

Chapter 2

Application Layer

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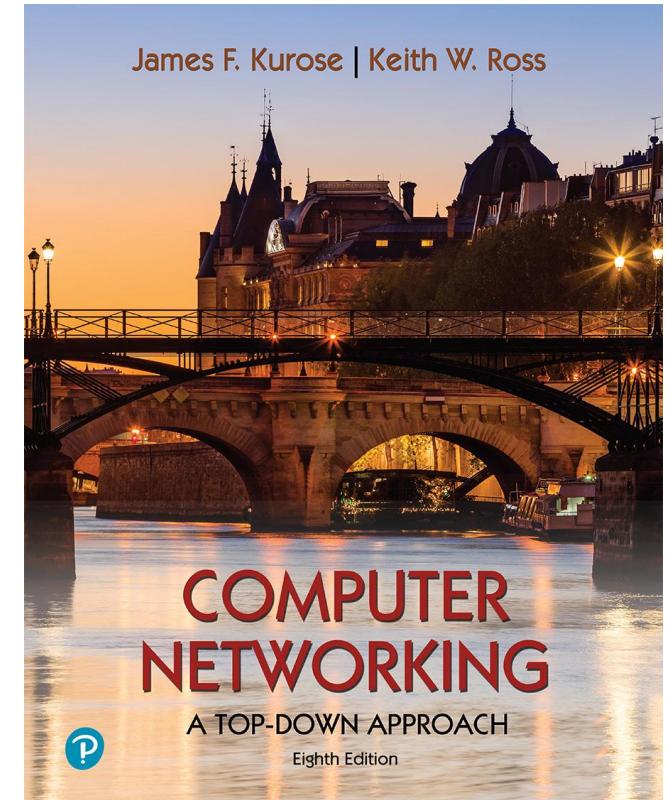
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*Computer Networking: A
Top-Down Approach*
8th edition n
Jim Kurose, Keith Ross
Pearson, 2020

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



Some network apps

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

Q: your favorites?

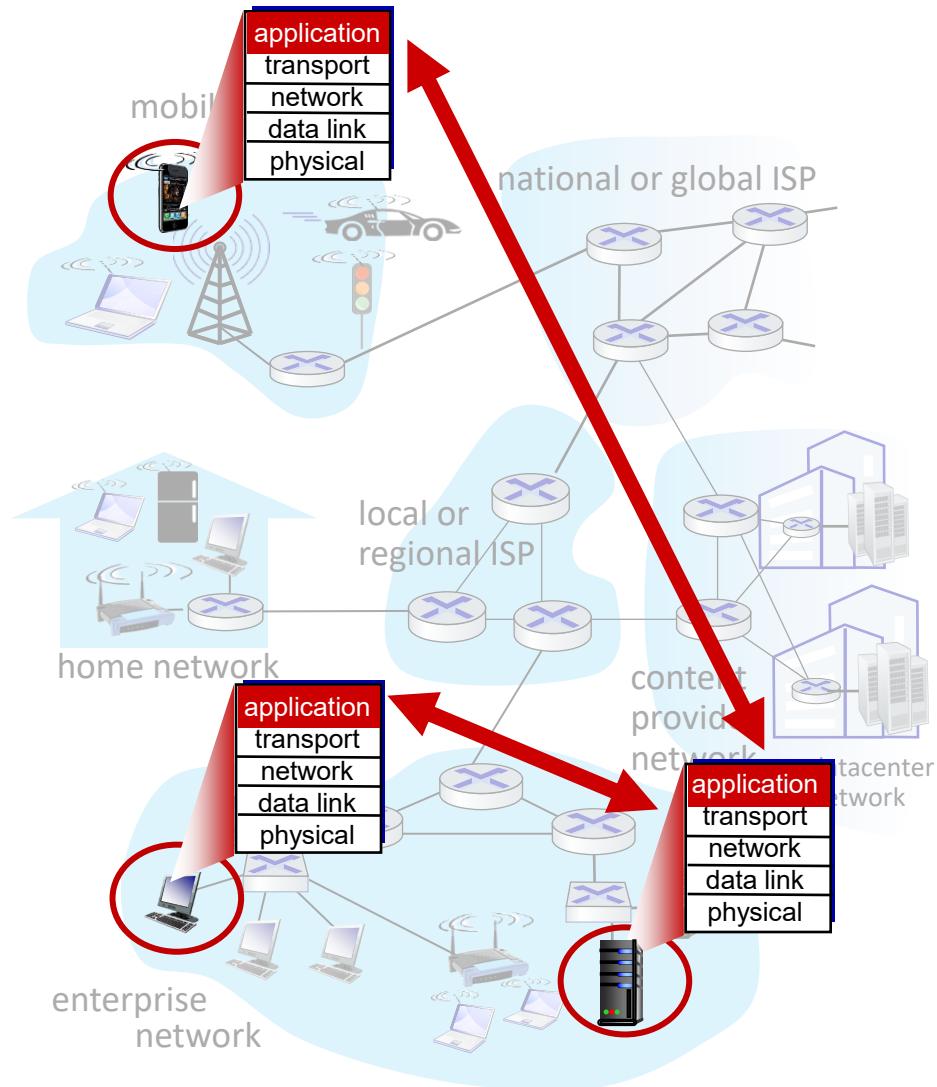
Creating a network app

write programs that:

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

no need to write software for
network-core devices

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



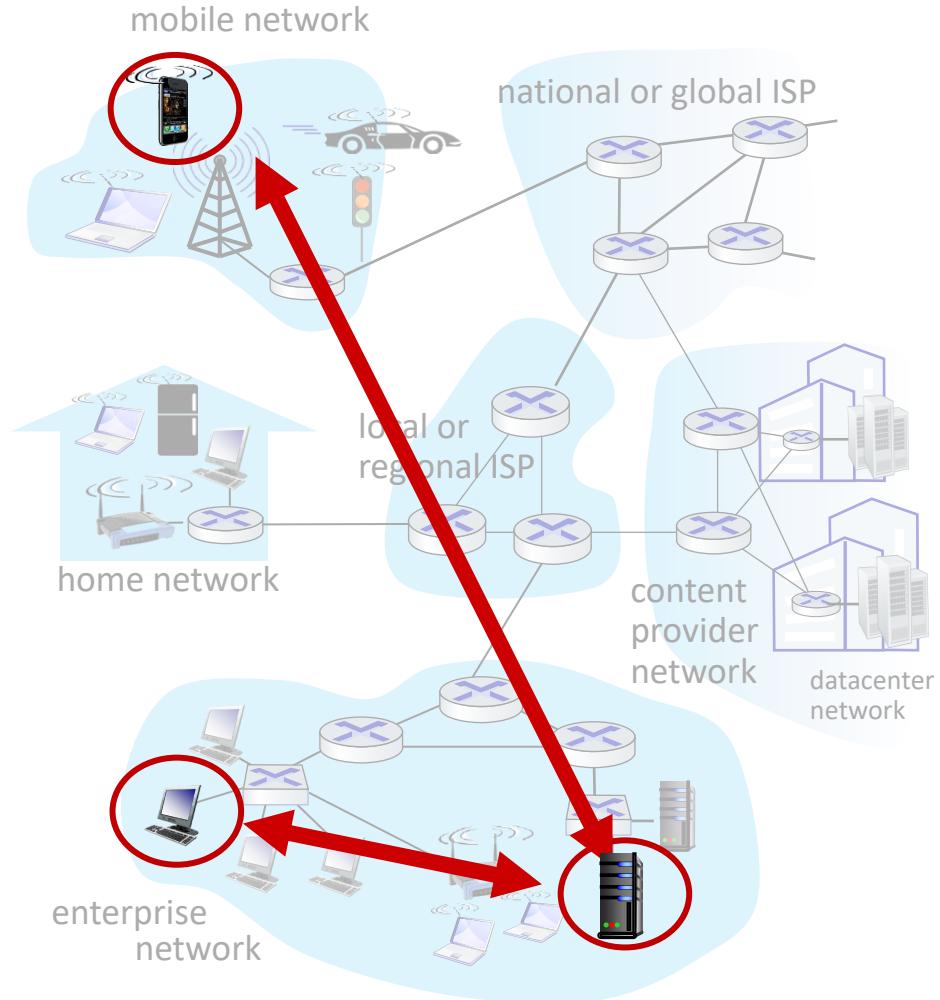
Client-server paradigm

server:

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

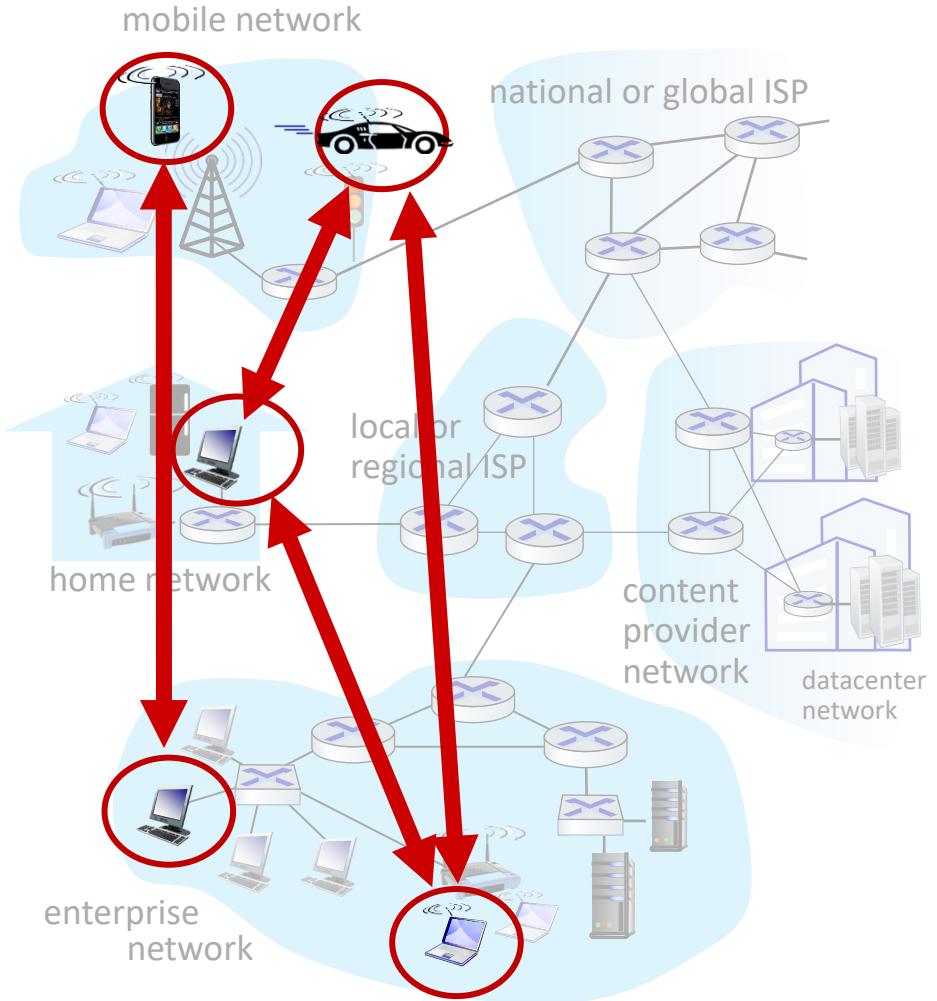
clients:

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



Peer-peer architecture

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



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

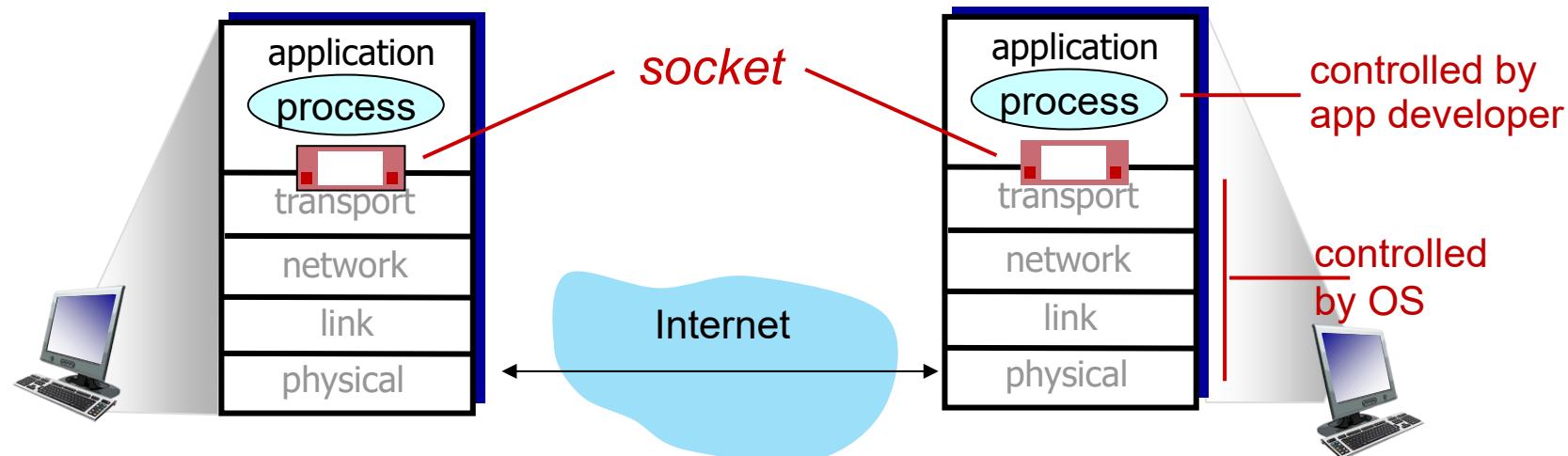
client process: process that initiates communication

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

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

timing

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

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 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

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
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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 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

Close connection after transfer

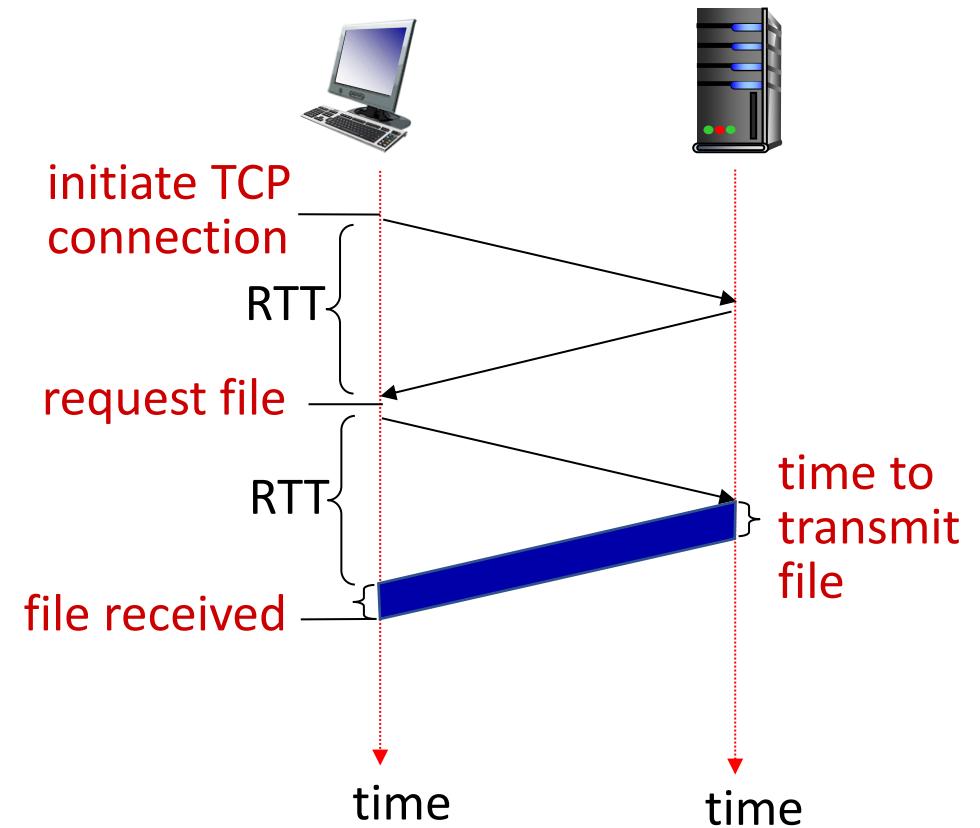
At most one object sent over
TCP connection

Persistent HTTP

Keep connection open

Multiple objects can be sent
over *single* TCP connection

Non-persistent HTTP: response 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)

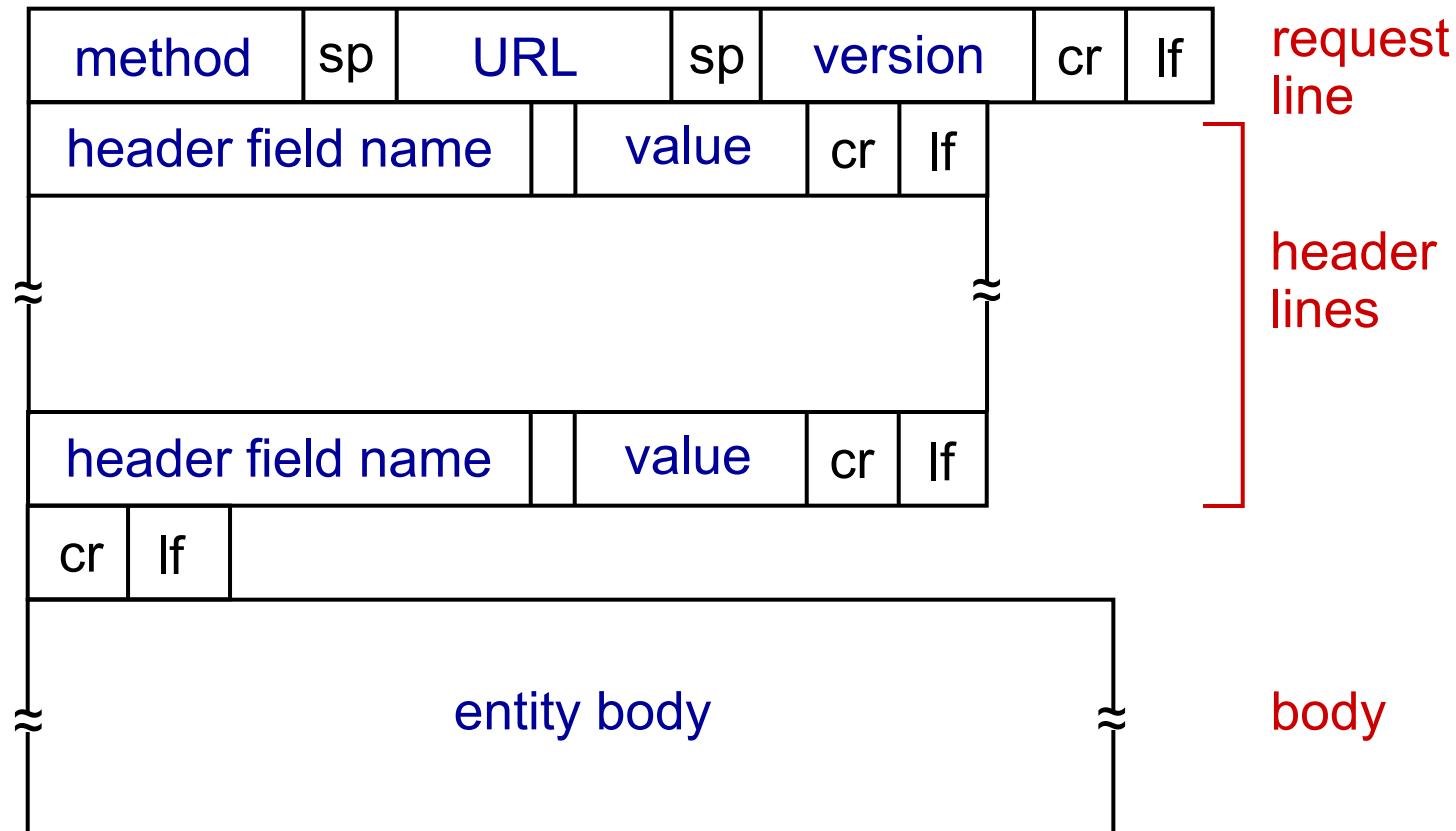
request line (GET, POST,
HEAD commands) →

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 request message: general format



HTTP response message

status line (protocol → **HTTP/1.1 200 OK**
status code status phrase)

HTTP response status codes

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

200 OK

- request succeeded, requested object later in this message

301 Moved Permanently

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

400 Bad Request

- request msg not understood by server

404 Not Found

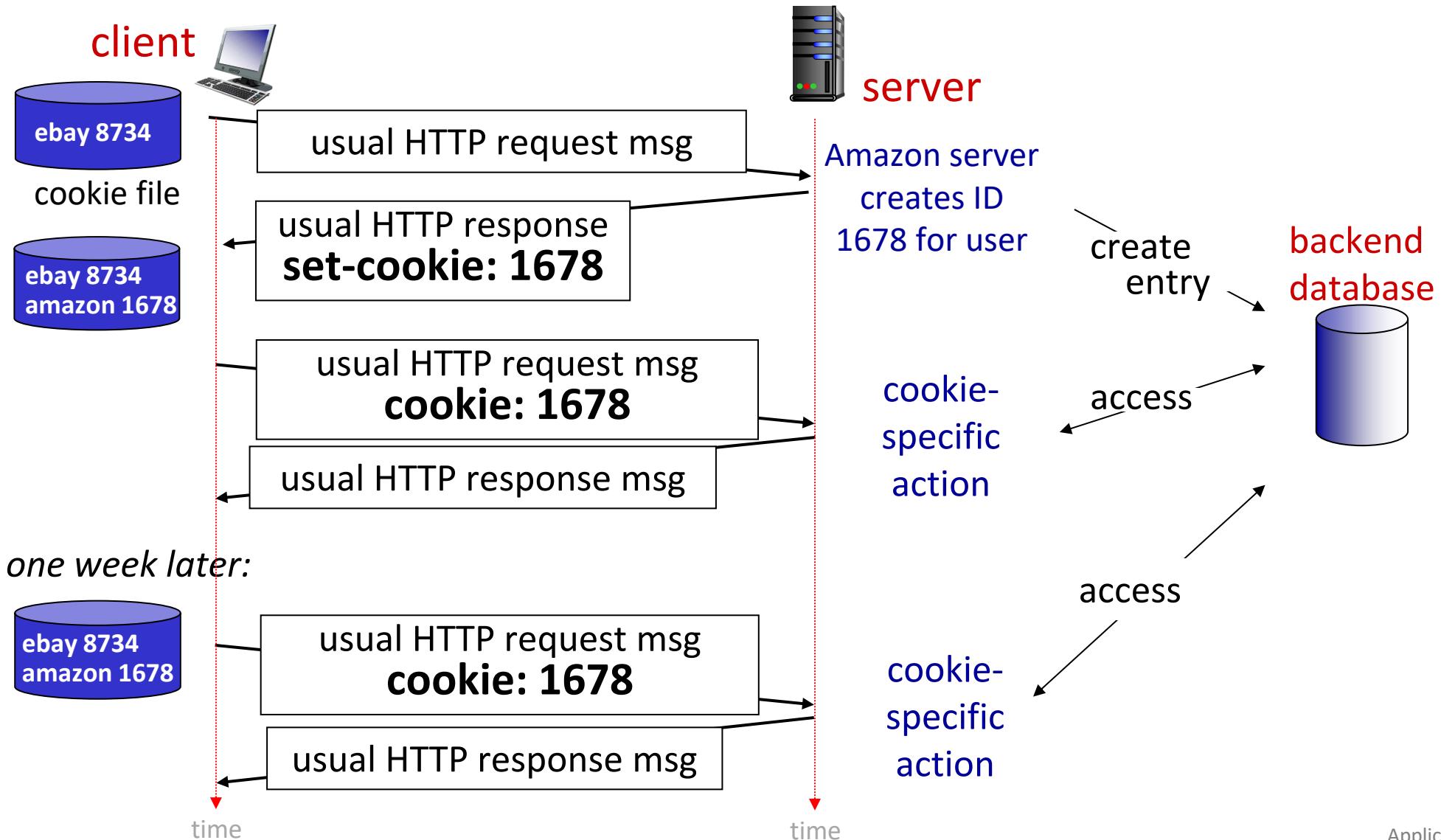
- requested document not found on this server

505 HTTP Version Not Supported

Maintaining user/server state: cookies

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

Maintaining user/server state: cookies



HTTP cookies: comments

What cookies can be used for:

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

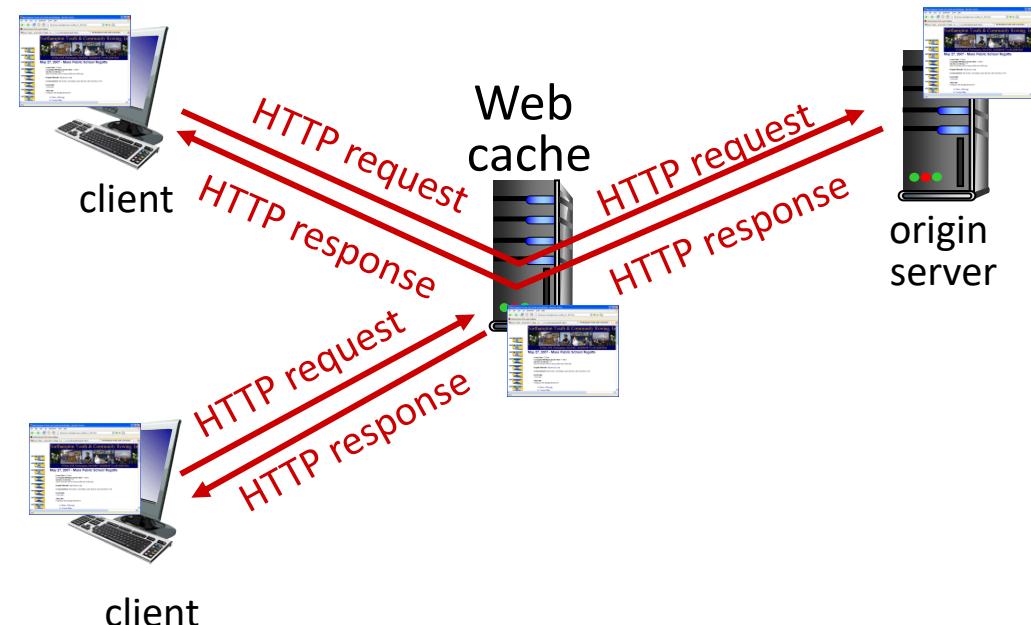
aside
cookies and privacy:

- 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

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:

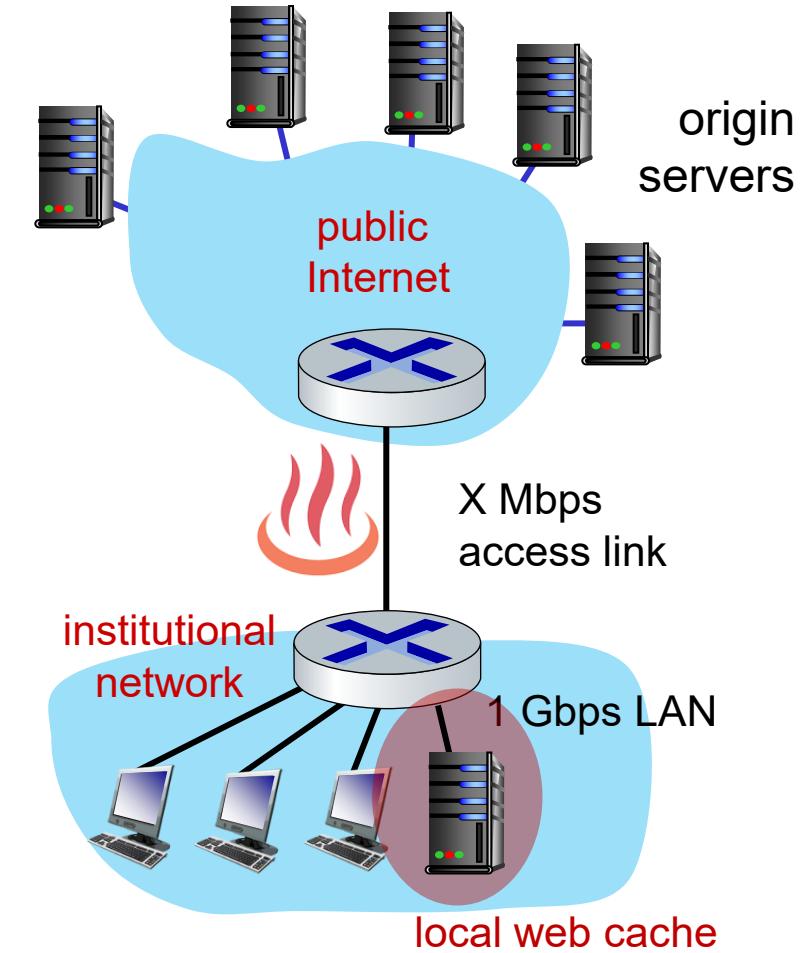
```
Cache-Control: max-age=<seconds>
```

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

Caching example

Why Web caching?

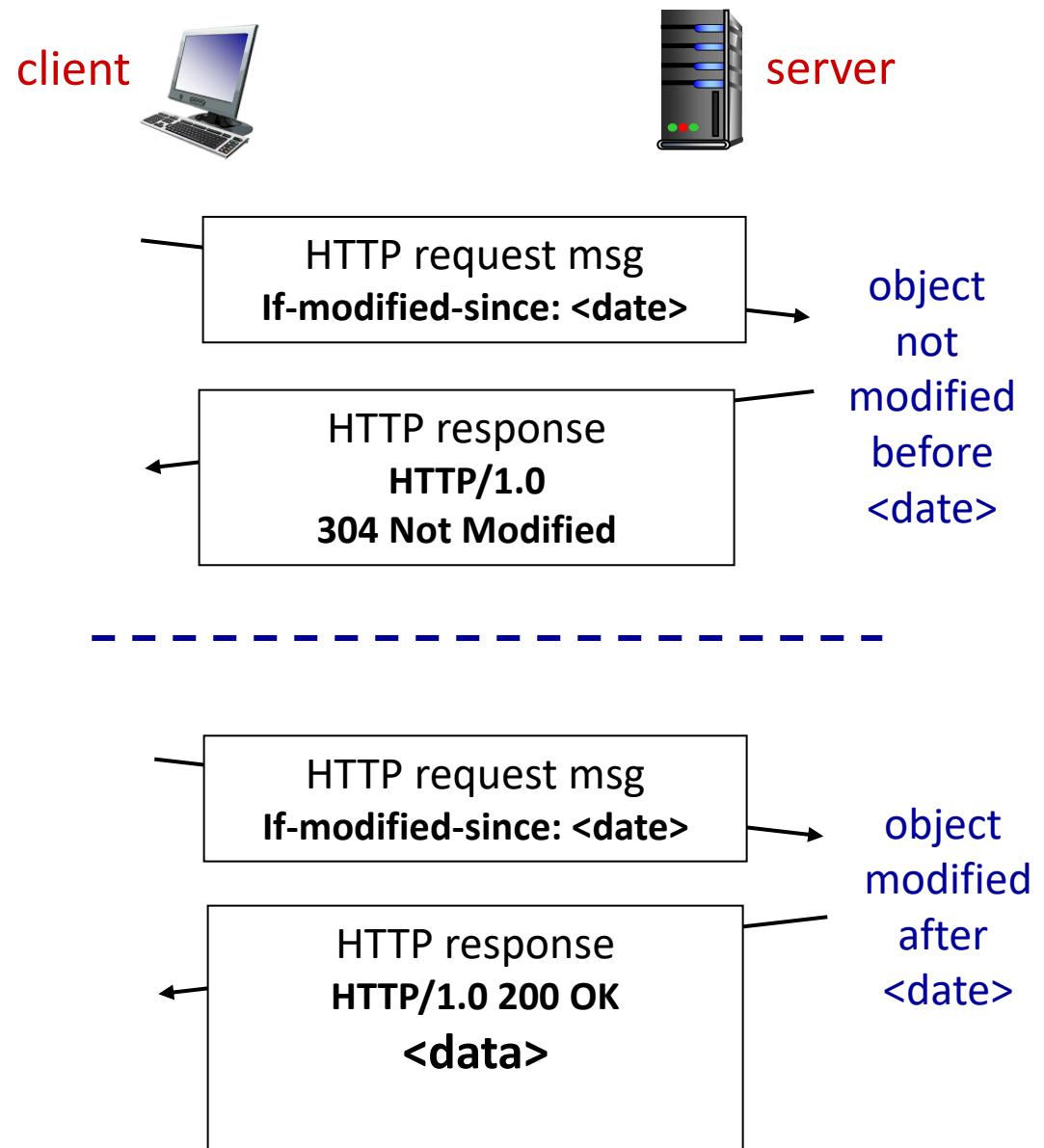
- reduce response time for client request
 - cache is closer to client
- reduce traffic on an institution's access link (e.g., reduce load and queuing delays + reduce bandwidth costs + delay link upgrades)
- Internet is dense with caches
 - enables “poor” content providers to more effectively deliver content



Conditional GET

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

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



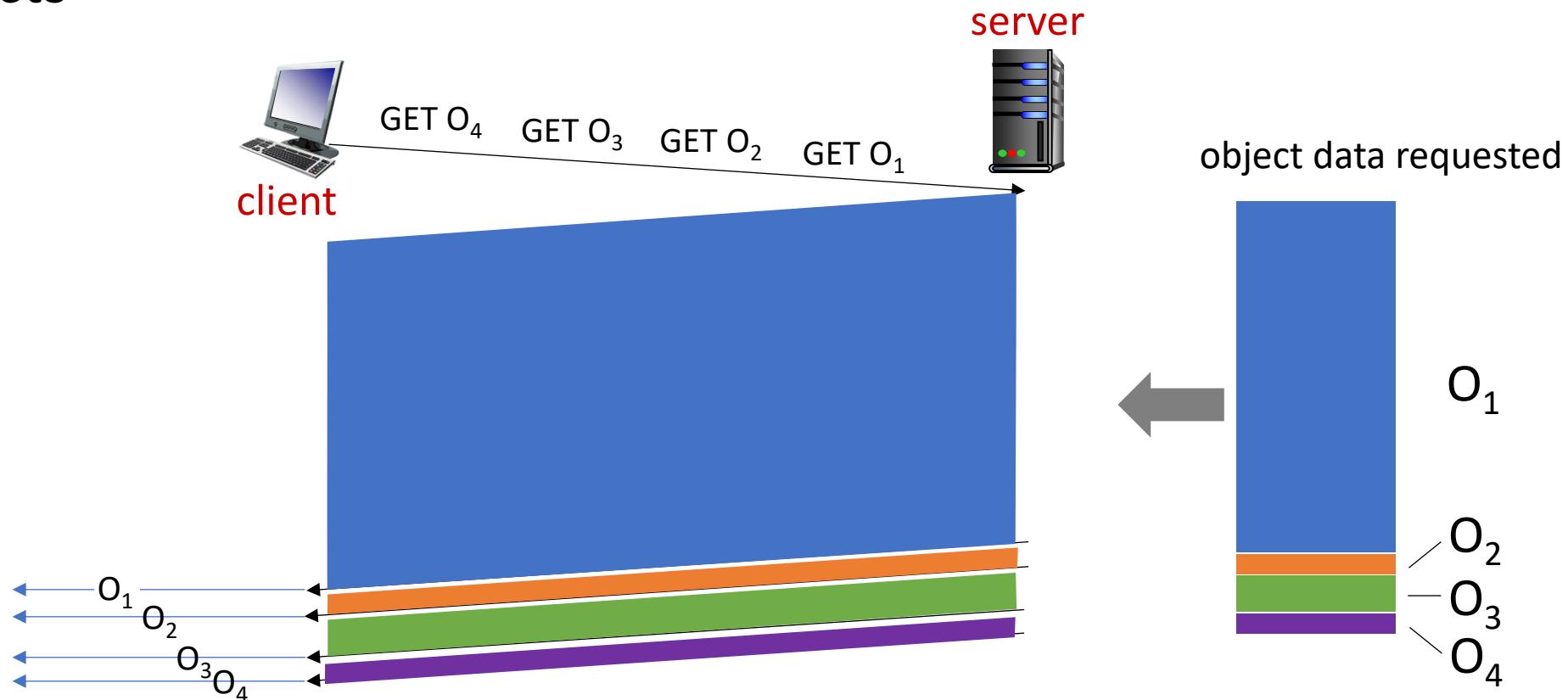
HTTP/2

Key goal: decreased delay in multi-object HTTP requests

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

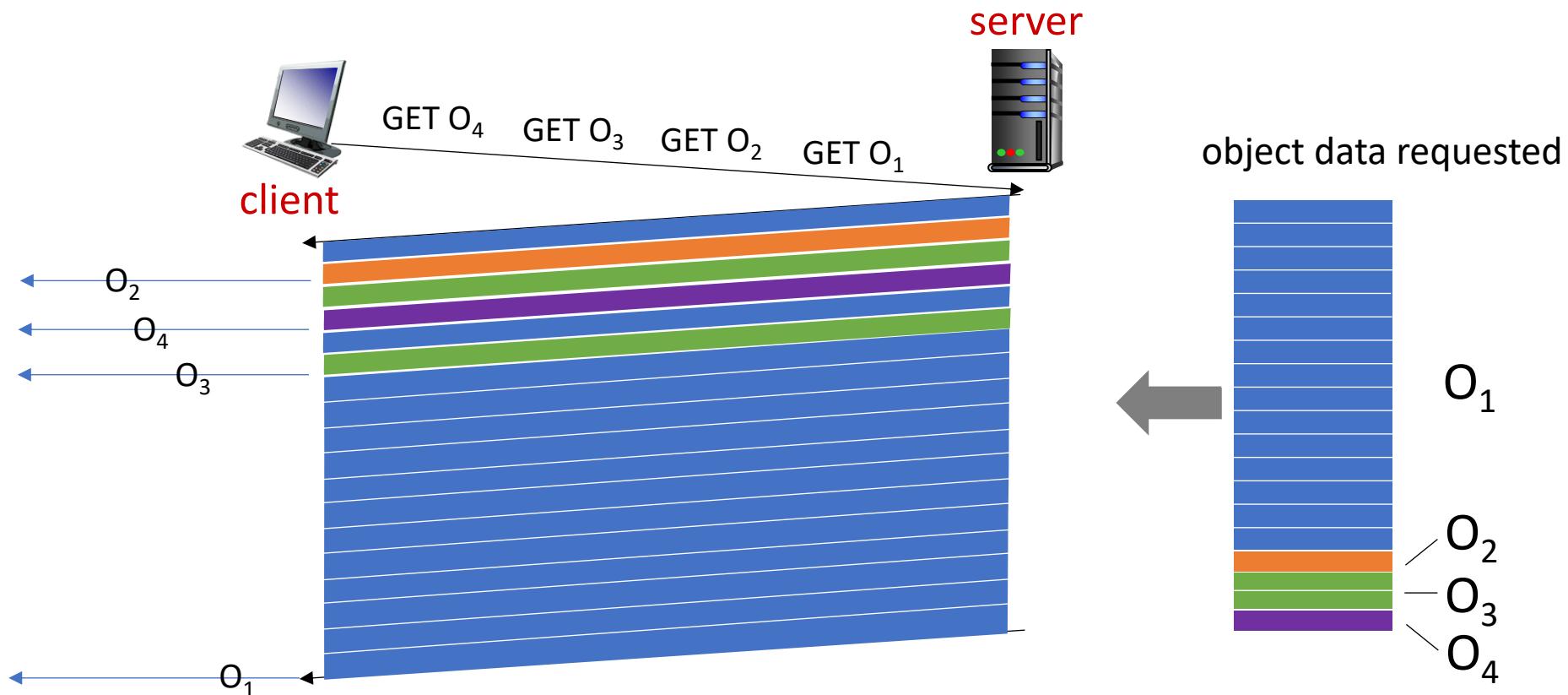
- methods, status codes, most header fields unchanged from HTTP 1.1
- transmission order of requested objects based on client-specified object priority (not necessarily FCFS)
- *push* unrequested objects to client
- divide objects into frames, schedule frames to mitigate HOL blocking

HTTP 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



O₂, O₃, O₄ delivered quickly, O₁ 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

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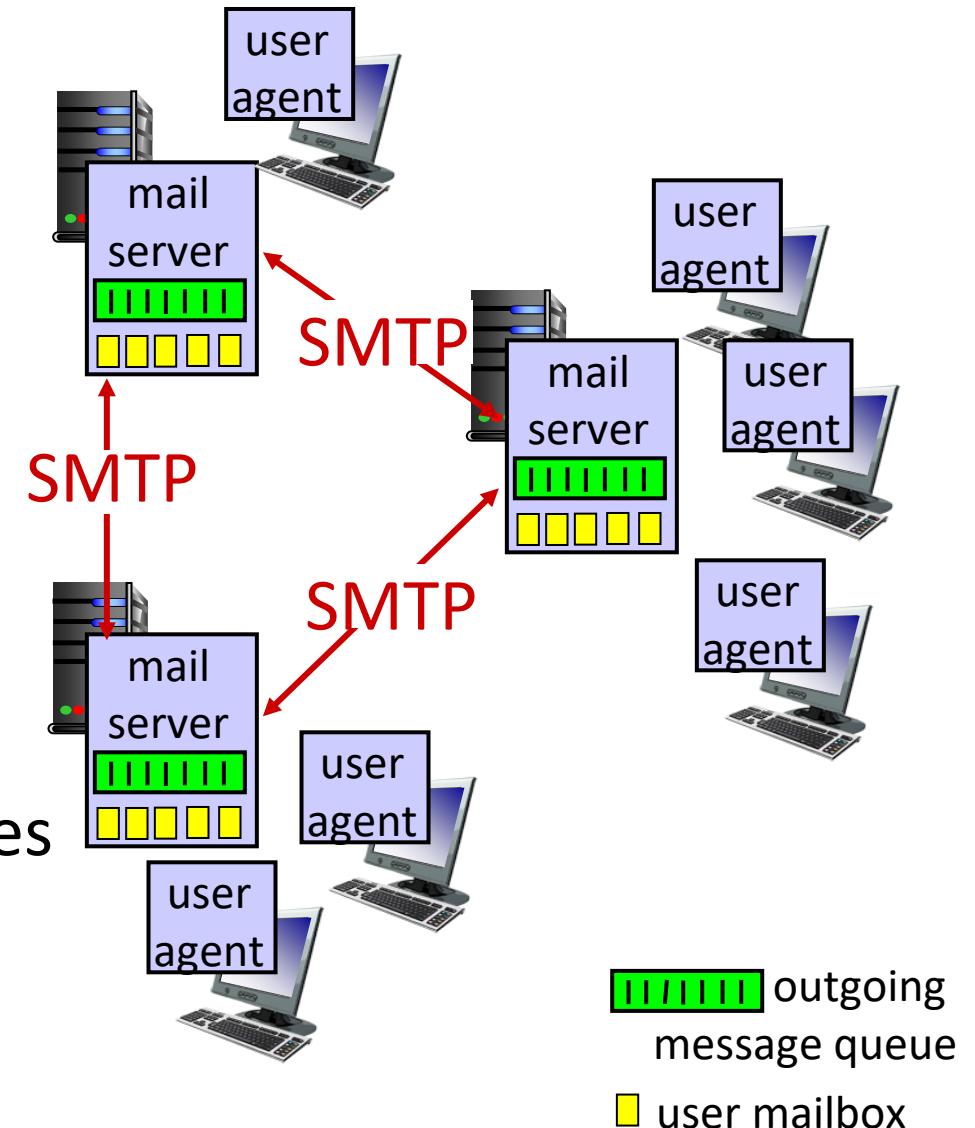
E-mail

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



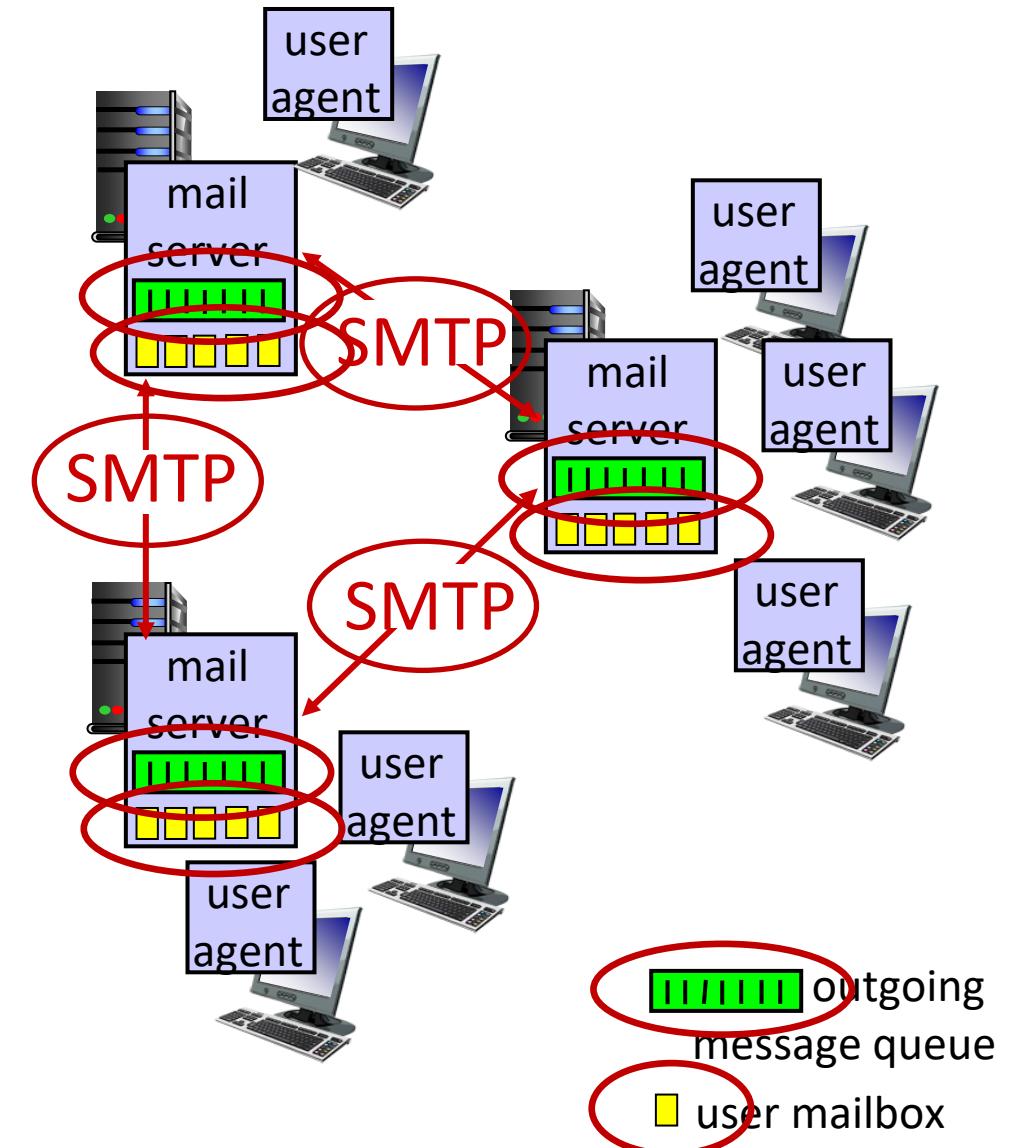
E-mail: mail servers

mail servers:

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

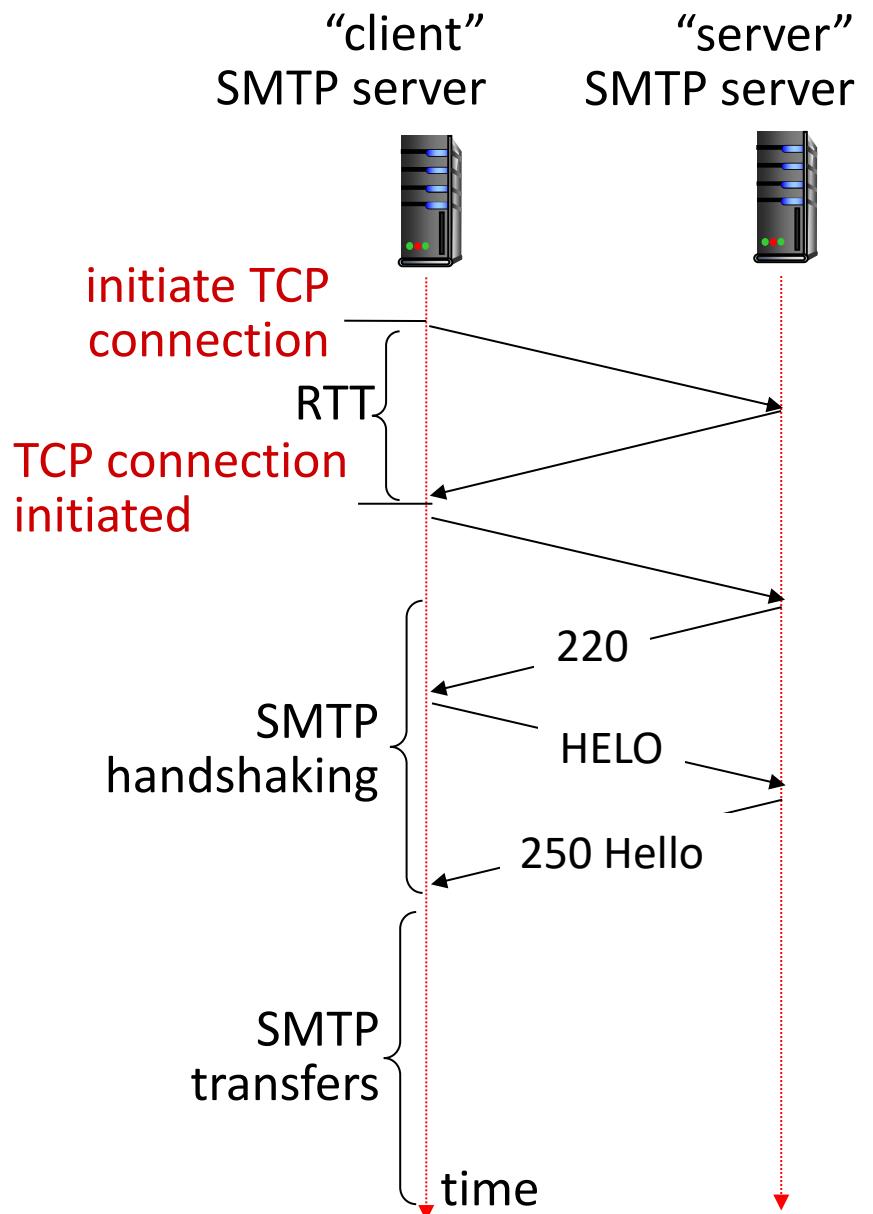
SMTP protocol between mail servers to send email messages

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

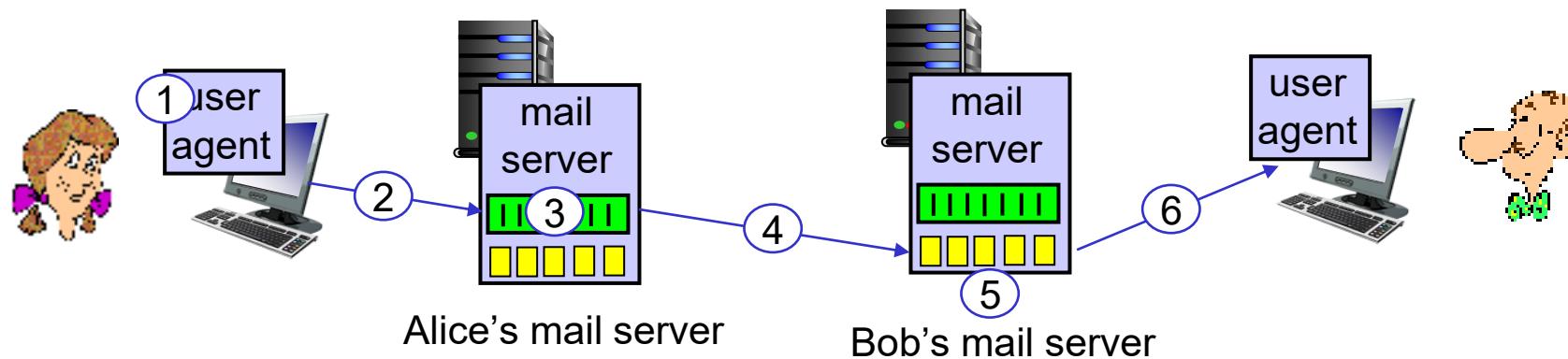


SMTP RFC (5321)

- 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



Sample SMTP interaction

S: 220 hamburger.edu

SMTP: observations

comparison with HTTP:

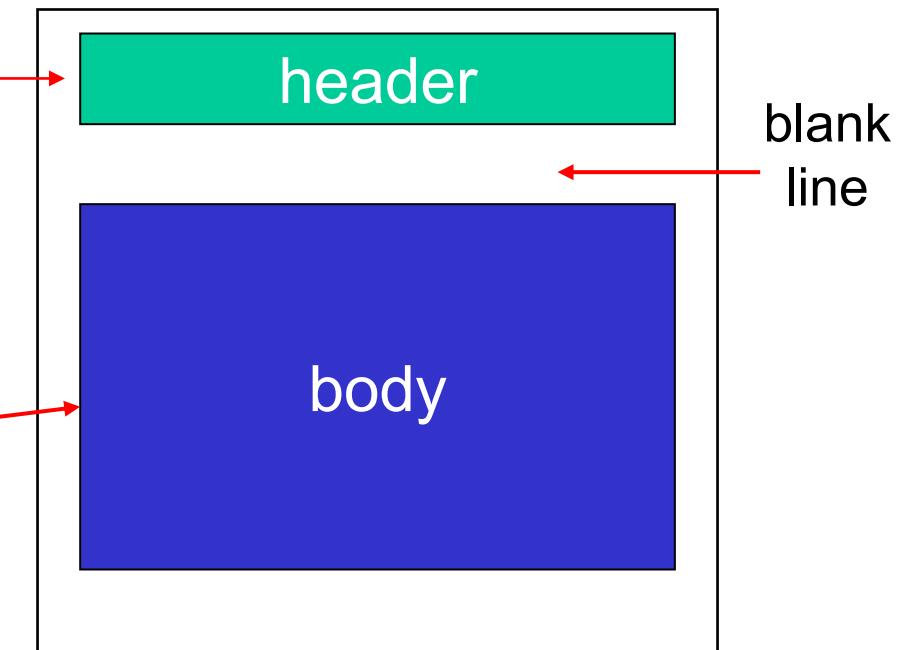
- HTTP: client pull
- SMTP: client push
- both have ASCII command/response interaction, status codes
- HTTP: each object encapsulated in its own response message
- SMTP: multiple objects sent in multipart message
- SMTP uses persistent connections
- SMTP requires message (header & body) to be in 7-bit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

Mail message format

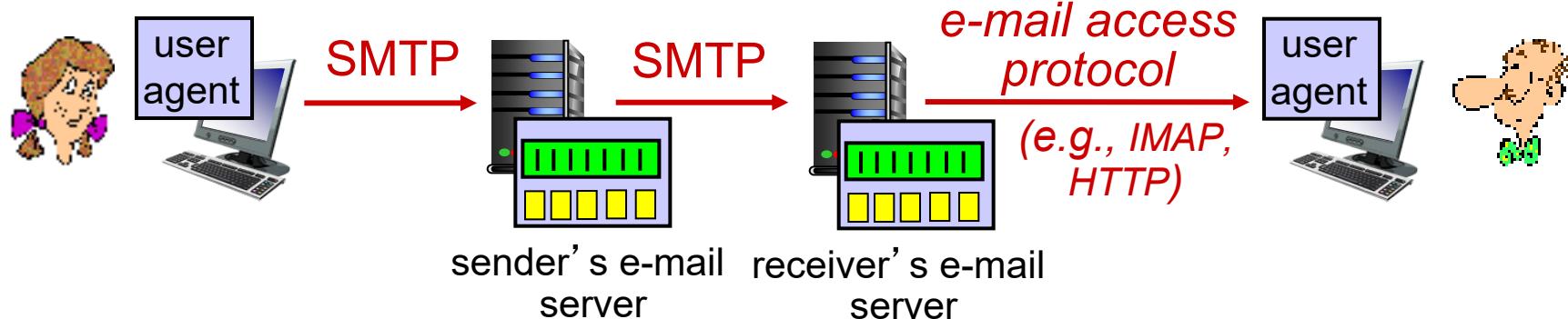
SMTP: protocol for exchanging e-mail messages, defined in RFC 5321
(like RFC 7231 defines HTTP)

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 STMP (to send), IMAP (or POP) to retrieve e-mail messages

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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!

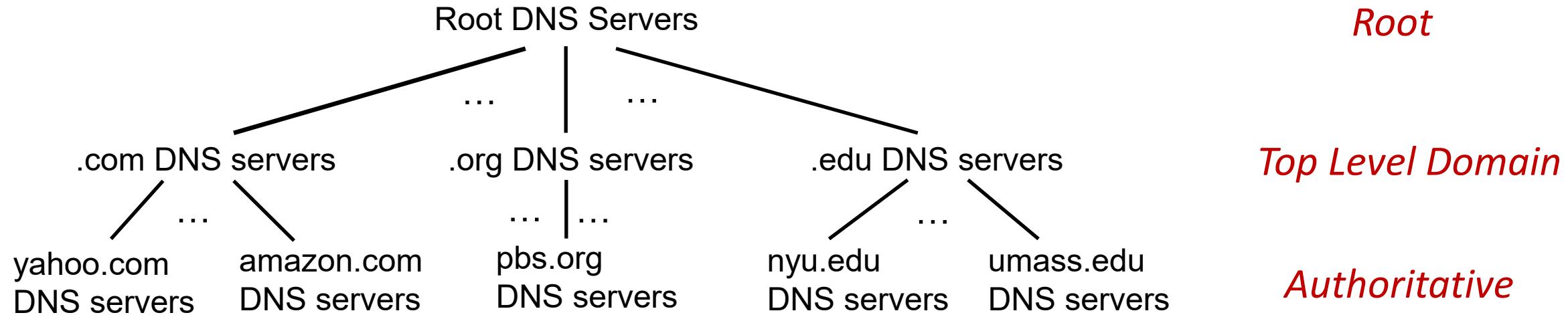
organizationally, physically decentralized:

- 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

Local DNS name servers

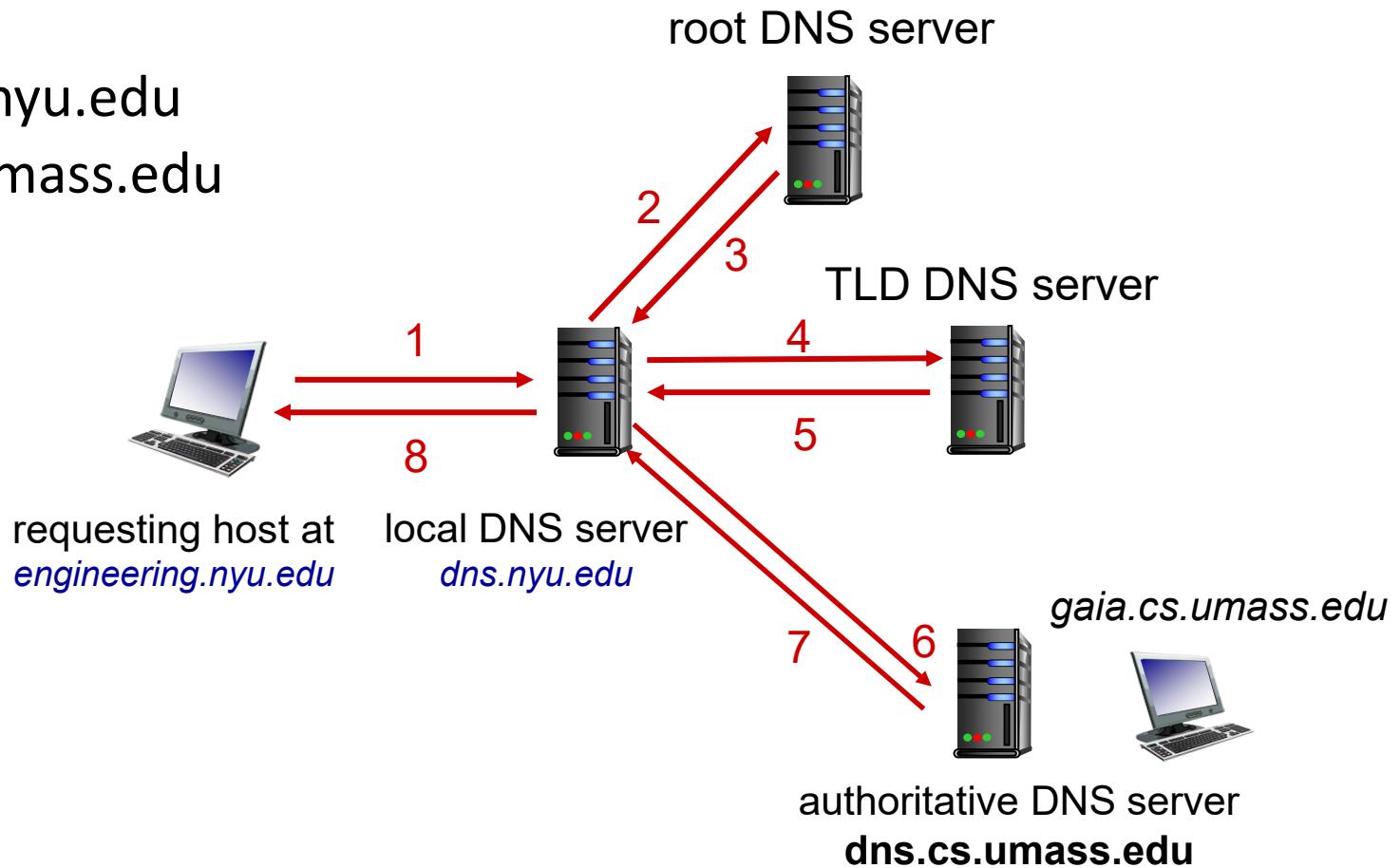
- when host makes DNS query, it is sent to its *local* DNS server
 - Local DNS server returns reply, answering:
 - from its local cache of recent name-to-address translation pairs (possibly out of date!)
 - forwarding request into DNS hierarchy for resolution
 - each ISP has local DNS name server; to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

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`

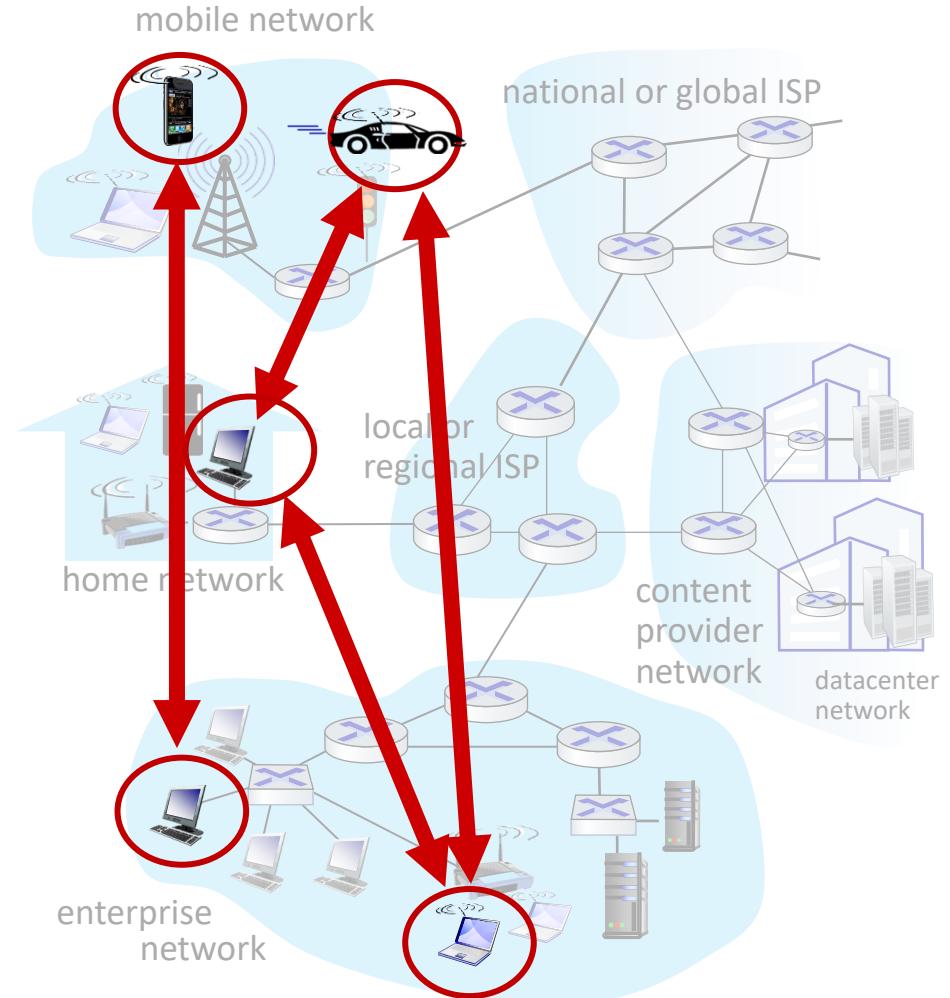
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Peer-to-peer (P2P) architecture

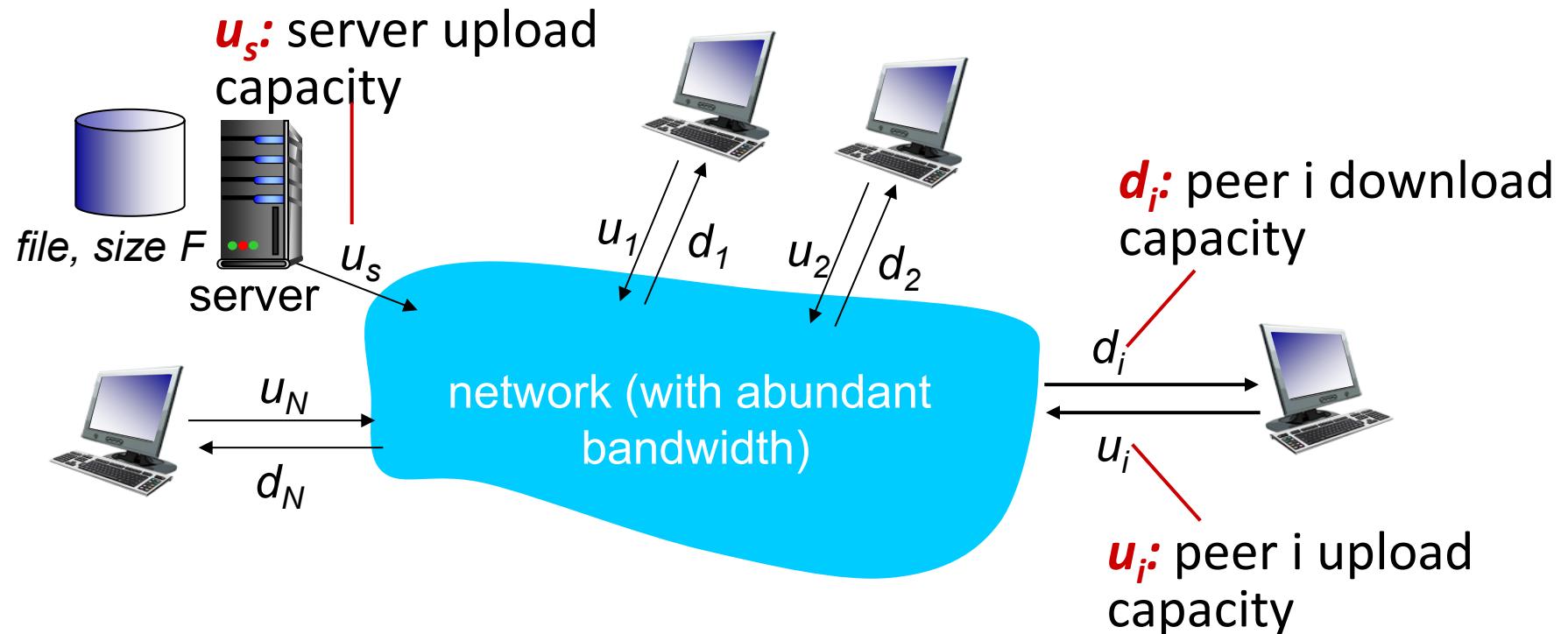
- no always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
 - *self scalability* – new peers bring new service capacity, and new service demands
- peers are intermittently connected and change IP addresses
 - complex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



File distribution: client-server vs P2P

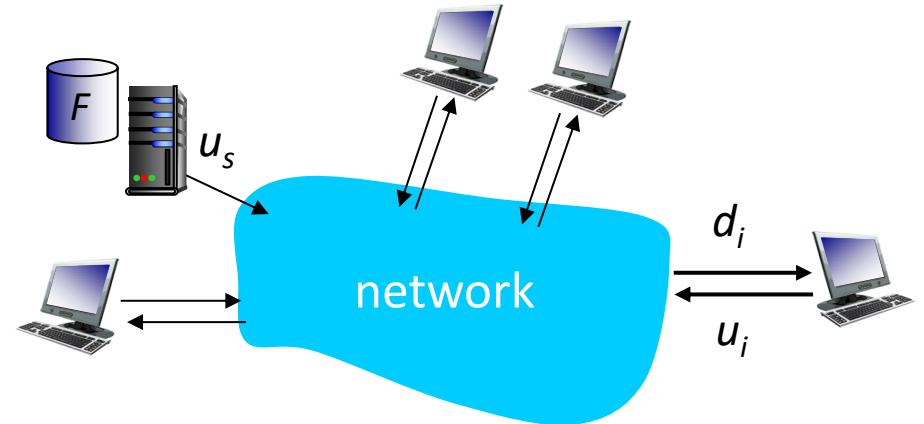
Q: how much time to distribute file (size F) from one server to N peers?

- peer upload/download capacity is limited resource



File distribution time: client-server

- *server transmission*: must sequentially send (upload) N file copies:
 - time to send one copy: F/u_s
 - time to send N copies: NF/u_s
- *client*: each client must download file copy
 - d_{min} = min client download rate
 - min client download time: F/d_{min}



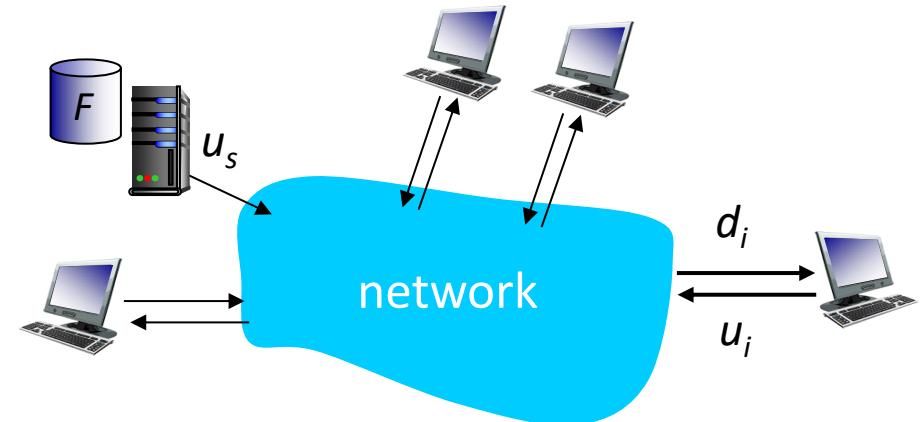
*time to distribute F
to N clients using
client-server approach*

$$D_{c-s} \geq \max\{NF/u_s, F/d_{min}\}$$

increases linearly in N

File distribution time: P2P

- *server transmission*: must upload at least one copy:
 - time to send one copy: F/u_s
- *client*: each client must download file copy
 - min client download time: F/d_{min}
- *clients*: as aggregate must download NF bits
 - max upload rate (limiting max download rate) is $u_s + \sum u_i$



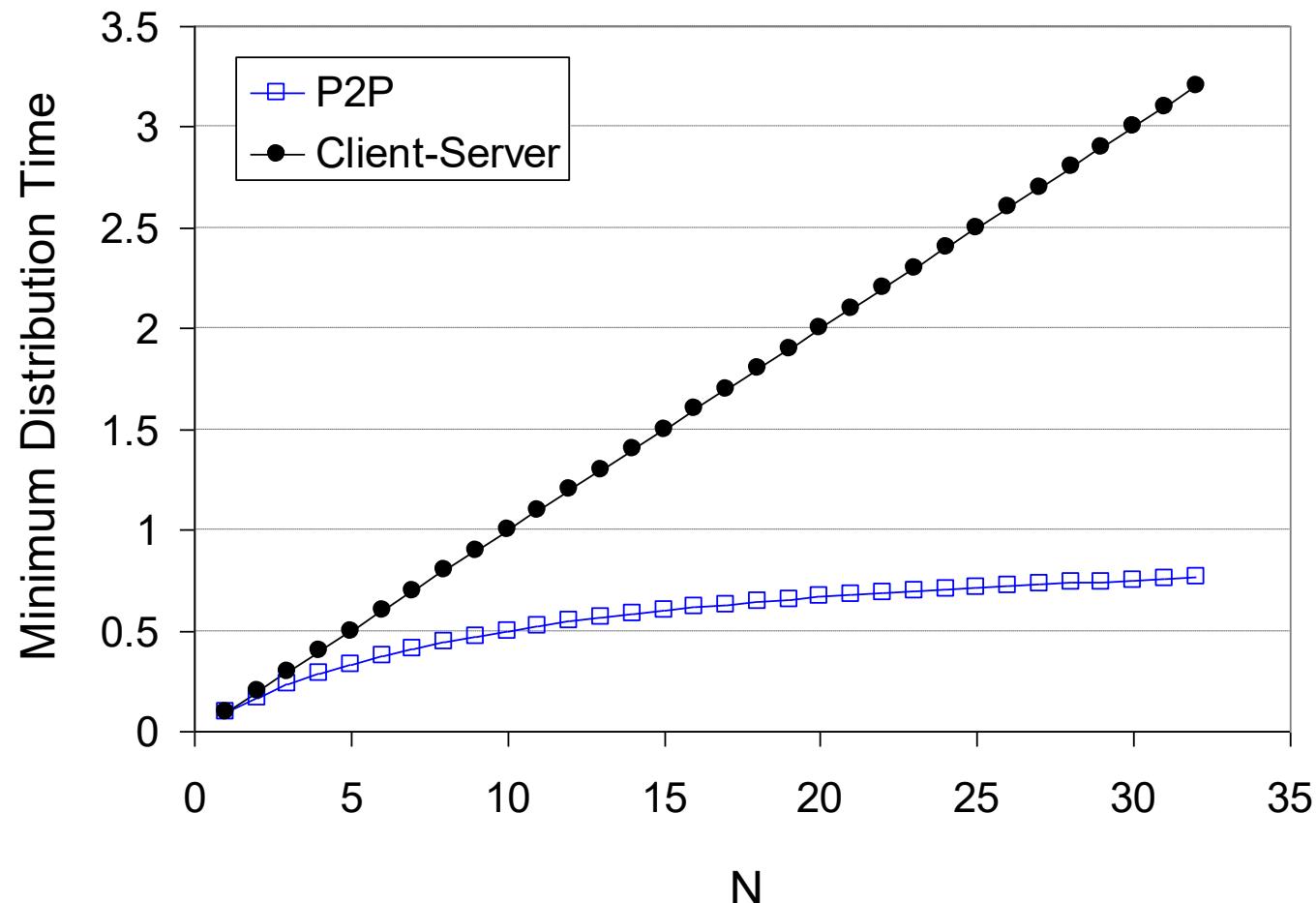
time to distribute F
to N clients using
P2P approach

$$D_{P2P} \geq \max\{F/u_s, F/d_{min}, NF/(u_s + \sum u_i)\}$$

increases linearly in N ...
... but so does this, as each peer brings service capacity

Client-server vs. P2P: example

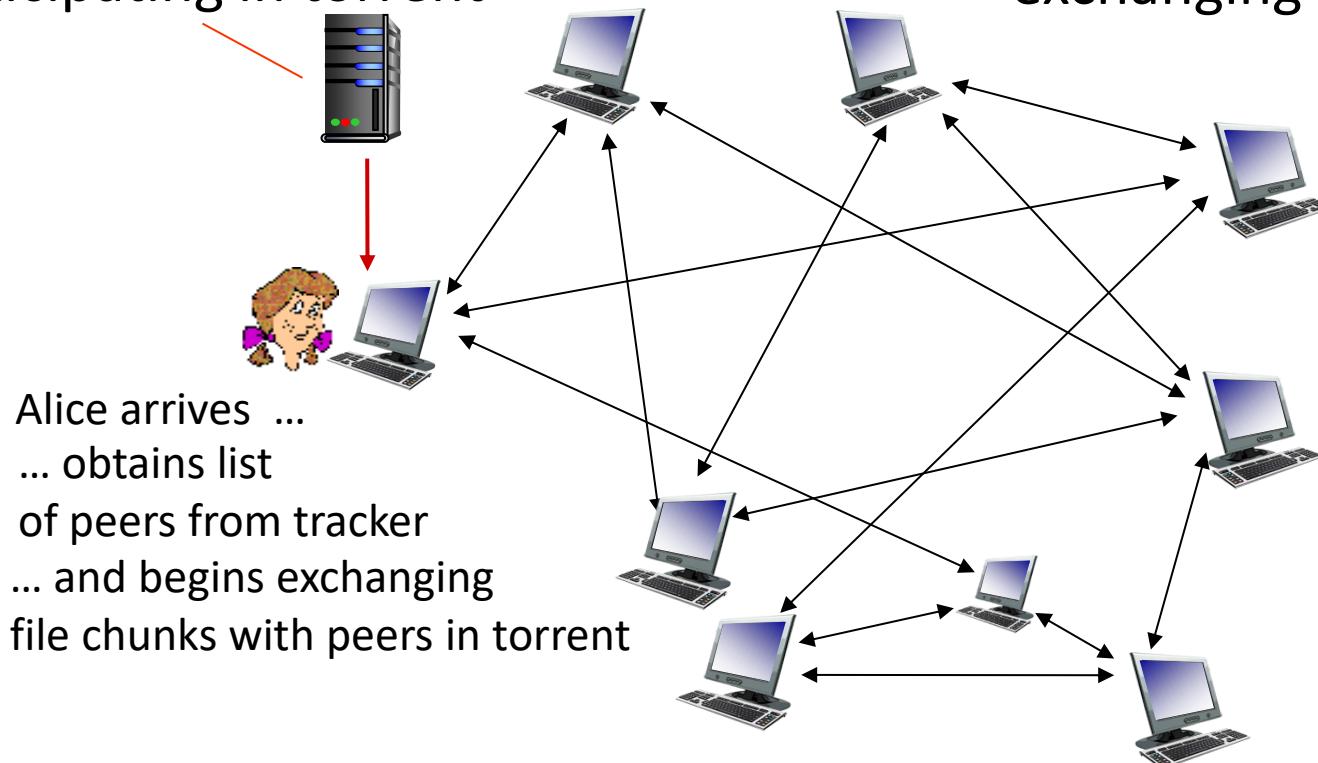
client upload rate = u , $F/u = 1$ hour, $u_s = 10u$, $d_{min} \geq u_s$



P2P file distribution: BitTorrent

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

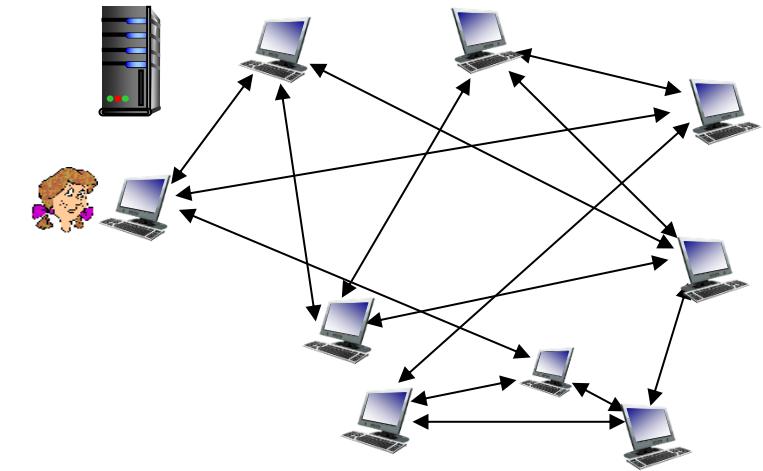
tracker: tracks peers
participating in torrent



torrent: group of peers
exchanging chunks of a file

P2P file distribution: BitTorrent

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



BitTorrent: requesting, sending file chunks

Requesting chunks:

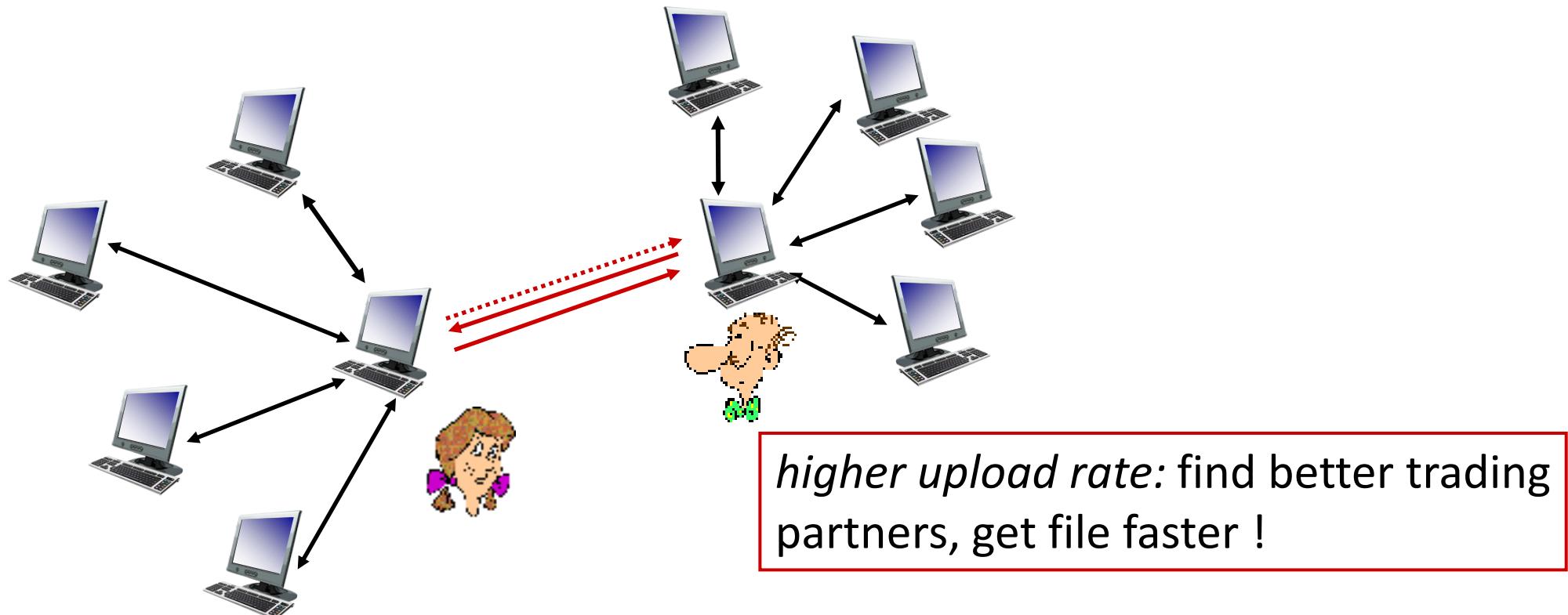
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

Sending chunks: tit-for-tat

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

BitTorrent: tit-for-tat

- (1) Alice “optimistically unchoke” Bob
- (2) Alice becomes one of Bob’s top-four providers; Bob reciprocates
- (3) Bob becomes one of Alice’s top-four providers



Application layer: overview

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



Video Streaming and CDNs: context

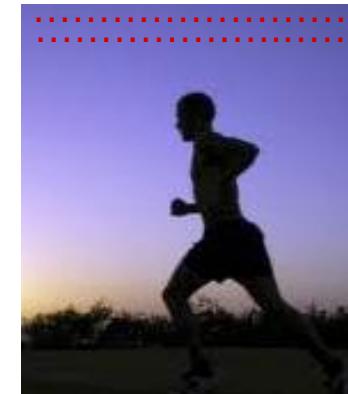
- stream video traffic: major consumer of Internet bandwidth
 - Netflix, YouTube, Amazon Prime: 80% of residential ISP traffic (2020)
- *challenge*: scale - how to reach ~1B users?
- *challenge*: heterogeneity
 - different users have different capabilities (e.g., wired versus mobile; bandwidth rich versus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

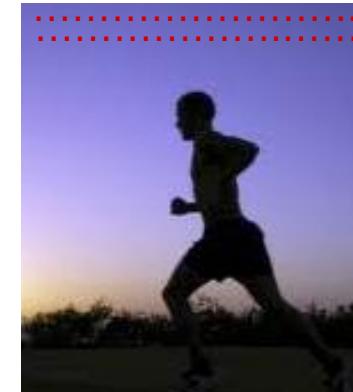


frame *i+1*

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*

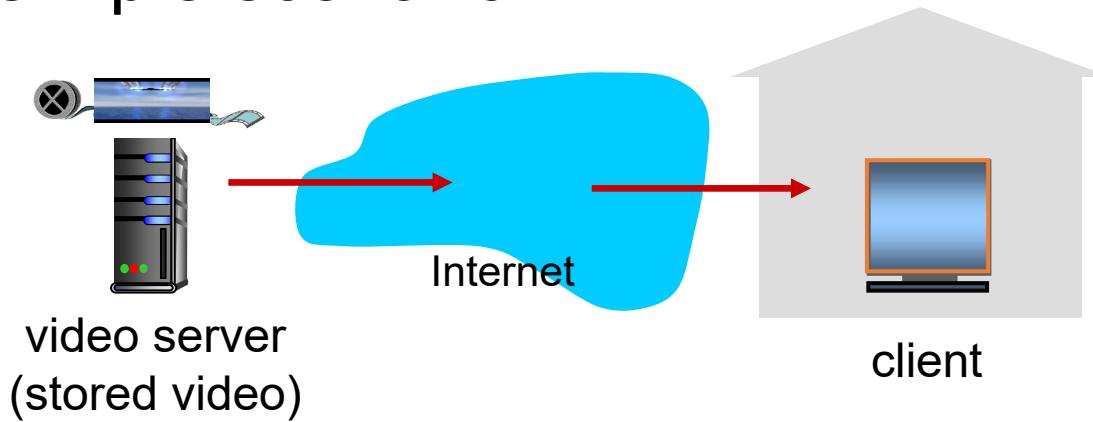
temporal coding example: instead of sending complete frame at $i+1$, send only differences from frame i



frame $i+1$

Streaming stored video

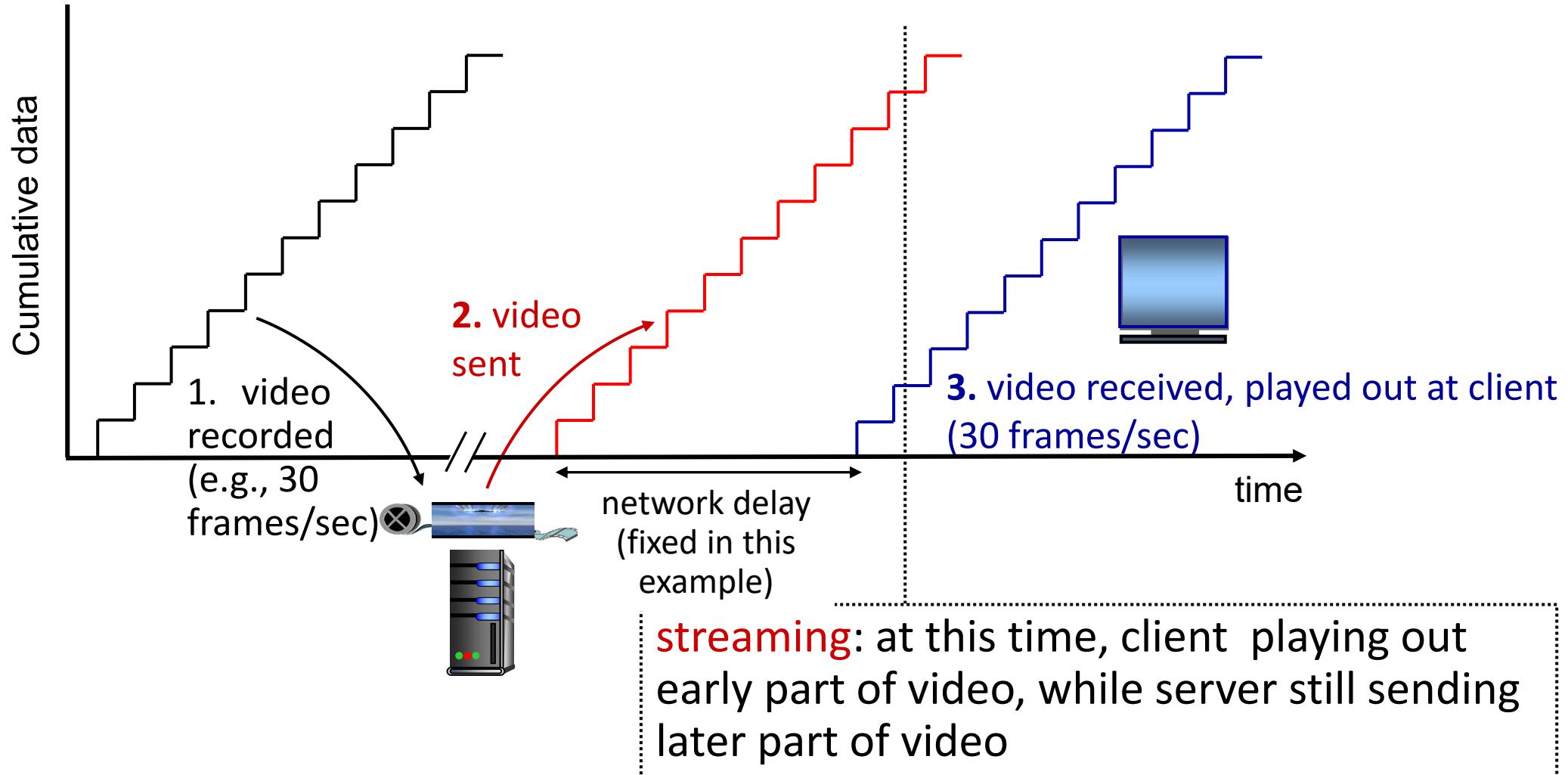
simple scenario:



Main challenges:

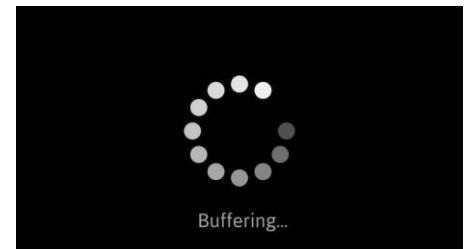
- server-to-client bandwidth will *vary* over time, with changing network congestion levels (in house, access network, network core, video server)
- packet loss, delay due to congestion will delay playout, or result in poor video quality

Streaming stored video

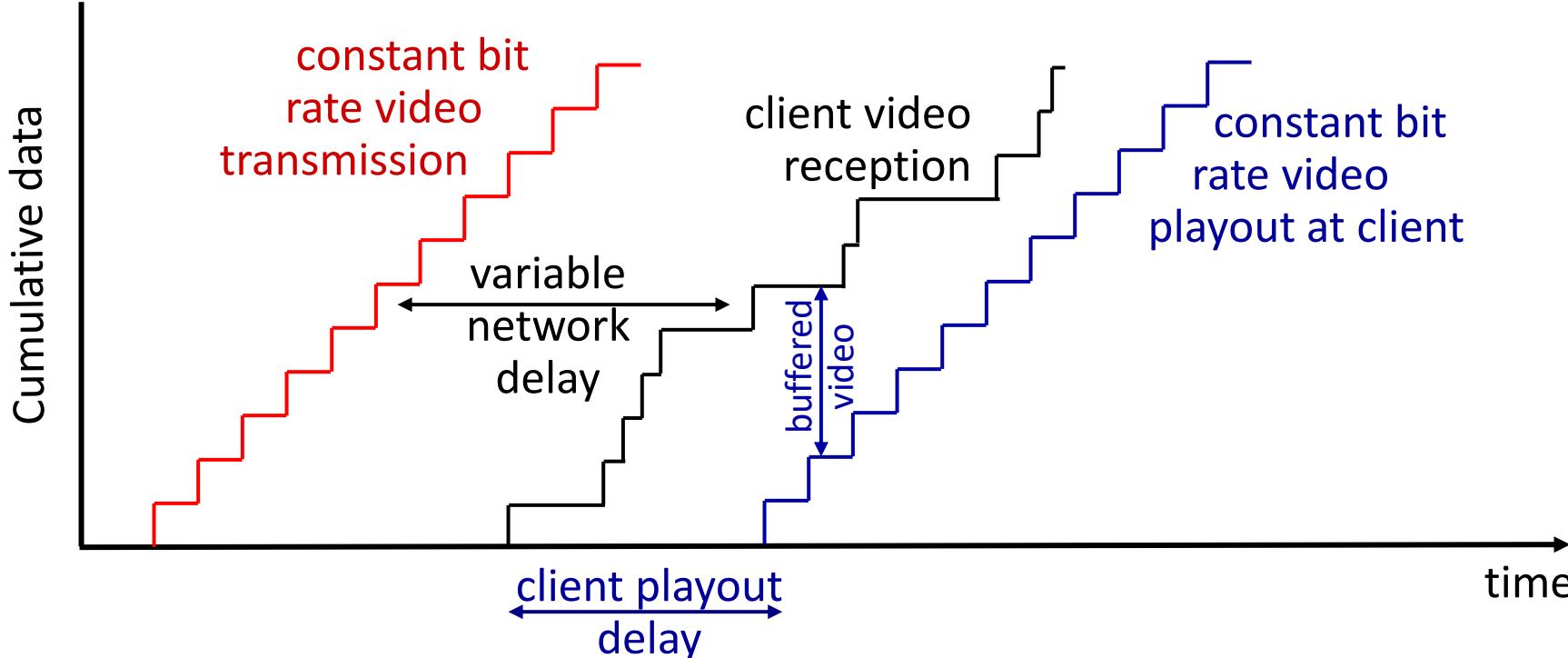


Streaming stored video: challenges

- **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



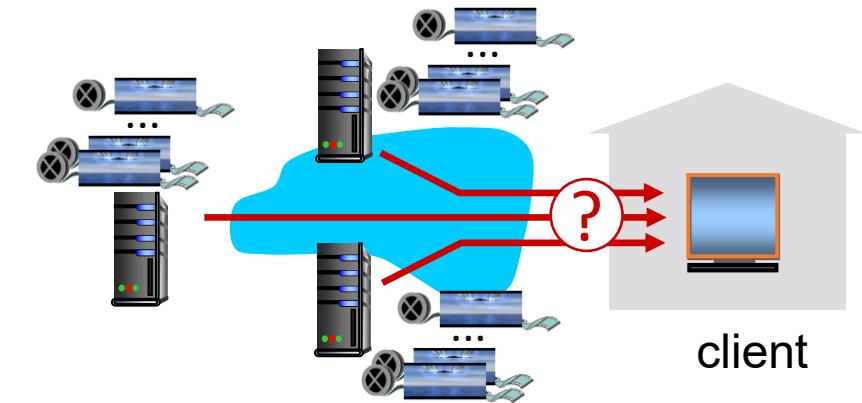
- *client-side buffering and playout delay*: compensate for network-added delay, delay jitter

Streaming multimedia: DASH

*Dynamic, Adaptive
Streaming over HTTP*

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

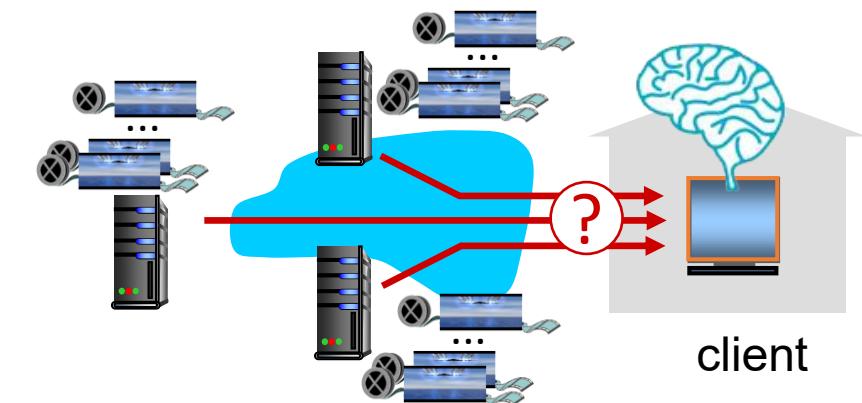


client:

- 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)

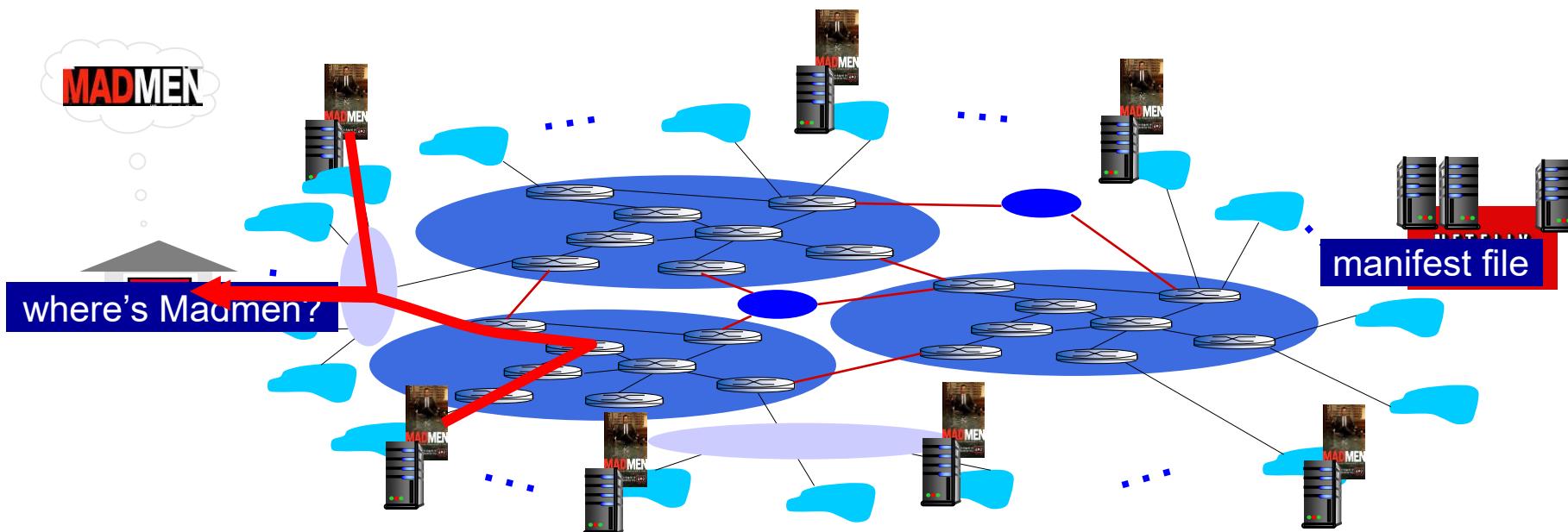
challenge: how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?

- *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?

Application Layer: Overview

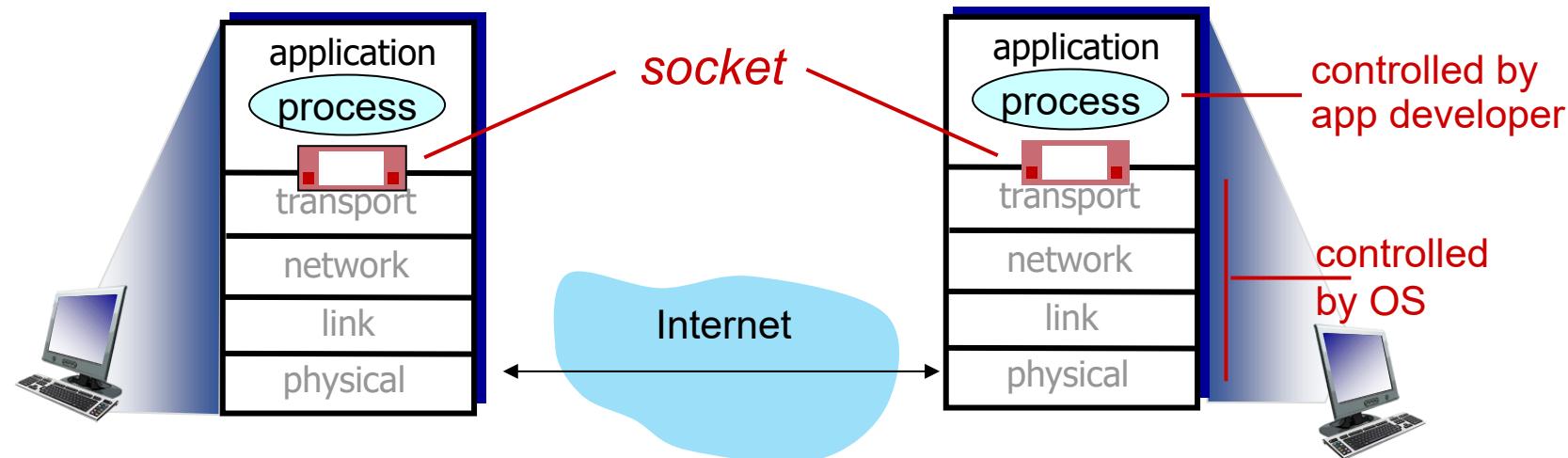
- Principles of network applications
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- The Domain Name System DNS
- P2P applications
- video streaming and content distribution networks
- **socket programming with UDP and TCP**



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 UDPCClient

```
include Python's socket library → from socket import *
serverName = 'hostname'
serverPort = 12000
create UDP socket for server → clientSocket = socket(AF_INET,
                                                    SOCK_DGRAM)
get user keyboard input → message = raw_input('Input lowercase sentence:')
attach server name, port to message; send into socket → clientSocket.sendto(message.encode(),
                           (serverName, serverPort))
read reply characters from socket into string → modifiedMessage, serverAddress =
                                               clientSocket.recvfrom(2048)
print out received string and close socket → print modifiedMessage.decode()
                                               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 →   message, clientAddress = serverSocket.recvfrom(2048)
client's address (client IP and port)           modifiedMessage = message.decode().upper()
                                               serverSocket.sendto(modifiedMessage.encode(),
send upper case string back to this client →   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:

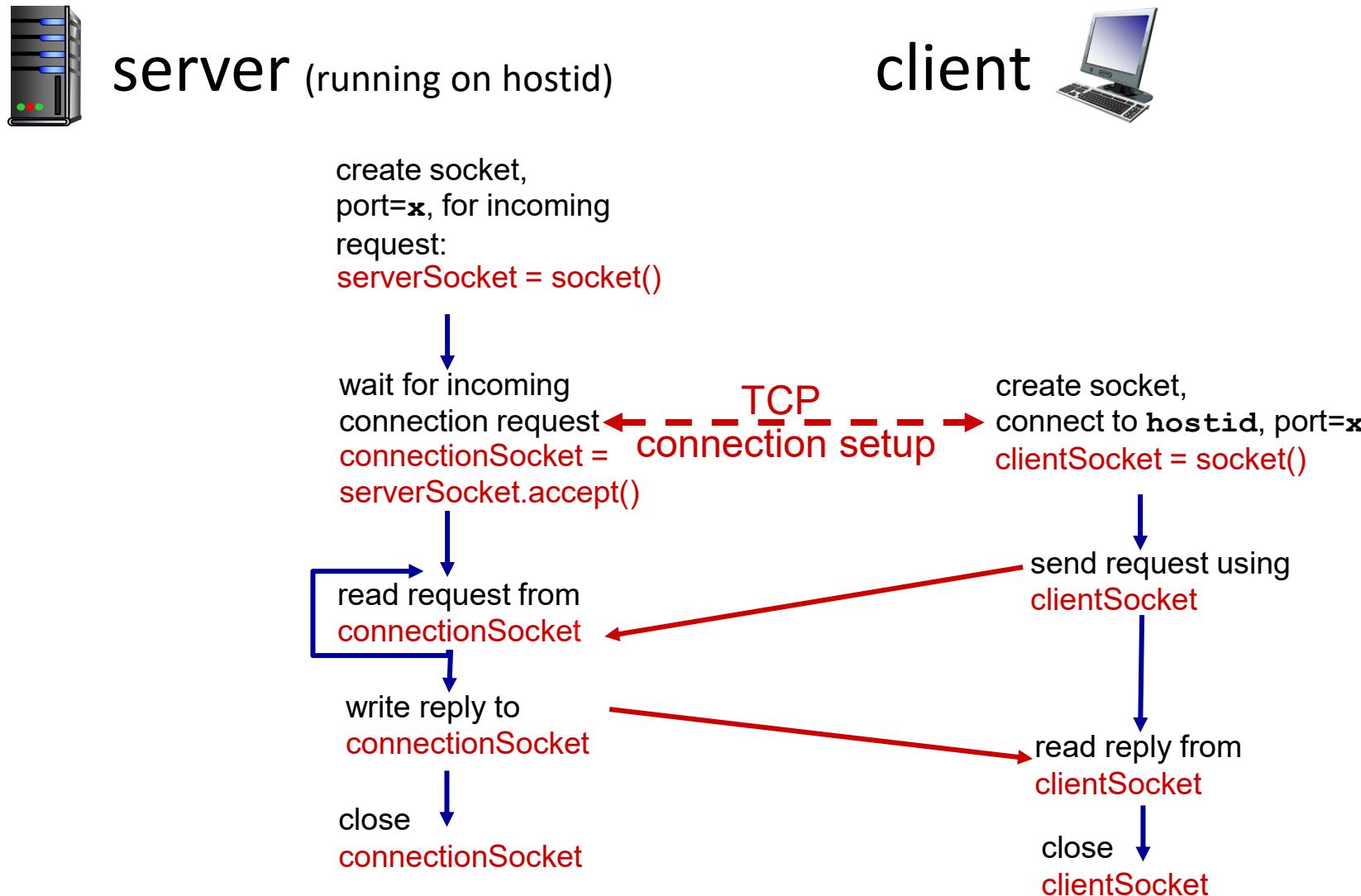
- Creating TCP socket, specifying IP address, port number of server process
- *when client creates socket*: client TCP establishes connection to server TCP

- 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
 - *source port numbers* 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



Example app: TCP client

Python TCPClient

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

create TCP socket for server, remote port 12000 → clientSocket = socket(AF_INET, SOCK_STREAM)

No need to attach server name, port → clientSocket.connect((serverName,serverPort))

Example app: TCP server

Python TCP Server

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind(("",serverPort))
serverSocket.listen(1)
print 'The server is ready to receive'
while True:
    connectionSocket, addr = serverSocket.accept()
    sentence = connectionSocket.recv(1024).decode()
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence.
                           encode())
    connectionSocket.close()
```

create TCP welcoming socket → from socket import *

server begins listening for incoming TCP requests → serverPort = 12000

loop forever → serverSocket = socket(AF_INET,SOCK_STREAM)

server waits on accept() for incoming requests, new socket created on return → serverSocket.bind(("",serverPort))

read bytes from socket (but not address as in UDP) → serverSocket.listen(1)

close connection to this client (but *not* welcoming socket) → print 'The server is ready to receive'

→ while True:

→ connectionSocket, addr = serverSocket.accept()

→ sentence = connectionSocket.recv(1024).decode()

→ capitalizedSentence = sentence.upper()

→ connectionSocket.send(capitalizedSentence.

→ encode())

→ connectionSocket.close()

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*!

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

important themes:

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

Additional Chapter 2 slides

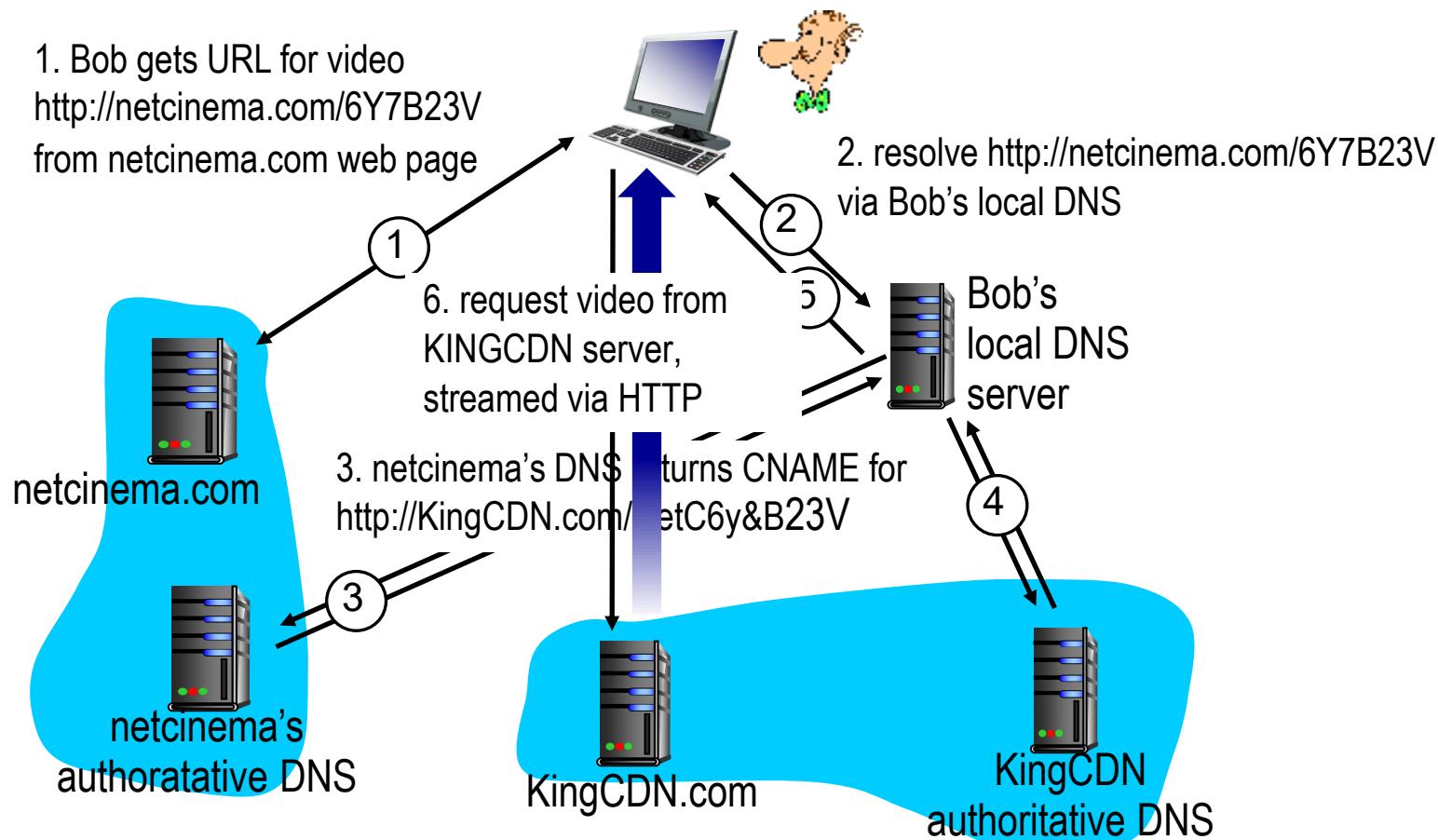
Sample SMTP interaction

```
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

