

# Application Layer

TDTS04 – Computer Networks and Distributed Systems

Ulf Kargén

*Division for Database and Information Techniques (ADIT)*

*Department of Computer and Information Science (IDA)*

# Application layer: overview

- Principles of network applications
- Web and HTTP
- (E-mail, SMTP, IMAP)
- The Domain Name System  
DNS
- P2P applications
- video streaming and content distribution networks



# Application layer: overview

## Our goals:

- conceptual *and* implementation aspects of application-layer protocols
  - transport-layer service models
  - client-server paradigm
  - peer-to-peer paradigm
- learn about protocols by examining popular application-layer protocols and infrastructure
  - HTTP
  - SMTP, IMAP
  - DNS
  - video streaming systems, CDNs

# Some network apps

- social networking
  - Web
  - text messaging
  - e-mail
  - multi-player games
  - streaming stored video (YouTube, Hulu, Netflix)
  - P2P file sharing
  - voice over IP (e.g., Skype)
  - real-time video conferencing (e.g., Zoom)
  - Internet search
  - remote login
  - ...
- Q: *your* favorites?

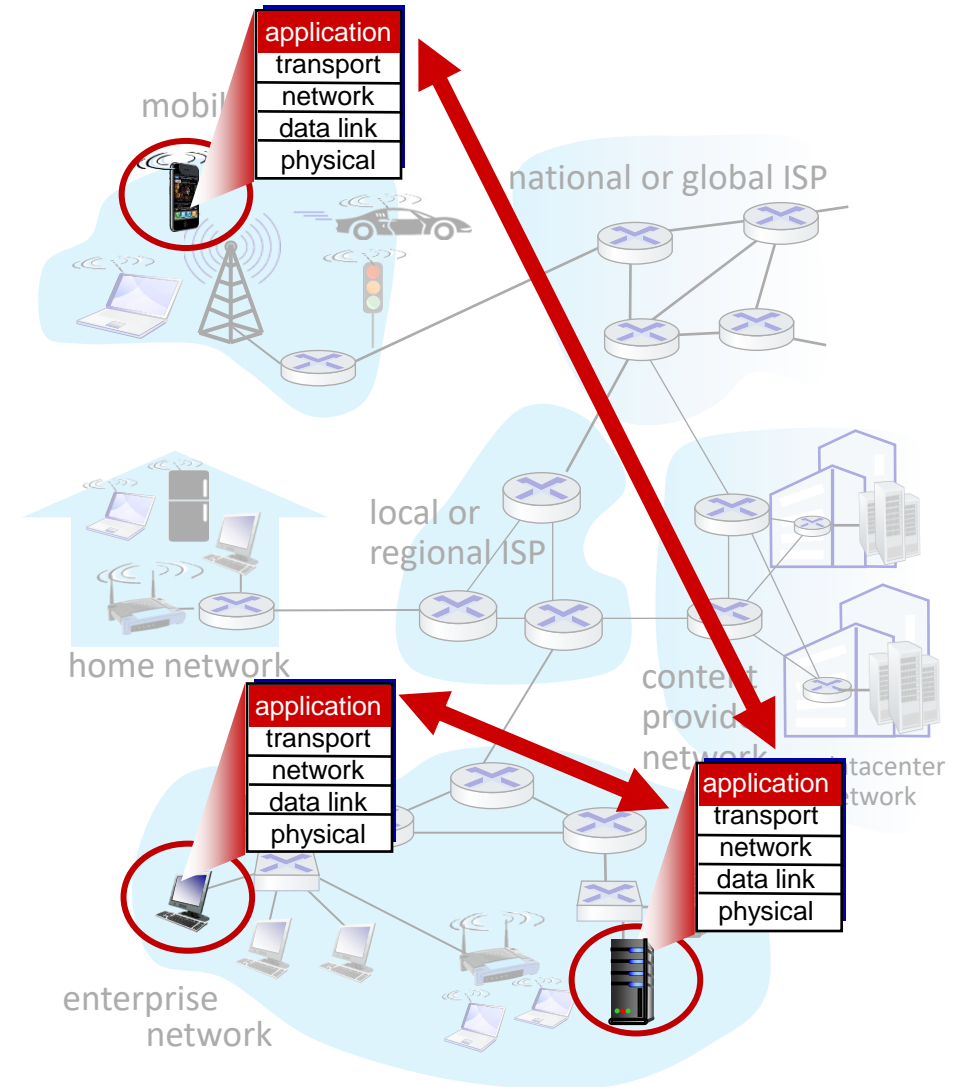
# Creating a network app

## write programs that:

- run on (different) end systems
- communicate over network
- e.g., web server software communicates with browser software

## no need to write software for network-core devices

- network-core devices do not run user applications
- applications on end systems allows for rapid app development, propagation



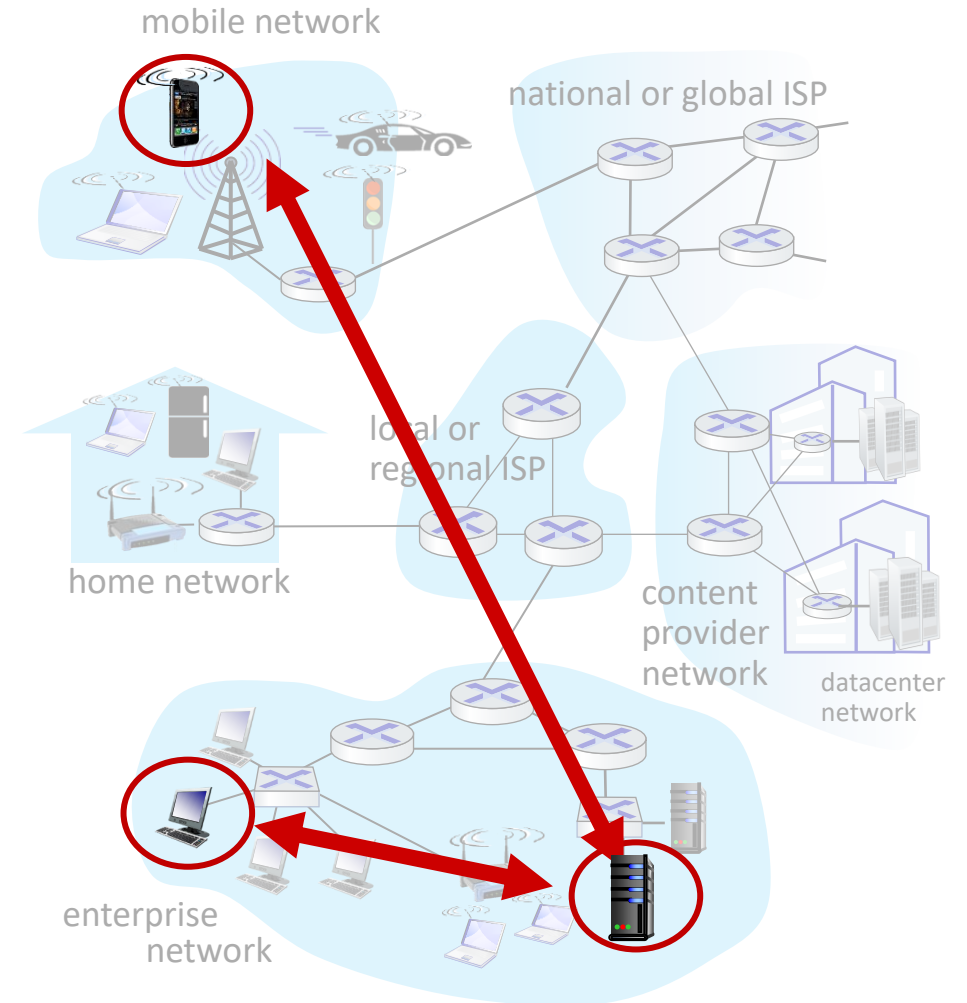
# Client-server paradigm

## server:

- always-on host
- permanent IP address
- often in data centers, for scaling

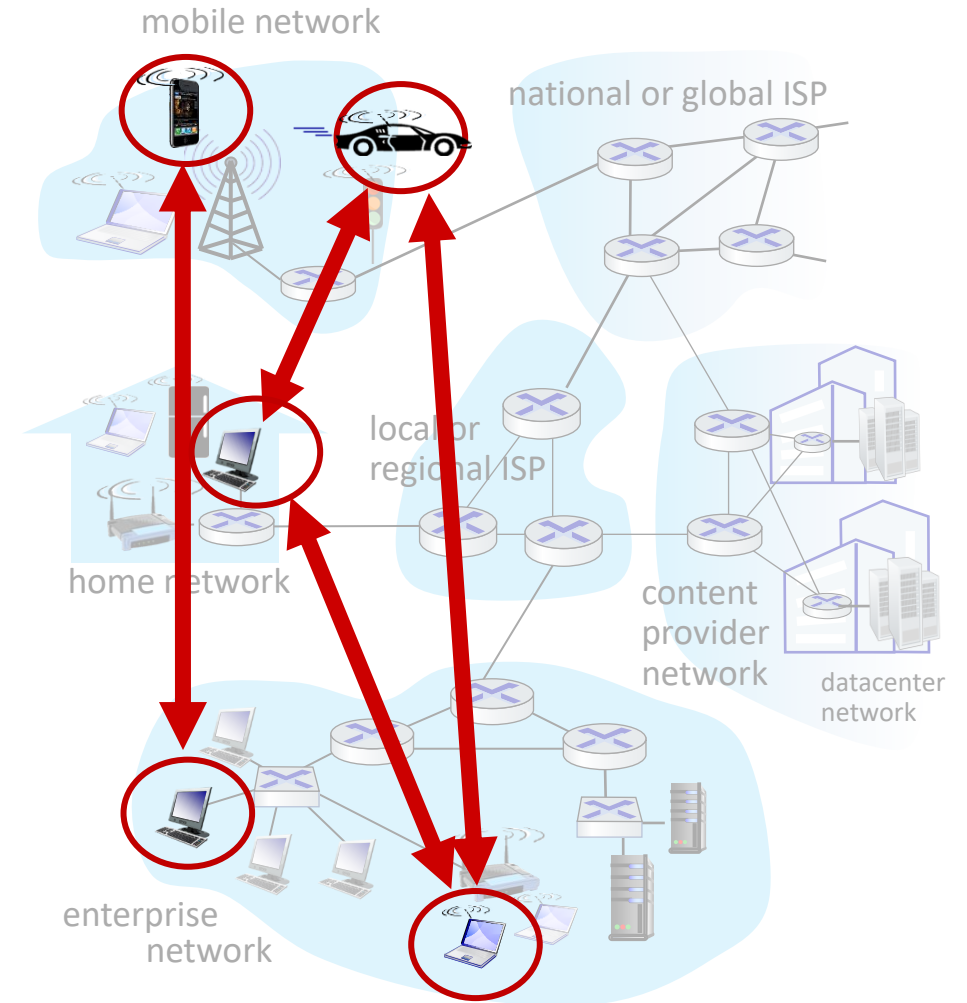
## clients:

- contact, communicate with server
- may be intermittently connected
- may have dynamic IP addresses
- do *not* communicate directly with each other
- examples: HTTP, IMAP, FTP



# Peer-peer architecture

- *no* always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, as well as new service demands
- peers are intermittently connected and change IP addresses
  - complex management
- example: P2P file sharing [BitTorrent]



# Processes communicating

- process*: program running within a host
- within same host, two processes communicate using **inter-process communication** (defined by OS)
  - processes in different hosts communicate by exchanging **messages**

clients, servers

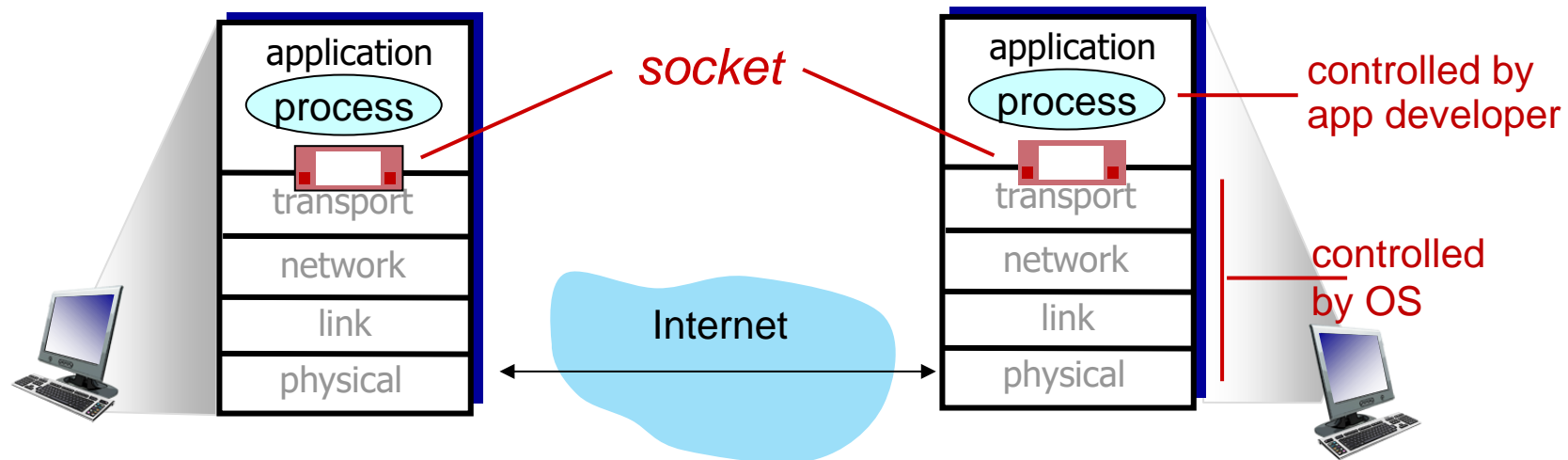
*client process*: process that **initiates** communication  
*server process*: process that **waits to be contacted**

- note: applications with P2P architectures have client processes & server processes



# Sockets

- process sends/receives messages to/from its **socket**
- socket analogous to door
  - sending process shoves message out door
  - sending process relies on transport infrastructure on other side of door to deliver message to socket at receiving process
  - two sockets involved: one on each side



# 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 gaia.cs.umass.edu web server:
  - IP address: 128.119.245.12
  - port number: 80
- more shortly...

# An application-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

## open protocols:

- defined in RFCs, everyone has access to protocol definition
- allows for interoperability
- e.g., HTTP, SMTP

## proprietary protocols:

- e.g., Skype, Zoom

# What transport service does an app need?

## data integrity

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

## 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, ...

# Transport service requirements: common apps

<b>application</b>	<b>data loss</b>	<b>throughput</b>	<b>time sensitive?</b>
file transfer/download	no loss	elastic	no
e-mail	no loss	elastic	no
Web documents	no loss	elastic	no
real-time audio/video	loss-tolerant	audio: 5Kbps-1Mbps video:10Kbps-5Mbps	yes, 10's msec
streaming audio/video	loss-tolerant	same as above	yes, few secs
interactive games	loss-tolerant	Kbps+	yes, 10's msec
text messaging	no loss	elastic	yes and no

# Internet transport protocols services

## *TCP service:*

- *reliable transport* between sending and receiving process
- *flow control*: sender won't overwhelm receiver
- *congestion control*: throttle sender when network overloaded
- *connection-oriented*: setup required between client and server processes
- *does not provide*: timing, minimum throughput guarantee, security

## *UDP service:*

- *unreliable data transfer* between sending and receiving process
- *does not provide*: reliability, flow control, congestion control, timing, throughput guarantee, security, or connection setup.

Q: why bother? *Why* is there a UDP?

# Internet applications, and transport protocols

<b>application</b>	<b>application layer protocol</b>	<b>transport protocol</b>
file transfer/download	FTP [RFC 959]	TCP
e-mail	SMTP [RFC 5321]	TCP
Web documents	HTTP [RFC 7230, 9110]	TCP
Internet telephony	SIP [RFC 3261], RTP [RFC 3550], or proprietary	TCP or UDP
streaming audio/video	HTTP [RFC 7230], DASH	TCP
interactive games	WOW, FPS (proprietary)	UDP or TCP

# Securing TCP

## Vanilla TCP & UDP sockets:

- no encryption
- cleartext passwords sent into socket traverse Internet in cleartext (!)

## Transport Layer Security (TLS)

- provides encrypted TCP connections
- data integrity
- end-point authentication

## TLS implemented in application layer

- apps use TLS libraries, that use TCP in turn
- cleartext sent into “socket” traverse Internet *encrypted*
- more: Chapter 8



# Application layer: overview

- Principles of network applications
- **Web and HTTP**
- (E-mail, SMTP, IMAP)
- The Domain Name System  
DNS
- P2P applications
- video streaming and content distribution networks



# Web and HTTP

*First, a quick review...*

- web page consists of *objects*, each of which can be stored on different Web servers
- object can be HTML file, JPEG image, Java applet, audio file,...
- web page consists of *base HTML-file* which includes *several referenced objects, each* addressable by a *URL*, e.g.,

`www.someschool.edu/someDept/pic.gif`

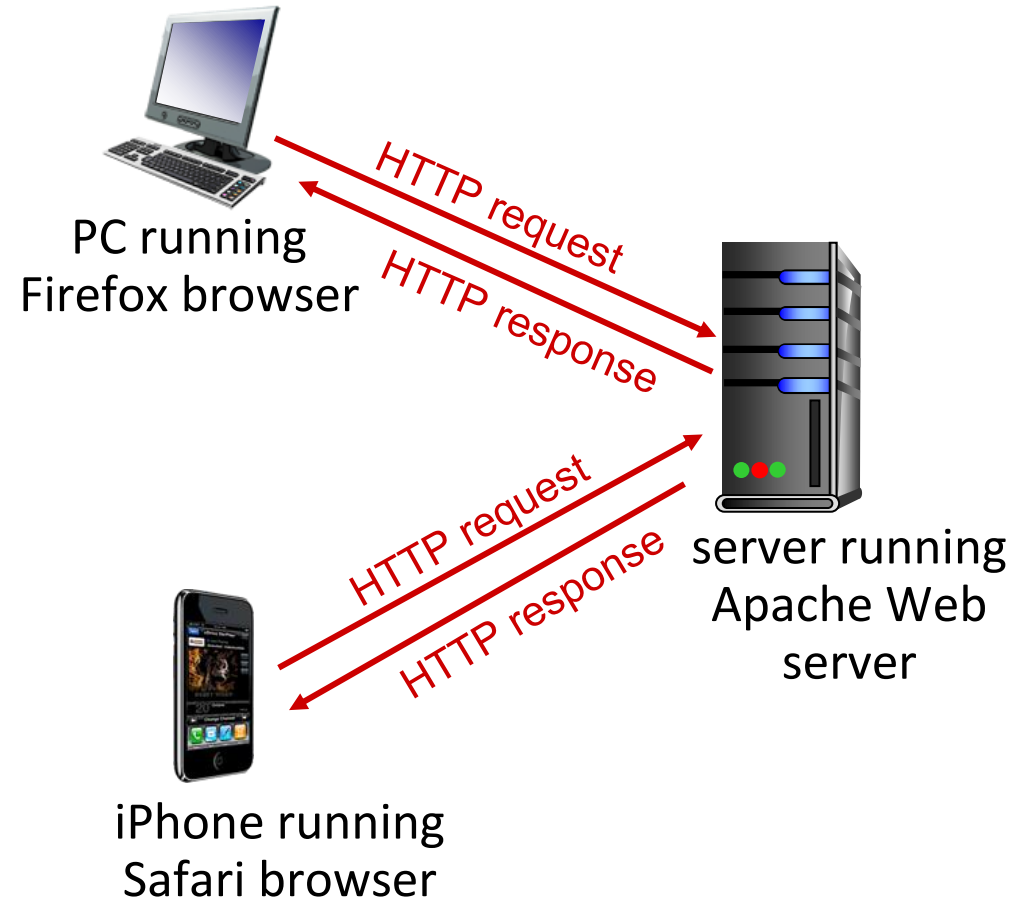
host name

path name

# HTTP overview

## HTTP: hypertext transfer protocol

- Web's application-layer protocol
- client/server model:
  - *client*: browser that requests, receives, (using HTTP protocol) and “displays” Web objects
  - *server*: Web server sends (using HTTP protocol) objects in response to requests



# HTTP overview (continued)

State (e.g., login) must be implemented on top of HTTP

## *HTTP uses TCP:*

- client initiates TCP connection (creates socket) to server, port 80
- server accepts TCP connection from client
- HTTP messages (application-layer protocol messages) exchanged between browser (HTTP client) and Web server (HTTP server)
- TCP connection closed

## *HTTP is “stateless”*

- server maintains *no* information about past client **requests**

*aside*  
protocols that maintain “state” are complex!

- past history (state) must be maintained
- if server/client crashes, their views of “state” may be inconsistent, must be reconciled

# HTTP connections: two types

## *Non-persistent HTTP*

1. TCP connection opened
2. at most one object sent over TCP connection
3. TCP connection closed

downloading multiple objects required multiple connections

## *Persistent HTTP*

- TCP connection opened to a server
- multiple objects can be sent over *single* TCP connection between client, and that server
- TCP connection closed

# Non-persistent HTTP: example

User enters URL: `www.someSchool.edu/someDepartment/home.index`  
(containing text, references to 10 jpeg images)



**1a.** HTTP client initiates **TCP connection** to HTTP server (process) at `www.someSchool.edu` on port 80



**1b.** HTTP server at host `www.someSchool.edu` waiting for TCP connection at port 80 **“accepts” connection**, notifying client

**2.** HTTP client sends HTTP *request message* (containing URL) into TCP connection socket. Message indicates that client wants object `someDepartment/home.index`

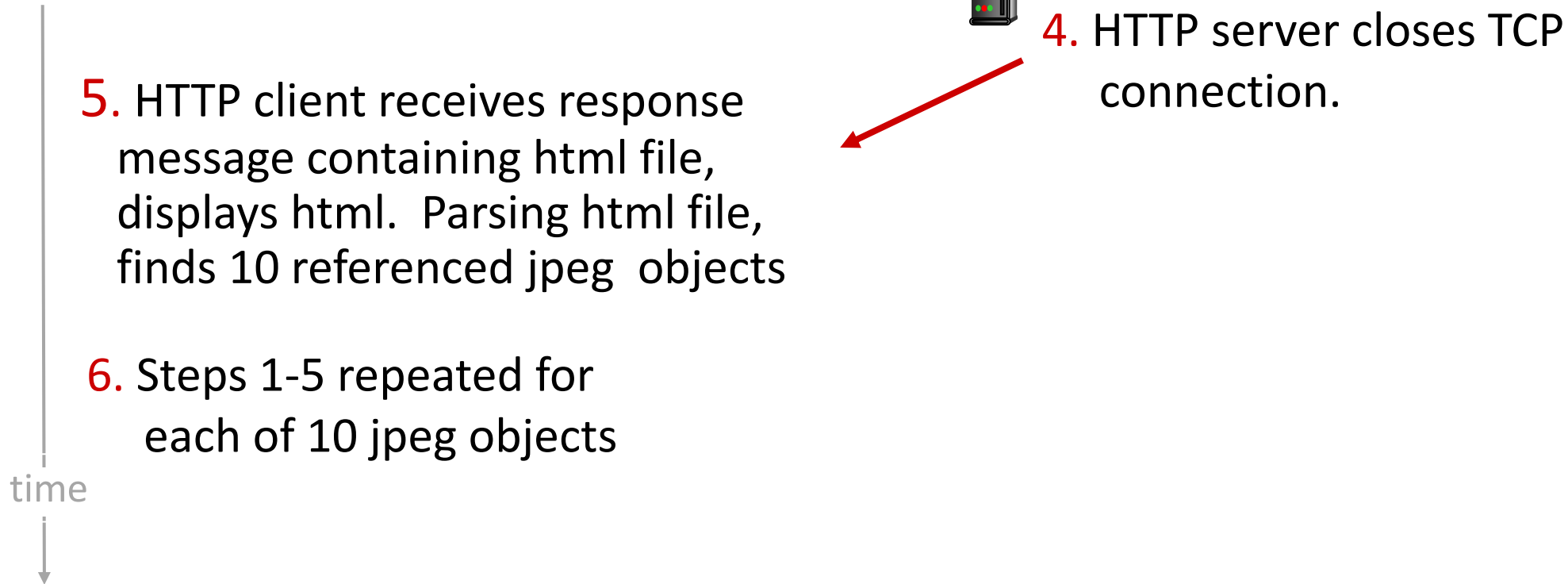
**3.** HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time



# Non-persistent HTTP: example (cont.)

User enters URL: `www.someSchool.edu/someDepartment/home.index`  
(containing text, references to 10 jpeg images)

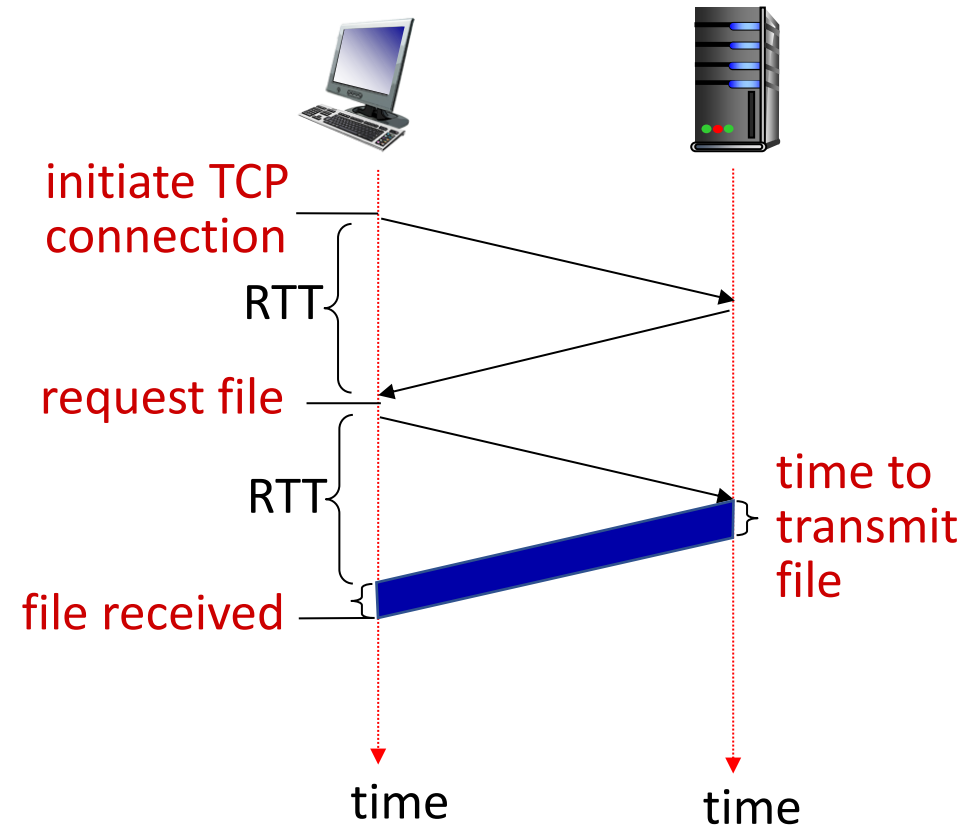


# Non-persistent HTTP: response time

**RTT (definition):** time for a small packet to travel from client to server and back

**HTTP response time (per object):**

- one RTT to initiate TCP connection
- one RTT for HTTP request and first few bytes of HTTP response to return
- object/file transmission time



*Non-persistent HTTP response time = 2RTT + file transmission time*



# Persistent HTTP (HTTP 1.1)

## *Non-persistent HTTP issues:*

- requires 2 RTTs per object
- OS overhead for *each* TCP connection
  - browsers often open multiple parallel TCP connections to fetch referenced objects in parallel
  - Limited number of TCP ports (65536), can run out
  - Memory (and other resources) needed at server for each connection

## *Persistent HTTP (HTTP1.1):*

- server leaves connection open after sending response (until a timeout configured on server)
- subsequent HTTP messages between same client/server sent over open connection
- client sends requests as soon as it encounters a referenced object
- as little as one RTT for all the referenced objects (cutting response time in half)

# Persistent HTTP with pipelining

Persistent connection (i.e., keep TCP connection open)

- **Without** pipelining: make separate request for each object referenced in HTML file
- **With** pipelining: make one request for all objects. Sent back-to-back one after another (default in HTTP/1.1)

[https://media.pearsoncmg.com/aw/ecs\\_kurose\\_compnetwork\\_7/cw/content/interactiveanimations/http-delay-estimation/index.html](https://media.pearsoncmg.com/aw/ecs_kurose_compnetwork_7/cw/content/interactiveanimations/http-delay-estimation/index.html)

# Persistent HTTP hints

Possible to give a hint to web server about wanted behavior using the **Connection** HTTP header:

- **Connection: close** tells server to close connection immediately  
default on HTTP/1.0
- **Connection: keep-alive** tells server to keep connection open until timeout  
default on HTTP/1.1

# HTTP request message

- two types of HTTP messages: *request, response*
- **HTTP request message:**
  - ASCII (human-readable format)

request line (GET, POST,  
HEAD commands)

header  
lines

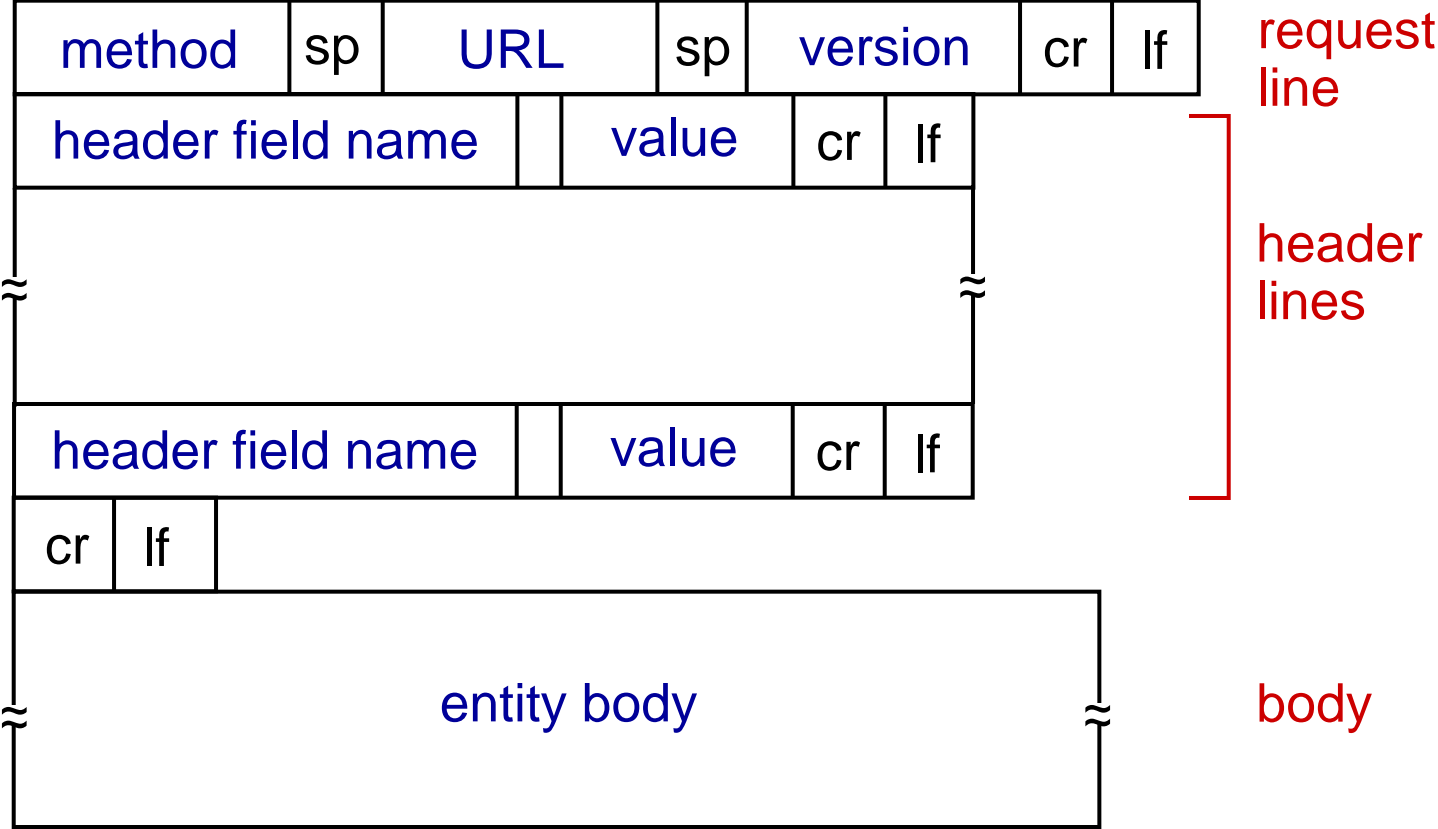
```
Host: www-net.cs.umass.edu\r\n
User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X
  10.15; rv:80.0) Gecko/20100101 Firefox/80.0 \r\n
Accept: text/html,application/xhtml+xml\r\n
Accept-Language: en-us,en;q=0.5\r\n
Accept-Encoding: gzip,deflate\r\n
Connection: keep-alive\r\n
\r\n
```

carriage return character  
/ line-feed character

carriage return, line feed  
at start of line indicates  
end of header lines

\* Check out the online interactive exercises for more  
examples: [http://gaia.cs.umass.edu/kurose\\_ross/interactive/](http://gaia.cs.umass.edu/kurose_ross/interactive/)

# HTTP request message: general format



# Other HTTP request messages

## POST method:

- web page often includes form input
- user input sent from client to server **in entity body** of HTTP POST request message

## GET method (for sending data to server):

- include user data **in URL field of HTTP** GET request message (following a '?'):

`www.somesite.com/animalsearch?monkeys&banana`

## HEAD method:

- requests headers (only) that would be returned *if* specified URL were requested with an HTTP GET method.

## PUT method (rarely used):

- uploads new file (object) to server
- completely replaces file that exists at specified URL with content in entity body of POST HTTP request message

# HTTP response message

status line (protocol  
status code status phrase)

header  
lines

```
HTTP/1.1 200 OK
Date: Tue, 08 Sep 2020 00:53:20 GMT
Server: Apache/2.4.6 (CentOS)
       OpenSSL/1.0.2k-fips PHP/7.4.9
       mod_perl/2.0.11 Perl/v5.16.3
Last-Modified: Tue, 01 Mar 2016 18:57:50 GMT
ETag: "a5b-52d015789ee9e"
Accept-Ranges: bytes
Content-Length: 2651
Content-Type: text/html; charset=UTF-8
\r\n
```

# HTTP response status codes

- status code appears in 1st line in server-to-client response message.
- some sample codes:

## 200 OK

- request succeeded, requested object later in this message

## 301 Moved Permanently

- requested object moved, new location specified later in this message (in Location: field)

## 400 Bad Request

- request msg not understood by server

## 404 Not Found

- requested document not found on this server

## 505 HTTP Version Not Supported

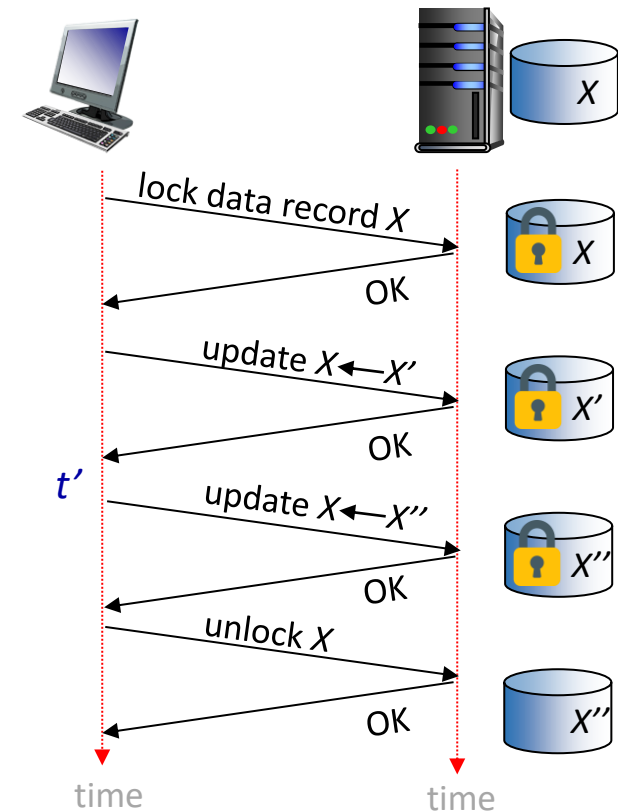


# Maintaining user/server state: cookies

Recall: HTTP GET/response interaction is *stateless*

- no notion of multi-step exchanges of HTTP messages to complete a Web “transaction”
  - no need for client/server to track “state” of multi-step exchange
  - all HTTP requests are independent of each other
  - no need for client/server to “recover” from a partially-completed-but-never-completely-completed transaction

a *stateful* protocol: client makes two changes to X, or none at all



*Q:* what happens if network connection or client crashes at  $t'$  ?

# Maintaining user/server state: cookies

Web sites and client browser use *cookies* to maintain some state between transactions

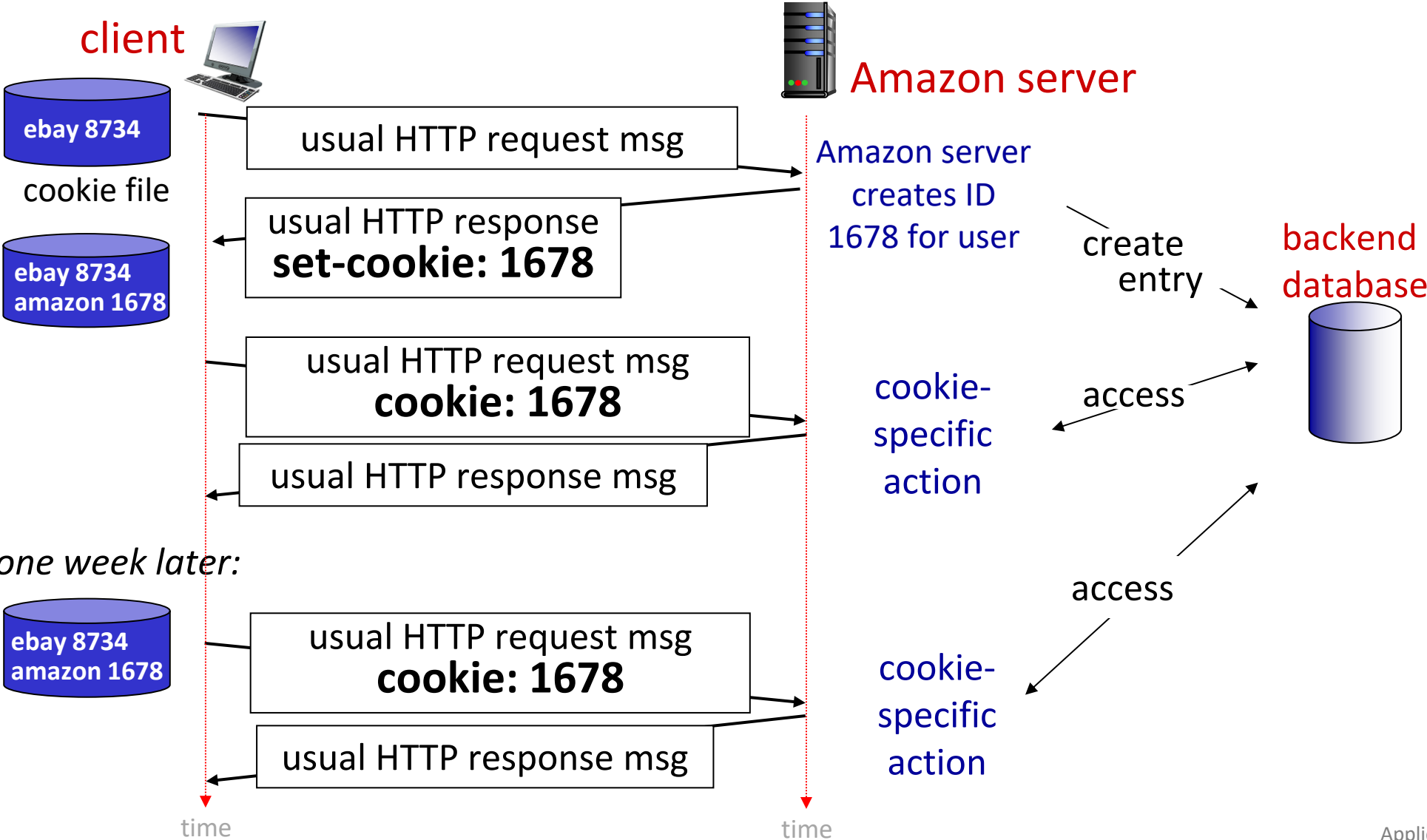
## *four components:*

- 1) cookie header line of HTTP *response* message
- 2) cookie header line in next HTTP *request* message
- 3) cookie file kept on user's host, managed by user's browser
- 4) back-end database at Web site

## Example:

- Susan uses browser on laptop, visits specific e-commerce site for first time
- when initial HTTP requests arrives at site, site creates:
  - unique ID (aka “cookie”)
  - entry in backend database for ID
- subsequent HTTP requests from Susan to this site will contain cookie ID value, allowing site to “identify” Susan

# Maintaining user/server state: cookies



# HTTP cookies: comments

## *What cookies can be used for:*

- authorization
- shopping carts
- recommendations
- user session state (Web e-mail)

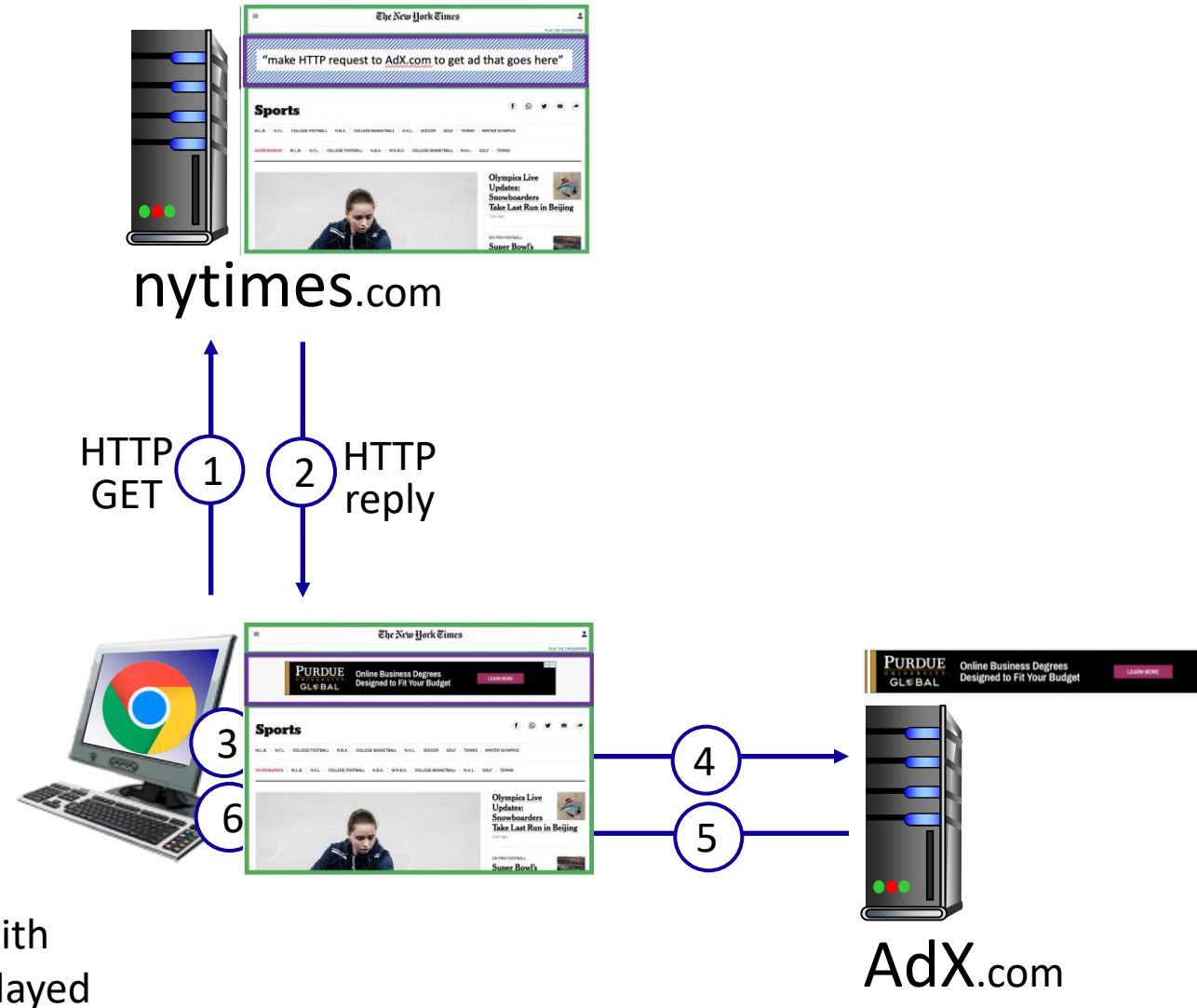
## *Challenge: How to keep state?*

- *at protocol endpoints:* maintain state at sender/receiver over multiple transactions
- *in messages:* cookies in HTTP messages carry state

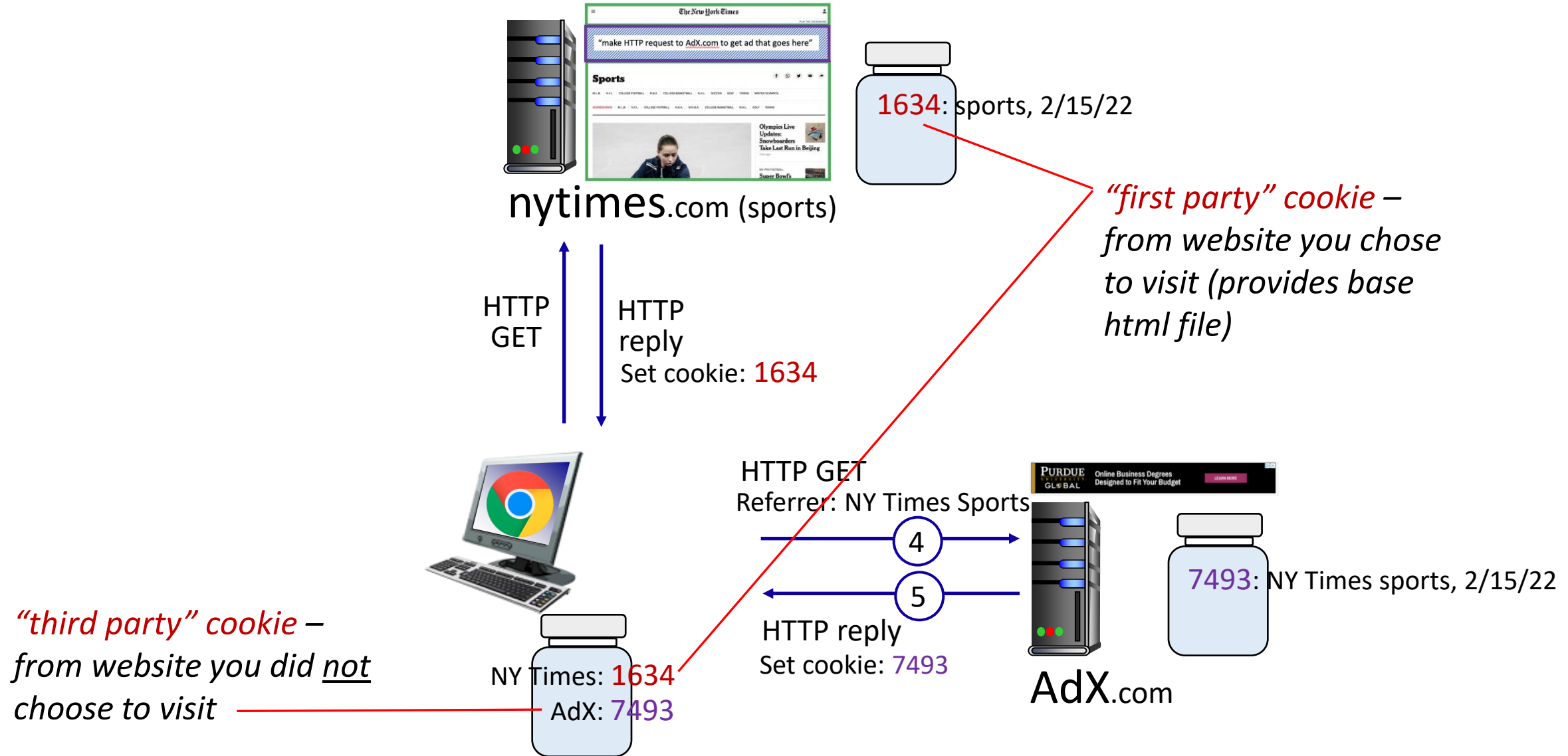
- aside
- cookies and privacy:*
- cookies permit sites to *learn* a lot about you on their site.
  - third party persistent cookies (tracking cookies) allow common identity (cookie value) to be tracked across multiple web sites

# Example: displaying a NY Times web page

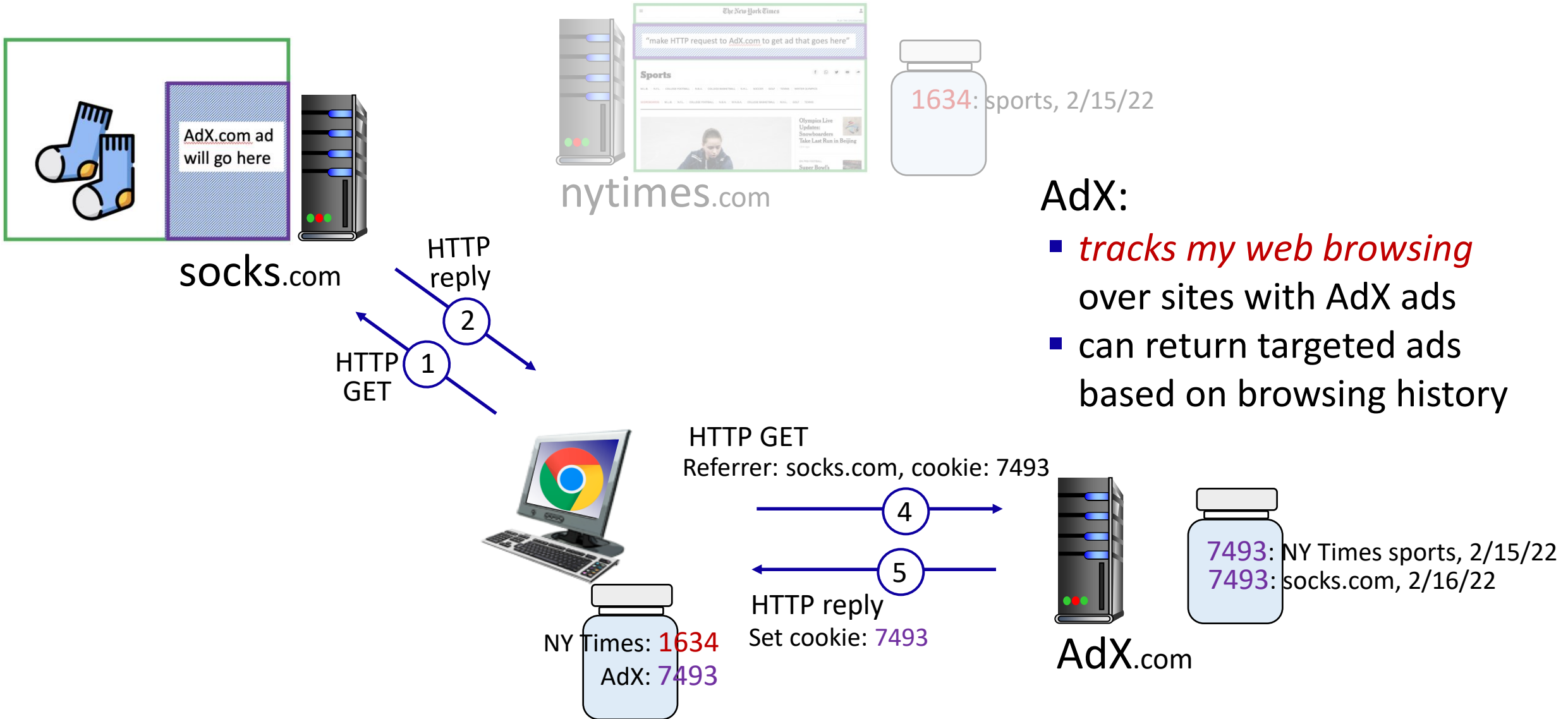
- 1 GET base html file
- 2 from nytimes.com
- 3
- 4 fetch ad from
- 5 AdX.com
- 6
- 7 display composed page



# Cookies: tracking a user's browsing behavior



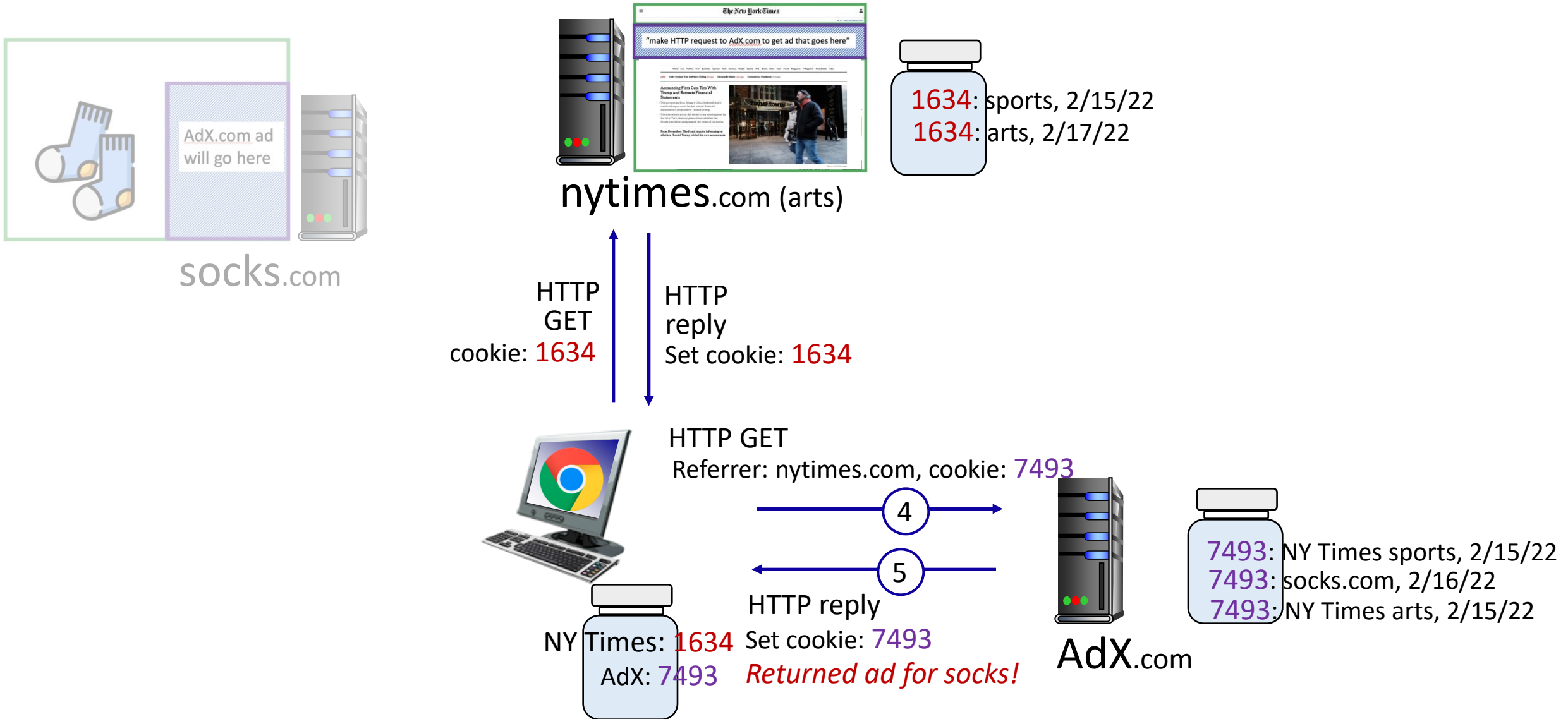
# Cookies: tracking a user's browsing behavior



AdX:

- *tracks my web browsing* over sites with AdX ads
- can return targeted ads based on browsing history

# Cookies: tracking a user's browsing behavior (one day later)





# Cookies: tracking a user's browsing behavior

Cookies can be used to:

- track user behavior on a given website (**first party cookies**)
- track user behavior across multiple websites (**third party cookies**) without user ever choosing to visit tracker site (!)
- tracking may be *invisible* to user:
  - rather than displayed ad triggering HTTP GET to tracker, could be an invisible link (e.g., invisible iframe, “tracking pixel”)

third party tracking via cookies:

- disabled by default in Firefox, Safari browsers
- to be disabled in Chrome browser in 2023

# GDPR (EU General Data Protection Regulation) and cookies

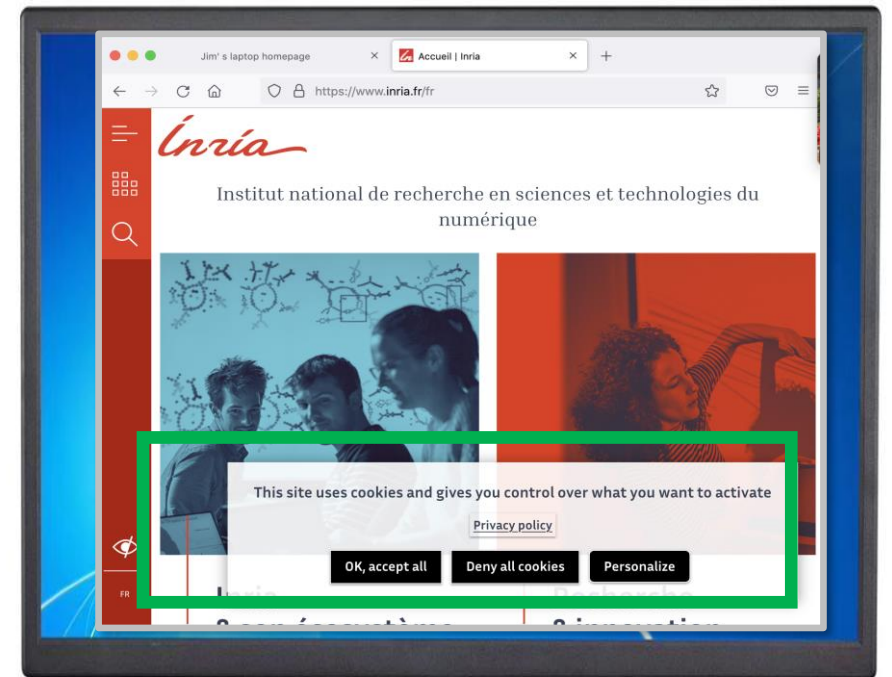
“Natural persons may be associated with online identifiers [...] such as internet protocol addresses, cookie identifiers or other identifiers [...].

This may leave traces which, in particular when combined with unique identifiers and other information received by the servers, may be used to create profiles of the natural persons and identify them.”

GDPR, recital 30 (May 2018)



when cookies can identify an individual, cookies are considered personal data, subject to GDPR personal data regulations

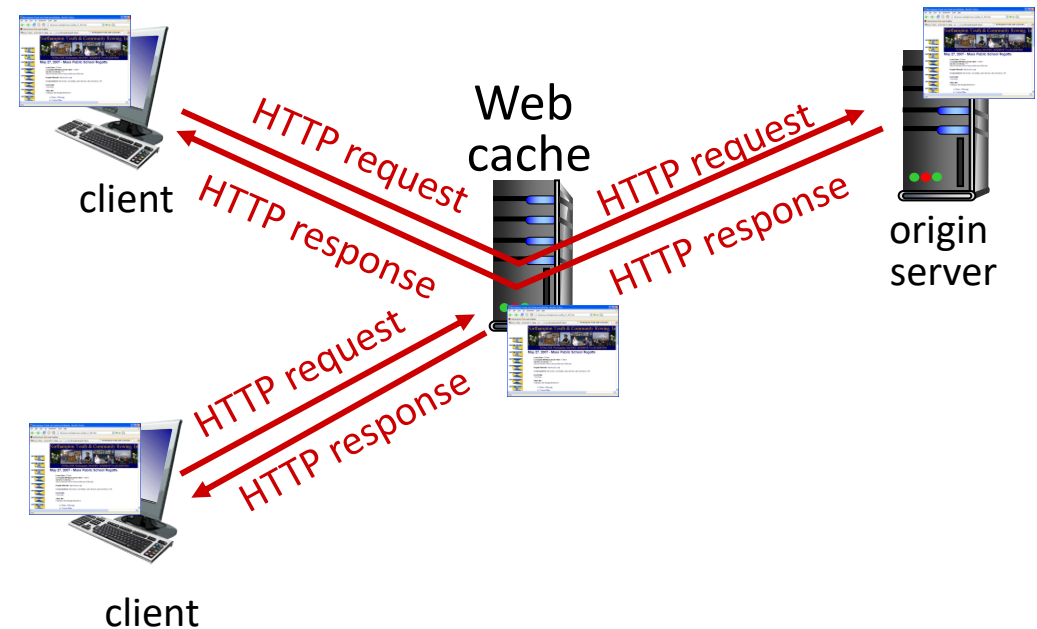


*User has explicit control over whether or not cookies are allowed*

# Web caches

*Goal:* satisfy client requests without involving origin server

- user configures browser to point to a (local) *Web cache*
- browser sends all HTTP requests to cache
  - *if* object in cache: cache returns object to client
  - *else* cache requests object from origin server, caches received object, then returns object to client



# Web caches (aka proxy servers)

- Web cache acts as both client and server
  - server for original requesting client
  - client to origin server
- server tells cache about object's allowable caching in response header:

```
Cache-Control: max-age=<seconds>
```

```
Cache-Control: no-cache
```

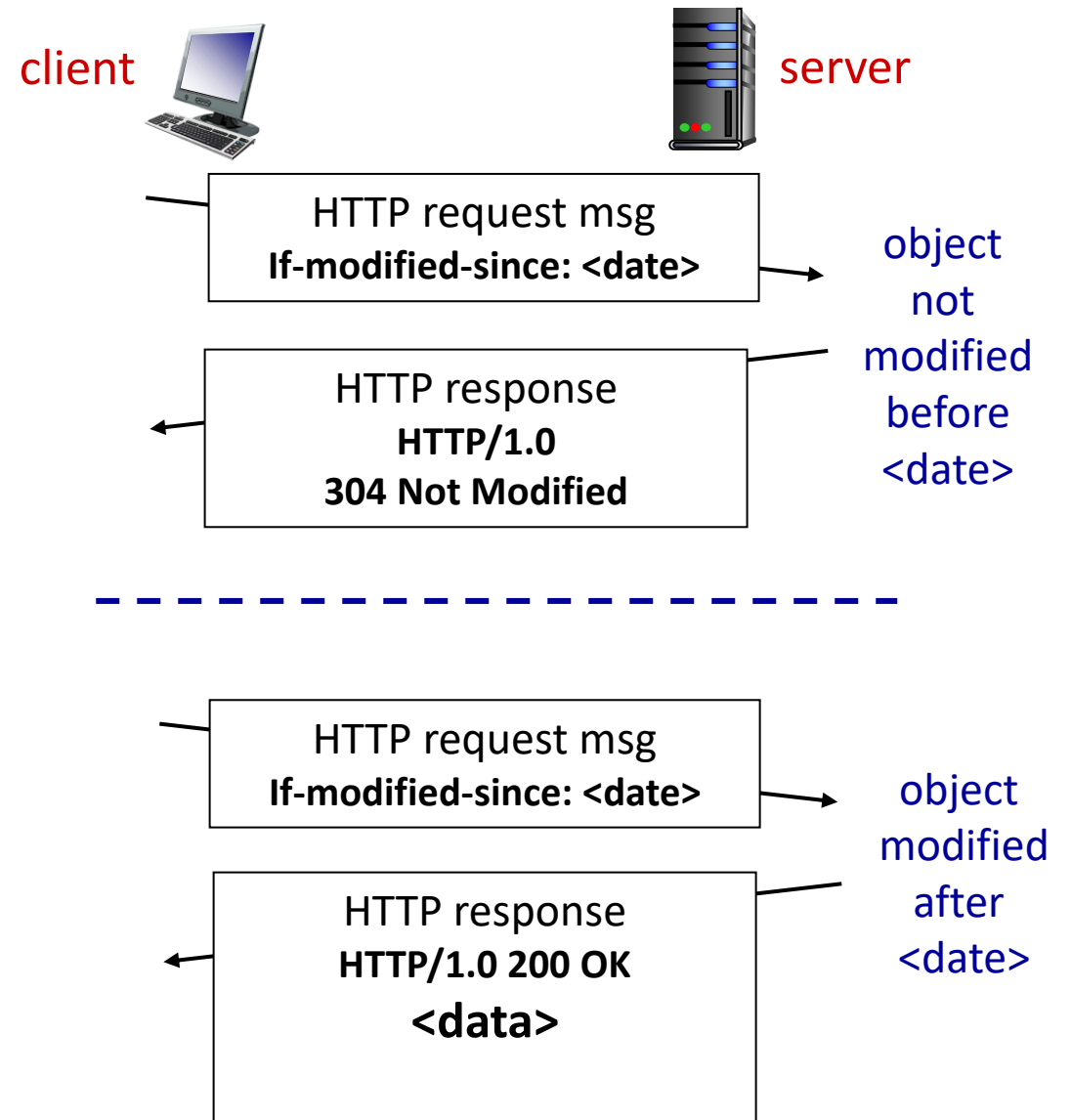
## *Why* Web caching?

- reduce response time for client request
  - cache is closer to client
- reduce traffic on an institution's access link
- Internet is dense with caches
  - enables “poor” content providers to more effectively deliver content

# Browser caching: Conditional GET

**Goal:** don't send object if browser has up-to-date cached version

- no object transmission delay (or use of network resources)
- **client:** specify date of browser-cached copy in HTTP request  
**If-modified-since: <date>**
- **server:** response contains no object if browser-cached copy is up-to-date:  
**HTTP/1.0 304 Not Modified**



# HTTP/2

*Key goal:* decreased delay in multi-object HTTP requests

HTTP1.1: introduced **multiple, pipelined GETs** over single TCP connection

- server responds *in-order* (FCFS: first-come-first-served scheduling) to GET requests
- with FCFS, small object may have to wait for transmission (**head-of-line (HOL) blocking**) behind large object(s)
- loss recovery (retransmitting lost TCP segments) stalls object transmission

# HTTP/2

*Key goal:* decreased delay in multi-object HTTP requests

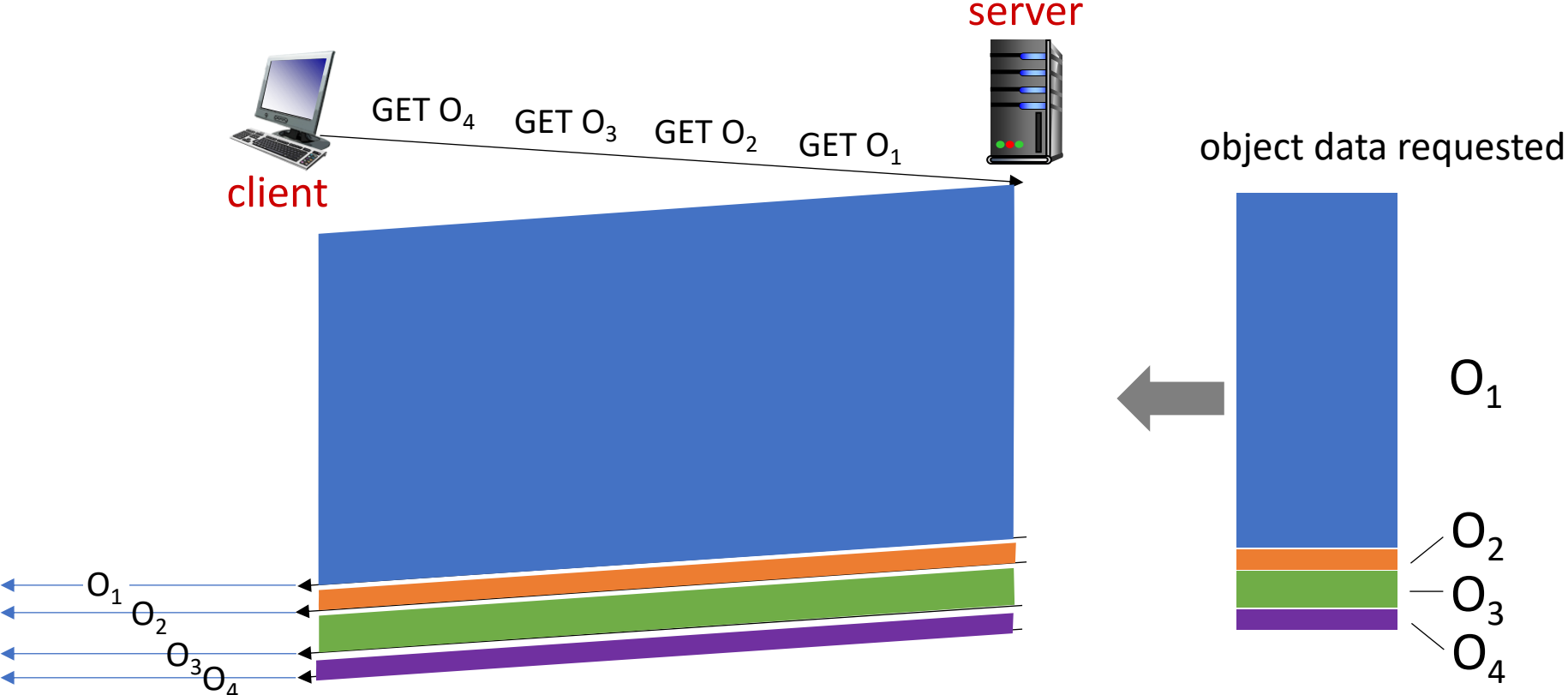
HTTP/2: [RFC 7540, 2015] increased flexibility at *server* in sending objects to client:

- methods, status codes, most header fields unchanged from HTTP 1.1
- transmission order of requested objects based on client-specified object priority (not necessarily FCFS)
- *push* selected objects to client without waiting for request
  - for example, elements of an HTML page
- divide objects into **frames**, schedule frames to mitigate HOL blocking

HTTP response packaged in binary packets with header (length, etc.)  
No longer purely "text-based"

# HTTP/2: mitigating HOL blocking

HTTP 1.1: client requests 1 large object (e.g., video file) and 3 smaller objects

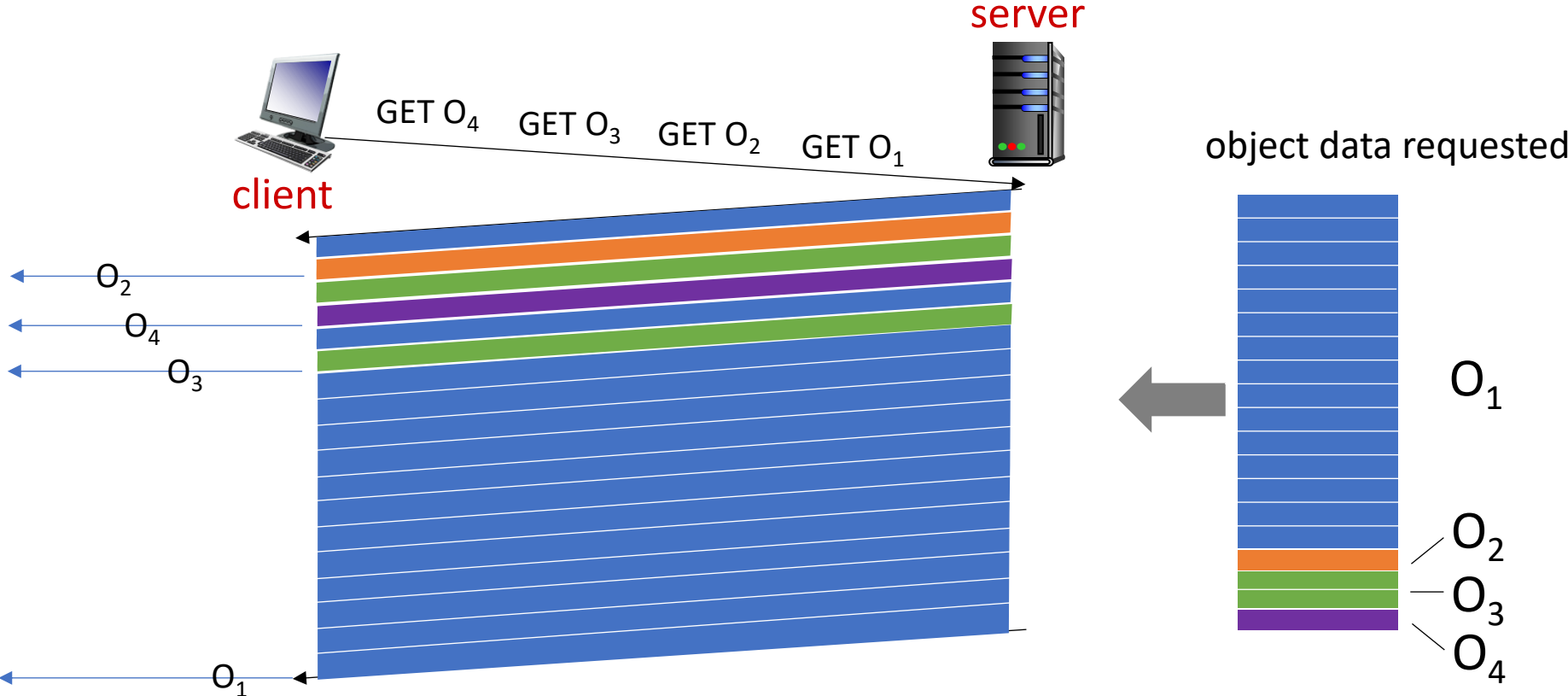


*objects delivered in order requested: O<sub>2</sub>, O<sub>3</sub>, O<sub>4</sub> wait behind O<sub>1</sub>*



# HTTP/2: mitigating HOL blocking

HTTP/2: objects divided into frames, frame transmission interleaved



*O<sub>2</sub>, O<sub>3</sub>, O<sub>4</sub> delivered quickly, O<sub>1</sub> slightly delayed*

# HTTP/2 to HTTP/3

HTTP/2 over single TCP connection means:

- recovery from packet loss still stalls all object transmissions
  - as in HTTP 1.1, browsers have incentive to open multiple parallel TCP connections to reduce stalling, increase overall throughput
- no security over vanilla TCP connection
- **HTTP/3**: adds security, per object error- and congestion-control (more pipelining) over UDP
  - more on HTTP/3 in transport layer

# Application layer: overview

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- Web and HTTP
- (E-mail, SMTP, IMAP)
- The Domain Name System  
DNS
- P2P applications
- video streaming and content distribution networks



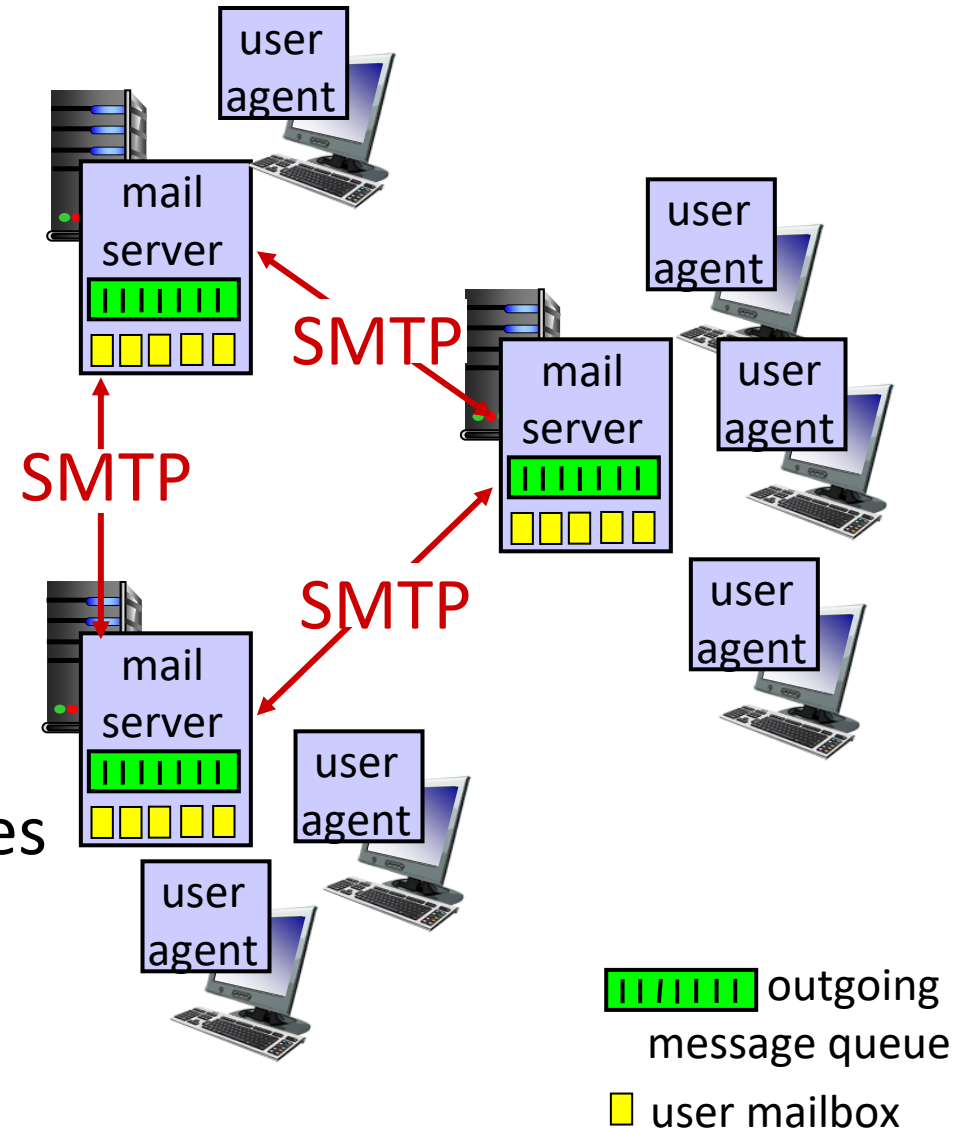
# E-mail

## Three major components:

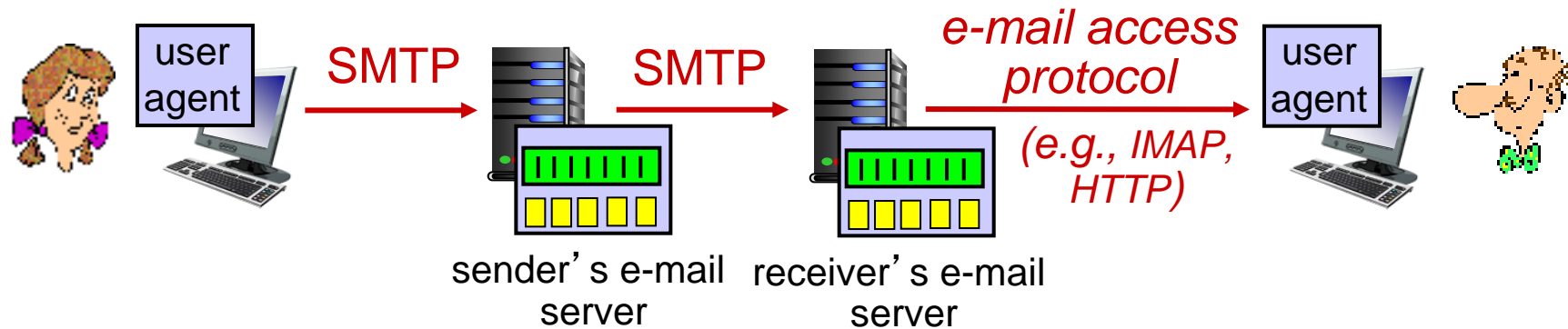
- user agents
- mail servers
- simple mail transfer protocol: SMTP

## User Agent

- a.k.a. “mail reader”
- composing, editing, reading mail messages
- e.g., Outlook, iPhone mail client
- outgoing, incoming messages stored on server



# Retrieving email: mail access protocols



- **SMTP**: delivery/storage of e-mail messages to receiver's server
- mail access protocol: retrieval from server
  - **IMAP**: Internet Mail Access Protocol [RFC 3501]: messages stored on server, IMAP provides retrieval, deletion, folders of stored messages on server
- **HTTP**: gmail, Hotmail, Yahoo!Mail, etc. provides web-based interface on top of SMTP (to send), IMAP (or POP) to retrieve e-mail messages

# DNS: Domain Name System

*people:* many identifiers:

- SSN, name, passport #

*Internet hosts, routers:*

- IP address (32 bit) - used for addressing datagrams
- “name”, e.g., cs.umass.edu - used by humans

Q: how to map between IP address and name, and vice versa ?

**Domain Name System (DNS):**

- *distributed database* implemented in hierarchy of many *name servers*
- *application-layer protocol:* hosts, DNS servers communicate to *resolve* names (address/name translation)
  - *note:* core Internet function, **implemented as application-layer protocol**
  - complexity at network’s “edge”

# DNS: services, structure

## DNS services:

- hostname-to-IP-address translation
- host aliasing
  - canonical, alias names
- mail server aliasing
- load distribution
  - replicated Web servers: many IP addresses correspond to one name

## *Q: Why not centralize DNS?*

- single point of failure
- traffic volume
- distant centralized database
- maintenance

## *A: doesn't scale!*

- Comcast DNS servers alone: 600B DNS queries/day
- Akamai DNS servers alone: 2.2T DNS queries/day

# Thinking about the DNS

humongous distributed database:

- ~ billion records, each simple

handles many *trillions* of queries/day:

- *many* more reads than writes
- *performance matters*: almost every Internet transaction interacts with DNS - msec count!

organizationally, physically decentralized:

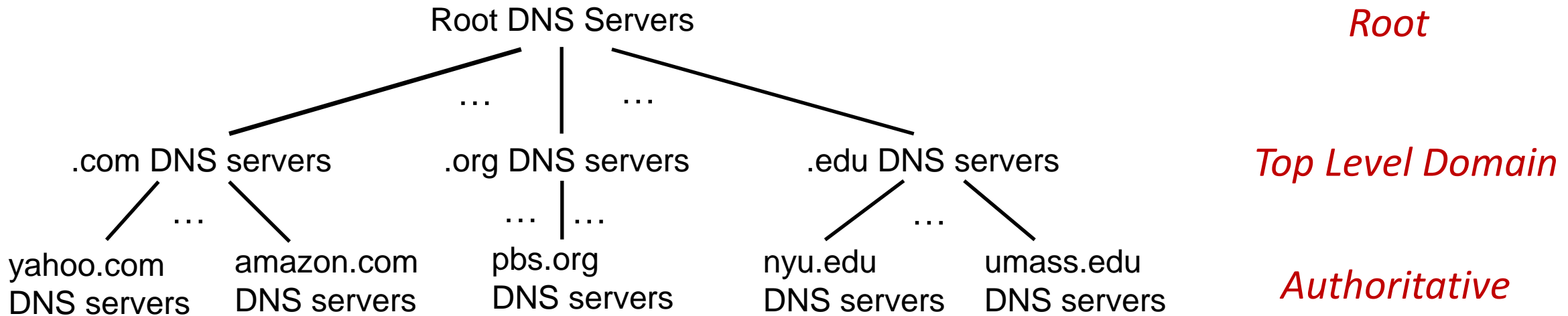
- millions of different organizations responsible for their records

“bulletproof”: reliability, security





# DNS: a distributed, hierarchical database

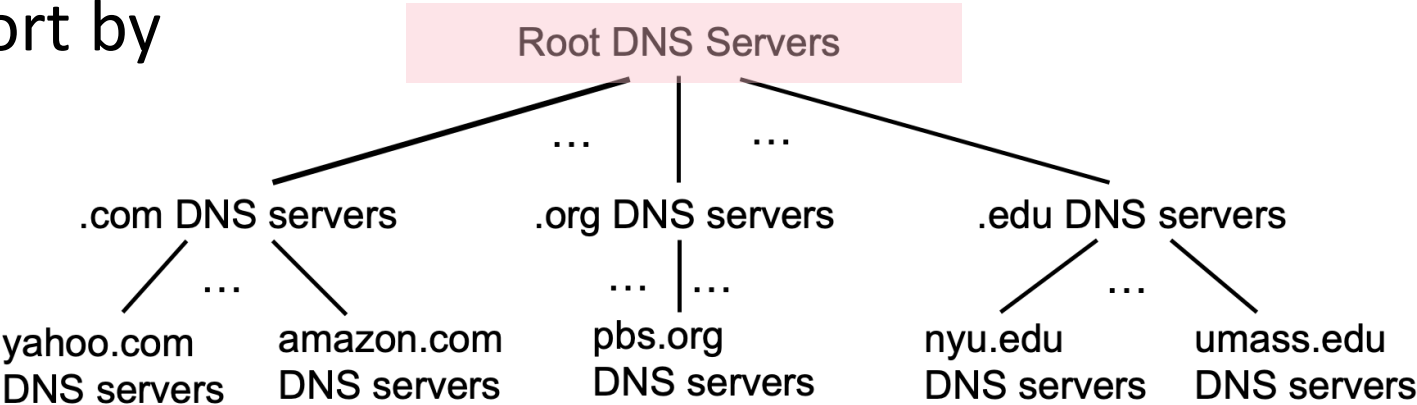


Client wants IP address for `www.amazon.com`; 1<sup>st</sup> approximation:

- client queries root server to find `.com` DNS server
- client queries `.com` DNS server to get `amazon.com` DNS server
- client queries `amazon.com` DNS server to get IP address for `www.amazon.com`

# DNS: root name servers

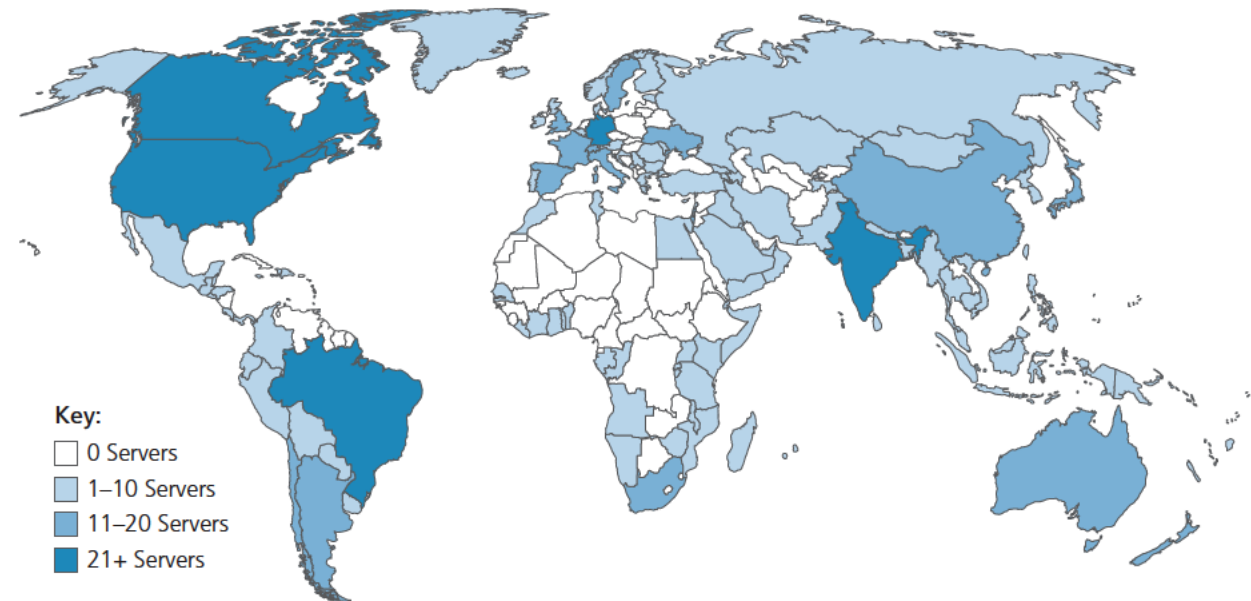
- official, contact-of-last-resort by name servers that can not resolve name



# DNS: root name servers

- official, contact-of-last-resort by name servers that can not resolve name
- *incredibly important* Internet function
  - Internet couldn't function without it!
  - DNSSEC – provides security (authentication, message integrity)
- ICANN (Internet Corporation for Assigned Names and Numbers) manages root DNS domain

13 logical root name “servers” worldwide each “server” replicated many times (~200 servers in US)





# Local DNS name servers

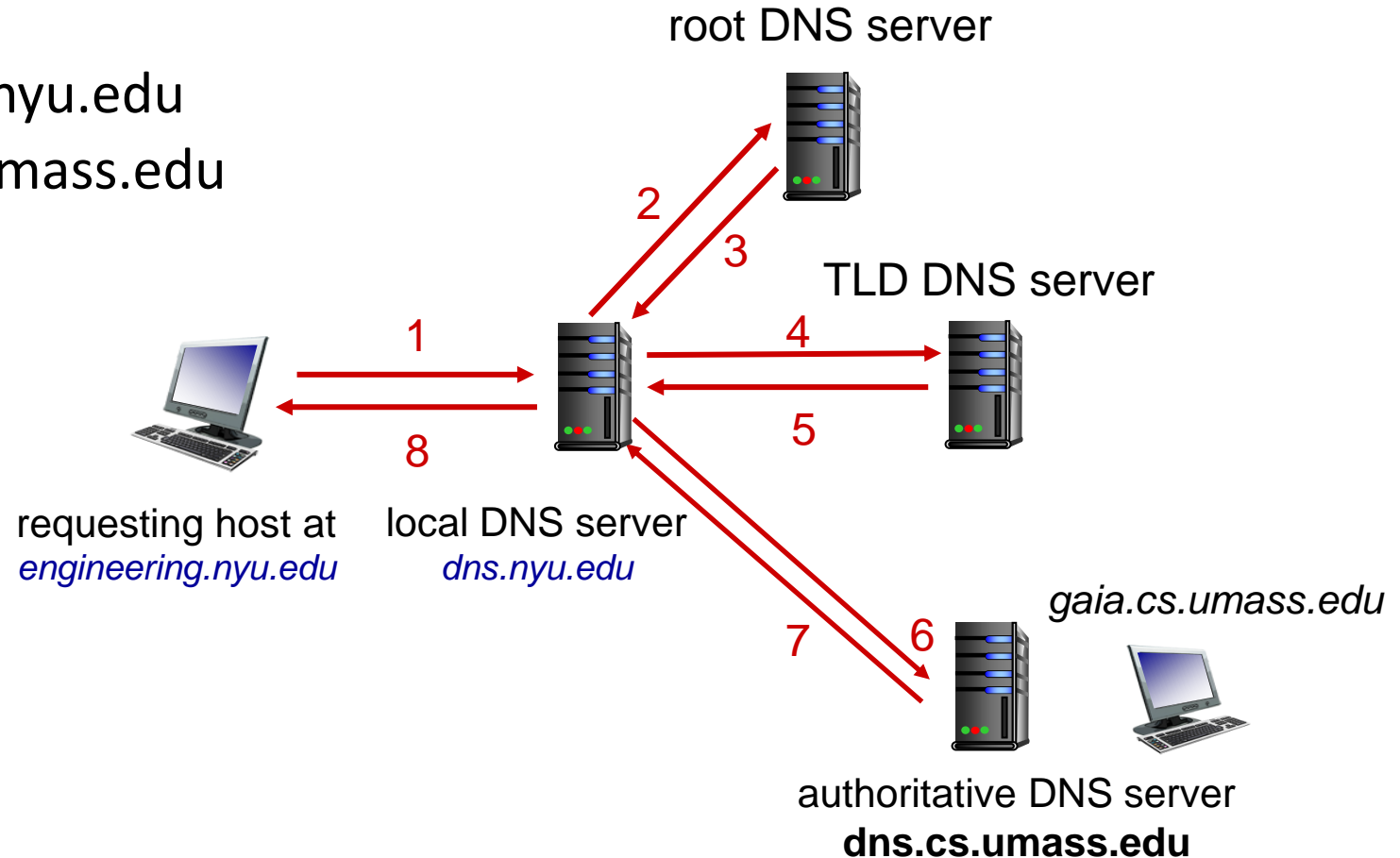
- when host makes DNS query, it is sent to its *local* DNS server
  - Local DNS server returns reply, answering:
    - from its local cache of recent name-to-address translation pairs (possibly out of date!)
    - forwarding request into DNS hierarchy for resolution
  - each ISP has local DNS name server; to find yours:
    - MacOS: `% scutil --dns`
    - Windows: `>ipconfig /all`
- local DNS server doesn't strictly belong to hierarchy

# DNS name resolution: iterated query

**Example:** host at `engineering.nyu.edu` wants IP address for `gaia.cs.umass.edu`

## Iterated query:

- contacted server replies with name of server to contact
- “I don’t know this name, but ask this server”

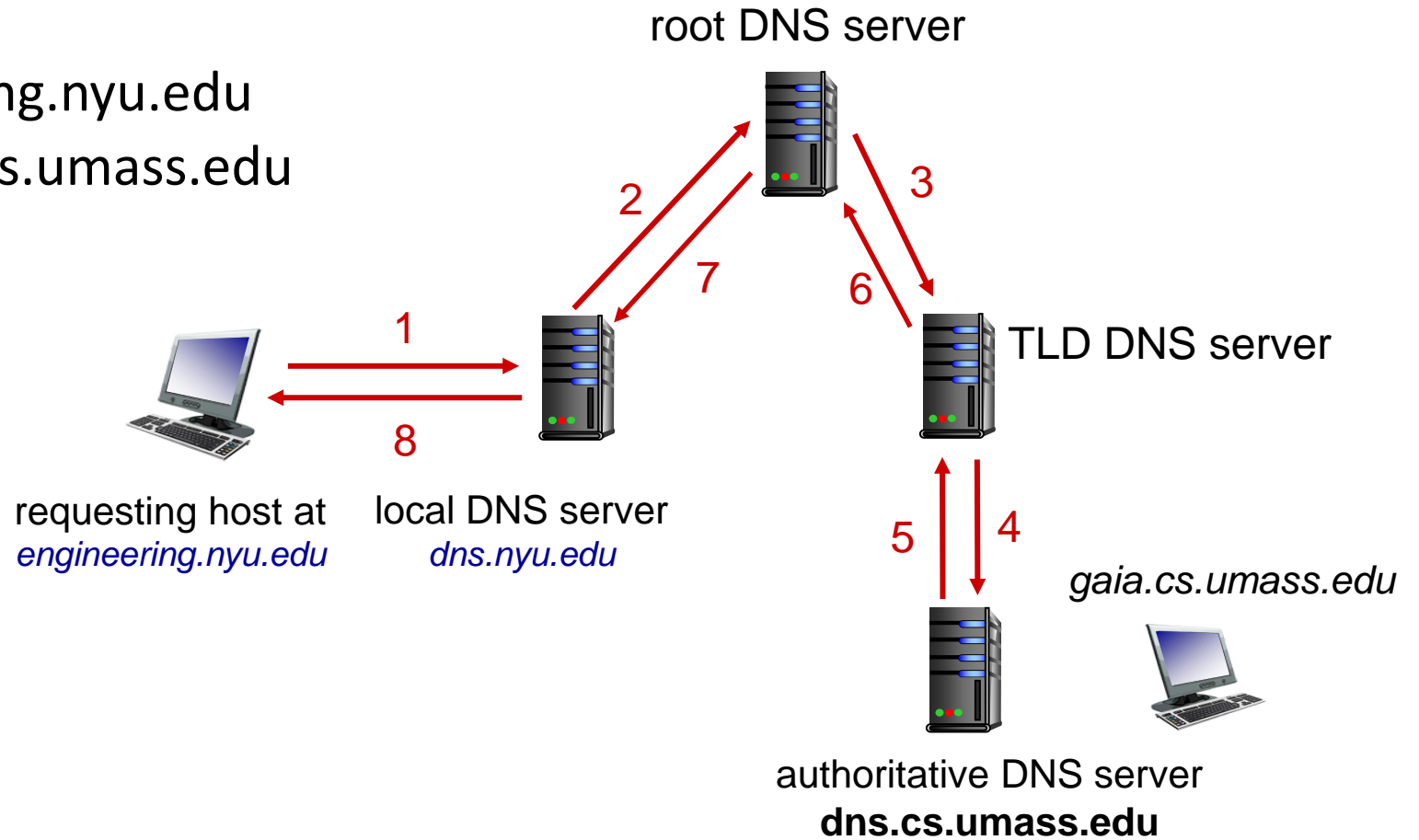


# DNS name resolution: recursive query

**Example:** host at `engineering.nyu.edu` wants IP address for `gaia.cs.umass.edu`

## Recursive query:

- puts burden of name resolution on contacted name server
- heavy load at upper levels of hierarchy?



# Caching DNS Information

- once (any) name server learns mapping, it *caches* mapping, and *immediately* returns a cached mapping in response to a query
  - caching improves response time
  - cache entries timeout (disappear) after some time (TTL)
  - TLD servers typically cached in local name servers
- cached entries may be *out-of-date*
  - if named host changes IP address, may not be known Internet-wide until all TTLs expire!
  - *best-effort name-to-address translation!*



# DNS records

**DNS:** distributed database storing resource records (RR)

RR format: (name, value, type, ttl)

## type=A

- name is hostname
- value is IP address

## type=NS

- name is domain (e.g., foo.com)
- value is hostname of authoritative name server for this domain

## type=CNAME

- name is alias name for some “canonical” (the real) name
- www.ibm.com is really servereast.backup2.ibm.com
- value is canonical name

## type=MX

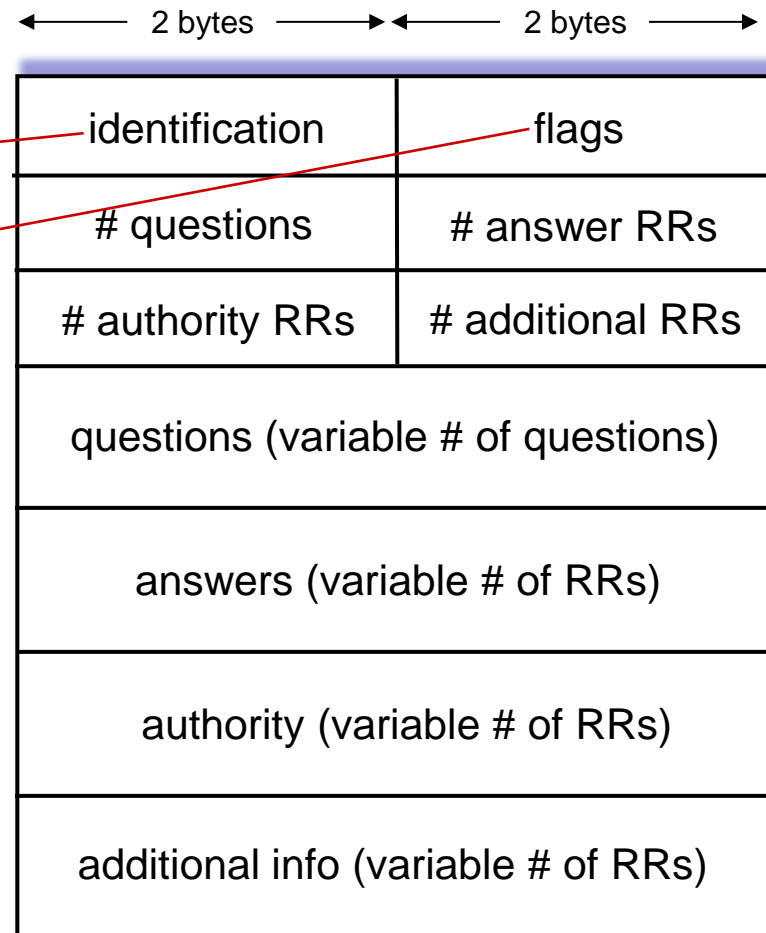
- value is name of SMTP mail server associated with name

# DNS protocol messages

DNS *query* and *reply* messages, both have same *format*:

message header:

- **identification**: 16 bit # for query, reply to query uses same #
- **flags**:
  - query or reply
  - recursion desired
  - recursion available
  - reply is authoritative



# DNS protocol messages

DNS *query* and *reply* messages, both have same *format*:

← 2 bytes → ← 2 bytes →

identification	flags
# questions	# answer RRs
# authority RRs	# additional RRs
questions (variable # of questions)	
answers (variable # of RRs)	
authority (variable # of RRs)	
additional info (variable # of RRs)	

name, type fields for a query

RRs in response to query

records for authoritative servers

additional “helpful” info that may be used

# Getting your info into the DNS

example: new startup “Network Utopia”

- register name networkutopia.com at *DNS registrar* (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts NS, A RRs into .com TLD server:  
(networkutopia.com, dns1.networkutopia.com, NS)  
(dns1.networkutopia.com, 212.212.212.1, A)
- create authoritative server locally with IP address 212.212.212.1
  - type A record for www.networkutopia.com
  - type MX record for networkutopia.com

# DNS security

## DDoS attacks

- bombard root servers with traffic
  - not successful to date
  - traffic filtering
  - local DNS servers cache IPs of TLD servers, allowing root server bypass
- bombard TLD servers
  - potentially more dangerous

## Spoofing attacks

- intercept DNS queries, returning bogus replies
  - DNS cache poisoning
  - RFC 4033: DNSSEC authentication services

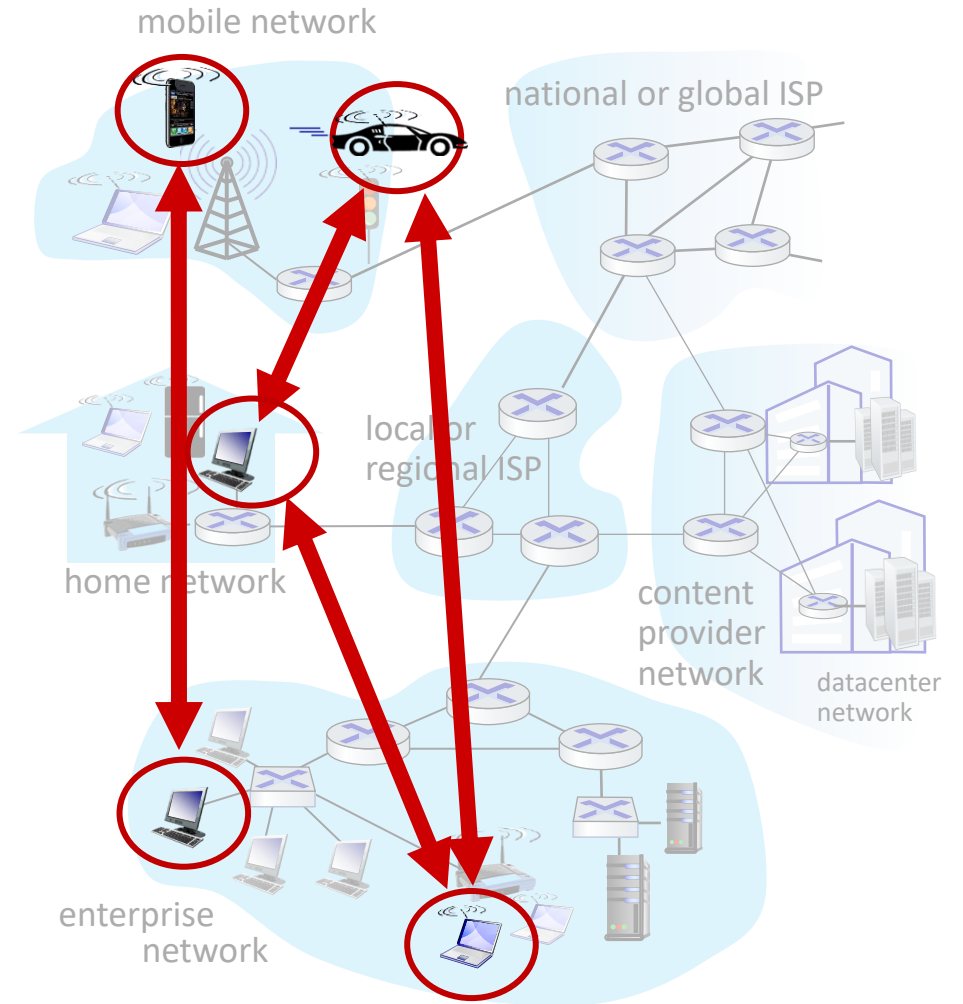
# Application Layer: Overview

- Principles of network applications
  - Web and HTTP
  - (E-mail, SMTP, IMAP)
  - The Domain Name System  
DNS
- P2P applications
  - video streaming and content distribution networks



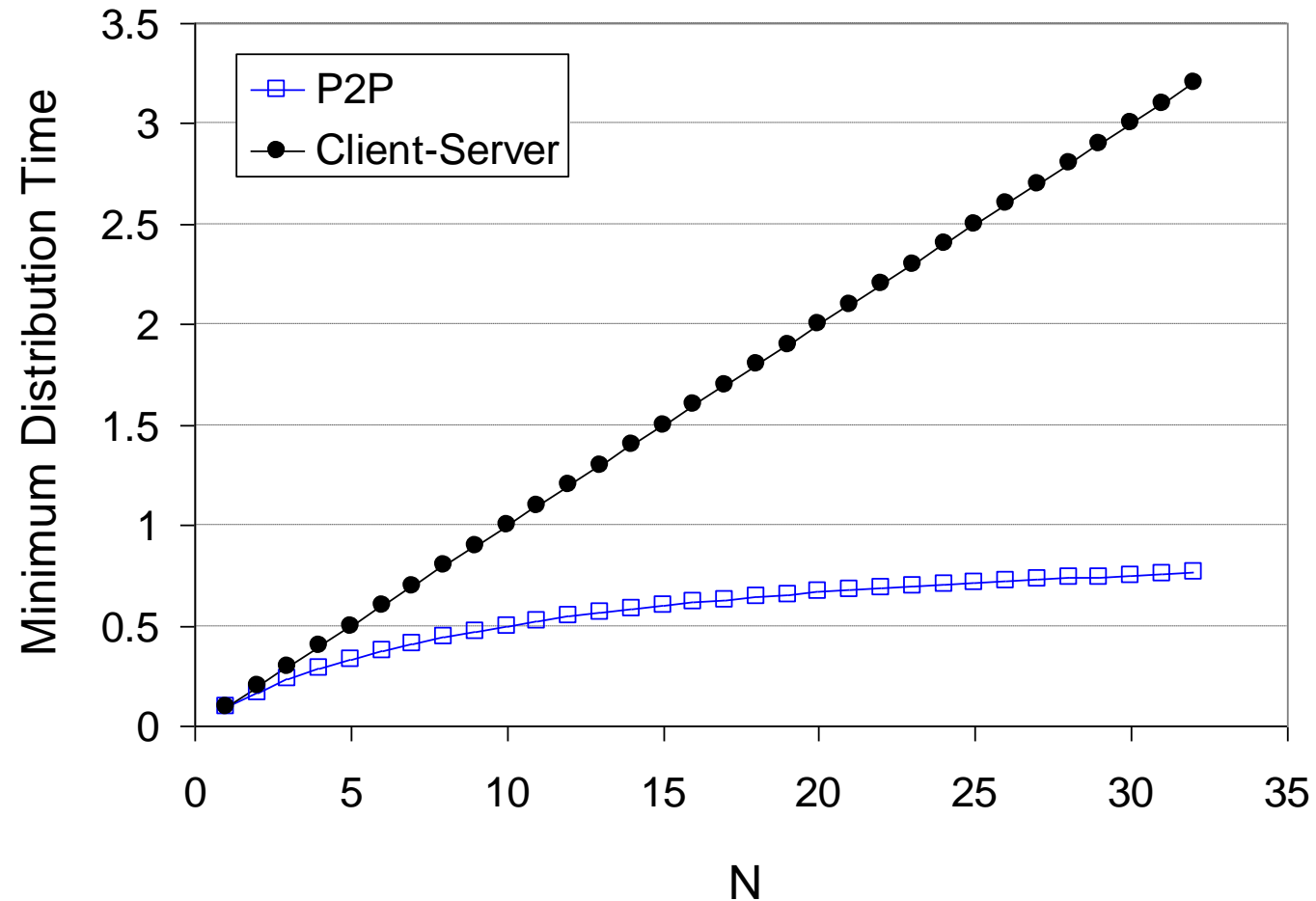
# Peer-to-peer (P2P) architecture

- *no* always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, and new service demands
- peers are intermittently connected and change IP addresses
  - complex management
- examples: P2P file sharing (BitTorrent), streaming (KanKan), VoIP (Skype)



# Client-server vs. P2P: example

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



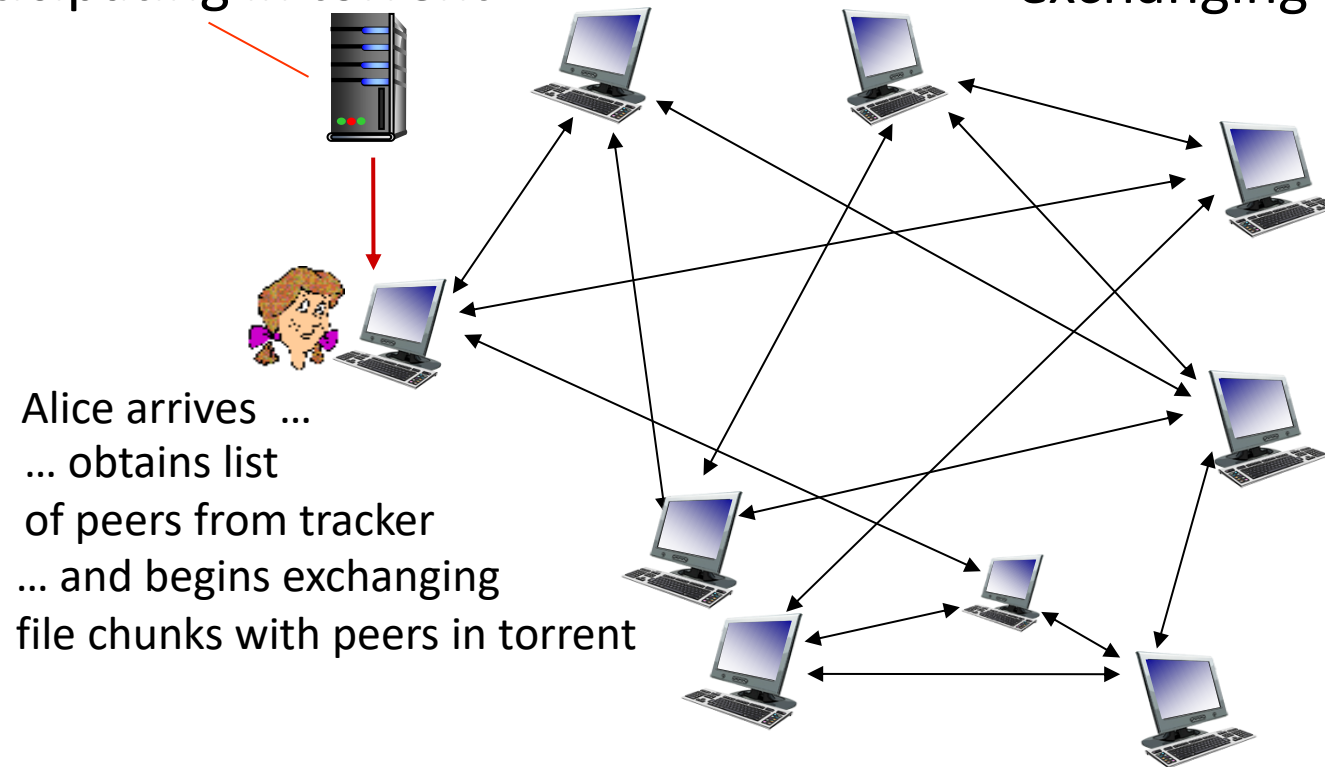


# P2P file distribution: BitTorrent

- file divided into 256Kb chunks
- peers in torrent send/receive file chunks

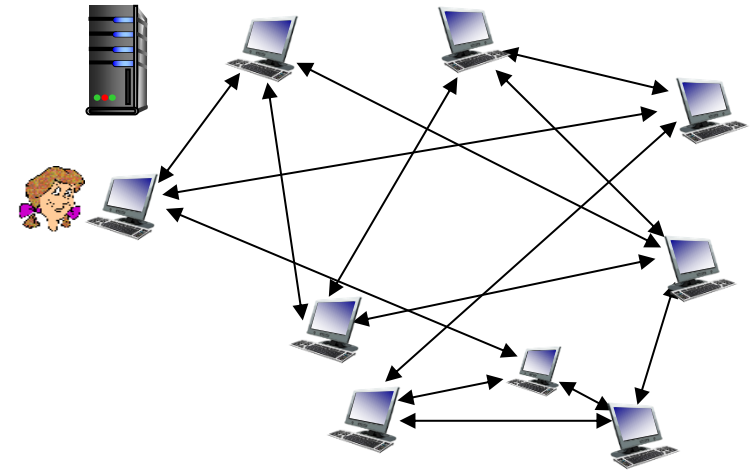
*tracker*: tracks peers participating in torrent

*torrent*: group of peers exchanging chunks of a file



# P2P file distribution: BitTorrent

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



# BitTorrent: requesting, sending file chunks

## Requesting chunks:

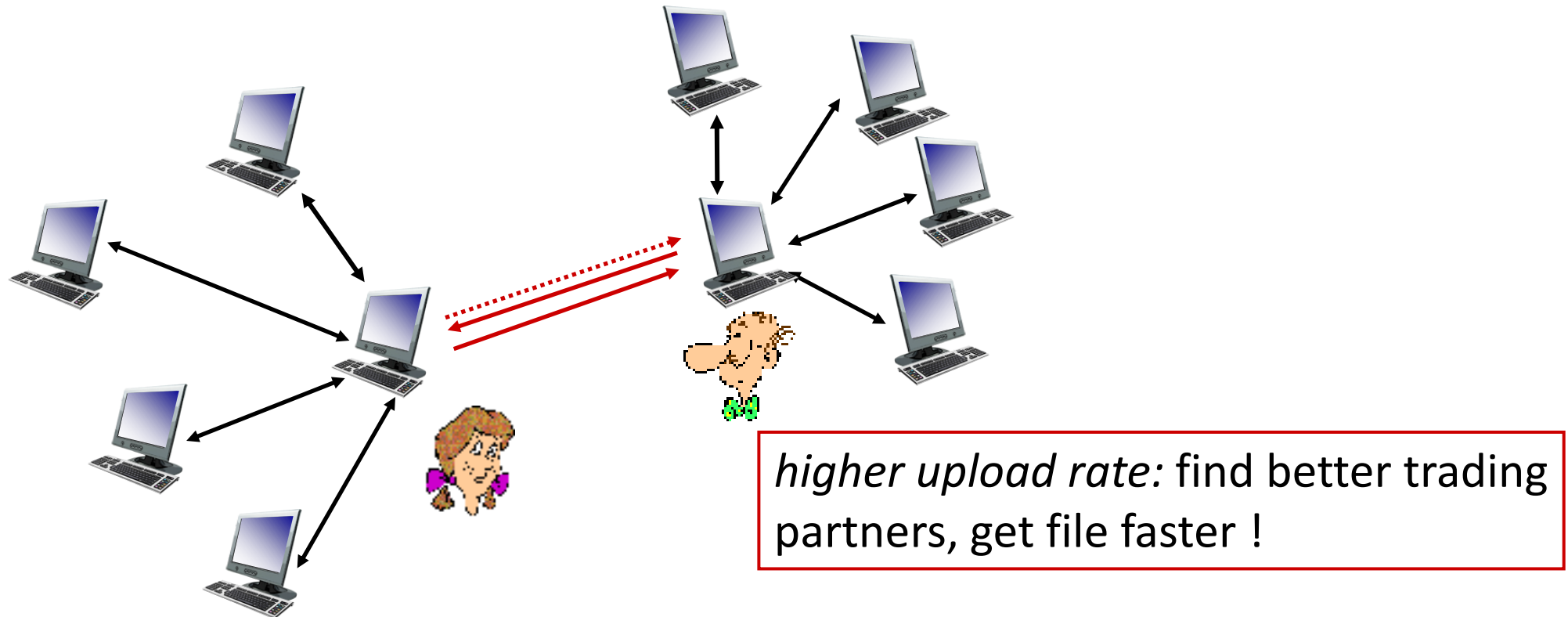
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

## Sending chunks: tit-for-tat

- Alice sends chunks to those four peers currently sending her chunks *at highest rate*
  - other peers are choked by Alice (do not receive chunks from her)
  - re-evaluate top 4 every 10 secs
- every 30 secs: randomly select another peer, starts sending chunks
  - “optimistically unchoke” this peer
  - newly chosen peer may join top 4

# 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



# Application layer: overview

- Principles of network applications
- Web and HTTP
- (E-mail, SMTP, IMAP)
- The Domain Name System  
DNS
- P2P applications
- video streaming and content distribution networks



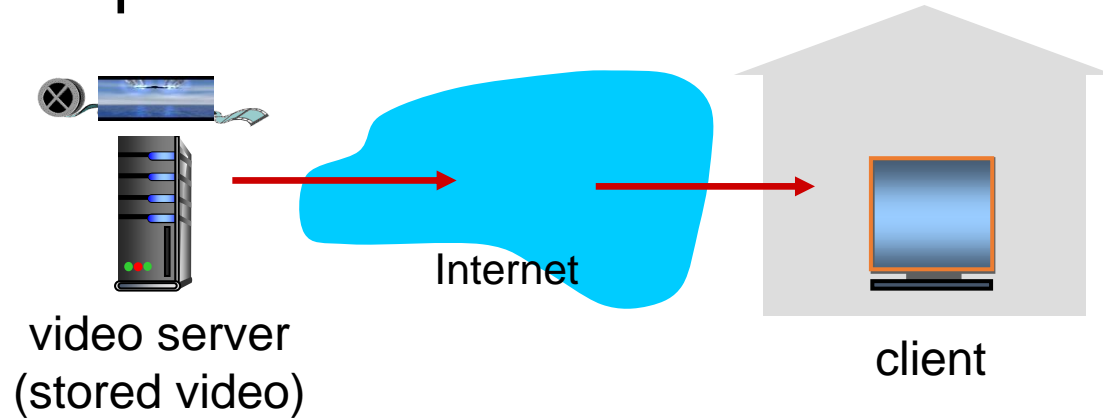
# Video Streaming and CDNs: context

- stream video traffic: major consumer of Internet bandwidth
  - Netflix, YouTube, Amazon Prime: 80% of residential ISP traffic (2020)
- *challenge*: scale - how to reach ~1B users?
- *challenge*: heterogeneity
  - different users have different capabilities (e.g., wired versus mobile; bandwidth rich versus bandwidth poor)
- *solution*: distributed, application-level infrastructure



# Streaming stored video

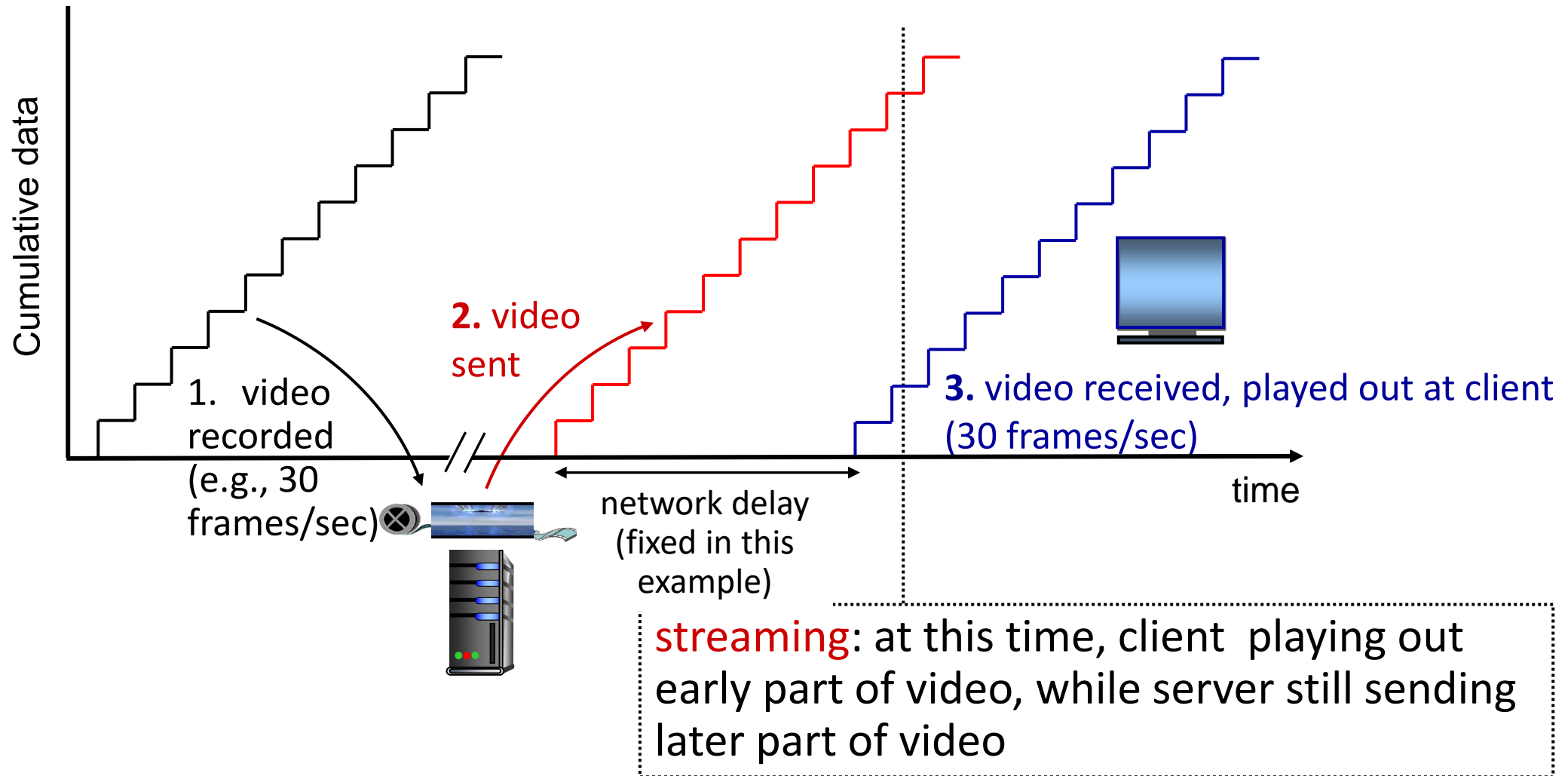
simple scenario:



Main challenges:

- server-to-client bandwidth will *vary* over time, with changing network congestion levels (in house, access network, network core, video server)
- packet loss, delay due to congestion will delay playout, or result in poor video quality

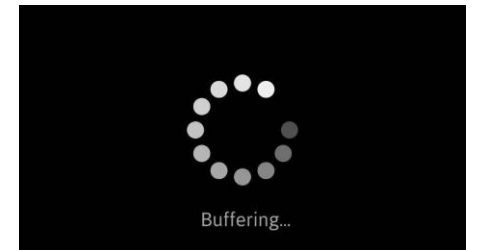
# Streaming stored video



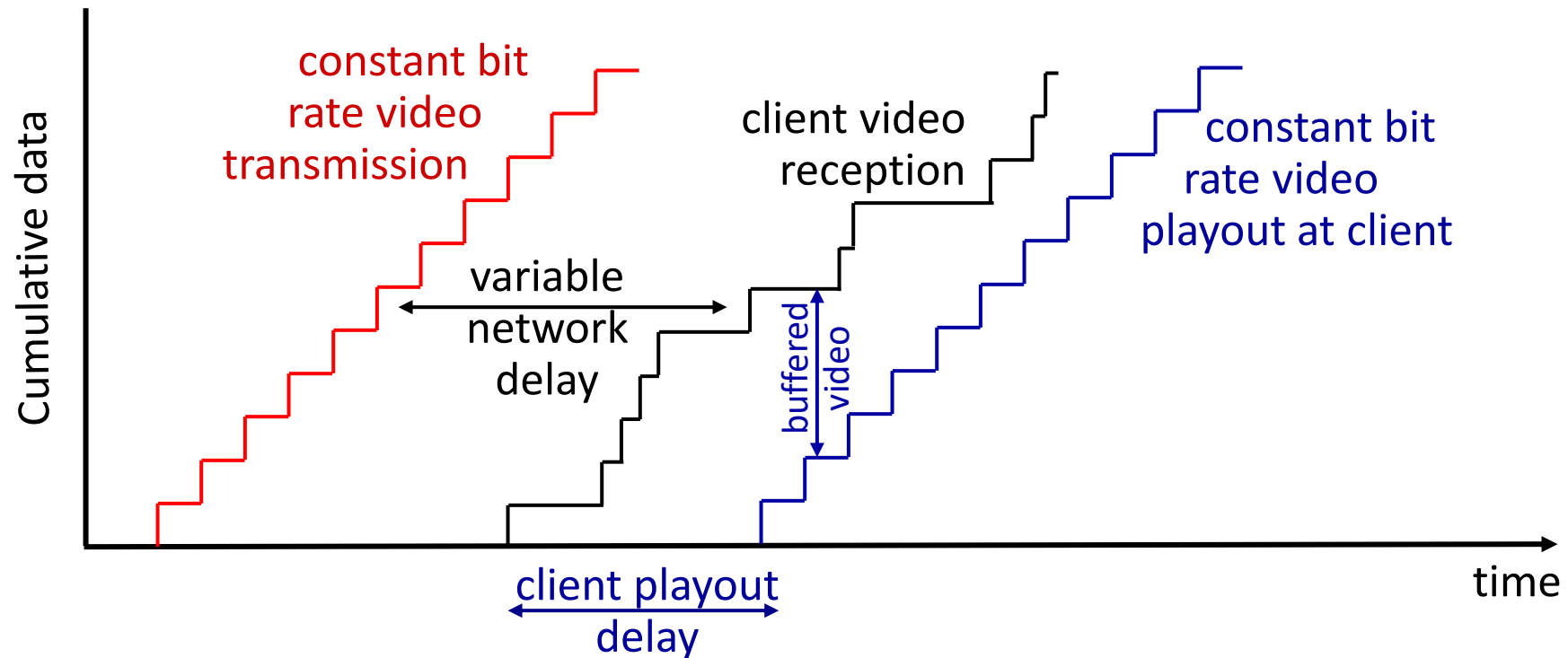


# Streaming stored video: challenges

- **continuous playout constraint**: during client video playout, playout timing must match original timing
  - ... but **network delays are variable** (jitter), so will need **client-side buffer** to match continuous playout constraint
- other challenges:
  - client interactivity: pause, fast-forward, rewind, jump through video
  - video packets may be lost, retransmitted



# Streaming stored video: playout buffering



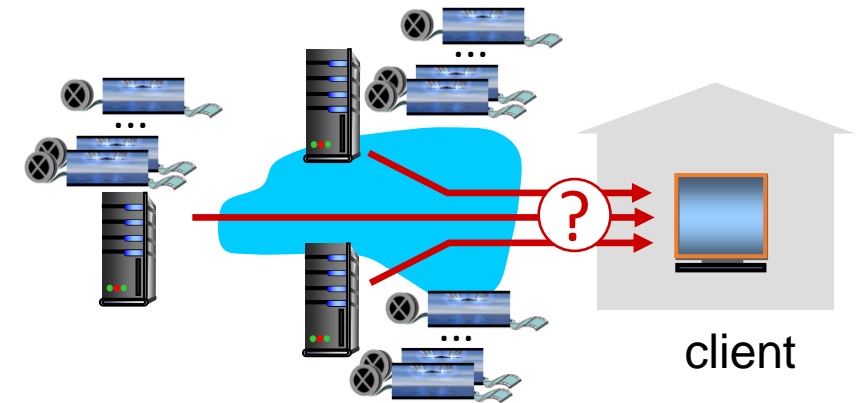
- *client-side buffering and playout delay*: compensate for network-added delay, delay jitter

# Streaming multimedia: DASH

*D*ynamic, *A*daptive  
*S*treaming over *H*TTP

## server:

- divides video file into multiple chunks
- each chunk encoded at multiple different rates
- different rate encodings stored in different files
- files replicated in various CDN nodes
- *manifest file*: provides URLs for different chunks

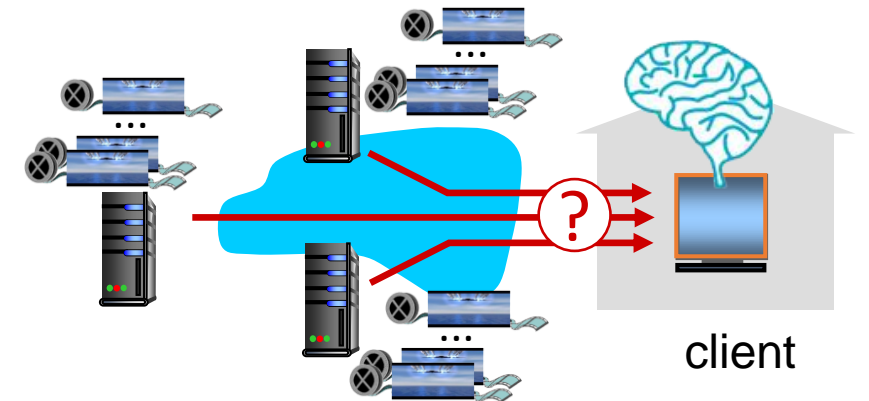


## client:

- periodically estimates server-to-client bandwidth
- consulting manifest, requests one chunk at a time
  - chooses maximum coding rate sustainable given current bandwidth
  - can choose different coding rates at different points in time (depending on available bandwidth at time), and from different servers

# Streaming multimedia: DASH

- “*intelligence*” at client: client determines
  - *when* to request chunk (so that buffer starvation, or overflow does not occur)
  - *what encoding rate* to request (higher quality when more bandwidth available)
  - *where* to request chunk (can request from URL server that is “close” to client or has high available bandwidth)



Streaming video = encoding + DASH + playout buffering

# Content distribution networks (CDNs)

*challenge:* how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?

- *option 1:* single, large “mega-server”
  - single point of failure
  - point of network congestion
  - long (and possibly congested) path to distant clients

....quite simply: this solution *doesn't scale*

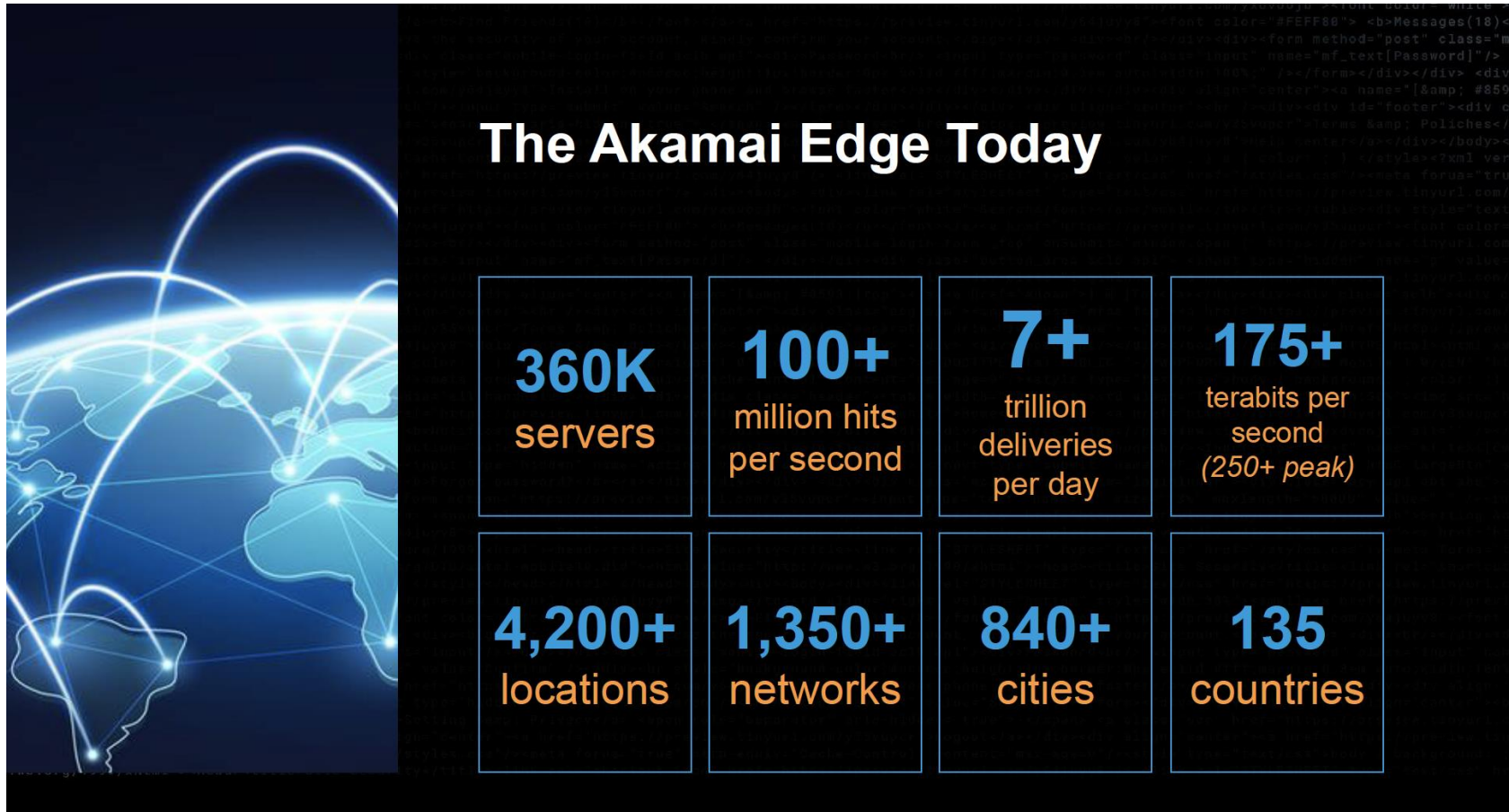
# Content distribution networks (CDNs)

*challenge:* how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?

- *option 2:* store/serve multiple copies of videos at multiple geographically distributed sites (*CDN*)
  - *enter deep:* push CDN servers deep into many access networks
    - close to users
    - Akamai: 240,000 servers deployed in > 120 countries (2015)
  - *bring home:* smaller number (10's) of larger clusters in points near access nets (e.g., in IXPs)
    - used by Limelight



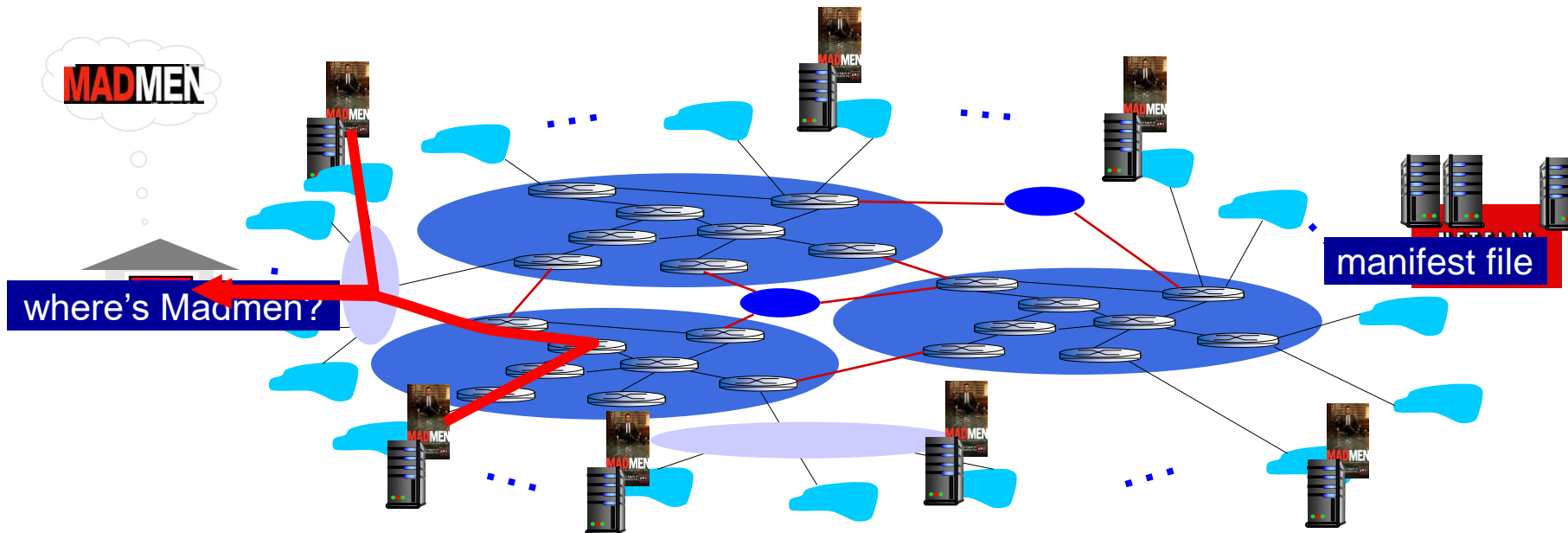
# Akamai today:



Source: <https://networkingchannel.eu/living-on-the-edge-for-a-quarter-century-an-akamai-retrospective-downloads/>

# How does Netflix work?

- Netflix: stores copies of content (e.g., MADMEN) at its (worldwide) OpenConnect CDN nodes
- subscriber requests content, service provider returns manifest
  - using manifest, client retrieves content at highest supportable rate
  - may choose different rate or copy if network path congested





# Content distribution networks (CDNs)



*OTT challenges:* coping with a congested Internet from the "edge"

- what content to place in which CDN node?
- from which CDN node to retrieve content? At which rate?

# Chapter 2: Summary

our study of network application layer is now complete!

- application architectures
  - client-server
  - P2P
- application service requirements:
  - reliability, bandwidth, delay
- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP
- specific protocols:
  - HTTP
  - SMTP, IMAP
  - DNS
  - P2P: BitTorrent
- video streaming, CDNs

# Chapter 2: Summary

Most importantly: learned about *protocols!*

- typical request/reply message exchange:
  - client requests info or service
  - server responds with data, status code
- message formats:
  - *headers*: fields giving info about data
  - *data*: info(payload) being communicated

important themes:

- centralized vs. decentralized
- stateless vs. stateful
- scalability
- reliable vs. unreliable message transfer
- “complexity at network edge”