# Chapter 2: Application Layer

**Applications**

… built on ...

**Reliable (or unreliable) transport**

… built on ...

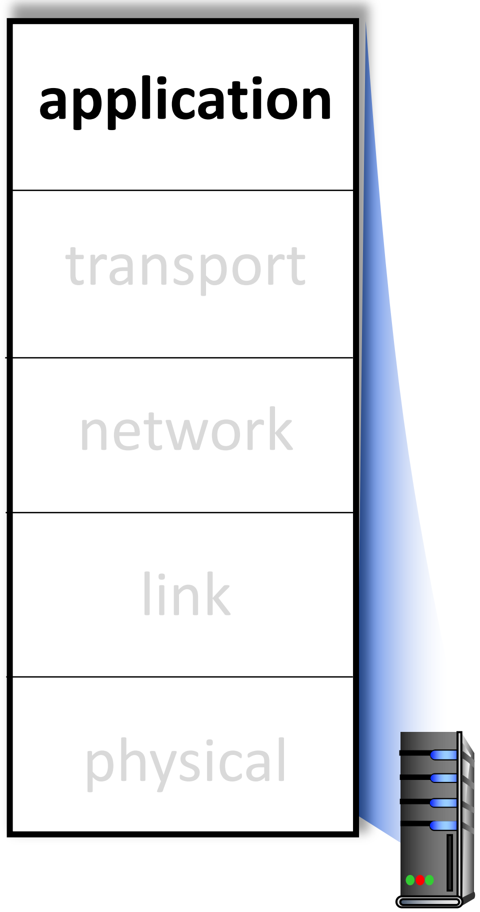
**Best-effort global packet delivery**

… built on ...

**Best-effort local packet delivery**

… built on ...

Physical transfer of bits




The source PowerPoint slides are public available, provided by Authors (JFK/KWR). They are revised for CS536@Purdue.

# 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
- socket programming with UDP and TCP (@PSO)

# 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
  - DASH
- programming network applications
  - socket API

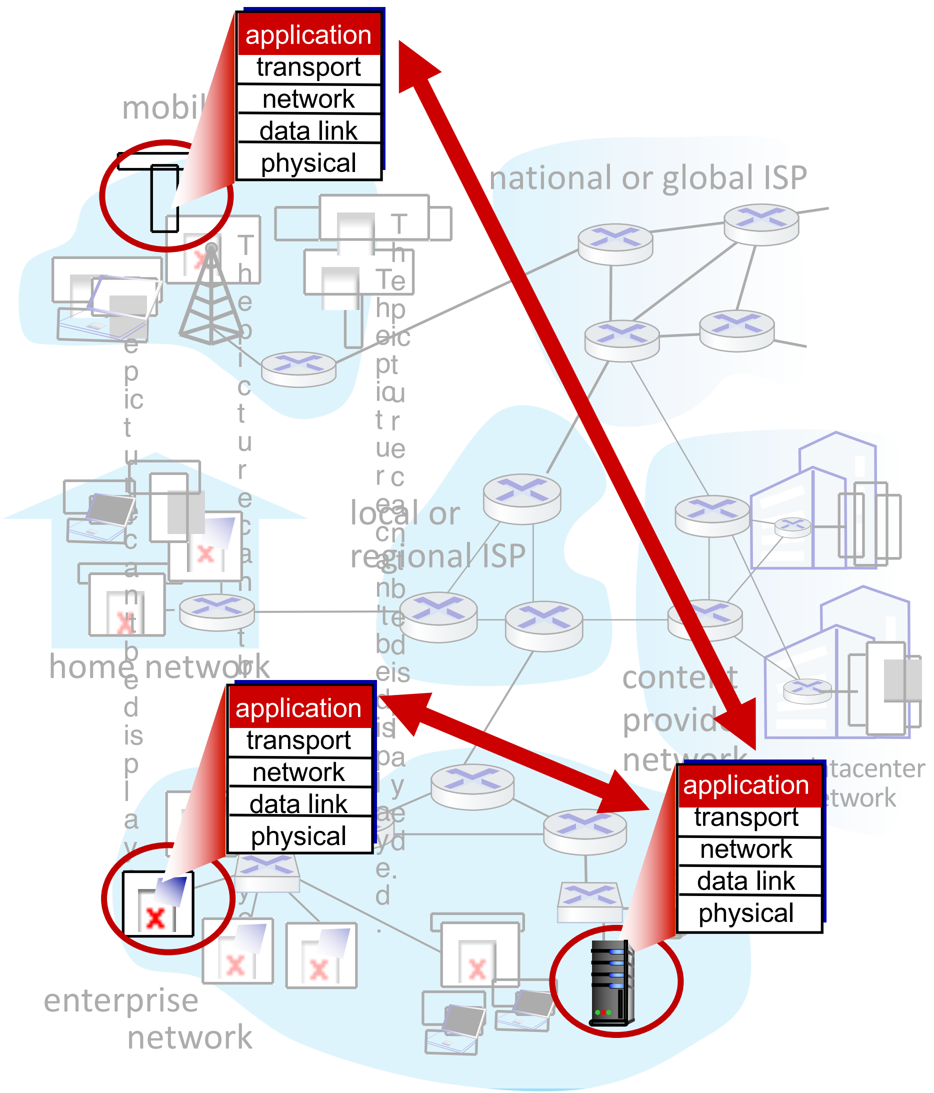
# Creating a network app

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

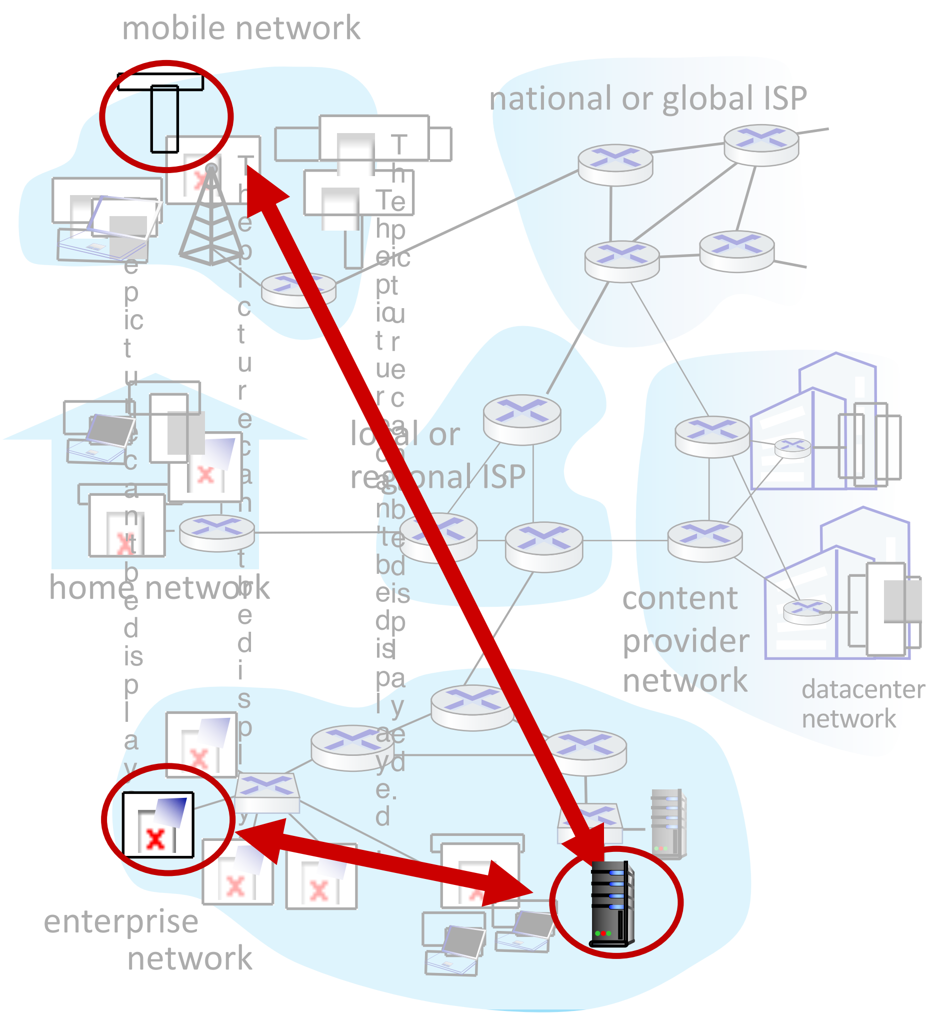
server:

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

clients:

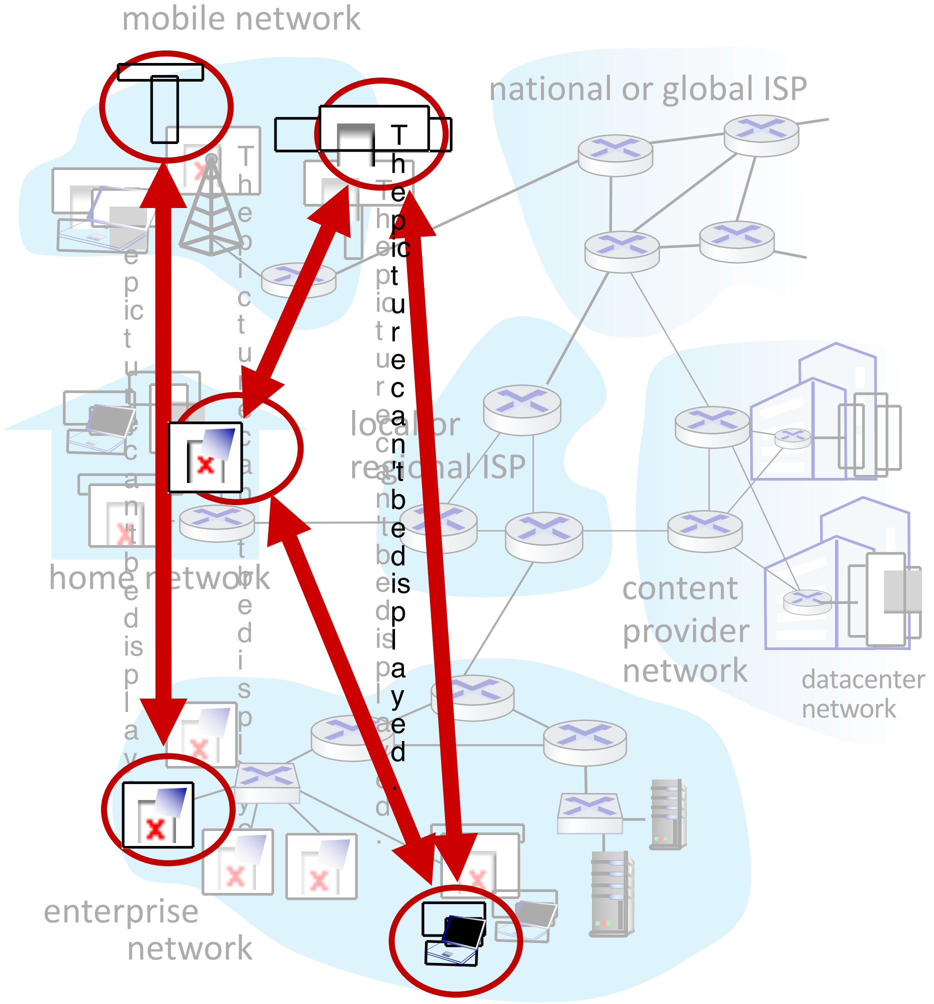
- contact, communicate with server
- may be intermittently connected
- may have dynamic IP addresses
- do *not* communicate directly with each other

- 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



# 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

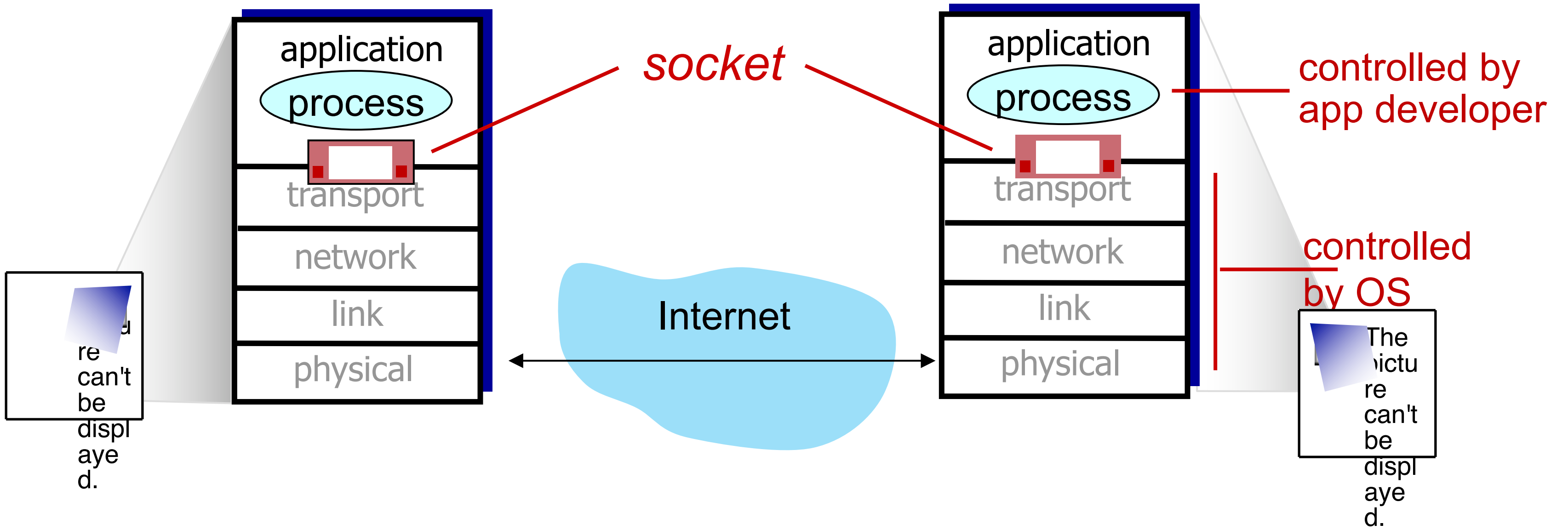
*client process:* process that initiates communication

*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

| application | data loss | throughput | time sensitive? |
| --- | --- | --- | --- |
| 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<br>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

| application | application layer protocol | transport protocol |
|---|---|---|
| file transfer/download | FTP [RFC 959] | TCP |
| e-mail | SMTP [RFC 5321] | TCP |
| Web documents | HTTP 1.1 [RFC 7320] | TCP |
| Internet telephony | SIP [RFC 3261], RTP [RFC 3550], or proprietary | TCP or UDP |
| streaming audio/video | HTTP [RFC 7320], 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

**TSL implemented in application layer**
- apps use TSL libraries, that use TCP in turn
- cleartext sent into "socket" traverse Internet *encrypted*
- more: Chapter 8

# Application layer: overview

- Principles of network applications
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- E-mail, SMTP, IMAP
- The Domain Name System DNS
- P2P applications
- video streaming and content distribution networks
- socket programming with UDP and TCP

# 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.,

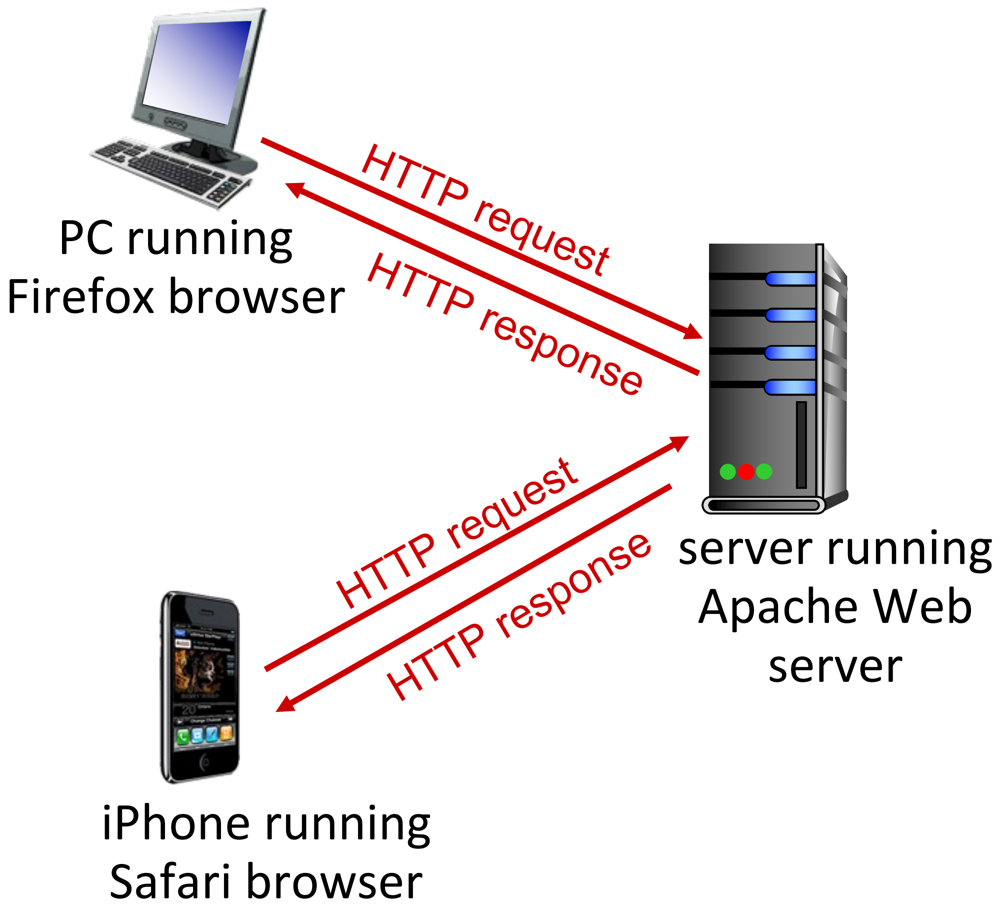
```
www.someschool.edu/someDept/pic.gif
```

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)

*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

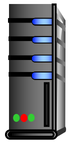
*Persistent HTTP*

- 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

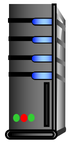
2. HTTP client sends HTTP *request message* (containing URL) into TCP connection socket. Message indicates that client wants object someDepartment/home.index

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)



4. HTTP server closes TCP connection.

5. HTTP client receives response message containing html file, displays html. Parsing html file, finds 10 referenced jpeg objects

6. Steps 1-5 repeated for each of 10 jpeg objects

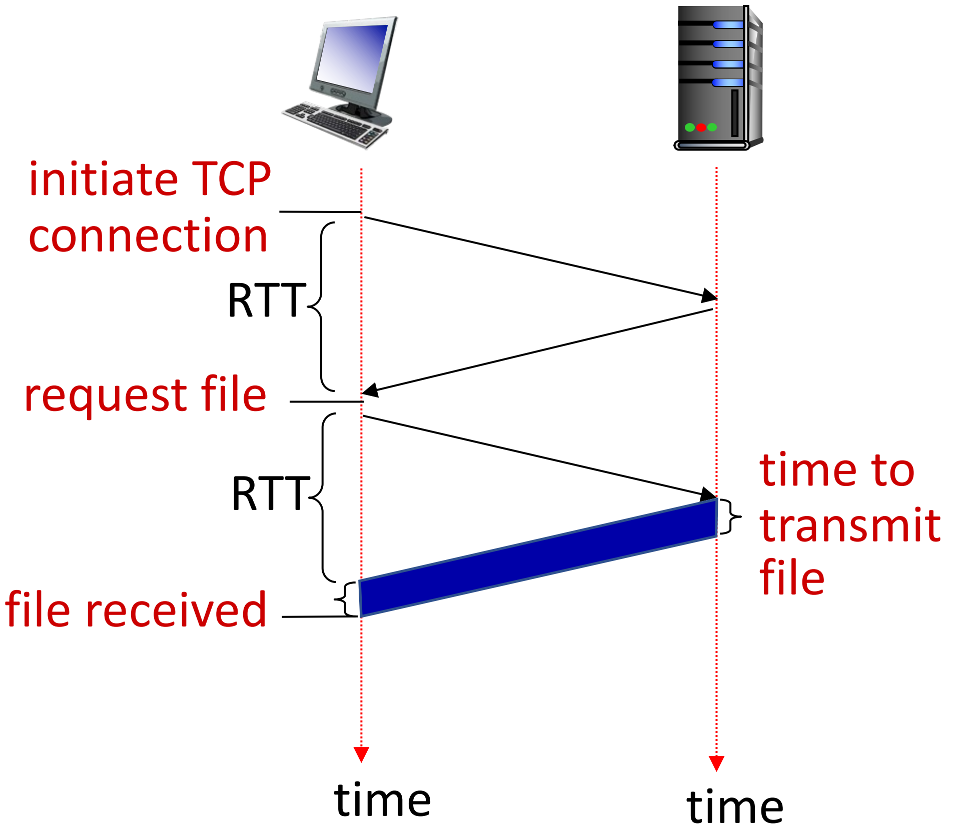
time

# 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

*Persistent HTTP (HTTP1.1):*

- server leaves connection open after sending response
- 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)

# HTTP request message

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

carriage return character

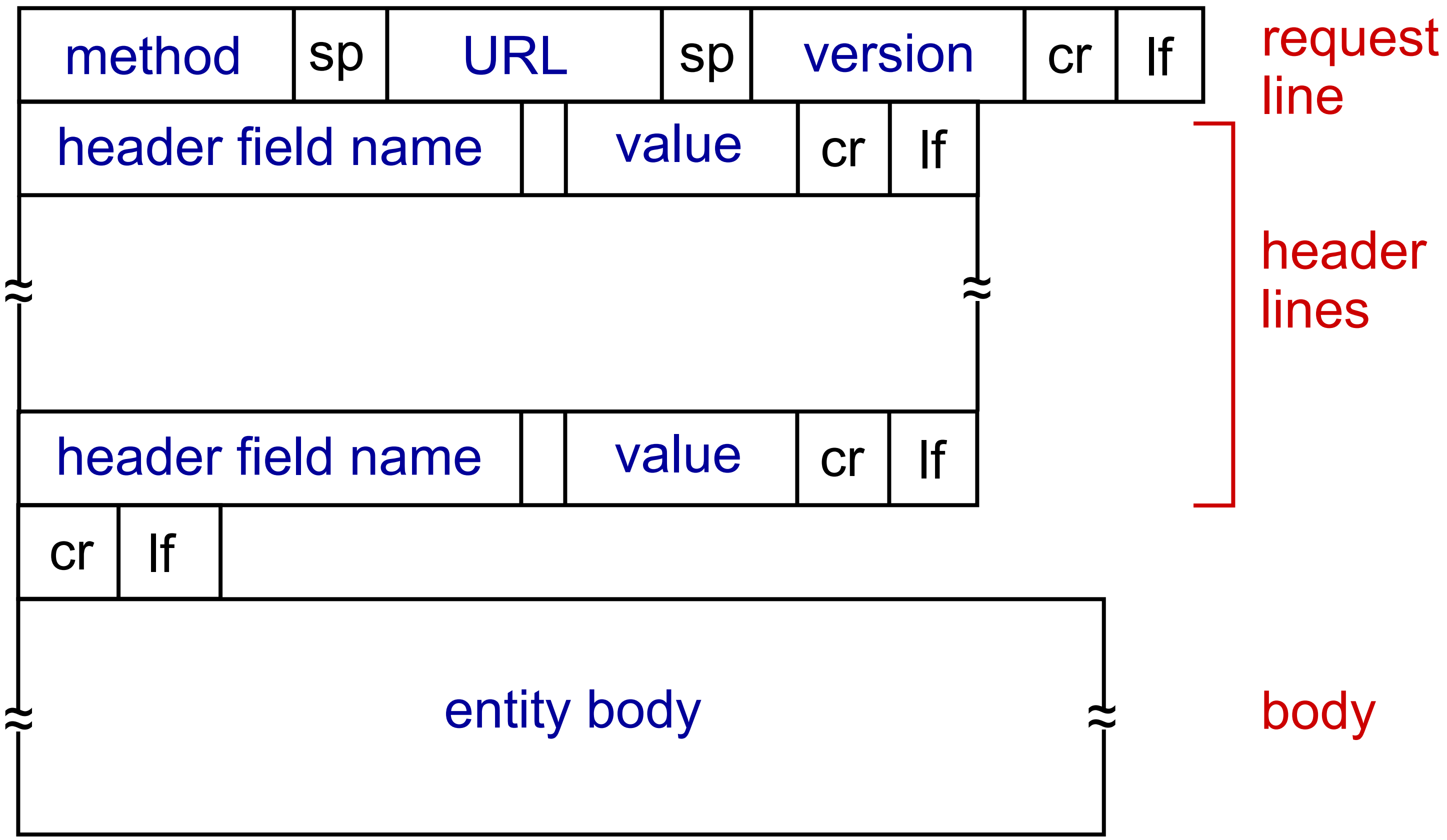
line-feed character

request line (GET, POST, HEAD commands)

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 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:

- 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) → **`HTTP/1.1 200 OK`**

# 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

# Trying out HTTP (client side) for yourself

1. netcat to your favorite Web server:

% nc -c -v gaia.cs.umass.edu 80

% telnet gaia.cs.umass.edu 80

- opens TCP connection to port 80 (default HTTP server port) at gaia.cs.umass. edu.
- anything typed in will be sent to port 80 at gaia.cs.umass.edu

2. type in a GET HTTP request:

```
GET /kurose_ross/interactive/index.php HTTP/1.1
Host: gaia.cs.umass.edu
```

- by typing this in (hit carriage return twice), you send this minimal (but complete) GET request to HTTP server

3. look at response message sent by HTTP server!

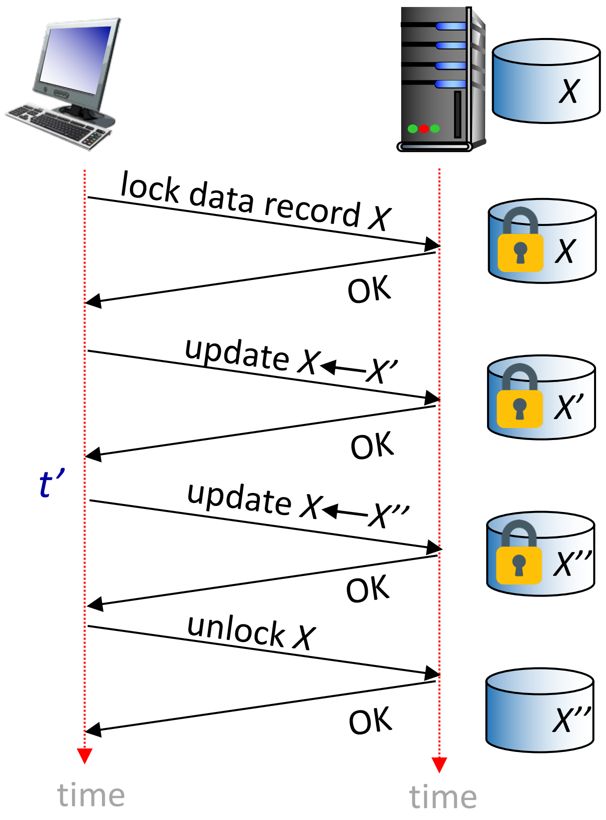
(or use Wireshark to look at captured HTTP request/response)

# 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

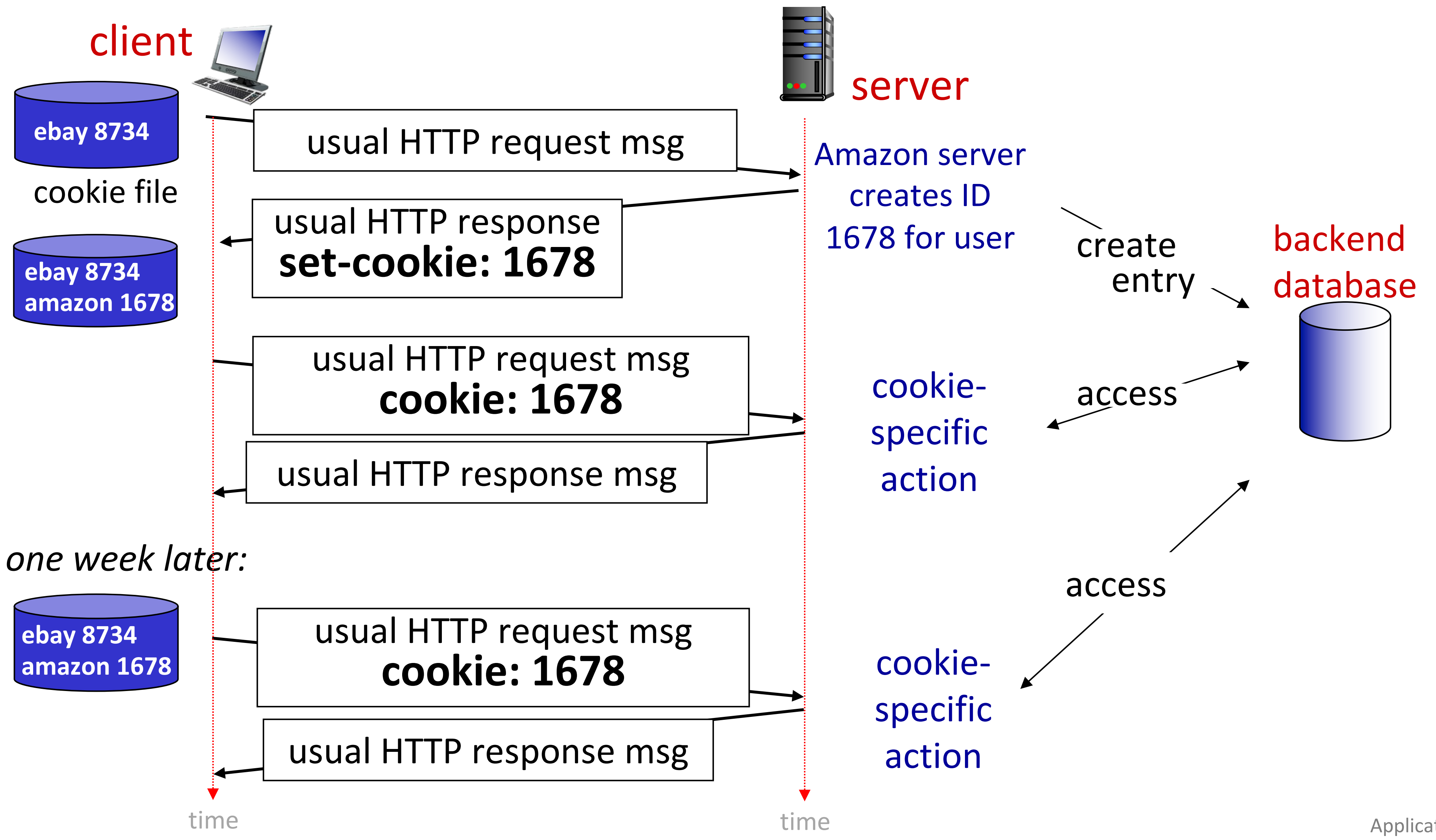
*four components:*

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 inHTTP messages carry state

aside

*cookies and privacy:*

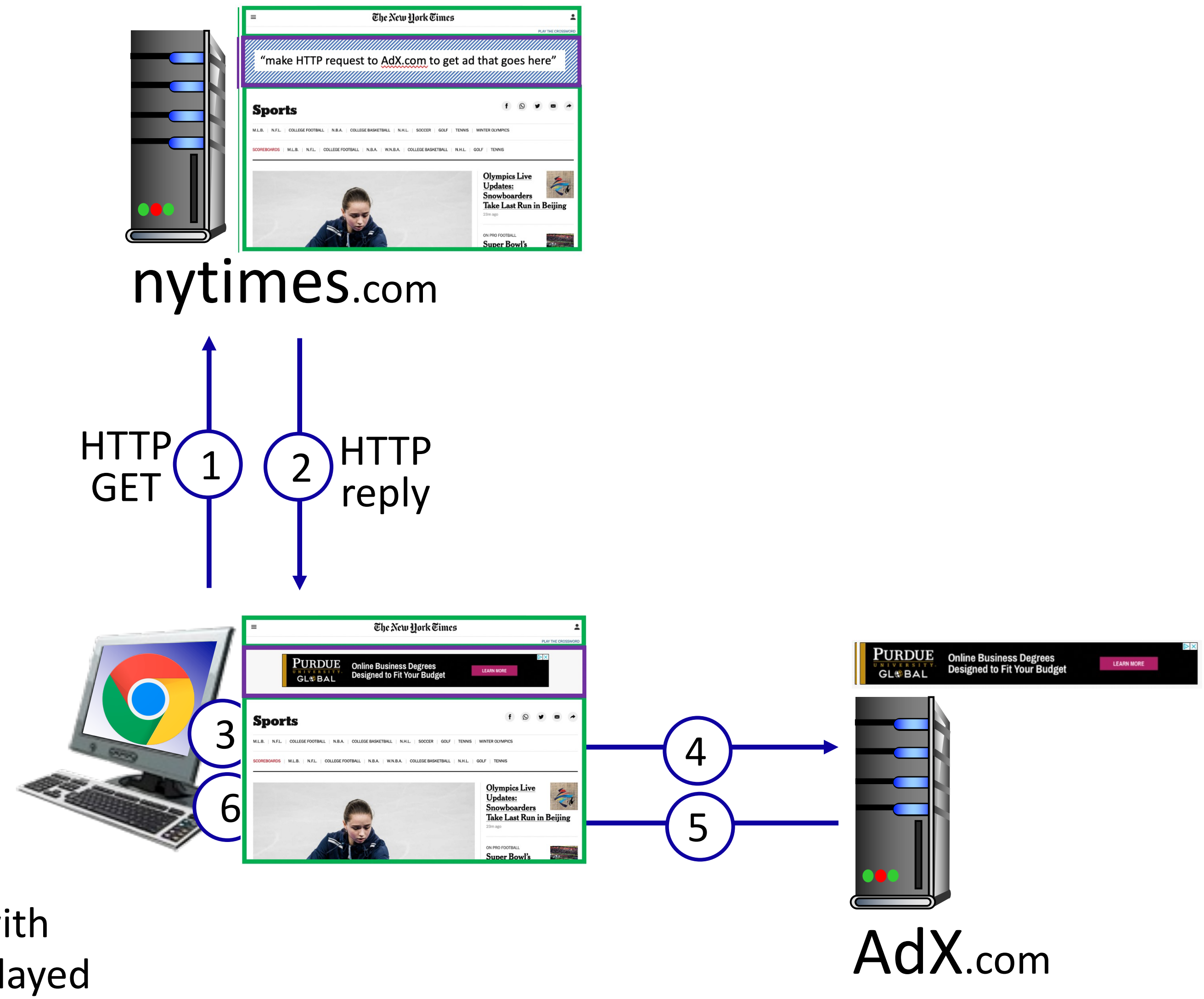
- cookies permit sites to *learn* a lot about you on their site.
- third party persistent cookies (tracking cookies) allow common identity (cookie value) to be tracked across multiple web sites

# Example: displaying a NY Times web page

(1) (2) GET base html file from nytimes.com

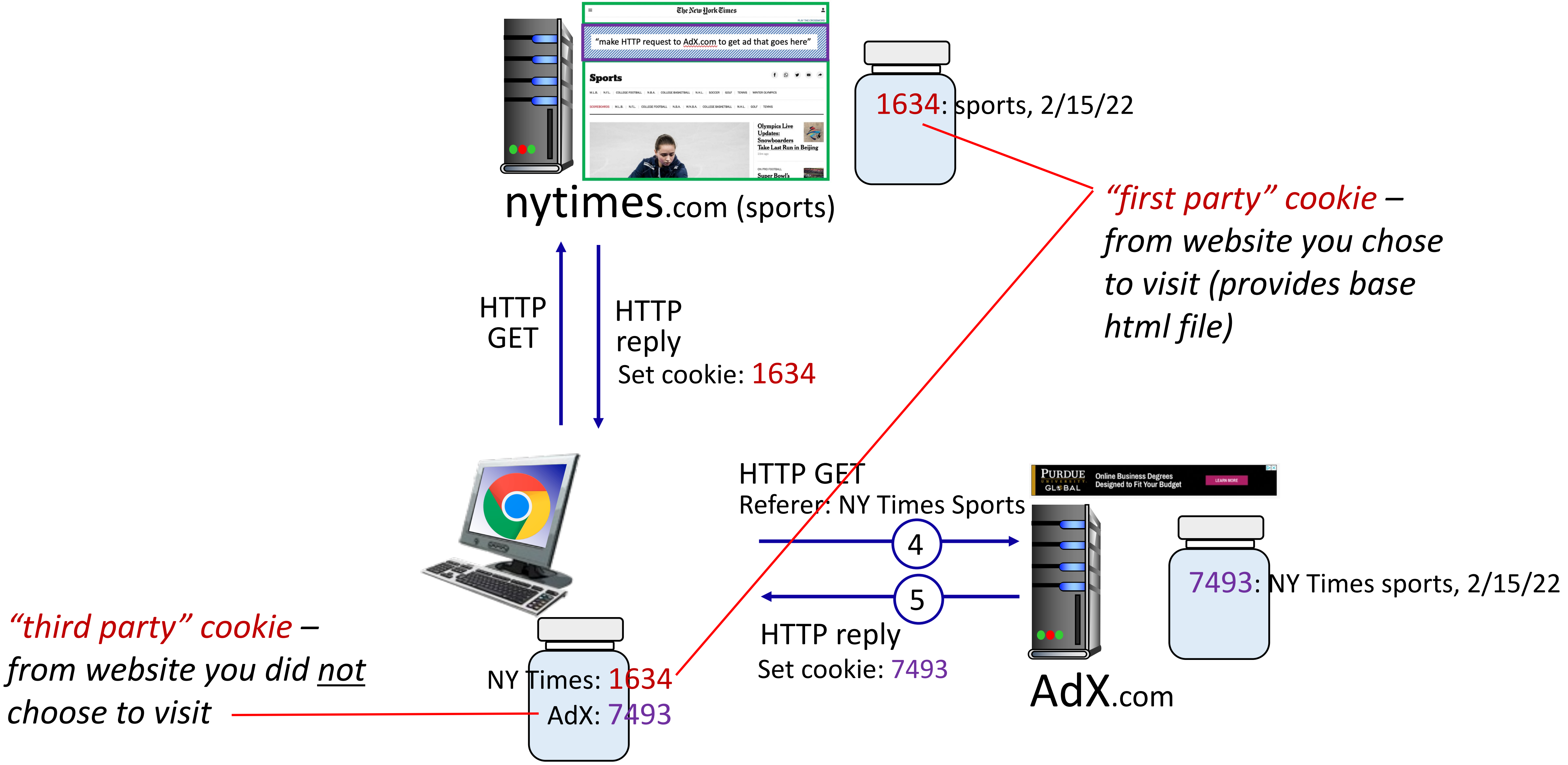
(4) (5) fetch ad from AdX.com

(7) display composed page

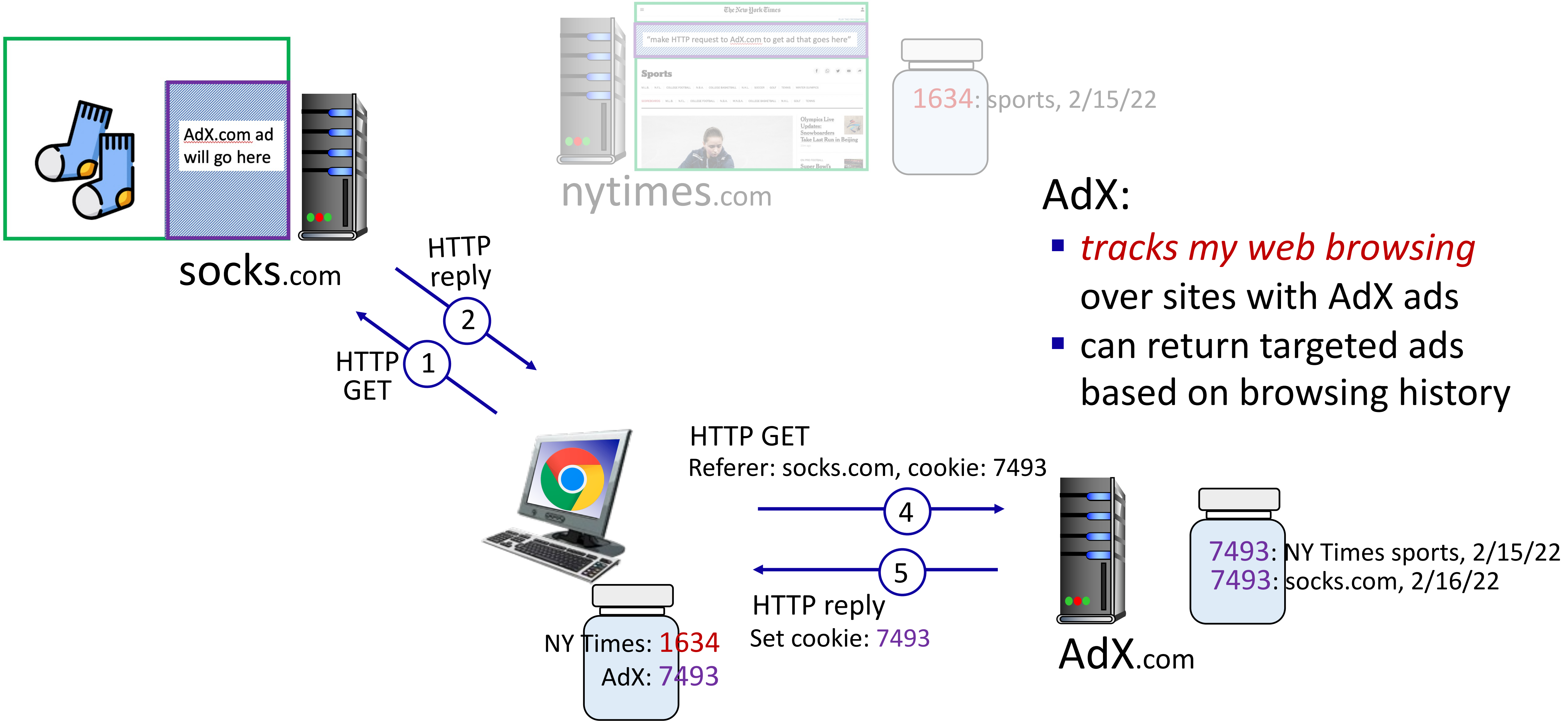



NY times page with embedded ad displayed

# Cookies: tracking a user's browsing behavior



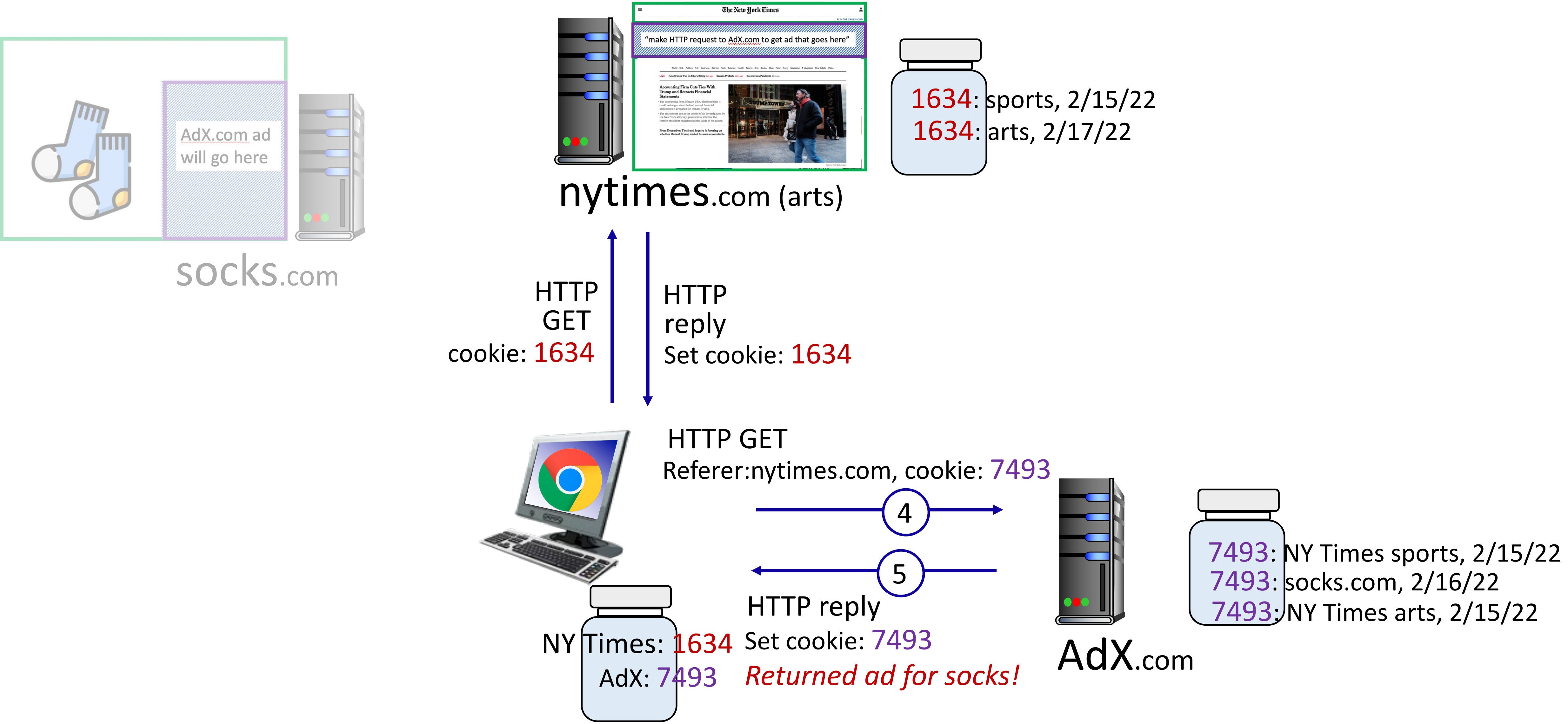
# Cookies: tracking a user's browsing behavior




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

third party tracking via cookies:

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

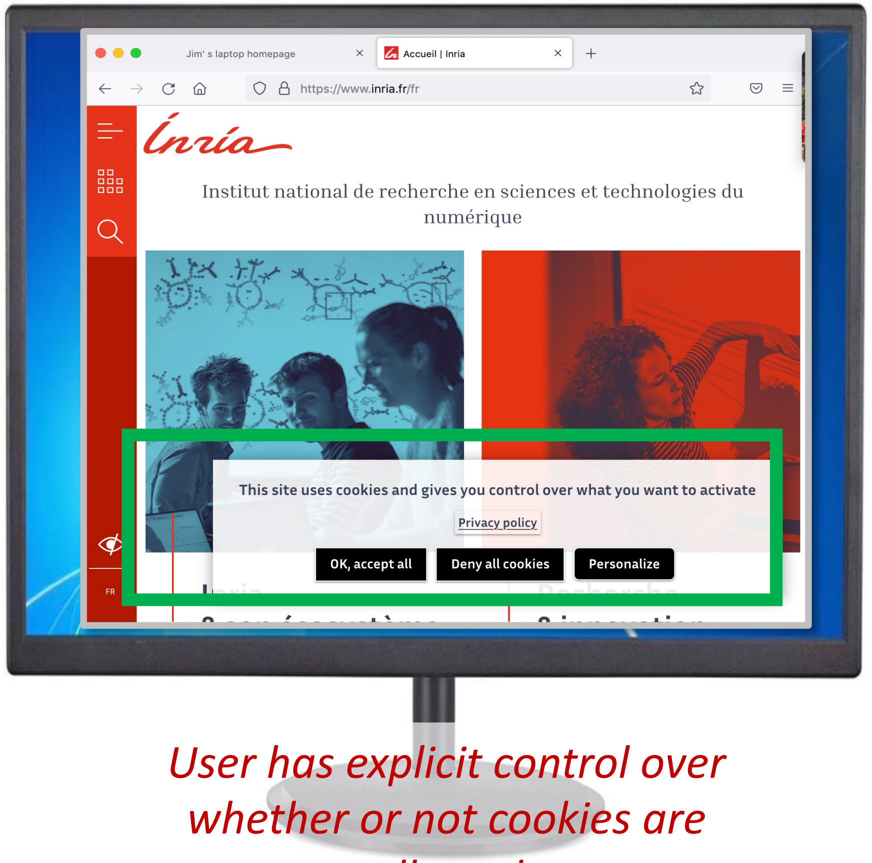
# GDPR (EU General Data Protection Regulation) and cookies

"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

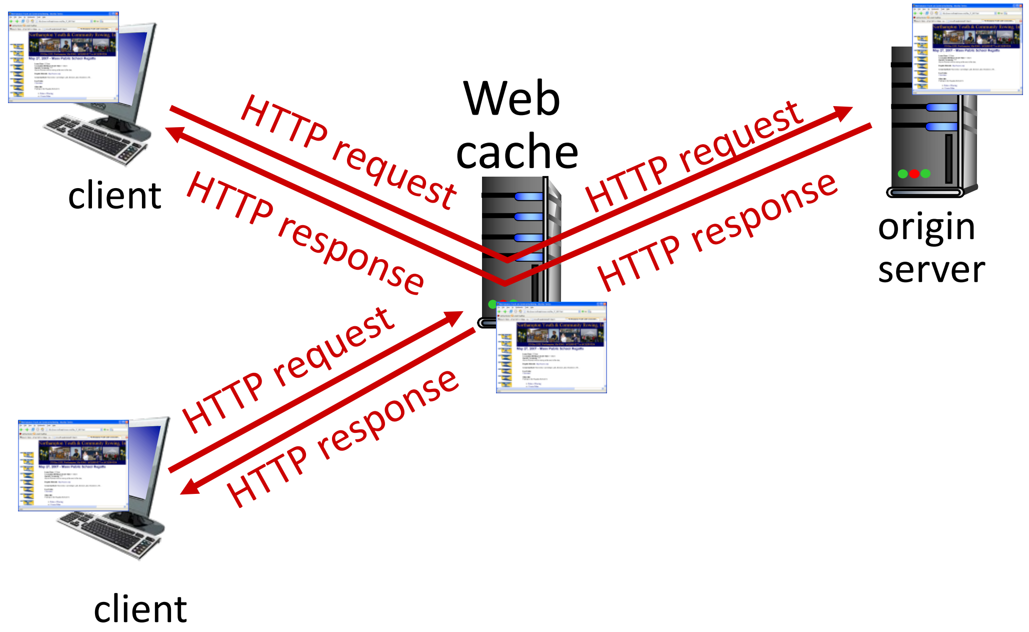



*User has explicit control over whether or not cookies are allowed*

# 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

# Caching example

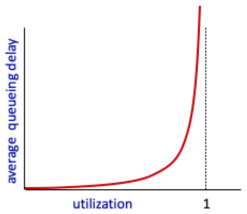
*Scenario:*

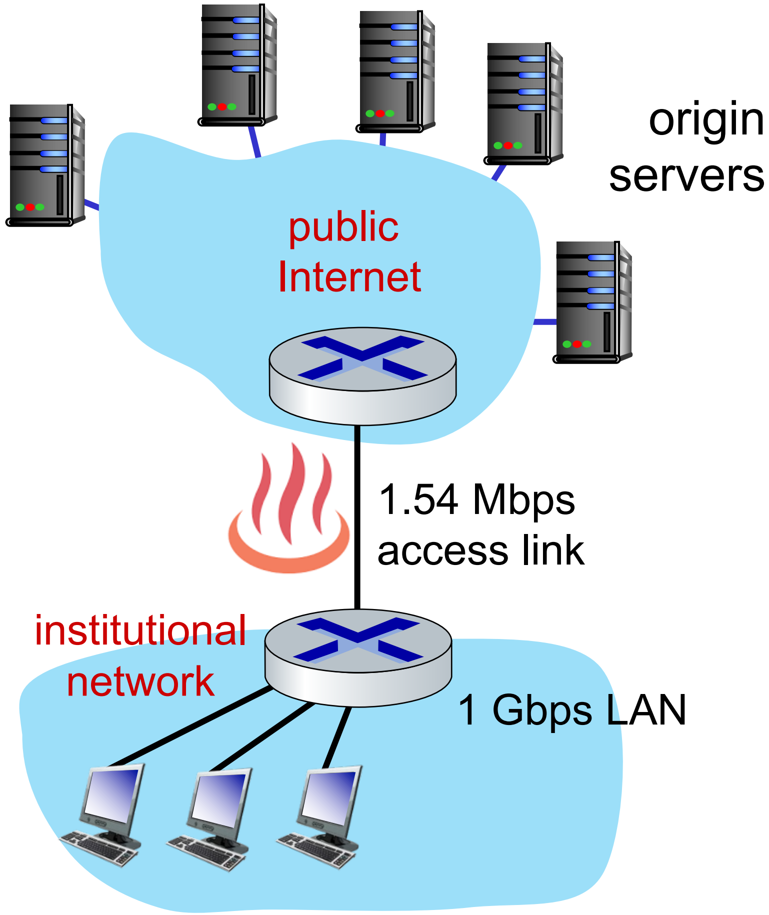
- access link rate: 1.54 Mbps
- RTT from institutional router to server: 2 sec
- web object size: 100K bits
- average request rate from browsers to origin servers: 15/sec
  - avg data rate to browsers: 1.50 Mbps

*Performance:*

- access link utilization = .97
- LAN utilization: .0015
- end-end delay = Internet delay + access link delay + LAN delay = 2 sec + minutes + usecs

*problem:* large queueing delays at high utilization!



# Option 1: buy a faster access link

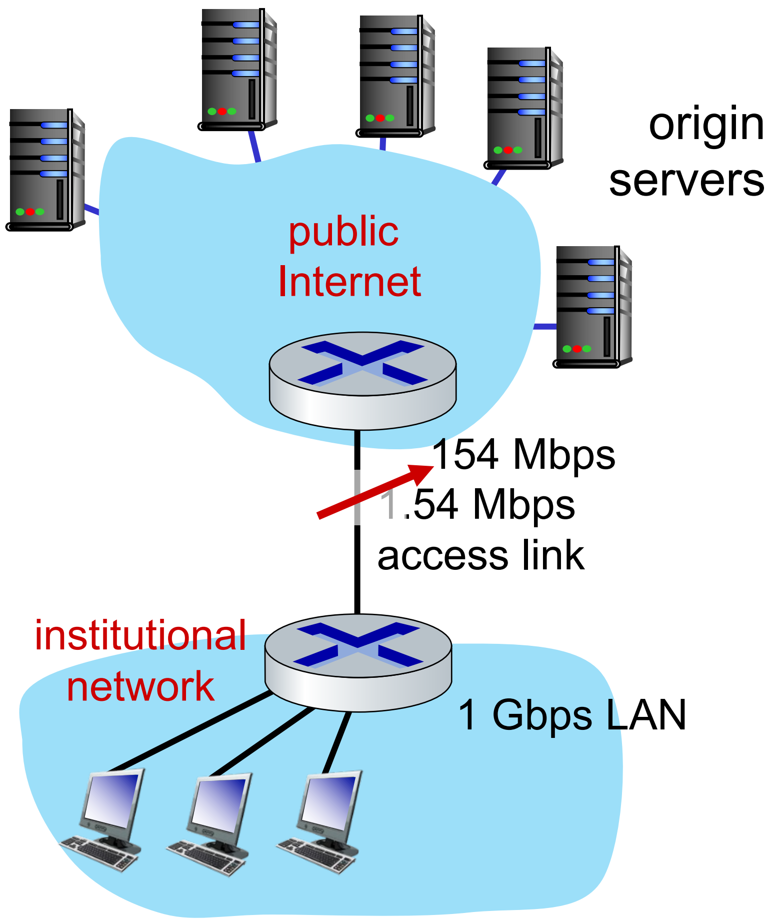
*Scenario:*

- access link rate: ~~1.54~~ → 154 Mbps
- RTT from institutional router to server: 2 sec
- web object size: 100K bits
- average request rate from browsers to origin servers: 15/sec
  - avg data rate to browsers: 1.50 Mbps

*Performance:*

- access link utilization = ~~.97~~ → .0097
- LAN utilization: .0015
- end-end delay = Internet delay + access link delay + LAN delay
  = 2 sec + ~~minutes~~ → msecs + usecs

*Cost:* faster access link (expensive!)



# Option 2: install a web cache

*Scenario:*

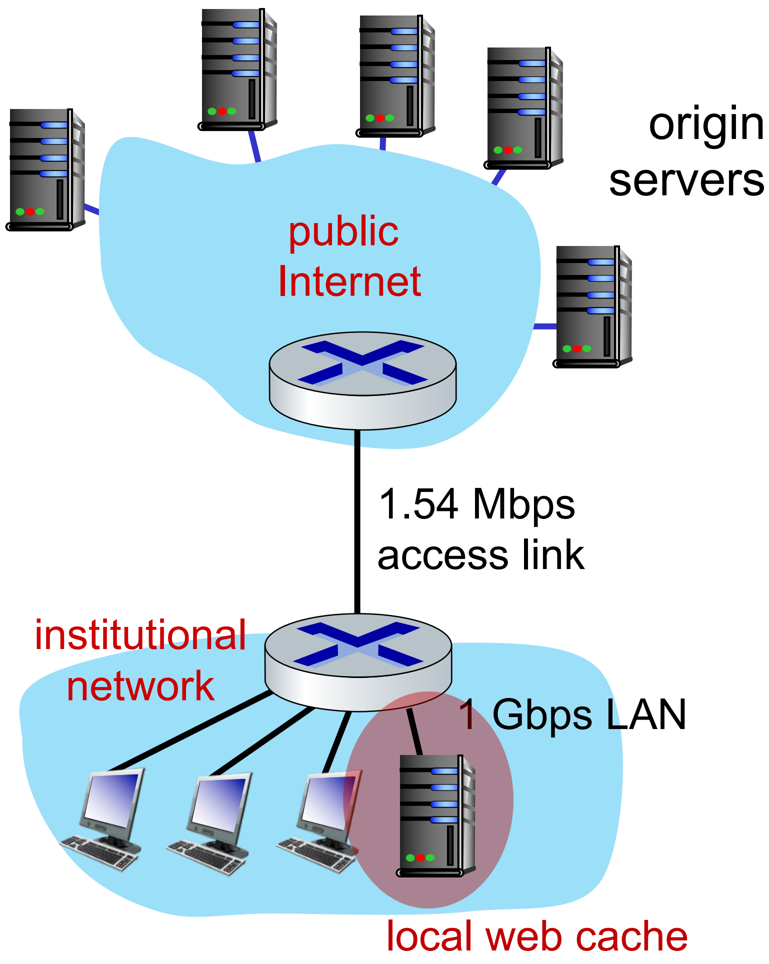
- access link rate: 1.54 Mbps
- RTT from institutional router to server: 2 sec
- web object size: 100K bits
- average request rate from browsers to origin servers: 15/sec
  - avg data rate to browsers: 1.50 Mbps

*Cost:* web cache (cheap!)

*Performance:*

- LAN utilization: .?
- access link utilization = ?
- average end-end delay = ?

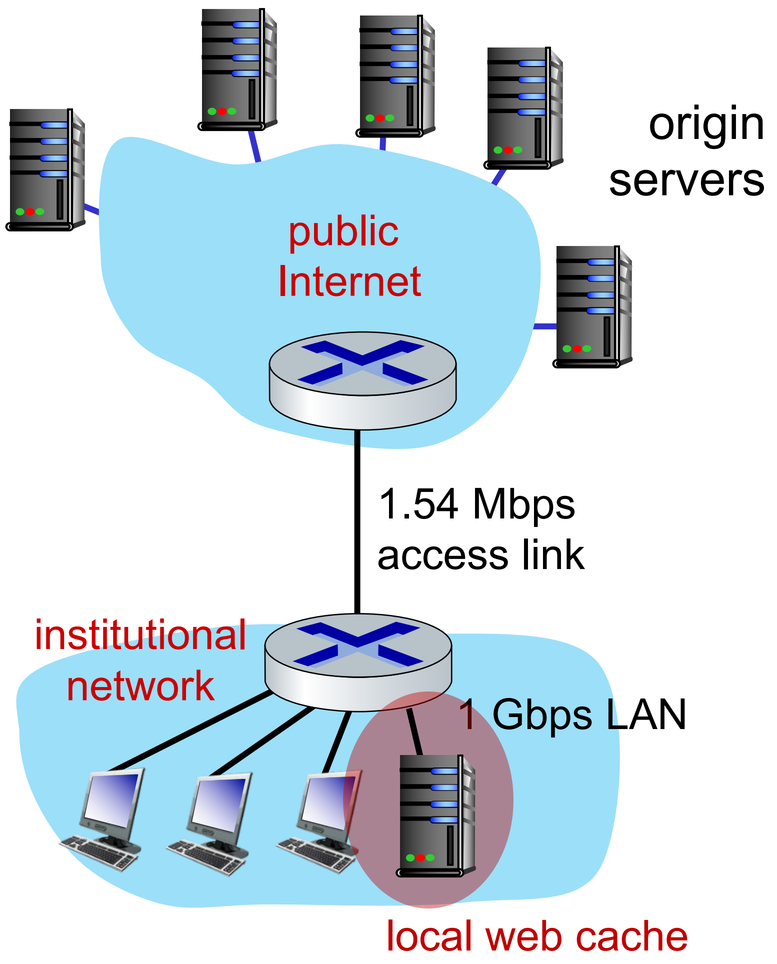
*How to compute link utilization, delay?*



# Calculating access link utilization, end-end delay with cache:

suppose cache hit rate is 0.4:

- 40% requests served by cache, with low (msec) delay
- 60% requests satisfied at origin
  - rate to browsers over access link
    = 0.6 * 1.50 Mbps = .9 Mbps
  - access link utilization = 0.9/1.54 = .58 means low (msec) queueing delay at access link
- average end-end delay:
  = 0.6 * (delay from origin servers)
  + 0.4 * (delay when satisfied at cache)
  = 0.6 (2.01) + 0.4 (~msecs) = ~ 1.2 secs




*lower average end-end delay than with 154 Mbps link (and cheaper too!)*

# Browser caching: Conditional GET

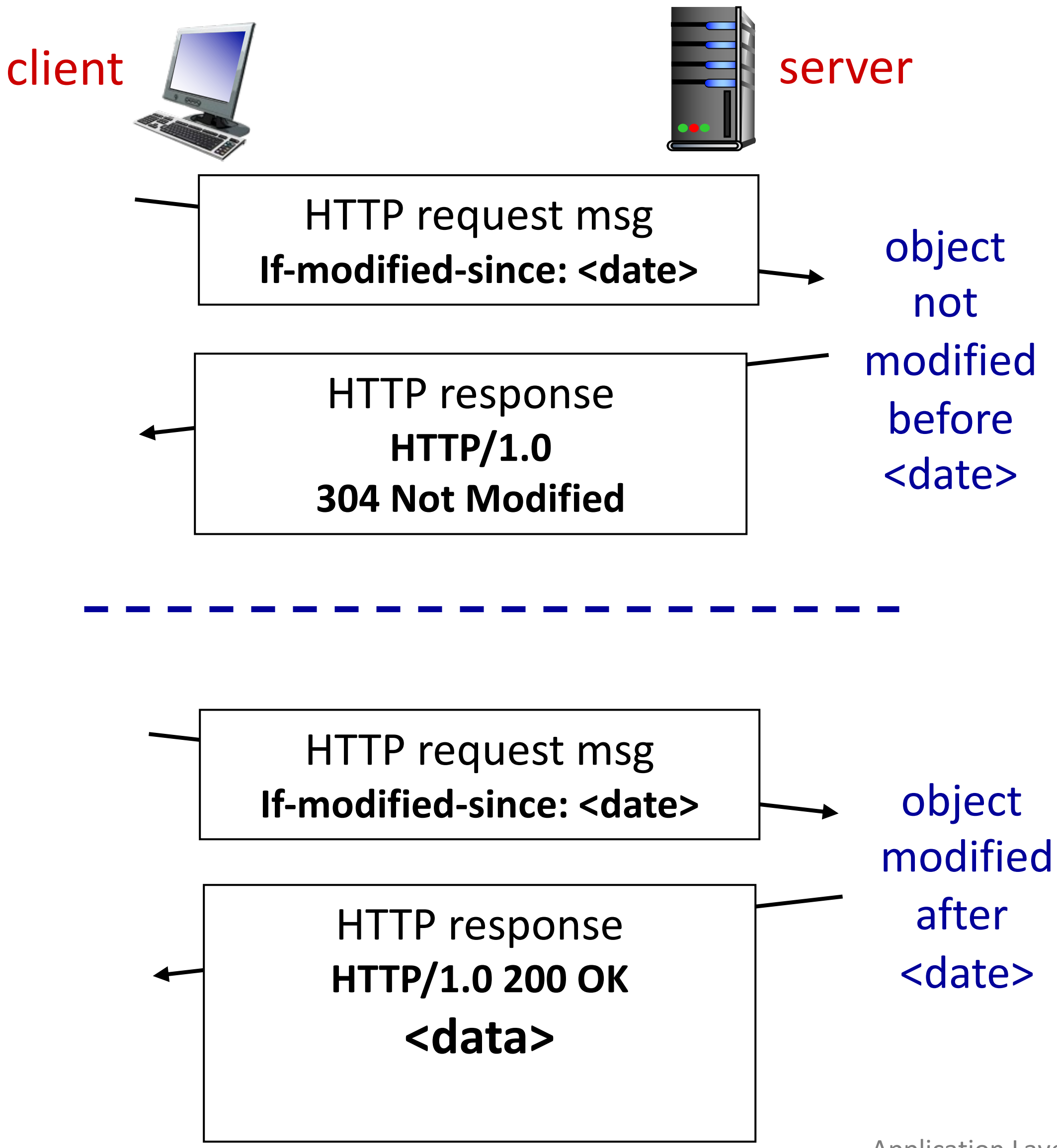
*Goal:* don't send object if browser has up-to-date cached version
- no object transmission delay (or use of network resources)

- *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

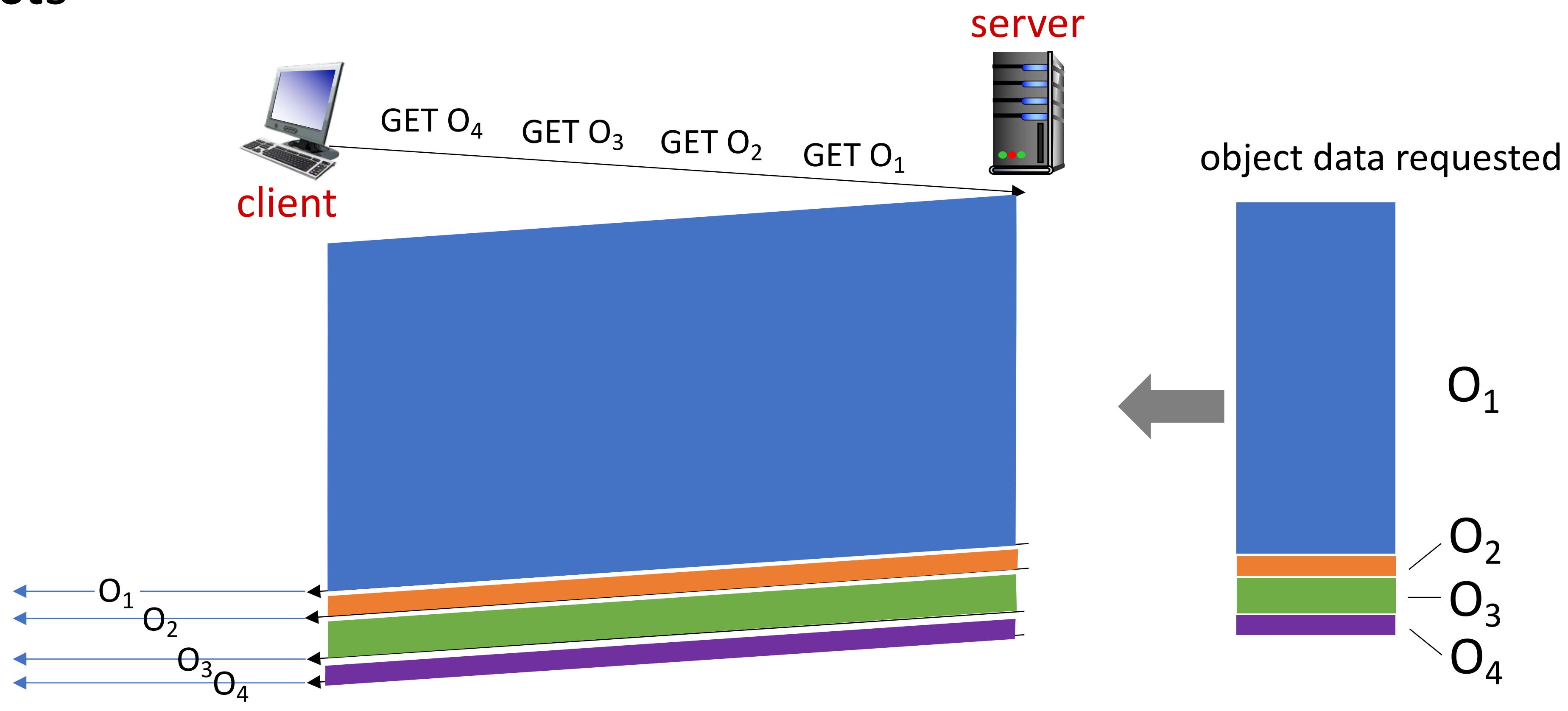
*Key goal:* decreased delay in multi-object HTTP requests

*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* unrequested objects to client
- divide objects into frames, schedule frames to mitigate HOL blocking

# HTTP/2: mitigating HOL blocking

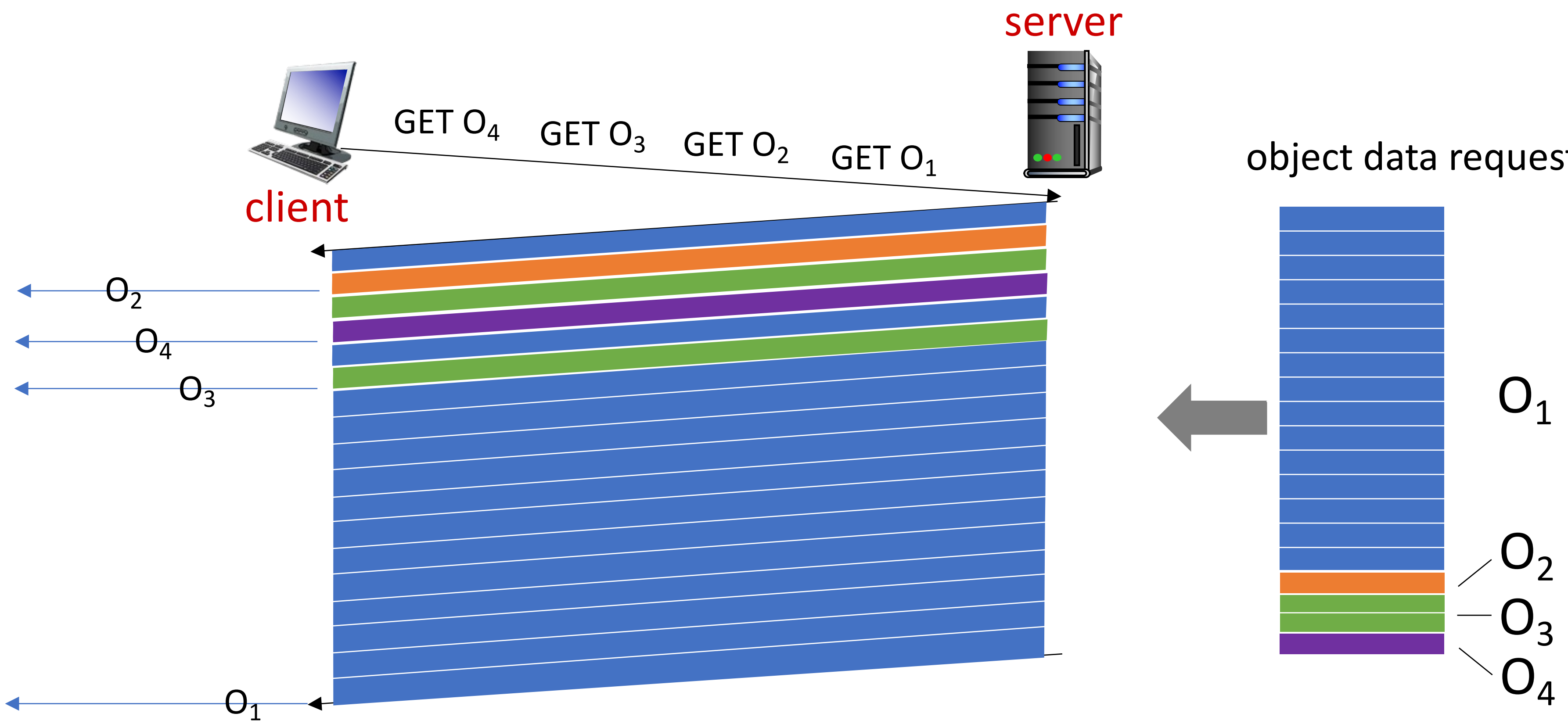
HTTP 1.1: client requests 1 large object (e.g., video file) and 3 smaller objects




*objects delivered in order requested: $O_2$, $O_3$, $O_4$ wait behind $O_1$*

# HTTP/2: mitigating HOL blocking

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




*$O_2$, $O_3$, $O_4$ delivered quickly, $O_1$ 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

- Principles of network applications
- Web and HTTP
- ~~E-mail, SMTP, IMAP~~
- The Domain Name System DNS
- ~~P2P applications~~
- video streaming and content distribution networks
- socket programming with UDP and TCP

# 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:

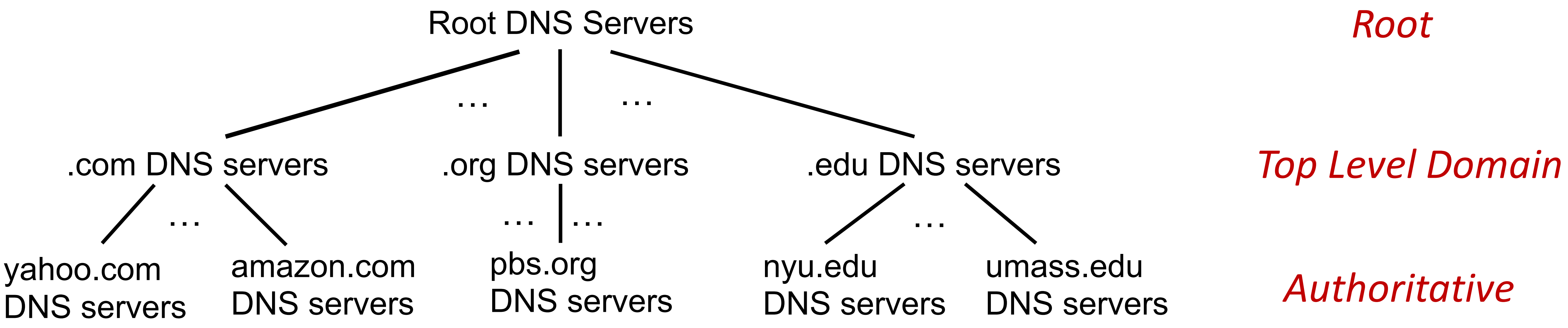
- *many* more reads than writes
- *performance matters:* almost every Internet transaction interacts with DNS - msecs count!

organizationally, physically decentralized:

- millions of different organizations responsible for their records

"bulletproof": reliability, security

# DNS: a distributed, hierarchical database

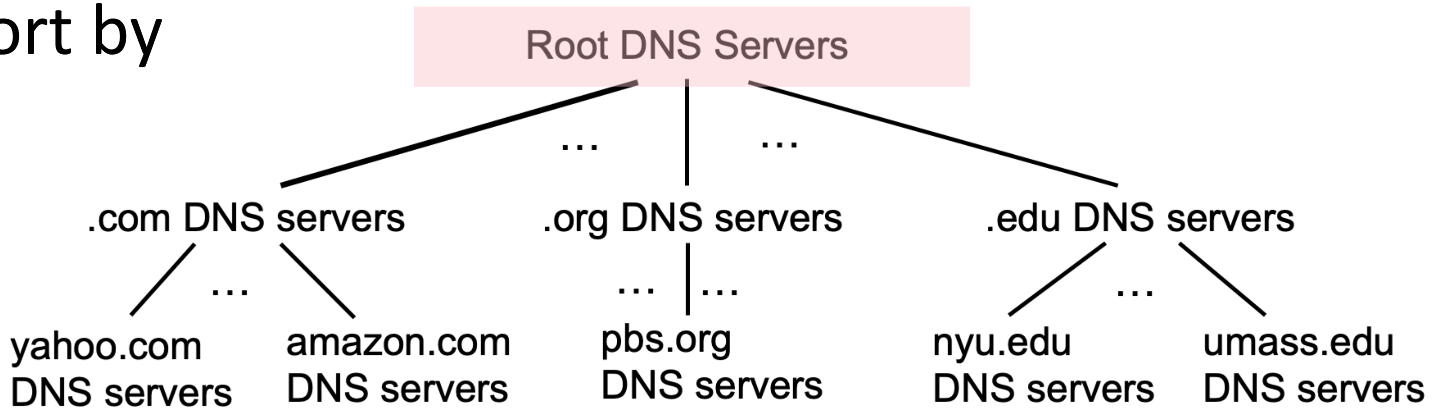



Client wants IP address for www.amazon.com; 1st approximation:

- 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

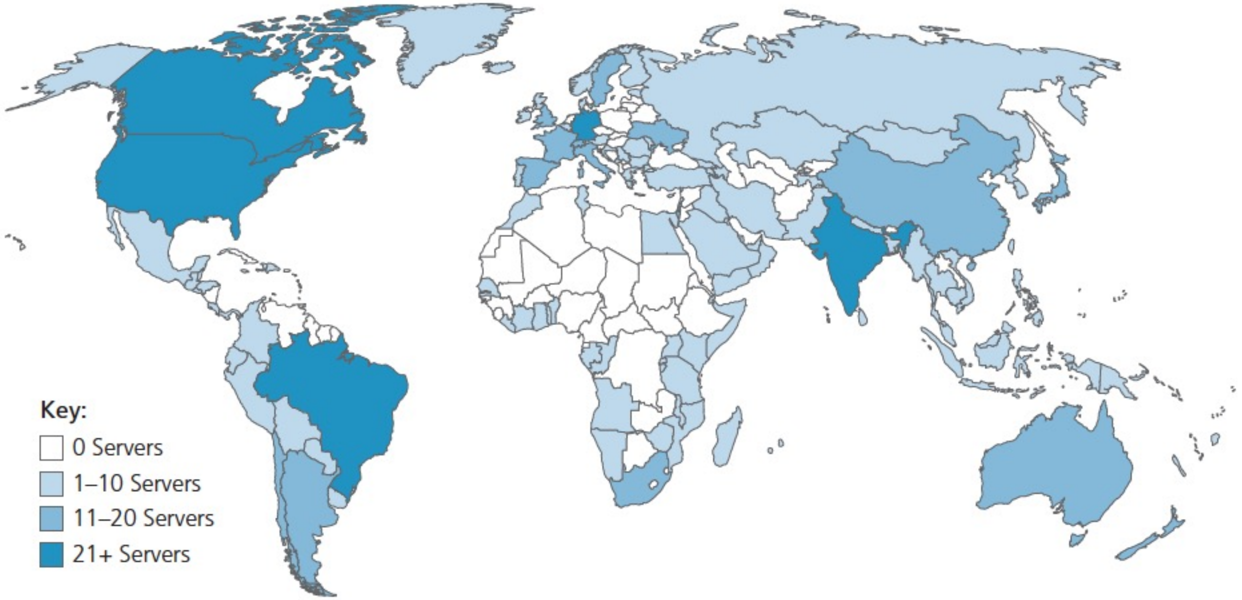
- official, contact-of-last-resort by name servers that can not resolve name



# 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

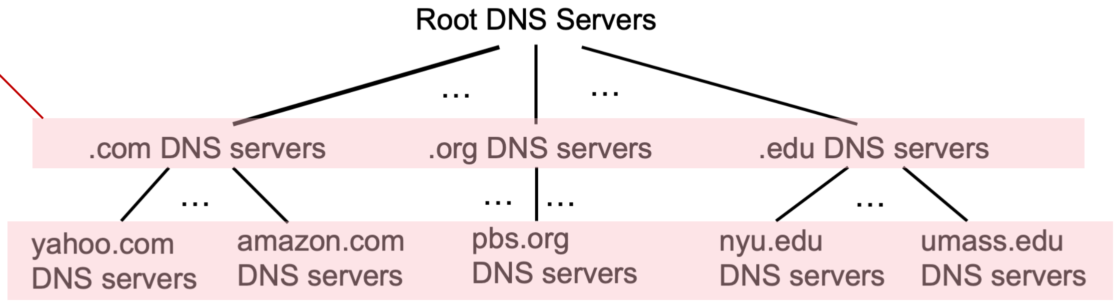
13 logical root name "servers" worldwide each "server" replicated many times (~200 servers in US)



# Top-Level Domain, and authoritative servers

## Top-Level Domain (TLD) servers:

- responsible for .com, .org, .net, .edu, .aero, .jobs, .museums, and all top-level country domains, e.g.: .cn, .uk, .fr, .ca, .jp
- Network Solutions: authoritative registry for .com, .net TLD
- Educause: .edu TLD




## authoritative DNS servers:

- organization's own DNS server(s), providing authoritative hostname to IP mappings for organization's named hosts
- can be maintained by organization or service provider

# Local DNS name servers

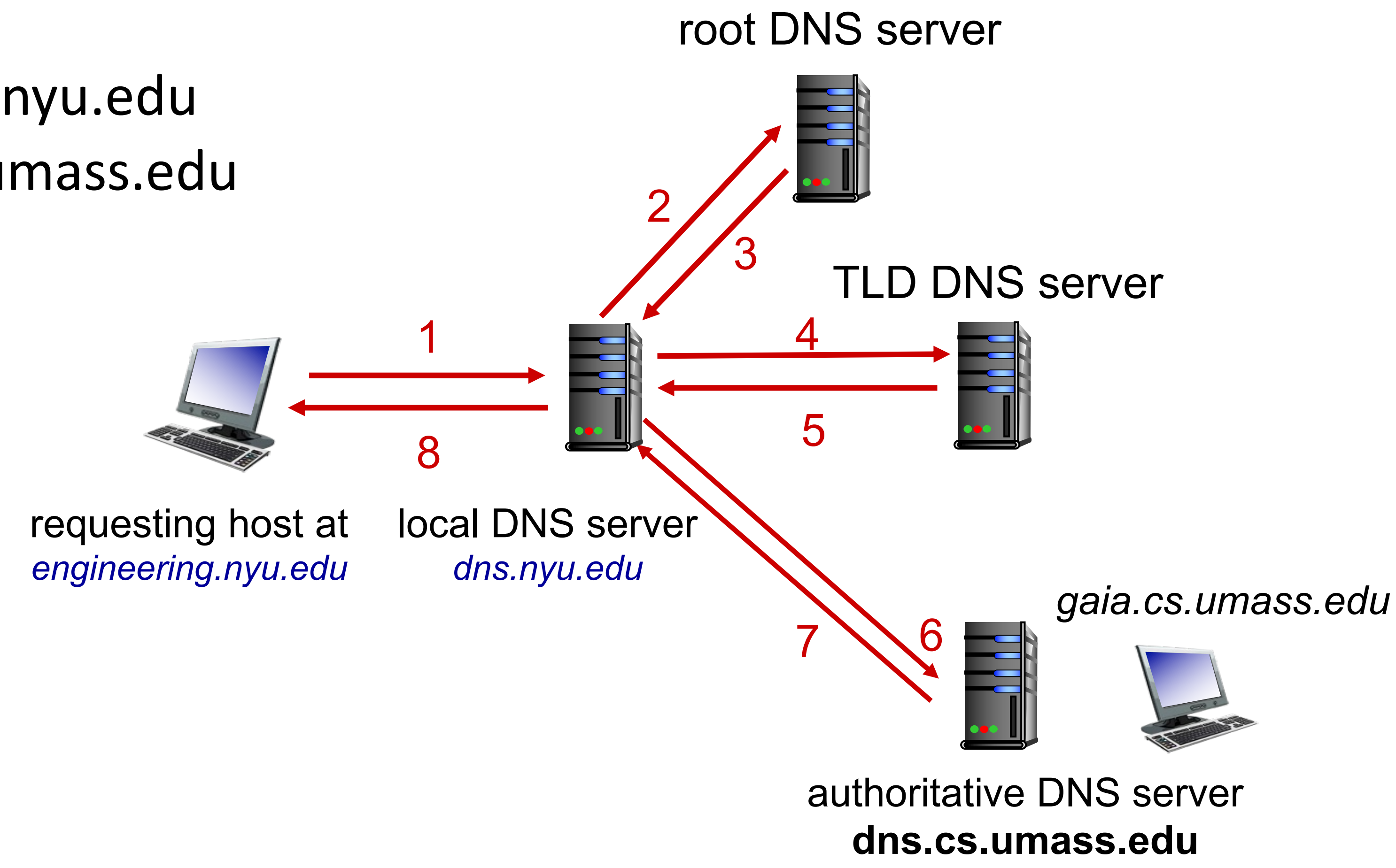
- when host makes DNS query, it is sent to its *local* DNS server
  - Local DNS server returns reply, answering:
    - from its local cache of recent name-to-address translation pairs (possibly out of date!)
    - forwarding request into DNS hierarchy for resolution
  - each ISP has local DNS name server; 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:

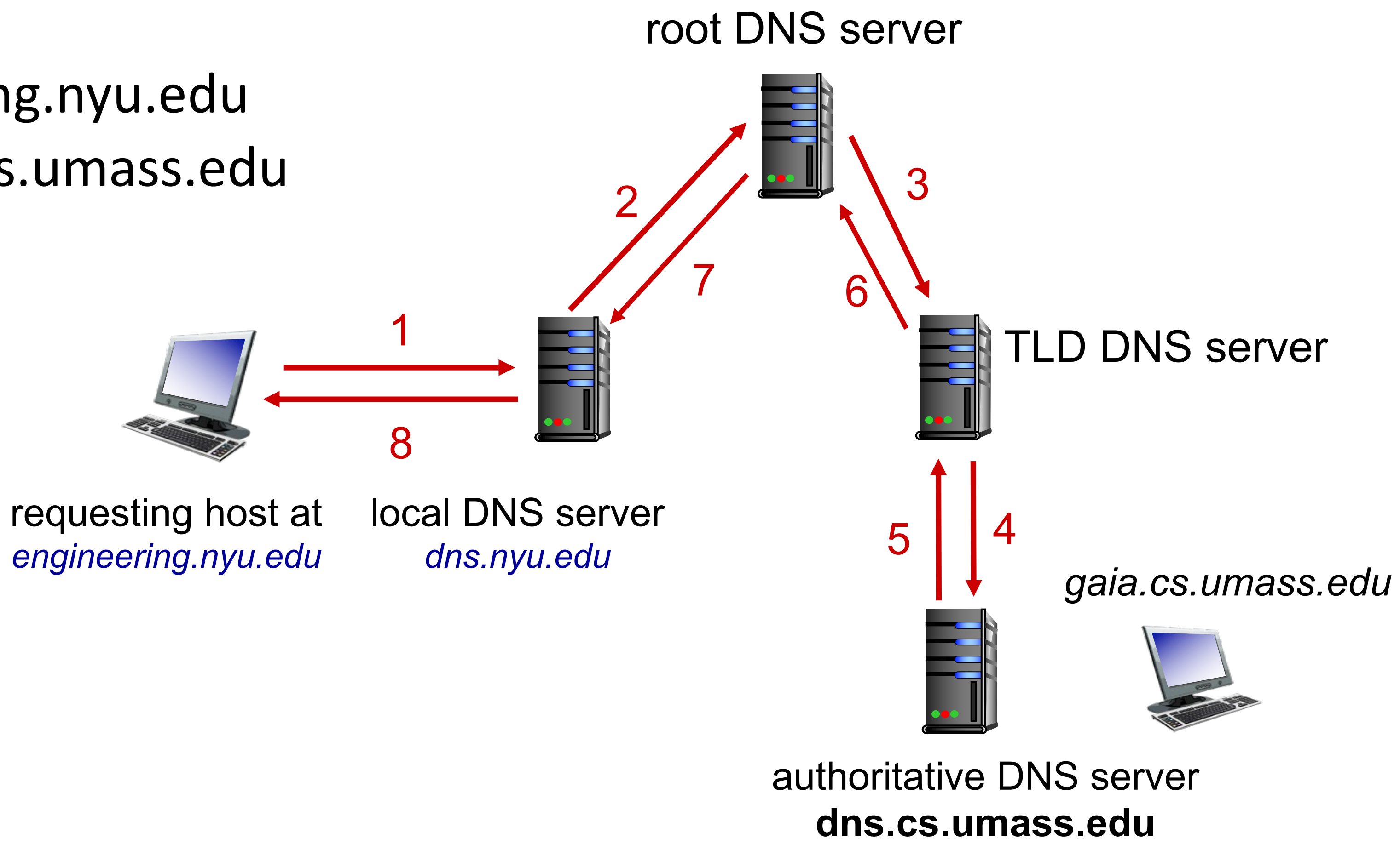
- contacted server replies with name of server to contact
- "I don't know this name, but ask this server"



# 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`

# Demo: Try DNS yourself (nslookup)

>nslookup amazon.com

>nslookup cs.purdue.edu

Authoritative name servers

>nslookup -type=NS cs.purdue.edu

> nslookup –type=A harbor.ecn.purdue.edu

Canonical name (alias)

>nslookup -type=CNAME amazon.com

>nslookup -type=CNAME purdue.edu

Mail server

>nslookup -type=MX gmail.com

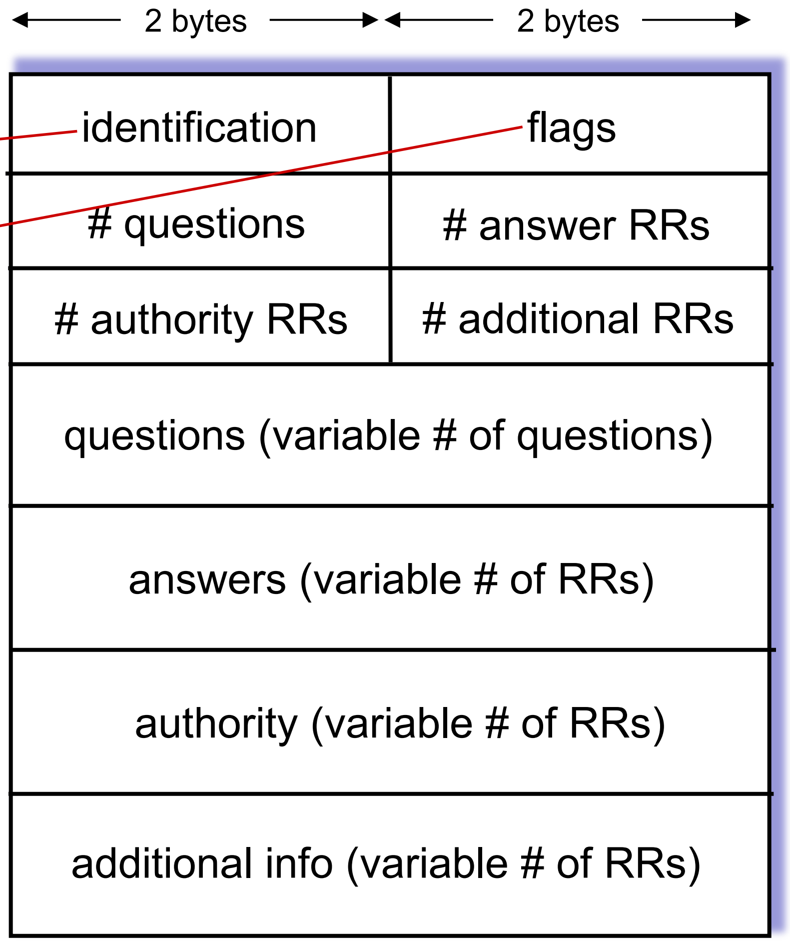
>nslookup -type=MX purdue.edu

# DNS protocol messages

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

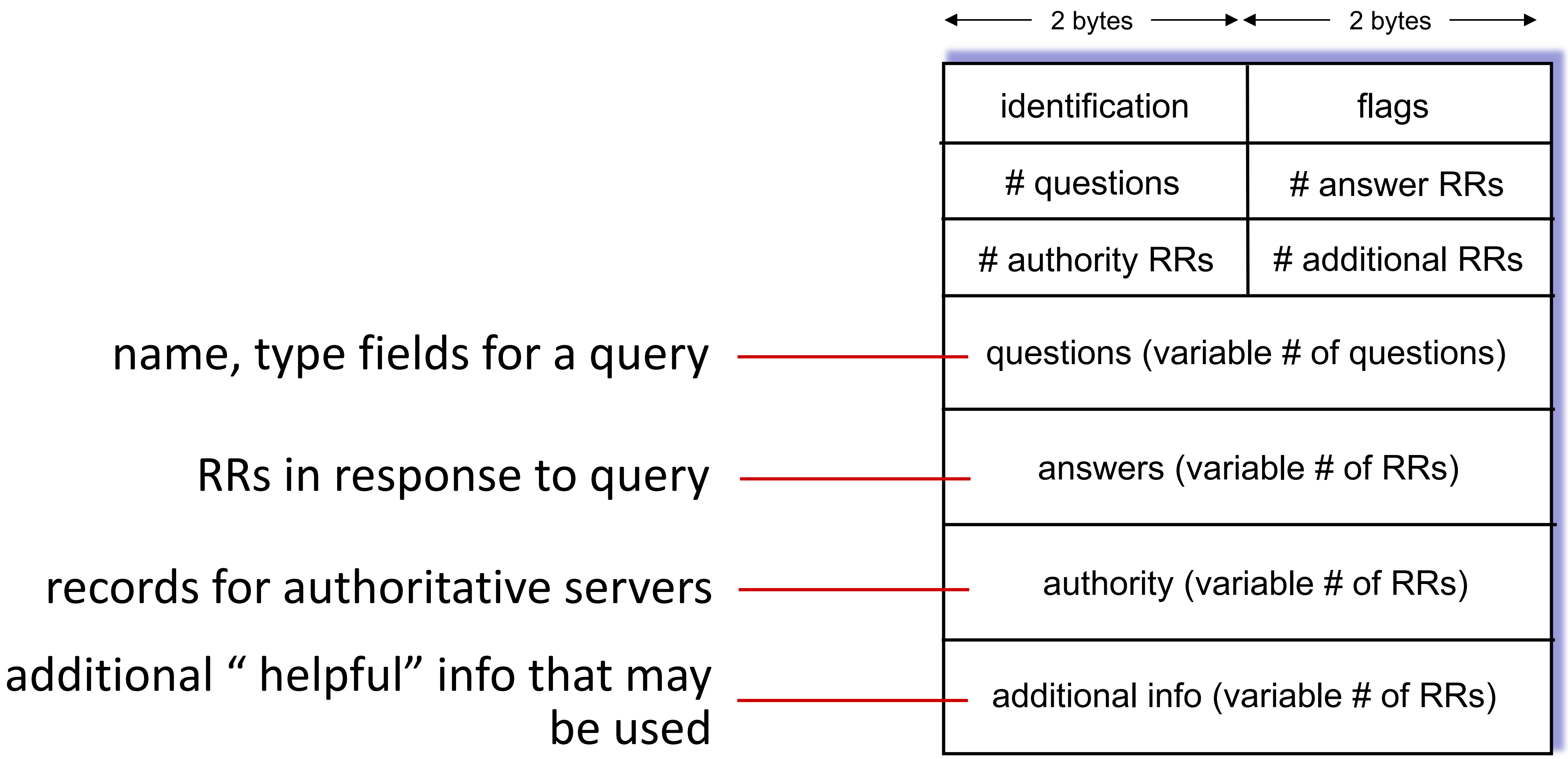
message header:

- 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:*



# Getting your info into the DNS

example: new startup "Network Utopia"

- register name networkuptopia.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.networkuptopia.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

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- socket programming with UDP and TCP

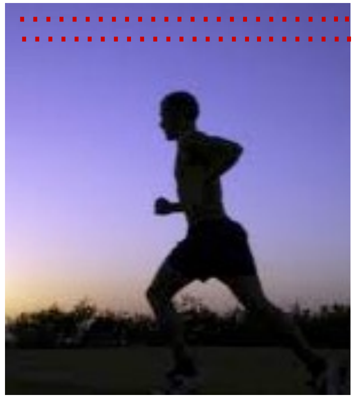
# Video Streaming and CDNs: context

- 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

# Multimedia: video

- video: sequence of images displayed at constant rate
  - e.g., 24 images/sec
- digital image: array of pixels
  - each pixel represented by bits
- coding: use redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)

*spatial coding example:* instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values* (N)



frame *i*

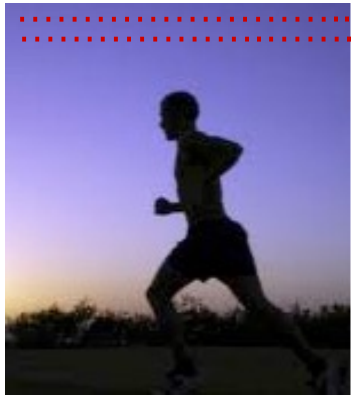
*temporal coding example:* instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

# Multimedia: video

- CBR: (constant bit rate): video encoding rate fixed
- VBR: (variable bit rate): video encoding rate changes as amount of spatial, temporal coding changes
- examples:
  - MPEG 1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, 64Kbps – 12 Mbps)

*spatial coding example:* instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values* (N)



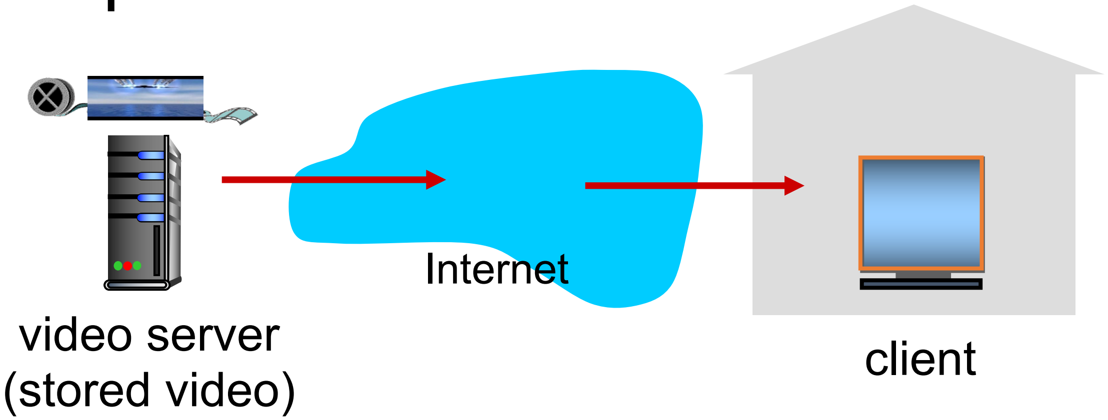
frame *i*

*temporal coding example:* instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

# Streaming stored video

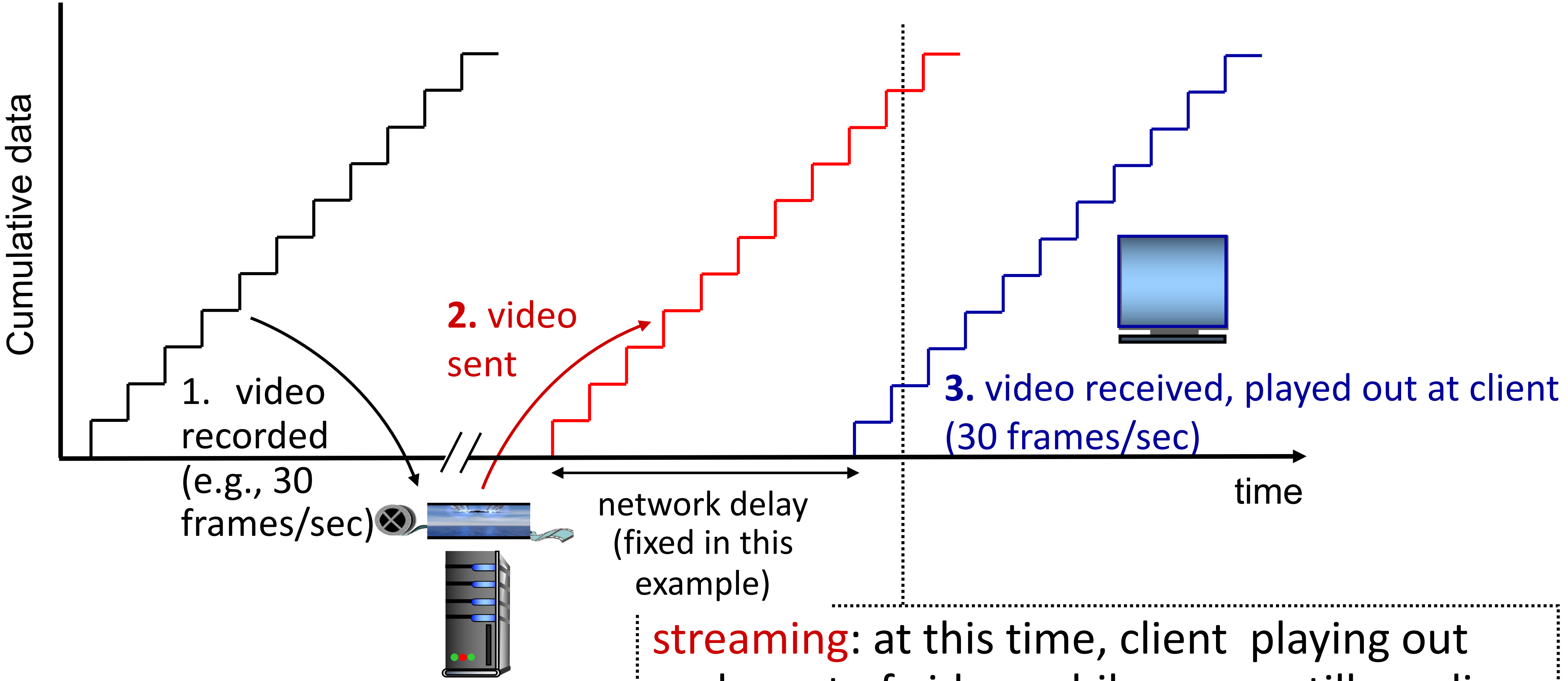
simple scenario:




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

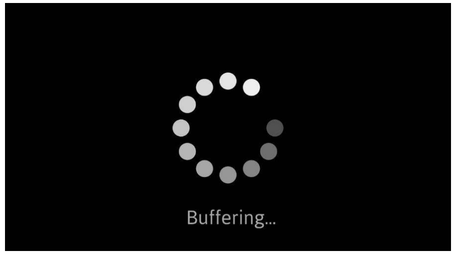
# Streaming stored video




streaming: at this time, client playing out early part of video, while server still sending later part of video

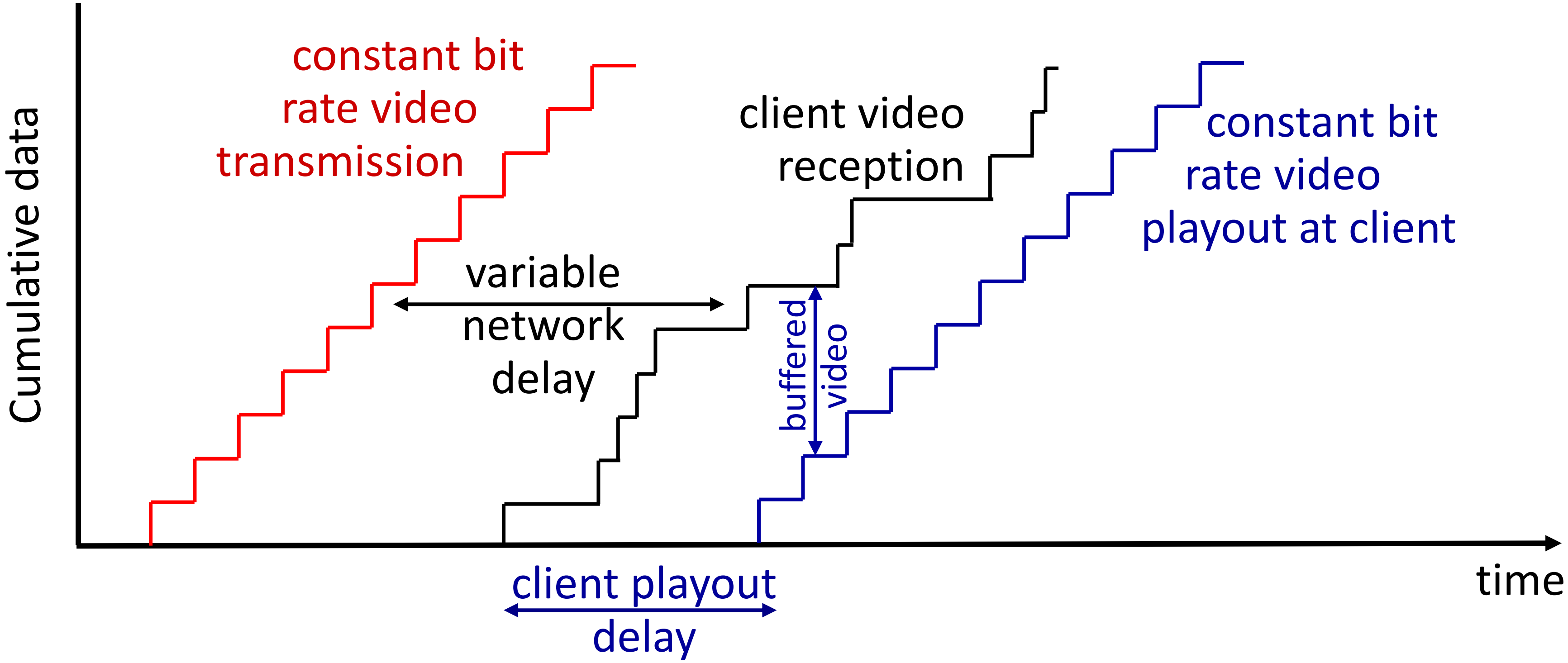
# Streaming stored video: challenges

- 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



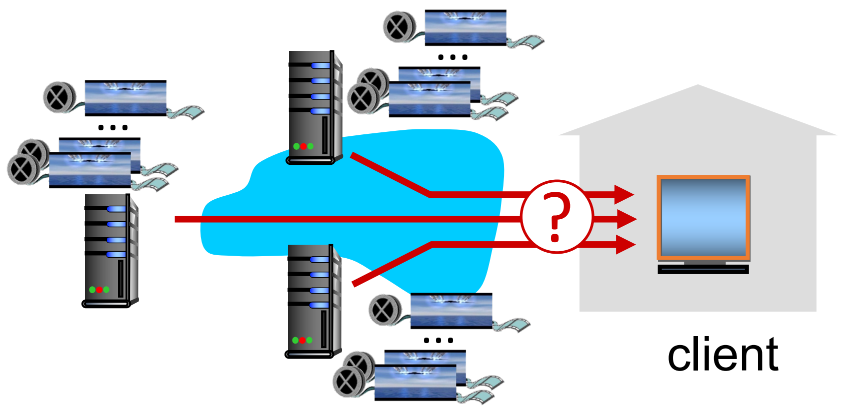

- *client-side buffering and playout delay:* compensate for network-added delay, delay jitter

# 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

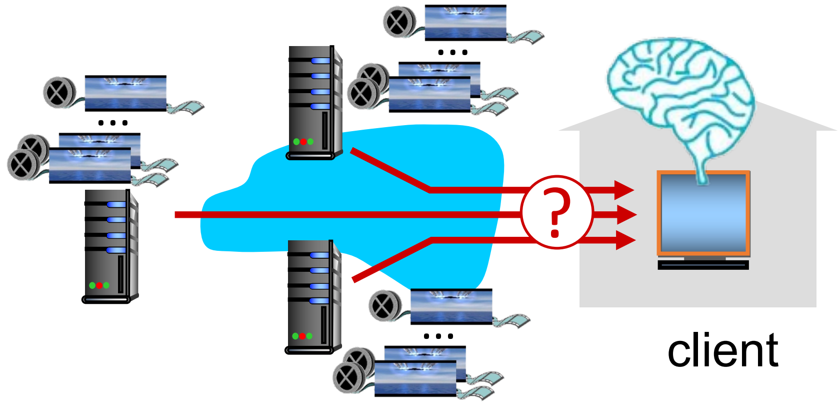



**client:**

- 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*

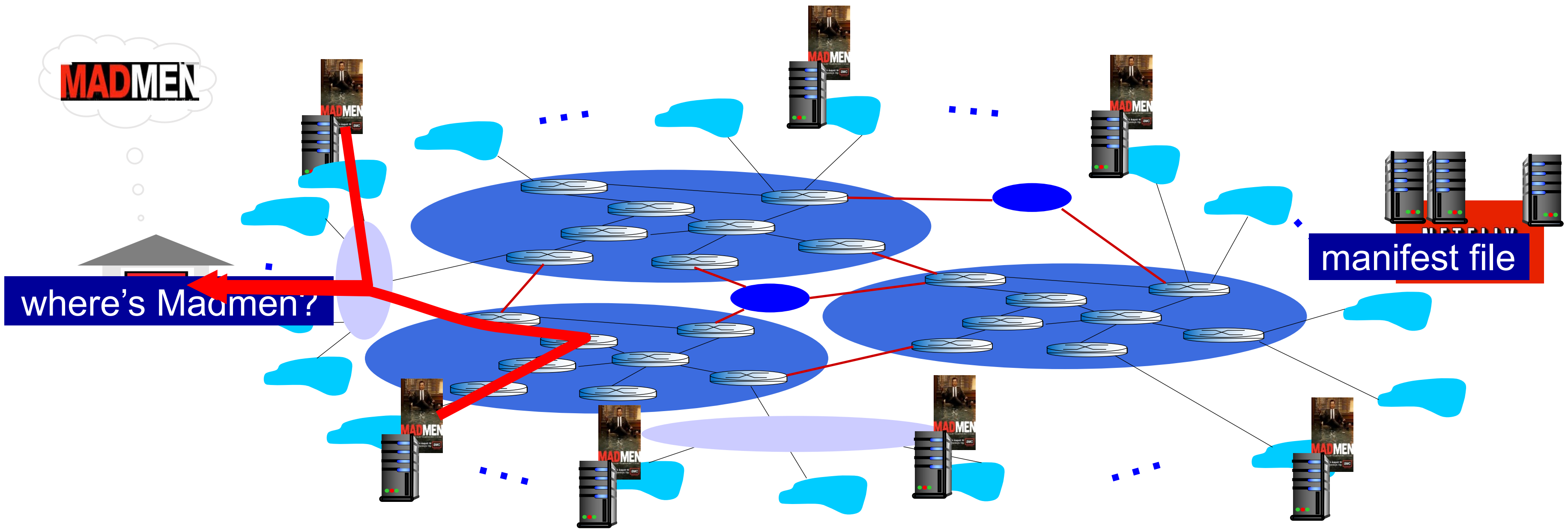
# Content distribution networks (CDNs)

*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 POPs near access nets
    - used by Limelight

# Content distribution networks (CDNs)

- CDN: stores copies of content (e.g. MADMEN) at 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
- socket programming: TCP, UDP sockets