

# Chapter 2

## Application Layer

### A note on the use of these Powerpoint slides:

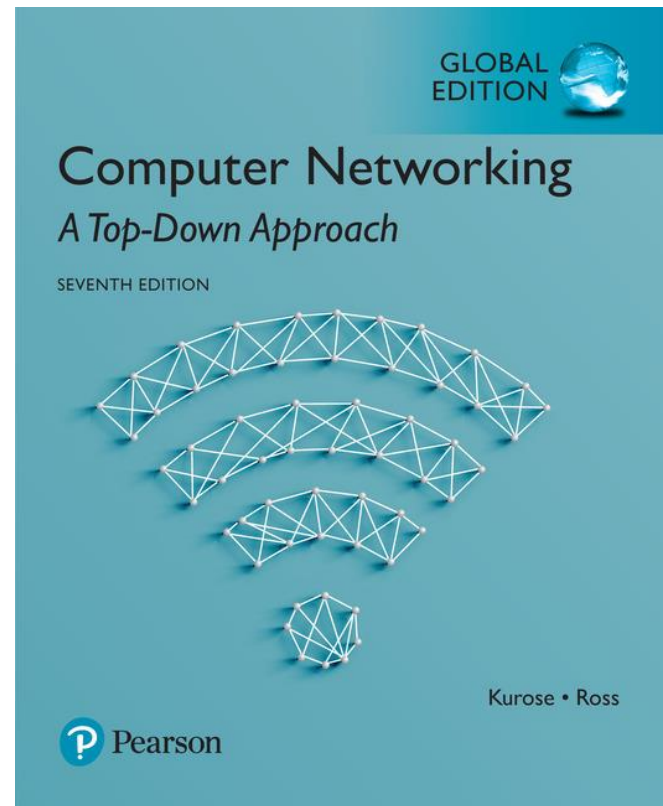
We're making these slides freely available to all (faculty, students, readers). They're in PowerPoint form so you see the animations; and can add, modify, and delete slides (including this one) and slide content to suit your needs. They obviously represent a *lot* of work on our part. In return for use, we only ask the following:

- If you use these slides (e.g., in a class) that you mention their source (after all, we'd like people to use our book!)
- If you post any slides on a www site, that you note that they are adapted from (or perhaps identical to) our slides, and note our copyright of this material.

Thanks and enjoy! JFK/KWR

© All material copyright 1996-2016

J.F Kurose and K.W. Ross, All Rights Reserved



## Computer Networking: A Top Down Approach

7<sup>th</sup> Edition, Global Edition

Jim Kurose, Keith Ross

Pearson

April 2016

# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming  
and content  
distribution  
networks

2.7 socket  
programming with  
UDP and TCP

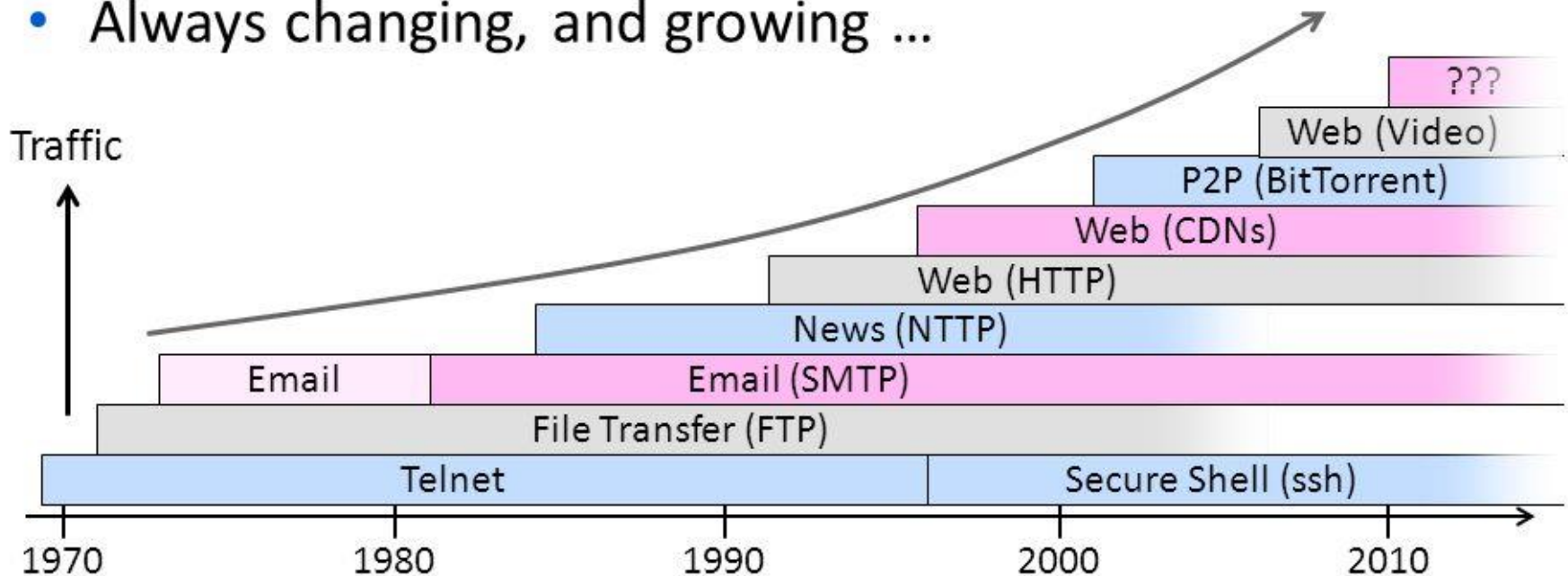
# Chapter 2: application layer

## our goals:

- conceptual, implementation aspects of network application protocols
  - transport-layer service models
  - client-server paradigm
  - peer-to-peer paradigm
  - content distribution networks
- learn about protocols by examining popular application-level protocols
  - HTTP
  - FTP
  - SMTP / POP3 / IMAP
  - DNS
- creating network applications
  - socket API

# Evolution of Internet Applications

- Always changing, and growing ...



# Some network apps

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

# Evolution of Internet Applications

Cisco Visual Networking Index:  
Forecast and Trends, 2017–2022

- Most traffic will be video (~82%)
- M2M connections will grow
- Wireless traffic will overtake wired traffic (~71%)
- Smartphone traffic will exceed PC traffic
- Growing attacks (DDoS, etc.)

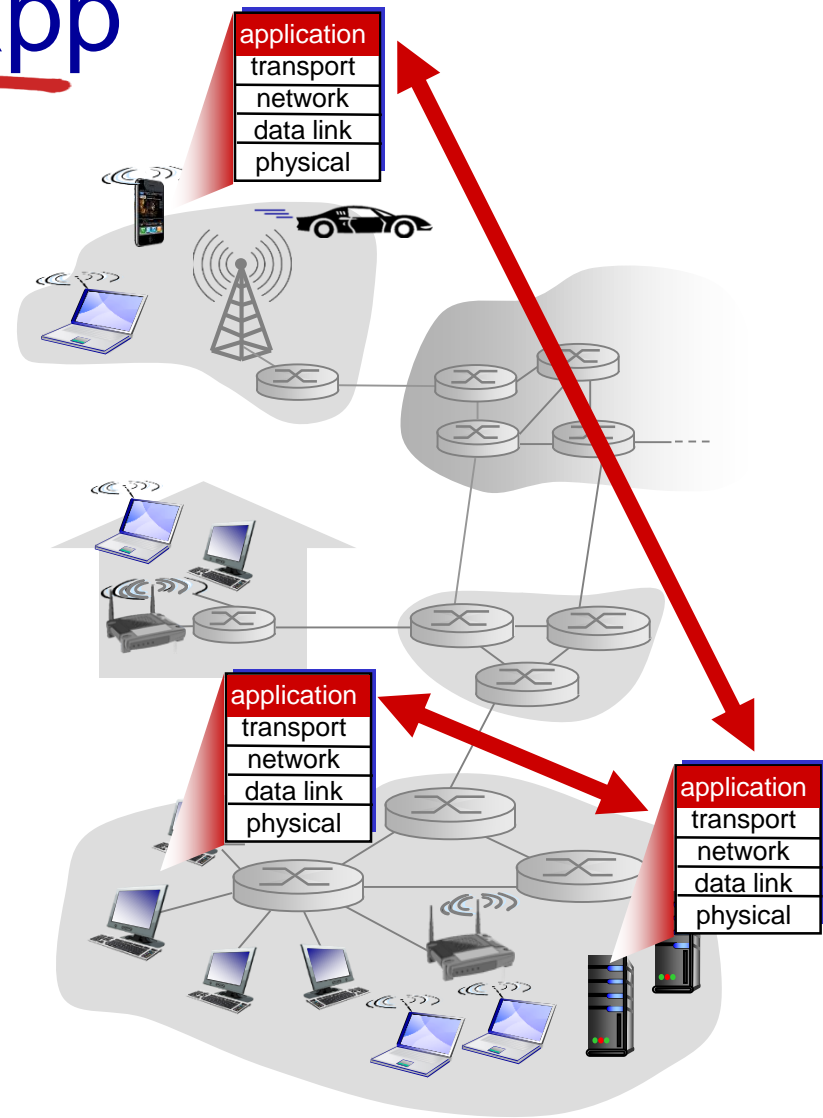
# Creating a network app

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



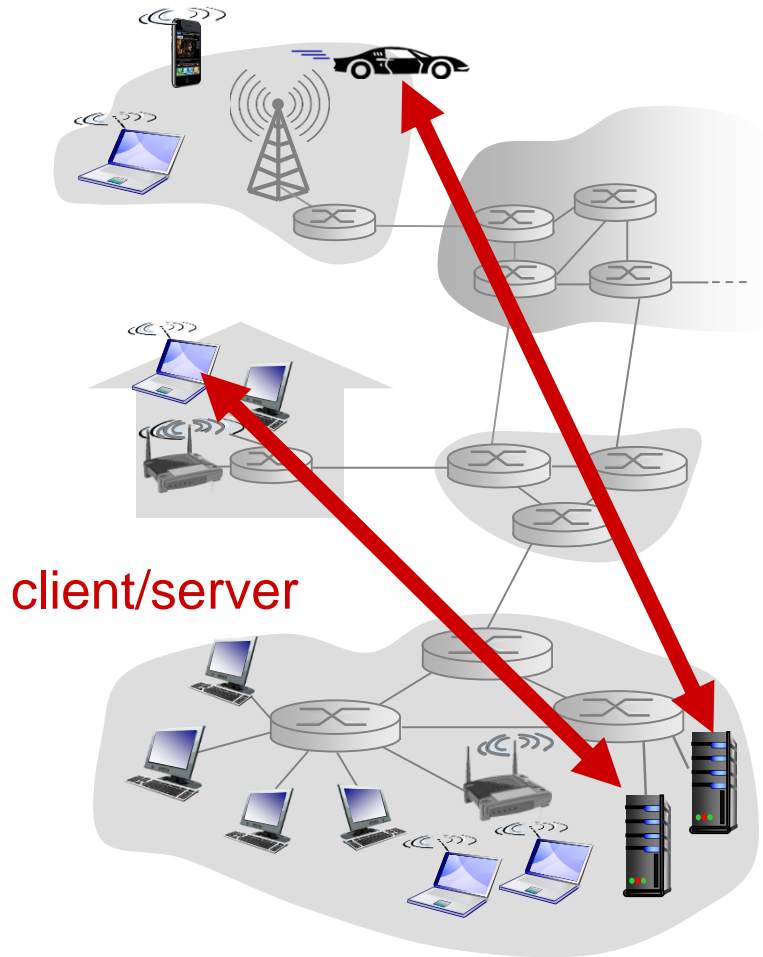
# Application architectures

possible structure of applications:

- client-server
- peer-to-peer (P2P)



# Client-server architecture



## server:

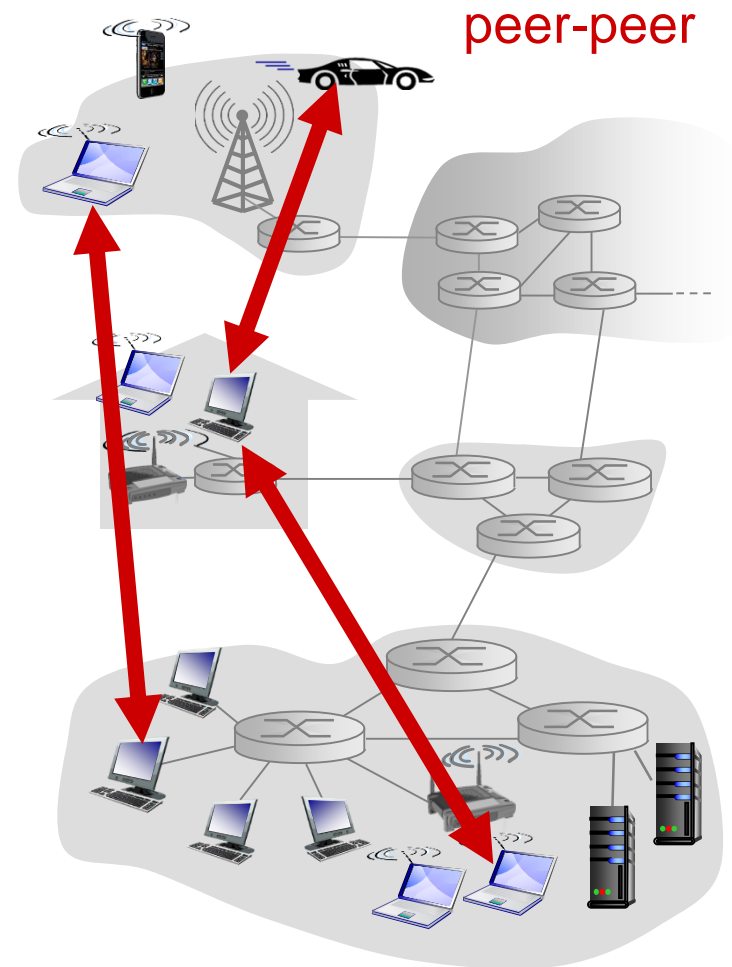
- always-on host
- permanent IP address
- data centers for scaling

## clients:

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

# 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, as well as new service demands
- peers are intermittently connected and change IP addresses
  - complex management



# 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

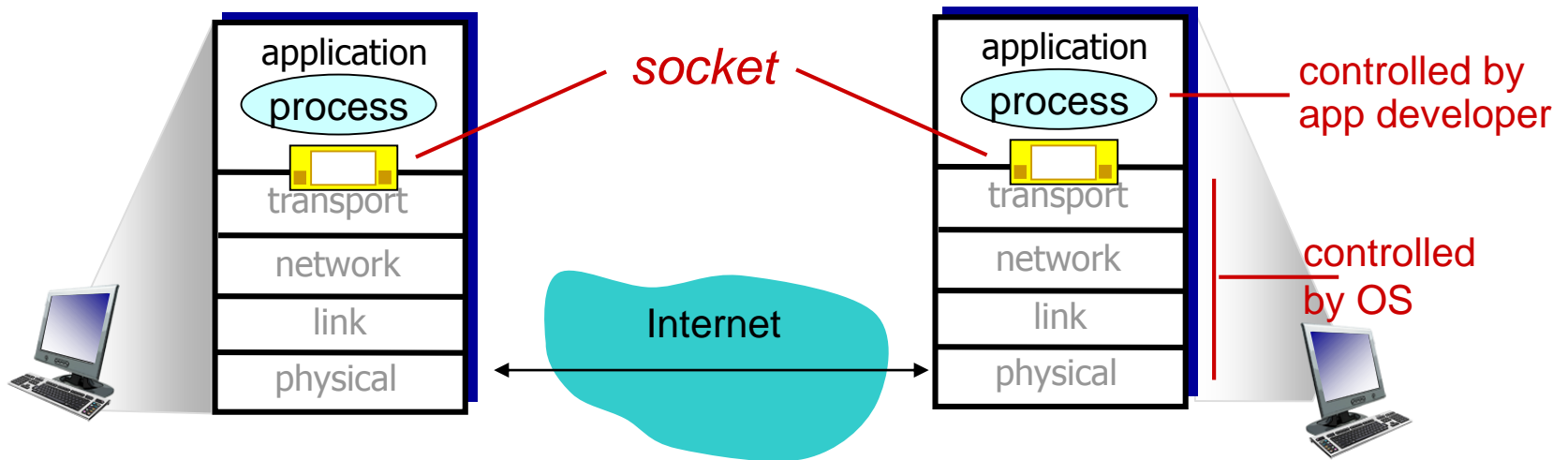
*client process*: process that initiates communication

*server process*: process that waits to be contacted

- aside: 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



# 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 (www.iana.org)
- more shortly...

# App-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
- allows for interoperability
- e.g., HTTP, SMTP

## proprietary protocols:

- e.g., Skype

# What transport service does an app need?

## data integrity

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

## timing

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

## throughput

- some apps (e.g., multimedia) require minimum amount of throughput to be “effective”
- other apps (“elastic apps”) make use of whatever throughput they get

## security

- encryption, data integrity, ...

# Transport service requirements: common apps

application	data loss	throughput	time sensitive
file transfer	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, 100' s msec
stored audio/video	loss-tolerant	same as above	
interactive games	loss-tolerant	few kbps up	yes, few secs
text messaging	no loss	elastic	yes, 100' s msec 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
- *does not provide*: timing, minimum throughput guarantee, security
- *connection-oriented*: setup required between client and server processes

## *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 apps: application, transport protocols

<b>application</b>	<b>application layer protocol</b>	<b>underlying transport protocol</b>
e-mail	SMTP [RFC 2821]	TCP
remote terminal access	Telnet [RFC 854]	TCP
Web	HTTP [RFC 2616]	TCP
file transfer	FTP [RFC 959]	TCP
streaming multimedia	HTTP (e.g., YouTube), RTP [RFC 1889]	TCP or UDP
Internet telephony	SIP, RTP, proprietary (e.g., Skype)	TCP or UDP

# Securing TCP

## TCP & UDP

- no encryption
- cleartext passwds sent into socket traverse Internet in cleartext

## SSL

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

## SSL is at app layer

- apps use SSL libraries, that “talk” to TCP

## SSL socket API

- cleartext passwords sent into socket traverse Internet encrypted
- see Chapter 8

# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming  
and content  
distribution  
networks

2.7 socket  
programming with  
UDP and TCP

# Web and HTTP

*First, a review...*

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

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

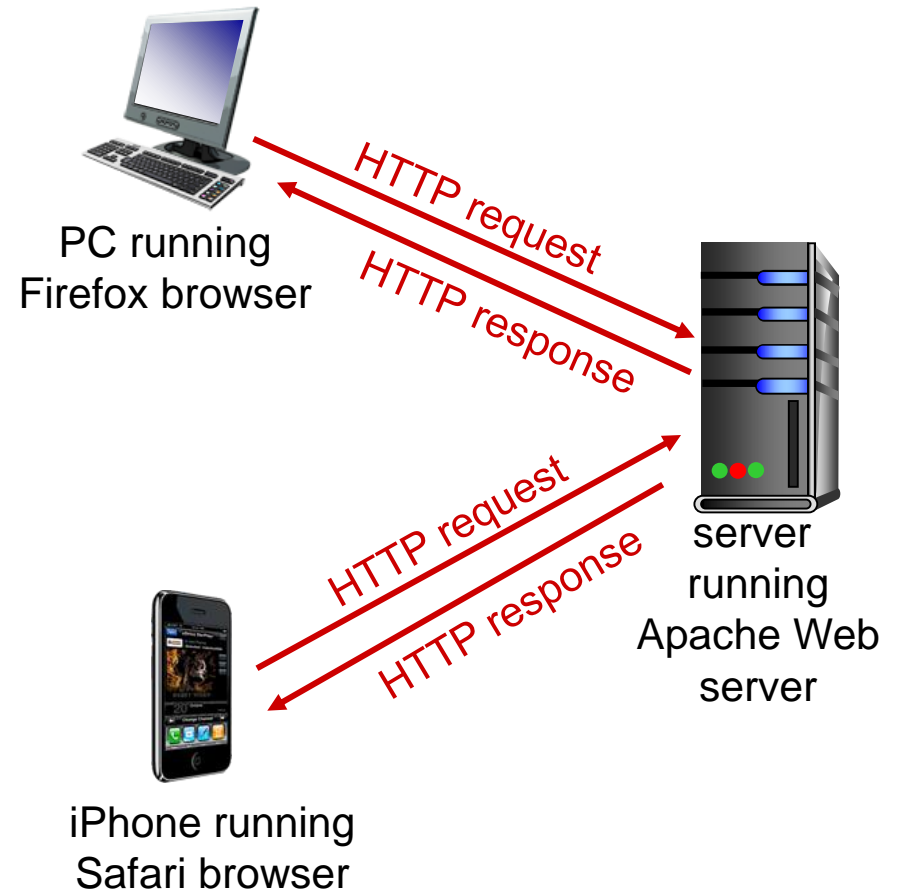
host name

path name

# HTTP overview

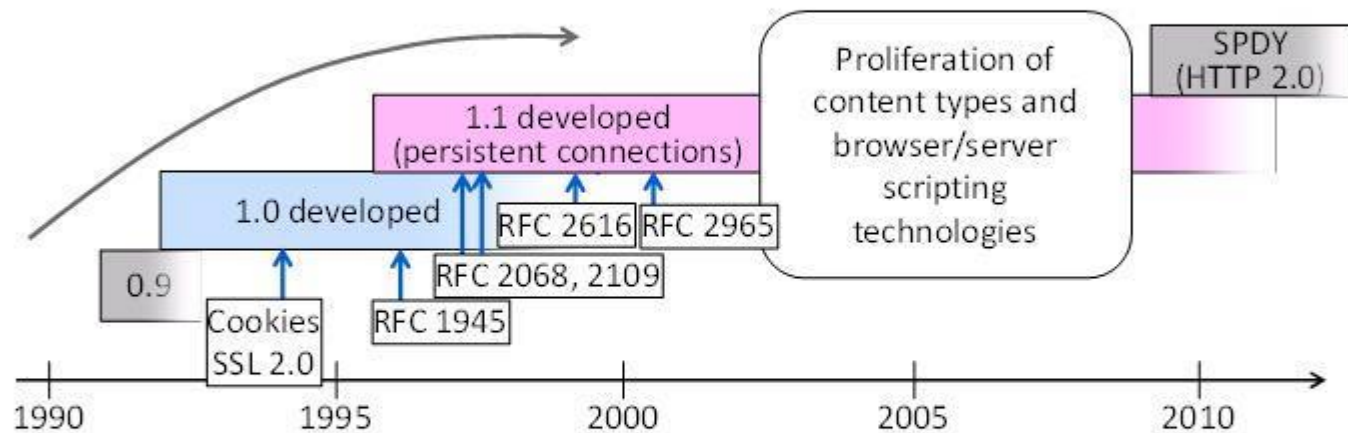
## HTTP: hypertext transfer protocol

- 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



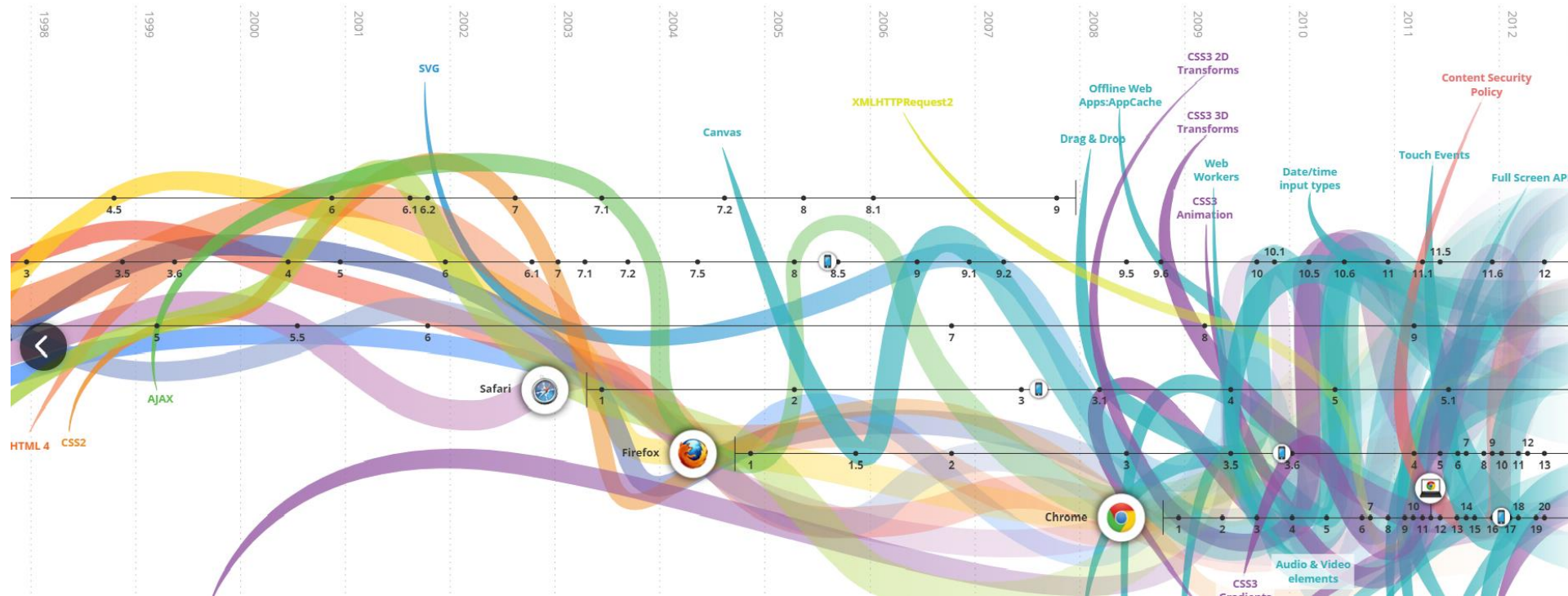
# Evolution of HTTP

- Consider security (SSL/TLS for HTTPS) later



128

# Evolution of the Web



<http://www.evolutionoftheweb.com/>



# HTTP overview (continued)

## *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

# PLT (page load time)

- PLT is the key measure of web performance
  - From click until user sees page
  - Small increase in PLT decrease sales
- PLT depends on many factors
  - Structure of page/content
  - HTTP (and TCP) protocol
  - Network RTT and bandwidth

# Ways to Decrease PLT

- Reduce content size for transfer
  - Smaller images, gzip
- Change HTTP to make better use of available bandwidth
- Change HTTP to avoid repeated transfers of the same content
  - Caching, and proxies
- Move content closer to client
  - CDN

# HTTP connections

## *non-persistent HTTP*

- at most one object sent over TCP connection
  - connection then closed
- downloading multiple objects required multiple connections

## *persistent HTTP*

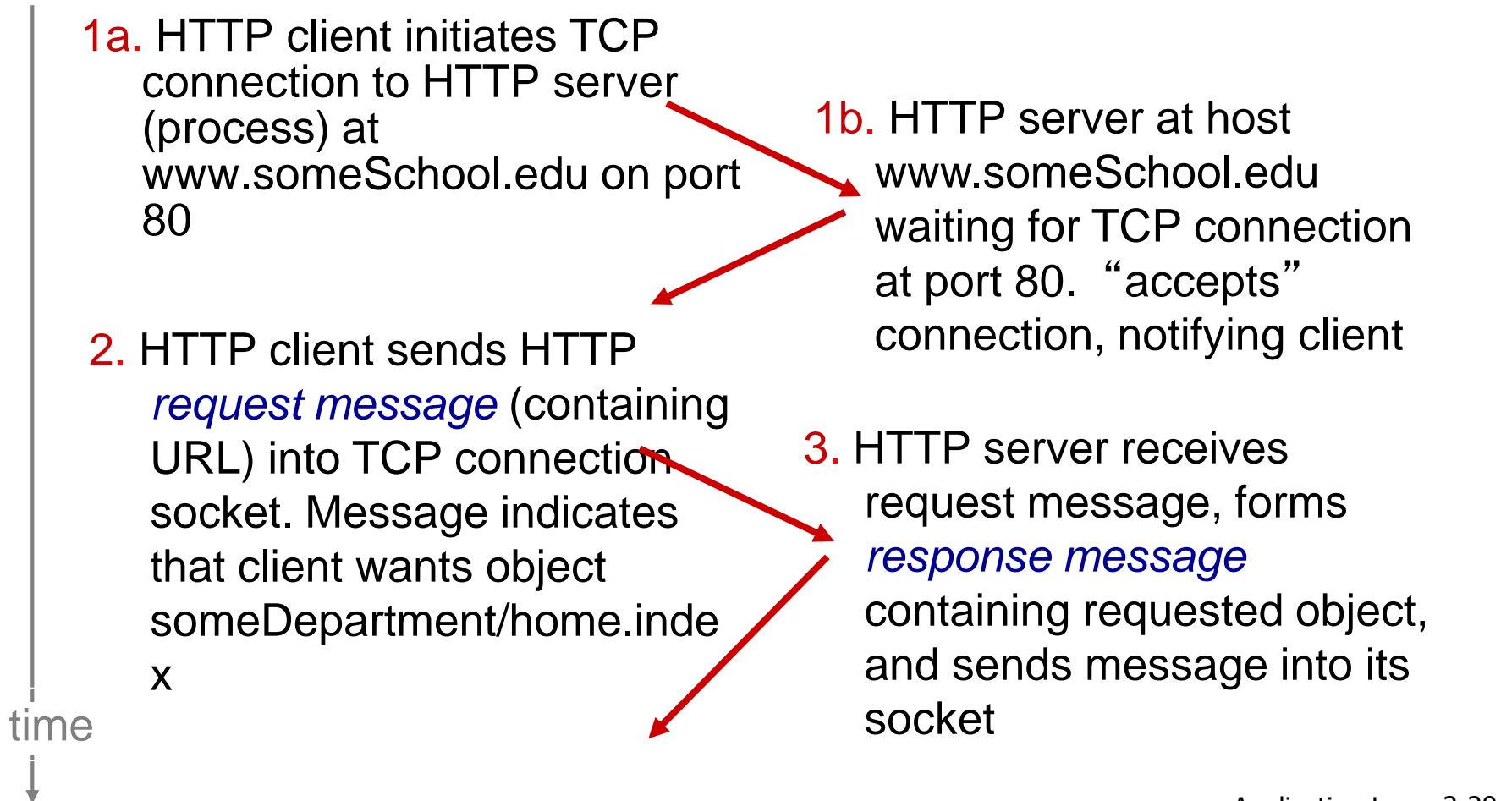
- multiple objects can be sent over single TCP connection between client, server

# Non-persistent HTTP

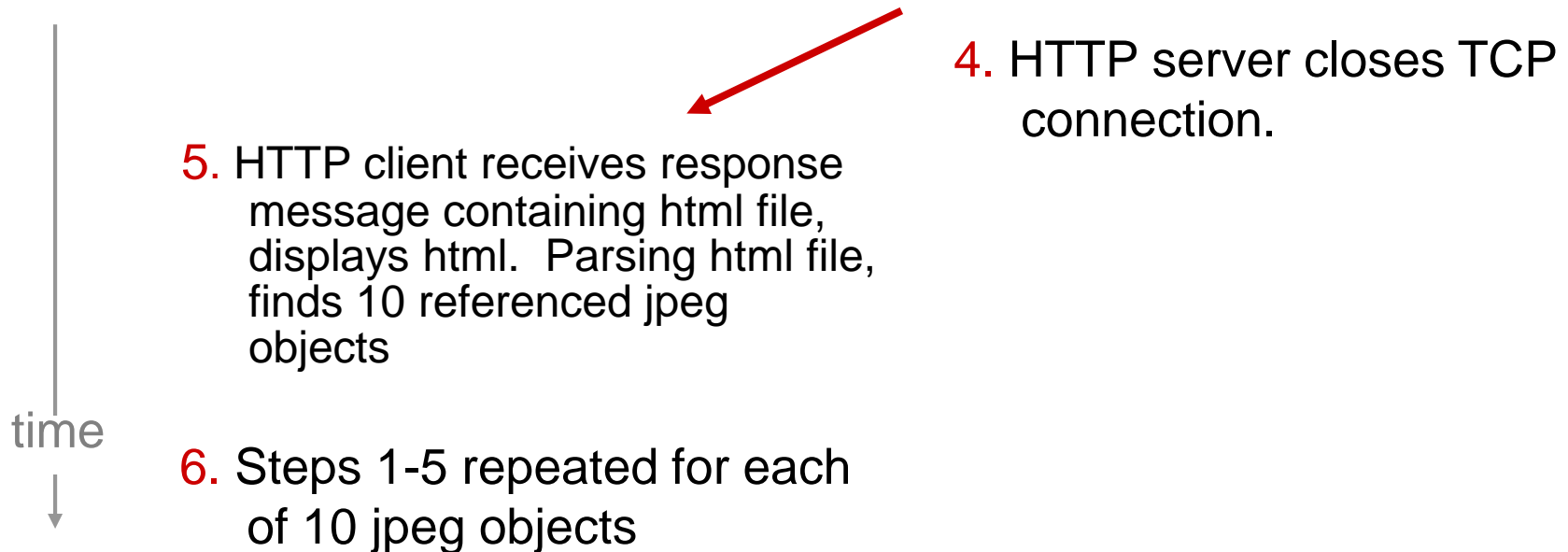
suppose user enters URL:

`www.someSchool.edu/someDepartment/home.index`

(contains text,  
references to 10  
jpeg images)



# Non-persistent HTTP (cont.)

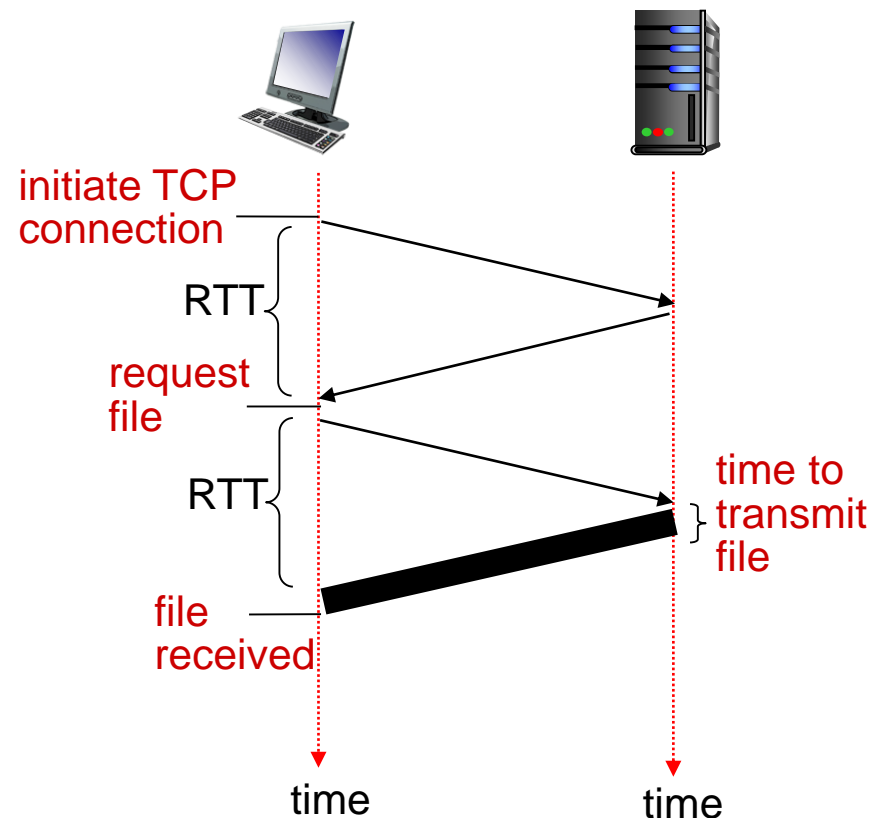


# Non-persistent HTTP: response time

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

**HTTP response time:**

- one RTT to initiate TCP connection
- one RTT for HTTP request and first few bytes of HTTP response to return
- file transmission time
- non-persistent HTTP response time =  
2RTT + file transmission time



# Persistent HTTP

## *non-persistent HTTP issues:*

- requires 2 RTTs per object
- OS overhead for *each* TCP connection
- browsers often open parallel TCP connections to fetch referenced objects

## *persistent HTTP:*

- 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



# HTTP request message

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

request line  
(GET, POST,  
HEAD commands)

header  
lines

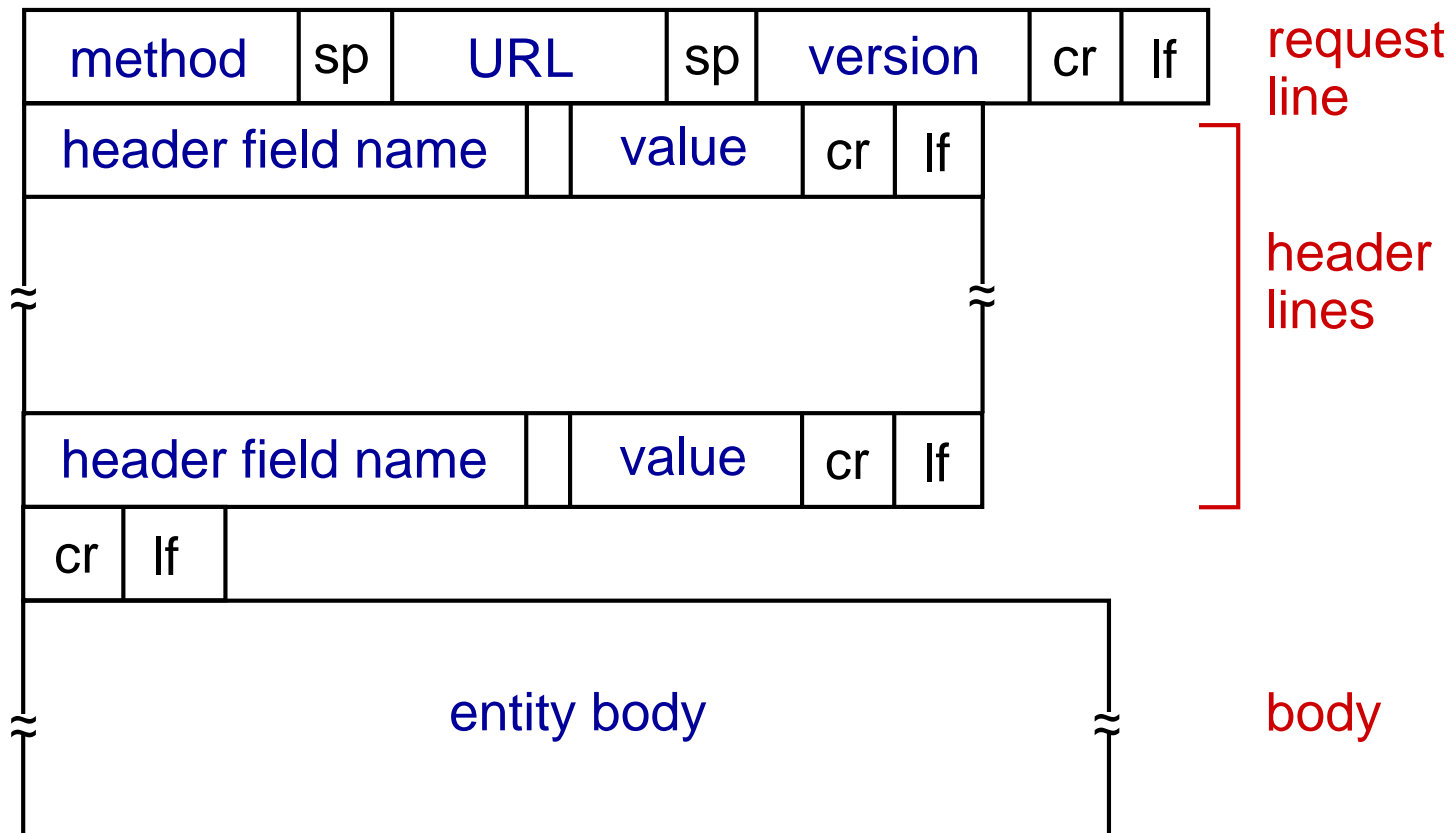
carriage return,  
line feed at start  
of line indicates  
end of header lines

```
GET /index.html HTTP/1.1\r\n
Host: www-net.cs.umass.edu\r\n
User-Agent: Firefox/3.6.10\r\n
Accept: text/html,application/xhtml+xml\r\n
Accept-Language: en-us,en;q=0.5\r\n
Accept-Encoding: gzip,deflate\r\n
Accept-Charset: ISO-8859-1,utf-8;q=0.7\r\n
Keep-Alive: 115\r\n
Connection: keep-alive\r\n
\r\n
```

carriage return character  
line-feed character

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

# HTTP request message: general format



# Uploading form input

## POST method:

- web page often includes form input
- input is uploaded to server in entity body

## URL method:

- uses GET method
- input is uploaded in URL field of request line:

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

# Method types

## HTTP/1.0:

- GET
- POST
- HEAD
  - asks server to leave requested object out of response

## HTTP/1.1:

- GET, POST, HEAD
- PUT
  - uploads file in entity body to path specified in URL field
- DELETE
  - deletes file specified in the URL field

# HTTP response message

status line

(protocol

status code

status phrase)

header  
lines

data, e.g.,  
requested  
HTML file

```
HTTP/1.1 200 OK\r\n
Date: Sun, 26 Sep 2010 20:09:20 GMT\r\n
Server: Apache/2.0.52 (CentOS)\r\n
Last-Modified: Tue, 30 Oct 2007 17:00:02
      GMT\r\n
ETag: "17dc6-a5c-bf716880"\r\n
Accept-Ranges: bytes\r\n
Content-Length: 2652\r\n
Keep-Alive: timeout=10, max=100\r\n
Connection: Keep-Alive\r\n
Content-Type: text/html; charset=ISO-8859-
      1\r\n
\r\n
data data data data data ...
```

\* 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 msg

## **301 Moved Permanently**

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

## **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. Telnet to your favorite Web server:

```
telnet gaia.cs.umass.edu 80
```

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

2. type in a GET HTTP request:

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

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

3. look at response message sent by HTTP server!  
(or use Wireshark to look at captured HTTP request/response)

# User-server state: cookies

many Web sites use cookies

## *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 always access Internet from PC
- visits specific e-commerce site for first time
- when initial HTTP requests arrives at site, site creates:
  - unique ID
  - entry in backend database for ID



# Cookies: keeping “state” (cont.)

client



server



cookie file



ebay 8734  
amazon 1678

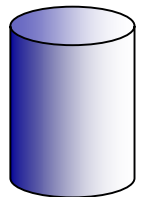
usual http request msg

Amazon server  
creates ID  
1678 for user

usual http response  
**set-cookie: 1678**

create  
entry

backend  
database



usual http request msg  
**cookie: 1678**

cookie-  
specific  
action

access

usual http response msg

access

cookie-  
specific  
action

one week later:



ebay 8734  
amazon 1678

usual http request msg  
**cookie: 1678**

usual http response msg

# Cookies (continued)

*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
- you may supply name and e-mail to sites

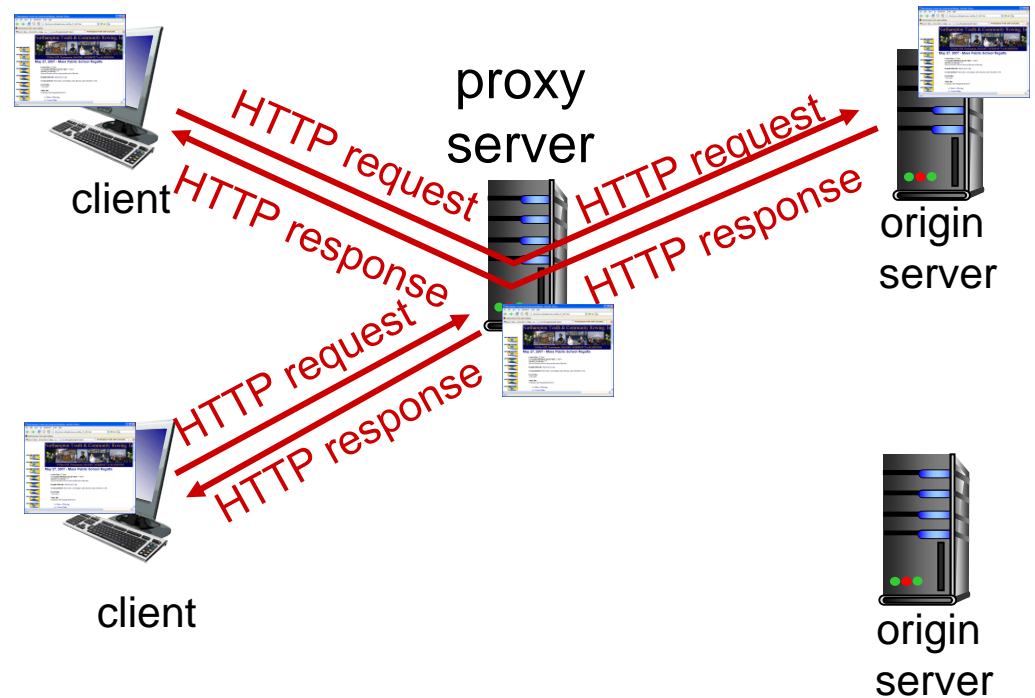
*how to keep “state”:*

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

# Web caches (proxy server)

*goal:* satisfy client request without involving origin

- server
  - user sets browser: Web accesses via cache
  - browser sends all HTTP requests to cache
    - object in cache: cache returns object
    - else cache requests object from origin server, then returns object to client



# More about Web caching

- cache acts as both client and server
  - server for original requesting client
  - client to origin server
- typically cache is installed by ISP (university, company, residential ISP)

## *why Web caching?*

- reduce response time for client request
- reduce traffic on an institution's access link
- Internet dense with caches: enables “poor” content providers to effectively deliver content (so too does P2P file sharing)

# Caching example:

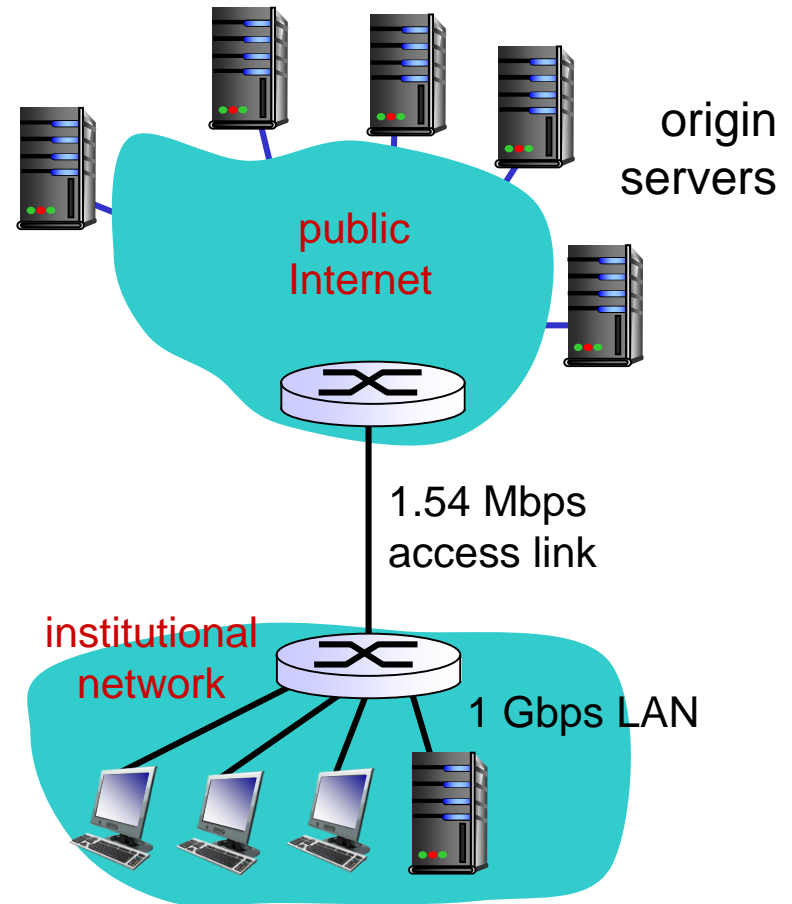
## *assumptions:*

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

## *consequences:*

- LAN utilization: 0.15%
- access link utilization = 99%
- total delay = Internet delay + access delay + LAN delay  
= 2 sec + minutes + usecs

*problem!*



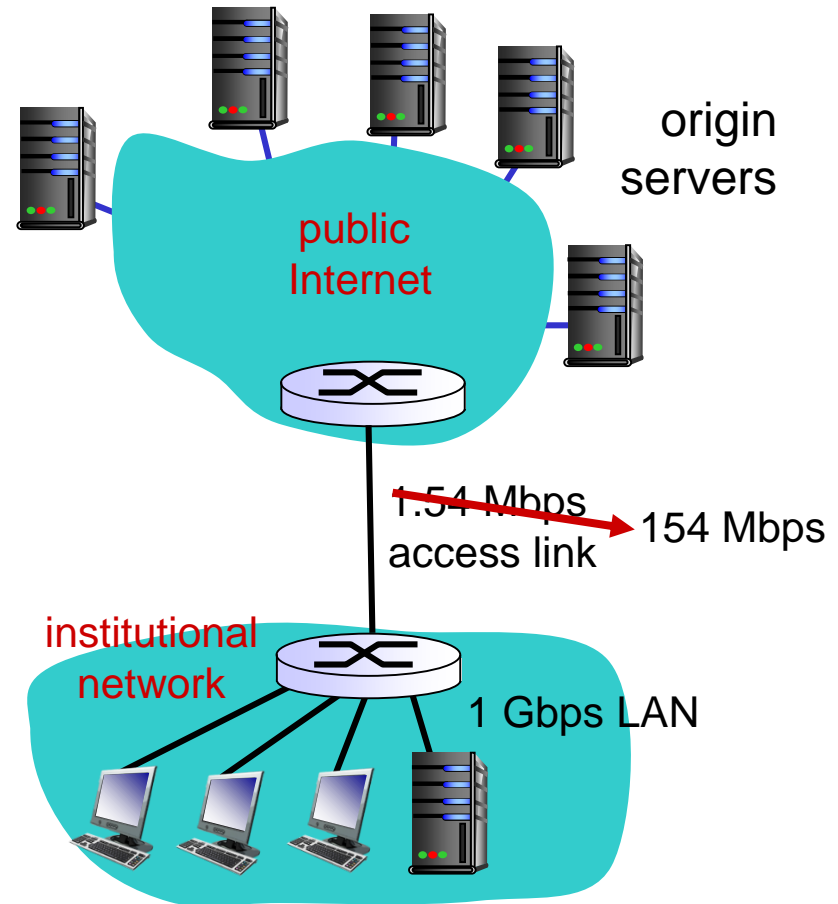
# Caching example: fatter access link

## *assumptions:*

- avg object size: 1Mbits
- avg request rate from browsers to origin servers: 15/sec
- avg data rate to browsers: 1.50 Mbps
- RTT from institutional router to any origin server: 2 sec
- access link rate: 1.54 Mbps  $\rightarrow$  154 Mbps

## *consequences:*

- LAN utilization: 0.15%  $\rightarrow$  9.9%
- access link utilization = 99%
- total delay = Internet delay + access delay + LAN delay  
 $= 2 \text{ sec} + \text{minutes}$   $\rightarrow$   $\text{microseconds}$



**Cost:** increased access link speed (not cheap!)

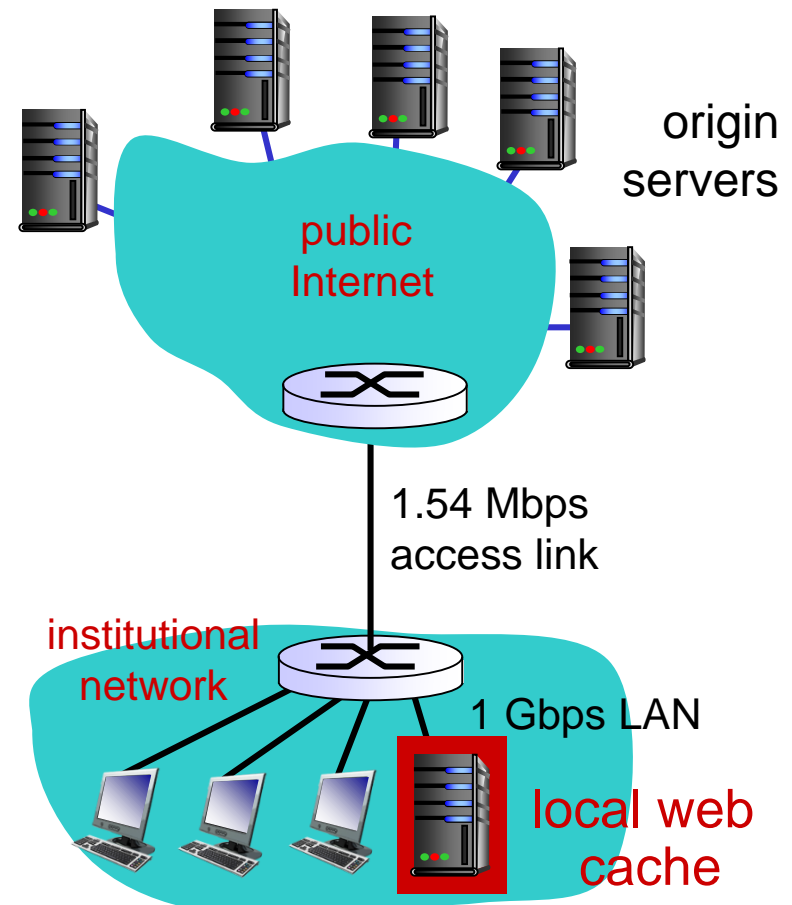
# Caching example: install local cache

## *assumptions:*

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

## *consequences:*

- LAN utilization: 0.15%?
- access link utilization = 100%
- total delay = Internet delay + access delay + LAN delay  
= 2 sec + minutes + usecs

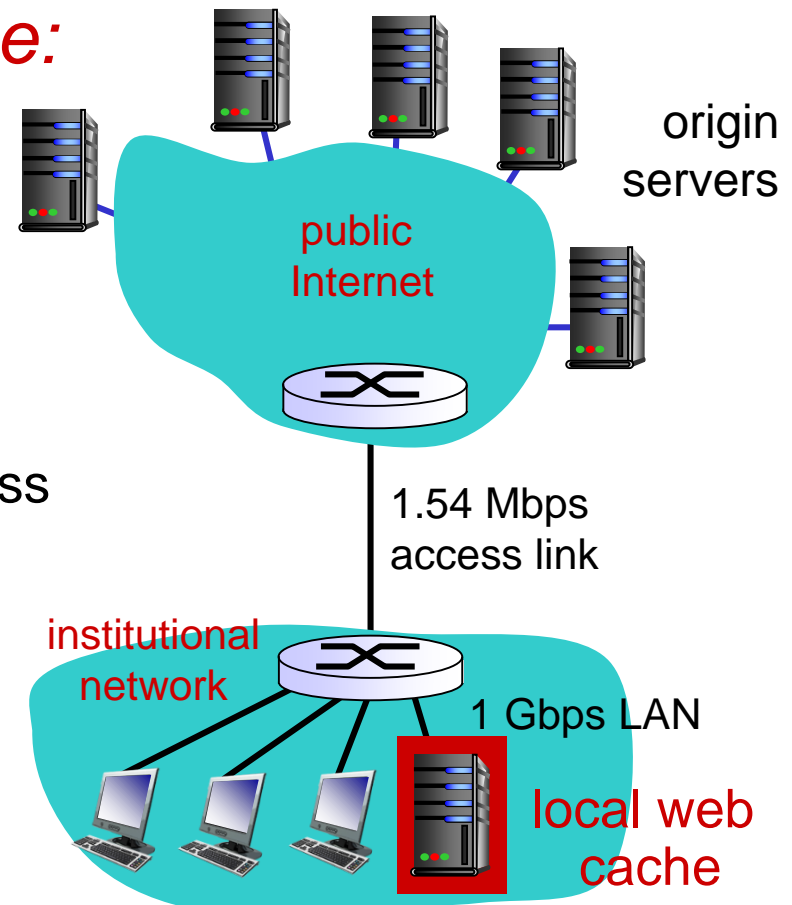


*Cost:* web cache (cheap!) *How to compute link utilization, delay?*

# Caching example: install local cache

## *Calculating access link utilization, delay with cache:*

- suppose cache hit rate is 0.4
  - 40% requests satisfied at cache, 60% requests satisfied at origin
- access link utilization:
  - 60% of requests use access link
- data rate to browsers over access link  
 $= 0.6 * 1.50 \text{ Mbps} = .9 \text{ Mbps}$ 
  - utilization =  $0.9 / 1.54 = .58$
- total delay
  - $= 0.6 * (\text{delay from origin servers}) + 0.4 * (\text{delay when satisfied at cache})$
  - $= 0.6 (2.01) + 0.4 (\sim \text{msecs}) = \sim 1.2 \text{ secs}$
  - less 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
- lower link utilization

- **cache:** 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**

client



server



HTTP request msg  
**If-modified-since: <date>**

object  
not  
modified  
before  
<date>

HTTP response  
**HTTP/1.0  
304 Not Modified**

-----

HTTP request msg  
**If-modified-since: <date>**

object  
modified  
after  
<date>

HTTP response  
**HTTP/1.0 200 OK  
<data>**

# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming  
and content  
distribution  
networks

2.7 socket  
programming with  
UDP and TCP

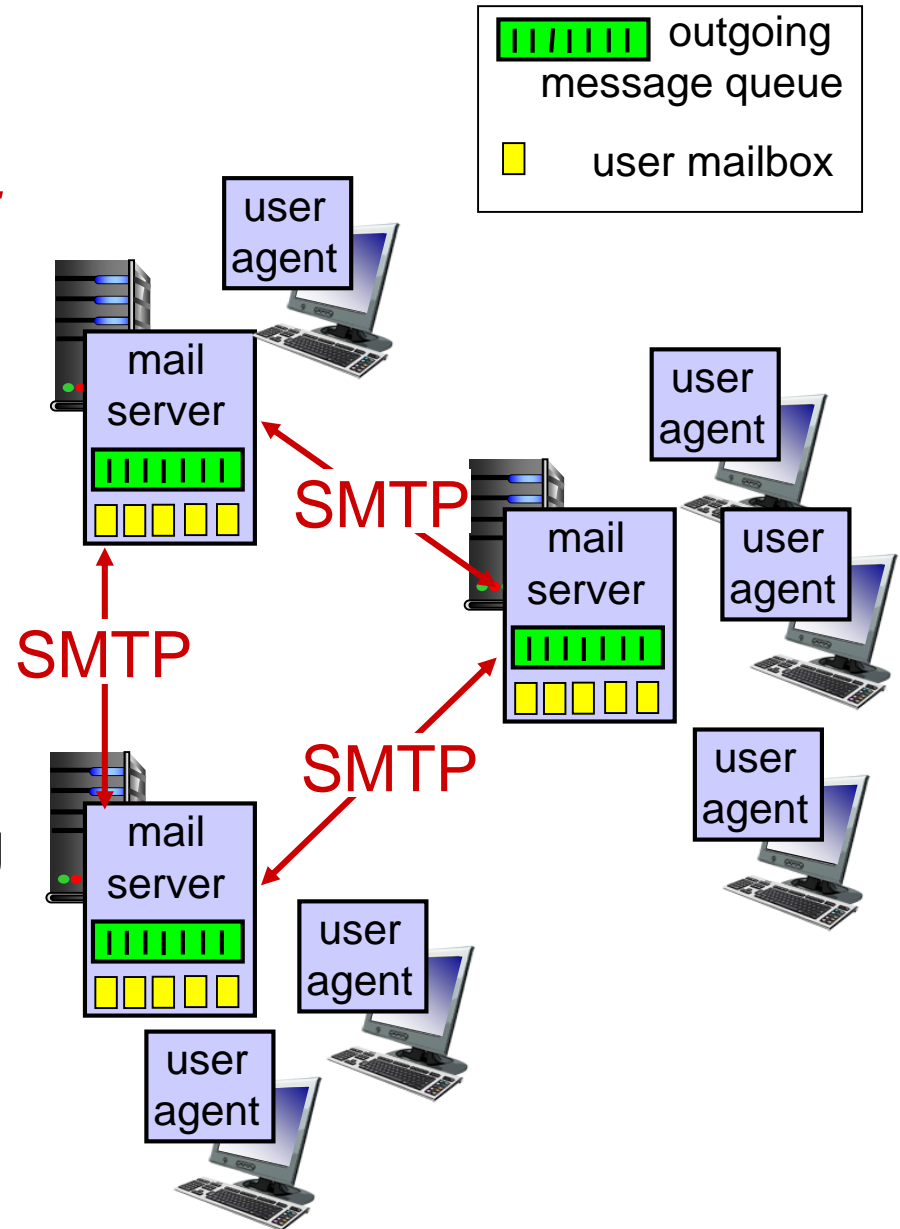
# Electronic mail

## *Three major components:*

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

## *User Agent*

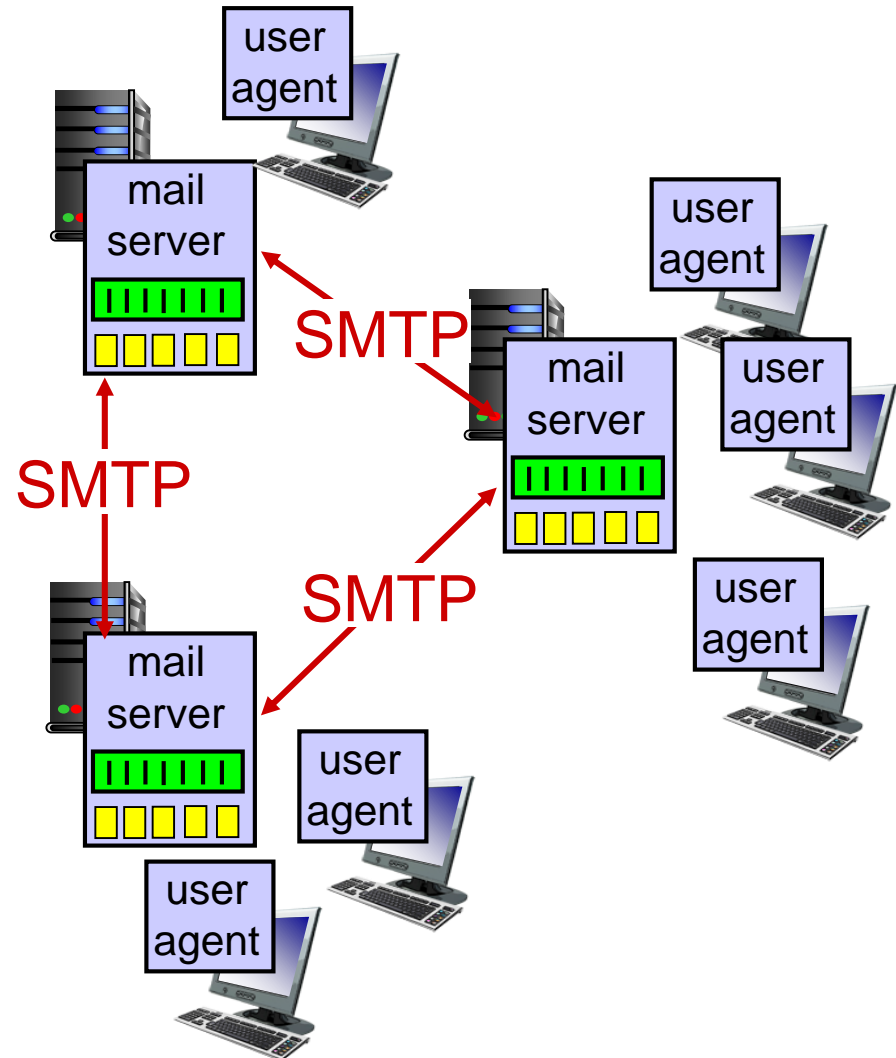
- a.k.a. “mail reader”
- composing, editing, reading mail messages
- e.g., Outlook, Thunderbird, iPhone mail client
- outgoing, incoming messages stored on server



# Electronic 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

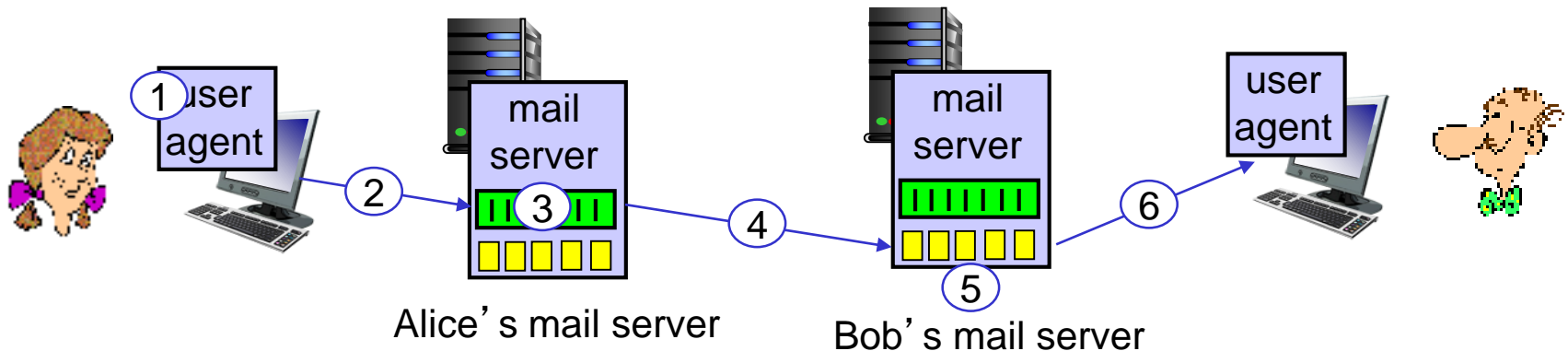


# Electronic Mail: SMTP [RFC 2821]

- uses TCP to reliably transfer email message from client to server, port 25
- direct transfer: sending server to receiving server
- three phases of transfer
  - handshaking (greeting)
  - transfer of messages
  - closure
- command/response interaction (like HTTP)
  - **commands**: ASCII text
  - **response**: status code and phrase
- messages must be in 7-bit ASCII

# Scenario: Alice sends message to Bob

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



# Sample SMTP interaction

```
S: 220 hamburger.edu
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
```

# Try SMTP interaction for yourself:

- `telnet servername 25`
- see 220 reply from server
- enter HELO, MAIL FROM, RCPT TO, DATA, QUIT commands

above lets you send email without using email client (reader)



# SMTP: final words

- 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

## *comparison with HTTP:*

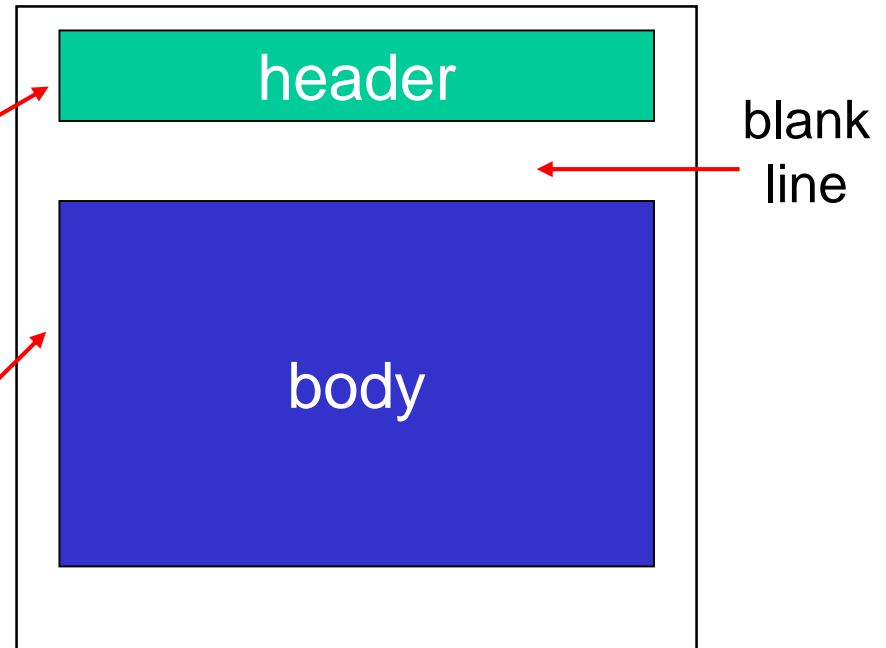
- HTTP: pull
- SMTP: push
- both have ASCII command/response interaction, status codes
- HTTP: each object encapsulated in its own response message
- SMTP: multiple objects sent in multipart message

# Mail message format

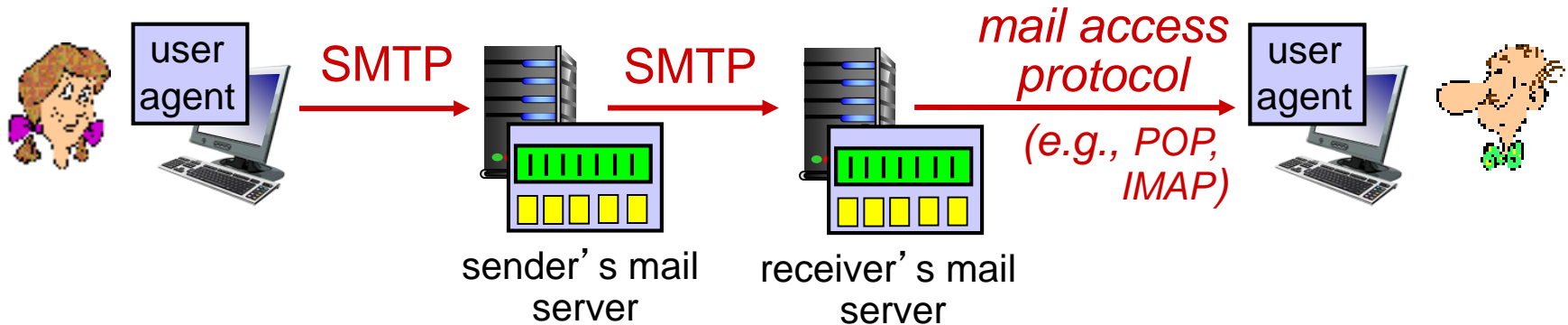
SMTP: protocol for exchanging email messages

RFC 822: standard for text message format:

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



# Mail access protocols



- **SMTP**: delivery/storage to receiver's server
- mail access protocol: retrieval from server
  - **POP**: Post Office Protocol [RFC 1939]: authorization, download
  - **IMAP**: Internet Mail Access Protocol [RFC 1730]: more features, including manipulation of stored messages on server
  - **HTTP**: gmail, Hotmail, Yahoo! Mail, etc.

# POP3 protocol

## *authorization phase*

- client commands:
  - **user**: declare username
  - **pass**: password
- server responses
  - **+OK**
  - **-ERR**

## *transaction phase,*

client:

- **list**: list message numbers
- **retr**: retrieve message by number
- **dele**: delete
- **quit**

```
S: +OK POP3 server ready
C: user bob
S: +OK
C: pass hungry
S: +OK user successfully logged on
```

```
C: list
S: 1 498
S: 2 912
S: .
C: retr 1
S: <message 1 contents>
S: .
C: dele 1
C: retr 2
S: <message 1 contents>
S: .
C: dele 2
C: quit
S: +OK POP3 server signing off
```

# POP3 (more) and IMAP

## *more about POP3*

- previous example uses POP3 “download and delete” mode
  - Bob cannot re-read e-mail if he changes client
- POP3 “download-and-keep”: copies of messages on different clients
- POP3 is stateless across sessions

## *IMAP*

- keeps all messages in one place: at server
- allows user to organize messages in folders
- keeps user state across sessions:
  - names of folders and mappings between message IDs and folder name

# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming  
and content  
distribution  
networks

2.7 socket  
programming with  
UDP and TCP

# DNS: domain name system

*people:* many identifiers:

- SSN, name, passport #

*Internet hosts, routers:*

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

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

*Domain Name System:*

- *distributed database* implemented in hierarchy of many *name servers*
- *application-layer protocol:* hosts, name 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

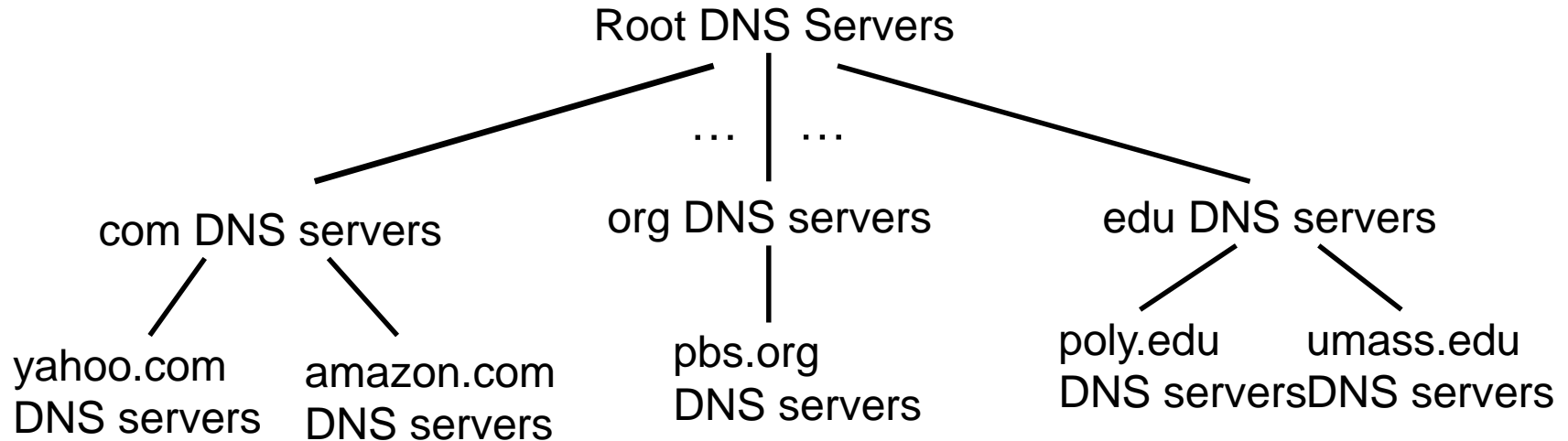
## *why not centralize DNS?*

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

*A: doesn't scale!*



# DNS: a distributed, hierarchical database

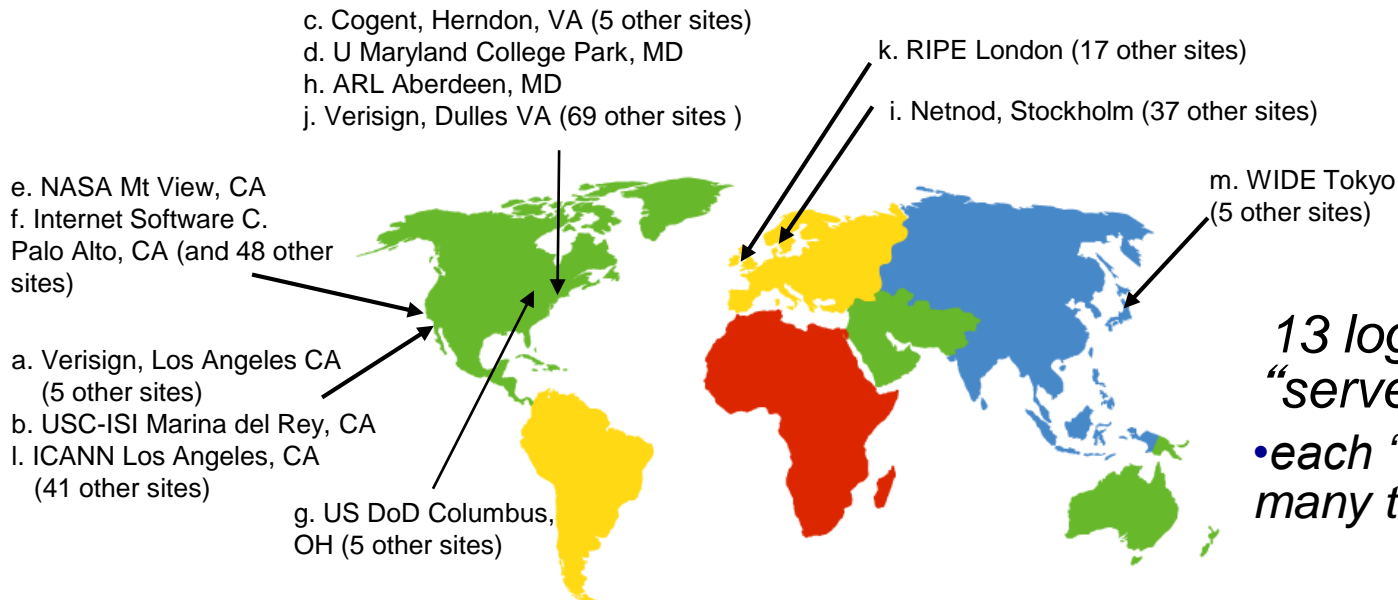


*client wants IP for www.amazon.com; 1<sup>st</sup> approximation:*

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

# DNS: root name servers

- contacted by local name server that can not resolve name
- root name server:
  - contacts authoritative name server if name mapping not known
  - gets mapping
  - returns mapping to local name server



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

# TLD, authoritative servers

## *top-level domain (TLD) servers:*

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

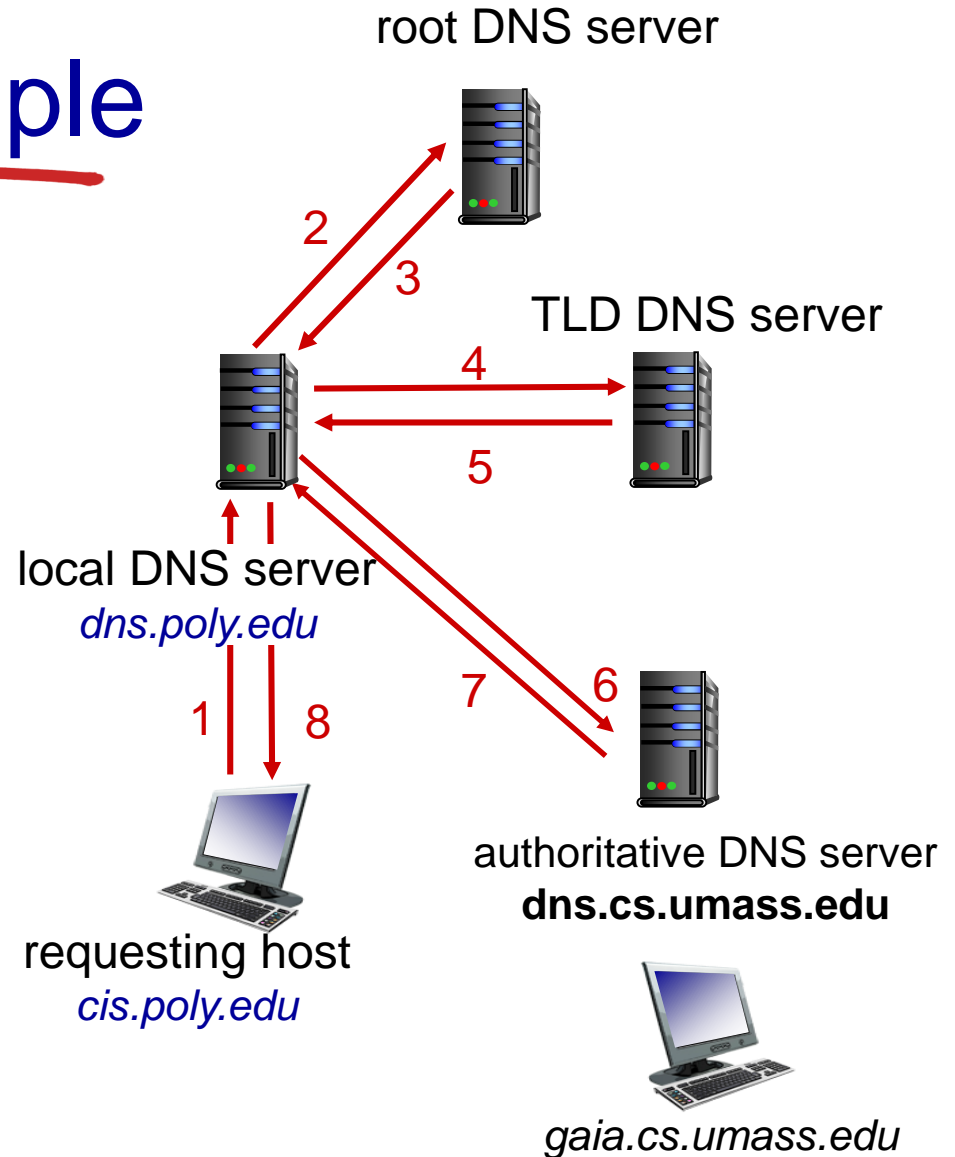
- does not strictly belong to hierarchy
- each ISP (residential ISP, company, university) has one
  - also called “default name server”
- when host makes DNS query, query is sent to its local DNS server
  - has local cache of recent name-to-address translation pairs (but may be out of date!)
  - acts as proxy, forwards query into hierarchy

# DNS name resolution example

- host at cis.poly.edu wants IP address for gaia.cs.umass.edu

## *iterated query:*

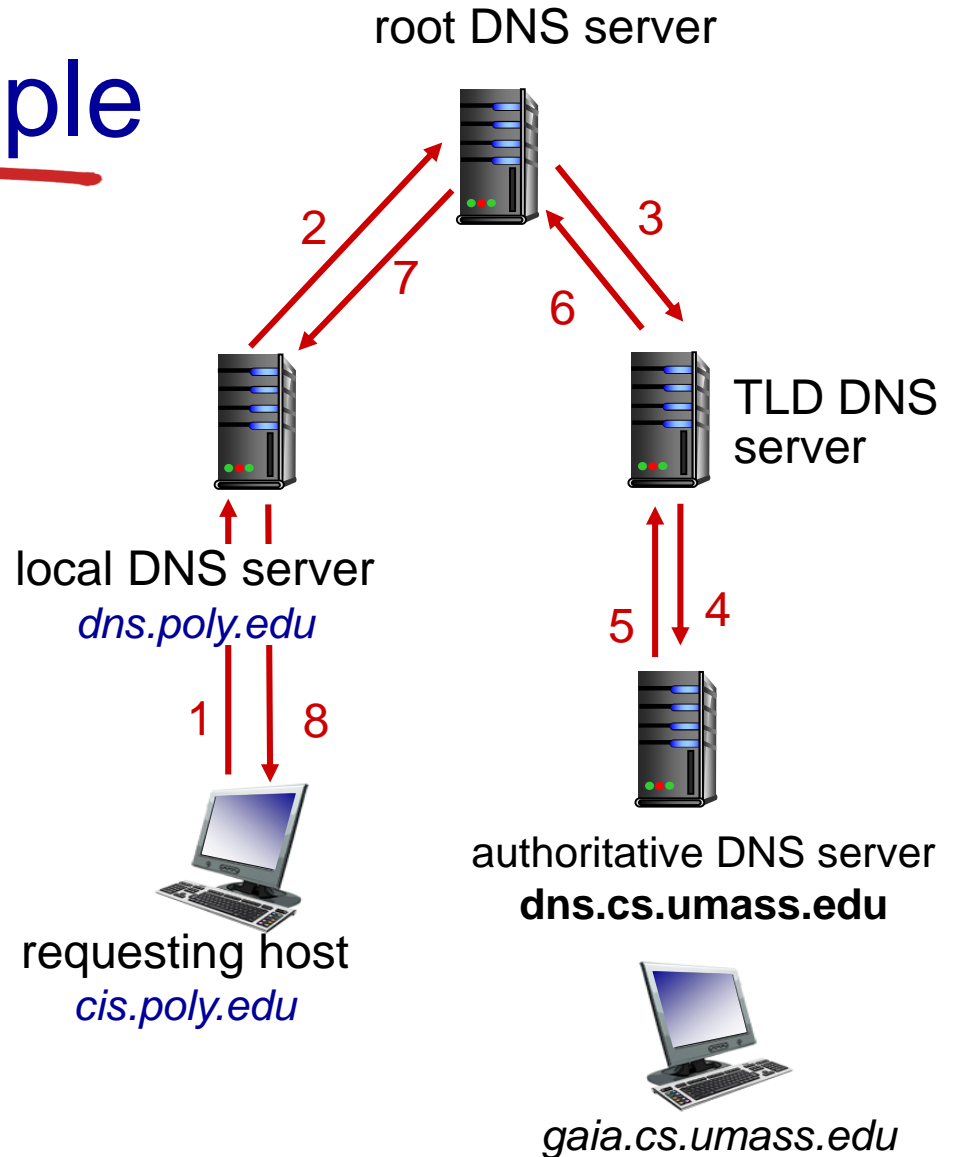
- contacted server replies with name of server to contact
- “I don’t know this name, but ask this server”



# DNS name resolution example

## *recursive query:*

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



# Why Iterative & Recursive

---

## Recursive

- Let server offload client burden for manageability
- Let server cache over a pool of clients for better performance.

## Iterative

- Let server query and forget
- Easy to build high load servers

# DNS: caching, updating records

- once (any) name server learns mapping, it *caches* mapping
  - cache entries timeout (disappear) after some time (TTL)
  - TLD servers typically cached in local name servers
    - thus root name servers not often visited
- cached entries may be *out-of-date* (best effort name-to-address translation!)
  - if name host changes IP address, may not be known Internet-wide until all TTLs expire
- update/notify mechanisms proposed IETF standard
  - RFC 2136



# 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

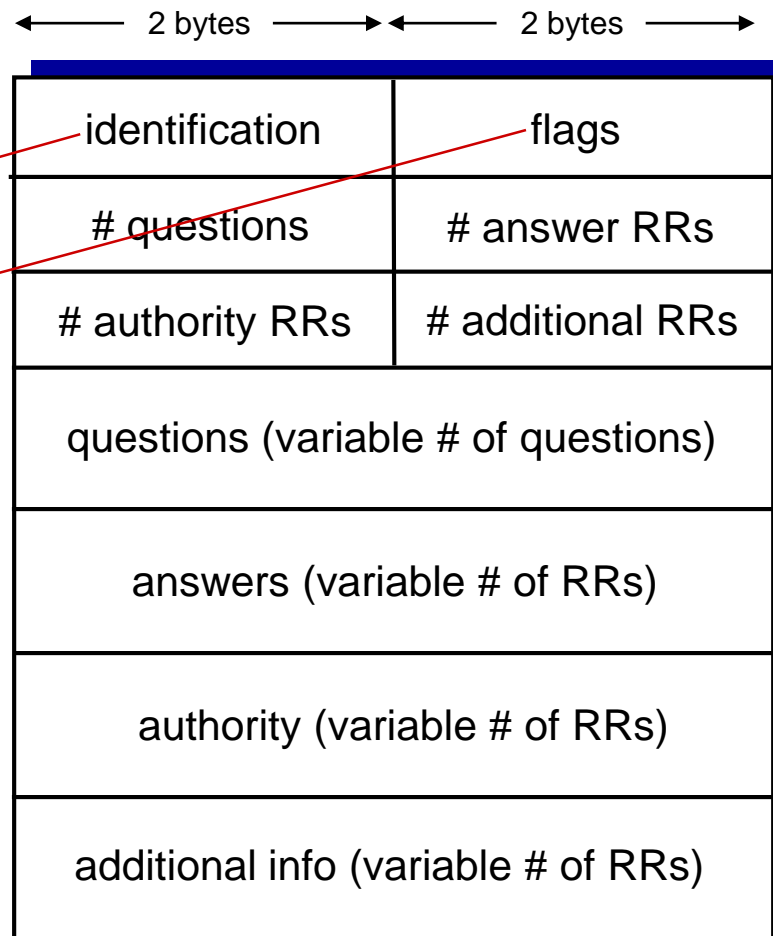
- **value** is name of mailserver associated with **name**

# DNS protocol, messages

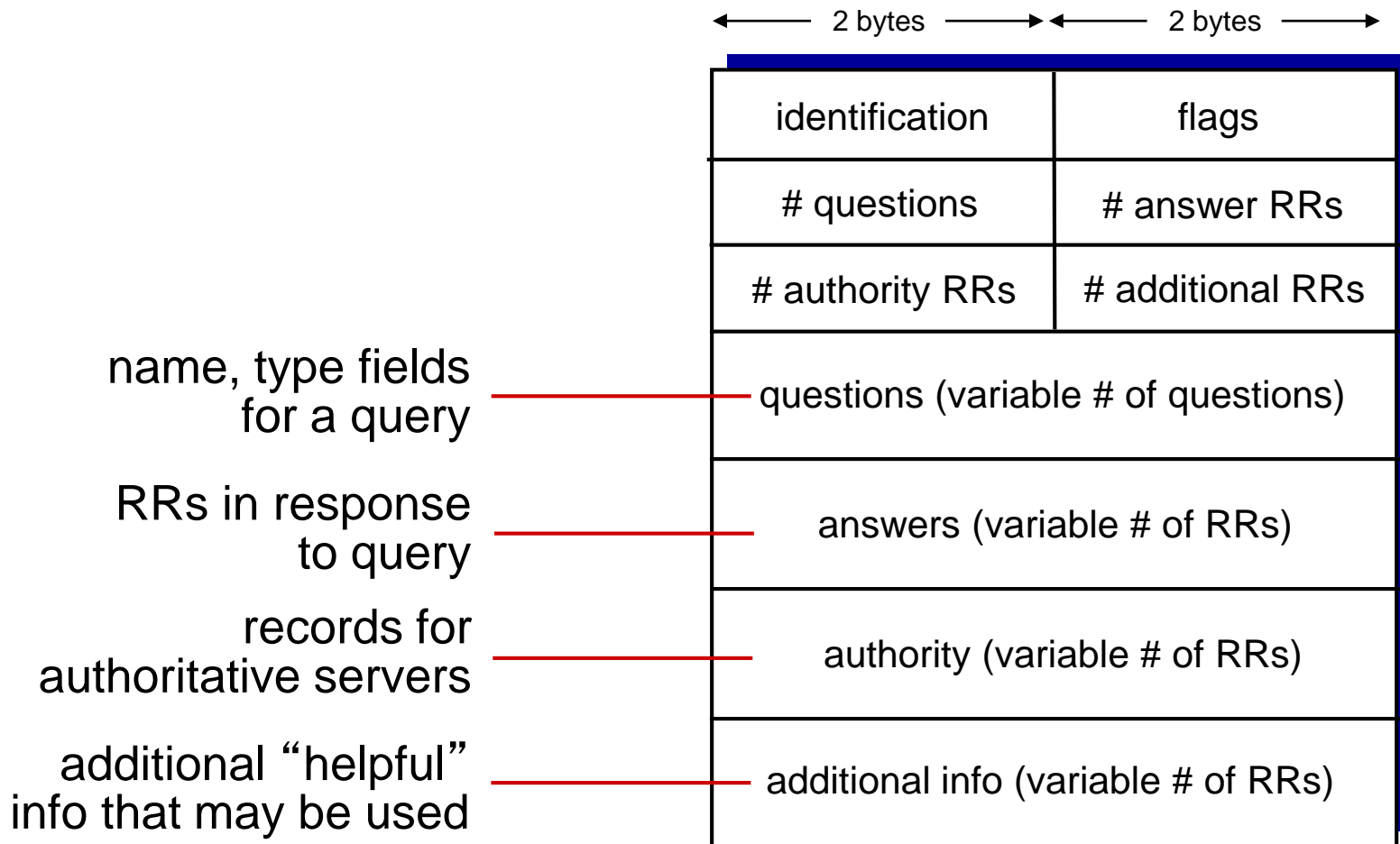
- *query* and *reply* messages, both with same *message format*

## 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



# Inserting records into DNS

- example: new startup “Network Utopia”
- register name networkutopia.com at *DNS registrar* (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts two RRs into .com TLD server:  
(networkutopia.com, dns1.networkutopia.com, NS)  
(dns1.networkutopia.com, 212.212.212.1, A)
- create authoritative server type A record for www.networkutopia.com; type MX record for networkutopia.com

# Attacking DNS

## 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

## redirect attacks

- man-in-middle
  - Intercept queries
- DNS poisoning
  - Send bogus replies to DNS server, which caches

## exploit DNS for DDoS

- send queries with spoofed source address: target IP
- requires amplification

# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming  
and content  
distribution  
networks

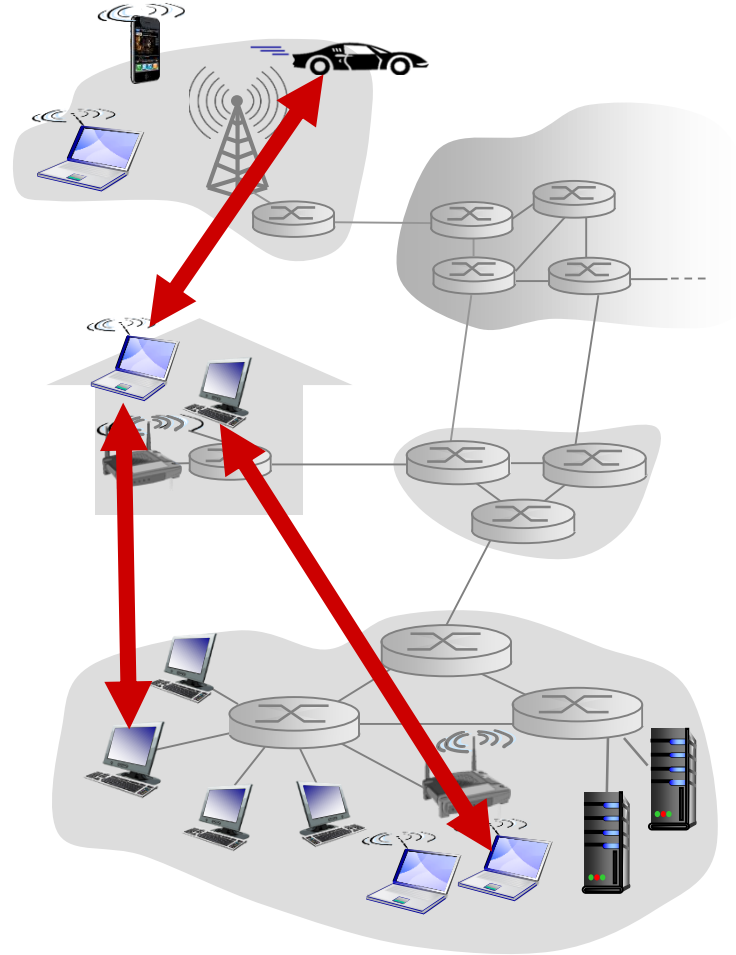
2.7 socket  
programming with  
UDP and TCP

# Pure P2P architecture

- *no* always-on server
- arbitrary end systems directly communicate
- peers are intermittently connected and change IP addresses

## *examples:*

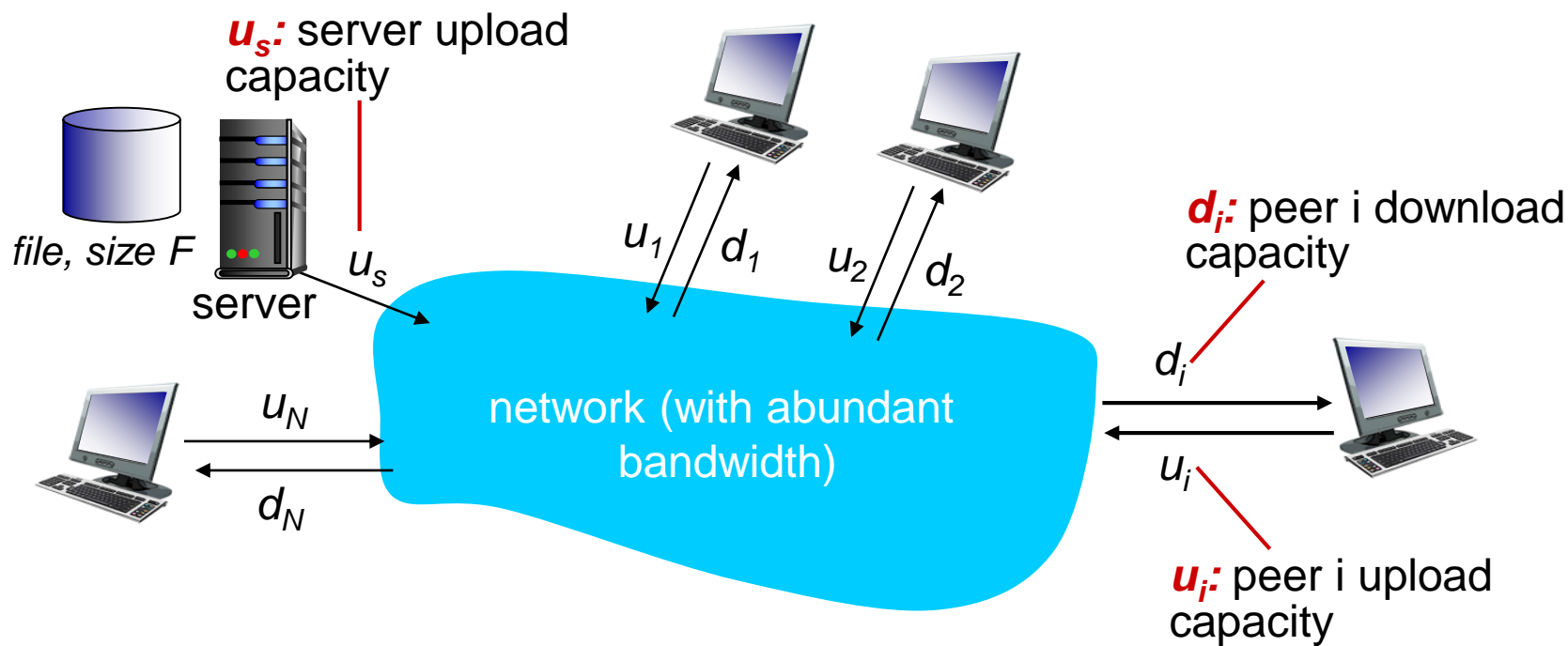
- file distribution (BitTorrent)
- Streaming (KanKan)
- VoIP (Skype)



# File distribution: client-server vs P2P

Question: 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:

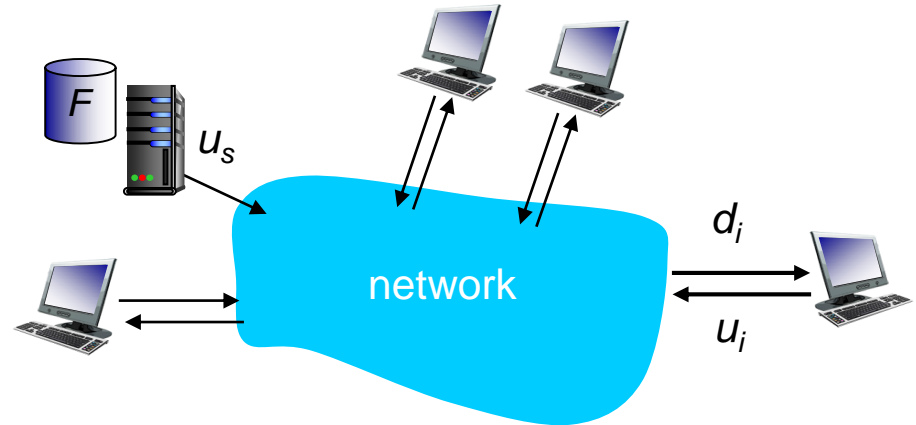
- **client:** each client must download file copy

- $d_{min}$  = min client download rate
- min client download time:

$F/d_{min}$  time to distribute  $F$   
to  $N$  clients using  
client-server approach

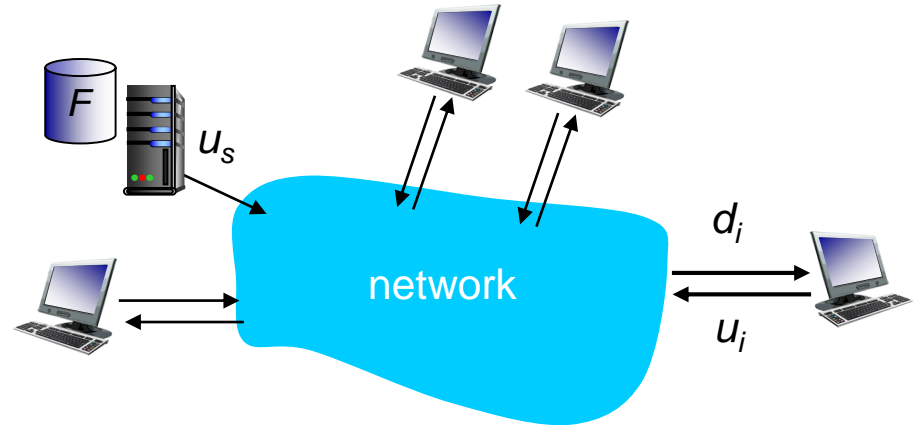
$$D_{c-s} \geq \max\{NF/u_s, F/d_{min}\}$$

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

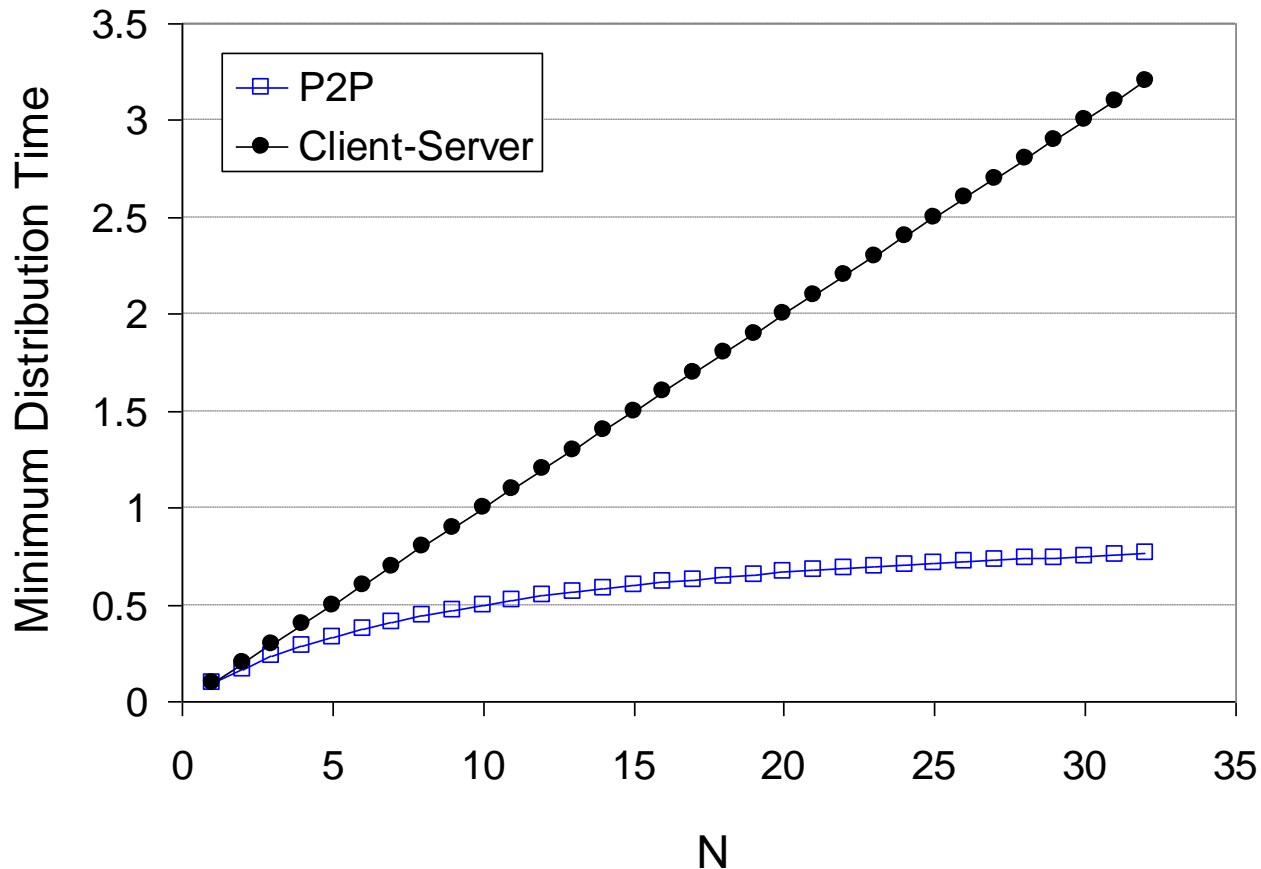
$$D_{P2P} \geq \max\{F/u_s, F/d_{\min}, NF/(u_s + \sum u_i)\}$$

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,  $u_s = 10u$ ,  $d_{min} \geq u_s$

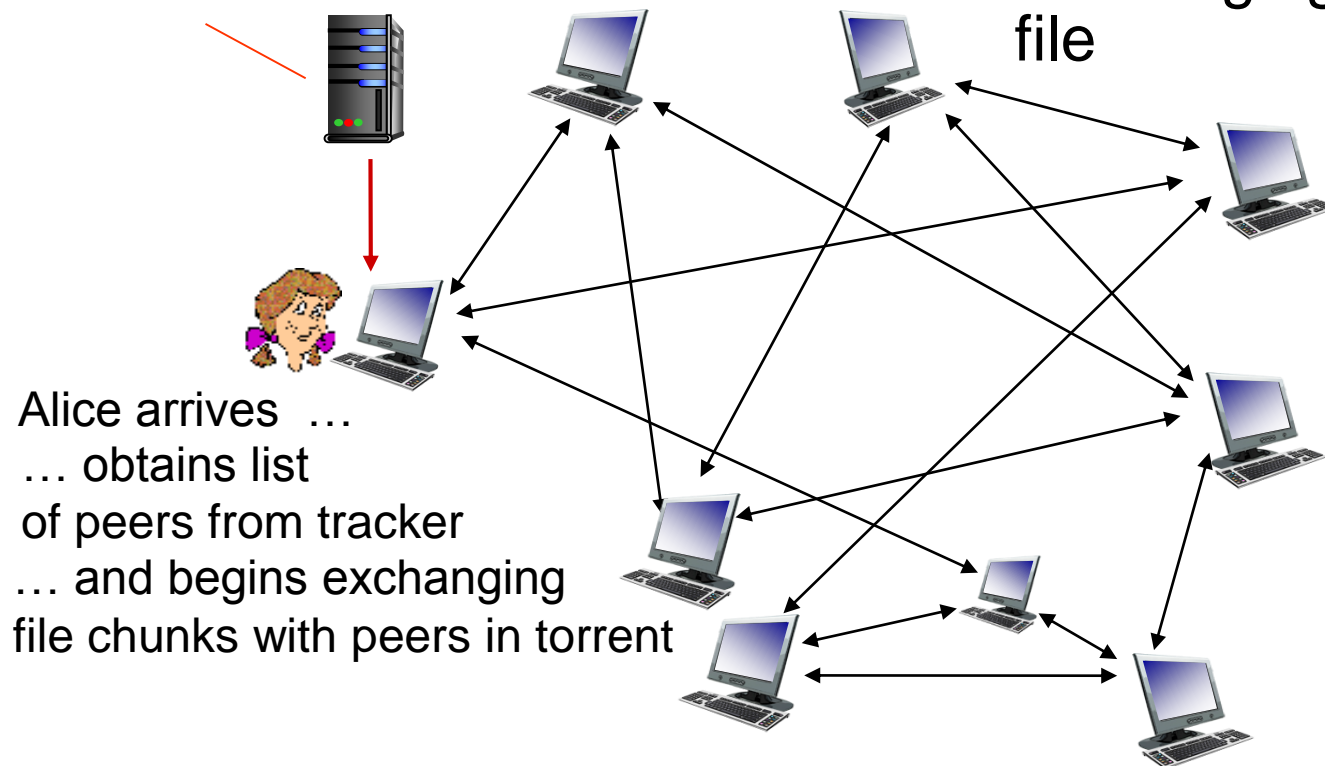


# P2P file distribution: BitTorrent

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

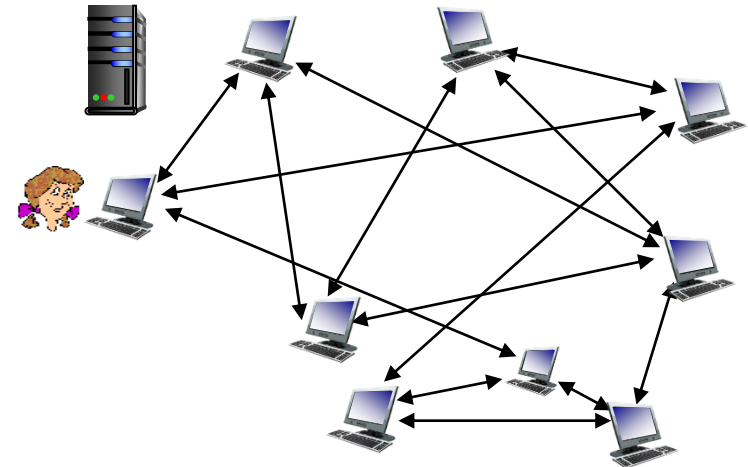
*tracker*: tracks peers participating in torrent

*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:*

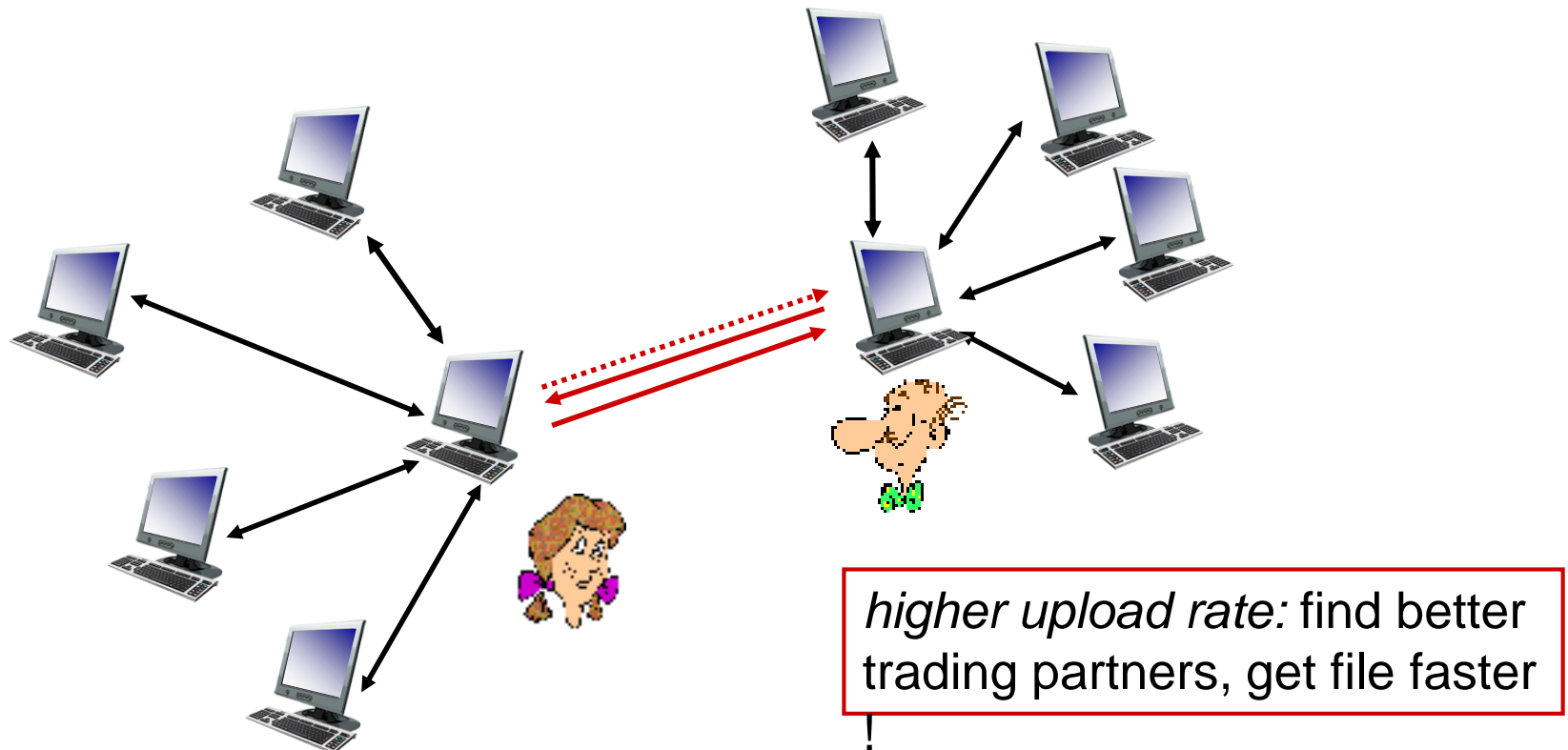
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

## *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 unchokes” Bob
- (2) Alice becomes one of Bob’s top-four providers; Bob reciprocates
- (3) Bob becomes one of Alice’s top-four providers



# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming  
and content  
distribution  
networks (CDNs)

2.7 socket  
programming with  
UDP and TCP



# Video Streaming and CDNs:

## ~~context~~

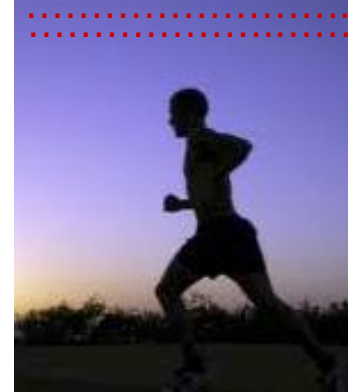
- video traffic: major consumer of Internet bandwidth
  - Netflix, YouTube: 37%, 16% of downstream residential ISP traffic
  - ~1B YouTube users, ~75M Netflix users
- challenge: scale - how to reach ~1B users?
  - single mega-video server won't work (why?)
- challenge: heterogeneity
  - different users 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  $i$

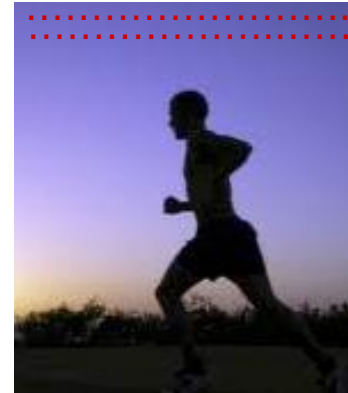


frame  $i+1$

# 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, < 1 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  $i$

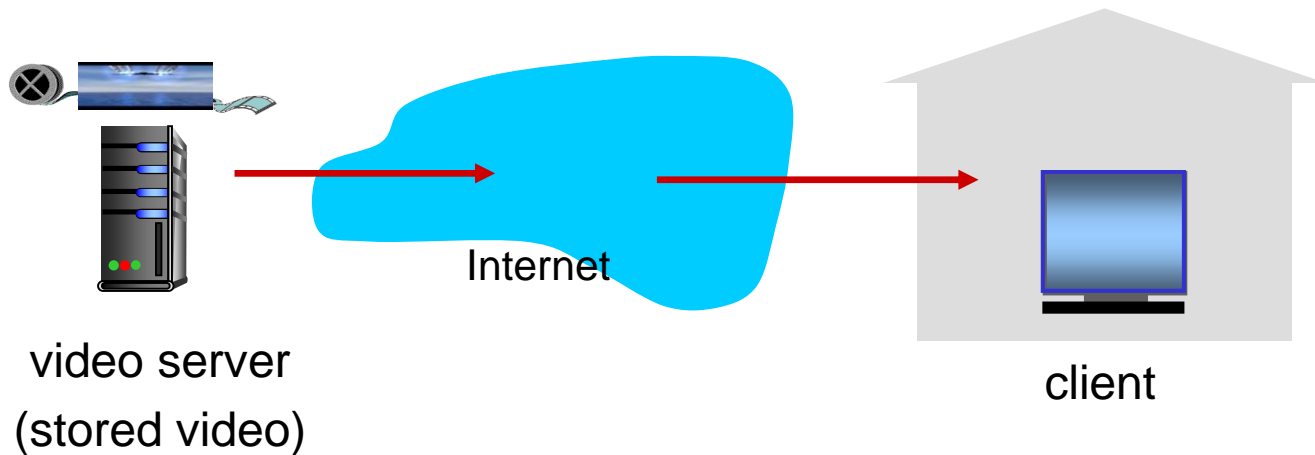
*temporal coding example:* instead of sending complete frame at  $i+1$ , send only differences from frame  $i$



frame  $i+1$

# Streaming stored video:

simple scenario:



# Streaming multimedia: DASH

- *DASH*: *D*ynamic, *A*daptive *S*treaming over *H*TTP
- *server*:
  - divides video file into multiple chunks
  - each chunk stored, encoded at different rates
  - *manifest file*: provides URLs for different chunks
- *client*:
  - periodically measures 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)

# Streaming multimedia: DASH

- *DASH: Dynamic, Adaptive Streaming over HTTP*
- “*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)

# Content distribution networks

- *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 path to distant clients
  - multiple copies of video sent over outgoing link

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

# Content distribution networks

---

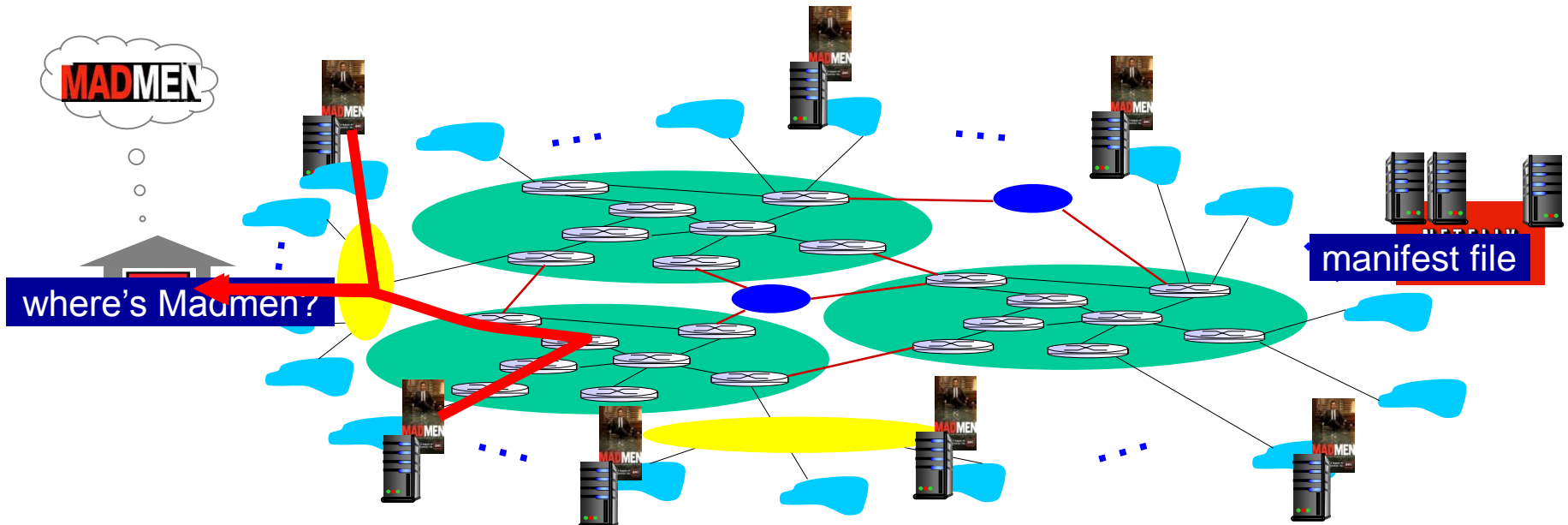
- *challenge*: how to stream content (selected from millions of videos) to hundreds of thousands of simultaneous users?
- *option 2*: store/serve multiple copies of videos at multiple geographically distributed sites (*CDN*)
  - *enter deep*: push CDN servers deep into many access networks
    - close to users
    - used by Akamai, 1700 locations
  - *bring home*: smaller number (10's) of larger clusters in POPs near (but not within) access networks
    - used by Limelight



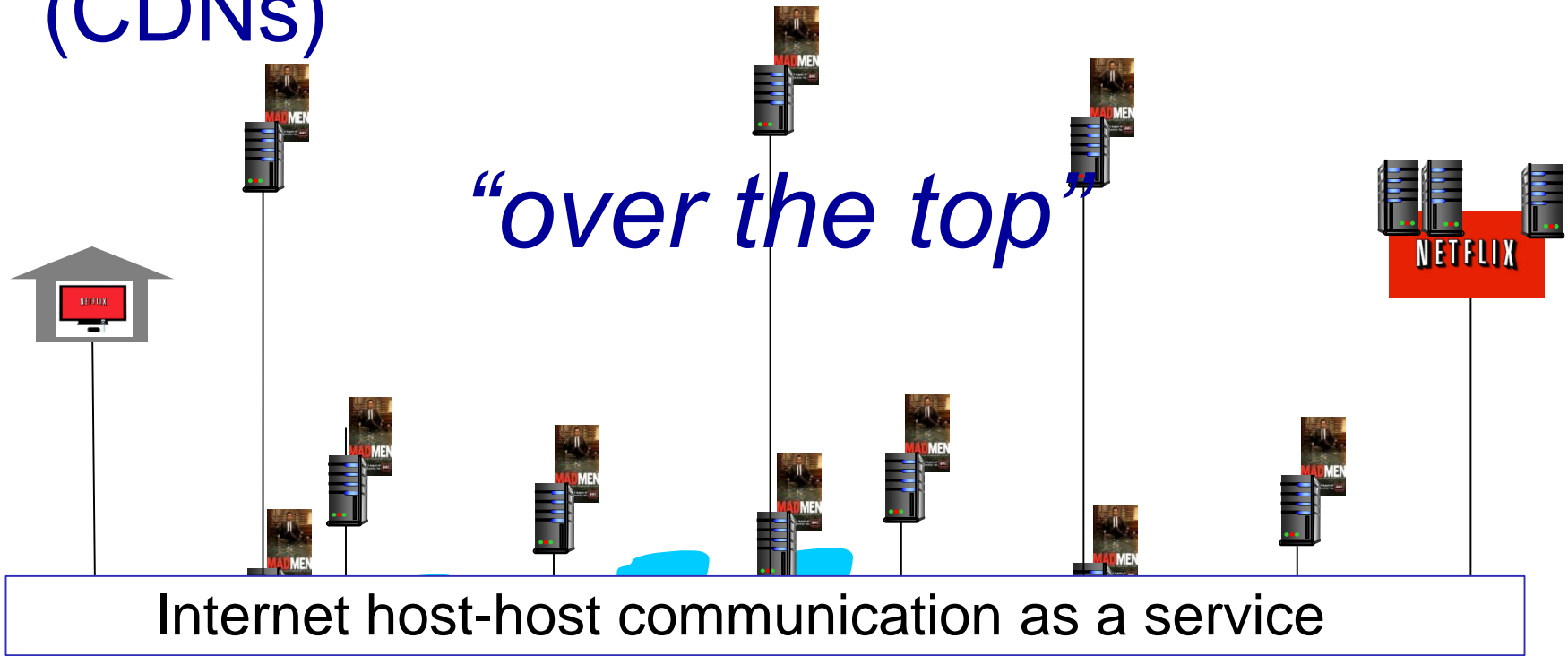
# Content Distribution Networks

(CDNs)

- CDN: stores copies of content at CDN nodes
  - e.g. Netflix stores copies of MadMen
- subscriber requests content from CDN
  - directed to nearby copy, retrieves content
  - may choose different copy if network path congested



# Content Distribution Networks (CDNs)



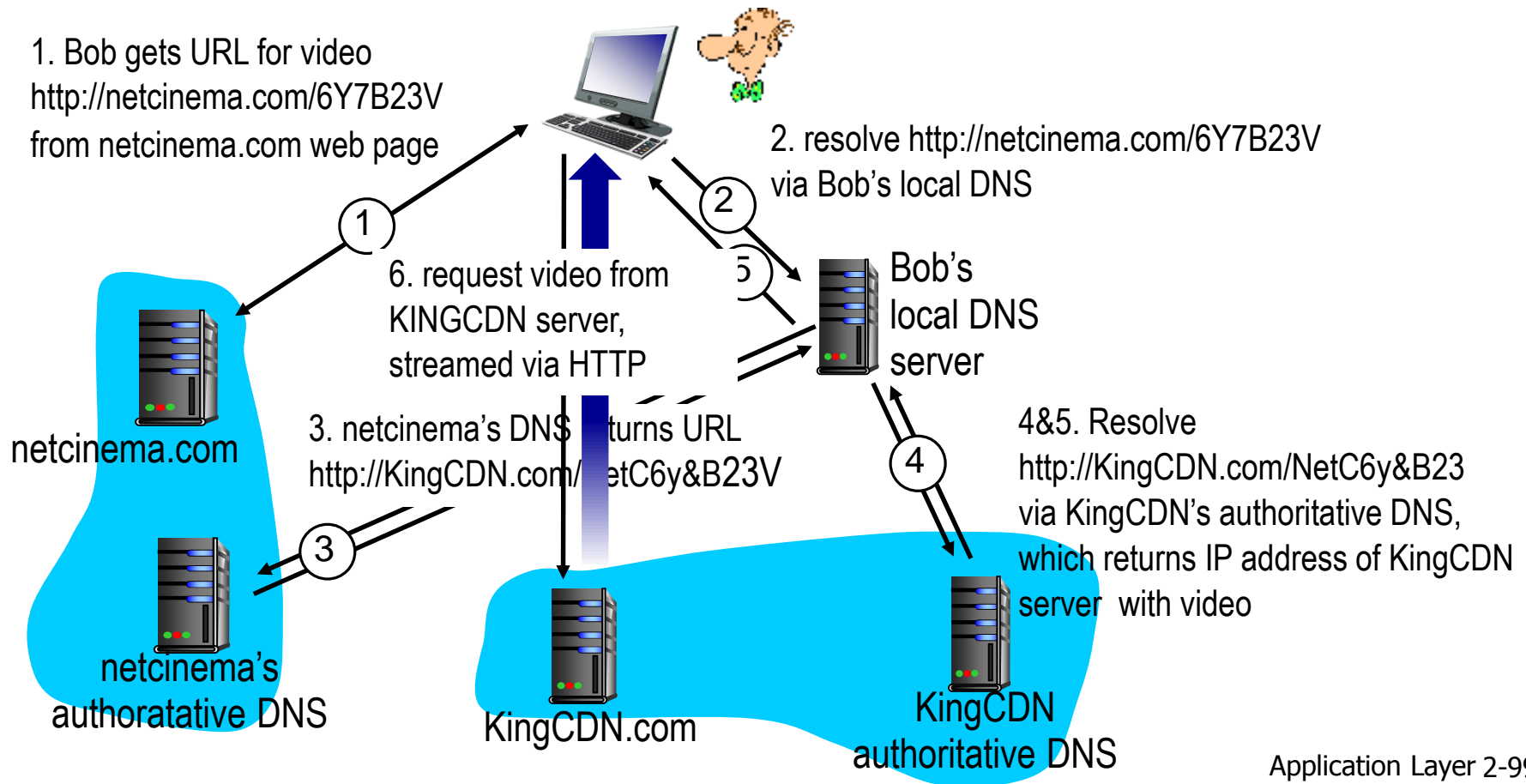
*OTT challenges:* coping with a congested Internet

- from which CDN node to retrieve content?
  - viewer behavior in presence of congestion?
  - what content to place in which CDN node?
- more... in chapter 7

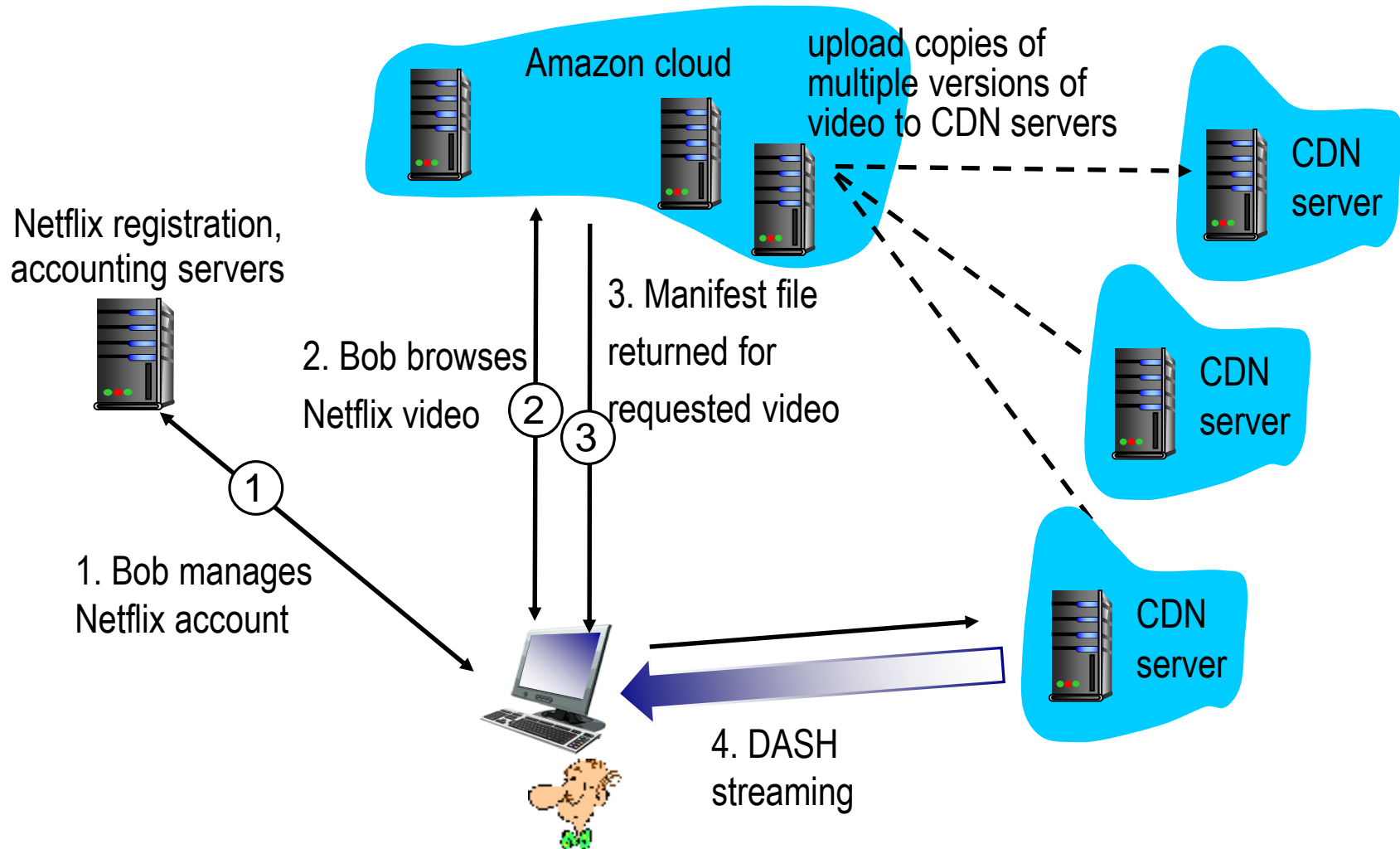
# CDN content access: a closer look

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

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



# Case study: Netflix



# Chapter 2: outline

2.1 principles of  
network  
applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

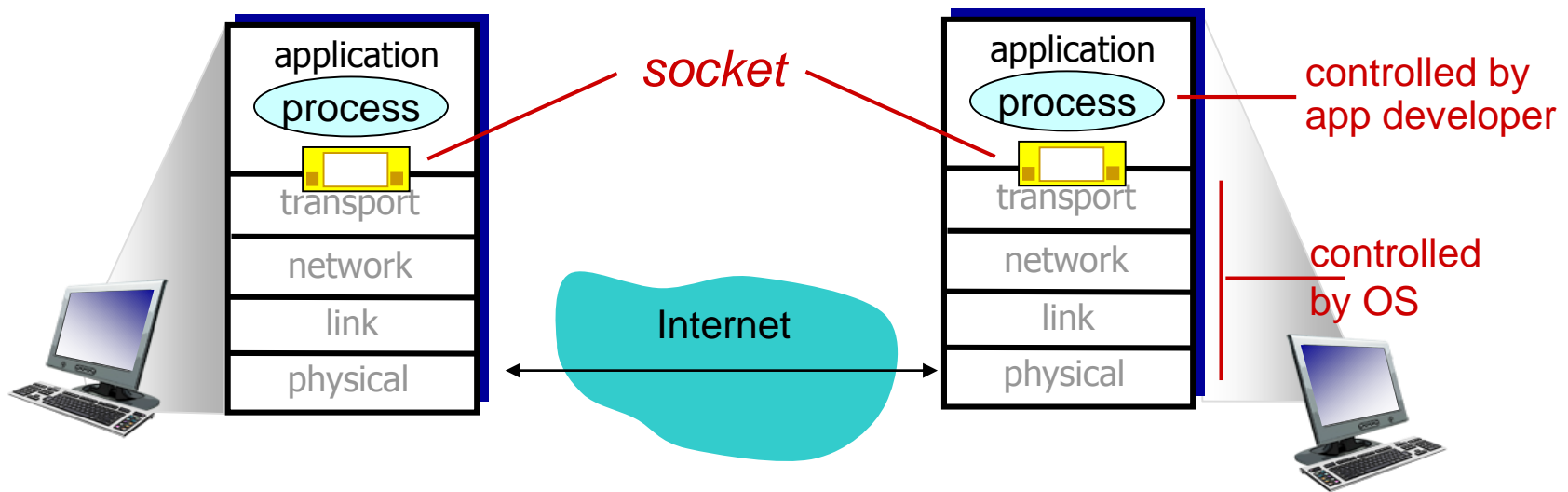
2.6 video streaming  
and content  
distribution  
networks

2.7 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 & 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



# 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 server IP and  
port=x; send datagram via  
`clientSocket`

↓  
read datagram from  
`clientSocket`

↓  
close  
`clientSocket`

# Example app: UDP client

## *Python UDPClient*

include Python's socket  
library

from socket import \*  
serverName = 'hostname'  
serverPort = 12000

create UDP socket 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 client's  
address (client IP and port) → 

```
message, clientAddress = serverSocket.recvfrom(2048)
```

```
modifiedMessage = message.decode().upper()
```

send upper case string  
back to this client → 

```
serverSocket.sendto(modifiedMessage.encode(),  
clientAddress)
```

# Socket programming *with TCP*

## *client must contact server*

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

## *client contacts server by:*

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

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

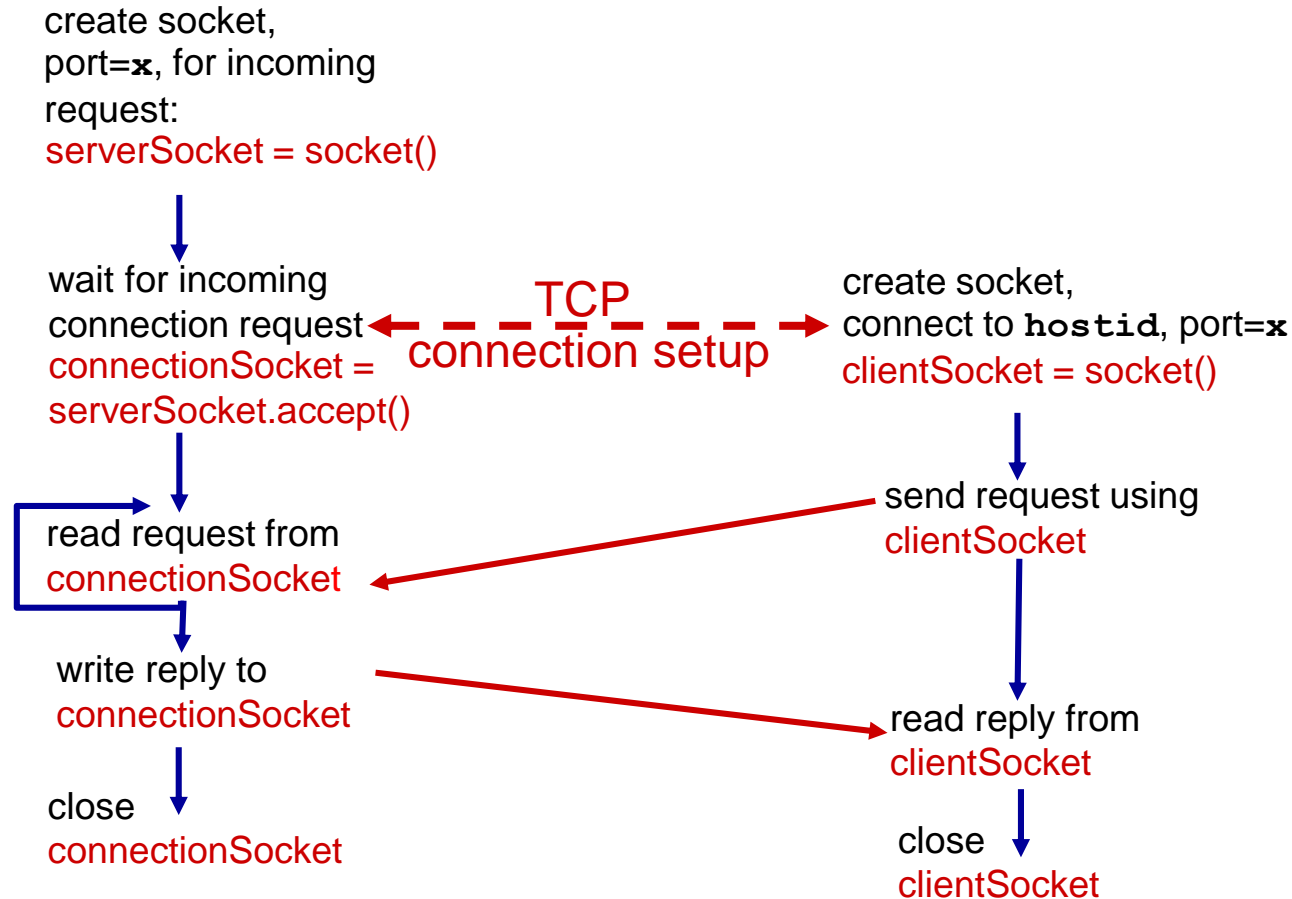
## *application viewpoint:*

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

# Client/server socket interaction: TCP

server (running on `hostid`)

client



# Example app: TCP client

## *Python TCPClient*

```
from socket import *
```

```
serverName = 'servername'
```

```
serverPort = 12000
```

create TCP socket for  
server, remote port 12000

```
→ clientSocket = socket(AF_INET, SOCK_STREAM)
```

```
clientSocket.connect((serverName, serverPort))
```

```
sentence = raw_input('Input lowercase sentence:')
```

No need to attach server  
name, port

```
→ clientSocket.send(sentence.encode())
```

```
modifiedSentence = clientSocket.recv(1024)
```

```
print ('From Server:', modifiedSentence.decode())
```

```
clientSocket.close()
```

# Example app: TCP server

## *Python TCPServer*

create TCP welcoming  
socket

server begins listening for  
incoming TCP requests

loop forever

server waits on accept()  
for incoming requests, new  
socket created on return

read bytes from socket (but  
not address as in UDP)

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

```
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()
```

# Chapter 2: summary

*our study of network apps 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, POP, 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:*

- control vs. messages
  - in-band, out-of-band
- centralized vs. decentralized
- stateless vs. stateful
- reliable vs. unreliable message transfer
- “complexity at network edge”