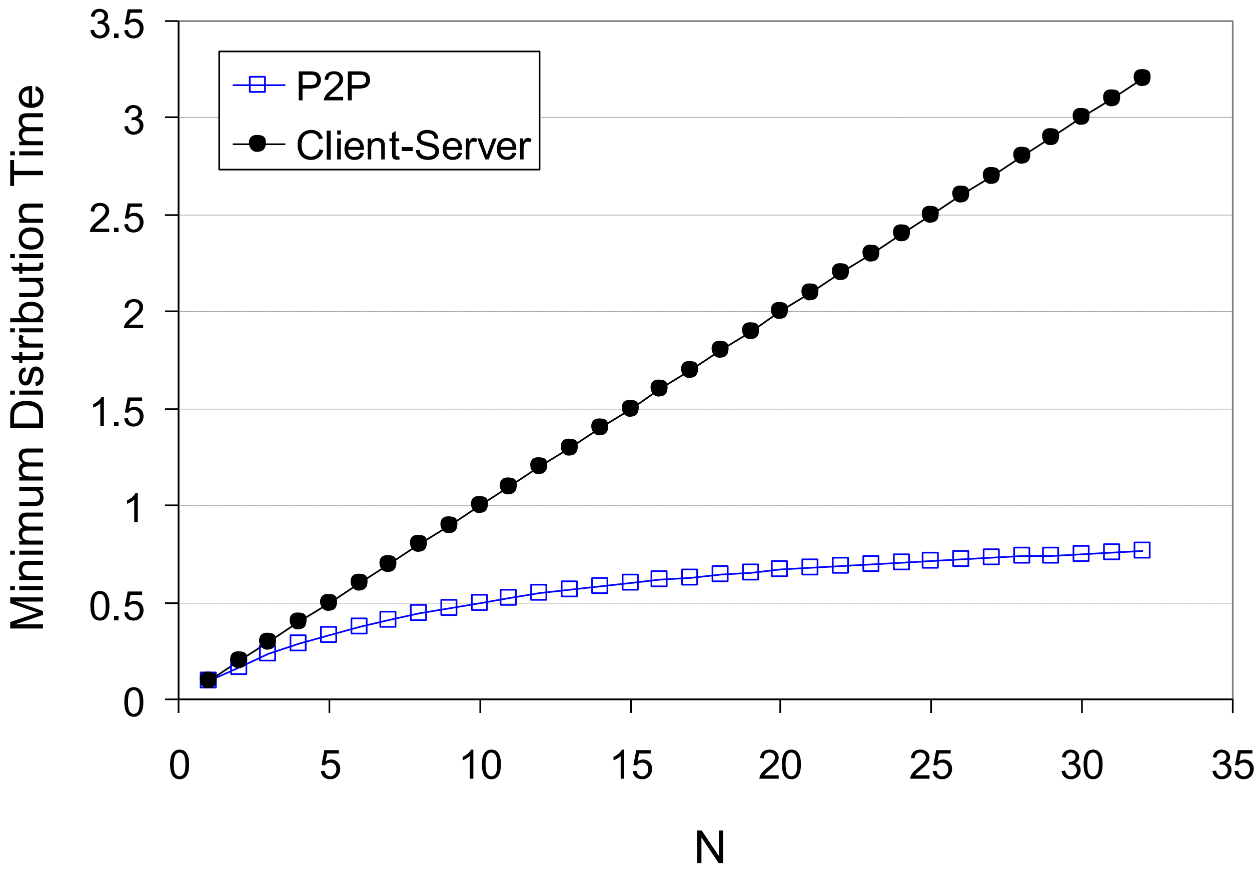
- server must send one copy: F/u_s time
- client i takes F/d_i time to download
- NF bits must be downloaded (aggregate)
  - ❐ fastest possible upload rate: $u_s + \sum u_i$



$$d_{P2P} = \max \left\{ F/u_s,\ F/\min_i(d_i)\ ,\ NF/(u_s + \sum u_i) \right\}$$

Server-client vs. P2P: example

Client upload rate = u, F/u = 1 hour, u_s = 10u, $d_{min} \geq u_s$



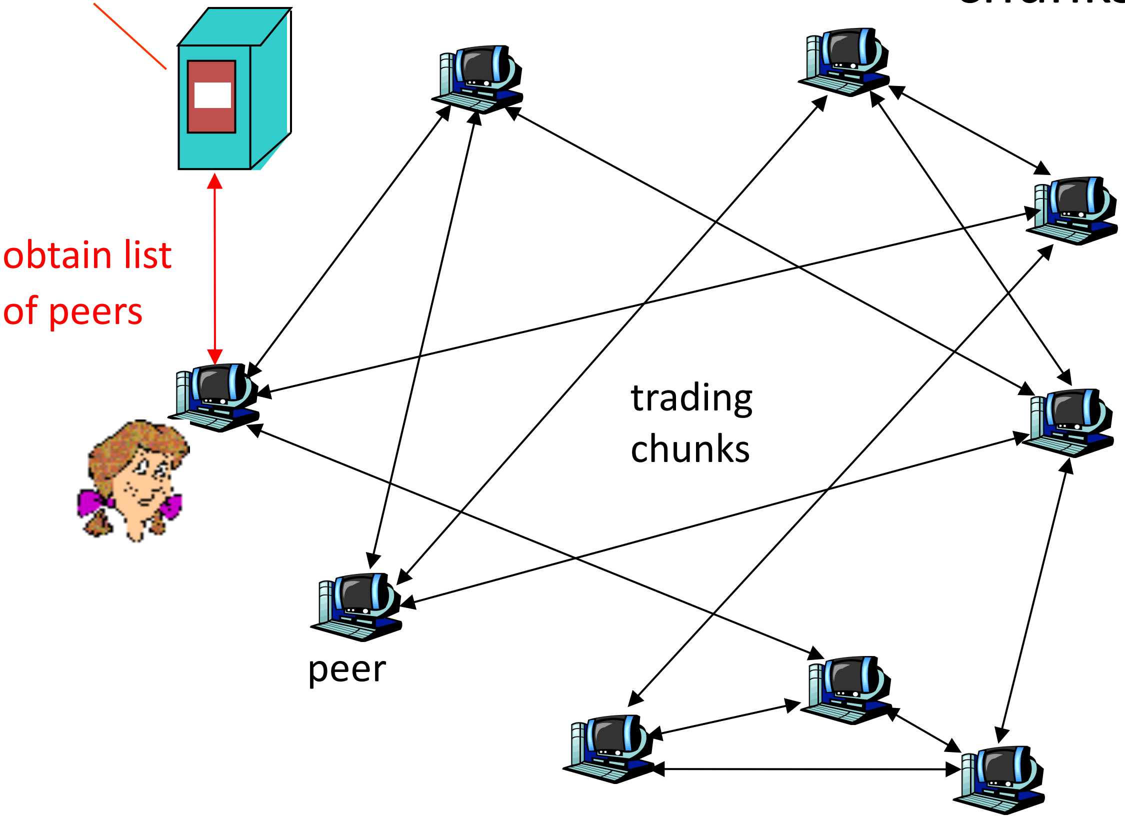
File distribution: BitTorrent*

*rather old BitTorrent

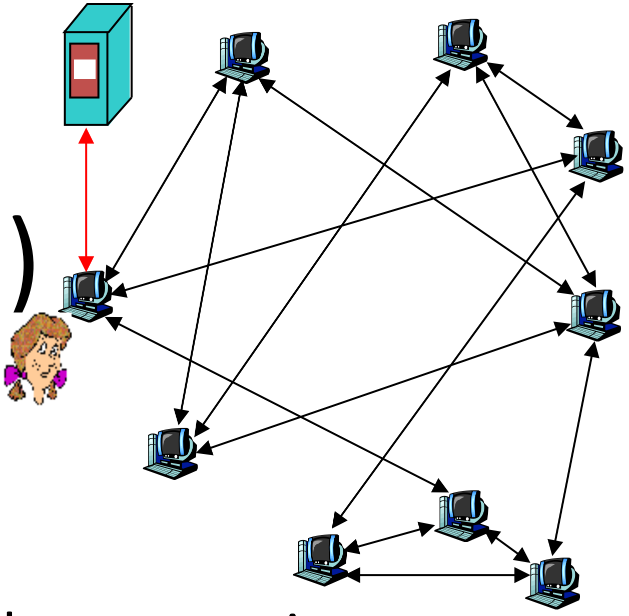
- P2P file distribution

tracker: tracks peers participating in torrent

torrent: group of peers exchanging chunks of a file



BitTorrent (1)



- file divided into 256KB *chunks*.
- peer joining torrent:
  - has no chunks, but will accumulate them over time
  - registers with tracker to get list of peers, connects to subset of peers (“neighbors”)
- while downloading, peer uploads chunks to other peers.
- peers may come and go
- once peer has entire file, it may (selfishly) leave or (altruistically) remain

BitTorrent (2)

Pulling Chunks

- at any given time, different peers have different subsets of file chunks
- periodically, a peer (Alice) asks each neighbor for list of chunks that they have.
- Alice sends requests for her missing chunks
  - rarest first

Sending Chunks: tit-for-tat

❒ Alice sends chunks to four neighbors currently sending her chunks *at the highest rate*

  ❖ re-evaluate top 4 every 10 secs

❒ every 30 secs: randomly select another peer, starts sending chunks

  ❖ newly chosen peer may join top 4

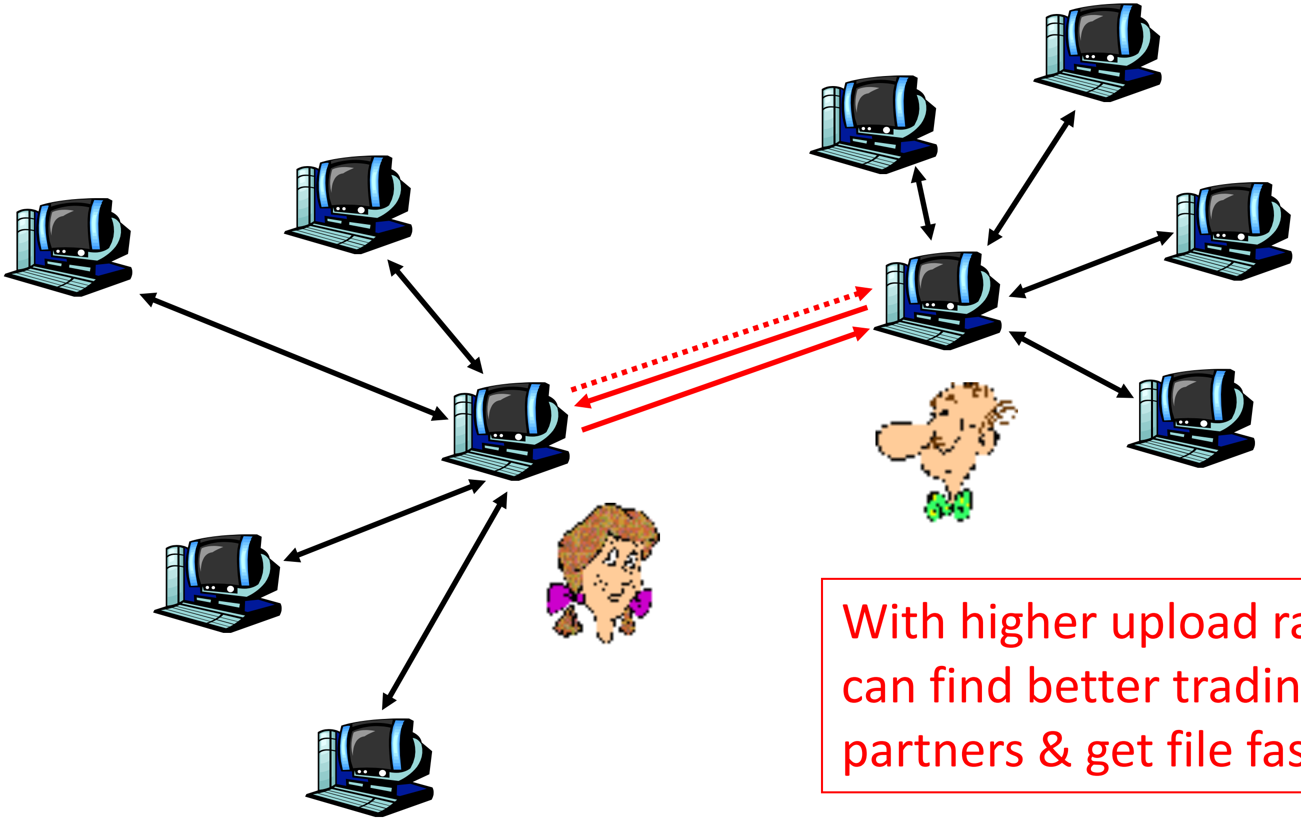
  ❖ "optimistically unchoke"

BitTorrent: Tit-for-tat

(1) Alice “optimistically unchokes” Bob

(2) Alice becomes one of Bob’s top-four providers; Bob reciprocates

(3) Bob becomes one of Alice’s top-four providers



With higher upload rate, can find better trading partners & get file faster!

Distributed Hash Table (DHT)

- DHT = distributed P2P database
- Database has (key, value) pairs;
  - key: ss number; value: human name
  - key: content type; value: IP address
- Peers query DB with key
  - DB returns values that match the key
- Peers can also insert (key, value) peers

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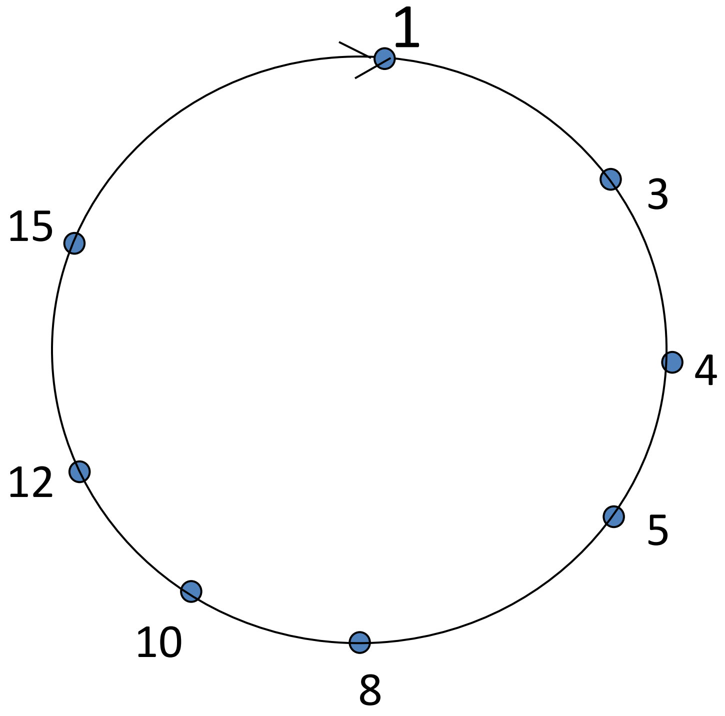
DHT Identifiers

- Assign integer identifier to each peer in range $[0,2^n-1]$.
  - Each identifier can be represented by n bits.
- Require each key to be an integer in same range.
- To get integer keys, hash original key.
  - eg, key = h("Game of Thrones season 4")
  - This is why they call it a distributed "hash" table

How to assign keys to peers?

- Central issue:
  - Assigning (key, value) pairs to peers.
- Rule: assign key to the peer that has the closest ID.
- Convention in lecture: closest is the immediate successor of the key.
- Ex: n=4; peers: 1,3,4,5,8,10,12,14;
  - key = 13, then successor peer = 14
  - key = 15, then successor peer = 1

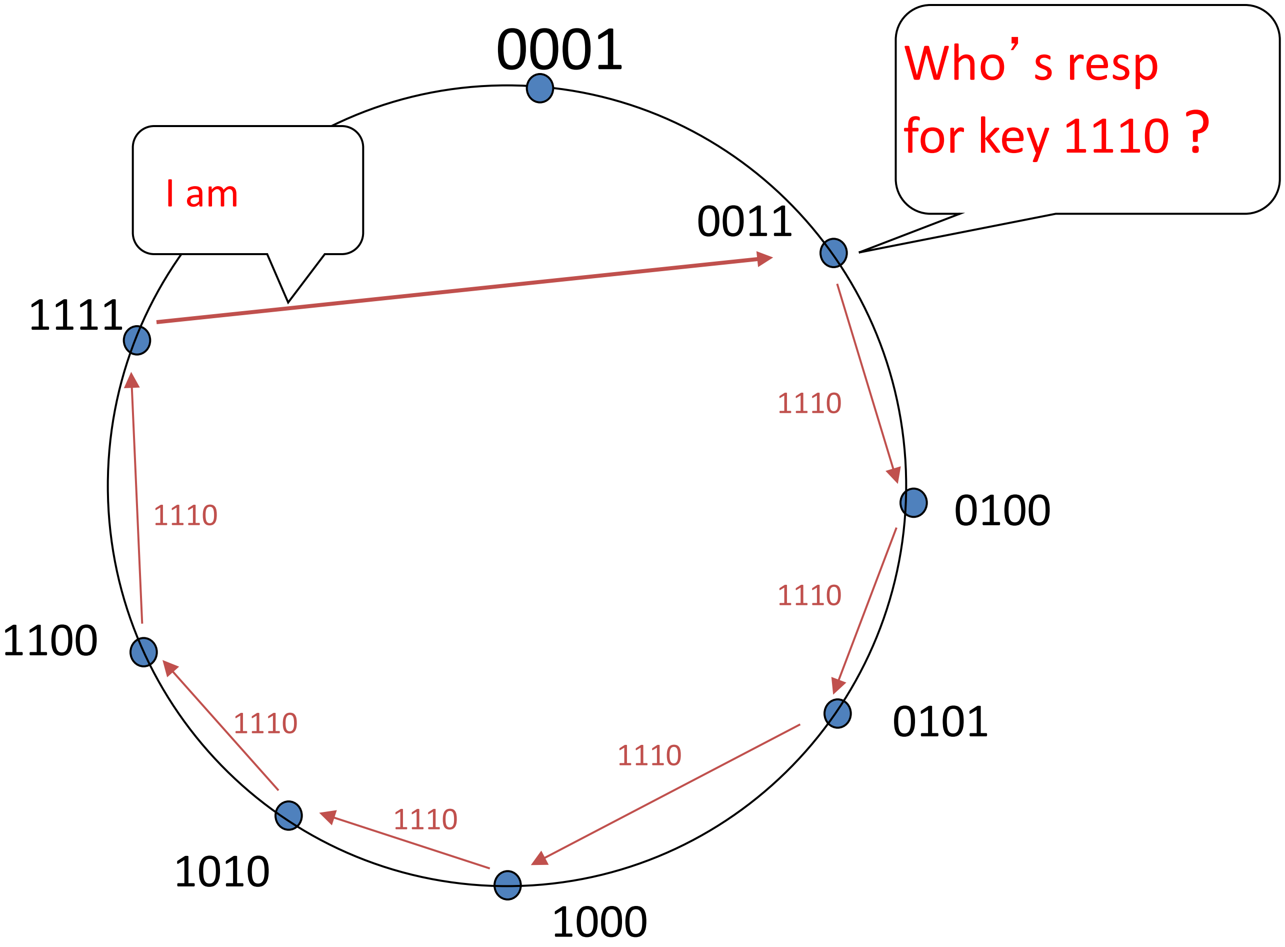
Circular DHT (1)



- Each peer *only* aware of immediate successor and predecessor.
- “Overlay network”

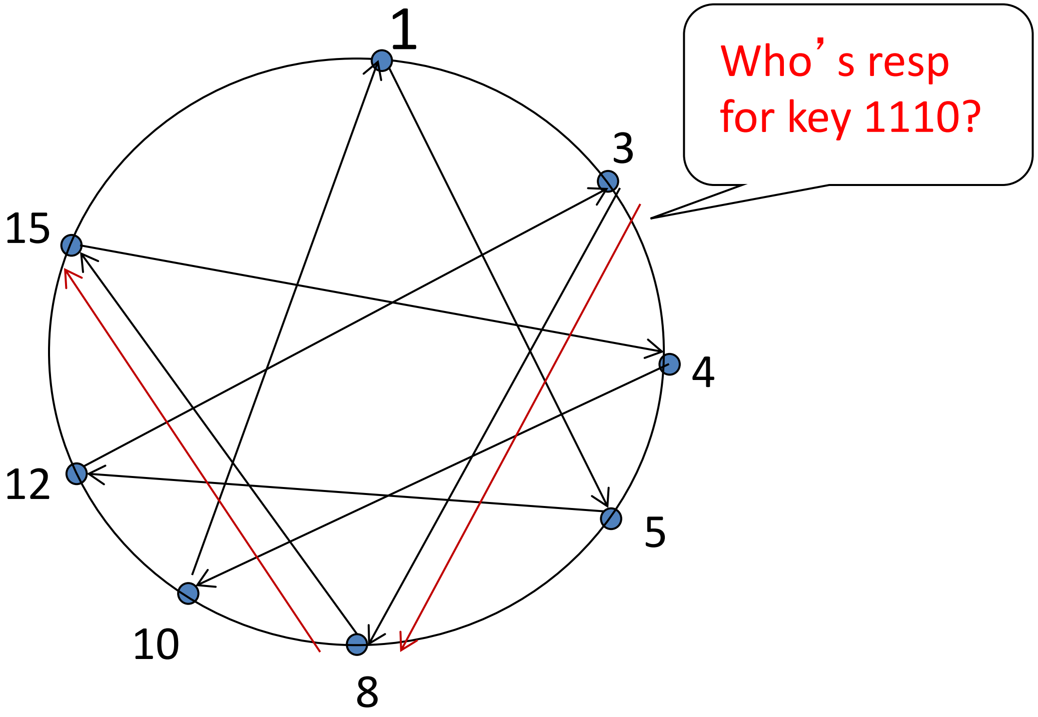
Circle DHT (2)

O(N) messages on avg to resolve query, when there are N peers



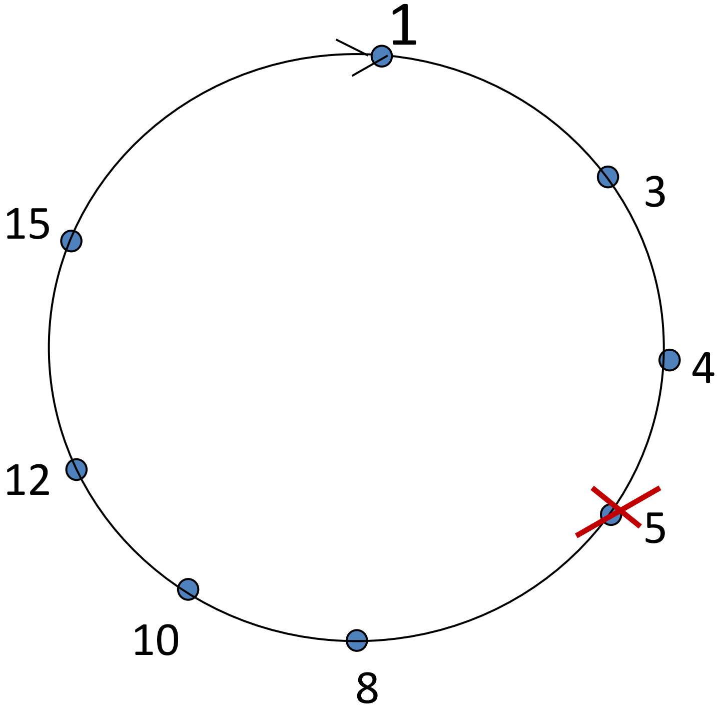
Define closest as closest successor

Circular DHT with Shortcuts



- Each peer keeps track of IP addresses of predecessor, successor, short cuts.
- Reduced from 6 to 2 messages.
- Possible to design shortcuts so O(log N) neighbors, O(log N) messages in query

Peer Churn

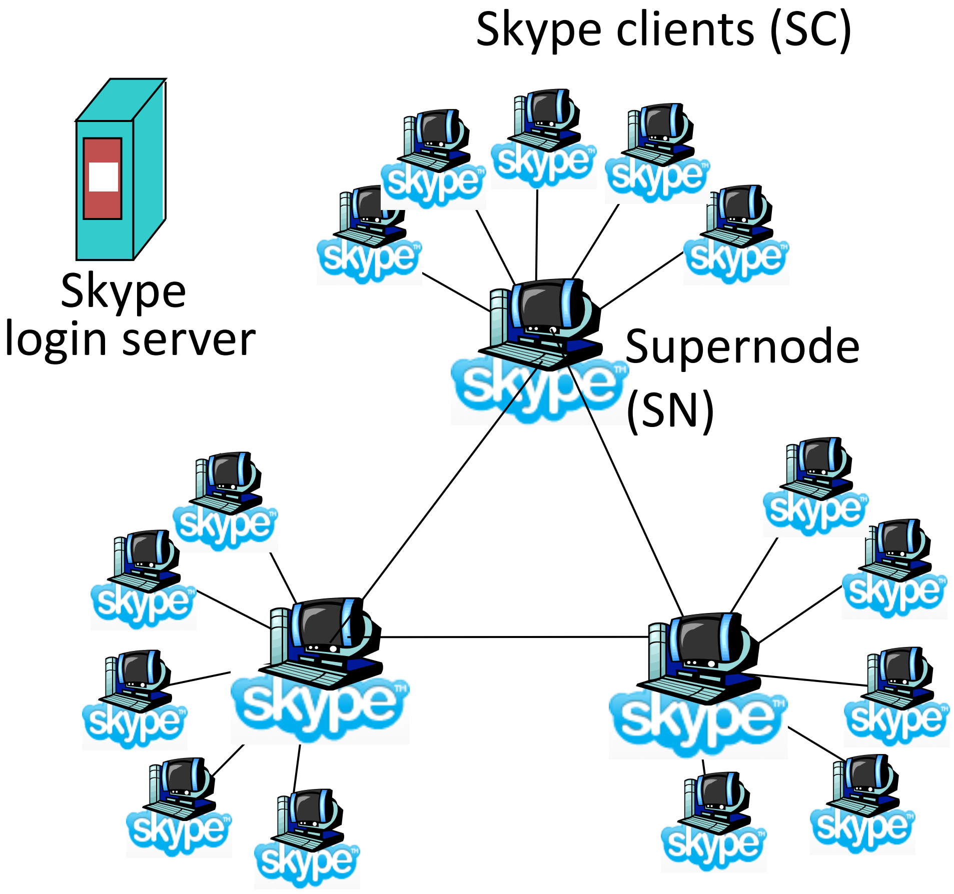


- To handle peer churn, require each peer to know the IP address of its two successors.
- Each peer periodically pings its two successors to see if they are still alive.

- Peer 5 abruptly leaves
- Peer 4 detects; makes 8 its immediate successor; asks 8 who its immediate successor is; makes 8's immediate successor its second successor.
- What if peer 13 wants to join?

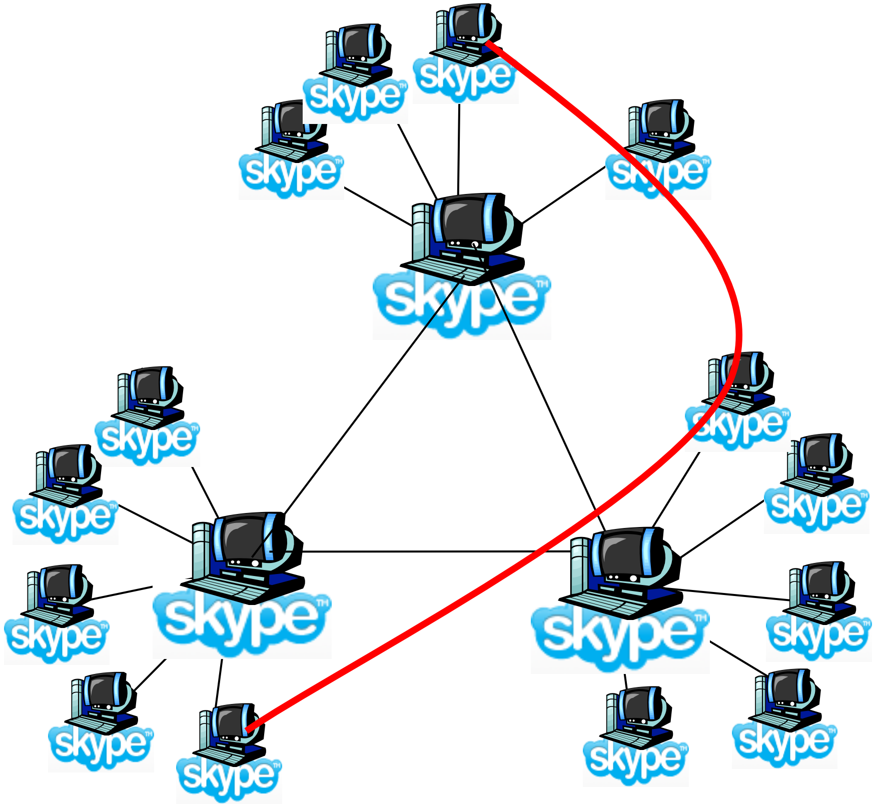
P2P Case study: Skype (pre-Microsoft)

- inherently P2P: pairs of users communicate.
- proprietary application-layer protocol (inferred via reverse engineering)
- hierarchical overlay with SNs
- Index maps usernames to IP addresses; distributed over SNs



Peers as relays

- Problem when both Alice and Bob are behind “NATs”.
  - NAT prevents an outside peer from initiating a call to insider peer
- Solution:
  - Using Alice’s and Bob’s SNs, Relay is chosen
  - Each peer initiates session with relay.
  - Peers can now communicate through NATs via relay



Summary.

- Apps need protocols too
- We covered examples from
  - Traditional Applications (web)
  - Scaling and Speeding the web (CDN/Cache tricks)
- Infrastructure Services (DNS)
  - Cache and Hierarchy
- Multimedia Applications (SIP)
  - Extremely hard to do better than worst-effort
- P2P Network examples