

# Chapter 2

## Application Layer

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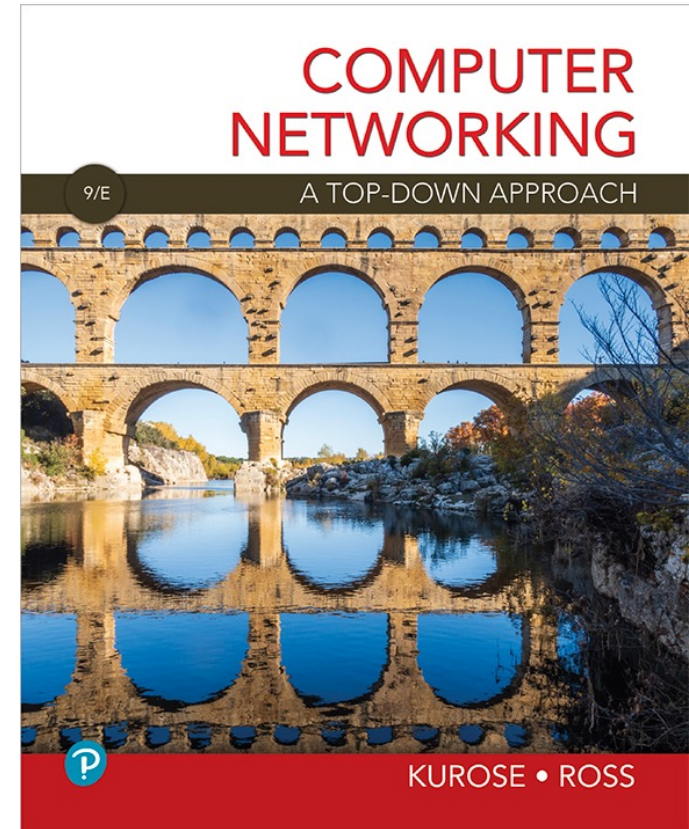
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## *Computer Networking: A Top-Down Approach*

9<sup>th</sup> edition

Jim Kurose, Keith Ross  
Pearson, 2025

# Application layer: overview

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



# 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
- programming network applications
  - socket API

# Some network apps

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



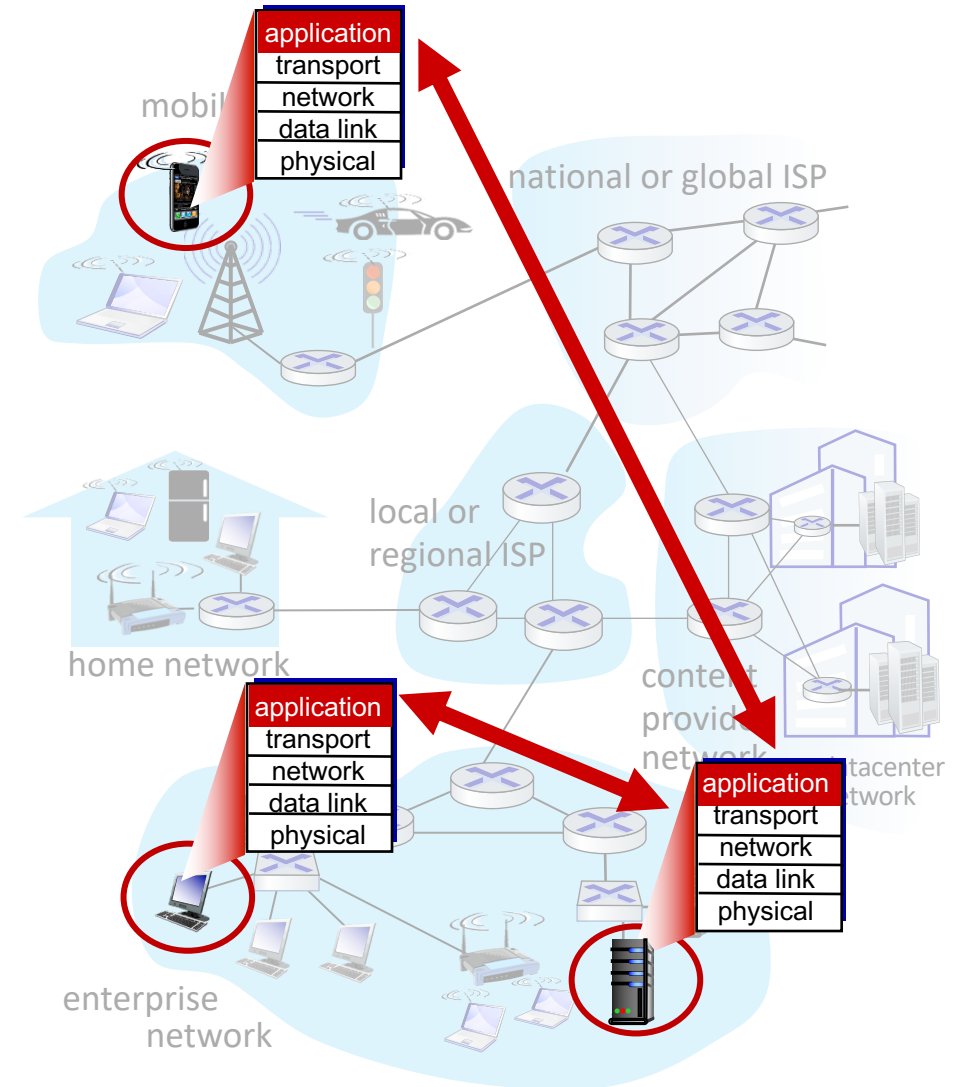
# Creating a network app

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



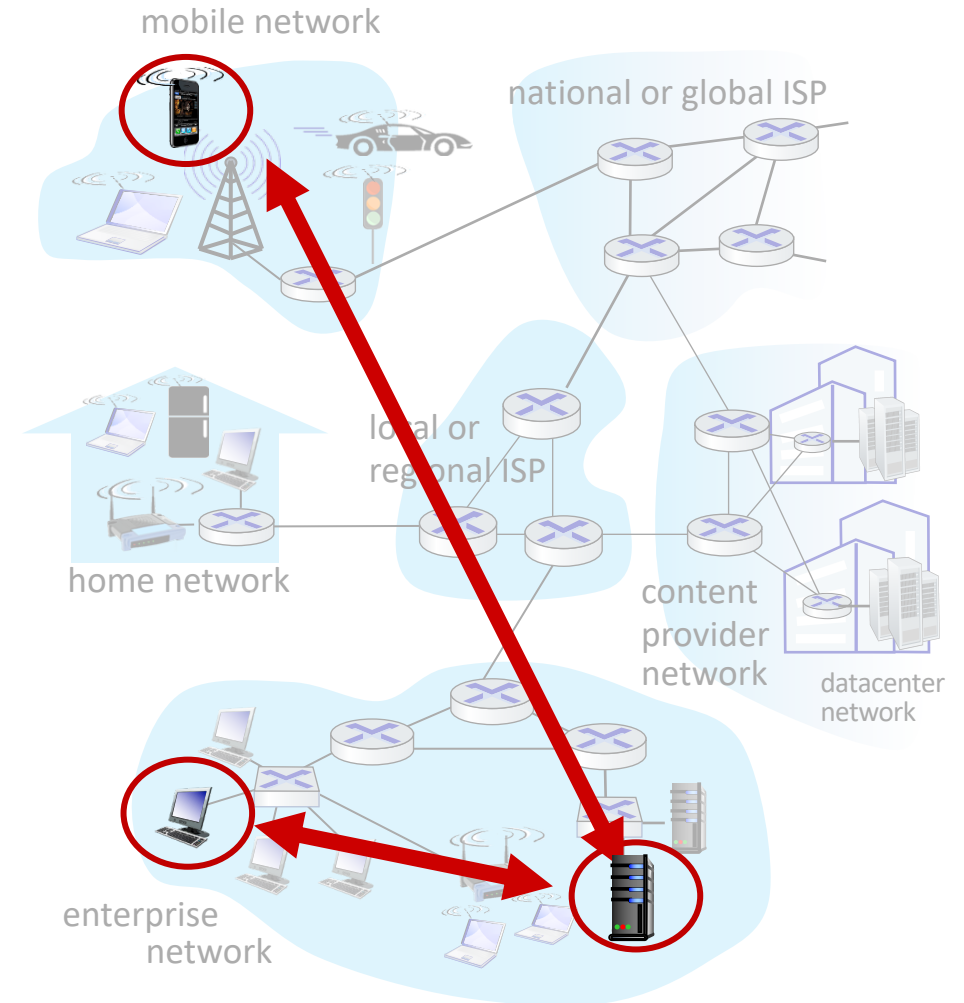
# Client-server paradigm

## server:

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

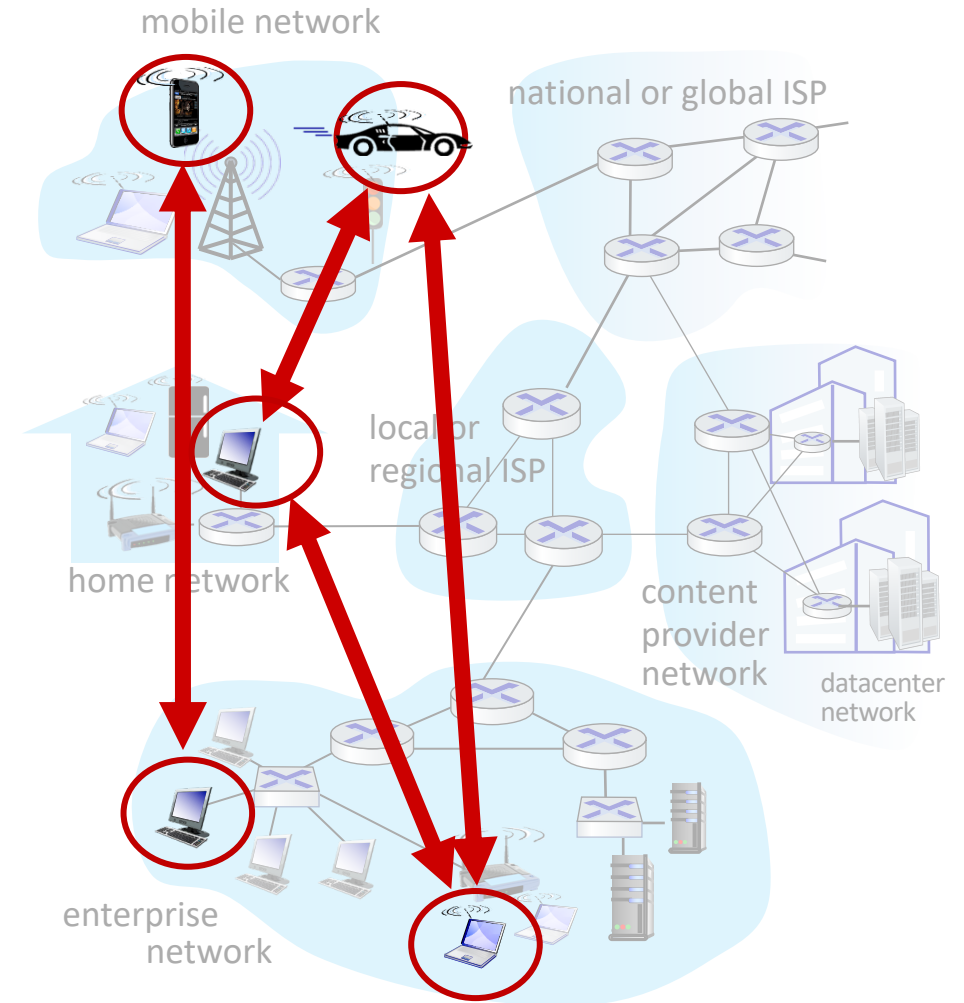
## clients:

- 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

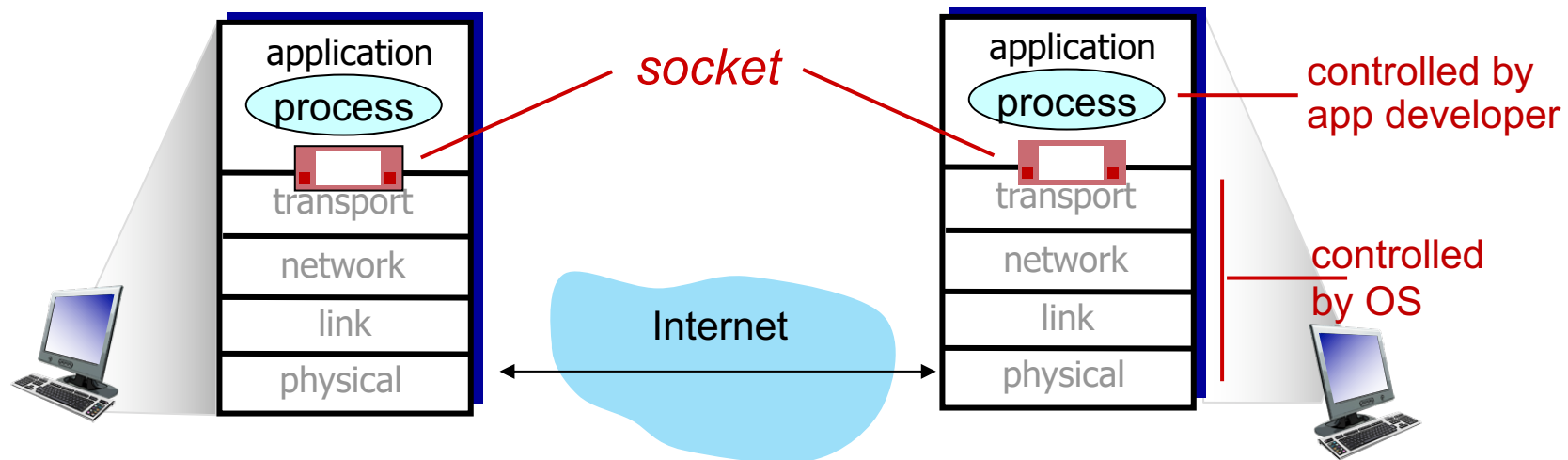
*client process*: process that initiates communication

*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., 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

| <b>application</b>     | <b>application<br/>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
- 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

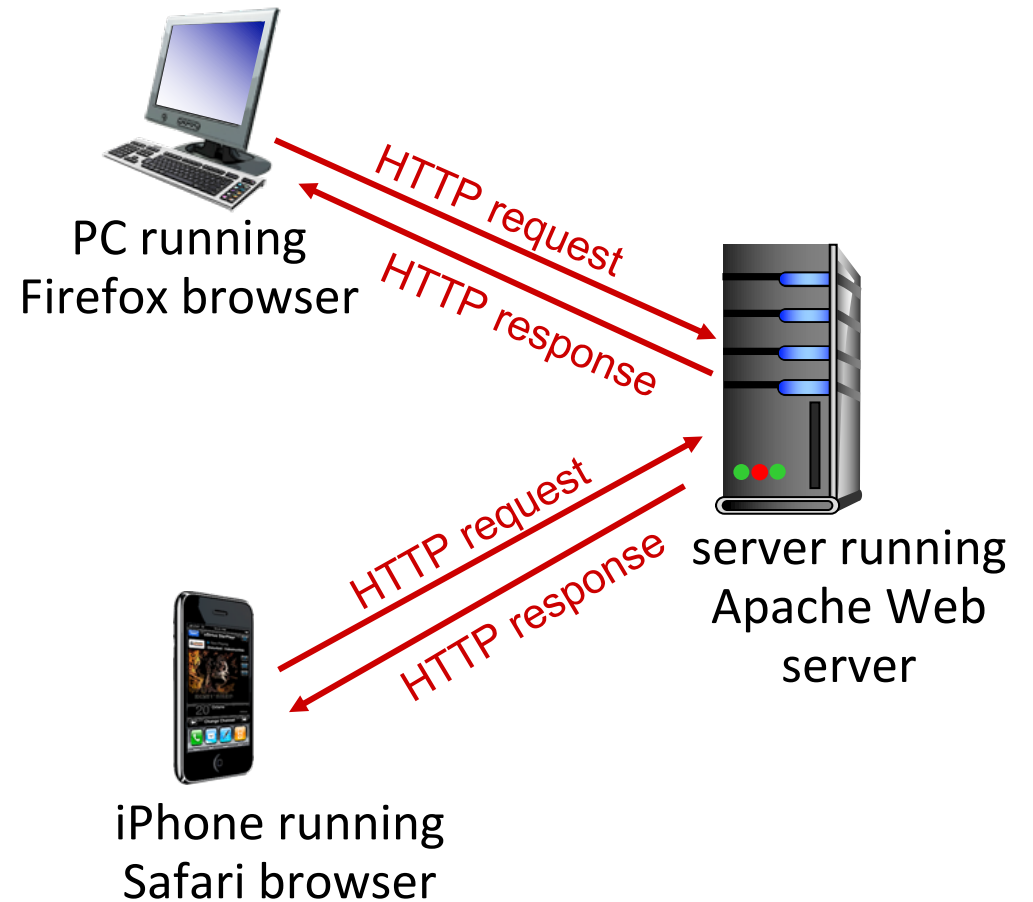
path name



# 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)



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

4. HTTP server closes TCP connection.

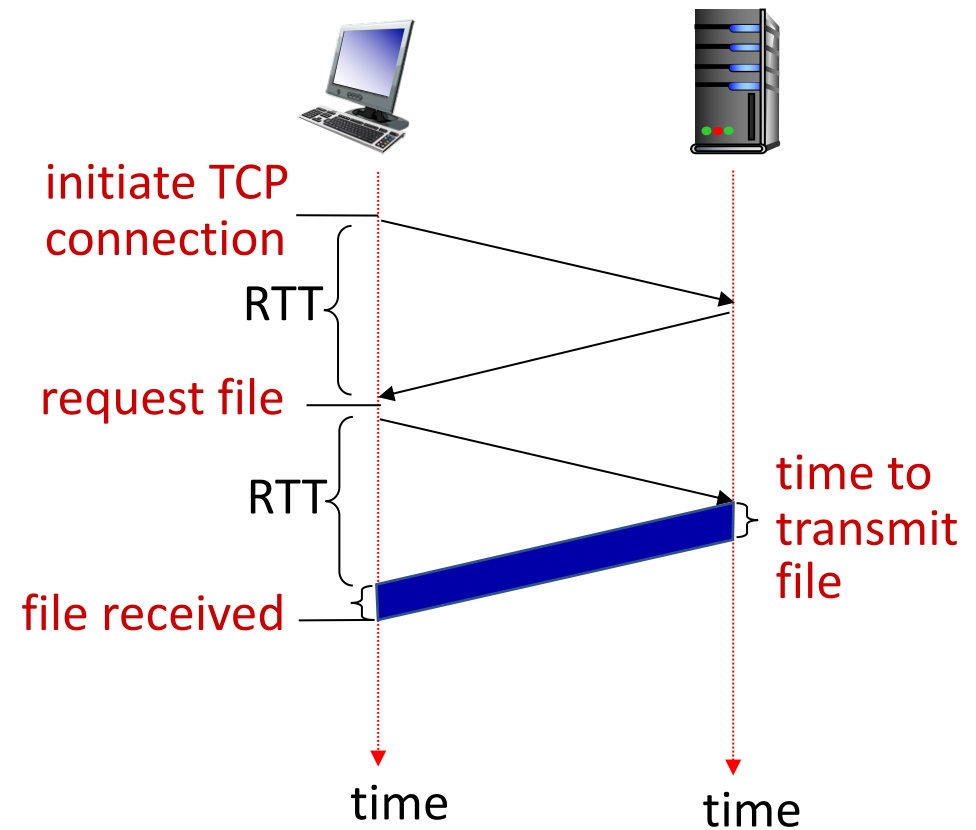


# Non-persistent HTTP: response time

**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 =  $2RTT + \text{file transmission time}$*

# 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)

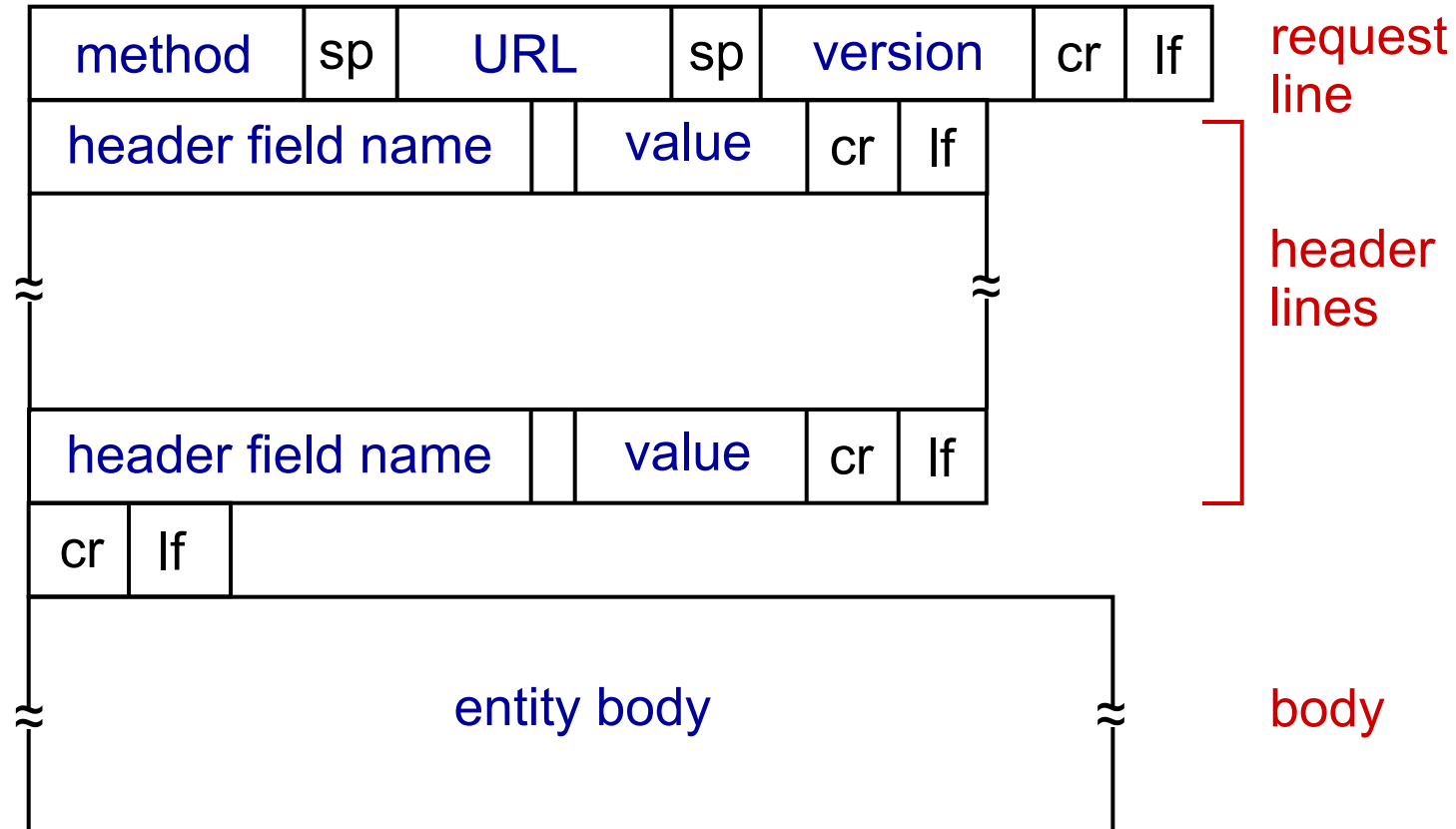
request line (GET, POST,  
HEAD commands) →

/ 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:

- 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 (for Mac)

>ncat -C gaia.cs.umass.edu 80 (for Windows)

- 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!

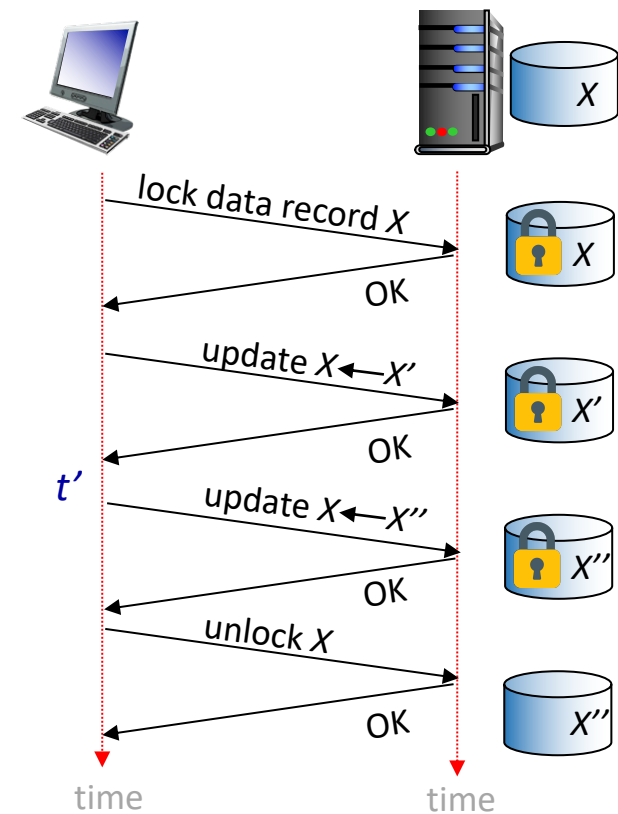
(or use Wireshark to look at captured HTTP request/response)

# 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

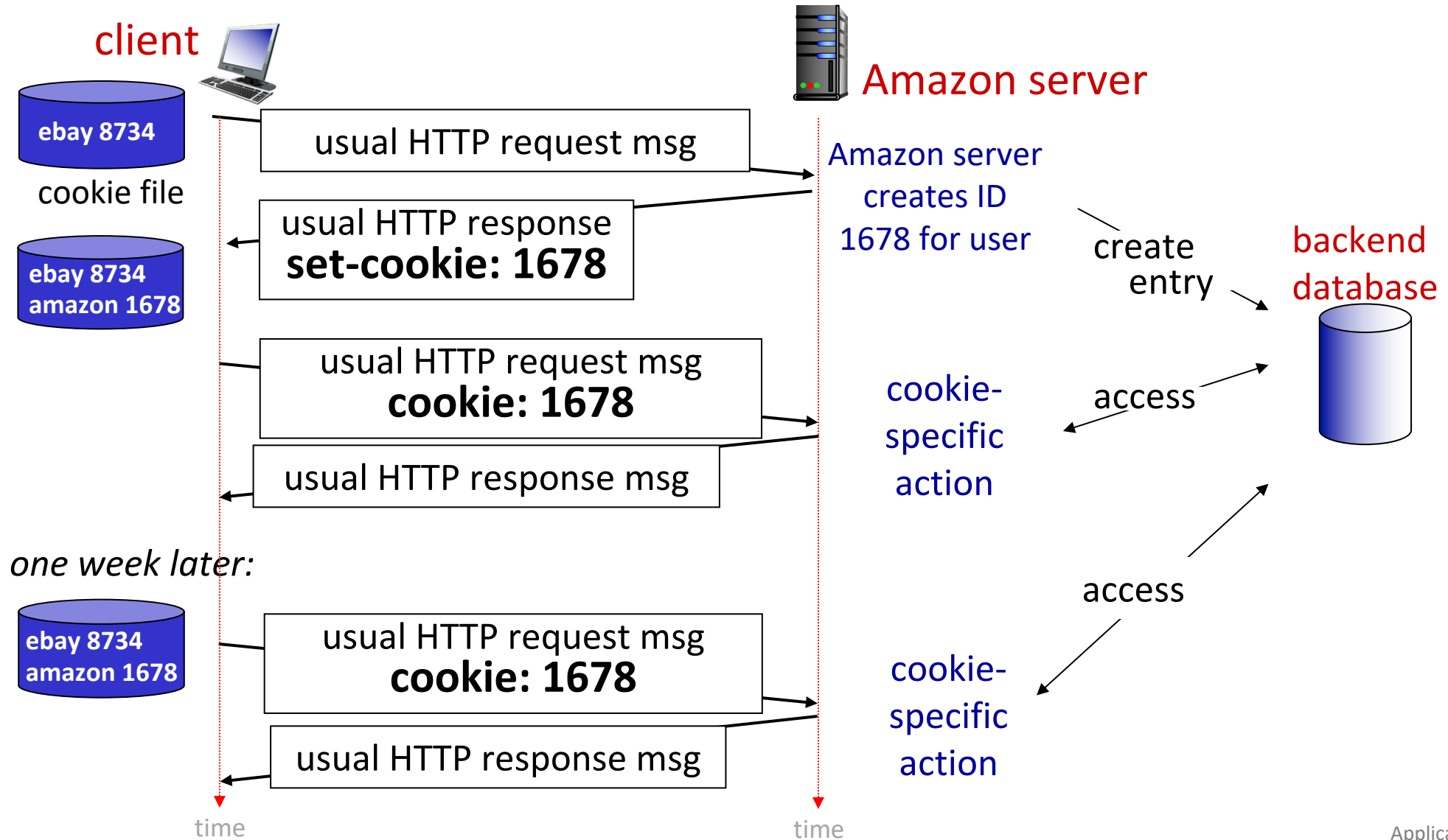
## *four components:*

- 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 in HTTP messages carry state

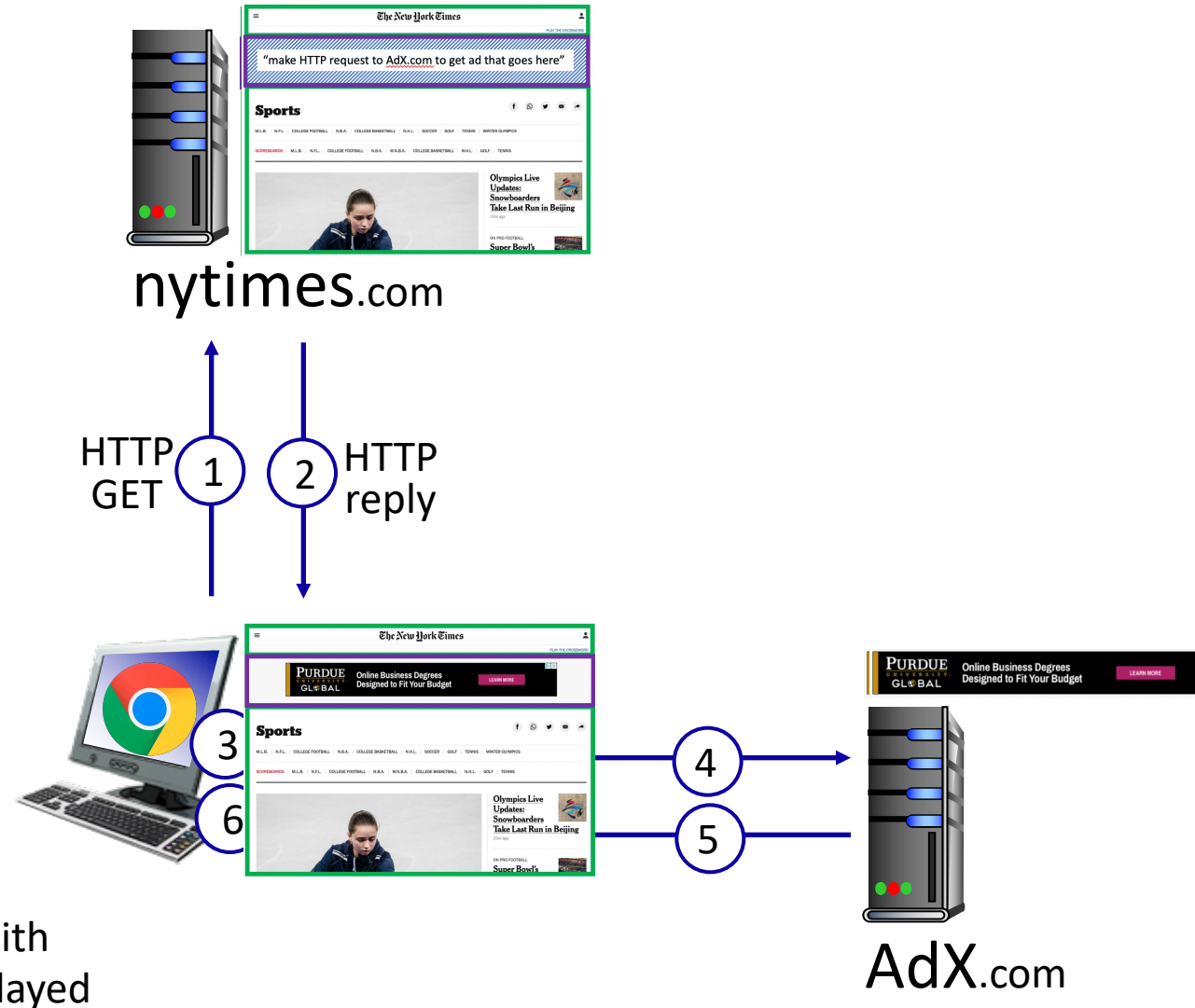
aside

*cookies and privacy:*

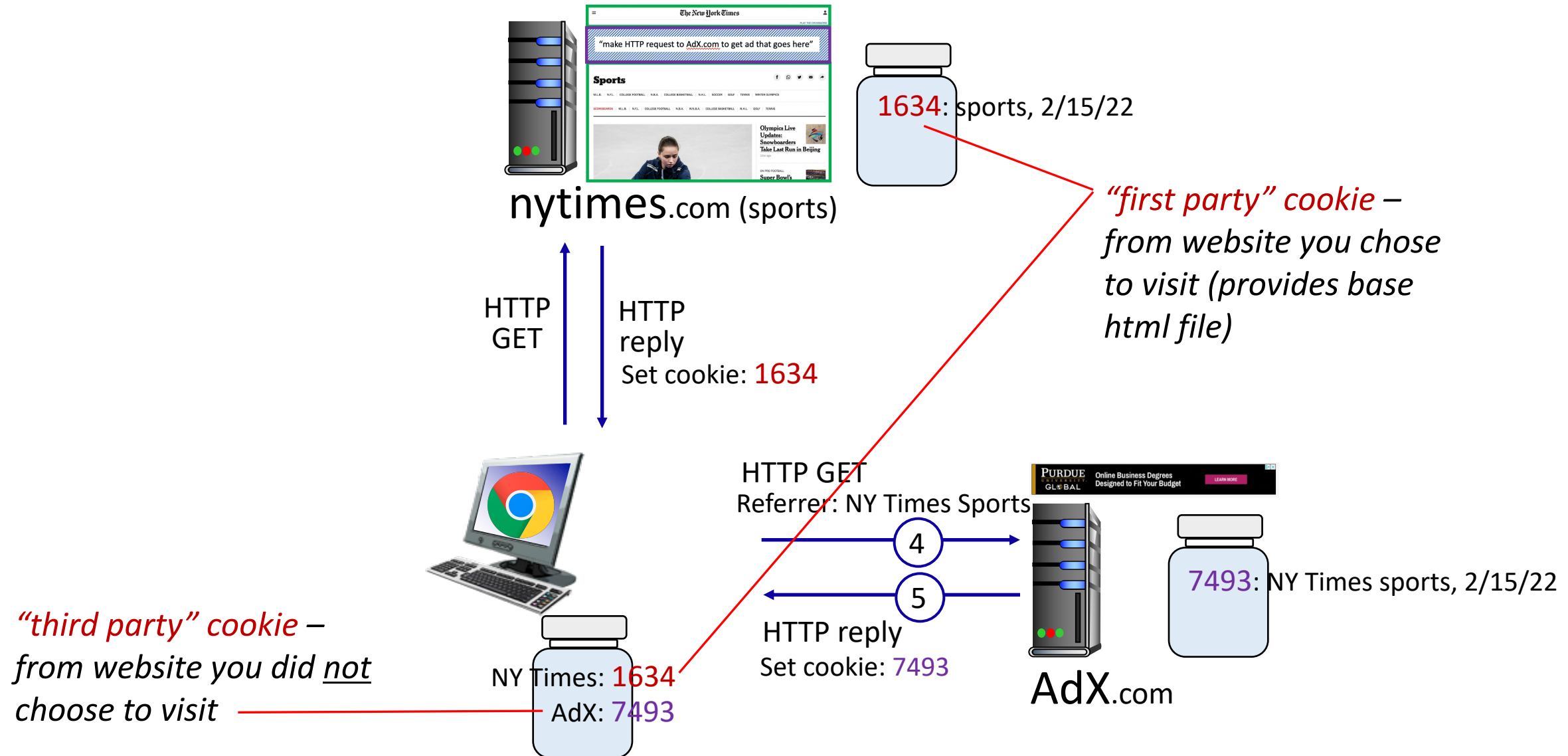
- cookies permit sites to *learn* a lot about you on their site.
- third party persistent cookies (tracking cookies) allow common identity (cookie value) to be tracked across multiple web sites

# Example: displaying a NY Times web page

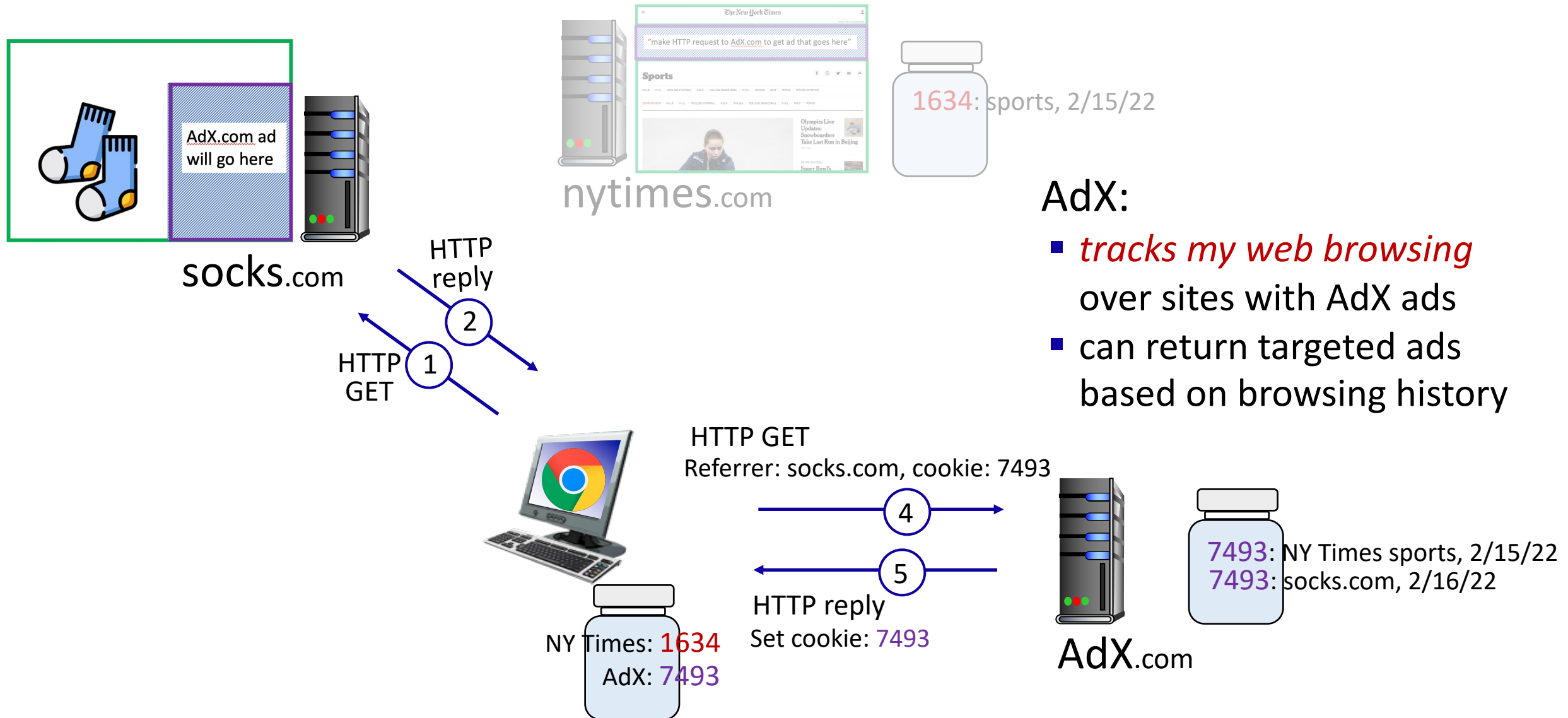
- 1 GET base html file from nytimes.com
- 2
- 4 fetch ad from AdX.com
- 5
- 7 display composed page



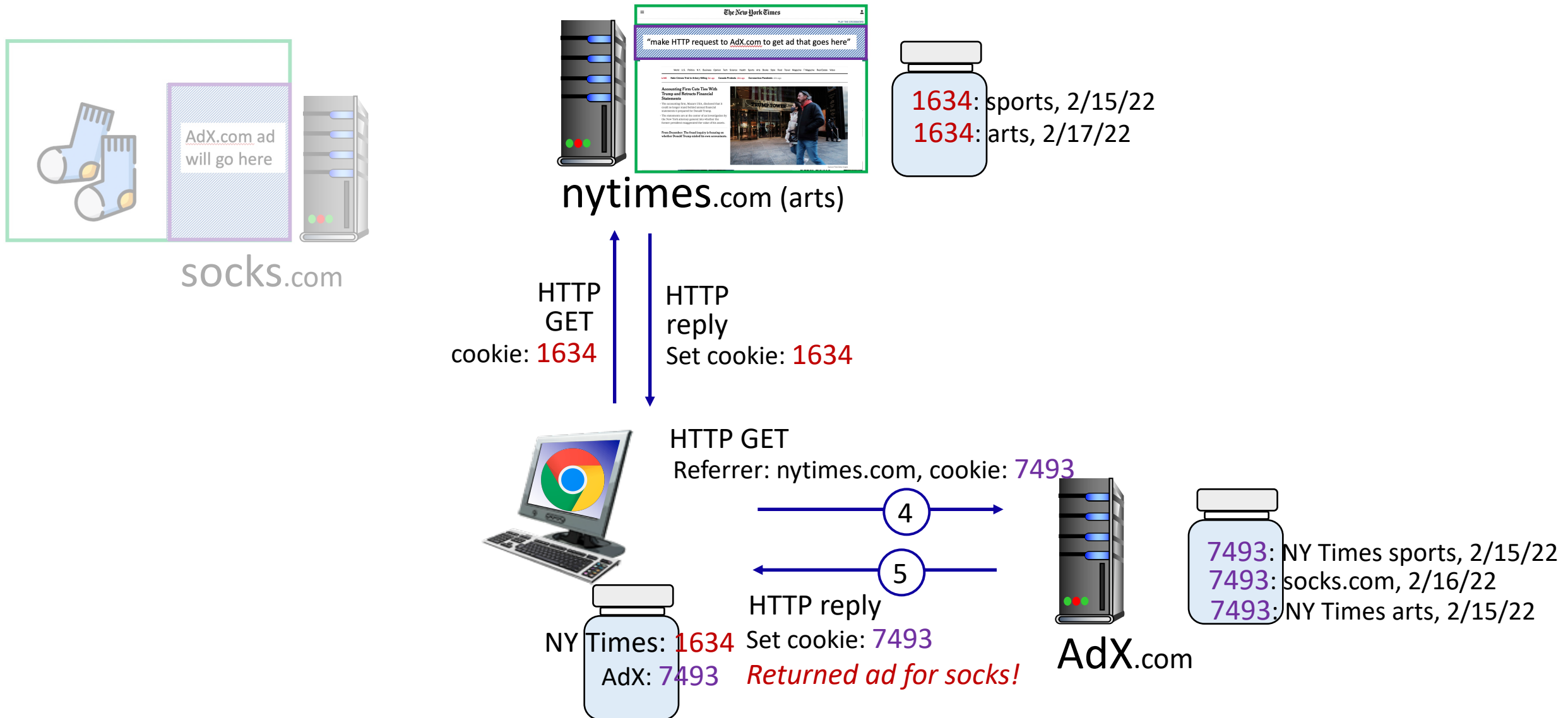
# Cookies: tracking a user's browsing behavior



# Cookies: tracking a user's browsing behavior



# 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

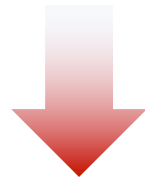


# GDPR (EU General Data Protection Regulation) and cookies

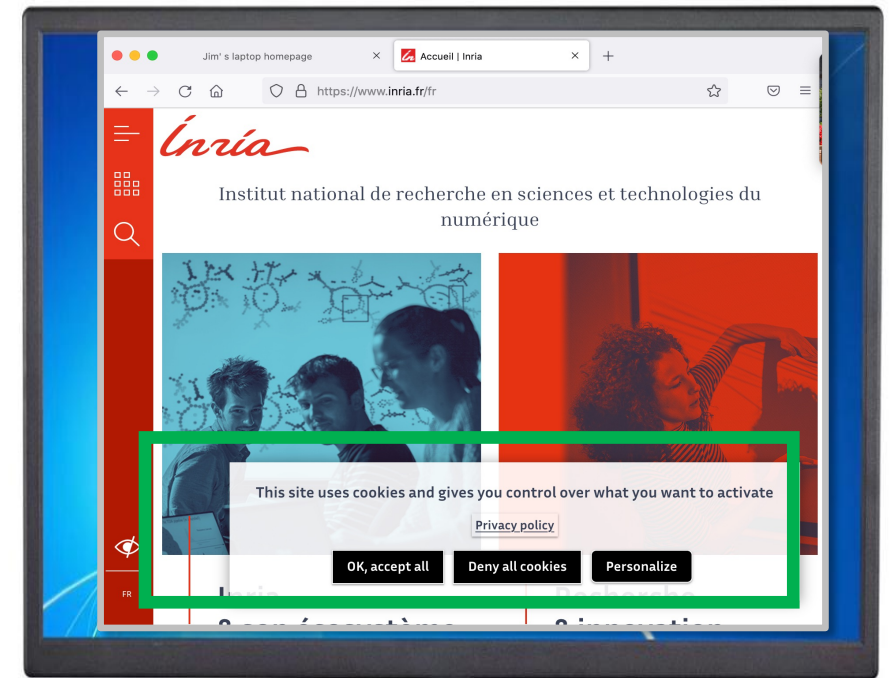
“Natural persons may be associated with online identifiers [...] such as internet protocol addresses, cookie identifiers or other identifiers [...].

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

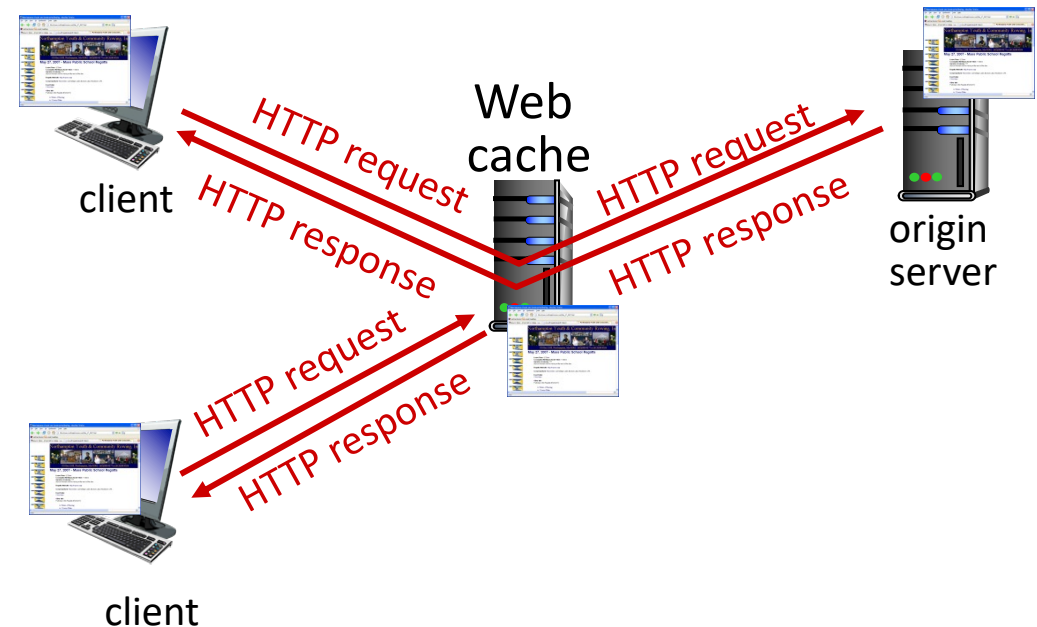


*User has explicit control over whether or not cookies are allowed*

# 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

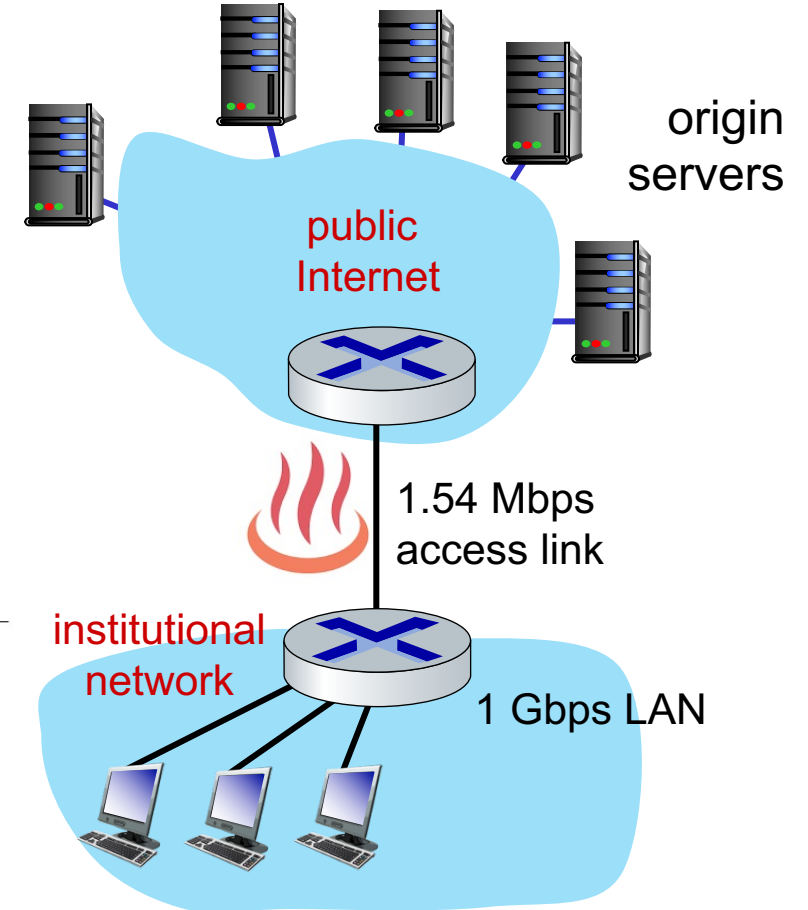
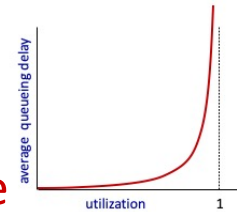
## Scenario:

- 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

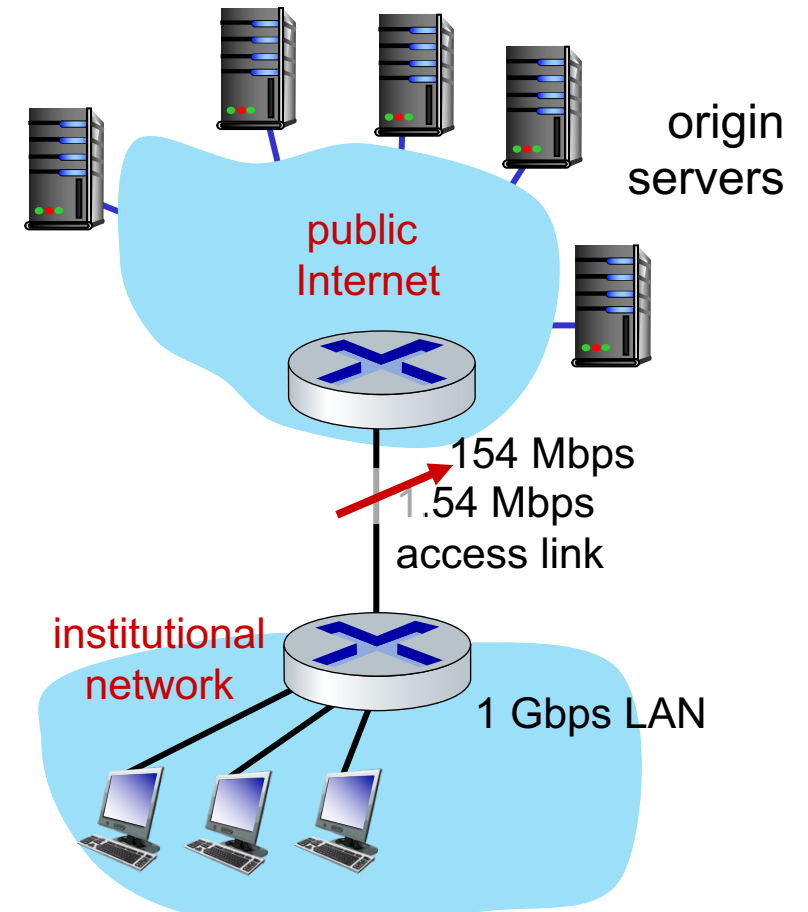
## Scenario:

- 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~~ + usecs

**Cost:** faster access link (expensive!) → msecs



# Option 2: install a web cache

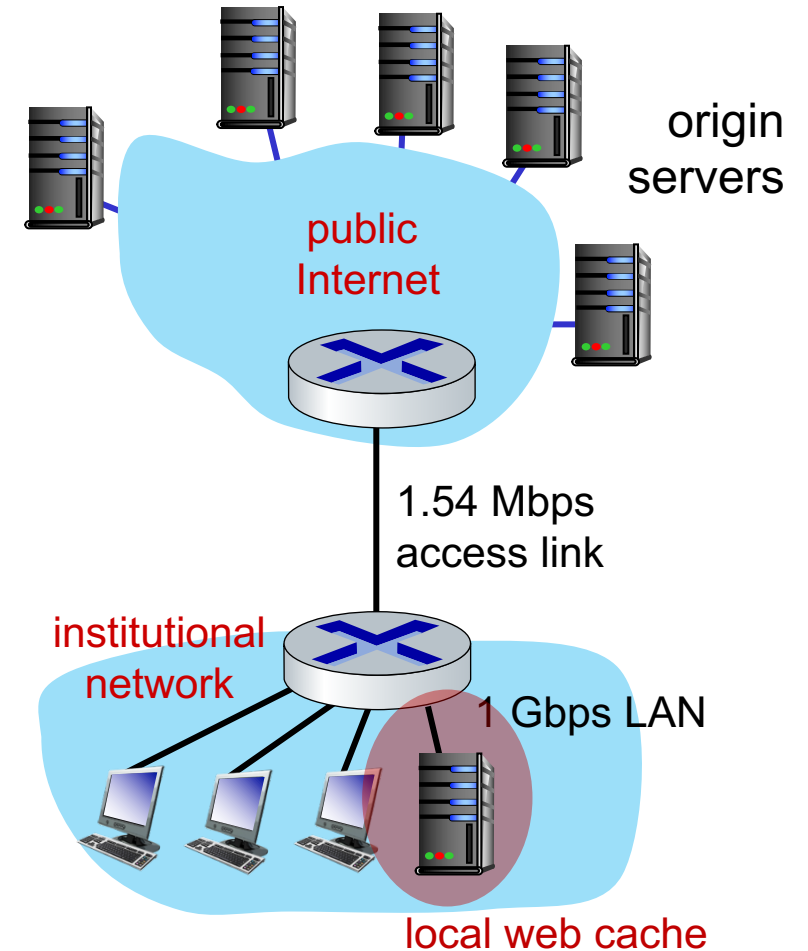
## *Scenario:*

- 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:*

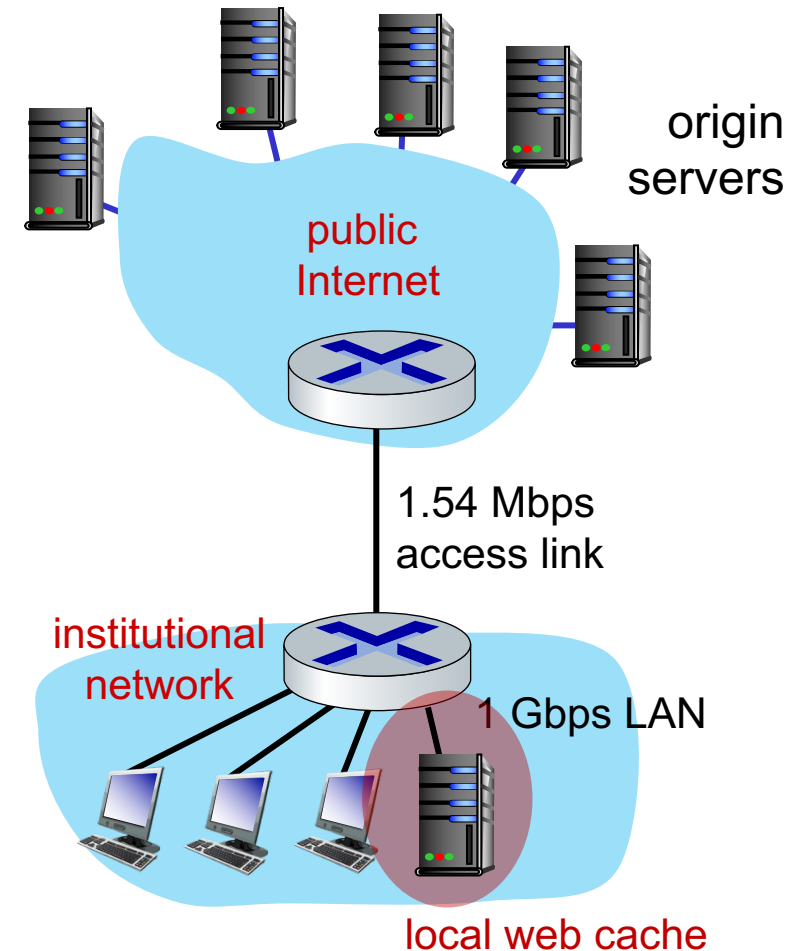
- LAN utilization: .?
  - access link utilization = ?
  - average end-end delay = ?
- How to compute link utilization, delay?*



# 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  
 $= 0.6 * 1.50 \text{ Mbps} = .9 \text{ Mbps}$
  - access link utilization  $= 0.9 / 1.54 = .58$  means low (msec) queueing delay at access link
- average end-end delay:  
 $= 0.6 * (\text{delay from origin servers})$   
 $+ 0.4 * (\text{delay when satisfied at cache})$   
 $= 0.6 (2.01) + 0.4 (\sim \text{msecs}) = \sim 1.2 \text{ secs}$

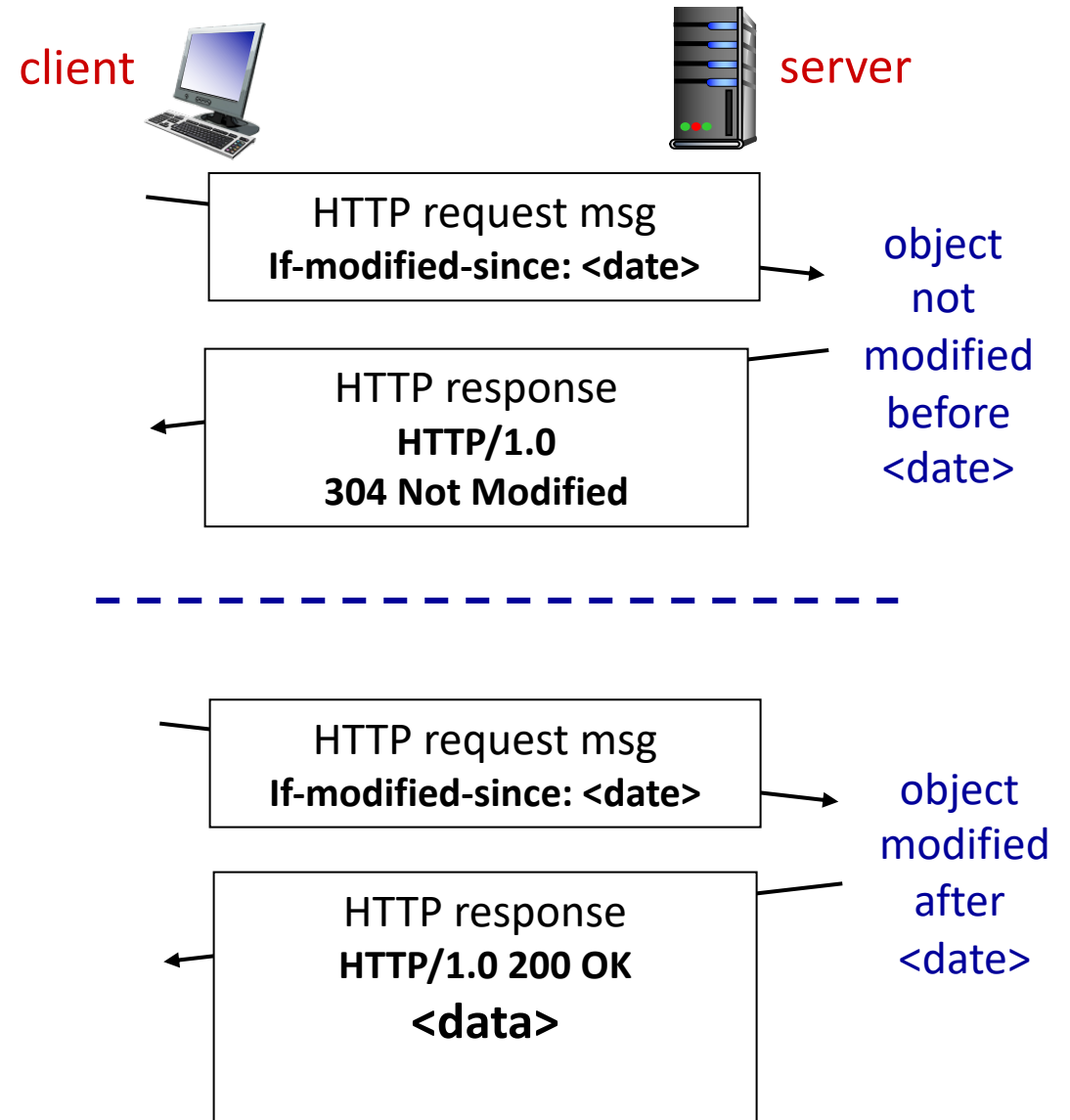


*lower average end-end delay than with 154 Mbps link (and cheaper too!)*

# 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

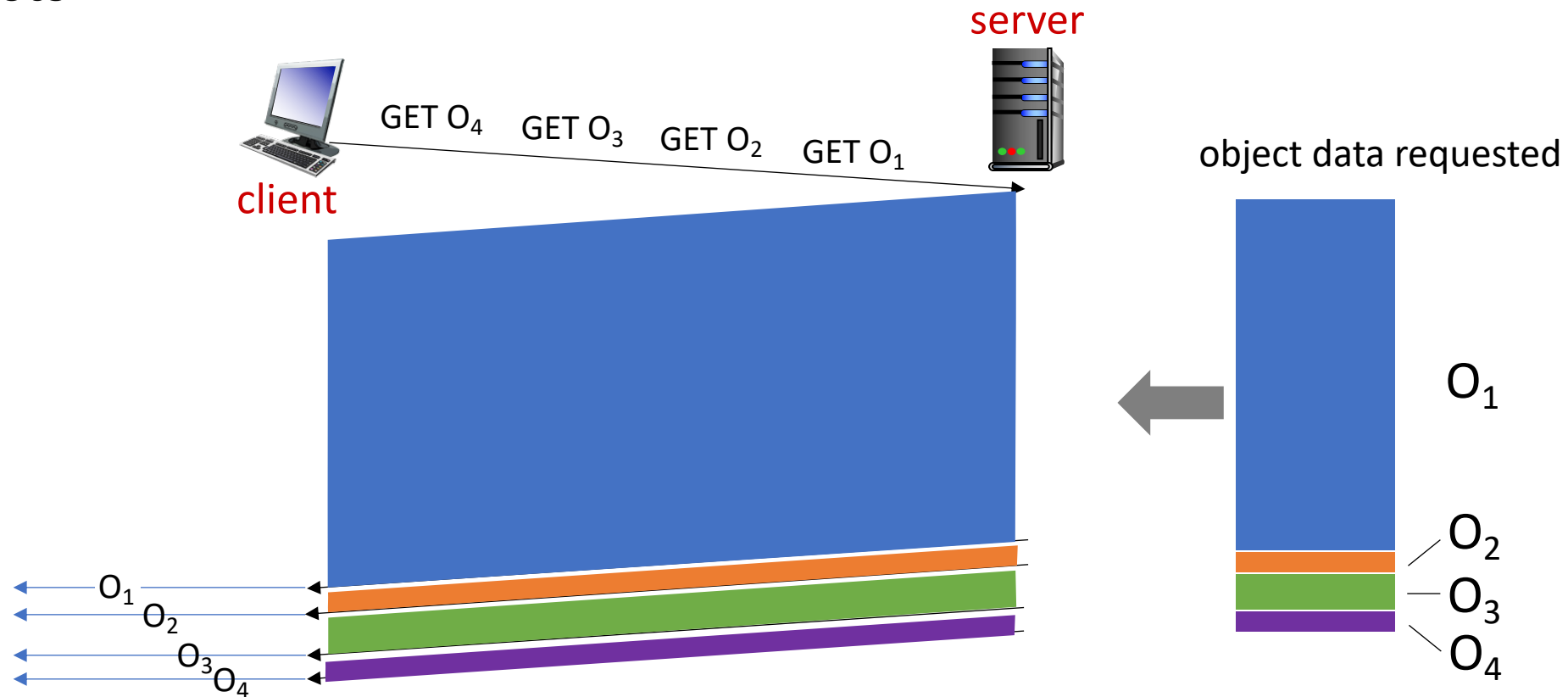
*Key goal:* decreased delay in multi-object HTTP requests

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

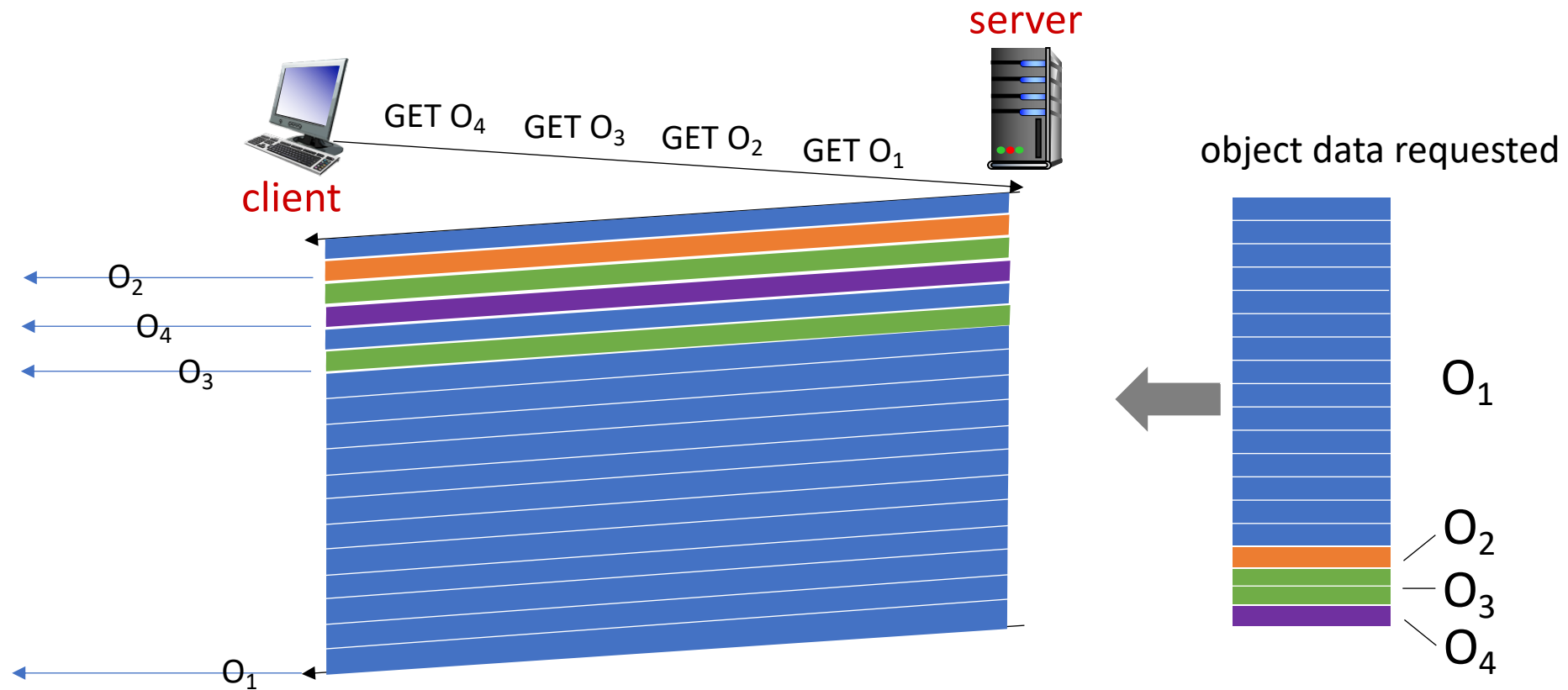
# HTTP/2: mitigating HOL blocking

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



# 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*

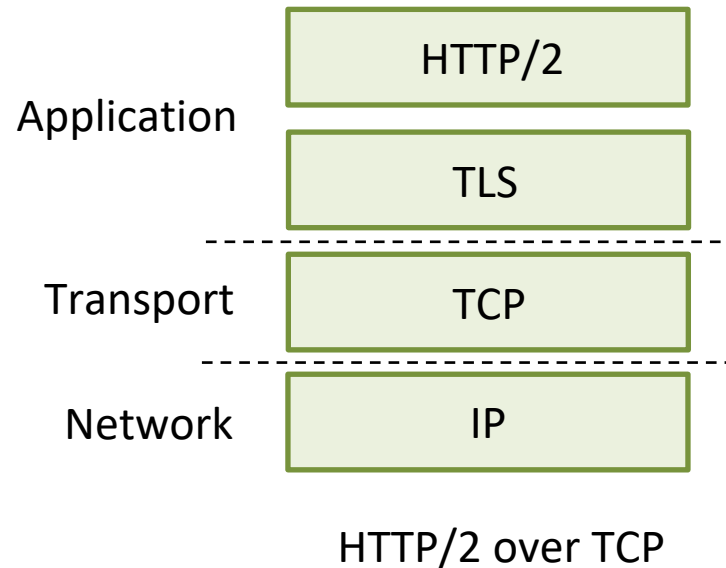
# HTTP/2 to HTTP/3

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

# QUIC: Quick UDP Internet Connections

- application-layer protocol, on top of UDP
  - increase performance of HTTP
  - deployed on many Google servers, apps (Chrome, mobile YouTube app)

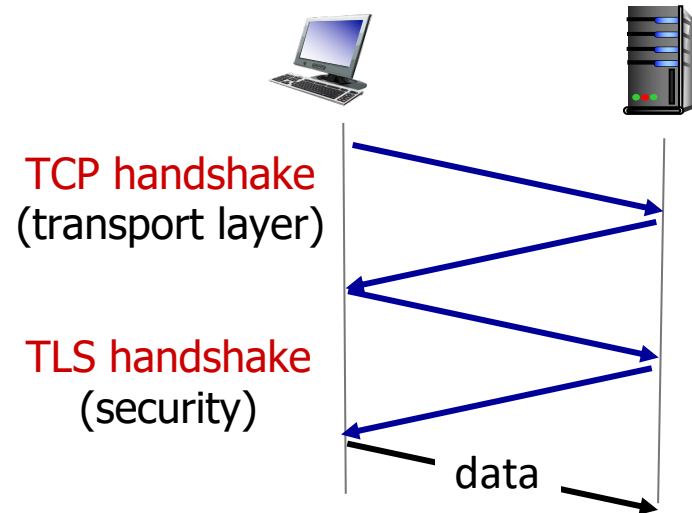


# QUIC: Quick UDP Internet Connections

adopts approaches we'll study in chapter for connection establishment, error control, congestion control

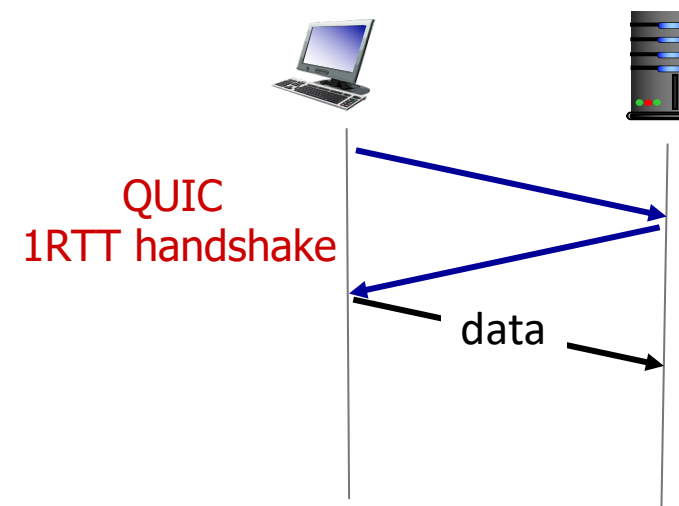
- **error and congestion control:** “Readers familiar with TCP’s loss detection and congestion control will find algorithms here that parallel well-known TCP ones.” [from QUIC specification]
- **connection establishment:** reliability, congestion control, authentication, encryption, state established in one RTT

# QUIC: Connection establishment



TCP (reliability, congestion control state) + TLS (authentication, crypto state)

- 2 serial handshakes



QUIC: reliability, congestion control, authentication, crypto state

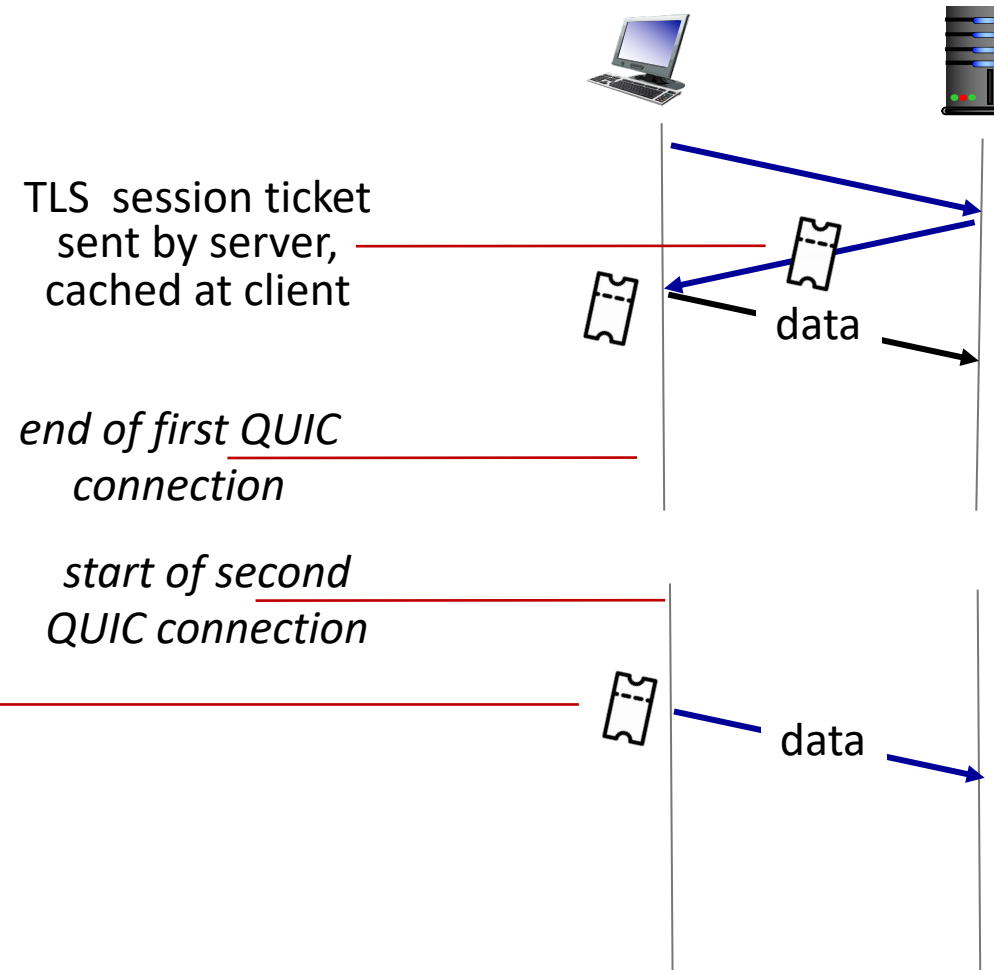
- 1 handshake



# QUIC: 0-RTT Connection establishment

Client uses last session ticket for encryption, authentication for new connection

- 0 RTT handshake delay



# Application layer: overview

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



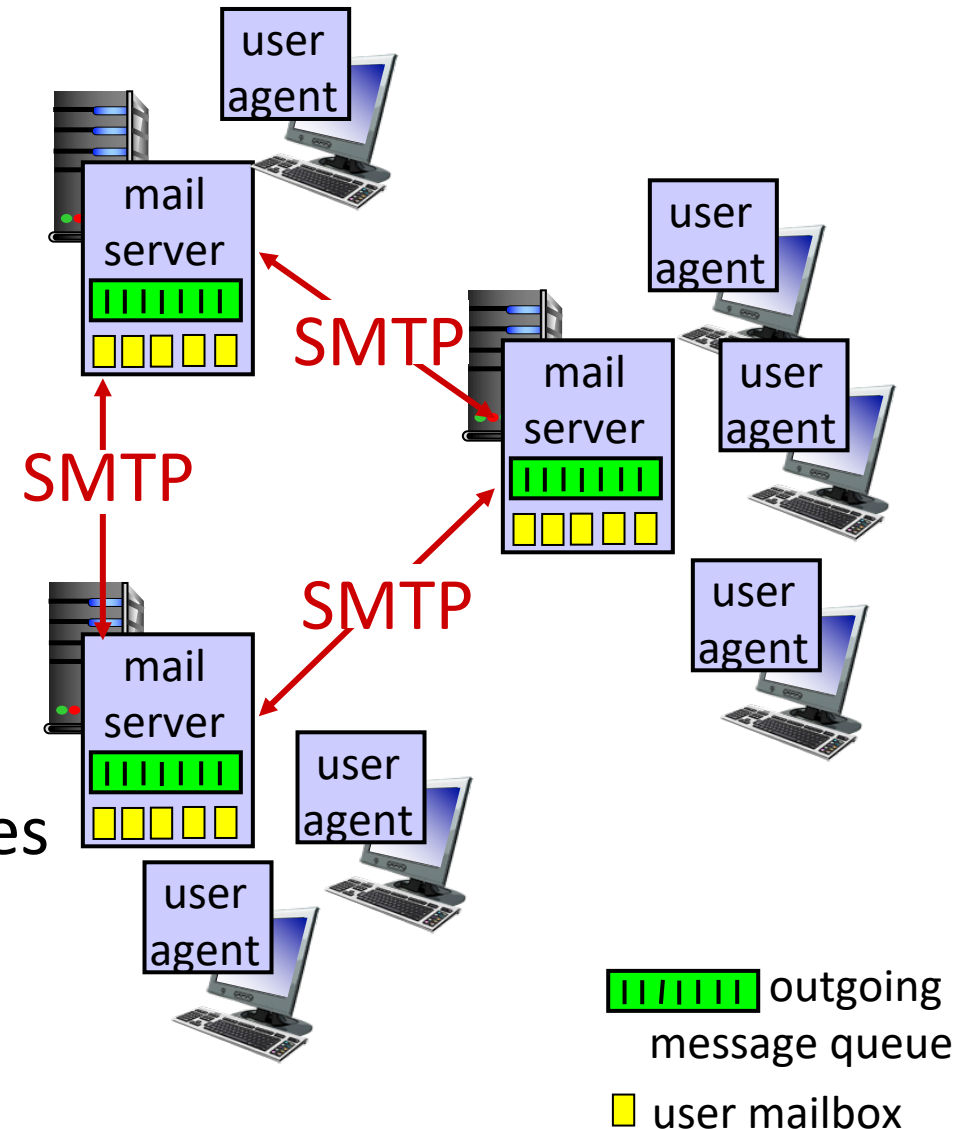
# E-mail

## 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



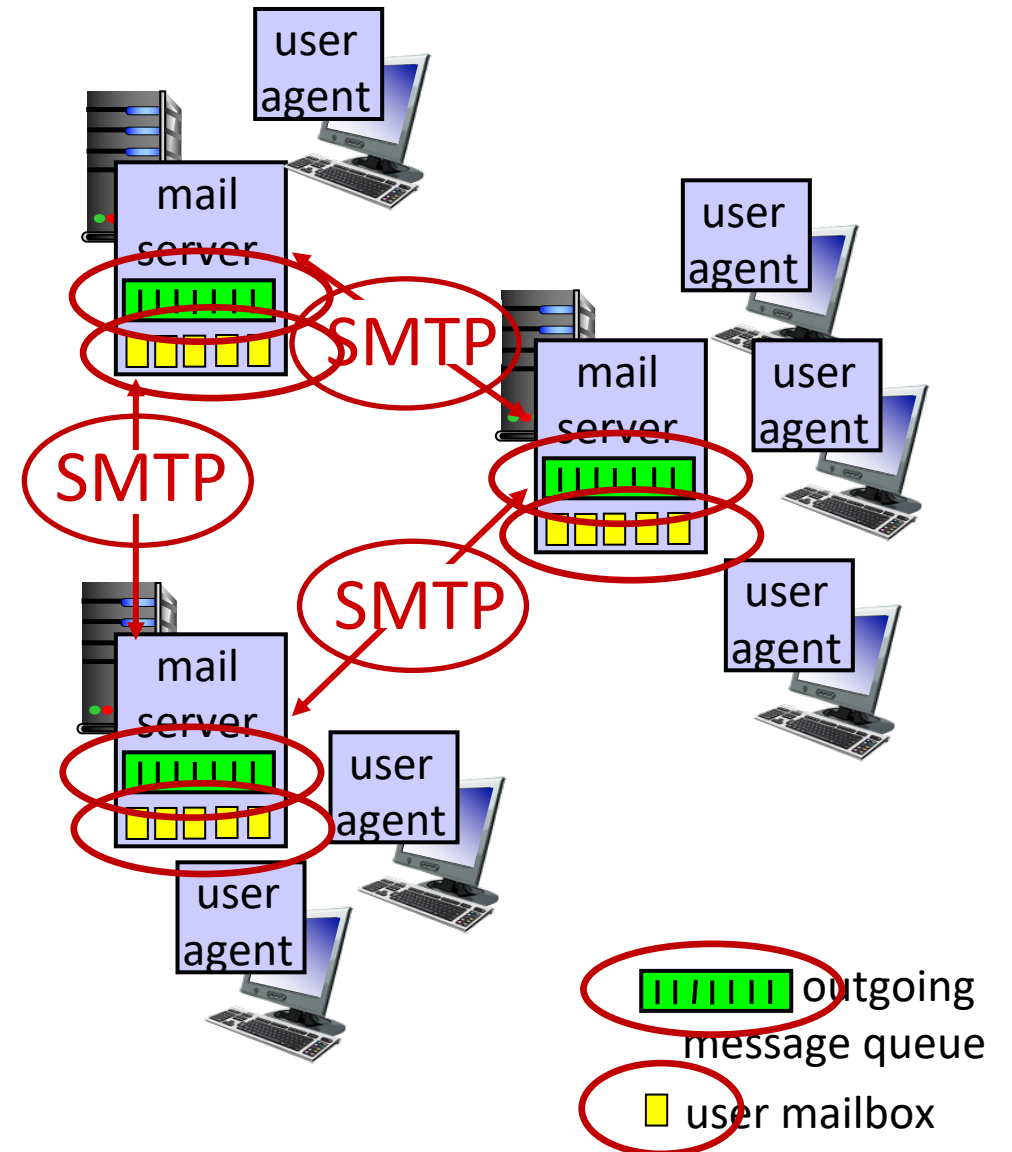
# E-mail: mail servers

## mail servers:

- *mailbox* contains incoming messages for user
- *message queue* of outgoing (to be sent) mail messages

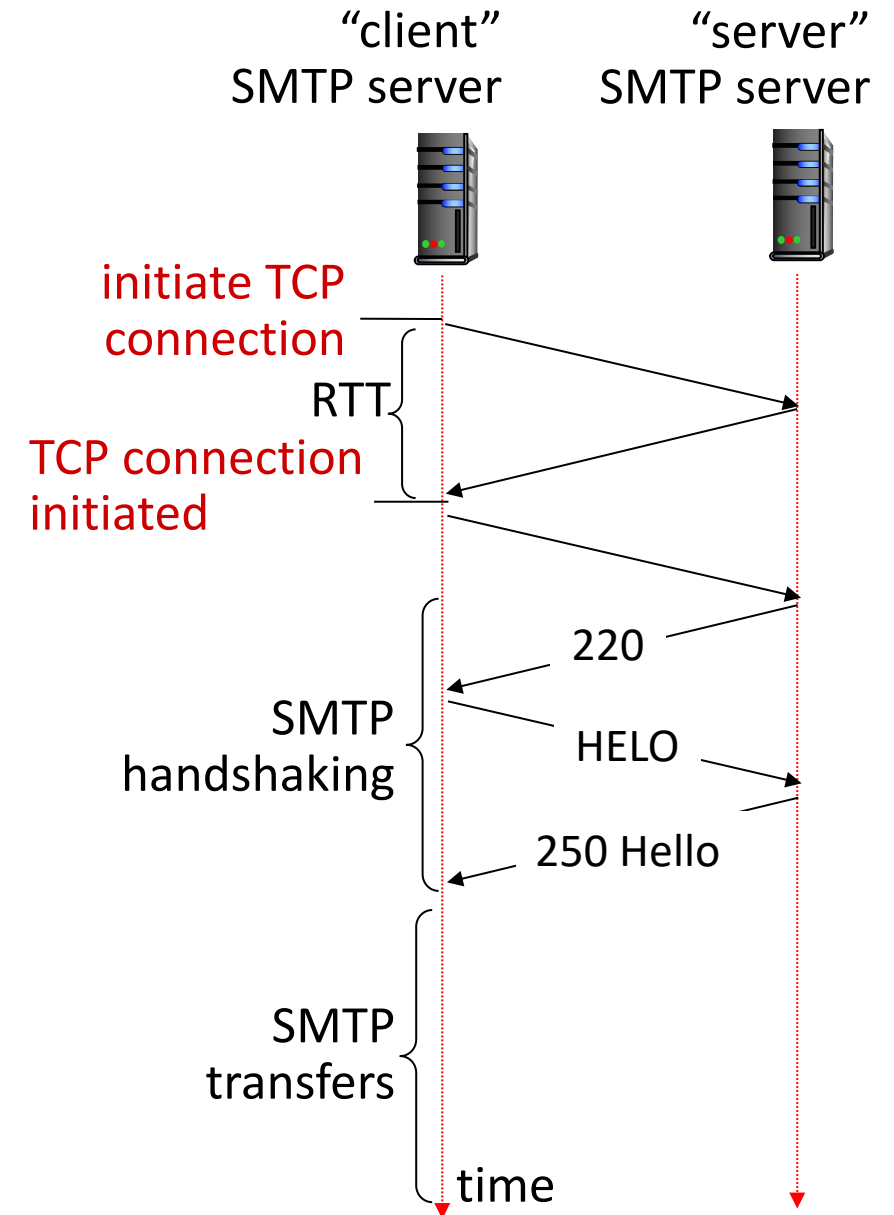
**SMTP protocol** between mail servers to send email messages

- *client*: sending mail server
- “*server*”: receiving mail server



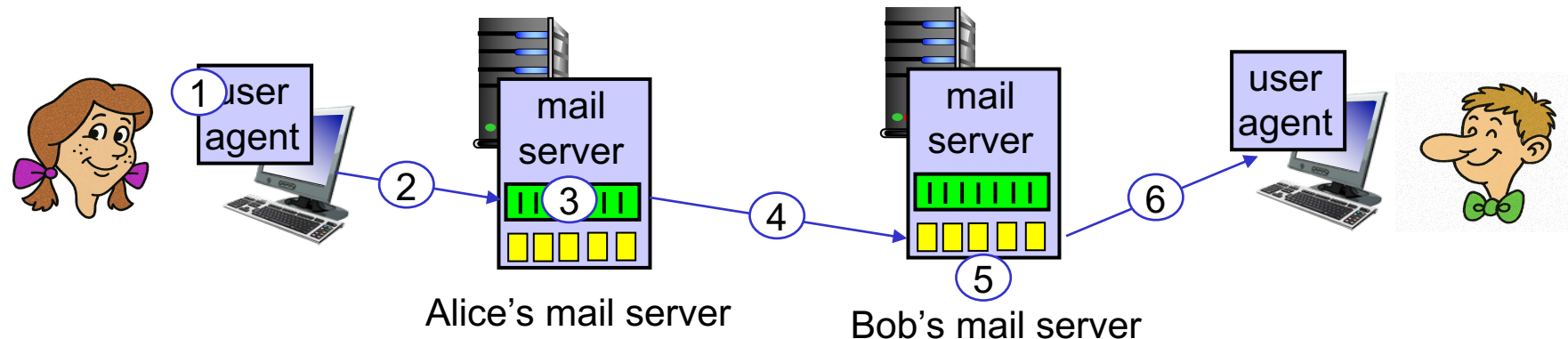
# SMTP RFC (5321)

- uses TCP to reliably transfer email message from client (mail server initiating connection) to server, port 25
  - direct transfer: sending server (acting like client) to receiving server
- three phases of transfer
  - SMTP handshaking (greeting)
  - SMTP transfer of messages
  - SMTP closure
- command/response interaction (like HTTP)
  - **commands**: ASCII text
  - **response**: status code and phrase



# Scenario: Alice sends e-mail to Bob

- 1) Alice uses UA to compose e-mail message "to" bob@some school.edu
- 2) Alice's UA sends message to her mail server using SMTP; message placed in message queue
- 3) client side of SMTP at mail server opens TCP connection with Bob's mail server
- 4) SMTP client sends Alice's message over the TCP connection
- 5) Bob's mail server places the message in Bob's mailbox
- 6) Bob invokes his user agent to read message



# Sample SMTP interaction

S: 220 hamburger.edu

# SMTP: observations

## *comparison with HTTP:*

- HTTP: client pull
- SMTP: client push
- both have ASCII command/response interaction, status codes
- HTTP: each object encapsulated in its own response message
- SMTP: multiple objects sent in multipart message
- SMTP uses persistent connections
- SMTP requires message (header & body) to be in 7-bit ASCII
- SMTP server uses CRLF.CRLF to determine end of message

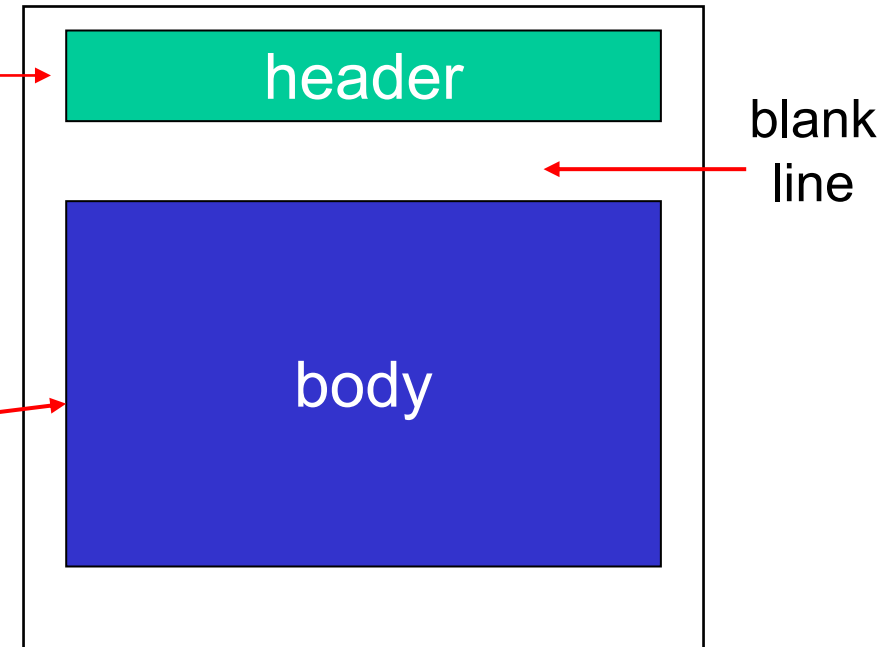


# Mail message format

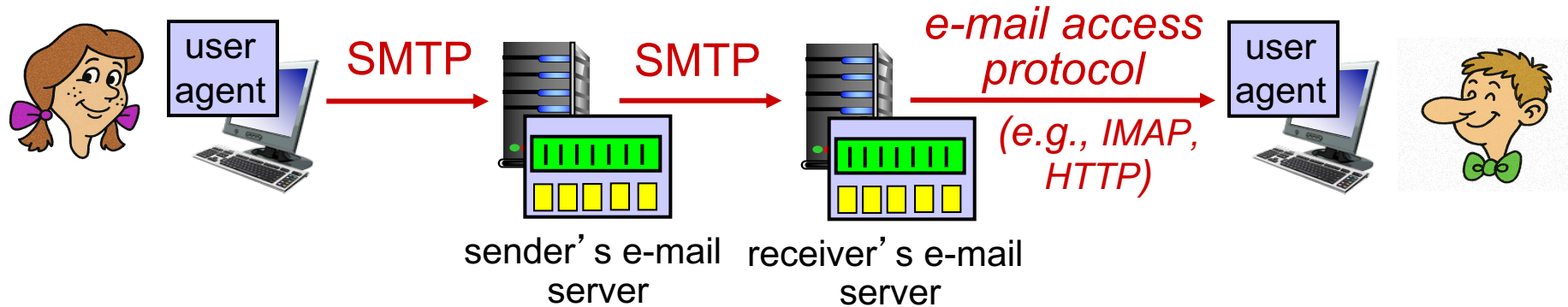
SMTP: protocol for exchanging e-mail messages, defined in RFC 5321 (like RFC 7231 defines HTTP)

RFC 2822 defines *syntax* for e-mail message itself (like HTML defines syntax for web documents)

- header lines, e.g.,
  - To:
  - From:
  - Subject:these lines, within the body of the email message area different from SMTP MAIL FROM:, RCPT TO: commands!
- Body: the “message” , ASCII characters only



# 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

# Application Layer: Overview

- Principles of network applications
- Web and HTTP
- E-mail, SMTP, IMAP
- **The Domain Name System  
DNS**
- 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 - msec count!

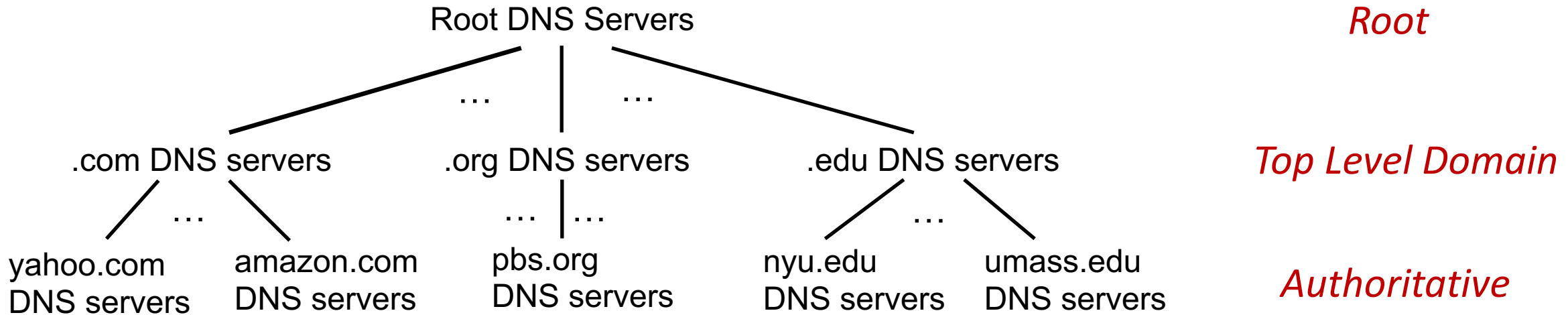
organizationally, physically decentralized:

- millions of different organizations responsible for their records

“bulletproof”: reliability, security



# DNS: a distributed, hierarchical database

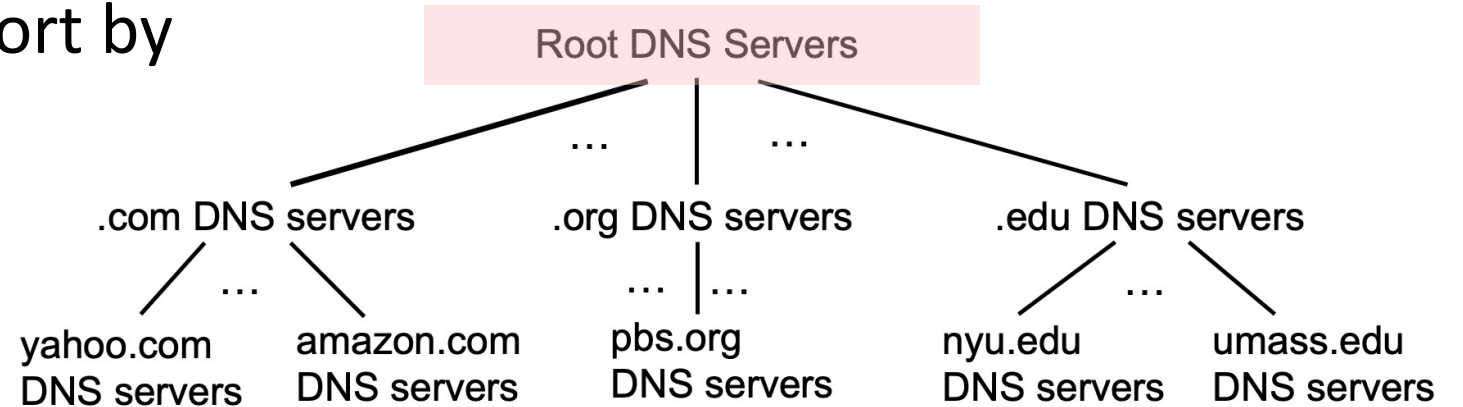


Client wants IP address for `www.amazon.com`; 1<sup>st</sup> approximation:

- 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
- ICANN (Internet Corporation for Assigned Names and Numbers) manages root DNS domain

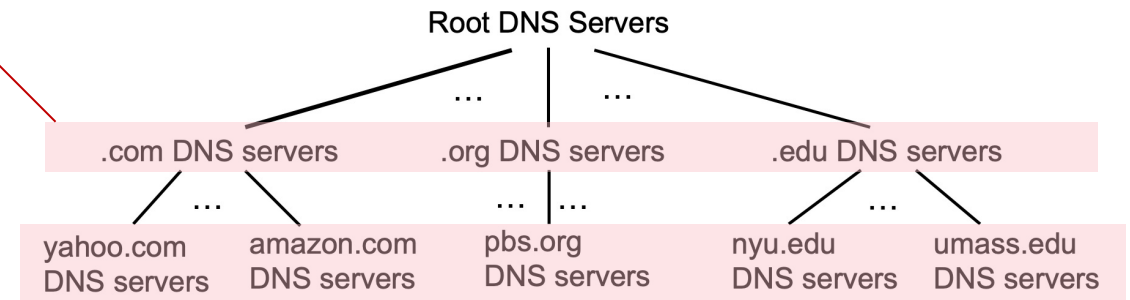


*13 logical root name “servers”  
worldwide; each “server,” replicated  
many times*

# 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

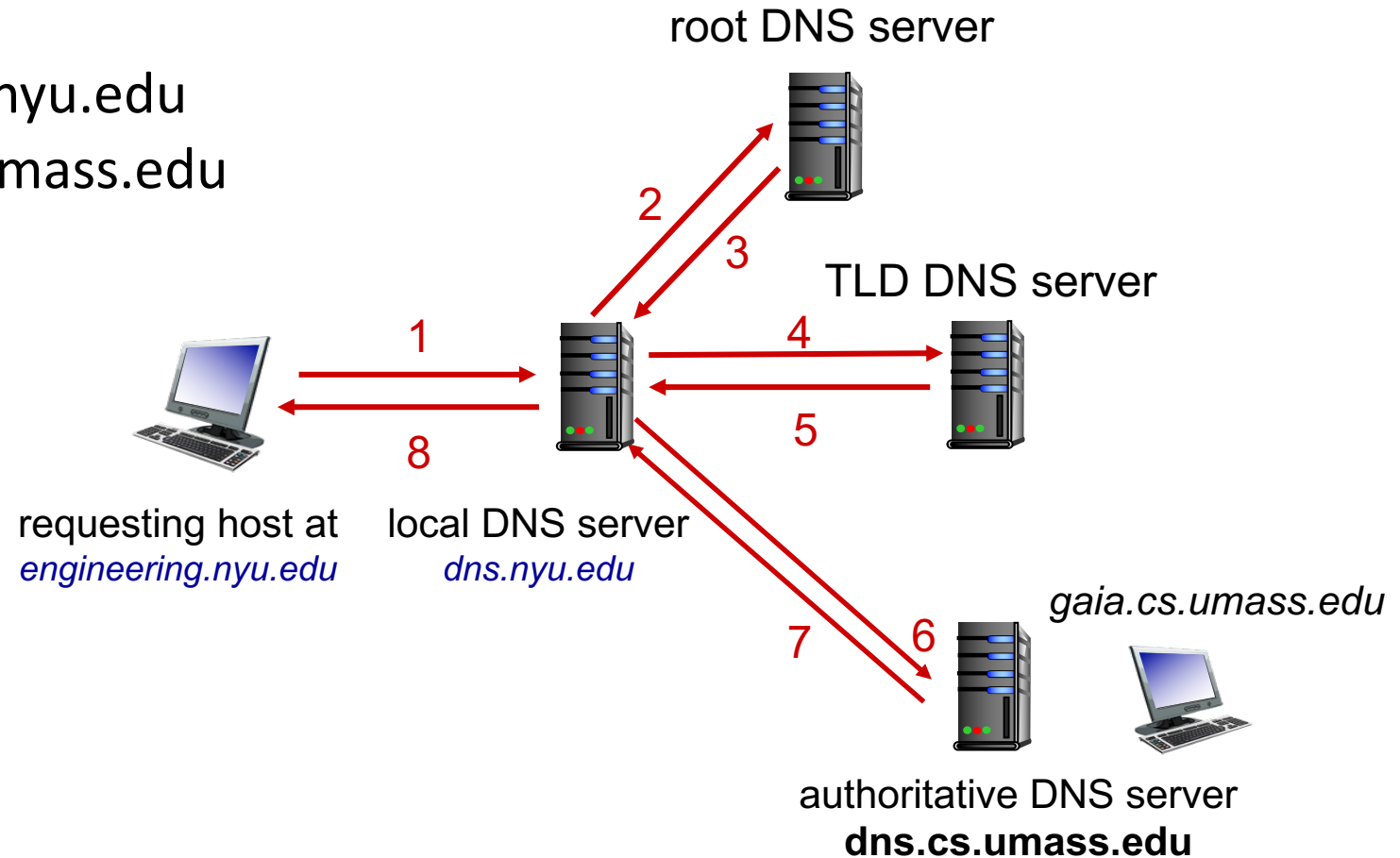
- when host makes DNS query, it is sent to its *local* DNS server
  - Local DNS server returns reply, answering:
    - from its local cache of recent name-to-address translation pairs (possibly out of date!)
    - forwarding request into DNS hierarchy for resolution
  - each ISP has local DNS name server;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

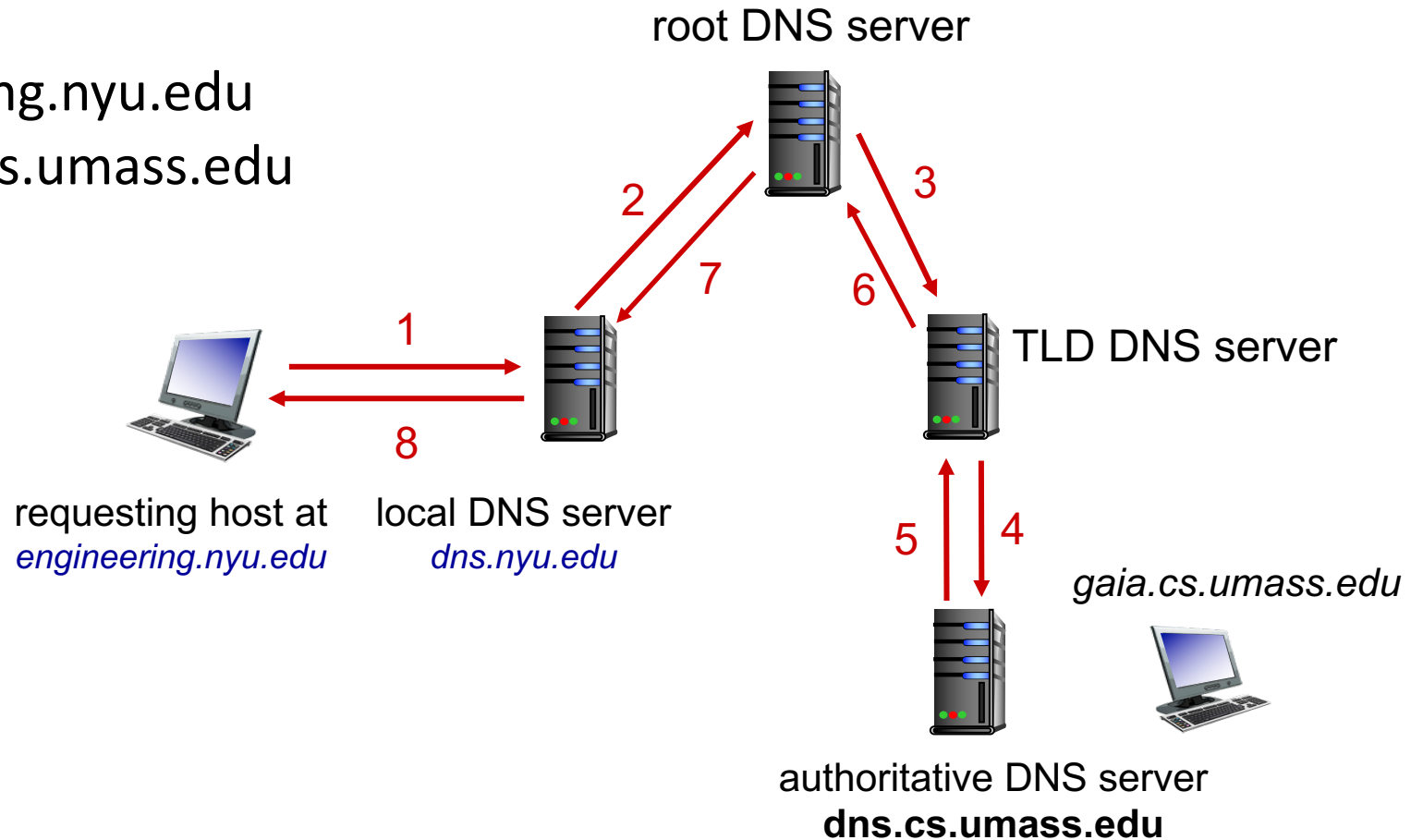


# DNS name resolution: recursive query

**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 *cached* 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

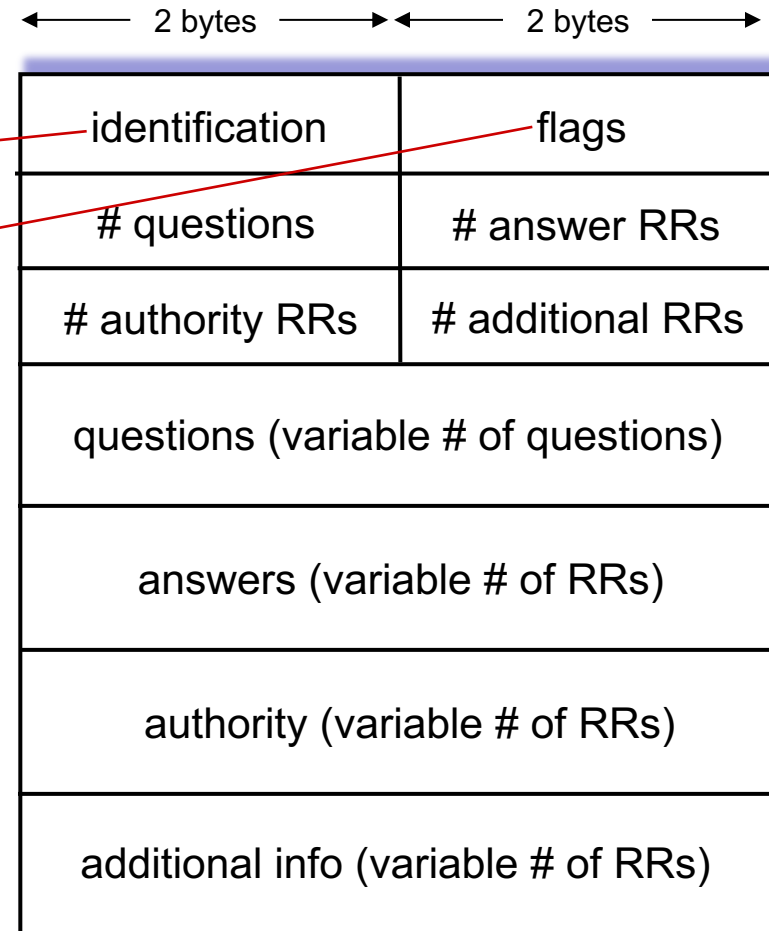
- value is name of SMTP mail server associated with name

# 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
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- P2P applications
- **video streaming and content distribution networks**
- socket programming with UDP and TCP



# Video Streaming and CDNs: context

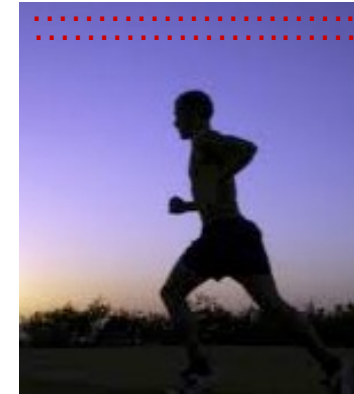
- stream video traffic: major consumer of Internet bandwidth
  - Netflix, YouTube, Amazon Prime: 80% of residential ISP traffic (2020)
- *challenge*: scale - how to reach ~1B users?
- *challenge*: heterogeneity
  - different users have different capabilities (e.g., wired versus mobile; bandwidth rich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



# Multimedia: video

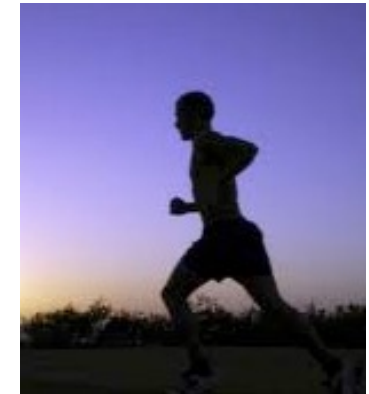
- video: sequence of images displayed at constant rate
  - e.g., 24 images/sec
- digital image: array of pixels
  - each pixel represented by bits
- coding: use redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to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

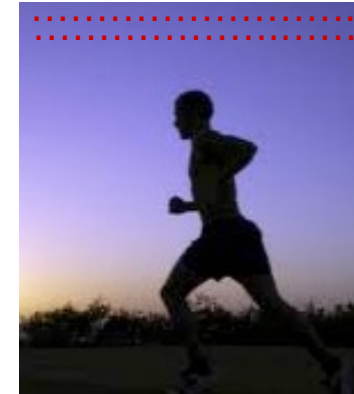


frame  $i+1$

# Multimedia: video

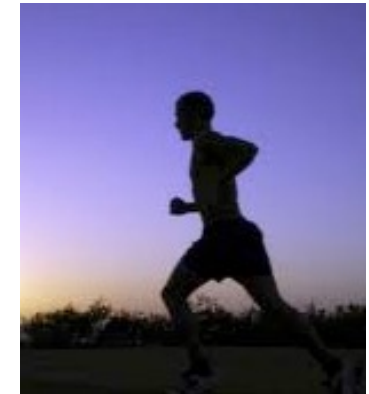
- **CBR: (constant bit rate):** video encoding rate fixed
- **VBR: (variable bit rate):** video encoding rate changes as amount of spatial, temporal coding changes
- **examples:**
  - MPEG 1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, 64Kbps – 12 Mbps)

*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  $i$

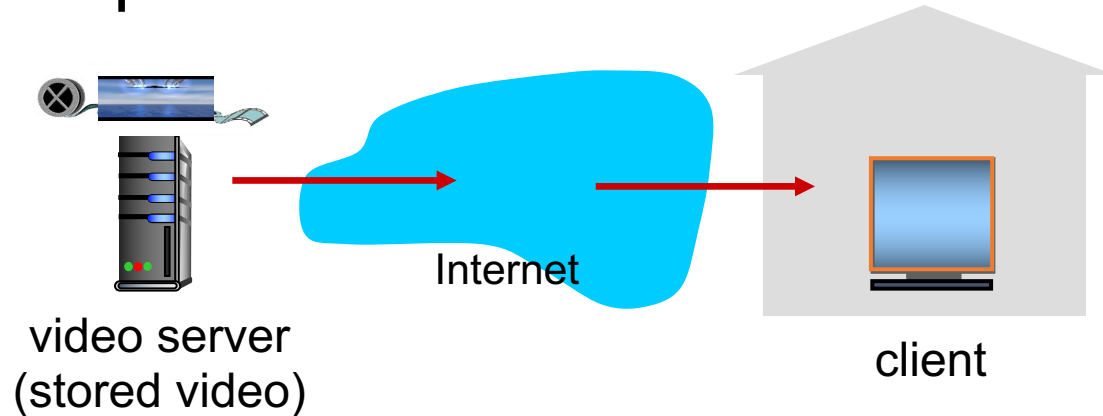
*temporal coding example:* instead of sending complete frame at  $i+1$ , send only differences from frame  $i$



frame  $i+1$

# Streaming stored video

simple scenario:

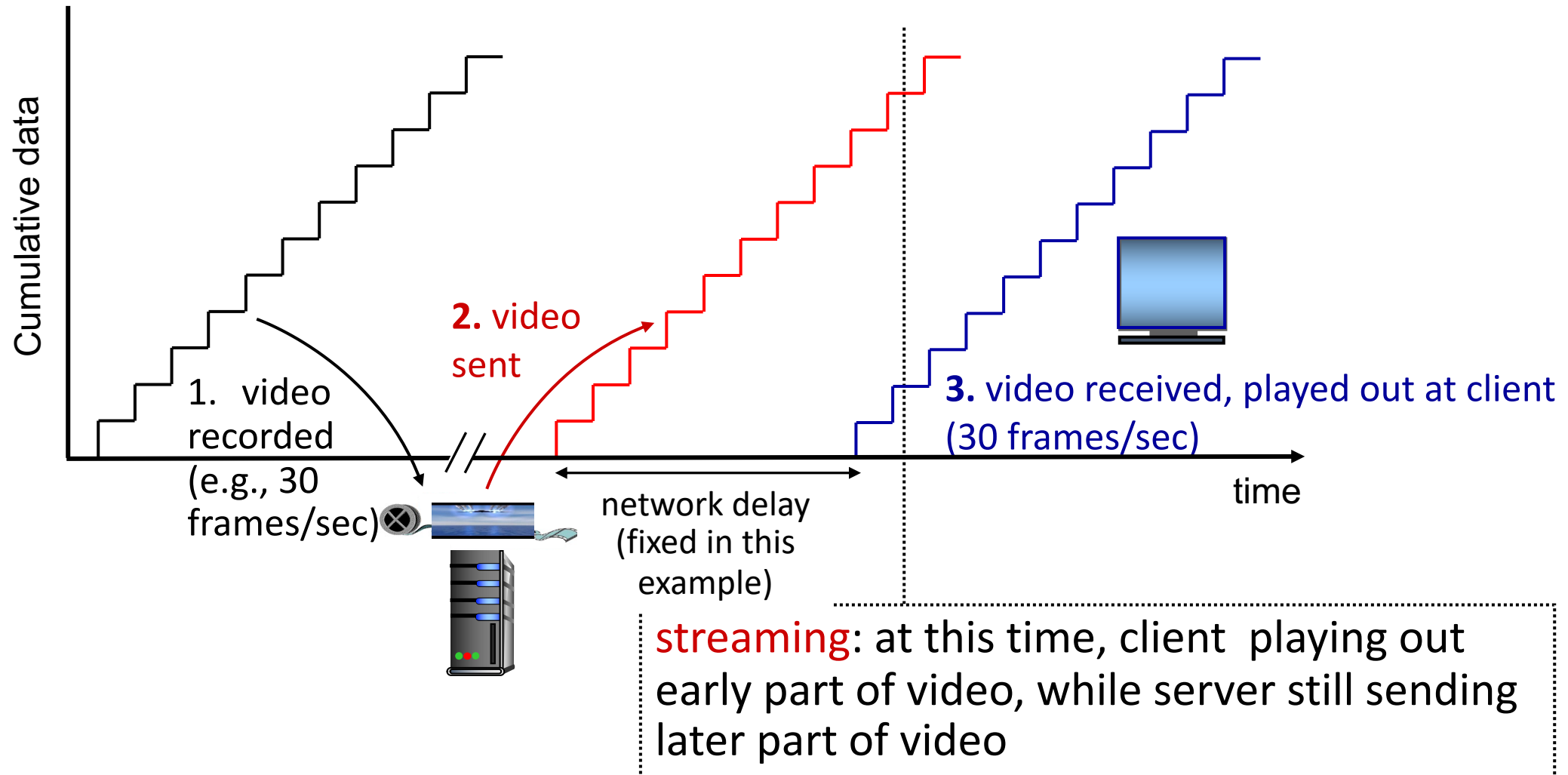


Main challenges:

- 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

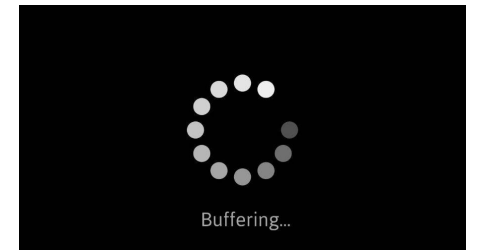


# Streaming stored video

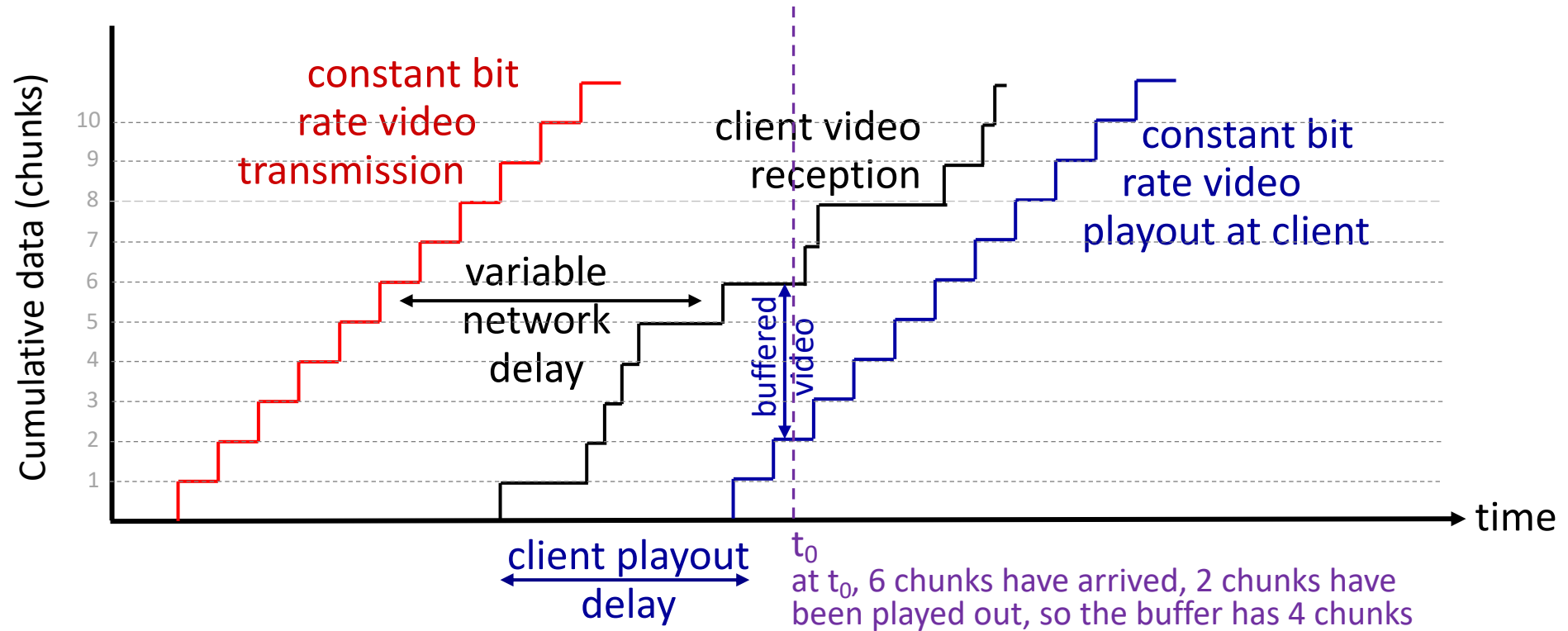


# Streaming stored video: challenges

- **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



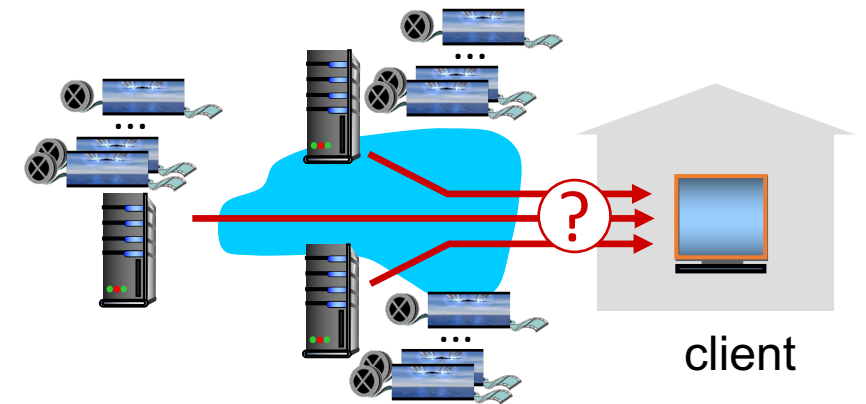
- ***client-side buffering and playout delay:*** compensate for network-added delay, delay jitter

# Streaming multimedia: DASH

*D*ynamic, *A*daptive  
*S*teaming 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

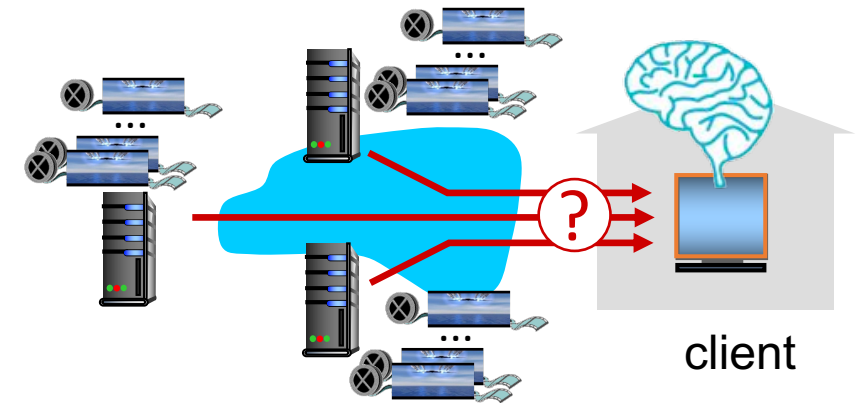


## client:

- 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*

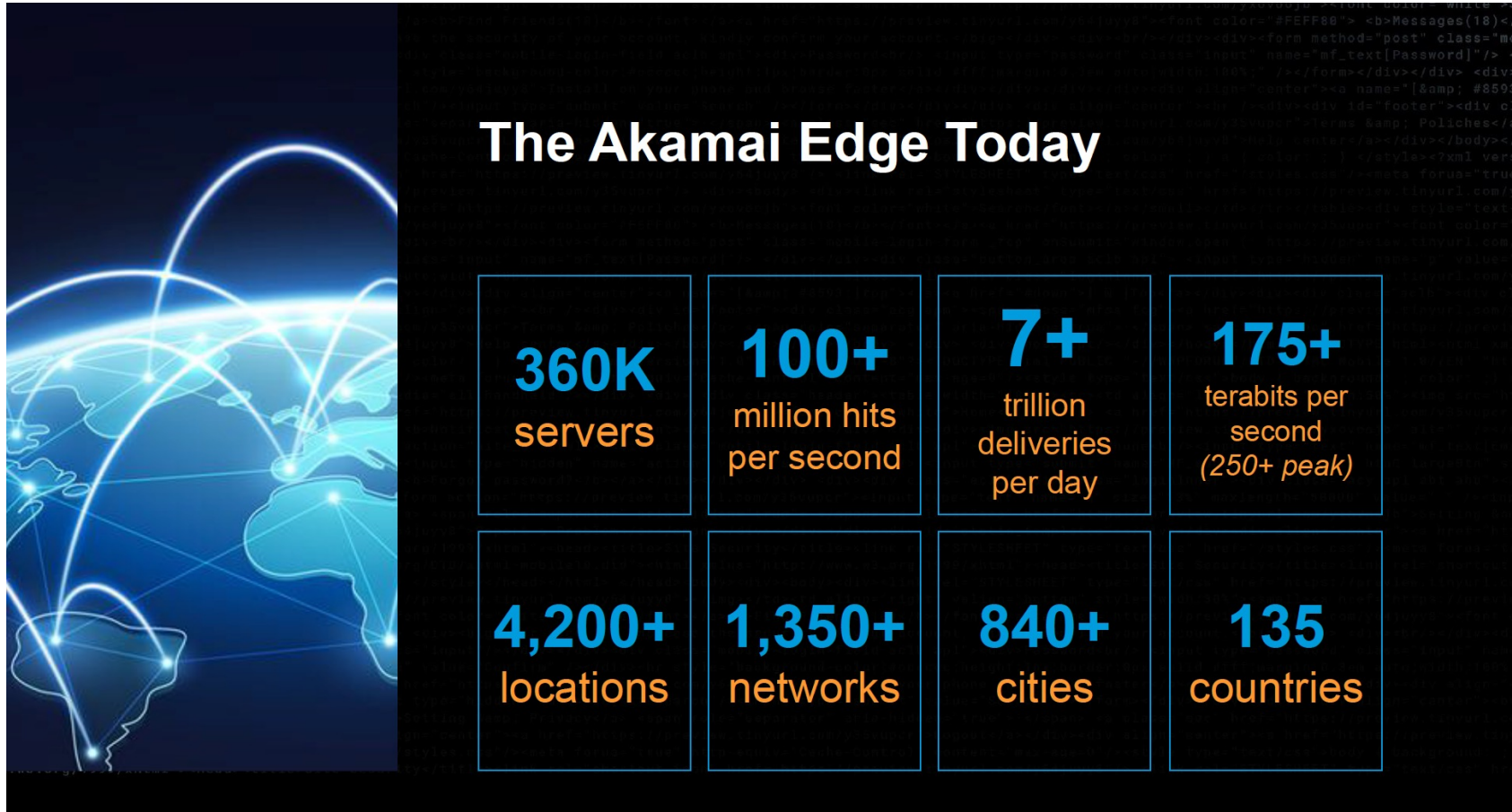
# Content distribution networks (CDNs)

*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



# Akamai today:

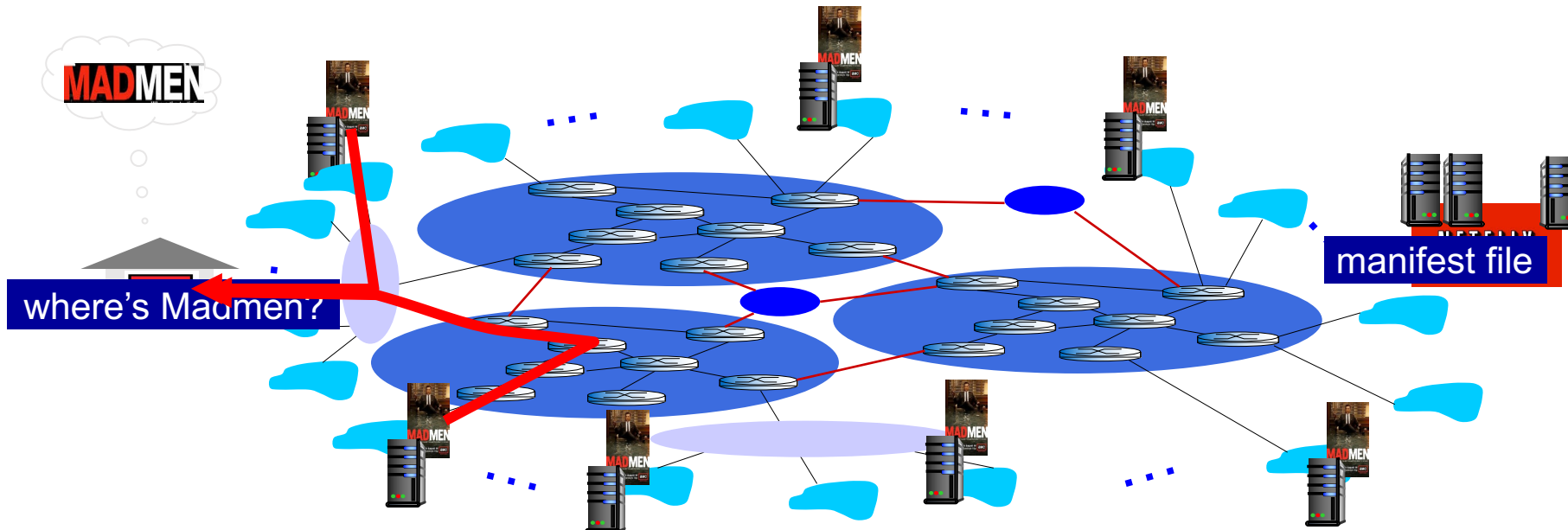


Source: <https://networkingchannel.eu/living-on-the-edge-for-a-quarter-century-an-akamai-retrospective-downloads/>



# 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?

# Application Layer: Overview

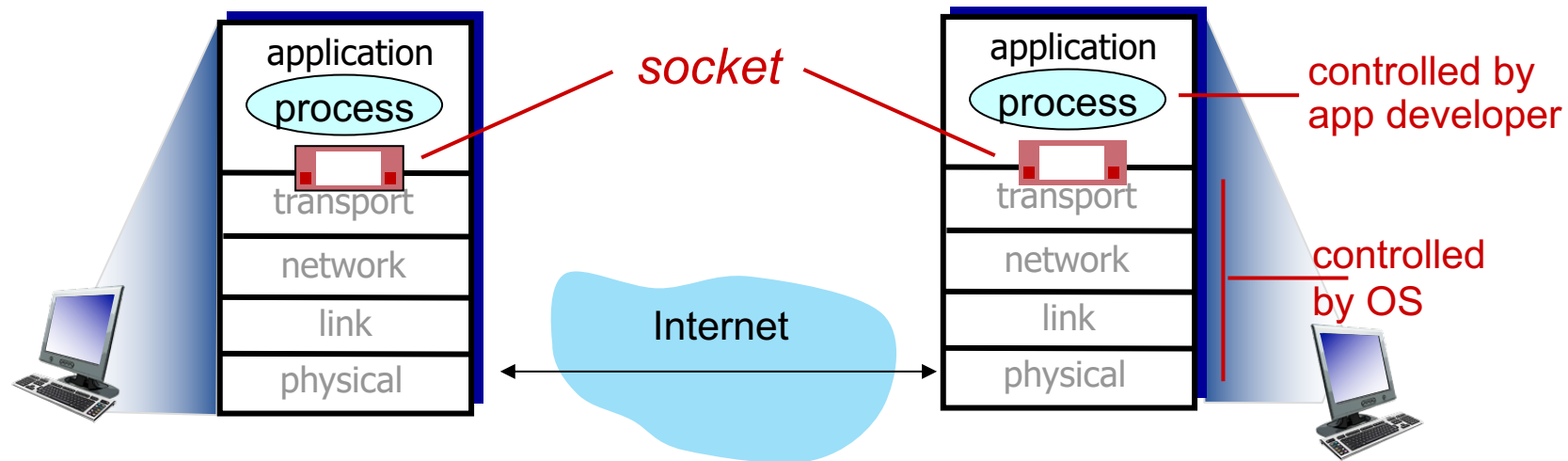
- Principles of network applications
- Web and HTTP
- E-mail, SMTP, IMAP
- The Domain Name System DNS
- P2P applications
- video streaming and content distribution networks
- **socket programming with UDP and TCP**



# Socket programming

*goal:* learn how to build client/server applications that communicate using sockets

*socket:* door between application process and end-end-transport protocol



# Socket programming

Two socket types for two transport services:

- *UDP*: unreliable datagram
- *TCP*: reliable, byte stream-oriented

## Application Example:

1. client reads a line of characters (data) from its keyboard and sends data to server
2. server receives the data and converts characters to uppercase
3. server sends modified data to client
4. client receives modified data and displays line on its screen

# Socket programming with UDP

**UDP:** no “connection” between client and server:

- no handshaking before sending data
- sender explicitly attaches IP destination address and port # to each packet
- receiver extracts sender IP address and port# from received packet

**UDP:** transmitted data may be lost or received out-of-order

**Application viewpoint:**

- UDP provides *unreliable* transfer of groups of bytes (“datagrams”) between client and server processes

# Client/server socket interaction: UDP



**server** (running on serverIP)

create socket, port= x:  
**serverSocket =**  
**socket(AF\_INET,SOCK\_DGRAM)**

read datagram from  
**serverSocket**

write reply to  
**serverSocket**  
specifying  
client address,  
port number

**client**



create socket:  
**clientSocket =**  
**socket(AF\_INET,SOCK\_DGRAM)**

Create datagram with serverIP address  
And port=x; send datagram via  
**clientSocket**

read datagram from  
**clientSocket**

close  
**clientSocket**

# Example app: UDP client

## *Python UDPClient*

|   |   |  |
|---|---|--|
| include Python's socket library                       | → | from socket import *   |
|   |   | serverName = 'hostname'  |
|   |   | serverPort = 12000   |
| create UDP socket                                     | → | clientSocket = socket(AF_INET,<br>SOCK_DGRAM)                      |
| get user keyboard input                               | → | message = input('Input lowercase sentence:')                       |
| attach server name, port to message; send into socket | → | clientSocket.sendto(message.encode(),<br>(serverName, serverPort)) |
| read reply data (bytes) from socket                   | → | modifiedMessage, serverAddress =<br>clientSocket.recvfrom(2048)    |
| print out received string and close socket            | → | print(modifiedMessage.decode())<br>clientSocket.close()            |



# Example app: UDP server

## *Python UDPServer*

```
from socket import *
serverPort = 12000
create UDP socket → serverSocket = socket(AF_INET, SOCK_DGRAM)
bind socket to local port number 12000 → serverSocket.bind(('', serverPort))
print('The server is ready to receive')
loop forever → while True:
    Read from UDP socket into message, getting client's address (client IP and port) → message, clientAddress = serverSocket.recvfrom(2048)
    modifiedMessage = message.decode().upper()
    send upper case string back to this client → serverSocket.sendto(modifiedMessage.encode(), clientAddress)
```

# Socket programming with TCP

## Client must contact server

- server process must first be running
- server must have created socket (door) that welcomes client's contact

## Client contacts server by:

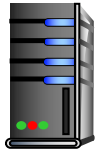
- Creating TCP socket, specifying IP address, port number of server process
- *when client creates socket:* client TCP establishes connection to server TCP

- when contacted by client, *server TCP creates new socket* for server process to communicate with that particular client
  - allows server to talk with multiple clients
  - client source port # and IP address used to distinguish clients (more in Chap 3)

## Application viewpoint

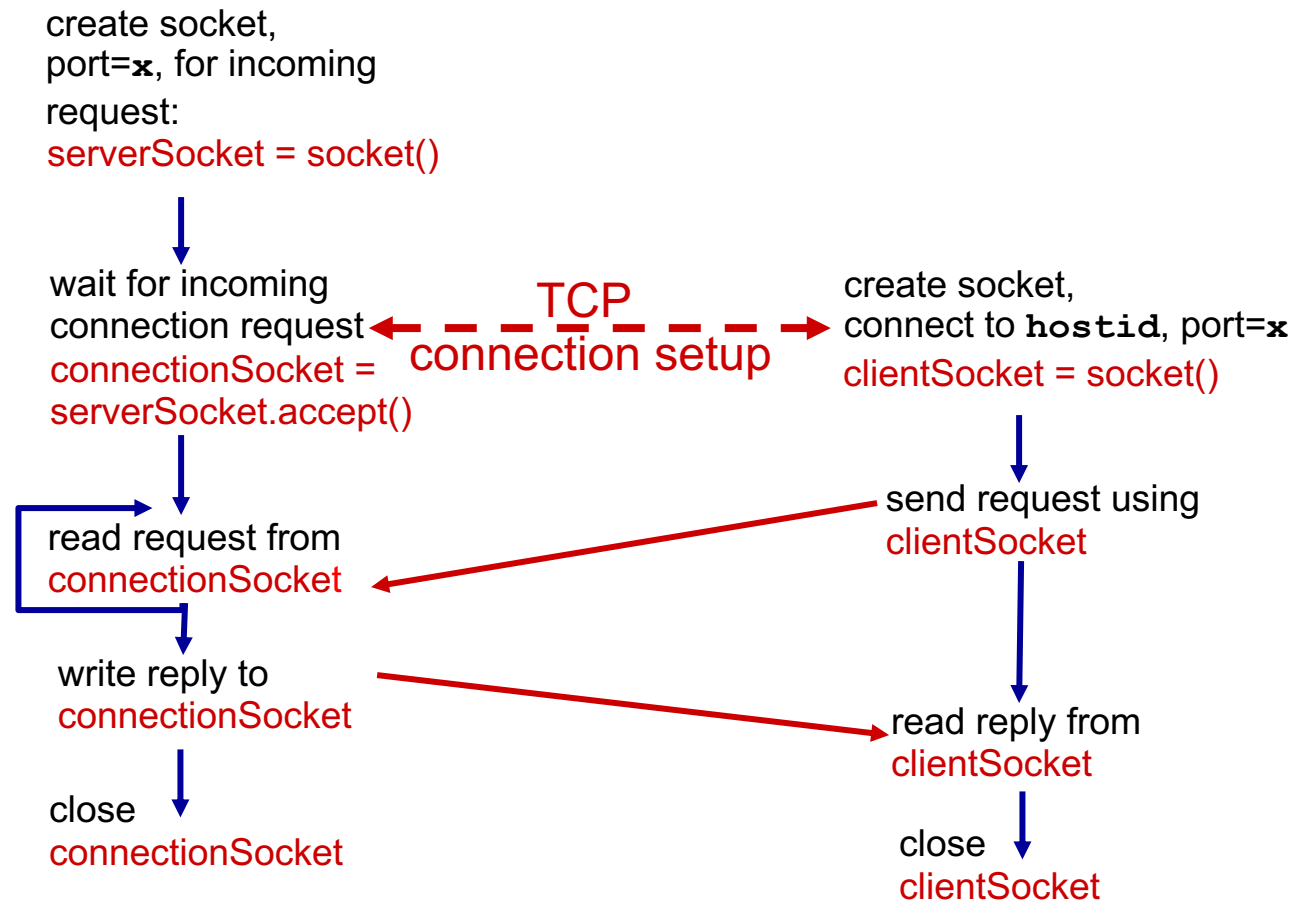
TCP provides reliable, in-order byte-stream transfer ("pipe") between client and server processes

# Client/server socket interaction: TCP



server (running on `hostid`)

client



# Example app: TCP client

## *Python TCPClient*

create TCP socket for server,  
remote port 12000

```
from socket import *
serverName = 'servername'
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName, serverPort))
sentence = input('Input lowercase sentence:')
clientSocket.send(sentence.encode())
modifiedSentence = clientSocket.recv(1024)
print ('From Server:', modifiedSentence.decode())
clientSocket.close()
```

No need to attach server name, port

# Example app: TCP server

## *Python TCPServer*

|  |   |  |
|--|---|--|
|  |   | <pre>from socket import *</pre>                                    |
|  |   | <pre>serverPort = 12000</pre>                                      |
| create TCP welcoming socket  | → | <pre>serverSocket = socket(AF_INET,SOCK_STREAM)</pre>              |
|  |   | <pre>serverSocket.bind(('',serverPort))</pre>                      |
| server begins listening for incoming TCP requests                            | → | <pre>serverSocket.listen(1)</pre>                                  |
|  |   | <pre>print('The server is ready to receive')</pre>                 |
| loop forever   | → | <pre>while True:</pre>   |
| server waits on accept() for incoming requests, new socket created on return | → | <pre>    connectionSocket, addr = serverSocket.accept()</pre>      |
|  |   | <pre>    sentence = connectionSocket.recv(1024).decode()</pre>     |
| read bytes from socket (but not address as in UDP)                           | → | <pre>    capitalizedSentence = sentence.upper()</pre>              |
|  |   | <pre>    connectionSocket.send(capitalizedSentence.encode())</pre> |
| close connection to this client (but <i>not</i> welcoming socket)            | → | <pre>    connectionSocket.close()</pre>                            |

# 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

# Chapter 2: Summary

Most importantly: learned about *protocols*!

## Important themes:

- typical client/server request/reply message exchange
- centralized vs. decentralized
- stateless vs. stateful
- scalability
- reliable vs. unreliable message transfer
- “complexity at network edge”



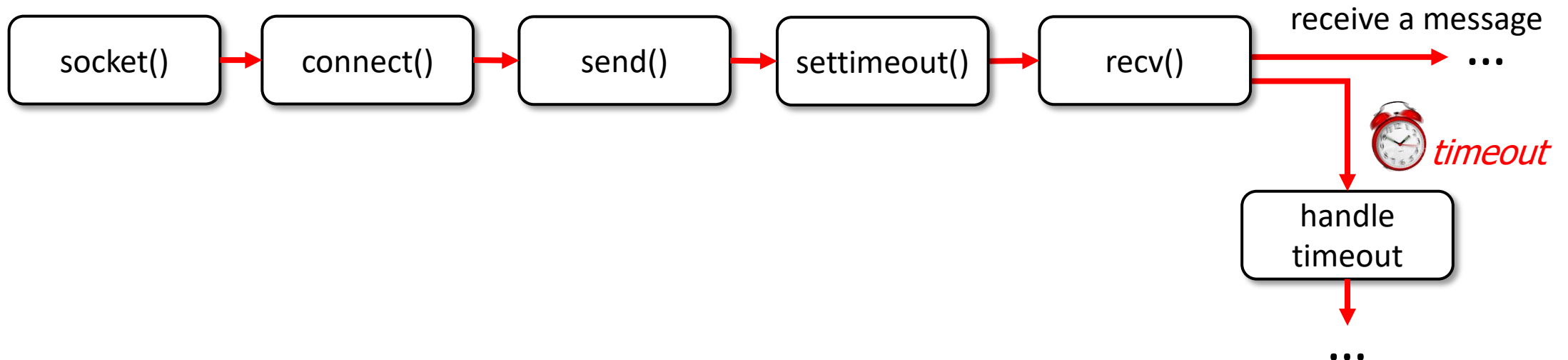
# Additional Chapter 2 slides

**JFK note:** the timeout slides are important IMHO if one is doing a programming assignment (especially an RDT programming assignment in Chapter 3), since students will need to use timers in their code, and the TRY/EXCEPT is really the easiest way to do this. I introduce this here in Chapter 2 with the socket programming assignment since it teaches something (how to handle exceptions/timeouts), and lets students learn/practice that before doing the RDT programming assignment, which is harder

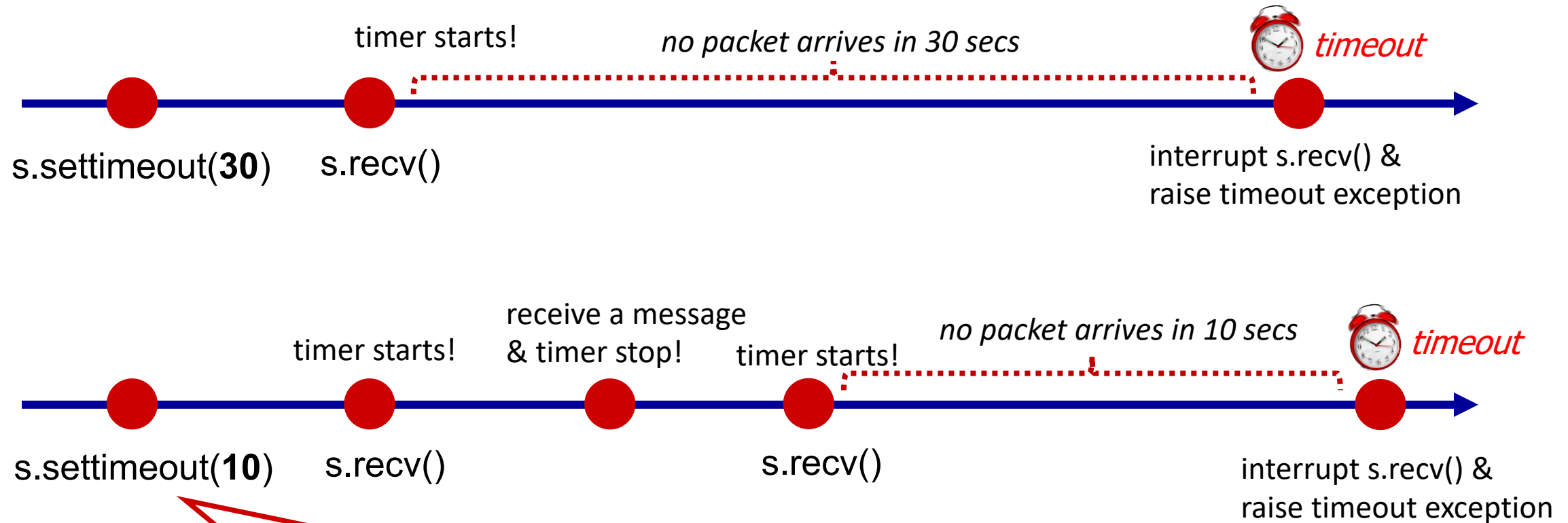


# Socket programming: waiting for multiple events

- sometimes a program must **wait for one of several events** to happen, e.g.,:
  - wait for either (i) a reply from another end of the socket, or (ii) timeout: **timer**
  - wait for replies from several different open sockets: **select()**, **multithreading**
- timeouts are used extensively in networking
- using timeouts with Python socket:



# How Python `socket.settimeout()` works?



Set a timeout on all future socket operations of that specific socket!

# Python try-except block

Execute a block of code, and handle “exceptions” that may occur when executing that block of code

try:

<do something>

{ Executing this **try code block** may cause exception(s) to catch. If an exception is raised, execution jumps from jumps directly into **except code block**

except <exception>:

<handle the exception>

{ this **except code block** is only executed *if an <exception> occurred* in the **try code block** (note: except block is *required* with a try block)

# Socket programming: socket timeouts

## Toy Example:



- A shepherd boy tends his master's sheep.
- If he sees a wolf, he can send a message to villagers for help using a TCP socket.
- The boy found it fun to connect to the server without sending any messages. But the villagers don't think so.
- And they decided that if the boy connects to the server and doesn't send the wolf location **within 10 seconds for three times**, they will **stop listening** to him forever and ever.

set a 10-seconds timeout on  
all future socket operations

timer starts when `recv()` is called and will  
raise timeout exception if there is no  
message within 10 seconds.

catch socket timeout exception

## *Python TCP Server (Villagers)*

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET, SOCK_STREAM)
serverSocket.bind(('', serverPort))
serverSocket.listen(1)
counter = 0
while counter < 3:
    connectionSocket, addr = serverSocket.accept()
    connectionSocket.settimeout(10)
    try:
        wolf_location = connectionSocket.recv(1024).decode()
        send_hunter(wolf_location) # a villager function
        connectionSocket.send('hunter sent')
    except timeout:
        counter += 1
    connectionSocket.close()
```

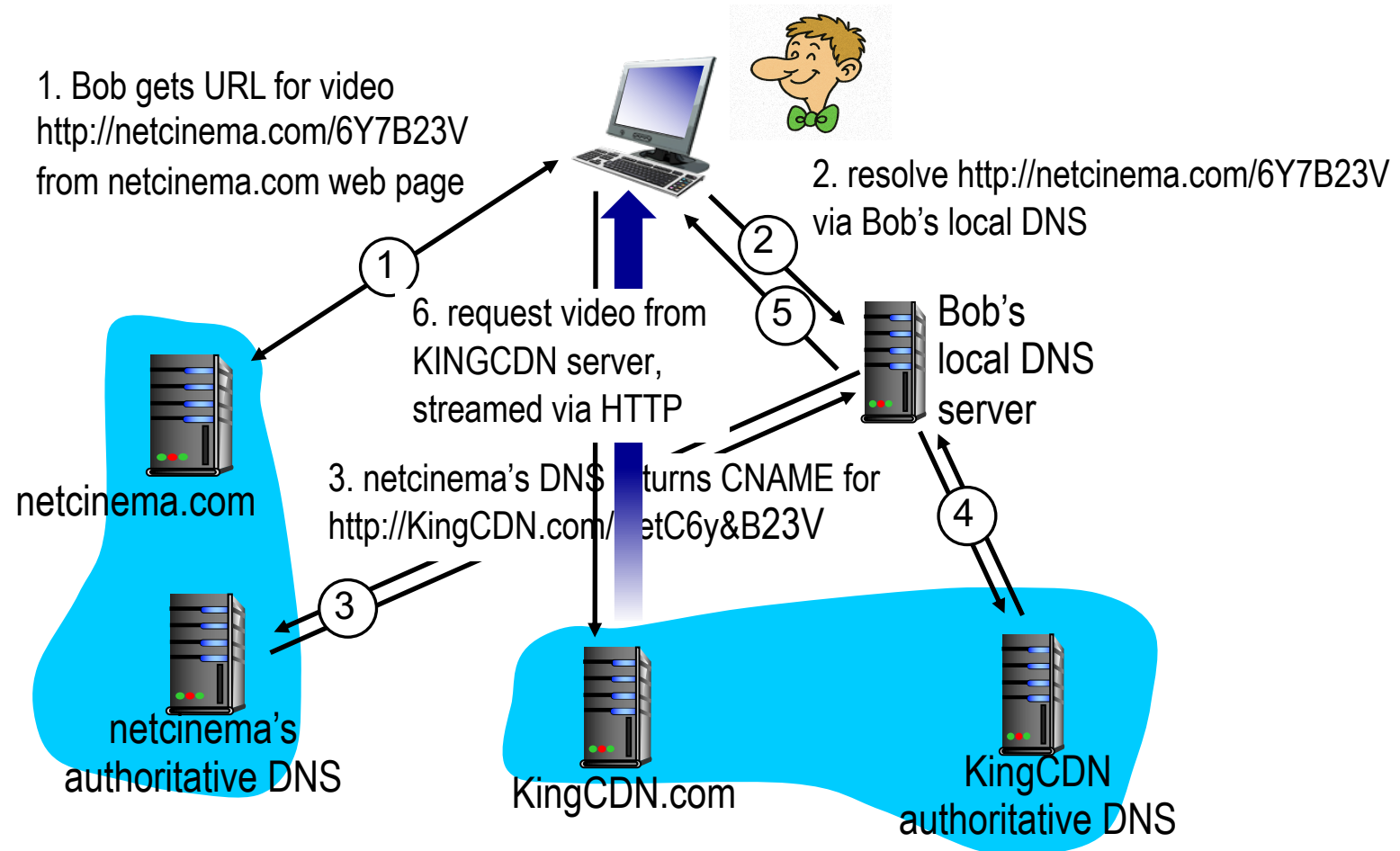
# Sample SMTP interaction

```
S: 220 hamburger.edu
C: HELO crepes.fr
S: 250 Hello crepes.fr, pleased to meet you
C: MAIL FROM: <alice@crepes.fr>
S: 250 alice@crepes.fr... Sender ok
C: RCPT TO: <bob@hamburger.edu>
S: 250 bob@hamburger.edu ... Recipient ok
C: DATA
S: 354 Enter mail, end with "." on a line by itself
C: Do you like ketchup?
C: How about pickles?
C: .
S: 250 Message accepted for delivery
C: QUIT
S: 221 hamburger.edu closing connection
```

# CDN content access: a closer look

Bob (client) requests video `http://netcinema.com/6Y7B23V`

- video stored in CDN at `http://KingCDN.com/NetC6y&B23V`



# Case study: Netflix

