

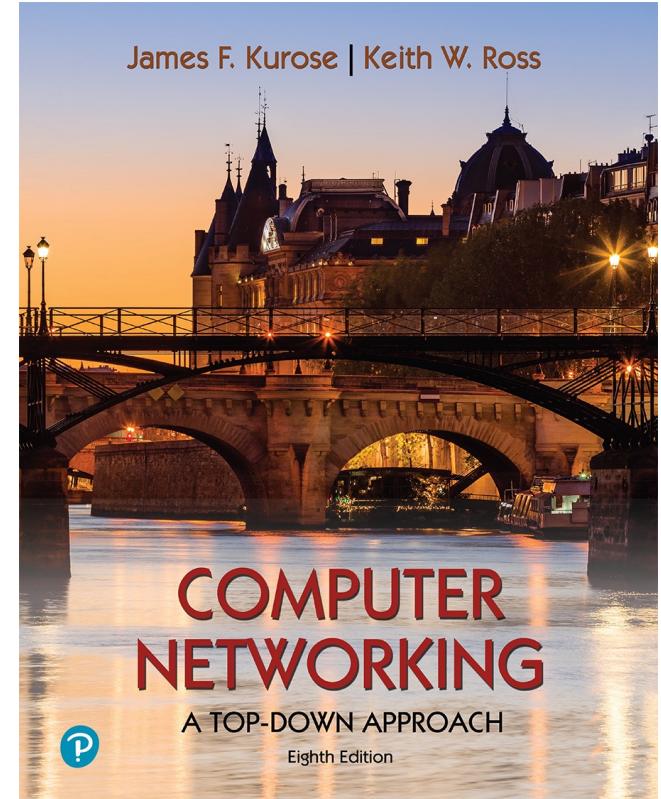
# Chapter 2

# Application Layer

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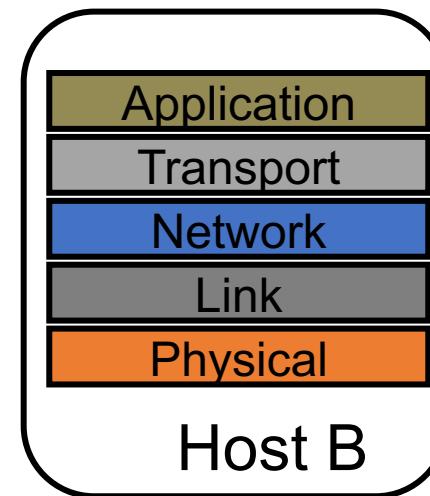
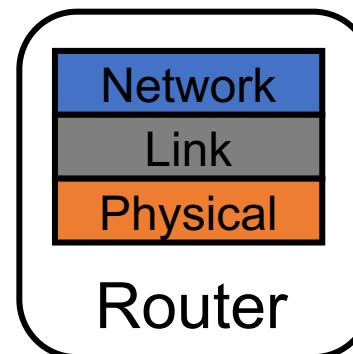
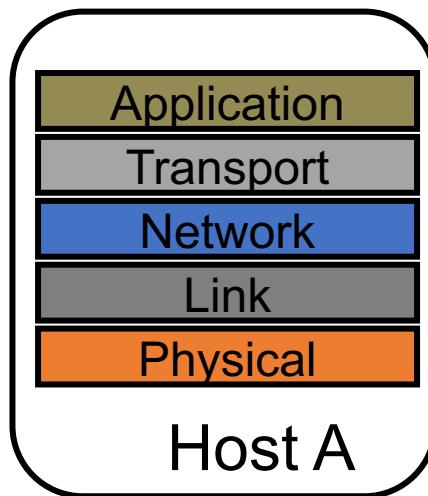
Adapted from the slides of the book's authors



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

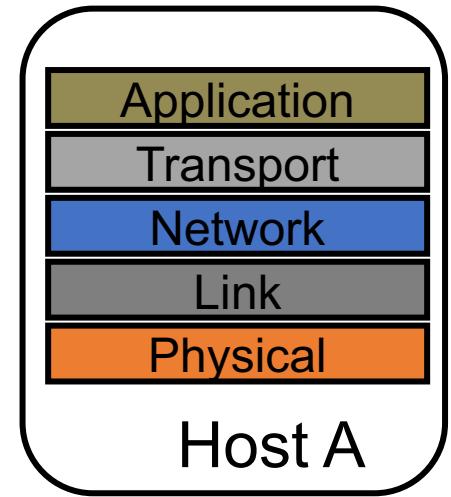
# End-to-End Application Layer

- Five layers
  - Lower three layers are implemented **everywhere**
  - Top two layers are implemented **only at end hosts**
    - Their protocols are *end-to-end*



# End-to-End Transport layer

- **Service:** Provide **end-to-end** communication between **processes on different hosts**
  - Demultiplex communication between hosts
  - Possibly reliability in the presence of errors
  - Rate adaptation (**flow control, congestion control**)
- **Interface:** send message to specific process at given destination; local process receives messages sent to it
- **Protocol:** perhaps implement reliability, flow control, packetization of large messages, framing



# Application layer: overview

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



# Application layer: overview

## Our goals:

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

# 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?*

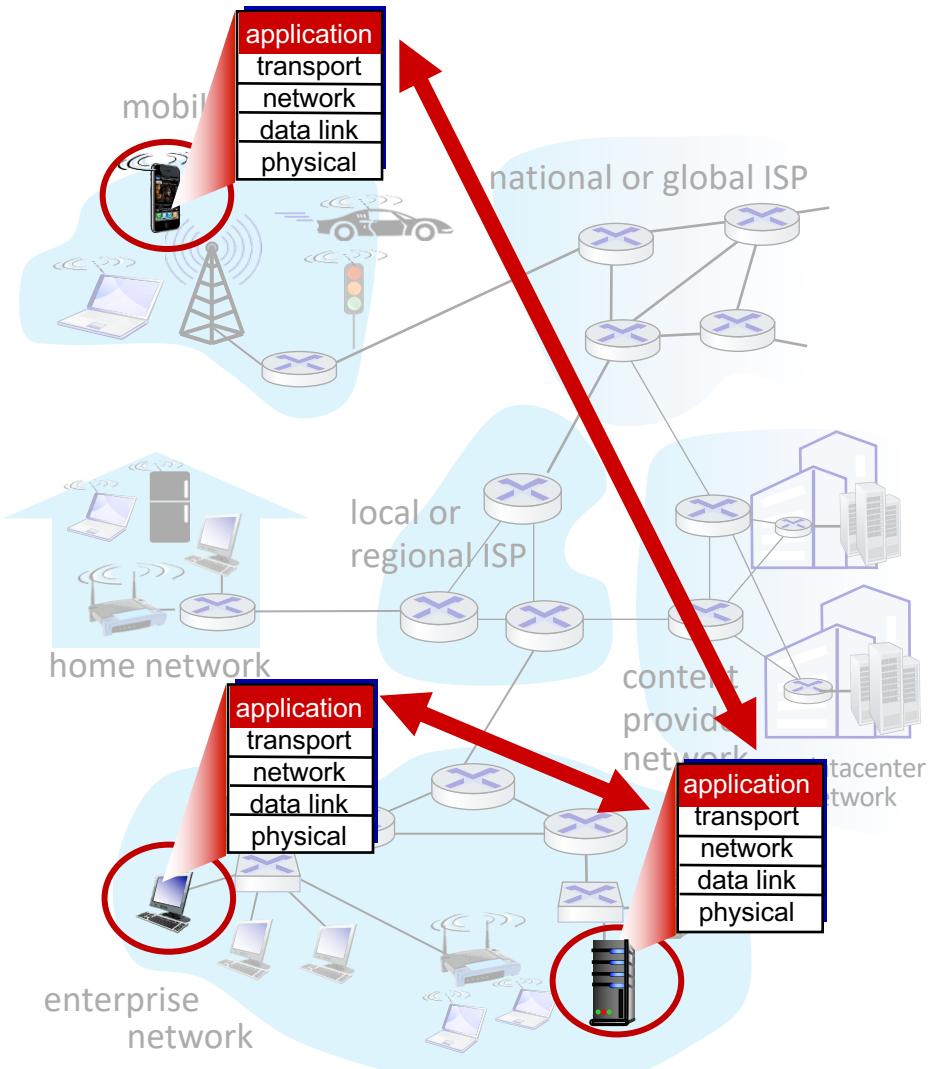
# Creating a network app

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 allow for rapid app development, propagation



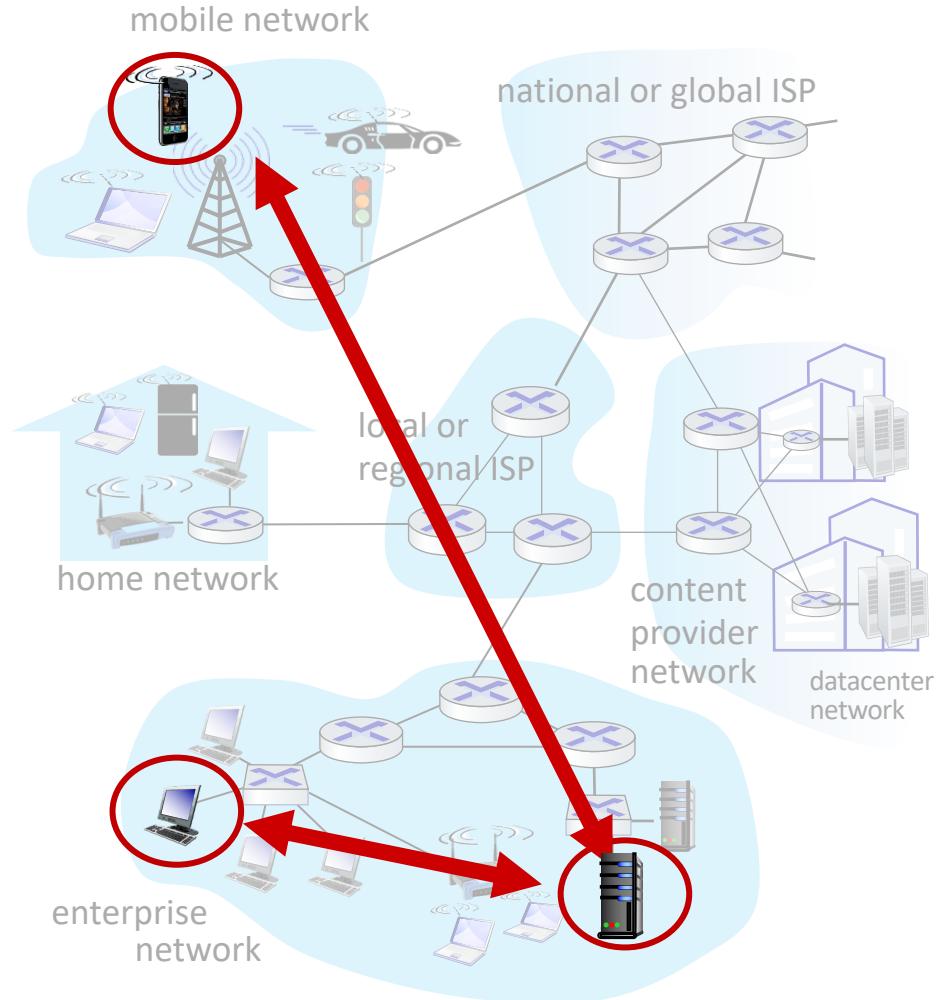
# Client-server paradigm

## server:

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

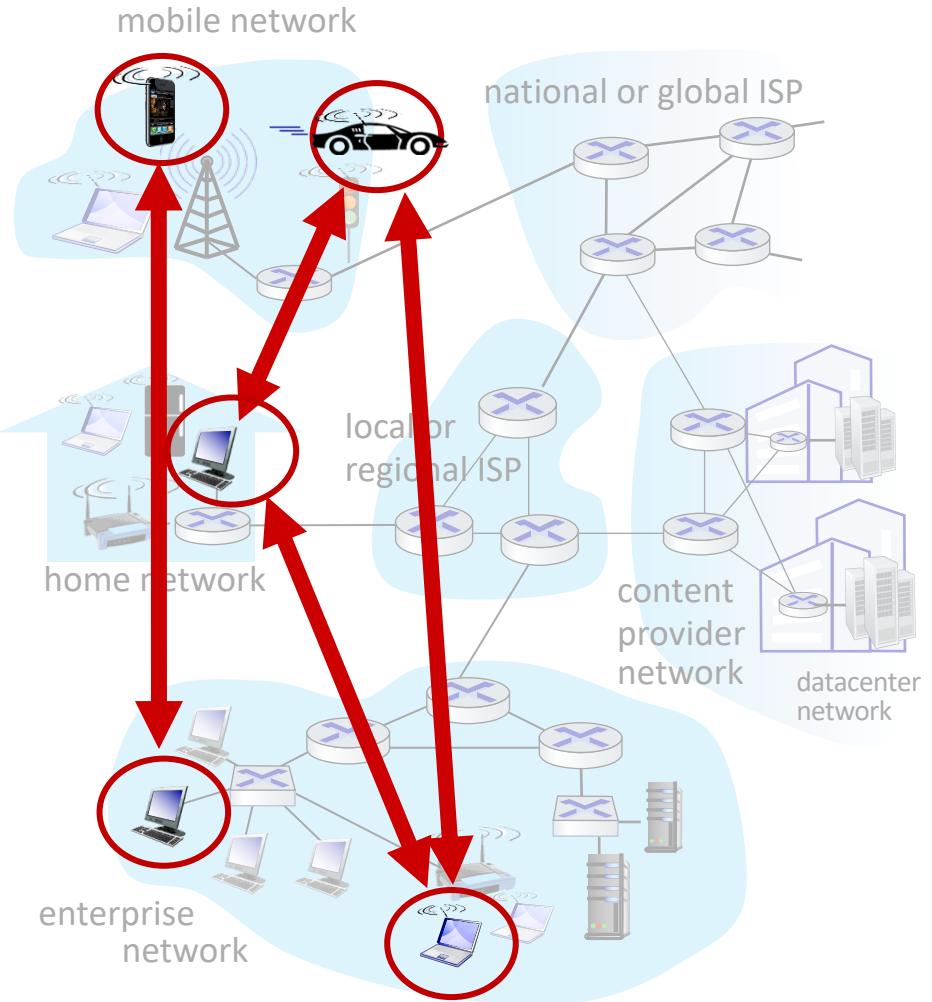
## clients:

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



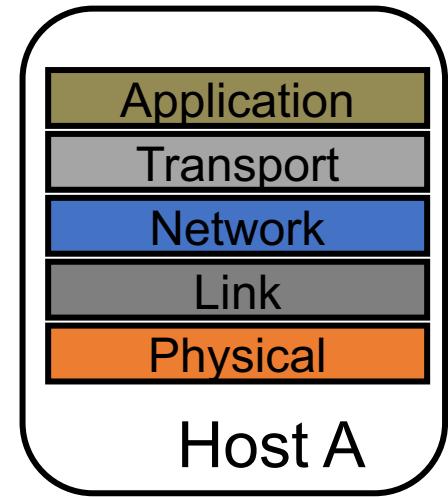
# Peer-peer architecture

- 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



# End-to-End Transport layer

- **Service:** Provide **end-to-end** communication between **processes on different hosts**
  - Demultiplex communication between hosts
  - Possibly reliability in the presence of errors
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- **Protocol:** perhaps implement reliability, flow control, packetization of large messages, framing



# 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

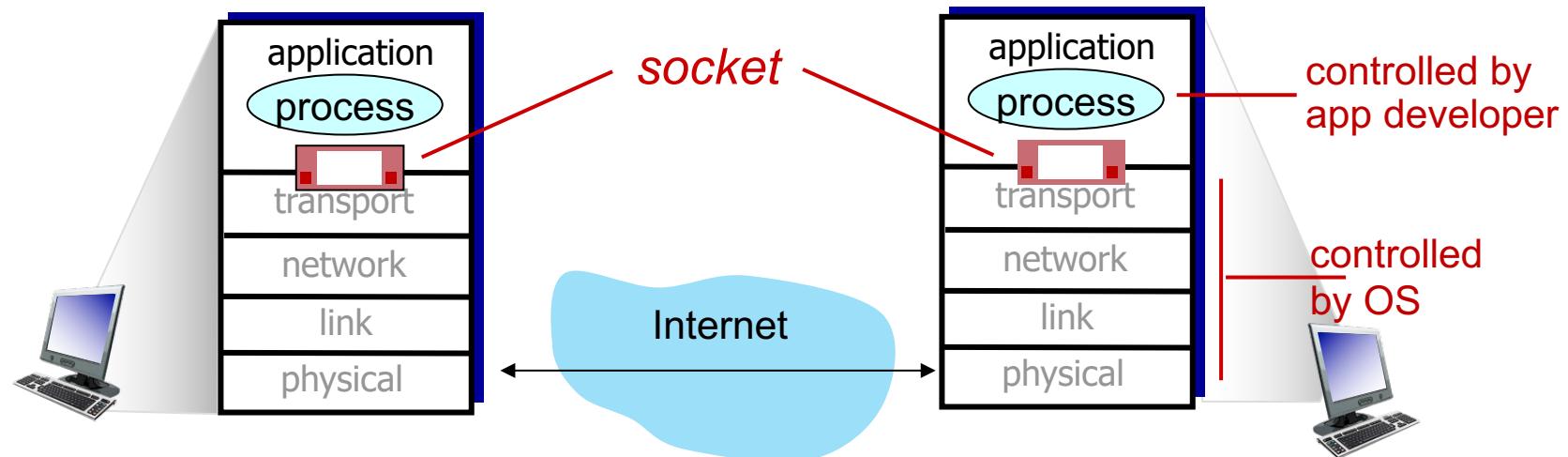
*client process*: process that initiates communication

*server process*: process that waits to be contacted

- note: applications with **P2P architectures** also 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, a process must have an *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 (Details in Chapter 3)

## 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, 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	UDP or TCP
interactive games	WOW, FPS (proprietary)	UDP or TCP

# Application Layer: Overview

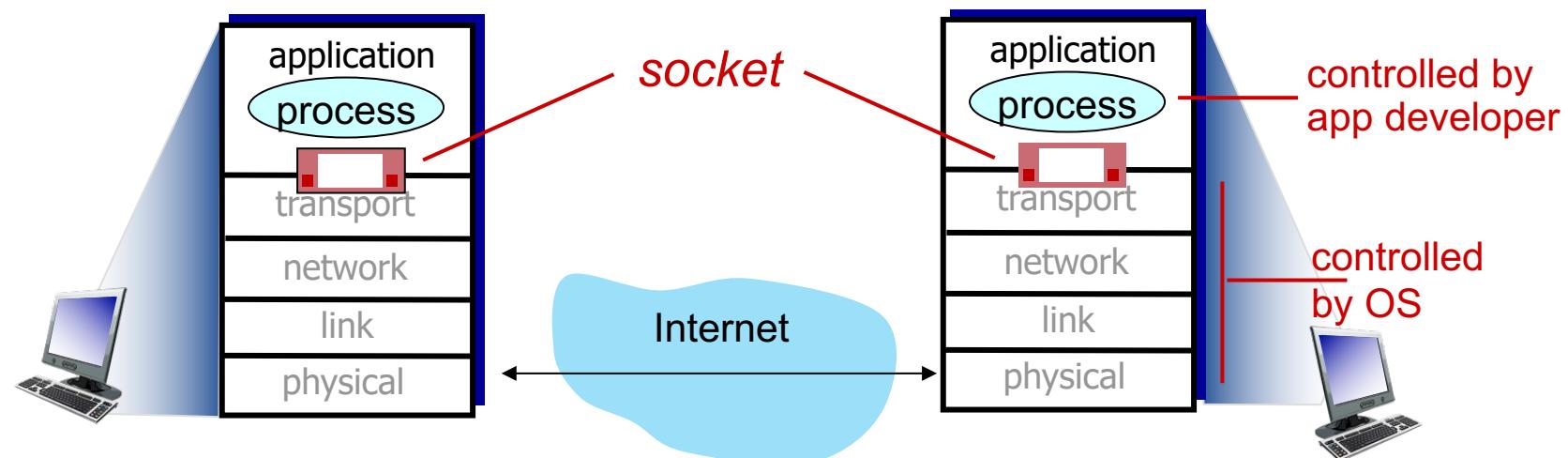
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# Socket programming

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

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



# Socket programming

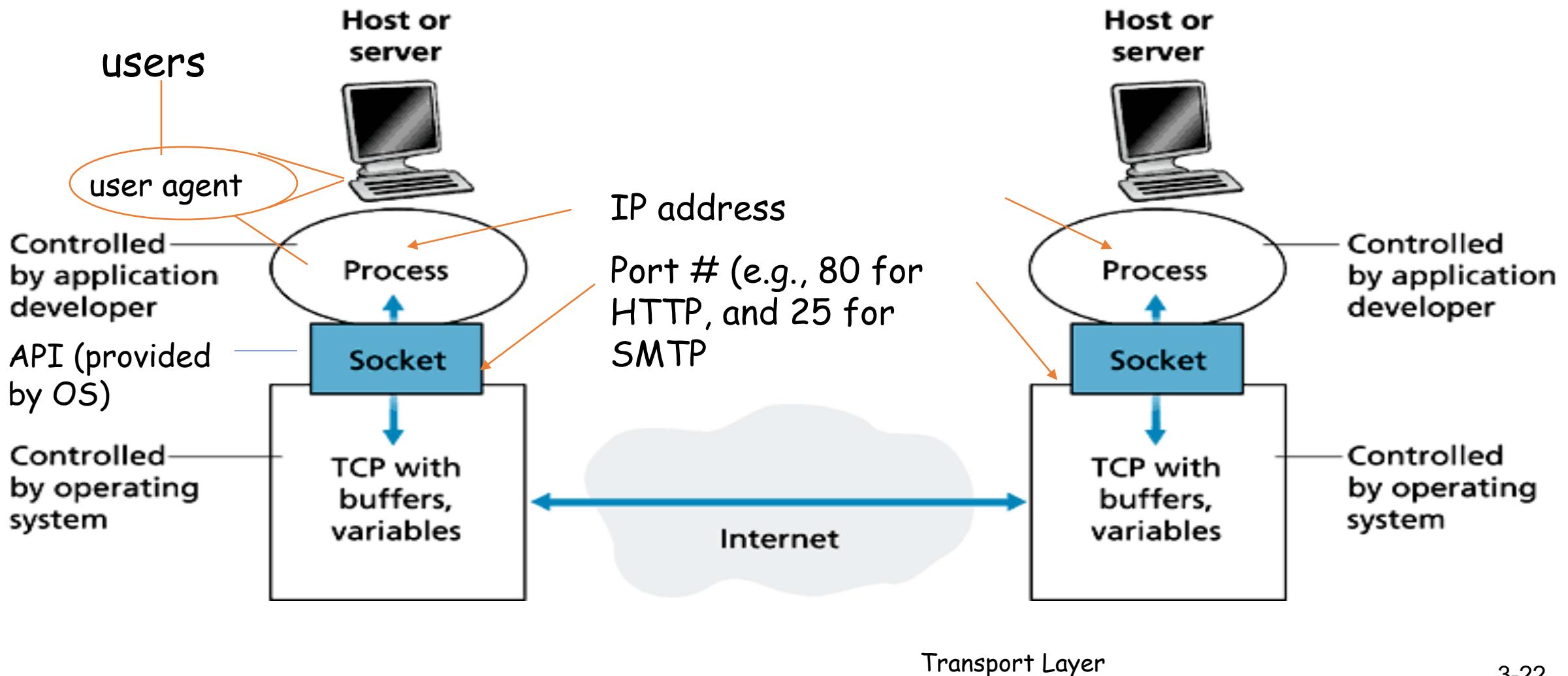
Two socket types for two transport services:

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

More on these protocols later (in Chapter 3), but

- relevant to application programming (API)
- useful for PA1

# An example: Email using HTTP or SMTP over TCP socket)



# Another 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 (e.g. client) explicitly attaches its IP destination address and port #, in addition to the destination’s IP/port info to each packet
- receiver (e.g. server) 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, assigns port= x:

```
serverSocket =  
socket(AF_INET,SOCK_DGRAM)
```

read datagram from  
**serverSocket**

write reply to  
**serverSocket**  
specifying  
client address,  
port number (y)



client

create socket (at some port y)

```
clientSocket =  
socket(AF_INET,SOCK_DGRAM)
```

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

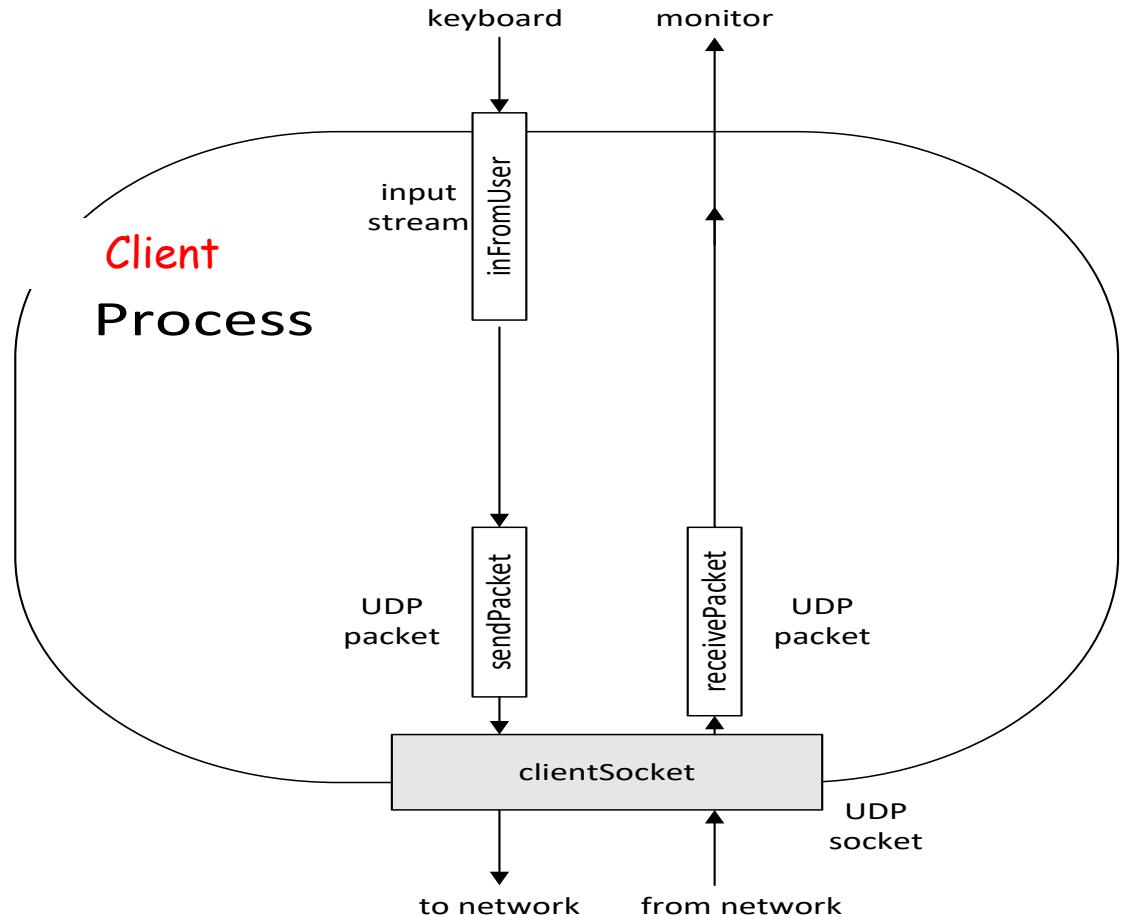
read datagram from  
**clientSocket**  
close  
**clientSocket**

# Example UDP Client (to request uppercase conversion)

Get keyboard input (in lowercase) from users

Send to a server for uppercase conversion

Receive the converted characters and display them



# Example app: UDP client

## *Python UDPCClient*

```
include Python's socket library → from socket import *
serverName = 'hostname'
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_DGRAM)

create UDP socket
(no need to specify port yet) →
get user keyboard input → message = raw_input('Input lowercase sentence:')

attach server name, port x to message; send into socket → clientSocket.sendto(message.encode(),
(OS inserts this client's IP address and port y) (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 a 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



server (running on hostid)



client

create socket,  
port=x, for incoming  
request:  
`serverSocket = socket()`

wait for incoming  
connection request  
`connectionSocket = serverSocket.accept()`

read request from  
`connectionSocket`

write reply to  
`connectionSocket`

close  
`connectionSocket`

create socket,  
connect to `hostid`, port=x  
`clientSocket = socket()`

send request using  
`clientSocket`

read reply from  
`clientSocket`

close  
`clientSocket`

TCP  
connection setup

# 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

No need to attach server name/IP , port  
Info anymore

TCP socket type

# Example app: TCP server

## Python TCP Server

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind(("",serverPort))
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 → serverSocket = socket(AF\_INET,SOCK\_STREAM)

server begins listening for incoming TCP requests → serverSocket.listen(1)

loop forever → while True:

server waits on accept() for incoming requests, new socket created on demand → connectionSocket, addr = serverSocket.accept()

read bytes from socket (but not address as in UDP) → sentence = connectionSocket.recv(1024).decode()

close connection to this client (but *not* welcoming socket) → connectionSocket.close()

TCP socket type ↑

# (Distinct) Feature of TCP Sockets

- TCP connection identified by 4-tuple:
  - source IP address
  - source port number
  - dest IP address
  - dest port number
- Server has two types of sockets:
  - When client knocks on serverSocket's "door," server creates a new **ConnectionSocket** and completes TCP connection
- Web servers have different sockets for each connecting client
  - non-persistent HTTP will have different socket for each request

# Securing TCP

## Vanilla TCP & UDP sockets:

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

## Transport Layer Security (TLS)

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

## TSL implemented in application layer

- apps use TSL libraries, that use TCP in turn
- cleartext sent into “socket” traverse Internet *encrypted*
- more: Chapter 8 and other network security courses

# Application layer: overview

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



CSE489/589 Modern Networking Concepts



Spring 2024

Objects

CSE610 Special Topics on Mobile Sensing & Mobile Networks



Fall 2023



Spring 2023

CSF710 Seminar on Wireless Networks



Fall 2022

# 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

The URL 'www.someschool.edu/someDept/pic.gif' is shown. A horizontal brace is positioned below the first part of the URL, 'www.someschool.edu', with the label 'host name' centered below it. Another horizontal brace is positioned below the remaining part of the URL, '/someDept/pic.gif', with the label 'path name' centered below it.

# 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)



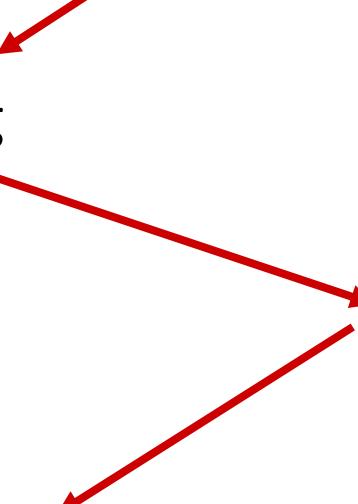
1a. HTTP client initiates TCP connection to HTTP server (process) at `www.someSchool.edu` on port 80



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

time  
↓

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

# Non-persistent HTTP: example (cont.)

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



- time ↓
1. User enters URL
  2. HTTP client sends TCP connection request
  3. HTTP server accepts connection request
  4. HTTP server sends response message containing html file
  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 --> re-establish a TCP connection each time

4. HTTP server closes **TCP connection.**

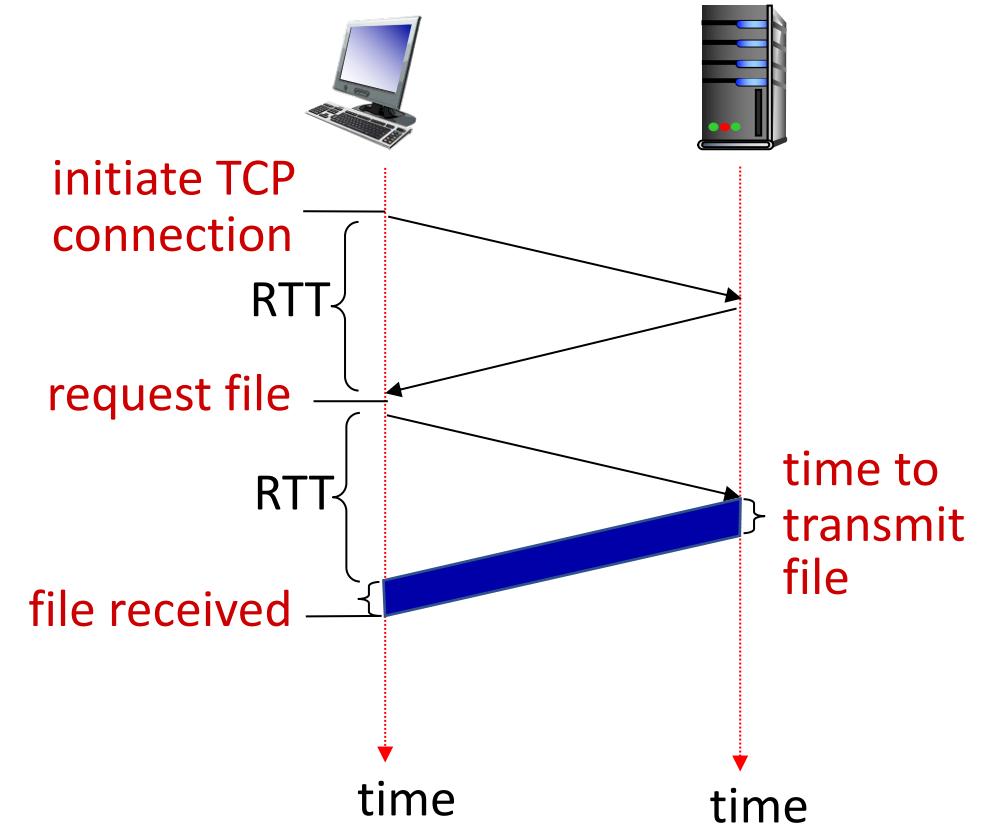


# Non-persistent HTTP: response time

**RTT (Round-Trip Time):** 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



$$\text{Non-persistent HTTP response time} = 2\text{RTT} + \text{file transmission time}$$

# 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 **TCP connection** open after sending response
- subsequent HTTP messages between same client/server sent over open TCP 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 ....)



carriage return character  
line-feed character

Followed by “entity  
body” or just “body”



\* 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

- two types of HTTP messages: *request, response*
- **HTTP request message:**

- ASCII (human-readable format)

request line  
(GET, POST ....)

→ GET /index.html HTTP/1.1\r\n  
Host: www-net.cs.umass.edu\r\nUser-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X  
10.15; rv:80.0) Gecko/20100101 Firefox/80.0 \r\nAccept: text/html,application/xhtml+xml\r\nAccept-Language: en-us,en;q=0.5\r\nAccept-Encoding: gzip,deflate\r\nConnection: keep-alive\r\n\r\n

carriage return character  
line-feed character

header  
lines

Followed by “entity  
body” or just “body”

\* 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/)

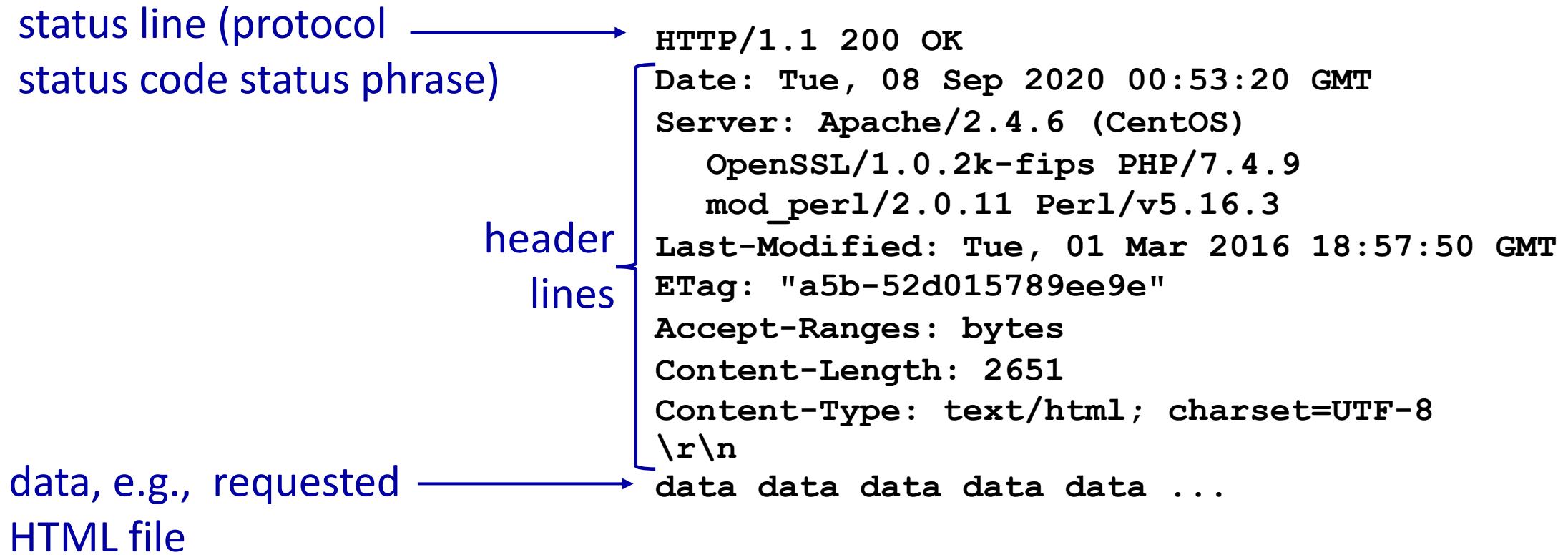
# Other HTTP request messages (omitted)

- PUT vs POST
- GET with a question mark after the URL vs GET vs POST
- Search StackOverflow and other documents

# HTTP response message

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

# HTTP response message



\* 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 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 (verified on Mac OS):

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

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

## 2. type in a GET HTTP request:

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

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

## 3. look at response message sent by HTTP server!

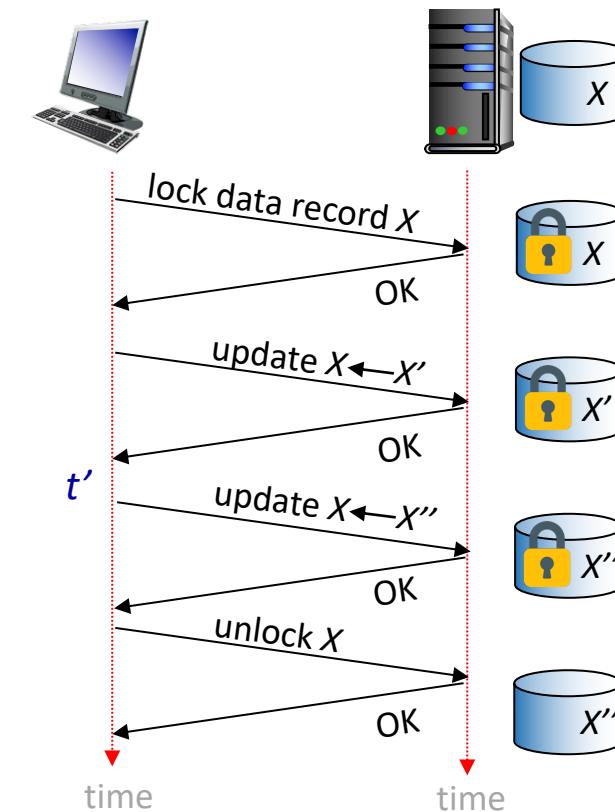
(or use Wireshark to look at captured HTTP request/response)

# Maintaining user/server state: cookies

Recall: HTTP GET/response interaction is *stateless*

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

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



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

# Maintaining user/server state: cookies

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

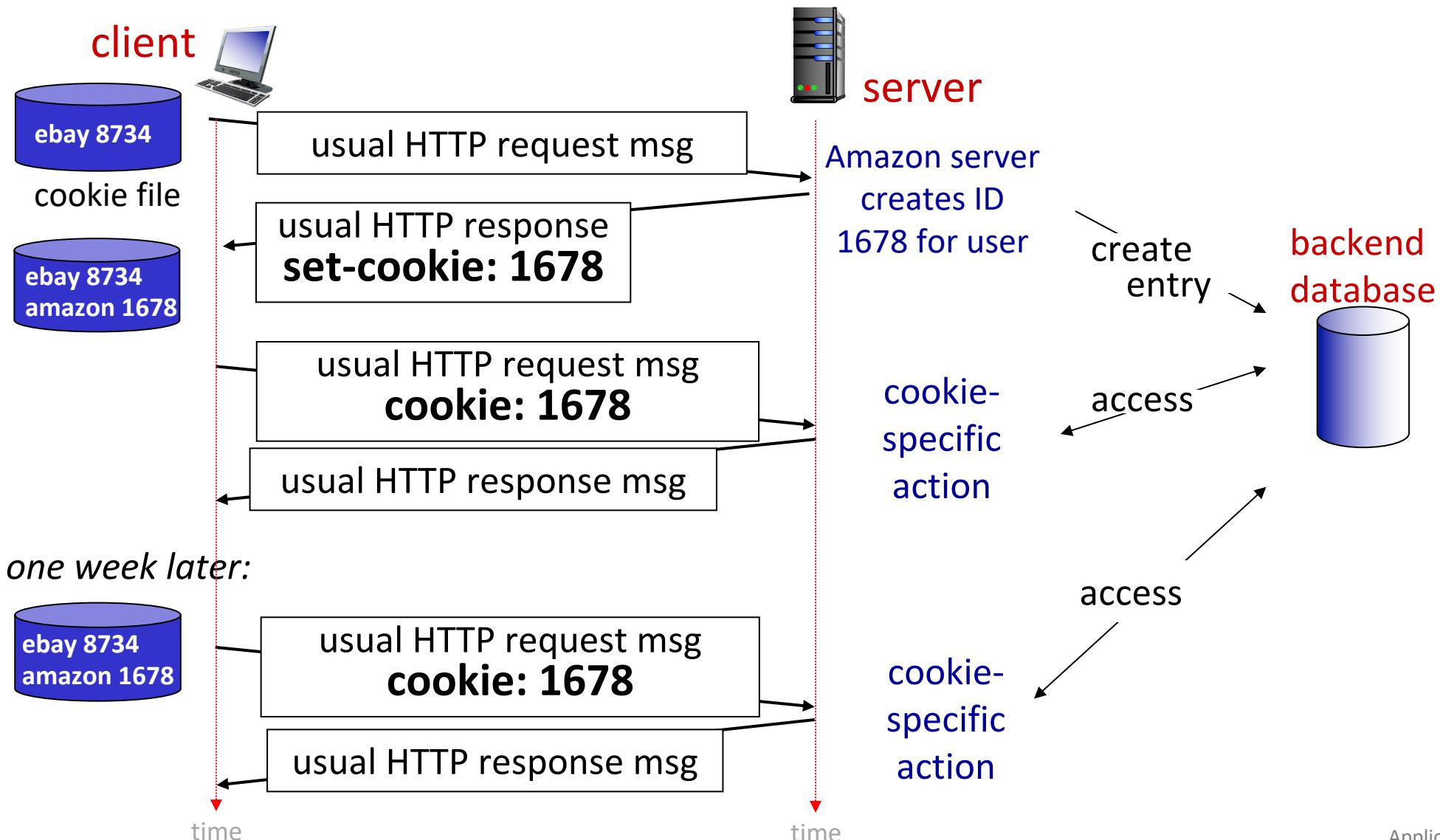
*four components:*

- 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 request 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

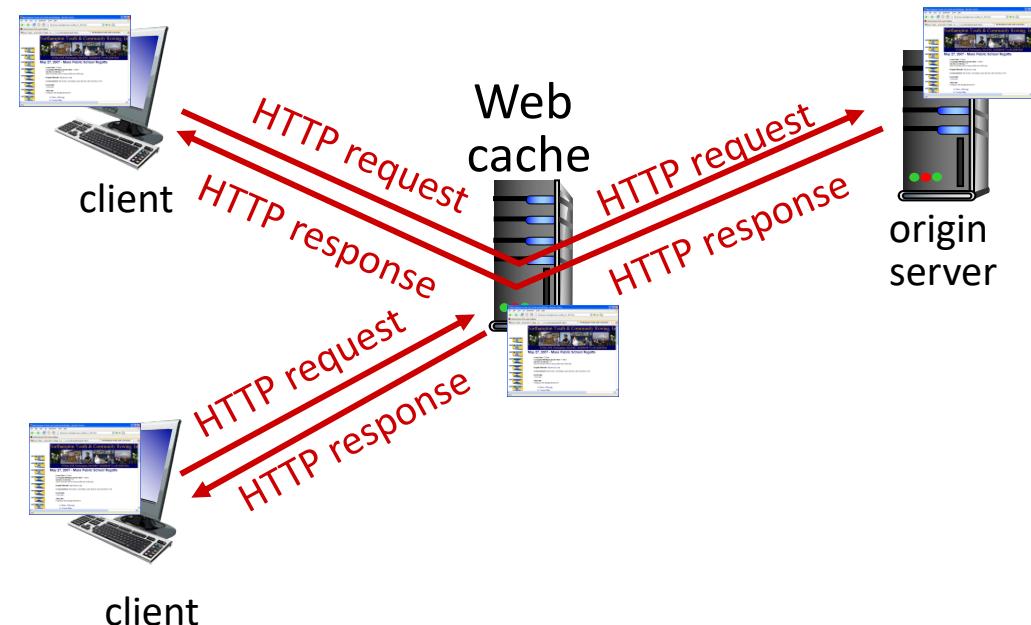
*aside  
cookies and privacy:*

- 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

# 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

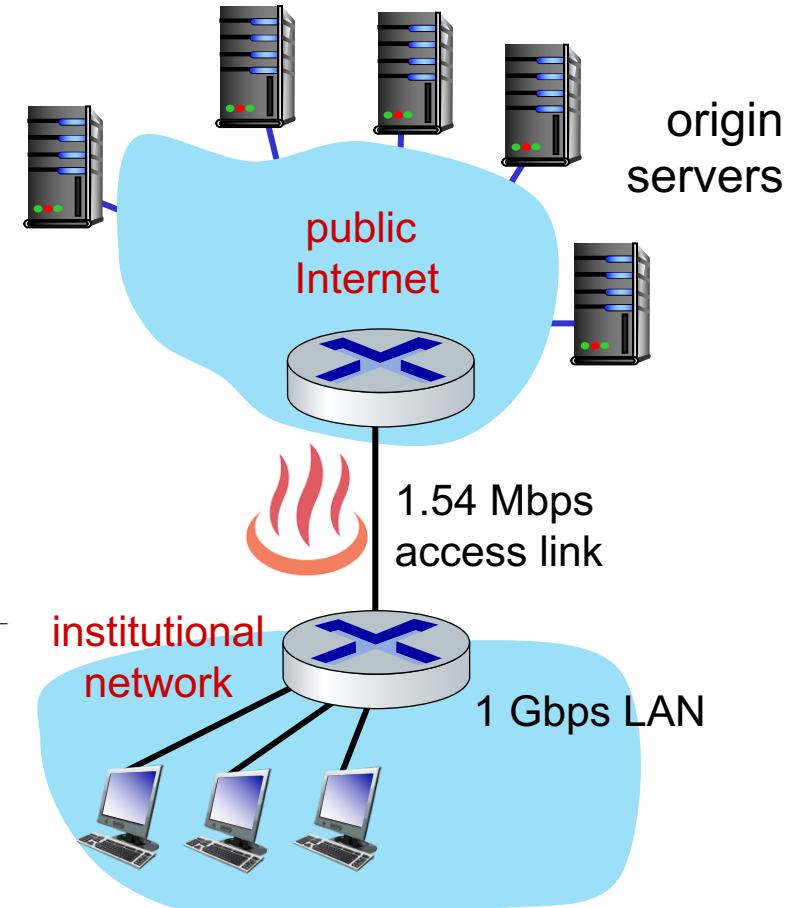
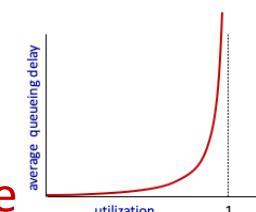
# Caching example

## 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** *problem: large queueing delays at high utilization!*
- LAN utilization: .0015
- end-end delay = Internet delay +  
access link delay + LAN delay  
= 2 sec + **minutes** + usecs



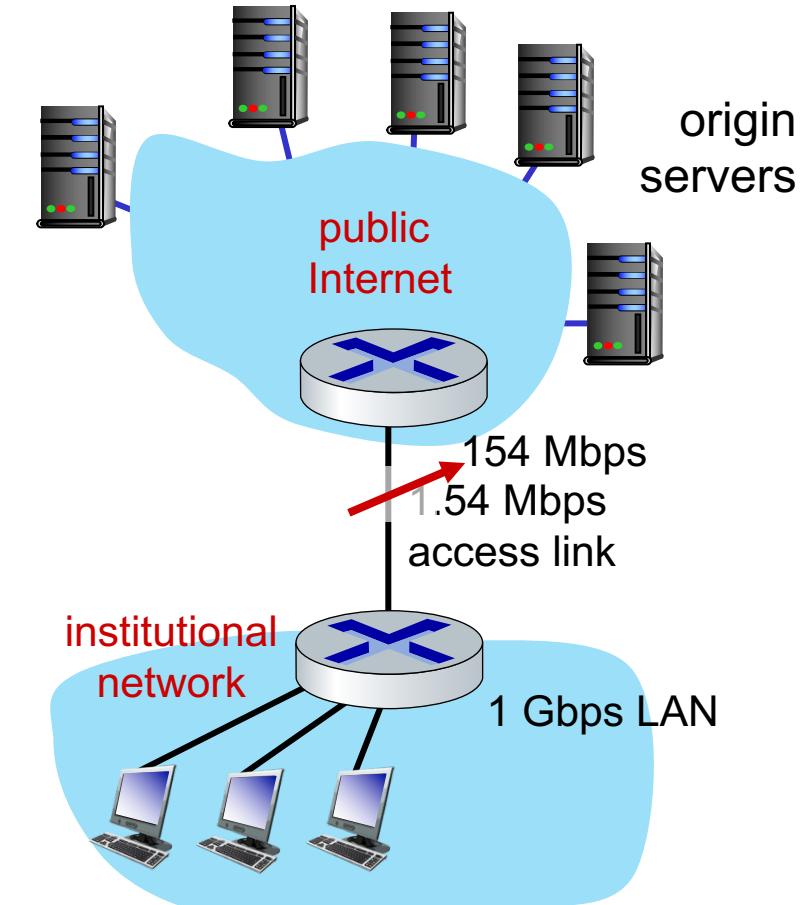
# Option 1: buy a faster access link

## *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~~ → .0097
- LAN utilization: .0015
- end-end delay = Internet delay +  
access link delay + LAN delay  
 $= 2 \text{ sec} + \cancel{\text{minutes}} + \cancel{\text{usecs}}$   
→ msecs



*Cost:* faster access link (expensive!)

# Option 2: install a web cache

## *Scenario:*

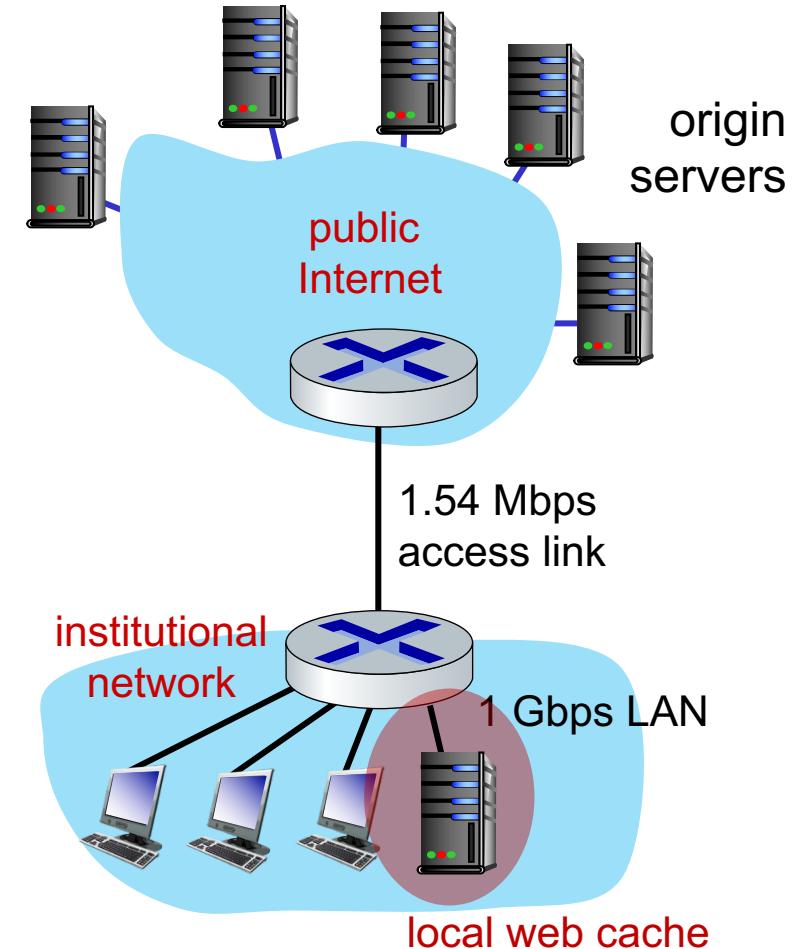
- access link rate: 1.54 Mbps
- RTT from institutional router to server: 2 sec
- web object size: 100K bits
- average request rate from browsers to origin servers: 15/sec
  - avg data rate to browsers: 1.50 Mbps

*Cost:* web cache (cheap!)

## *Performance:*

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

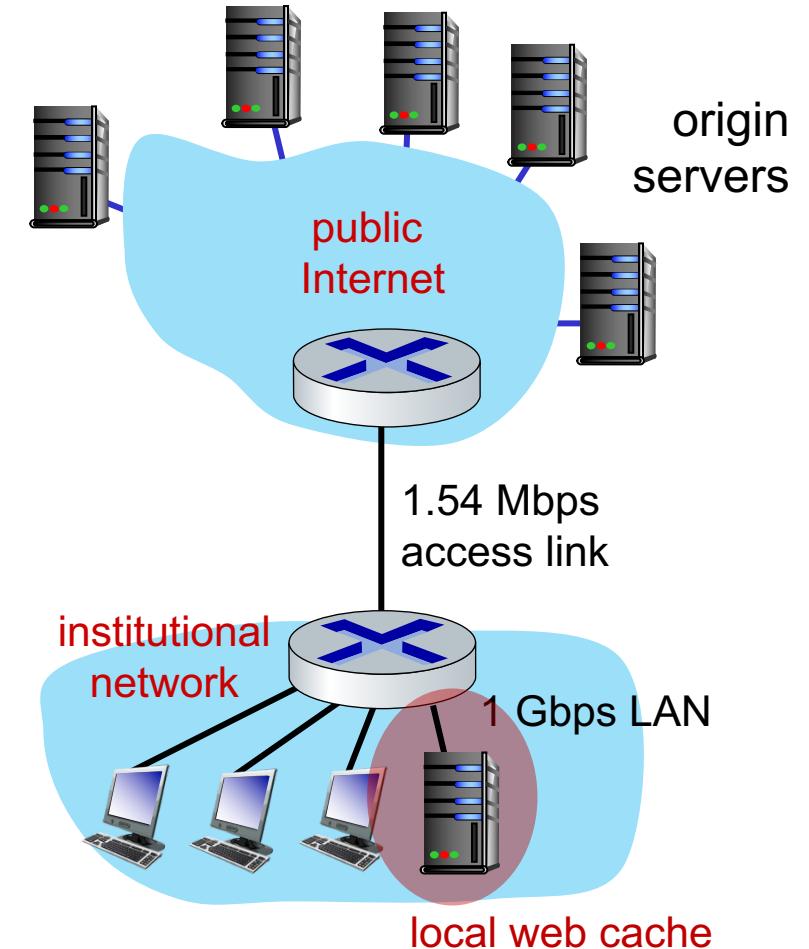
*How to compute link utilization, delay?*



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

suppose cache hit rate is 0.4:

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

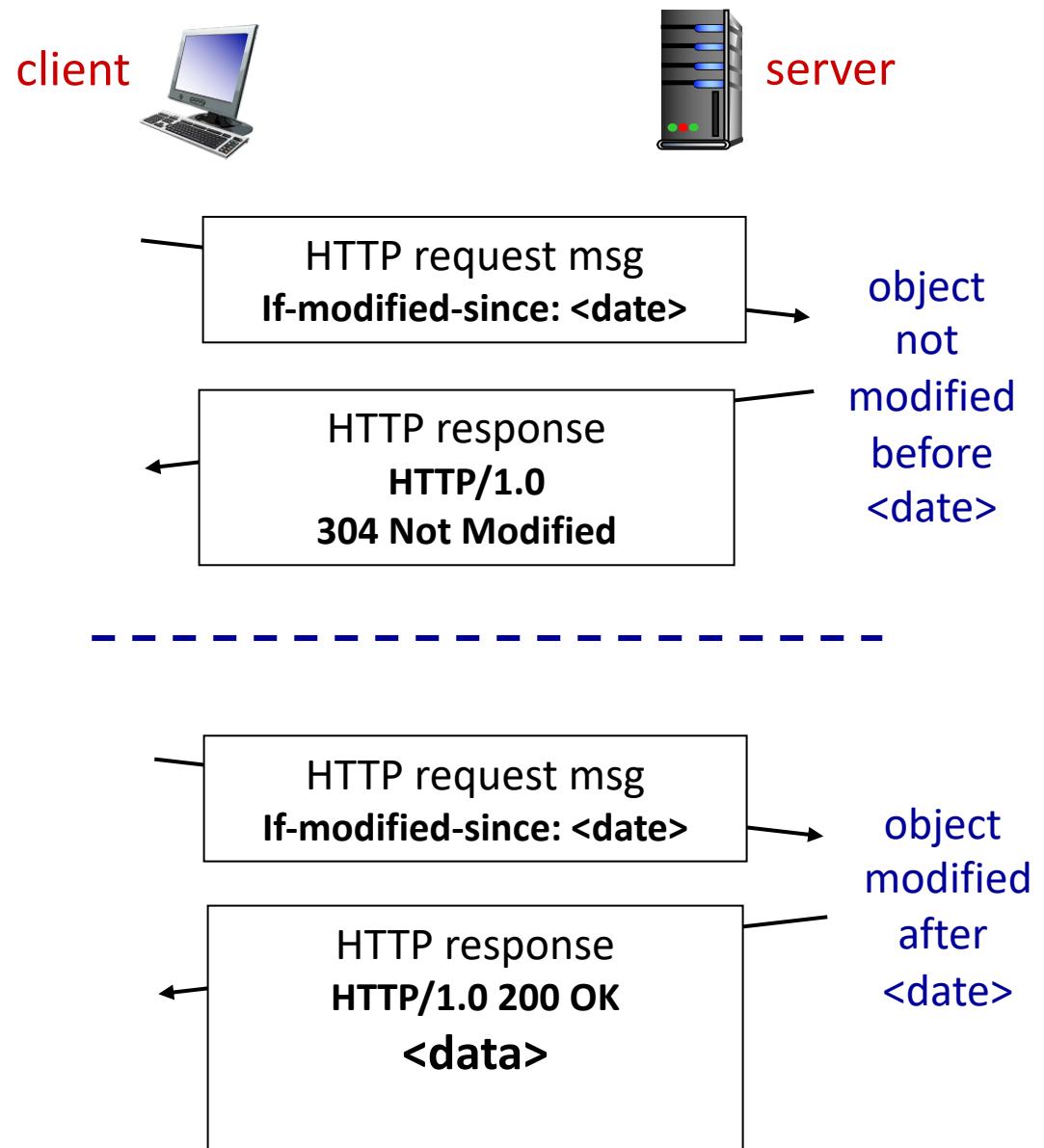


*lower average end-end delay than with 154 Mbps link (and cheaper too!)*

# 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

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

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

# HTTP/2

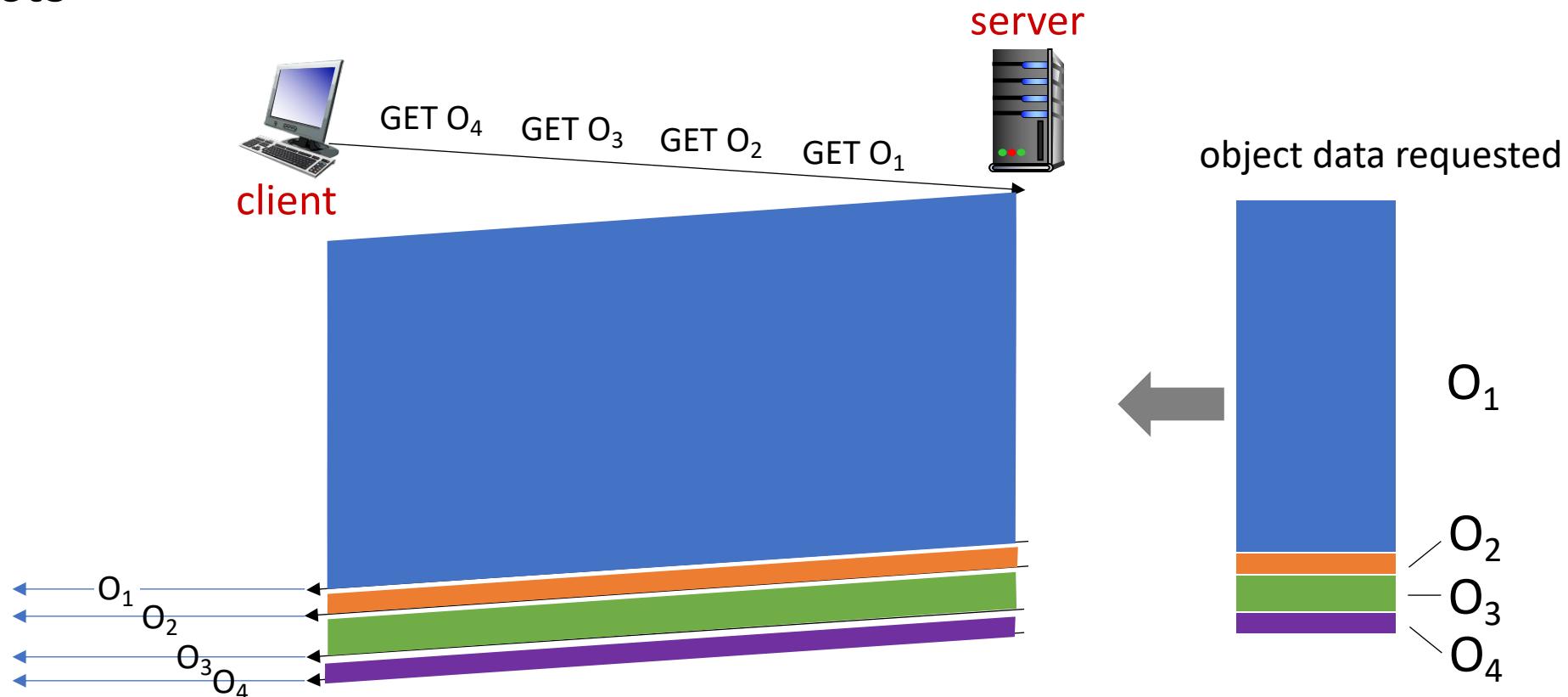
*Key goal:* decreased delay in multi-object HTTP requests

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

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

# HTTP/2: mitigating HOL blocking

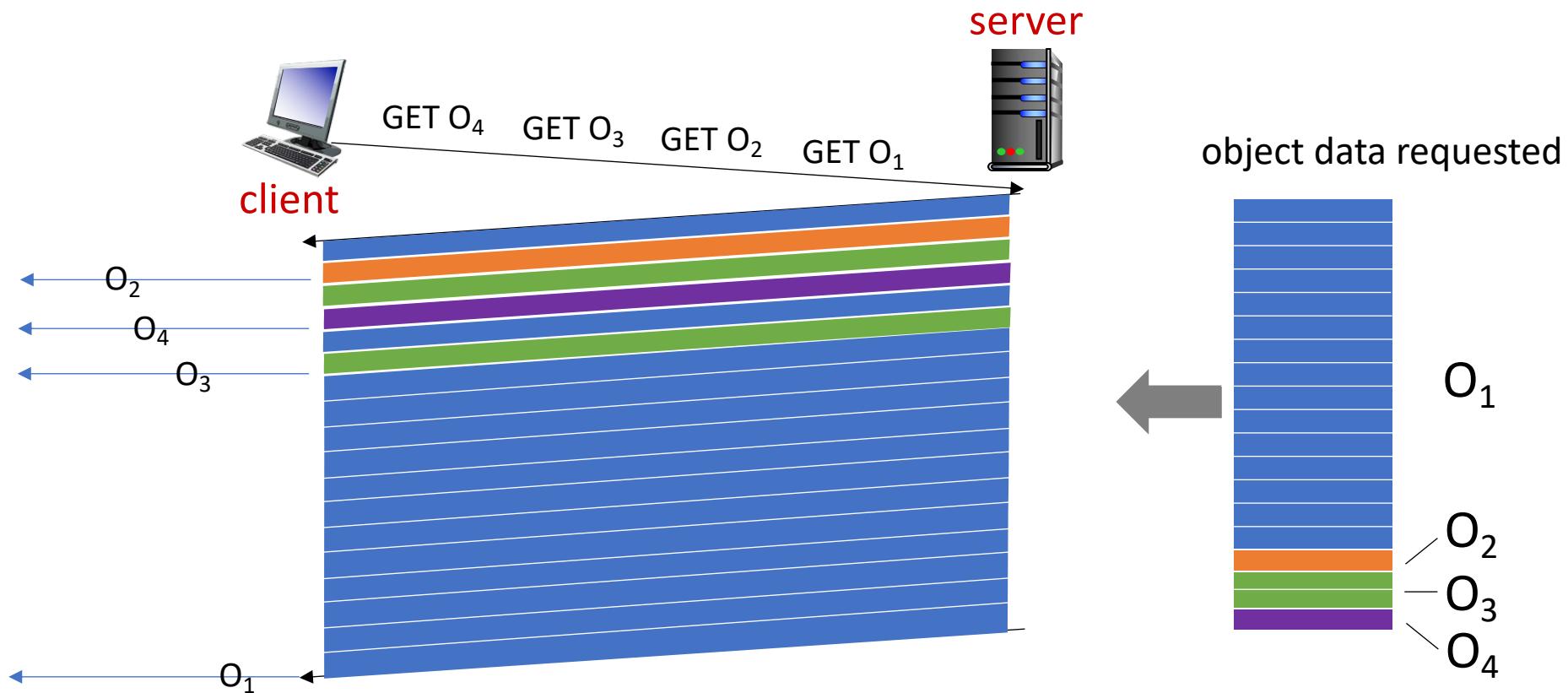
HTTP 1.1: client requests 1 large object (e.g., video file) and 3 smaller objects



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

# HTTP/2: mitigating HOL blocking

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



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

# HTTP/2 to HTTP/3

HTTP/2 over **single** TCP connection means:

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

# Application layer: overview

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



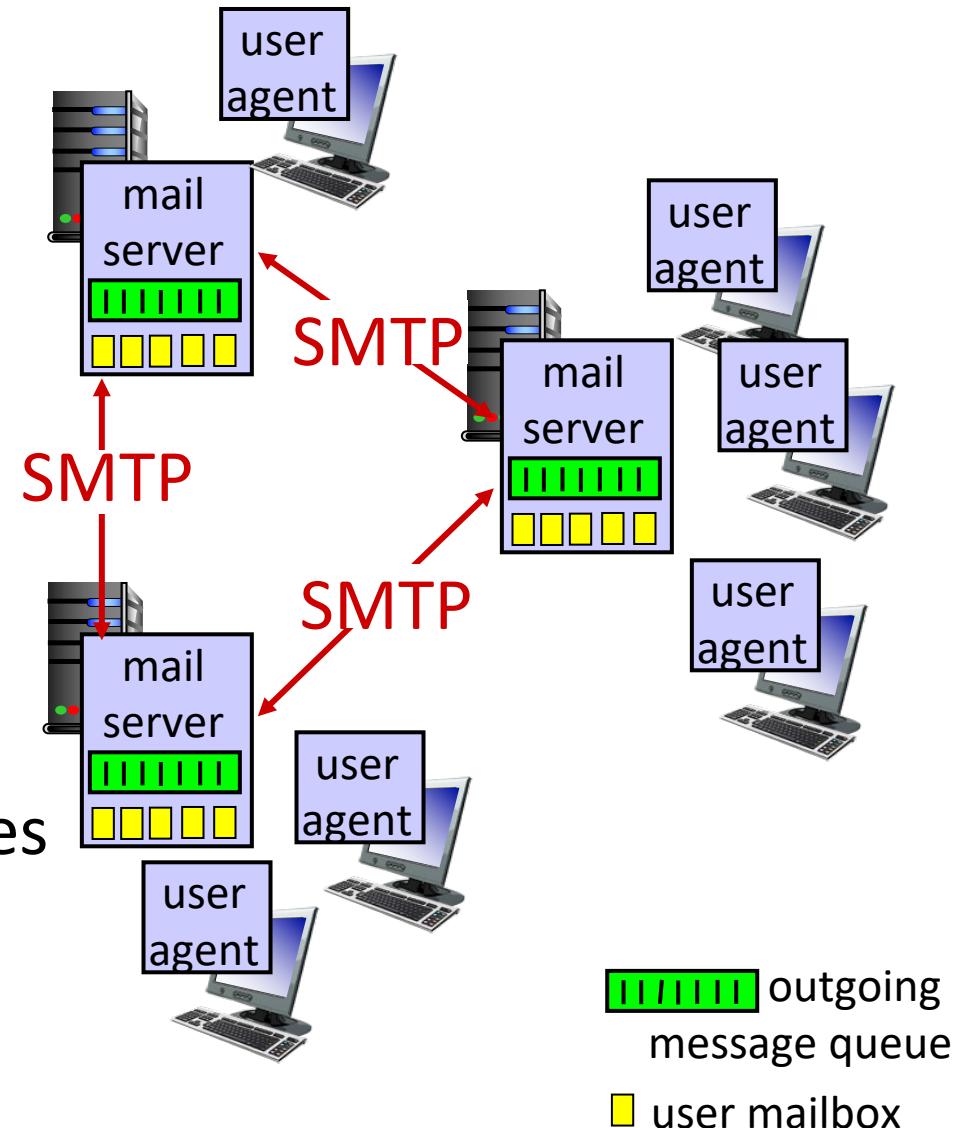
# E-mail

Three major components:

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

## User Agent

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



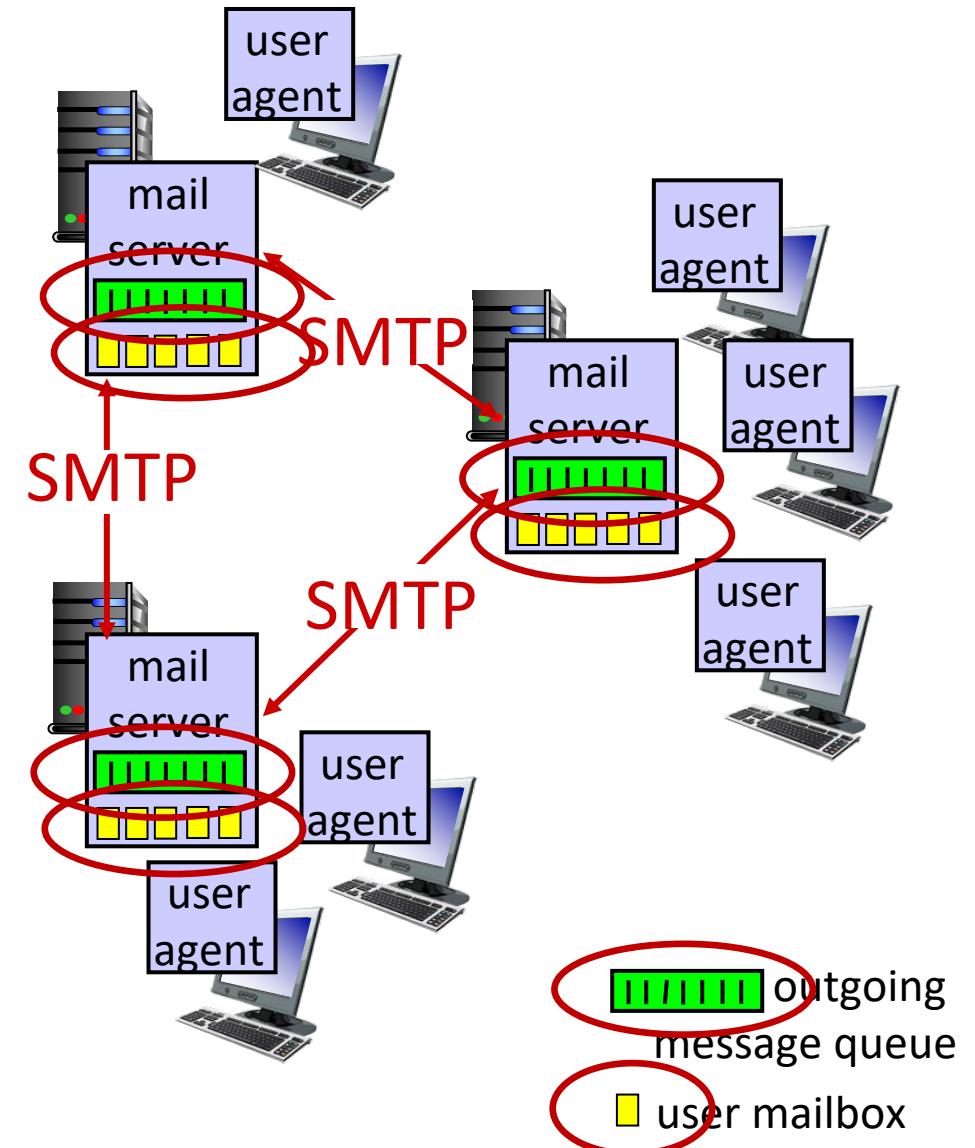
# E-mail: mail servers

## mail servers:

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

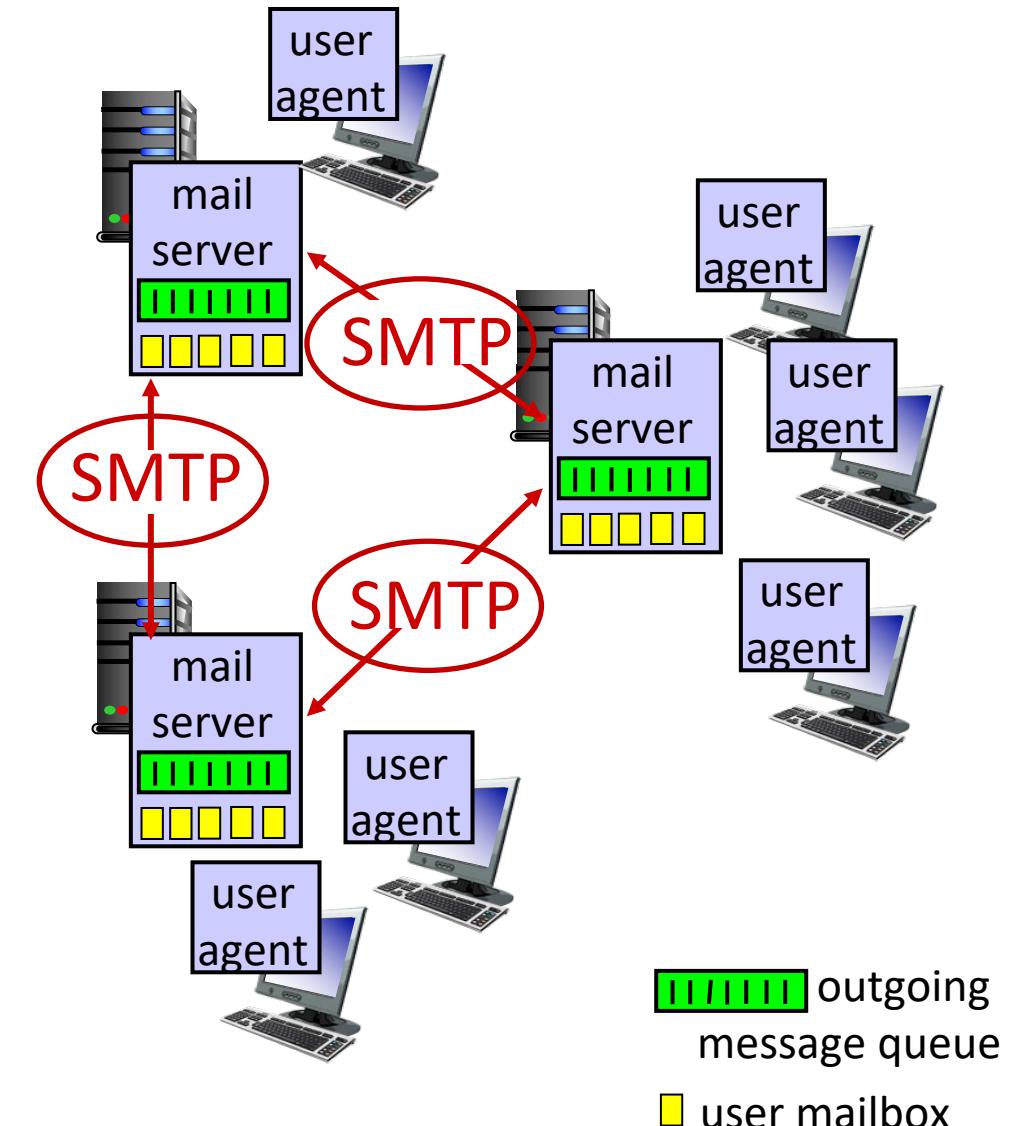
**SMTP protocol** between mail servers to send email messages

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

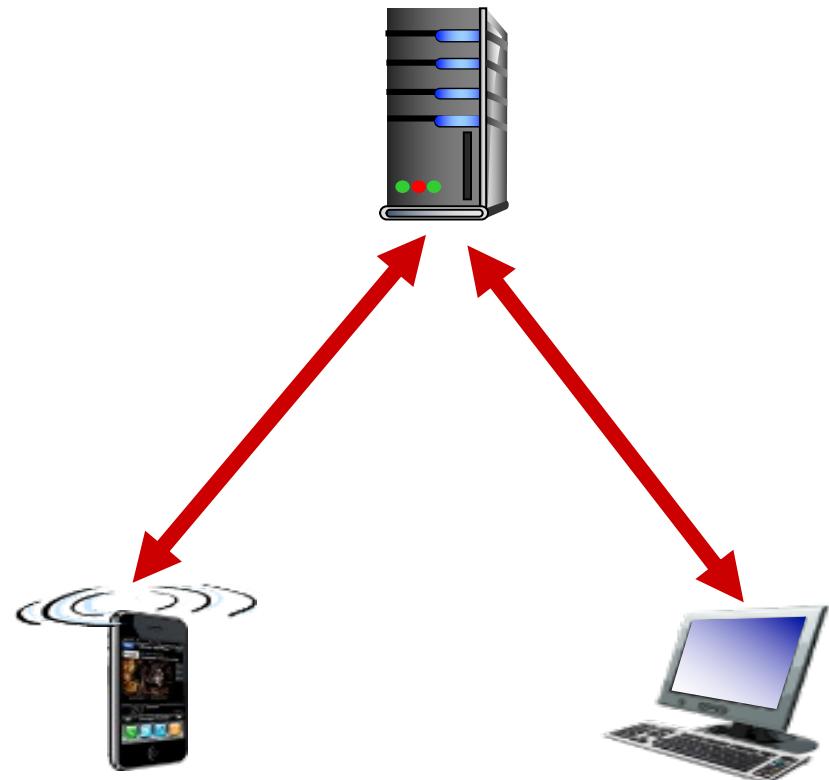


# E-mail: mail servers

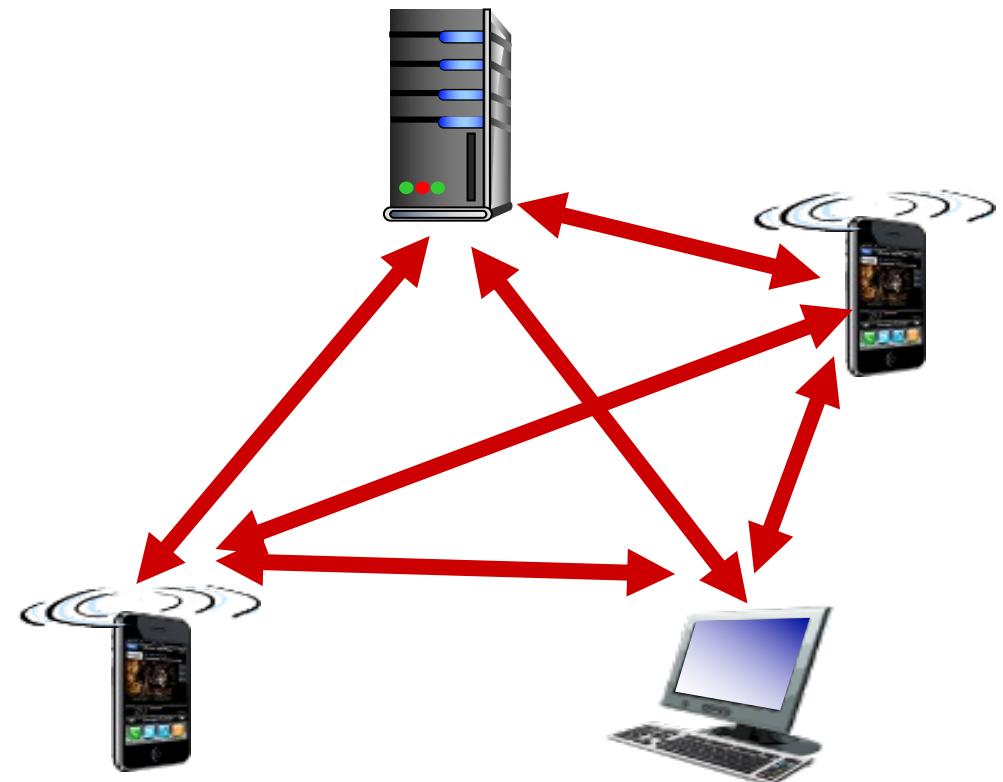
**SMTP protocol** between mail servers to send email messages



# Two widely adopted paradigm



**Server-Client Mode**

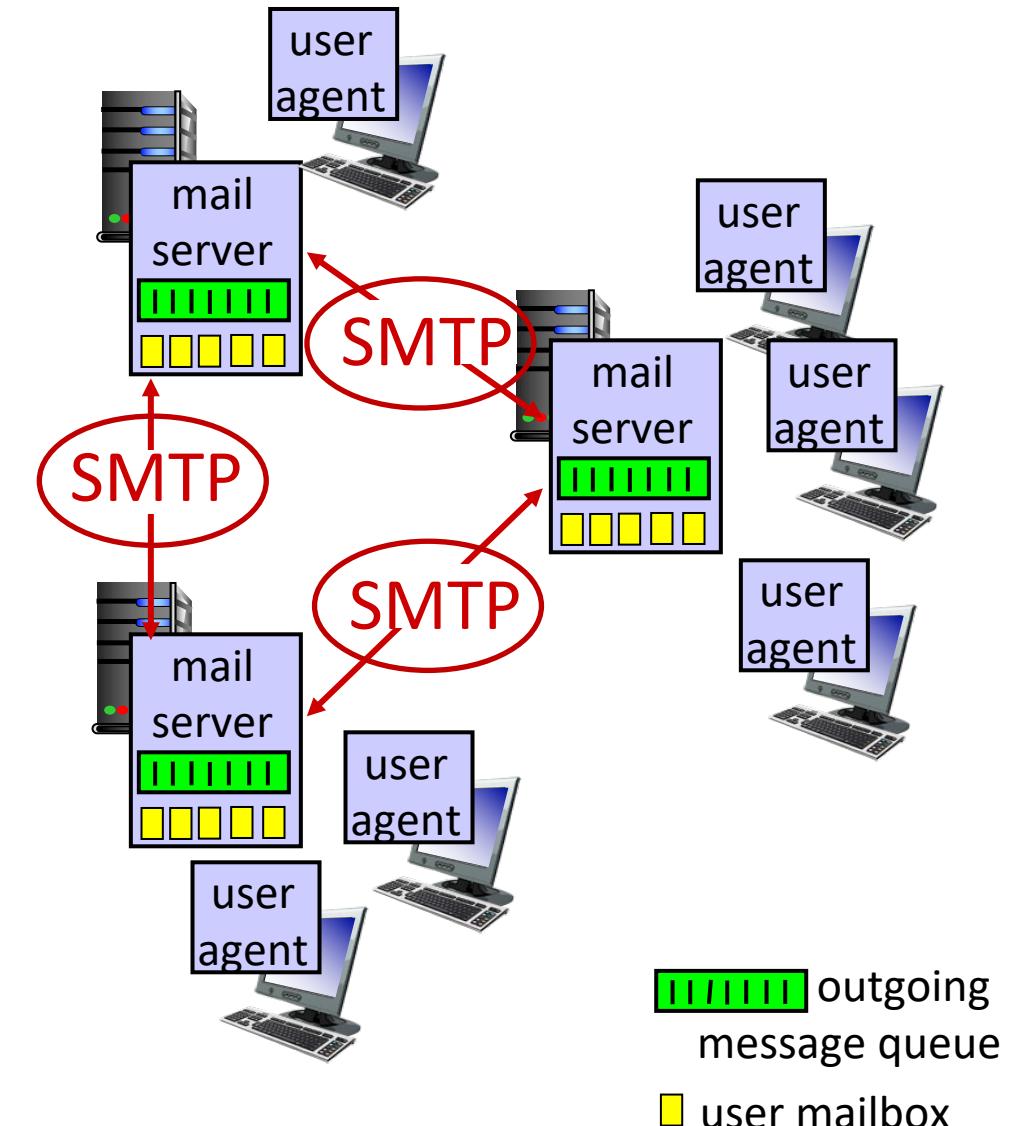
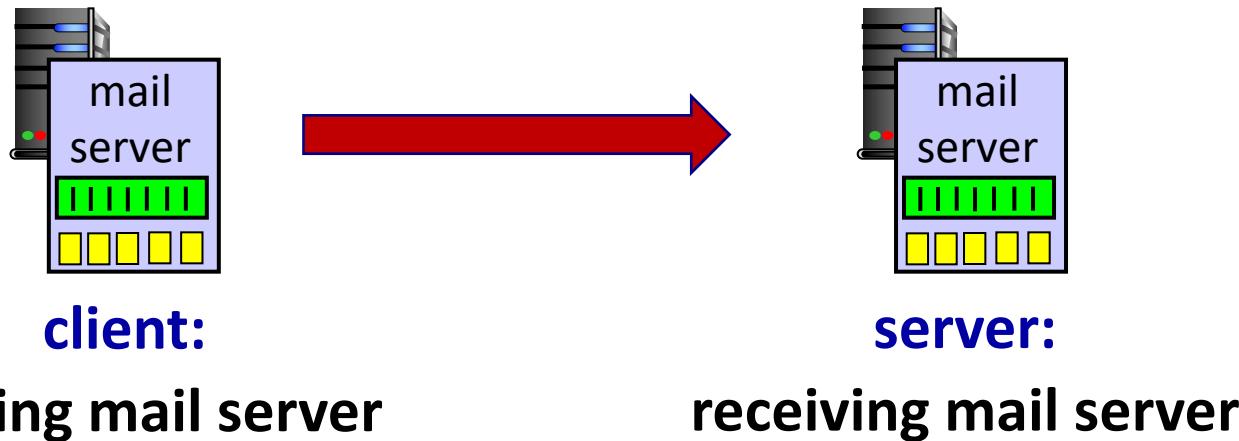


**P2P Mode**

# E-mail: mail servers

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

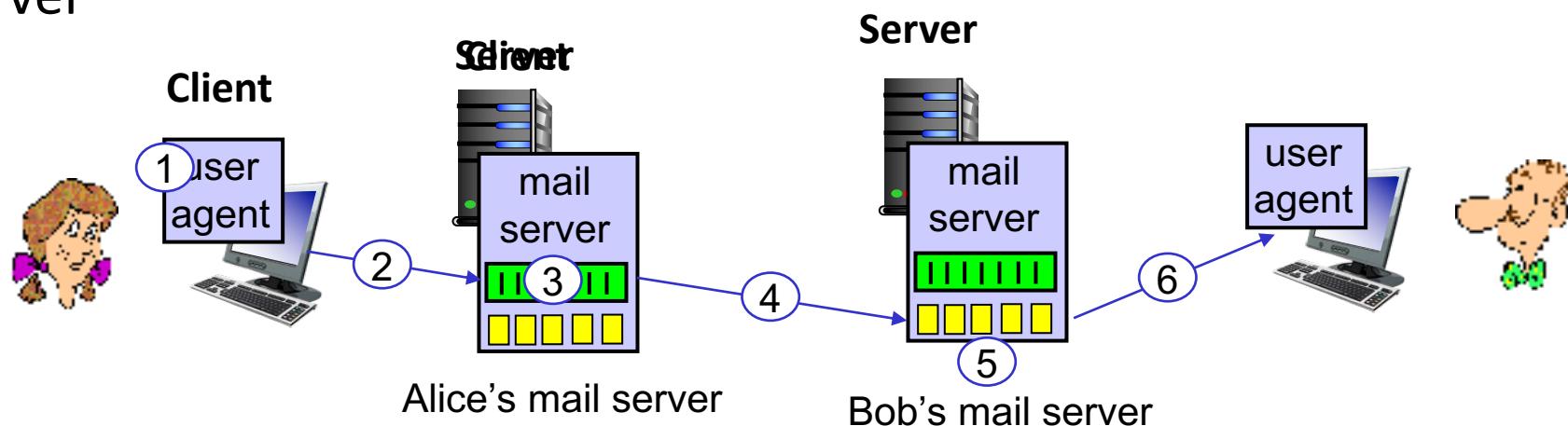
- client: sending mail server
- server: receiving mail server



# Scenario: Alice sends e-mail to Bob

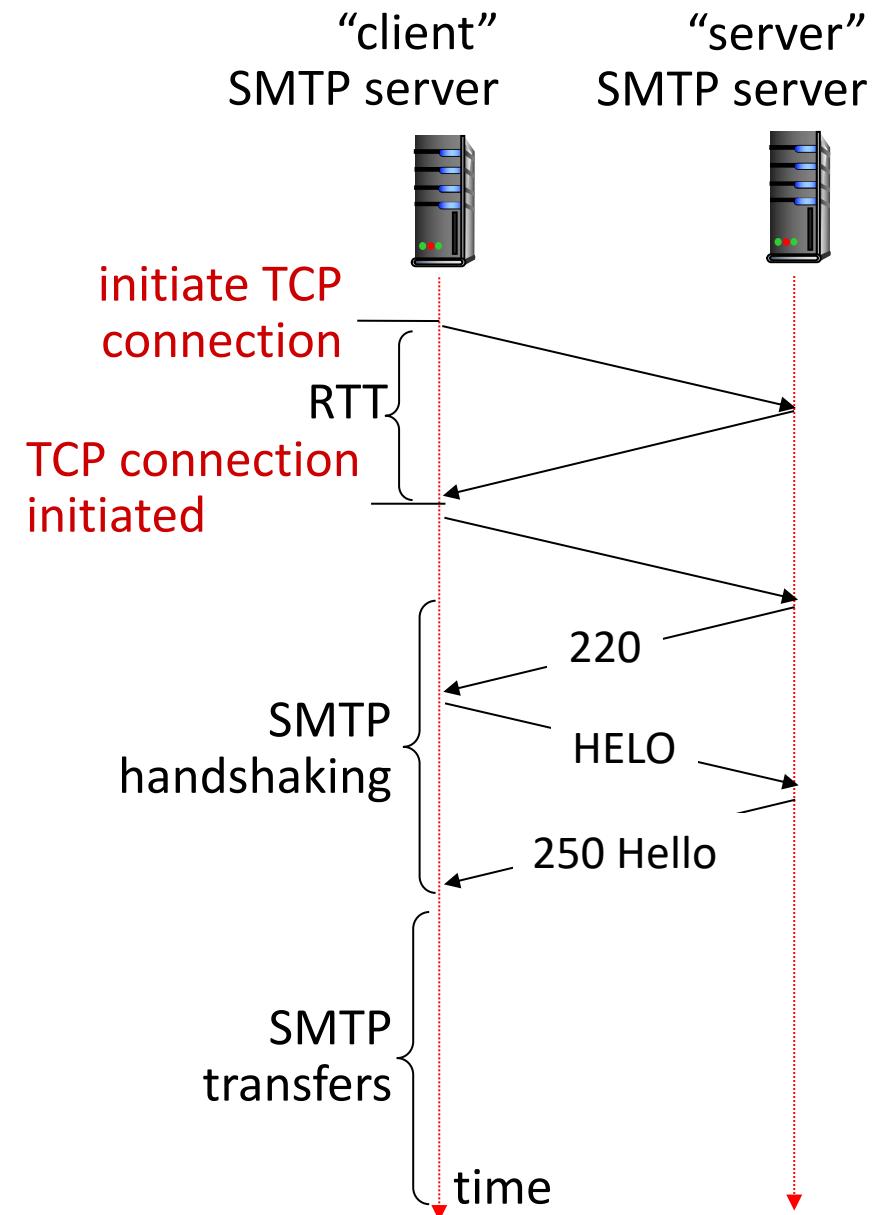
- 1) Alice uses UA to compose e-mail message “to” bob@someschool.edu
- 2) Alice’s UA sends message to her mail server using SMTP; message placed in message queue
- 3) client side of SMTP at mail server opens TCP connection with Bob’s mail server

- 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



# SMTP RFC (5321)

- uses TCP to reliably transfer email messages 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



# 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

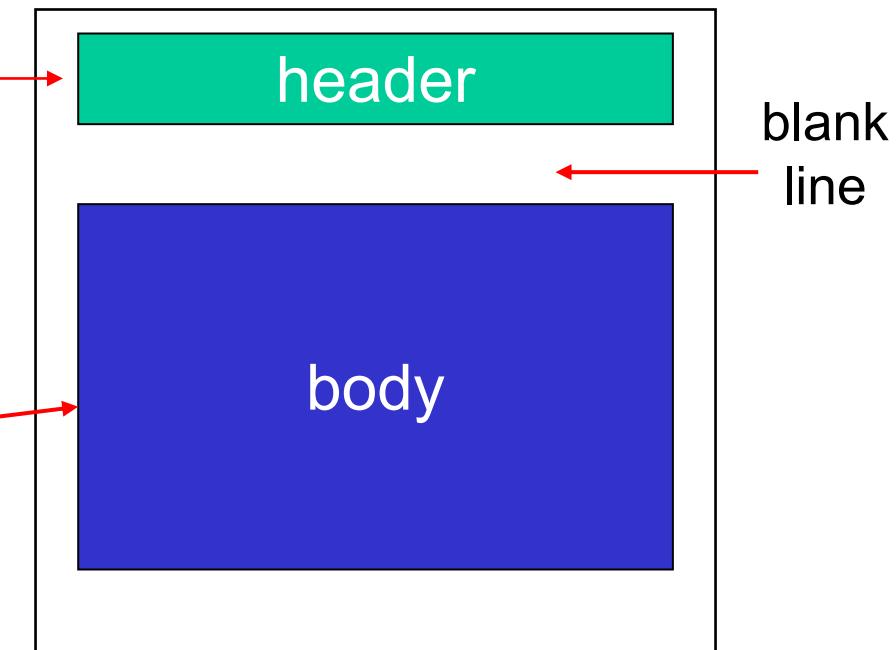
# Mail message format

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

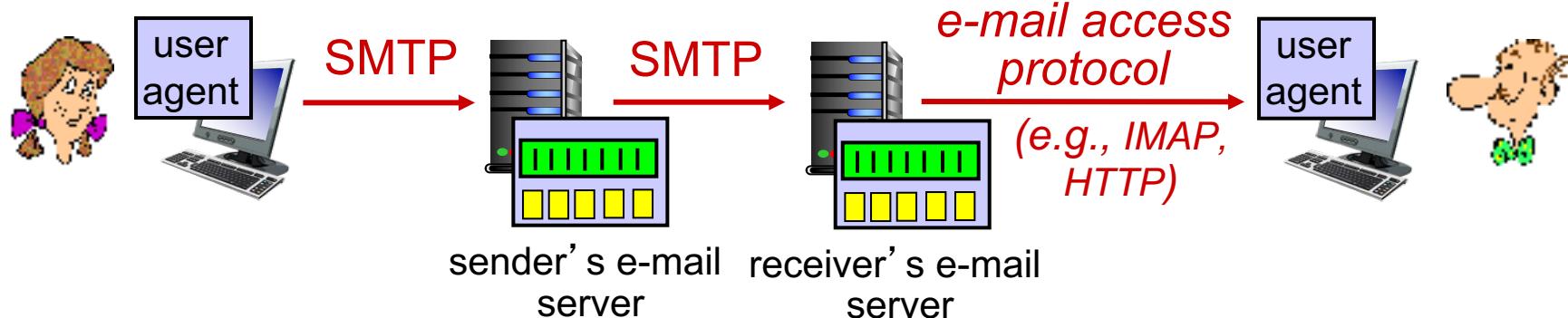
RFC 2822 defines *syntax* for e-mail message itself (like HTML defines syntax for web documents)

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



# DNS: Domain Name System

*people*: many identifiers:

- SSN, name, passport #

*Internet hosts, routers*:

- IP address (32 bit, e.g. 12.115.66.89) - used for addressing datagrams
- “name”, e.g., www.google.com - 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

*www.google.com*



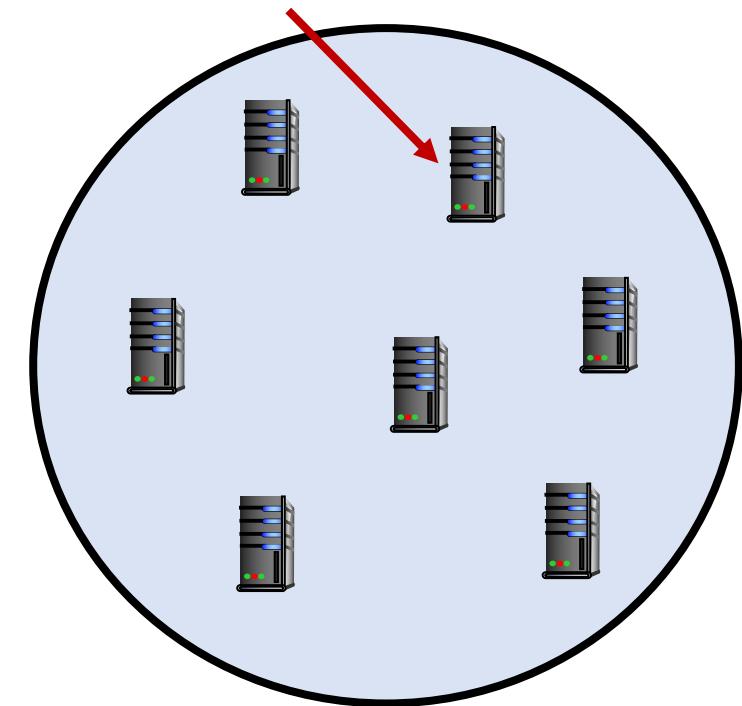
12.34.56.78

# DNS: services, structure

## DNS services:

- hostname-to-IP-address translation
- host aliasing
  - canonical, alias names

*www.google.com/abc/edf/ghj*

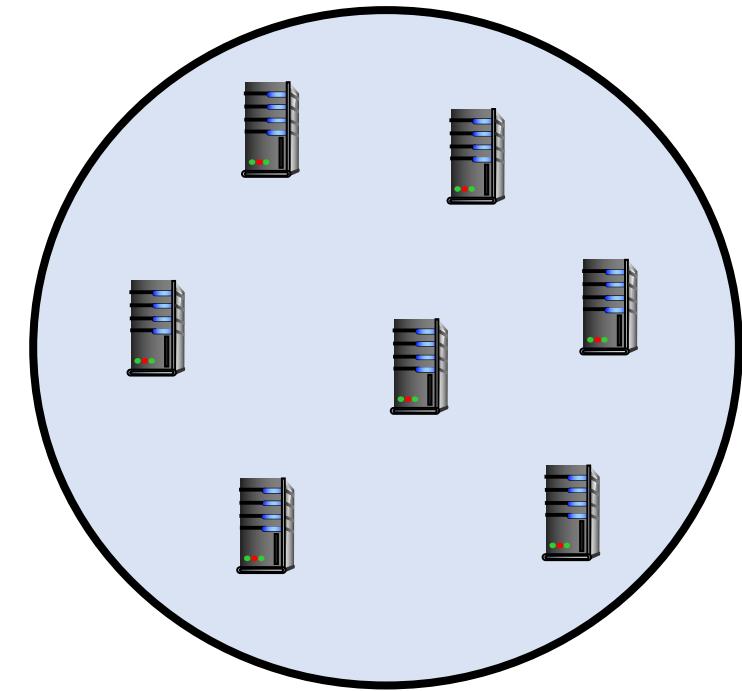


*www.google.com*

# DNS: services, structure

## DNS services:

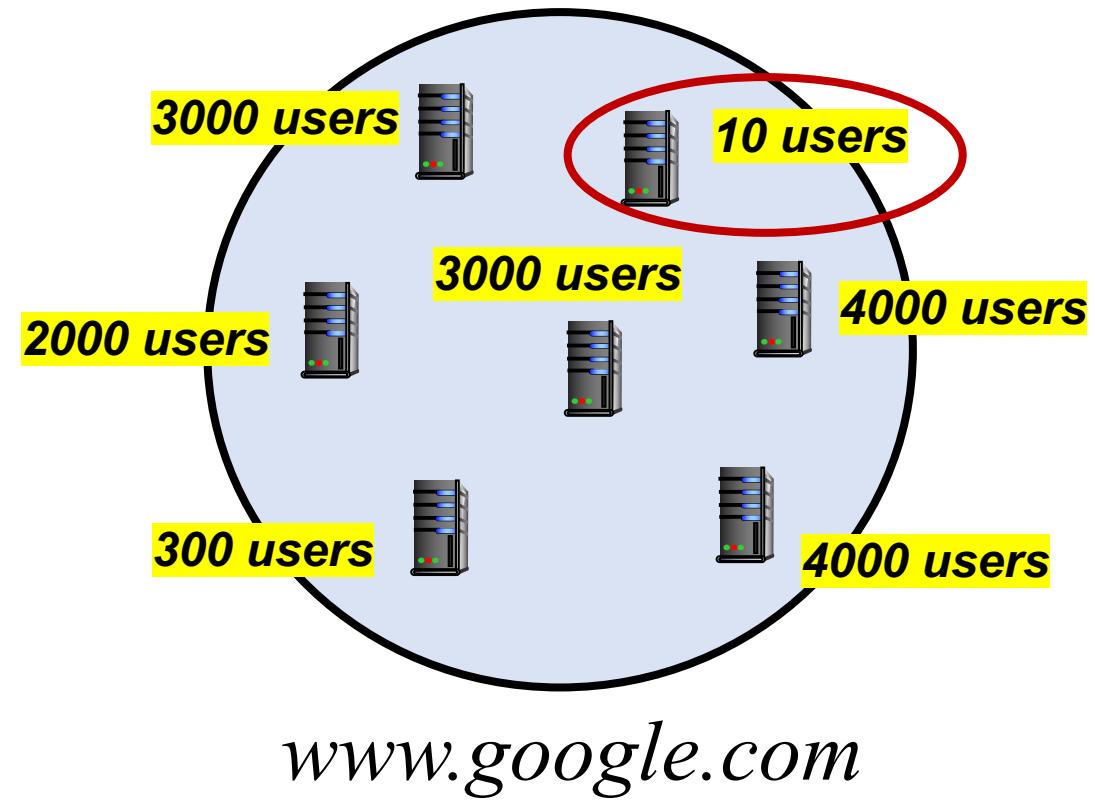
- hostname-to-IP-address translation
- host aliasing
  - canonical, alias names
- mail server aliasing



# 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



*www.google.com*

# 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

**Size:** humongous distributed database:

- ~ billion records, each simple

**Performance:** handles many *trillions* of queries/day:

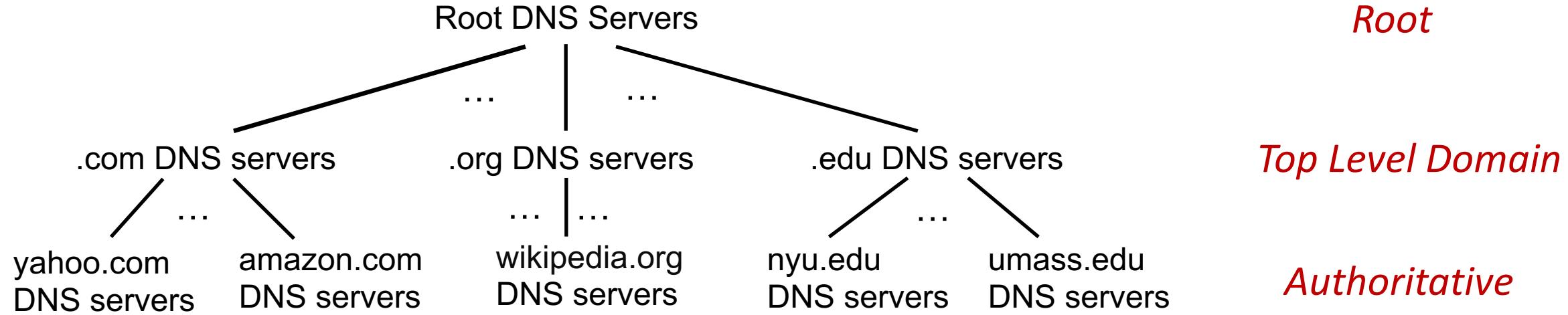
- *many* more reads than writes
- *performance matters*: almost every Internet transaction interacts with DNS - msecs count!

**Geographical distribution:** organizationally, physically decentralized:

- millions of different organizations responsible for their records

**“bulletproof”:** reliability, security

# DNS: a distributed, hierarchical database

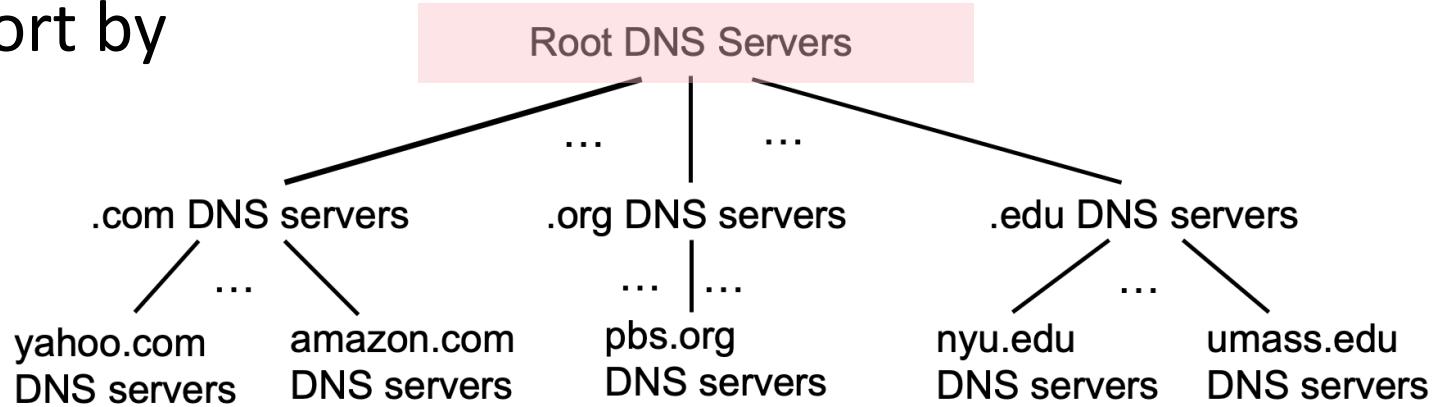


Client wants IP address for [www.amazon.com](http://www.amazon.com); 1<sup>st</sup> approximation:

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

# DNS: root name servers

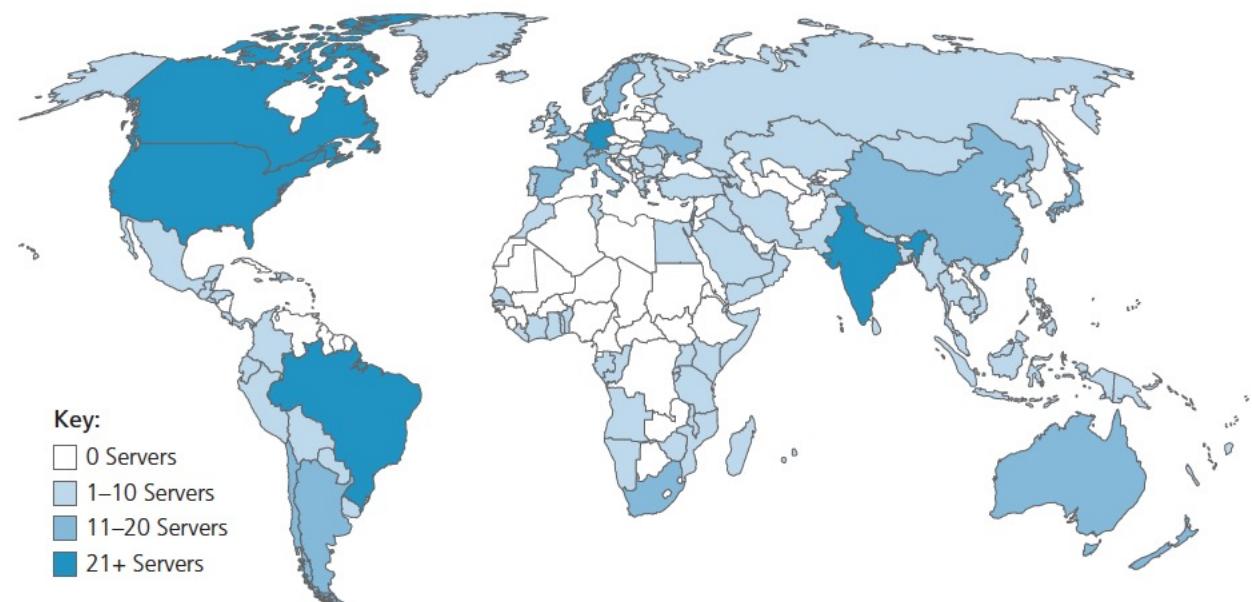
- official, contact-of-last-resort by name servers that can not resolve name



# DNS: root name servers

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

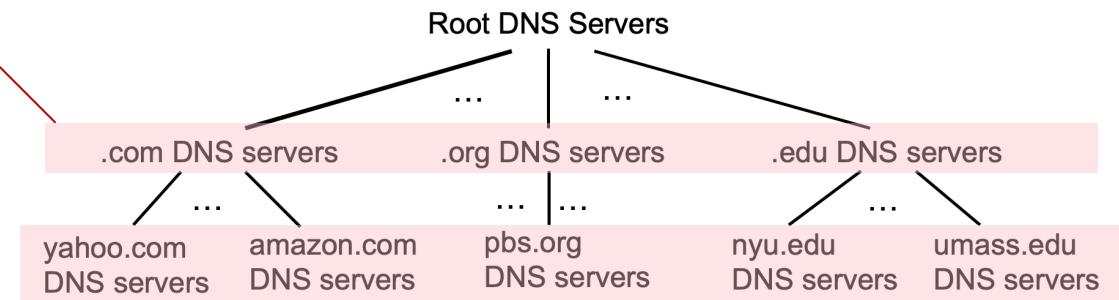
13 logical root name “servers” worldwide each “server” replicated many times (~200 servers in US)



# 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

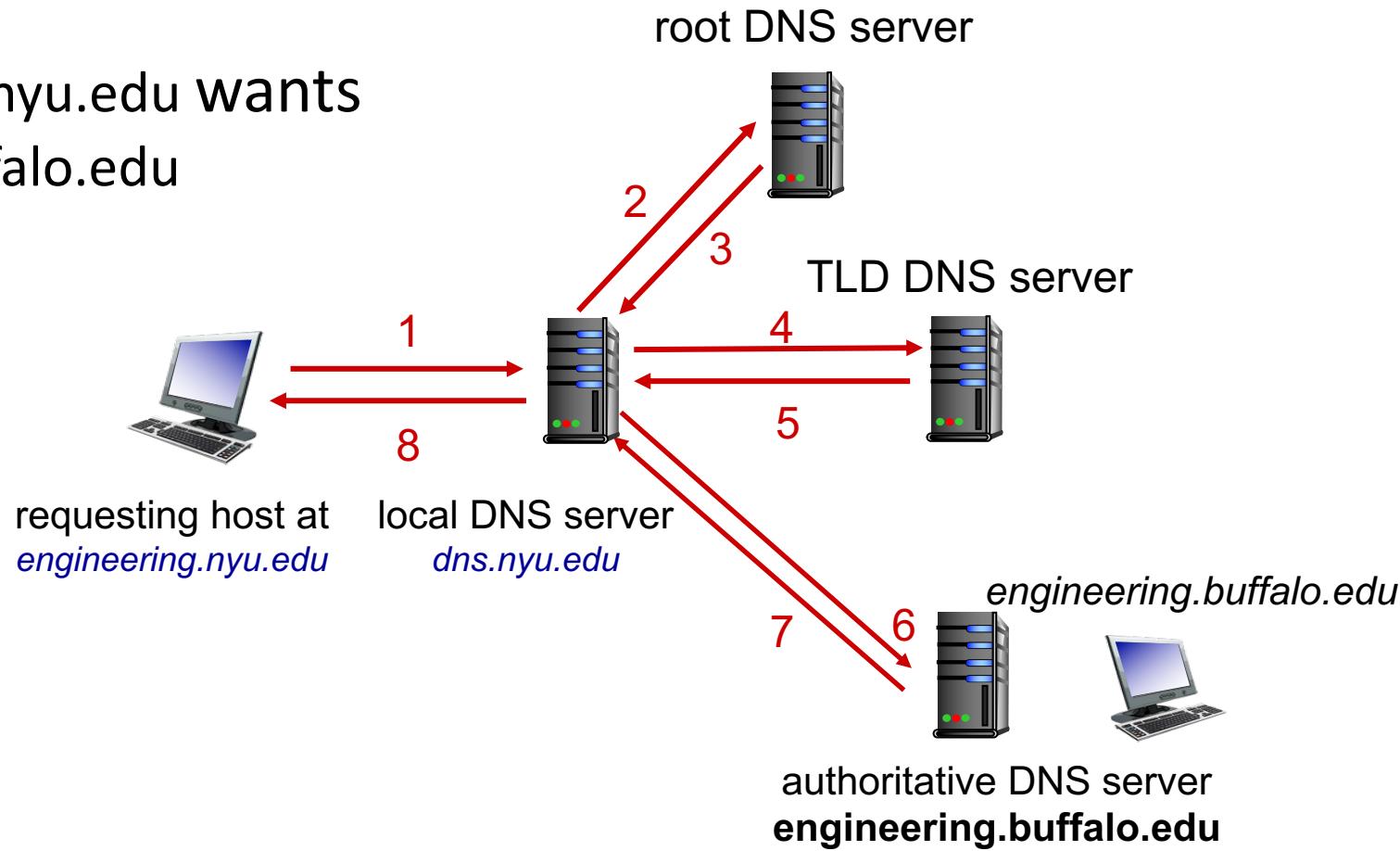
- when host makes DNS query, it is sent to its *local* DNS server
  - Local DNS server returns reply, answering:
    - from its local cache of recent name-to-address translation pairs (possibly out of date!)
    - forwarding request into DNS hierarchy for resolution
  - each ISP has local DNS name server;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

## Iterated query:

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

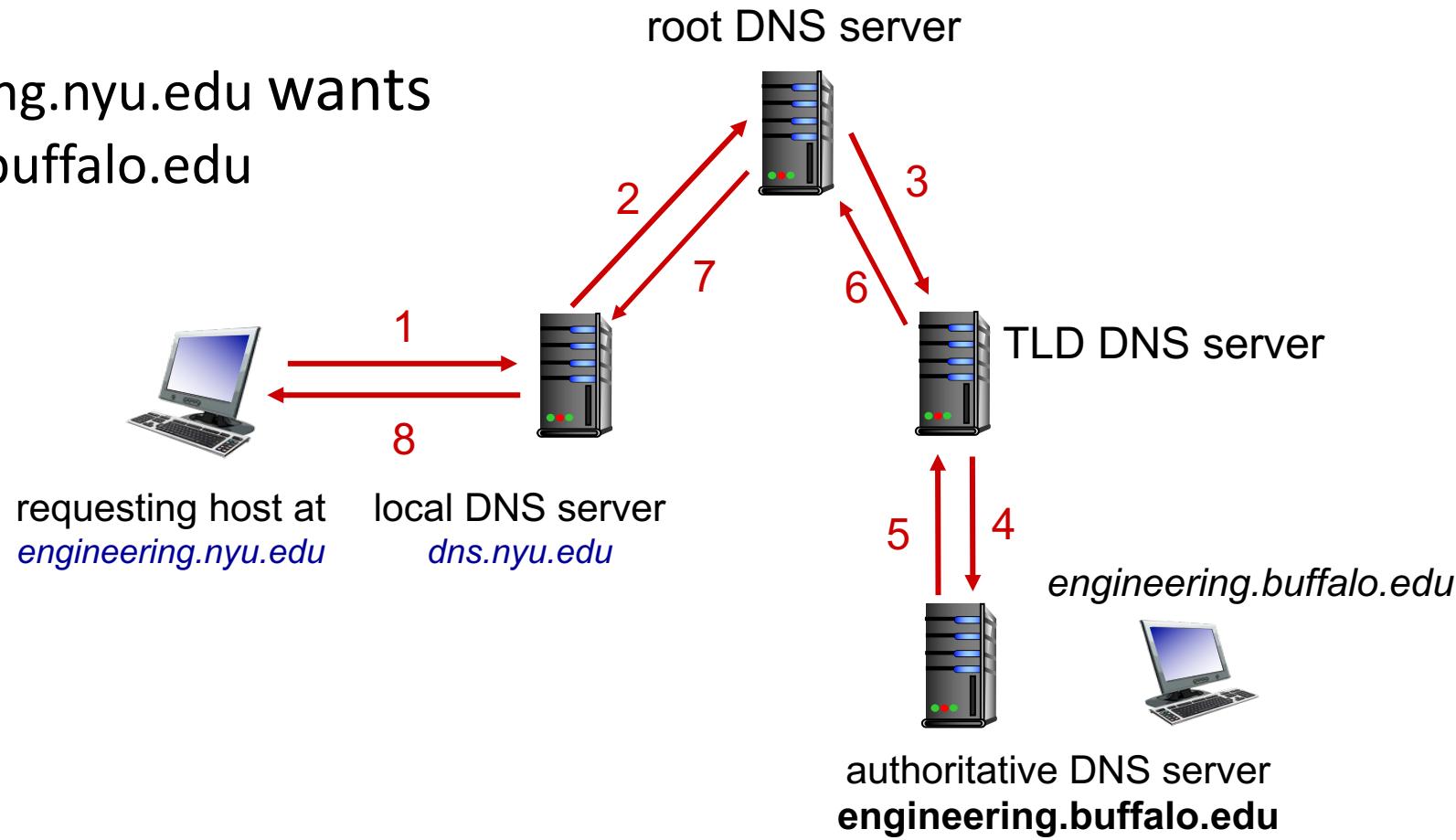


# DNS name resolution: recursive query

Example: host at engineering.nyu.edu wants IP address for engineering.buffalo.edu

## Recursive query:

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



# Caching DNS Information

- once (any) name server learns mapping, it *caches* mapping, and *immediately* returns a cached mapping in response to a query
  - caching improves response time
  - cache entries **timeout (disappear) after some time (TTL)**
  - TLD servers typically cached in local name servers
- cached entries may be *out-of-date*
  - if the 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 severeast.backup2.ibm.com
- value is canonical name

## **type=MX**

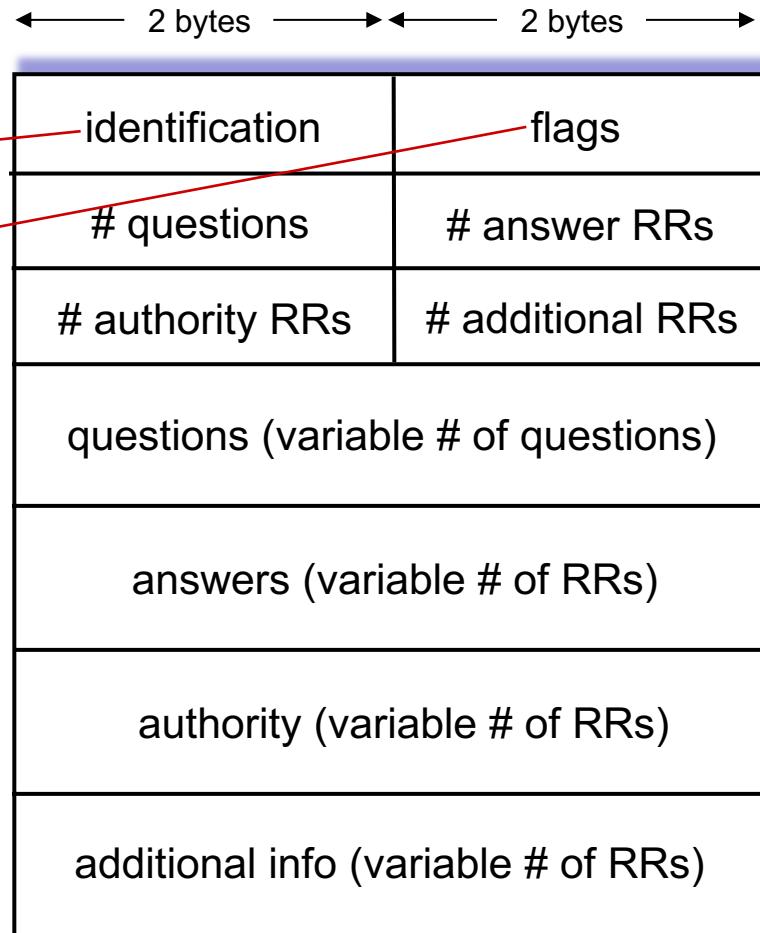
- value is name of SMTP mail server associated with name

# 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

—

questions (variable # of questions)

RRs in response to query

—

answers (variable # of RRs)

records for authoritative servers

—

authority (variable # of RRs)

additional “helpful” info that may  
be used

—

additional info (variable # of RRs)

# 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 info 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

Q: Does DNS use UDP or TCP?

# DNS security

## DDoS attacks

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

## Spoofing attacks

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

# Application Layer: Overview

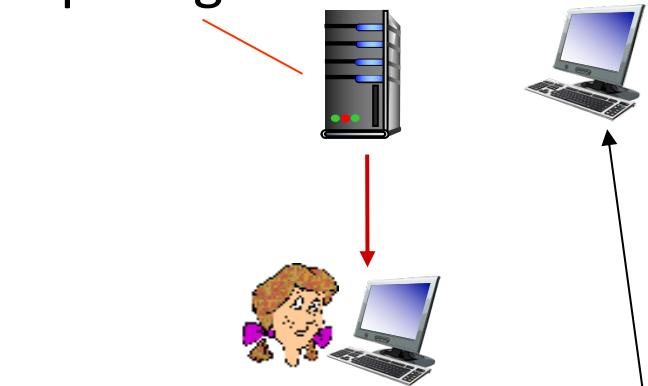
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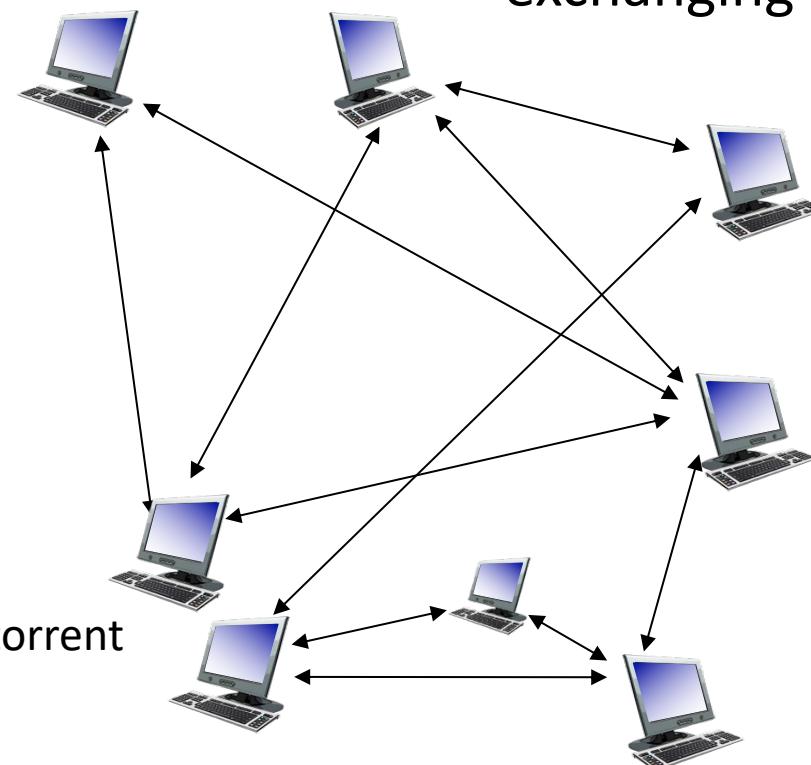
# P2P file distribution: BitTorrent

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

*tracker:* tracks peers  
participating in torrent



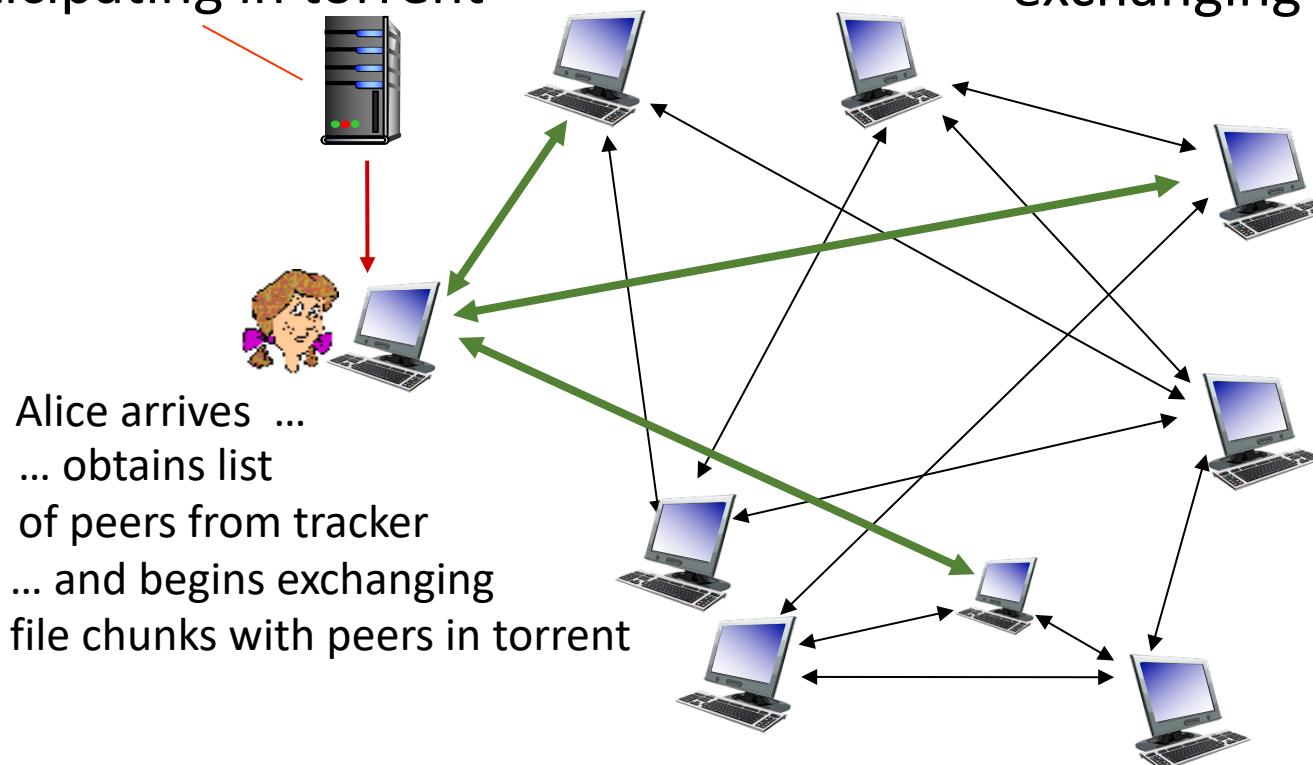
*torrent:* group of peers  
exchanging chunks of a file



# P2P file distribution: BitTorrent

- file divided into 256Kb chunks
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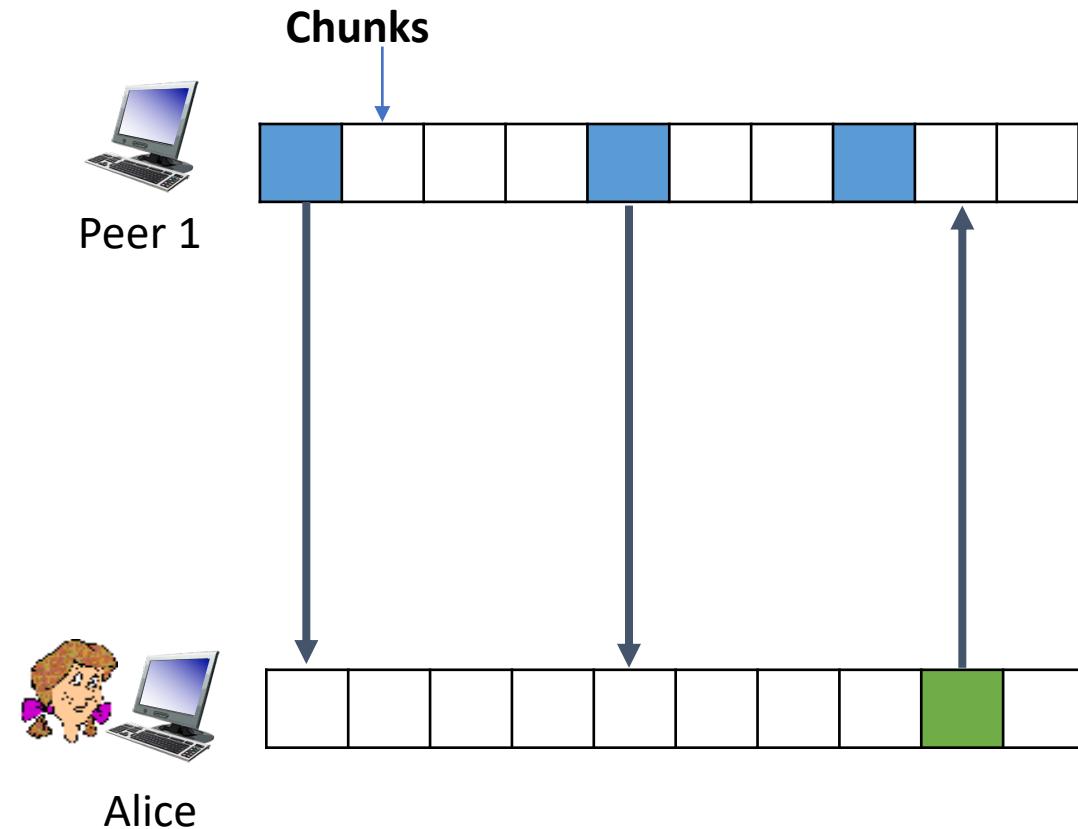
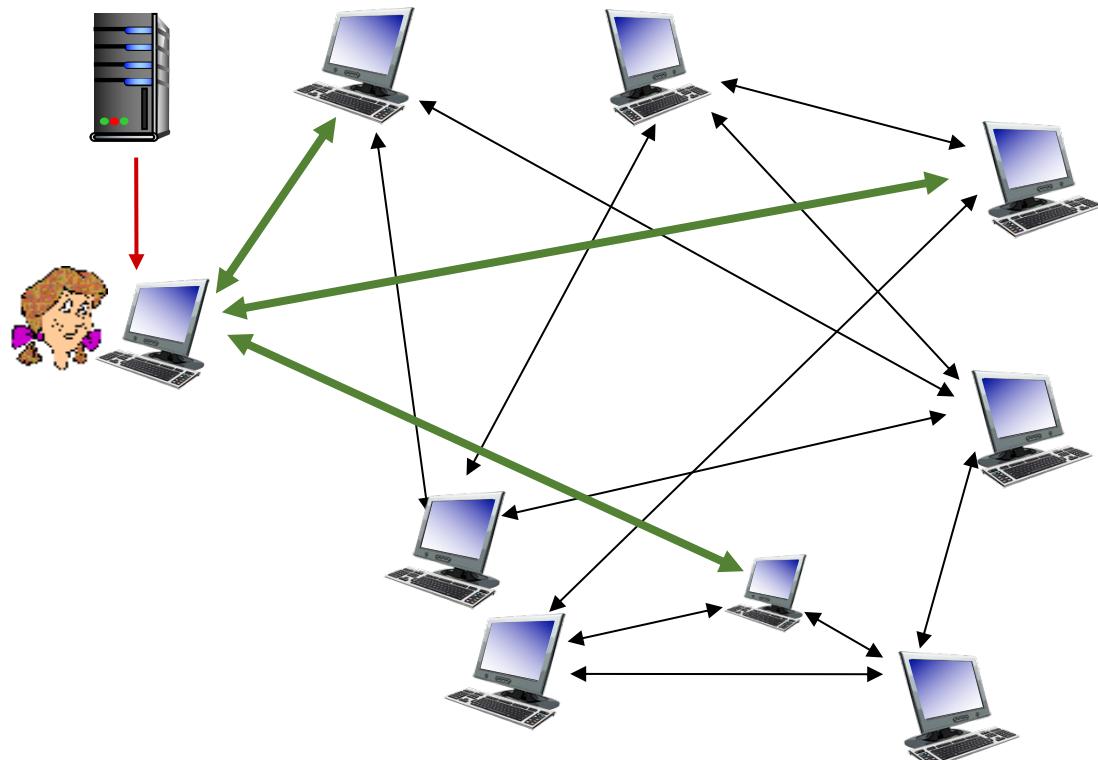
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*torrent:* group of peers  
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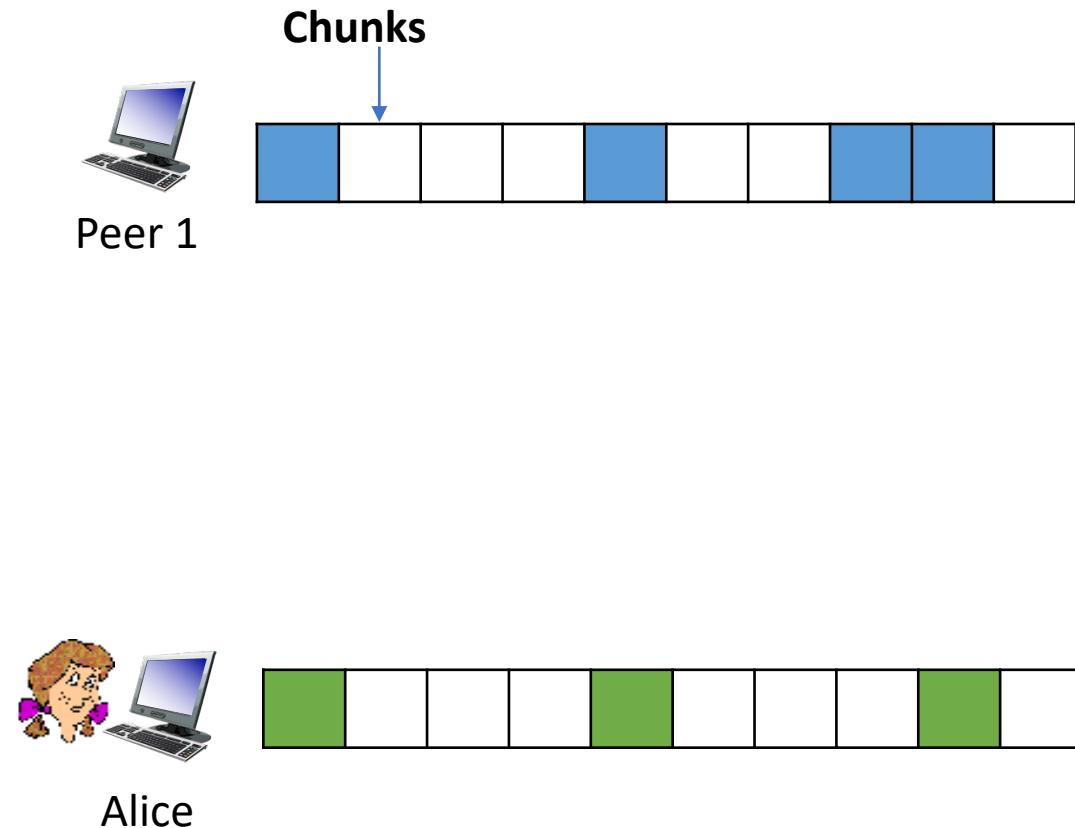
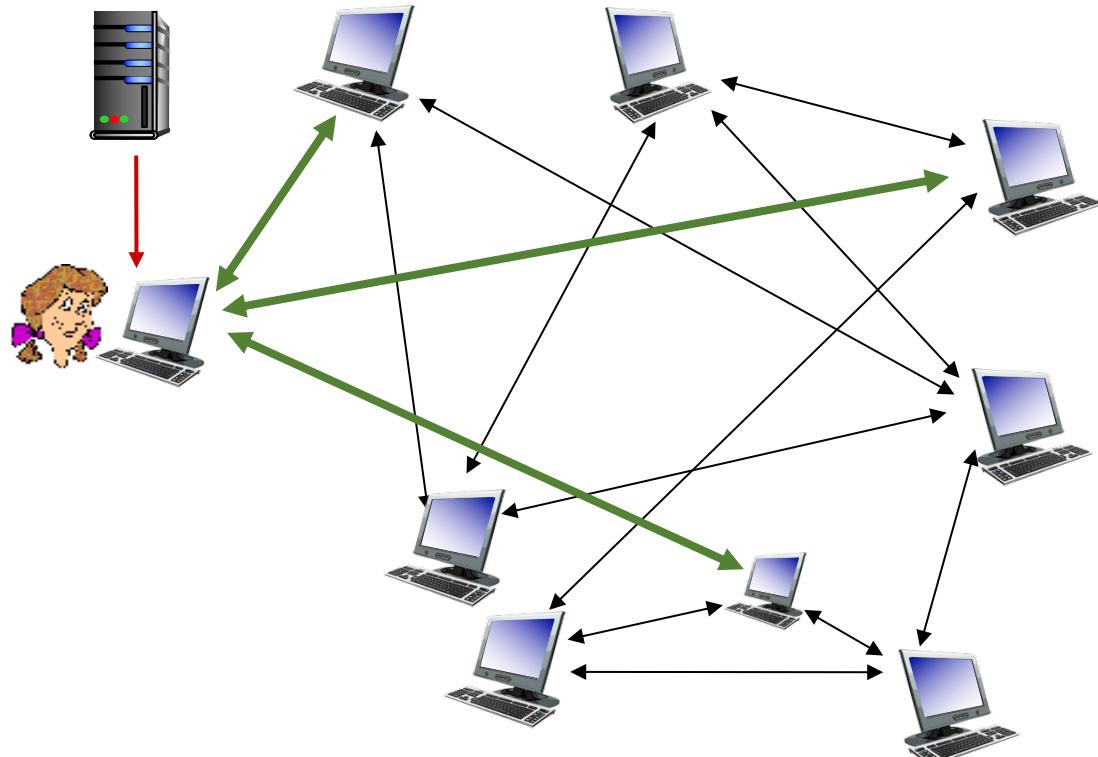
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- file divided into 256Kb chunks
- peers in torrent send/receive file chunks



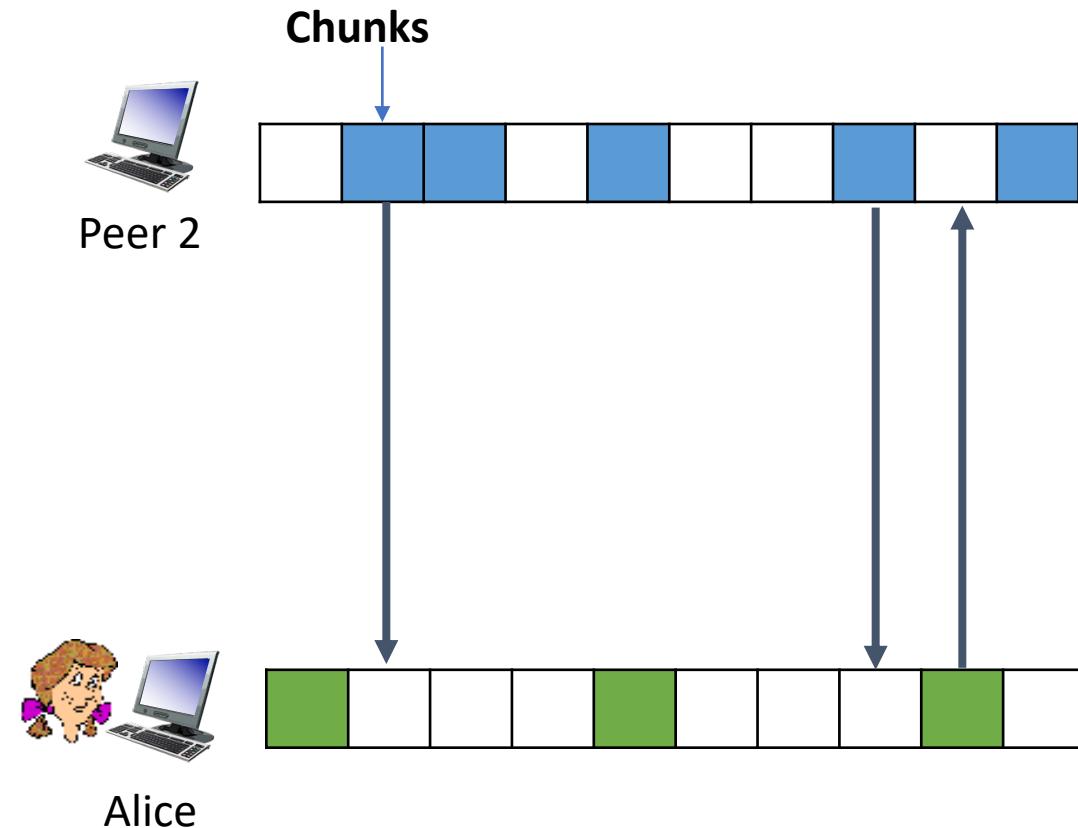
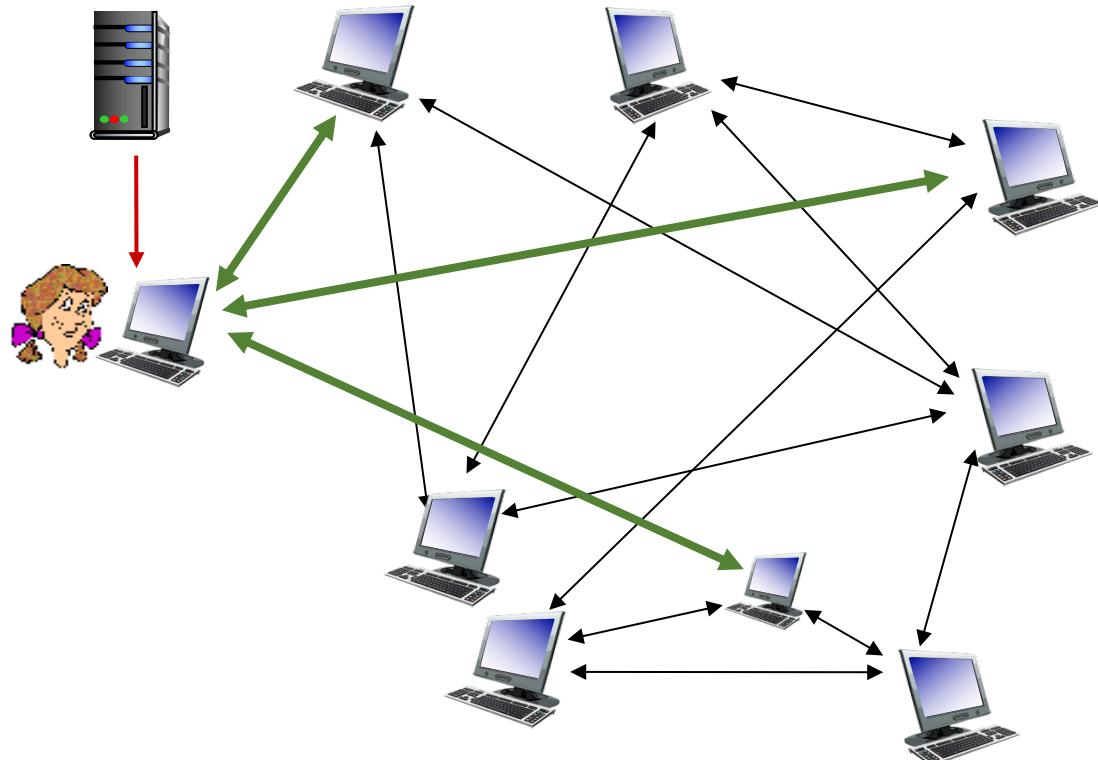
# P2P file distribution: BitTorrent

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



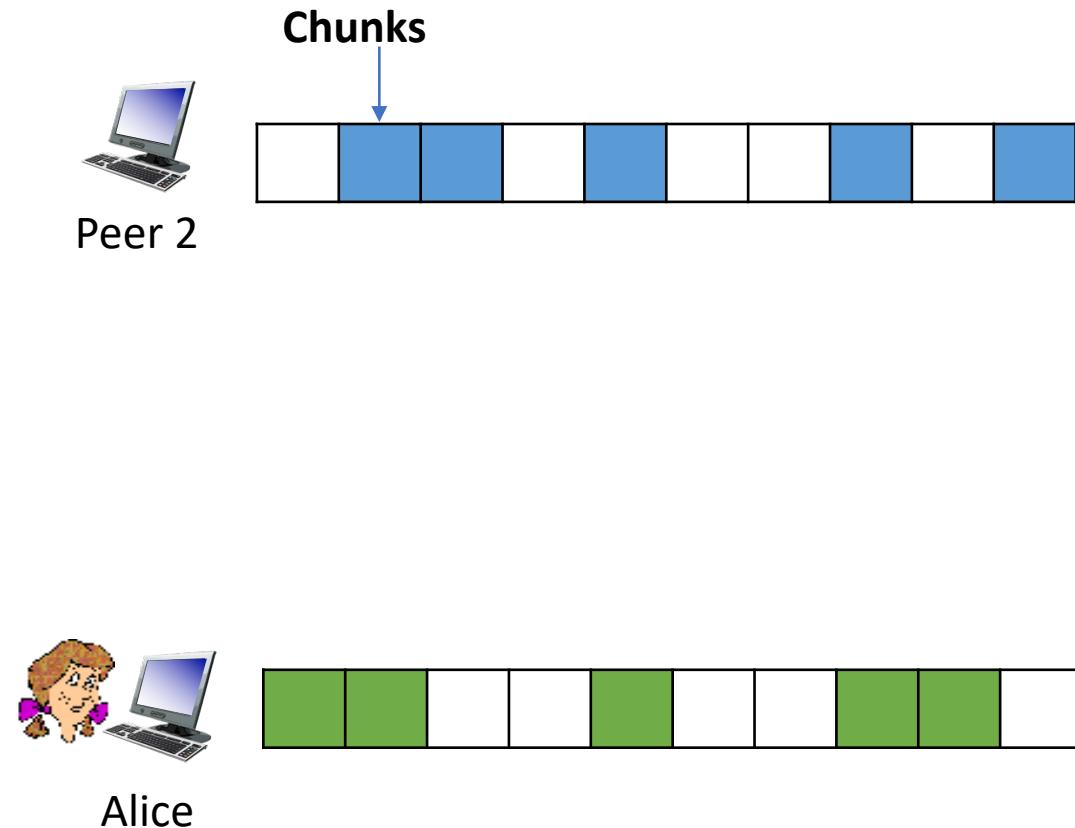
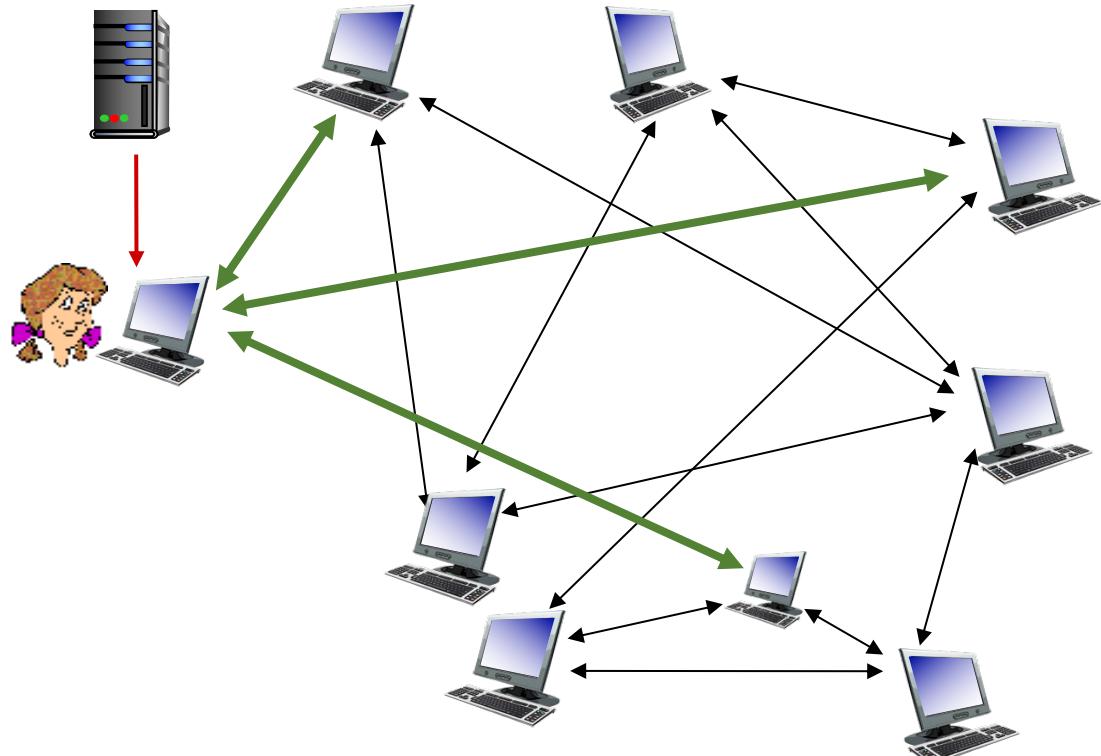
# P2P file distribution: BitTorrent

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



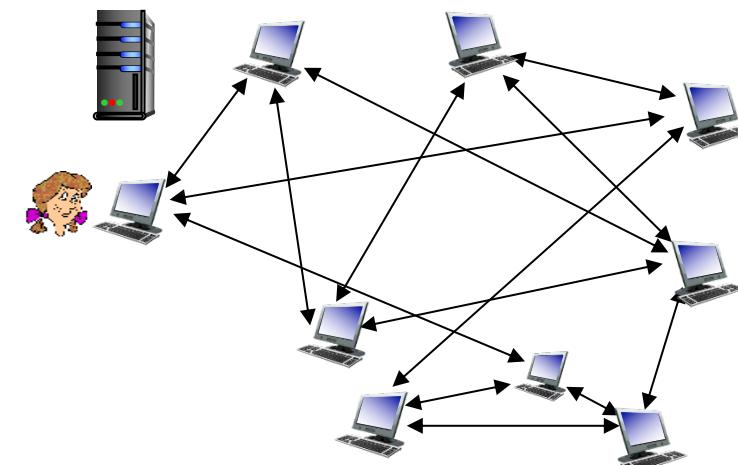
# P2P file distribution: BitTorrent

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

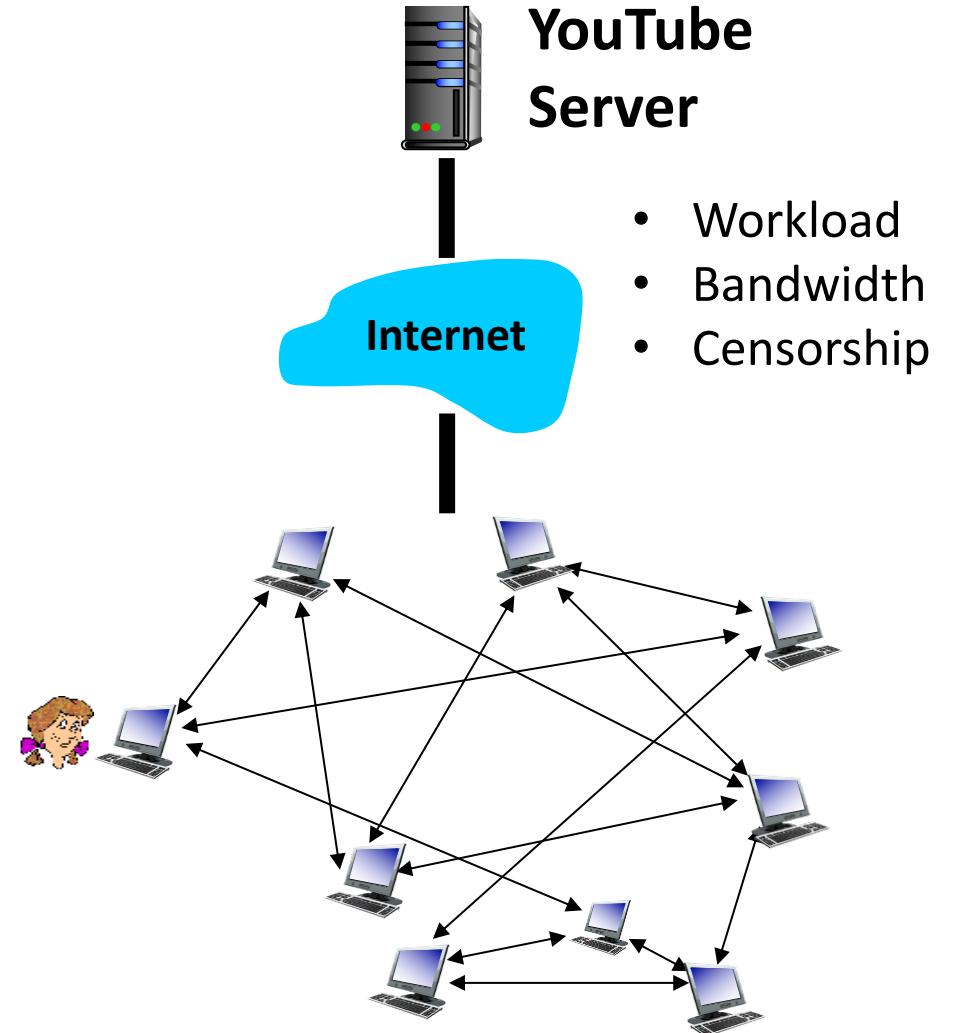
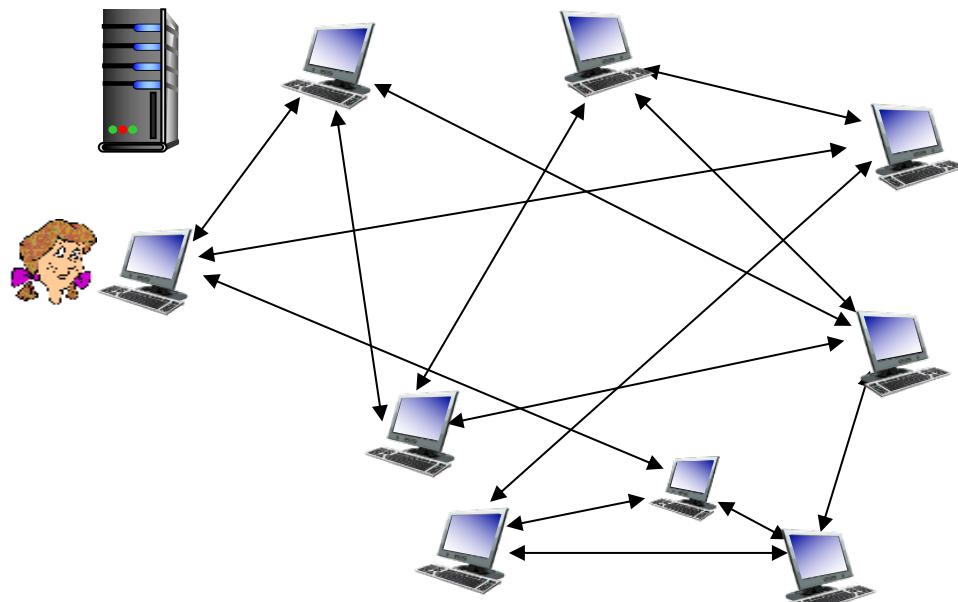


# P2P file distribution: BitTorrent

- while downloading, peer uploads chunks to other peers
- peer may change peers with whom it exchanges chunks
- Peers may come and go
- once peer has entire file, it may (selfishly) leave or (altruistically) remain in torrent



# P2P file distribution: BitTorrent WHY?



- Workload
- Bandwidth
- Censorship

# Application layer: overview

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



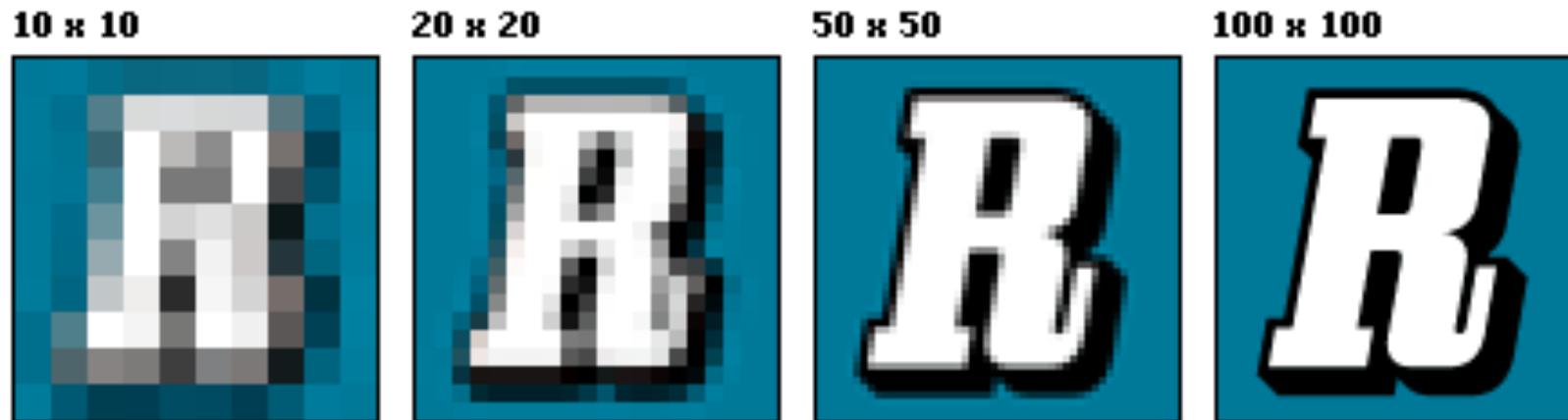
# Video Streaming and CDNs: context

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



# 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



# Multimedia: video coding

- Why we need video coding?

**8000x5000**



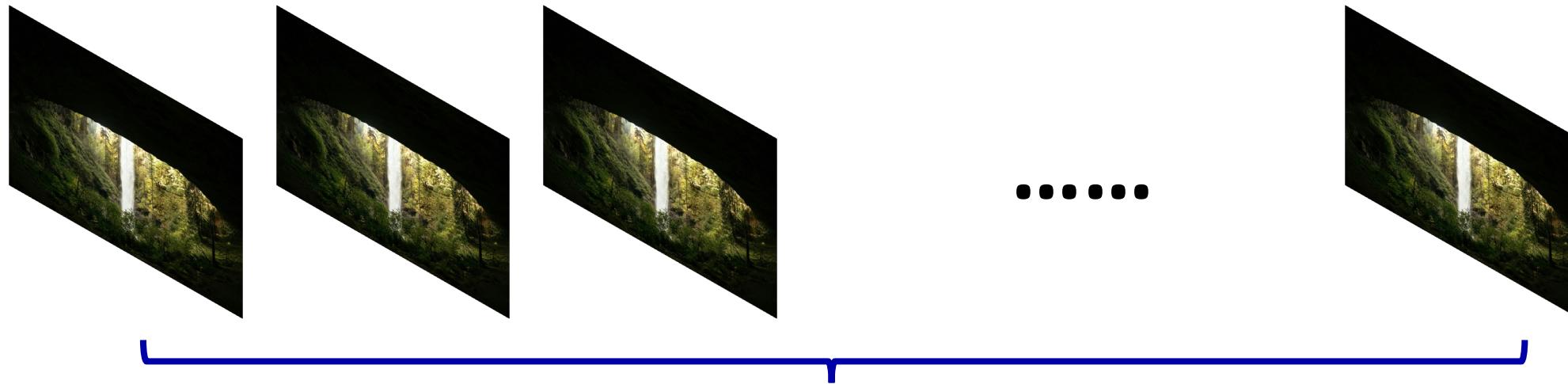
# Multimedia: video coding

- Why we need video coding?



**Example:** a video with **30 fps**

**8 MByte = 64 Mbit**

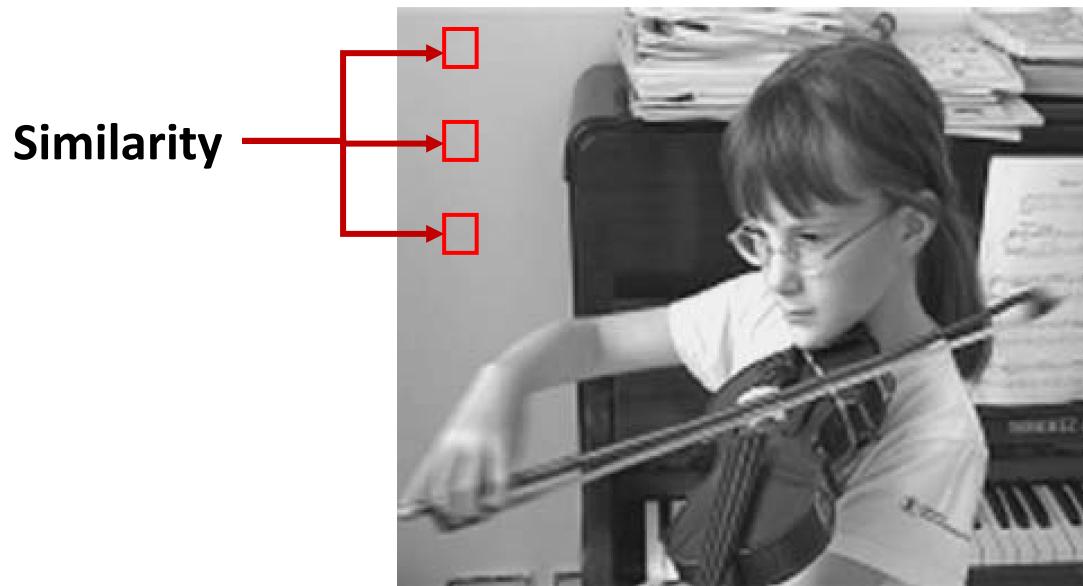


**30 images per second**

**Data Rate:**  $30 \times 60 \text{ Mbit} = 1800 \text{ Mbps} = 1.8 \text{ Gbps}$

# Multimedia: video coding

- coding: leveraging redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)



# Multimedia: video coding

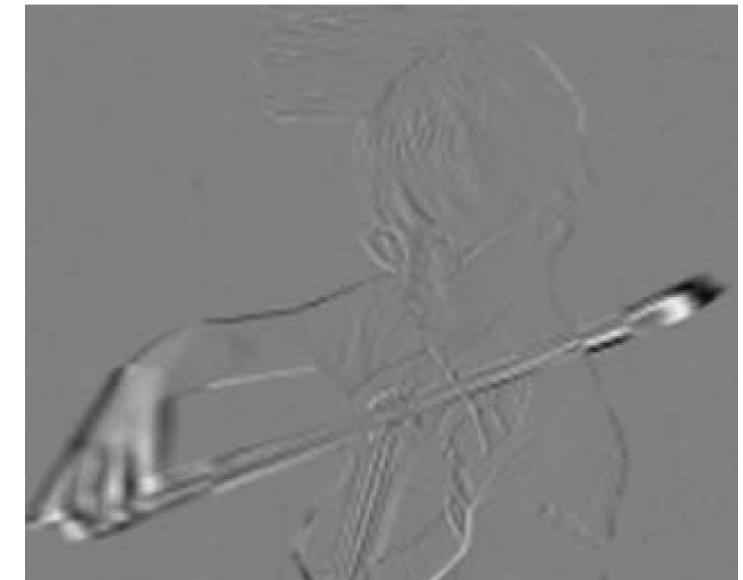
- coding: leveraging redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)



Frame i



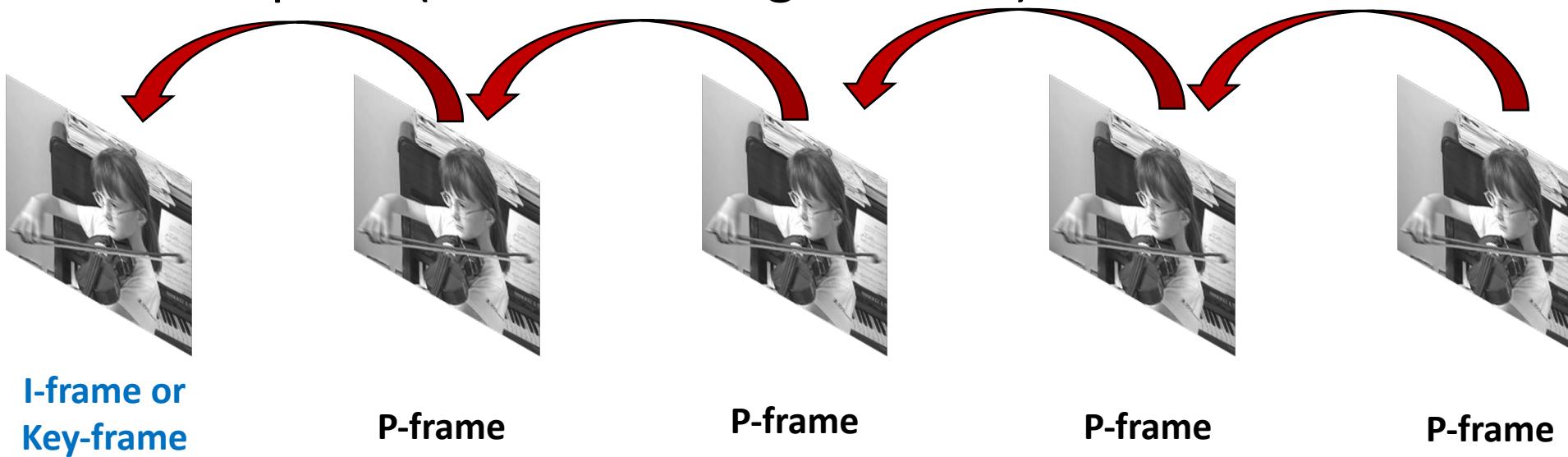
Frame i+1



Difference between frames

# Multimedia: video coding

- coding: leveraging redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)



# Multimedia: video coding

- coding: leveraging redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)



I-frame or  
Key-frame      P-frame      P-frame      P-frame      P-frame

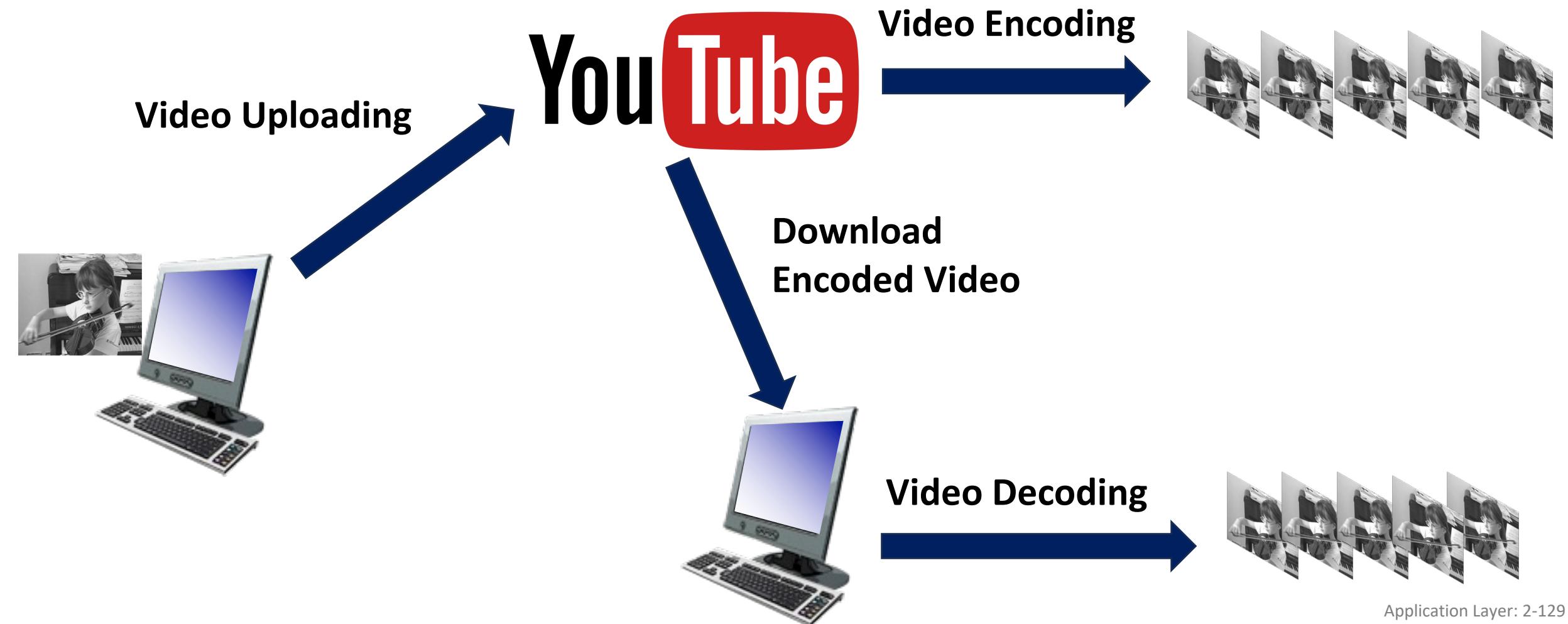


I-frame or  
Key-frame      P-frame      P-frame      P-frame      P-frame

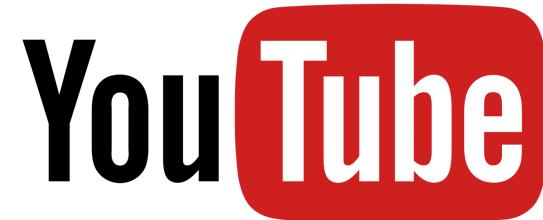
# Video Streaming Applications



# Video Streaming Applications: Encoding



# Video Streaming Applications: QoE (Quality of User Experience)



## Video Start Time

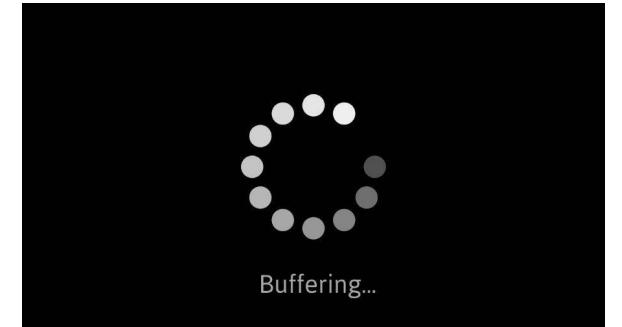
The time between your click of the video and the playing of the video



## Video Quality



## Rebuffering Event



# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



PSY - GENTLEMAN M/V



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PSY - 'I LUV IT' M/V @ PSY - 'I LUV IT' M/V  
PSY - 'I LUV IT' M/V @ PSY - 'I LUV IT' M/V

# Streaming multimedia: DASH

Dynamic, Adaptive Streaming over *HTTP*



PSY - GENTLEMAN M/V

 officialpsy 18.5M subscribers

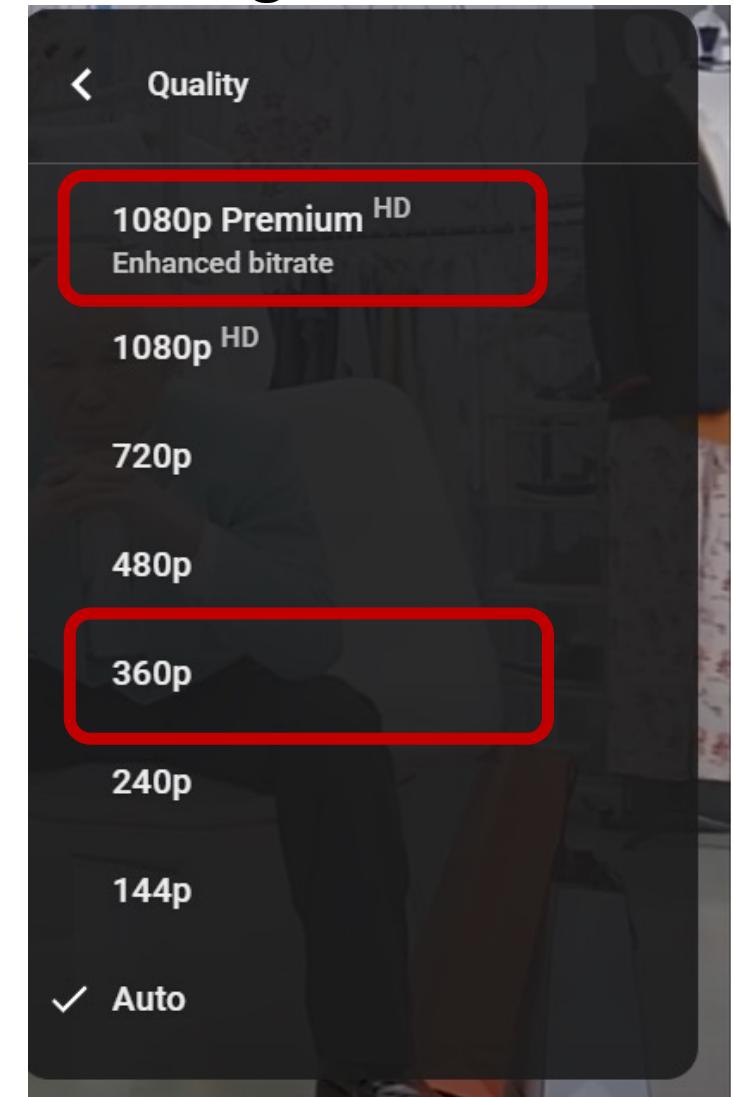
Subscribe

Like 8.4M | Dislike Share Download Clip Save ...

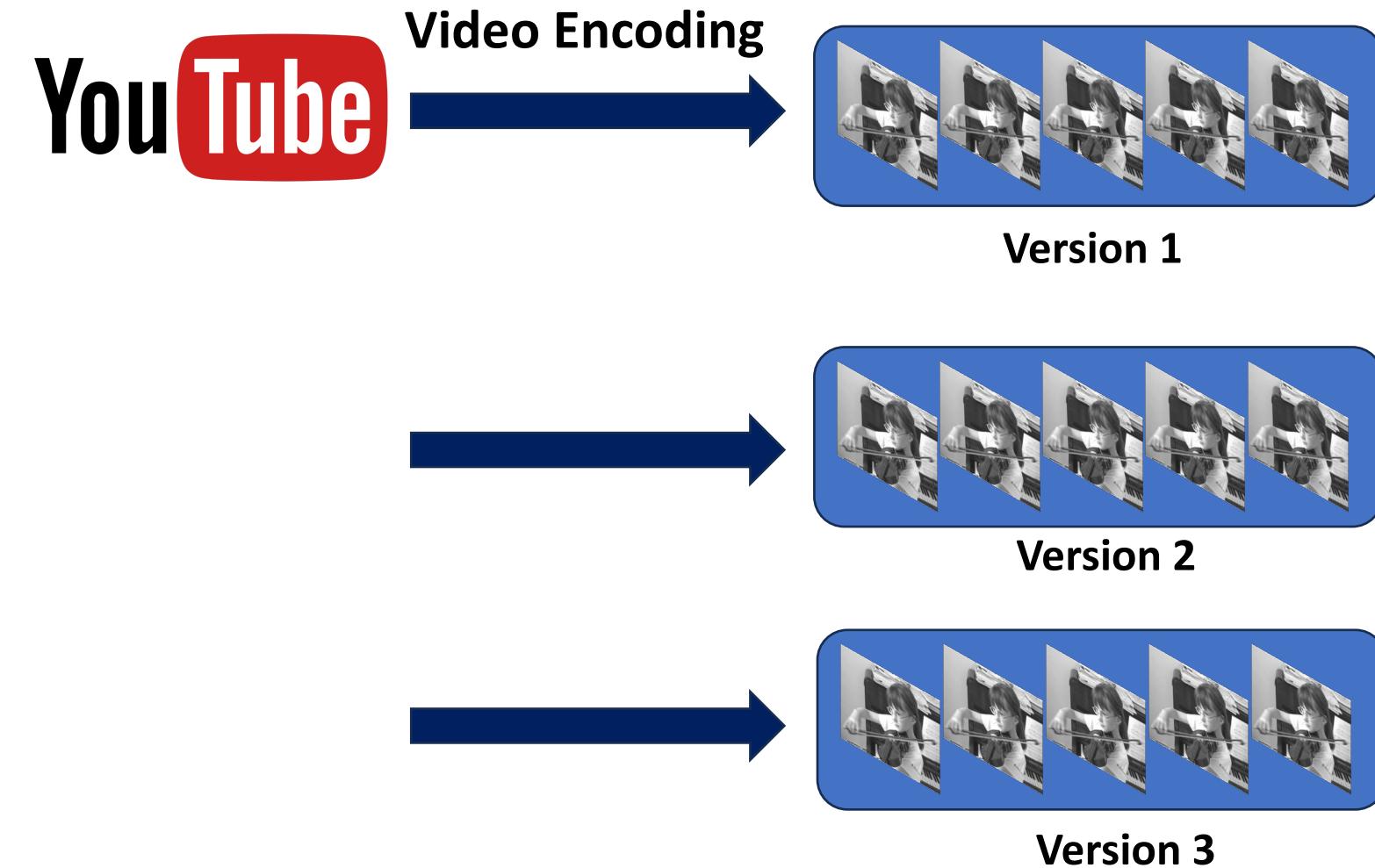
# Streaming multimedia: DASH



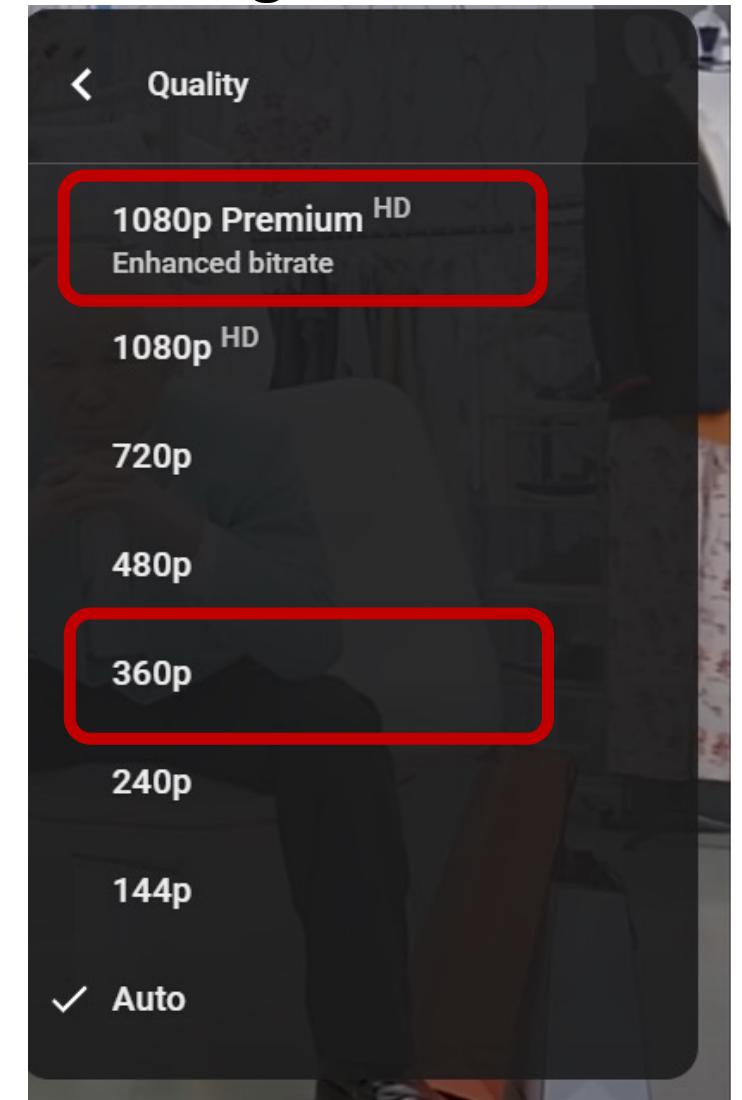
Dynamic, Adaptive Streaming over HTTP



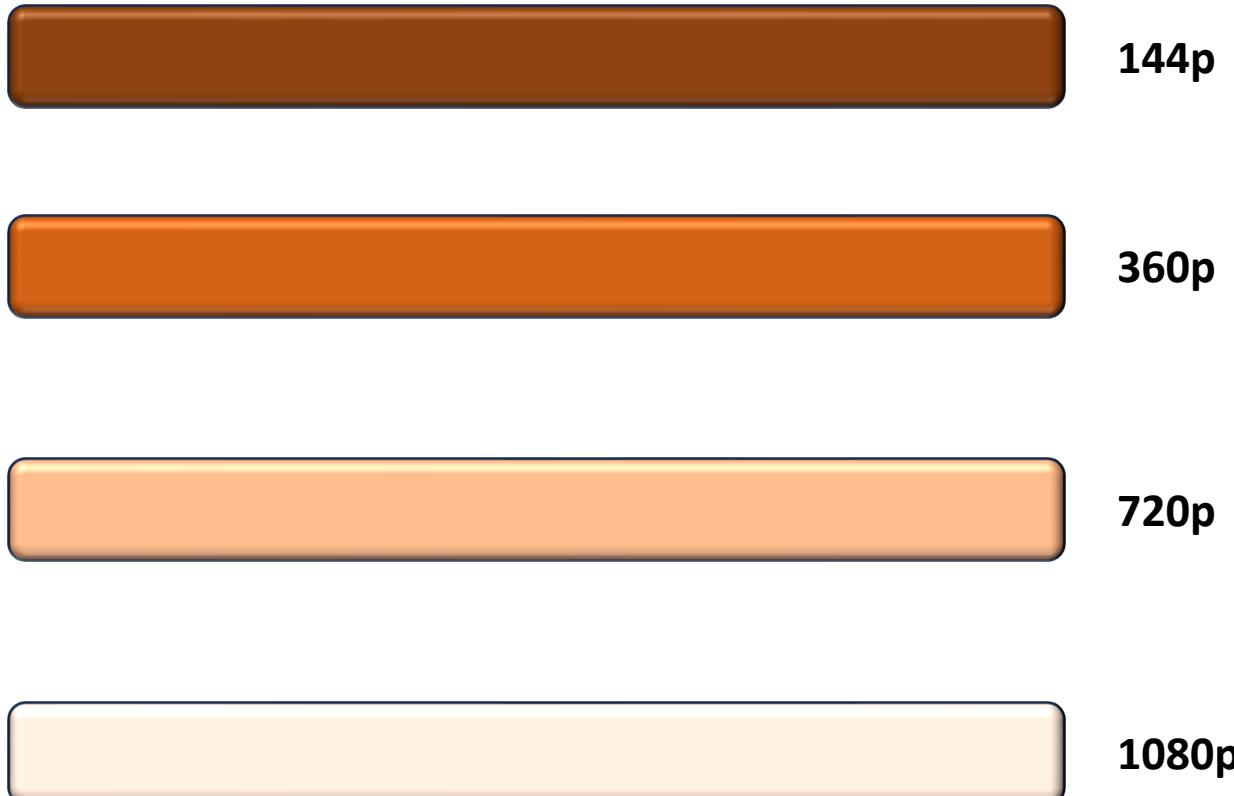
# Streaming multimedia: DASH



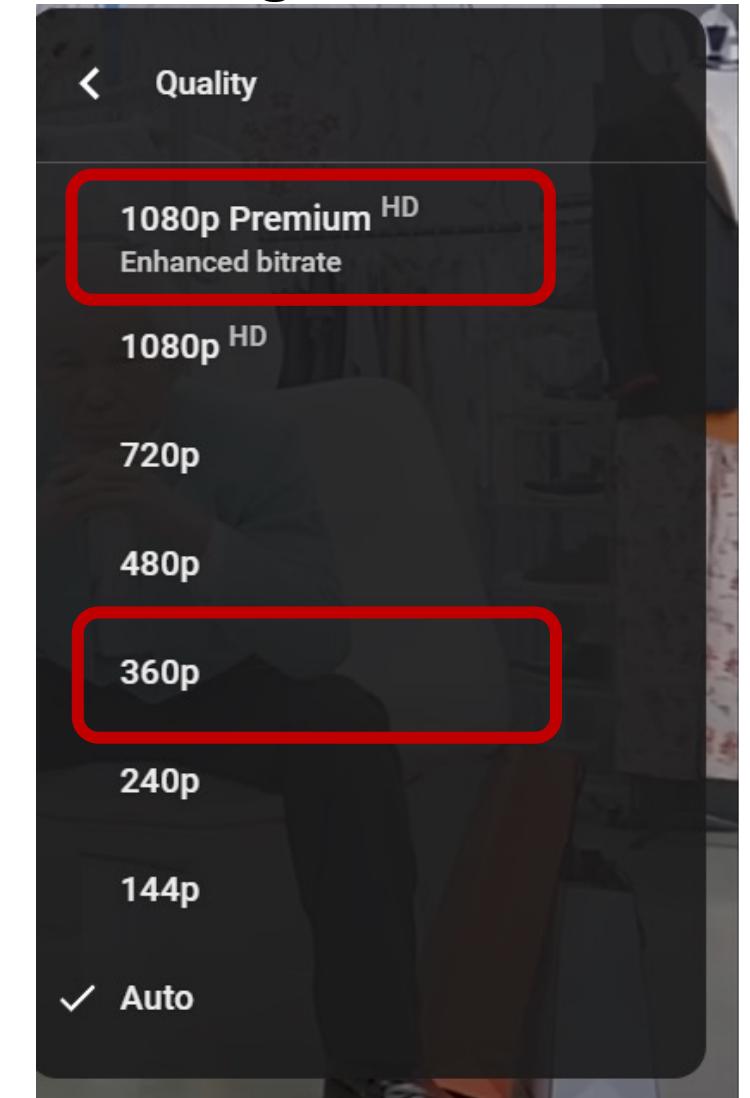
*Dynamic, Adaptive  
Streaming over HTTP*



# Streaming multimedia: DASH



*Dynamic, Adaptive  
Streaming over HTTP*



# Streaming multimedia: DASH

Chunk, e.g., 5 seconds



144p



360p

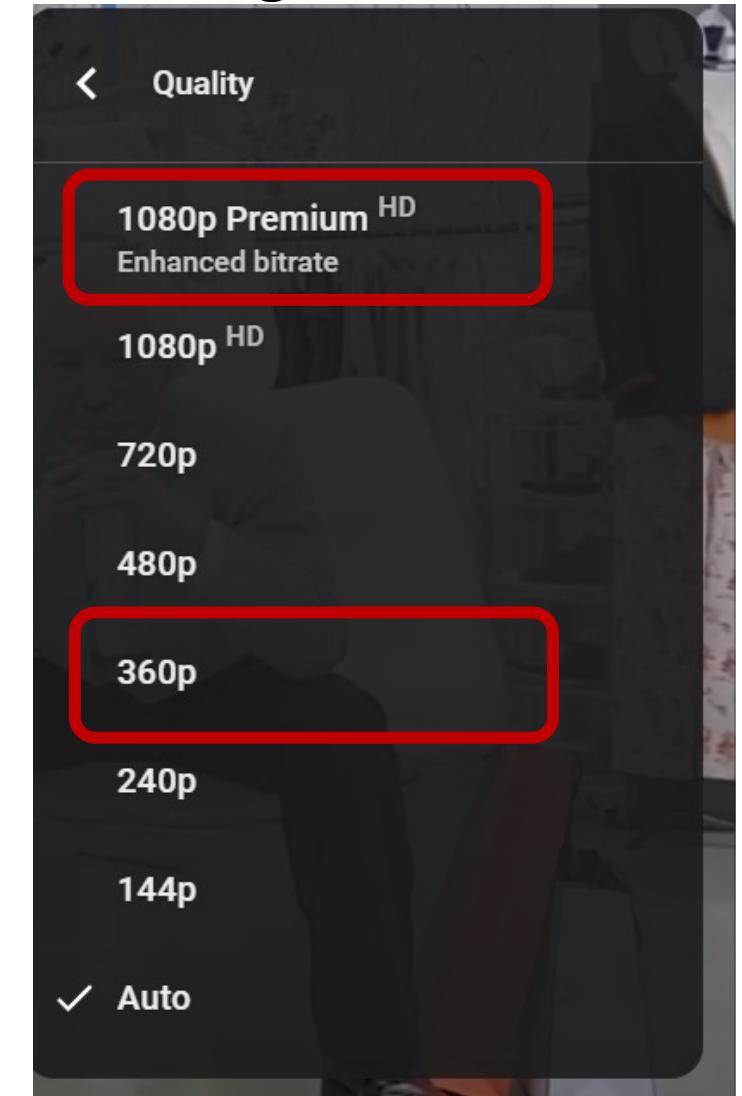


720p



1080p

*Dynamic, Adaptive Streaming over HTTP*

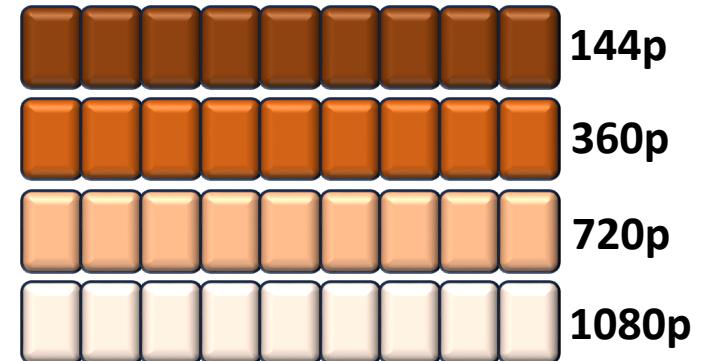


# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*

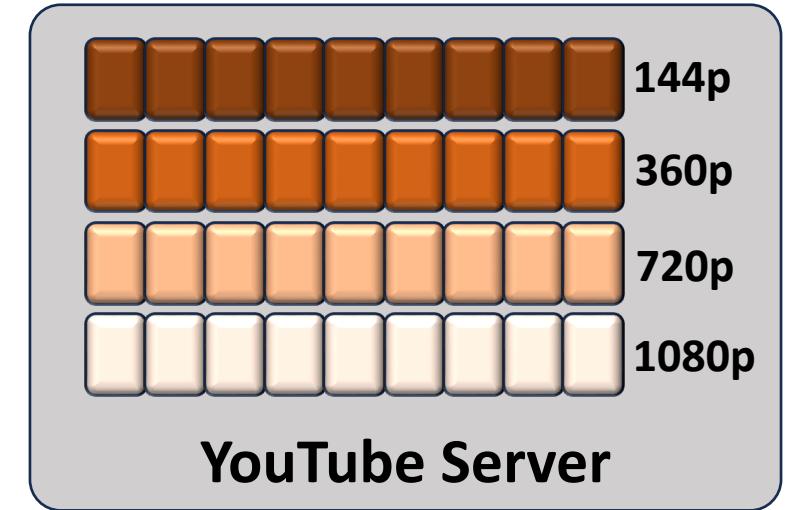
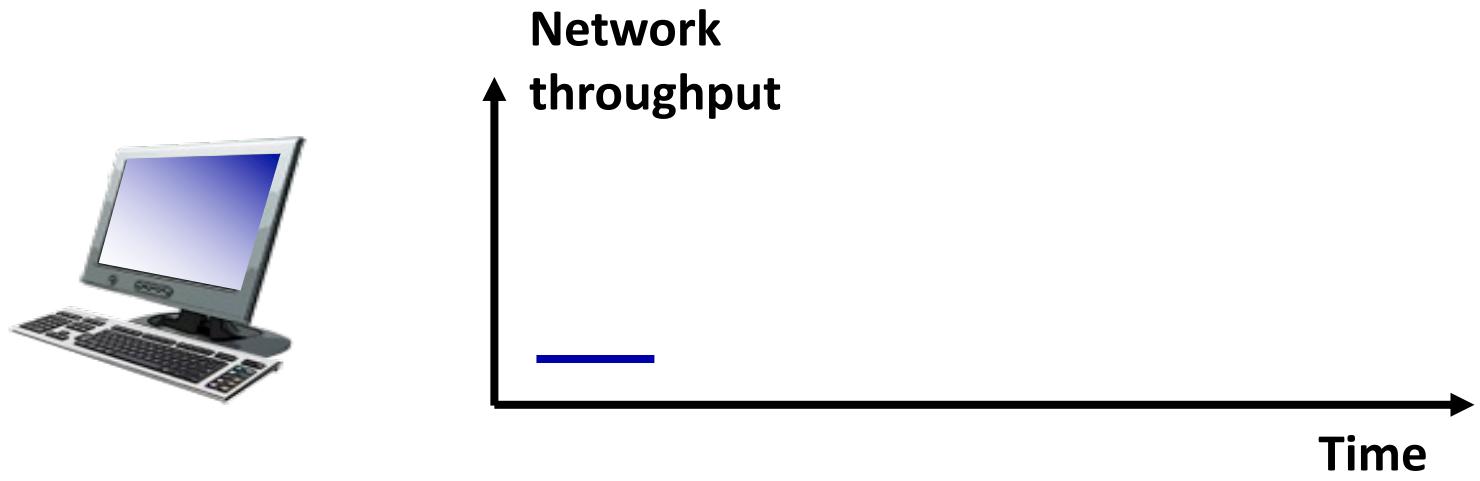
server:

- 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



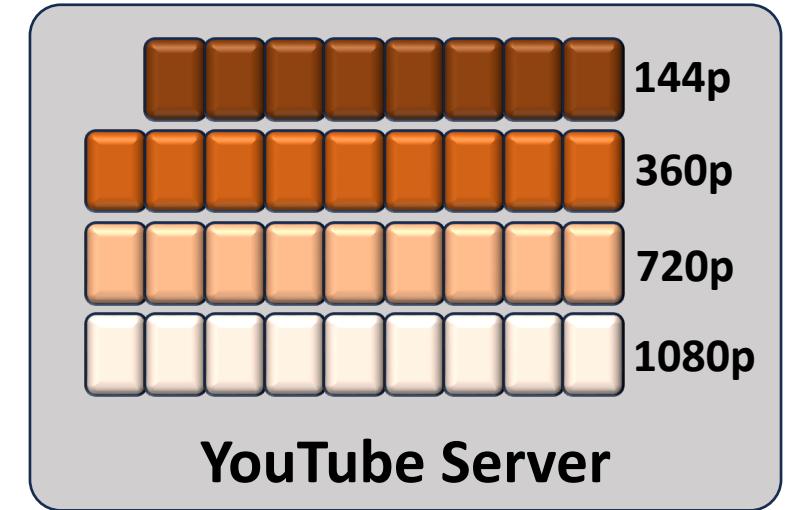
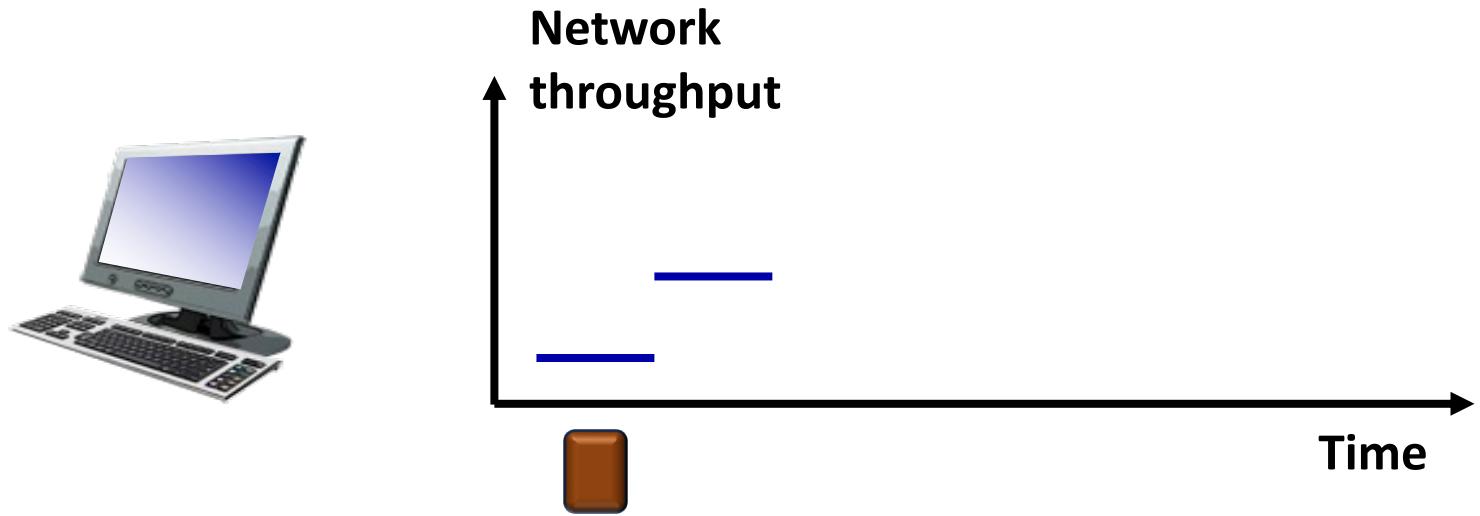
# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



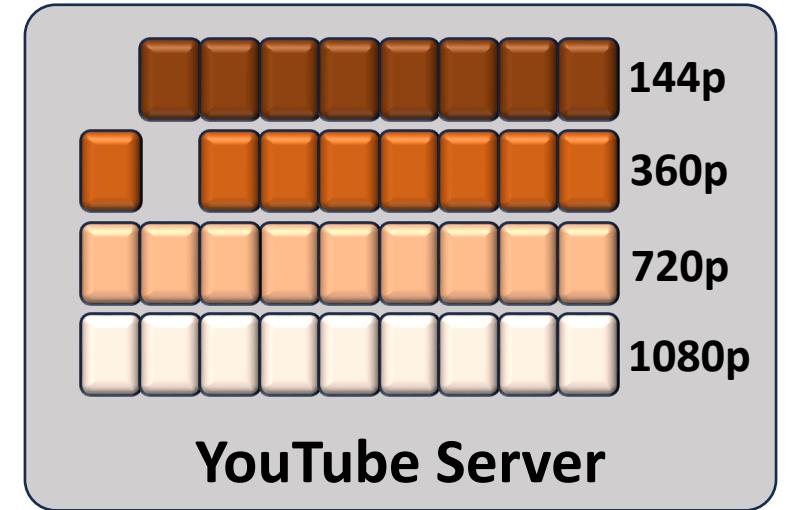
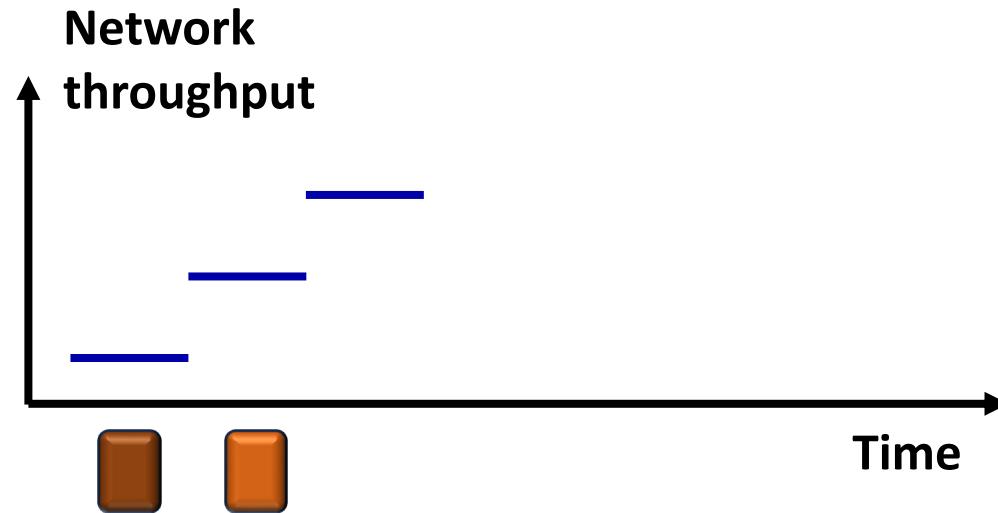
# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



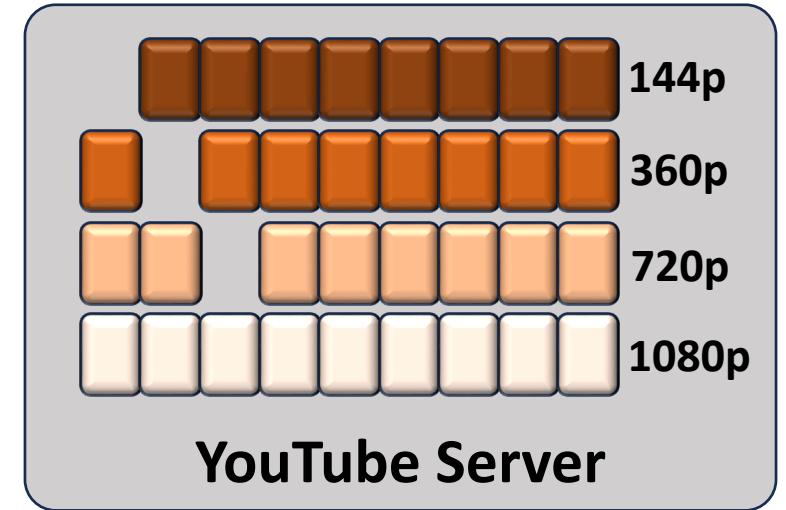
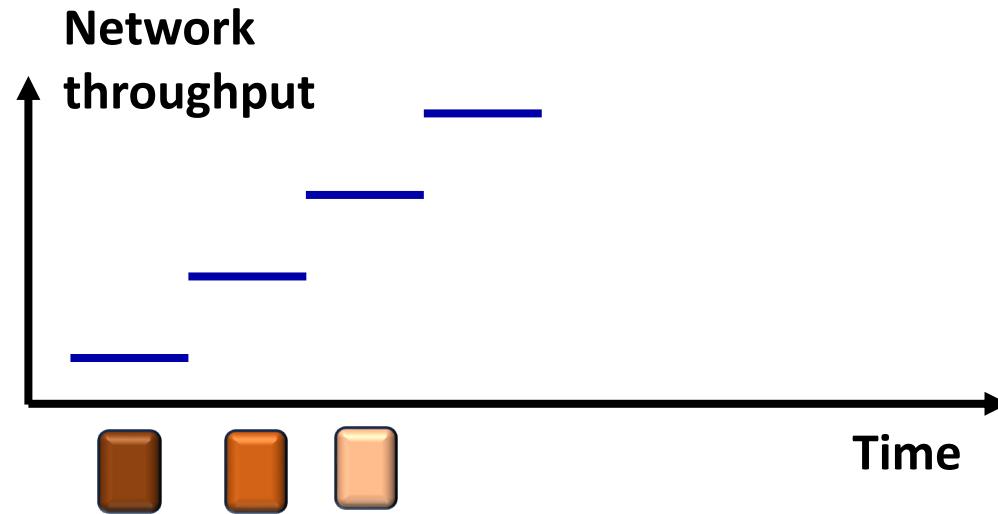
# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



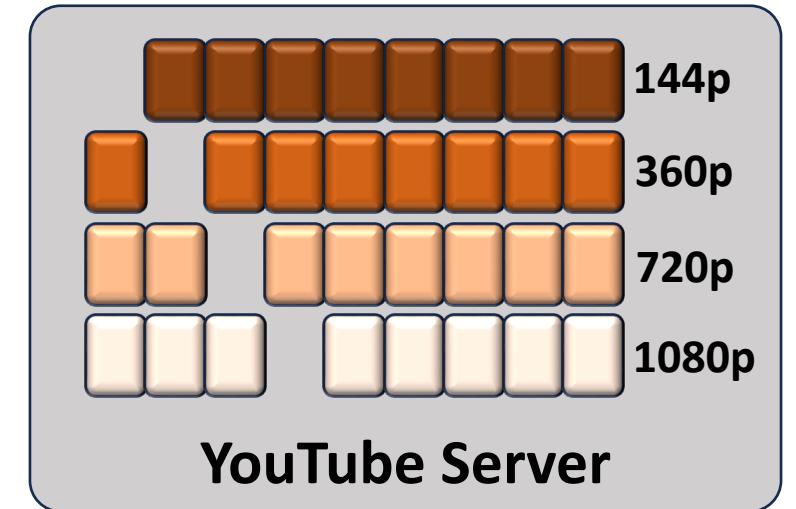
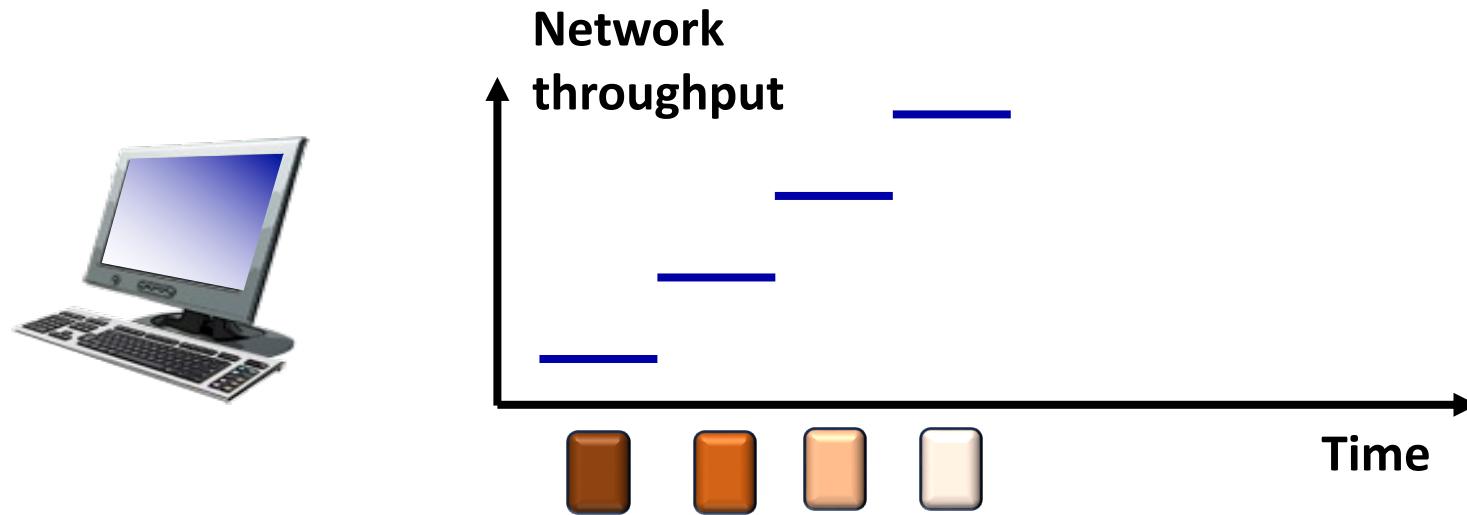
# Streaming multimedia: DASH

*Dynamic, Adaptive  
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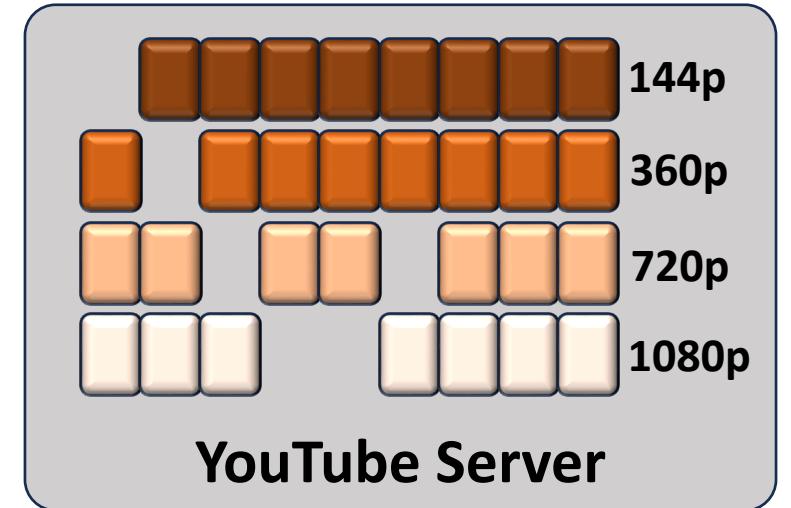
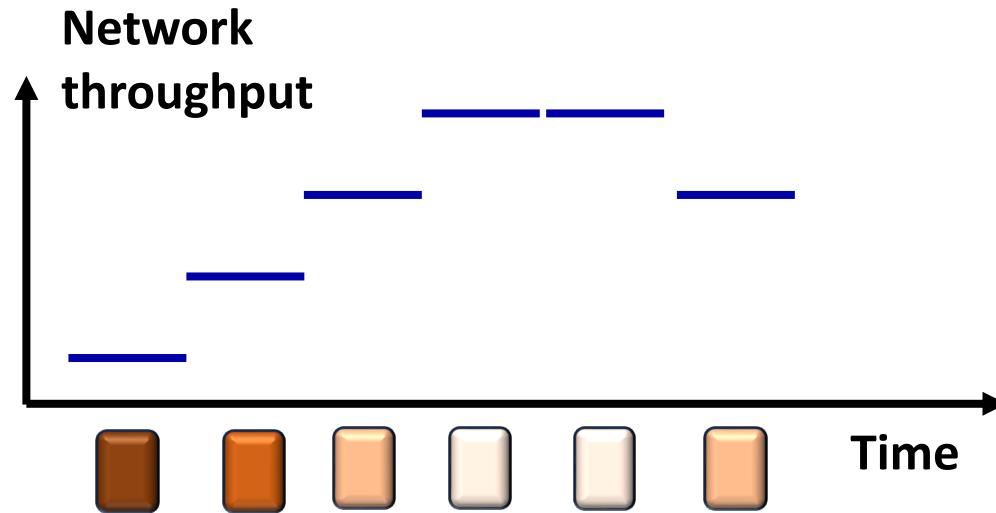
# Streaming multimedia: DASH

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Streaming over HTTP*



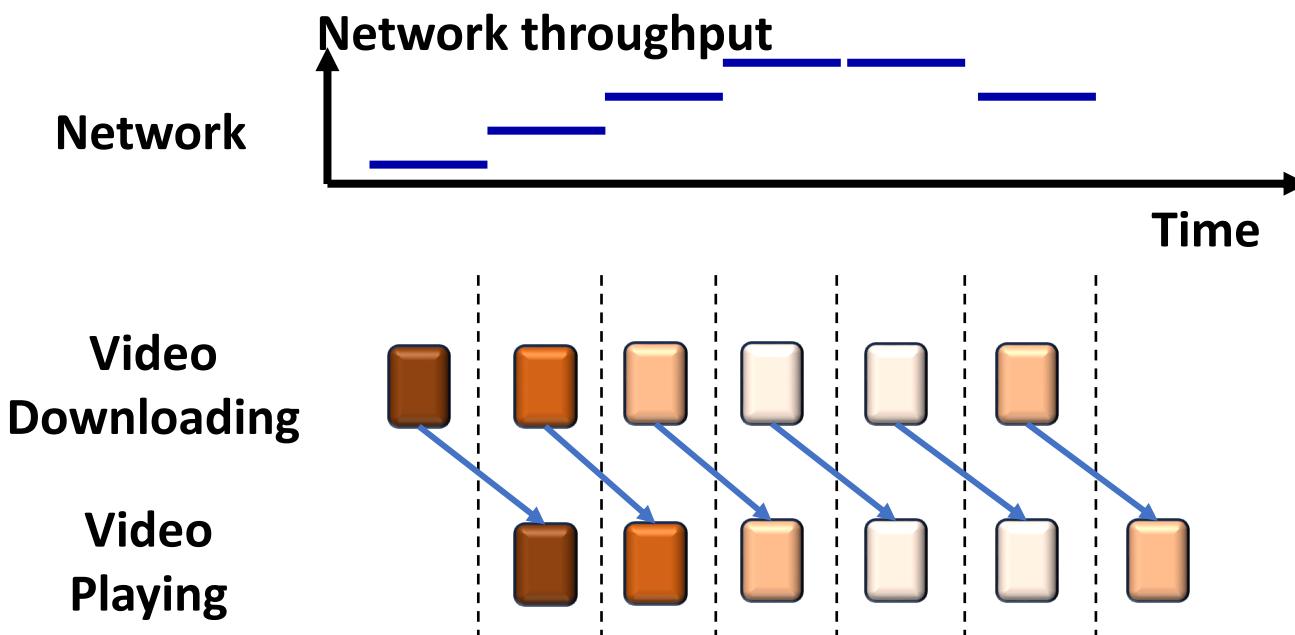
# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



# Streaming multimedia: DASH

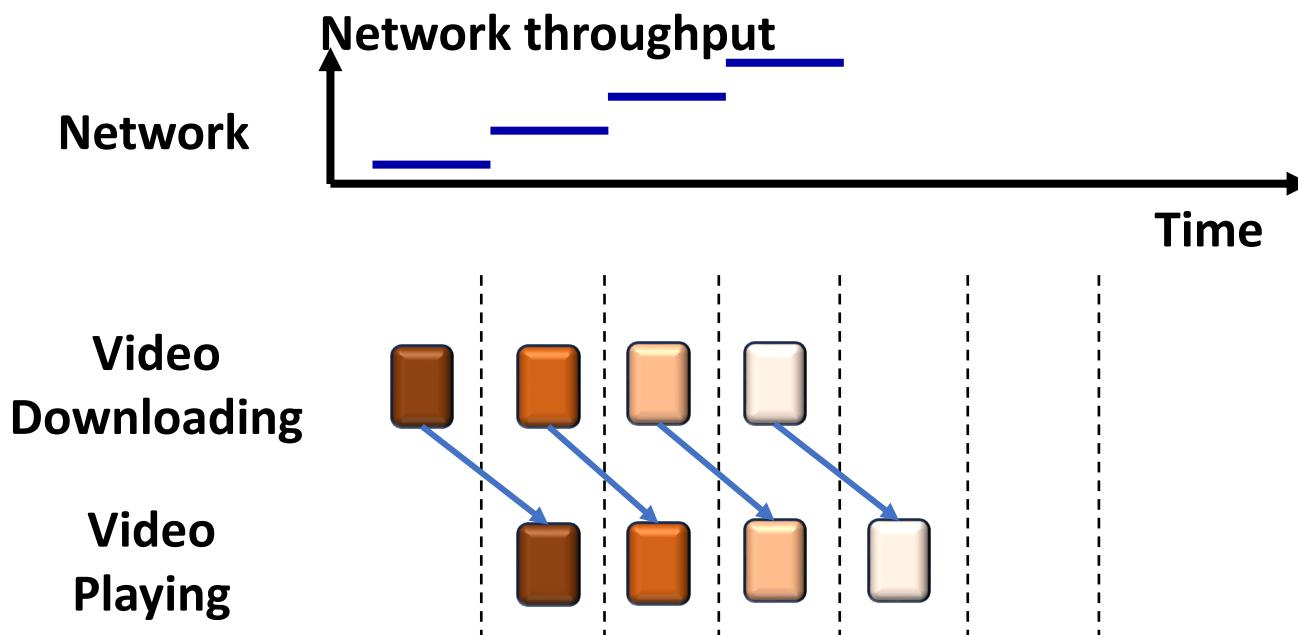
*Dynamic, Adaptive  
Streaming over HTTP*



**Minimize Video Start Time**

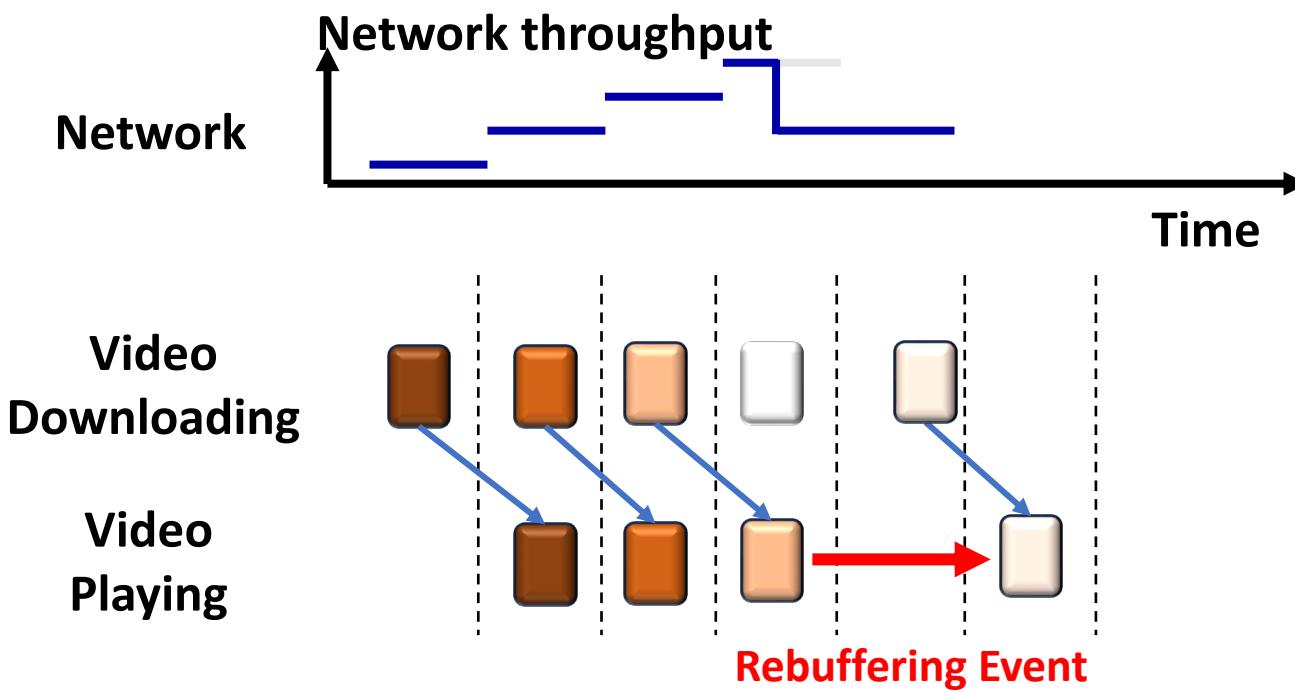
# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



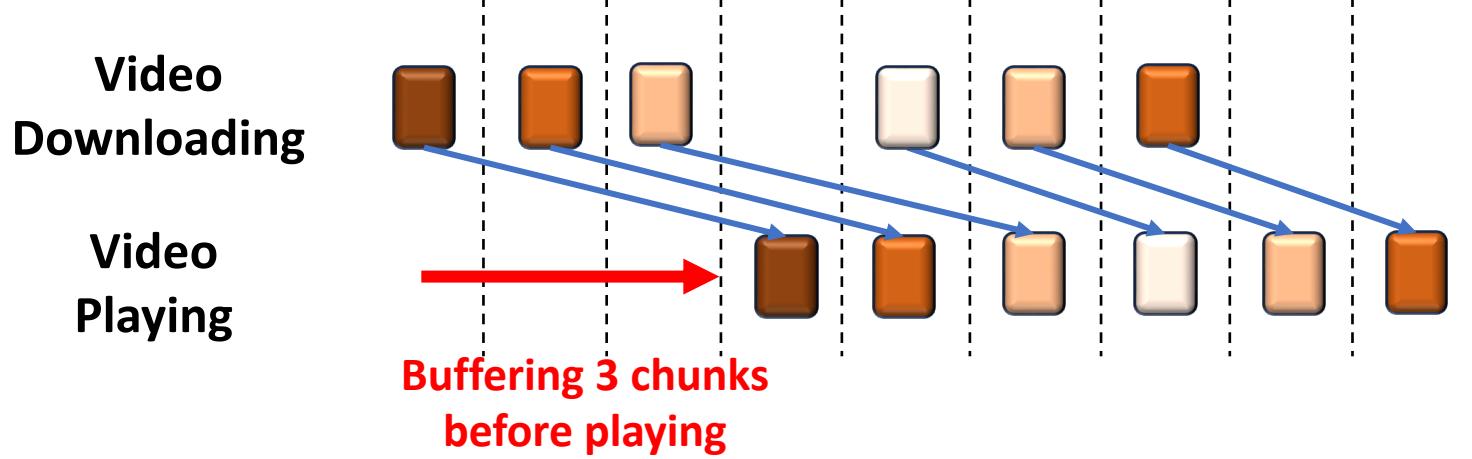
# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*



# Streaming multimedia: DASH

*Dynamic, Adaptive  
Streaming over HTTP*

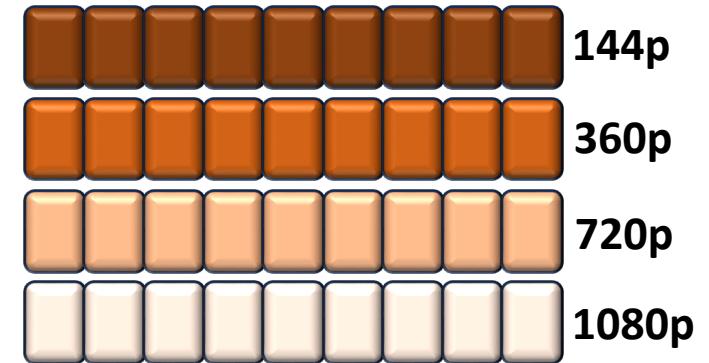


# Streaming multimedia: DASH

*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

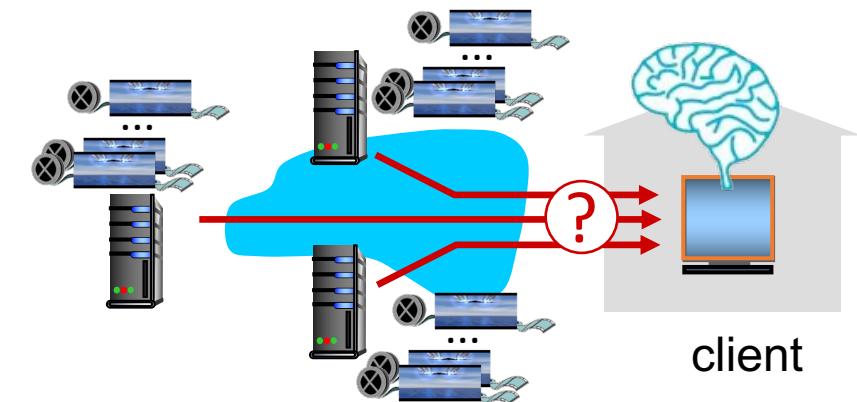


## client:

- 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)

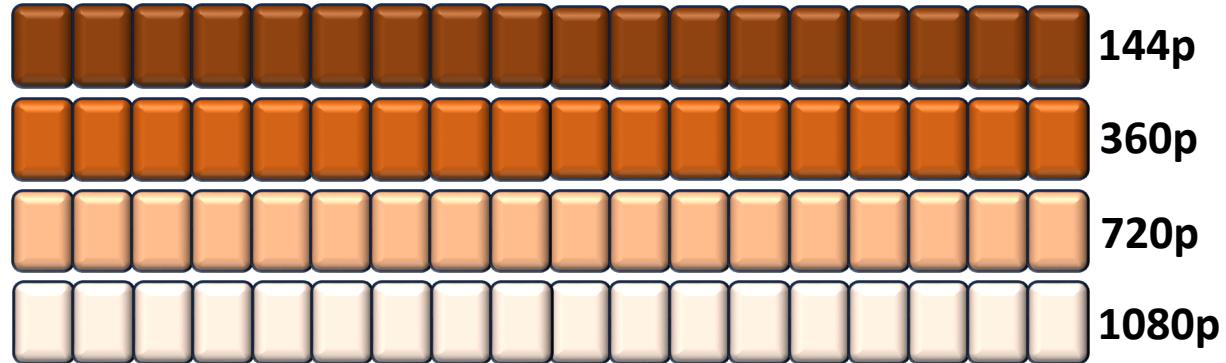


Streaming video = encoding + DASH + playout buffering

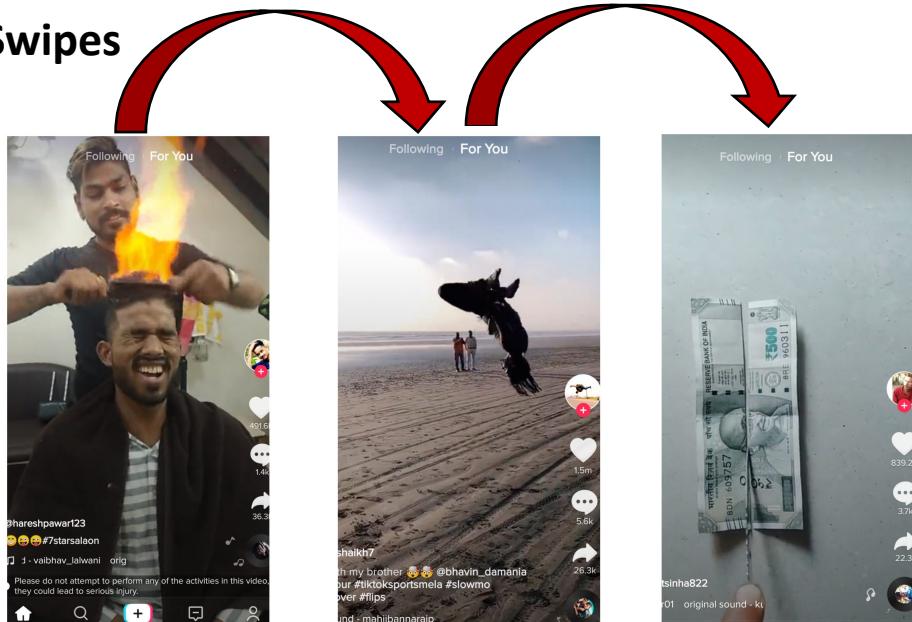
# Video Streaming Applications



# Video Streaming Applications



User Swipes



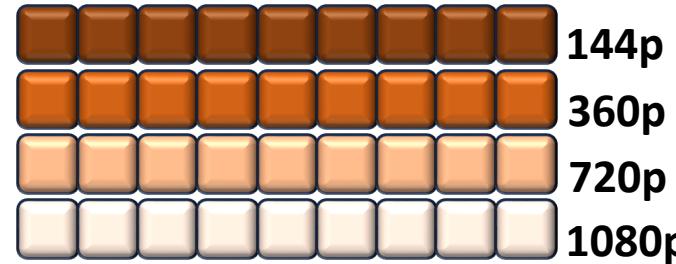
Is the next video ready for playing  
when the user swipes?

# Video Streaming Applications



Download next video

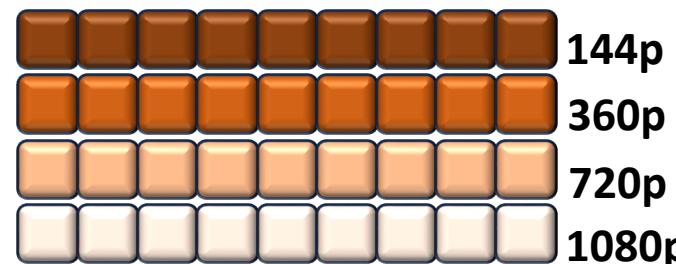
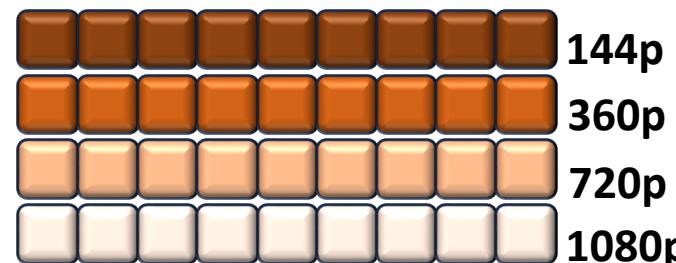
Download the next chunk of current video



Video  $i$ : Currently playing video

Video  $i+1$

Video  $i+2$



# 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:



## The Akamai Edge Today

**360K**  
servers

**100+**  
million hits  
per second

**7+**  
trillion  
deliveries  
per day

**175+**  
terabits per  
second  
(250+ peak)

**4,200+**  
locations

**1,350+**  
networks

**840+**  
cities

**135**  
countries

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

