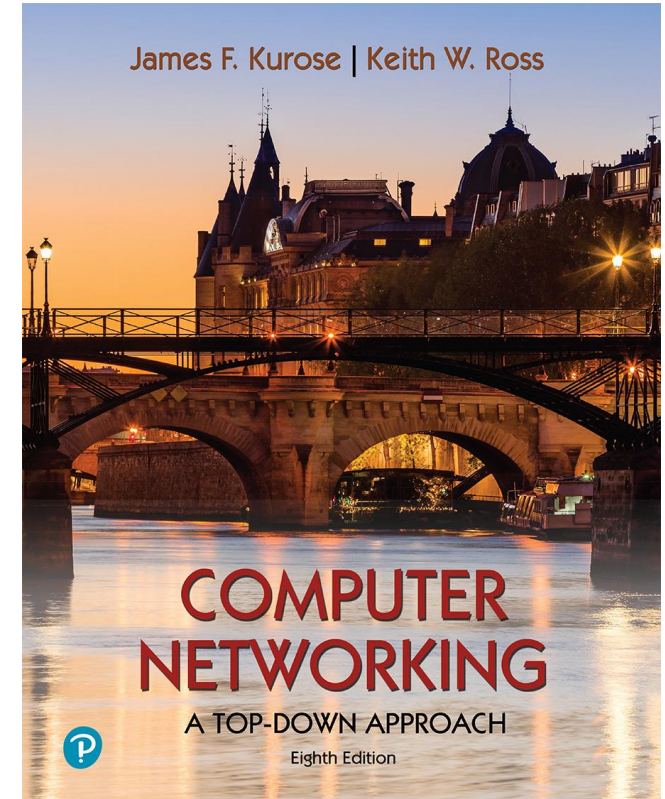


# COMP211: Computer Networks

## Chapter 2 Application Layer

Material adapted from; All material copyright 1996-2023  
J.F Kurose and K.W. Ross, All Rights Reserved



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

8<sup>th</sup> edition  
Jim Kurose, Keith Ross  
Pearson, 2020

# 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
- programming network applications
  - socket API

# Application layer: overview

- Principles of network applications
  - Architectures
  - Processes communicating
  - Transport services available
- Web and HTTP
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- The Domain Name System DNS
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# Some network apps

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

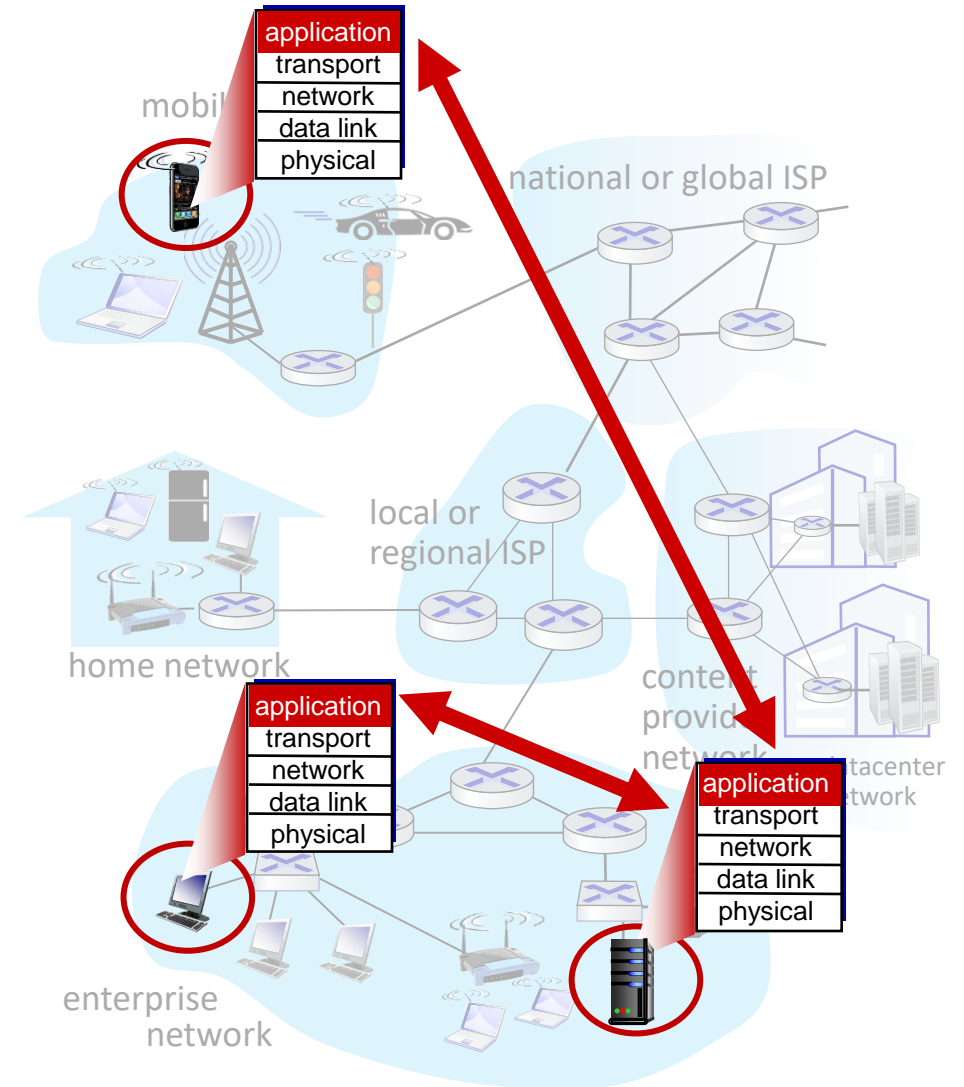
# Creating a network app

write programs that:

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

no need to write software for network-core devices

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



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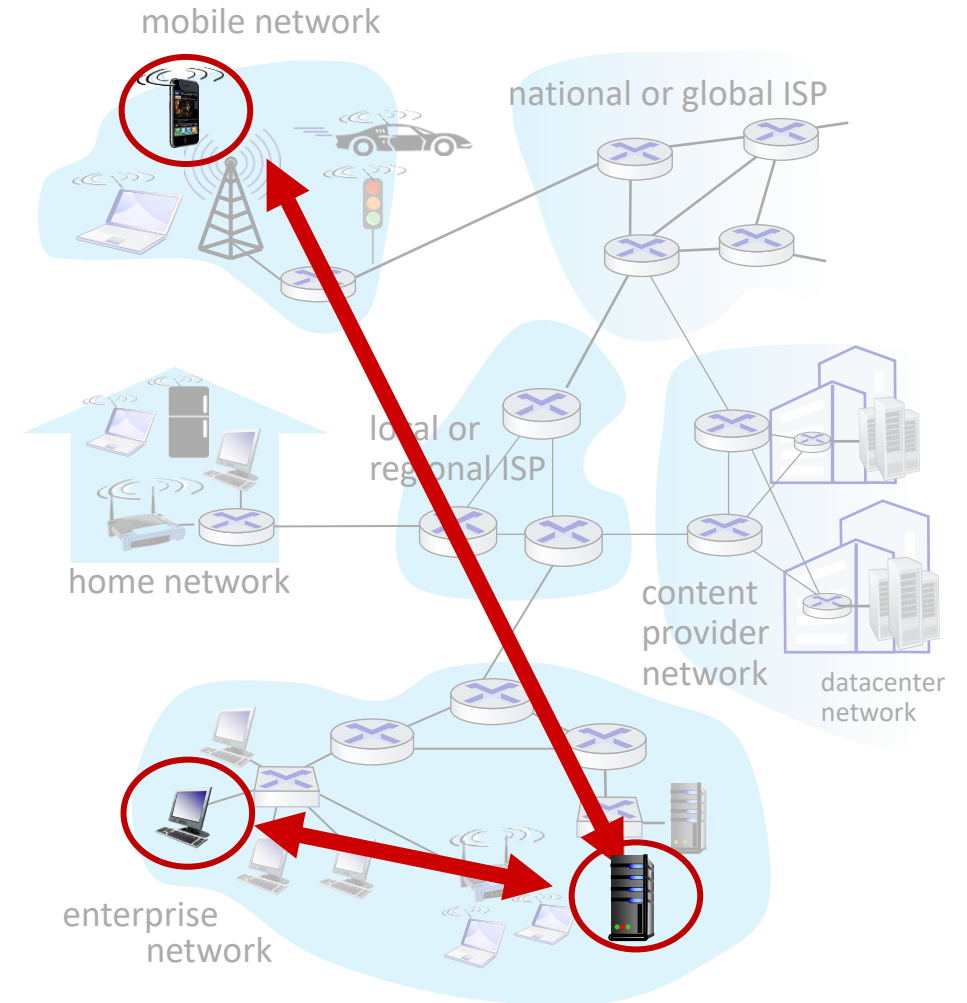
# Client-server paradigm

## server:

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

## clients:

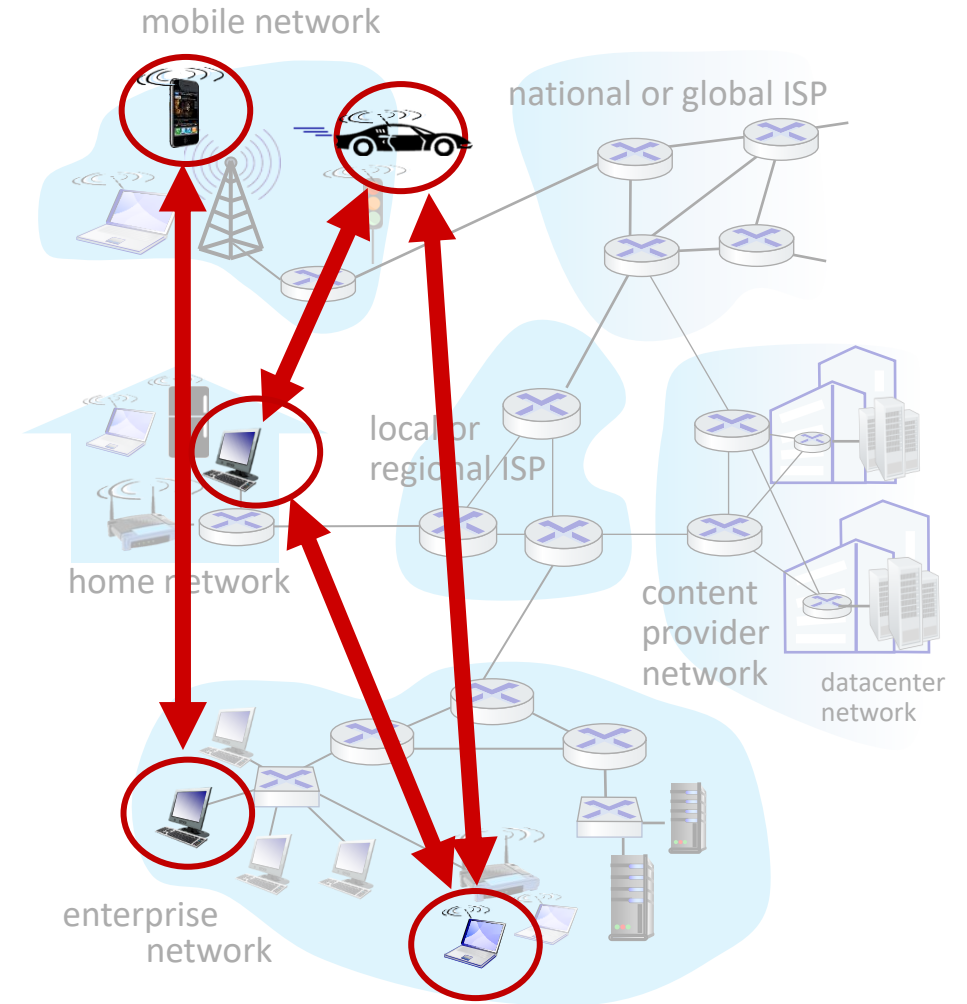
- contact, communicate with server
- may be intermittently connected
- may have dynamic IP addresses
- do *not* communicate directly with each other
- examples: HTTP, IMAP, FTP





# Peer-peer architecture

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





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# Processes communicating

*process*: program running within a host

- within same host, two processes communicate using *inter-process communication* (defined by OS)
- processes in different hosts communicate by exchanging *messages*

clients, servers

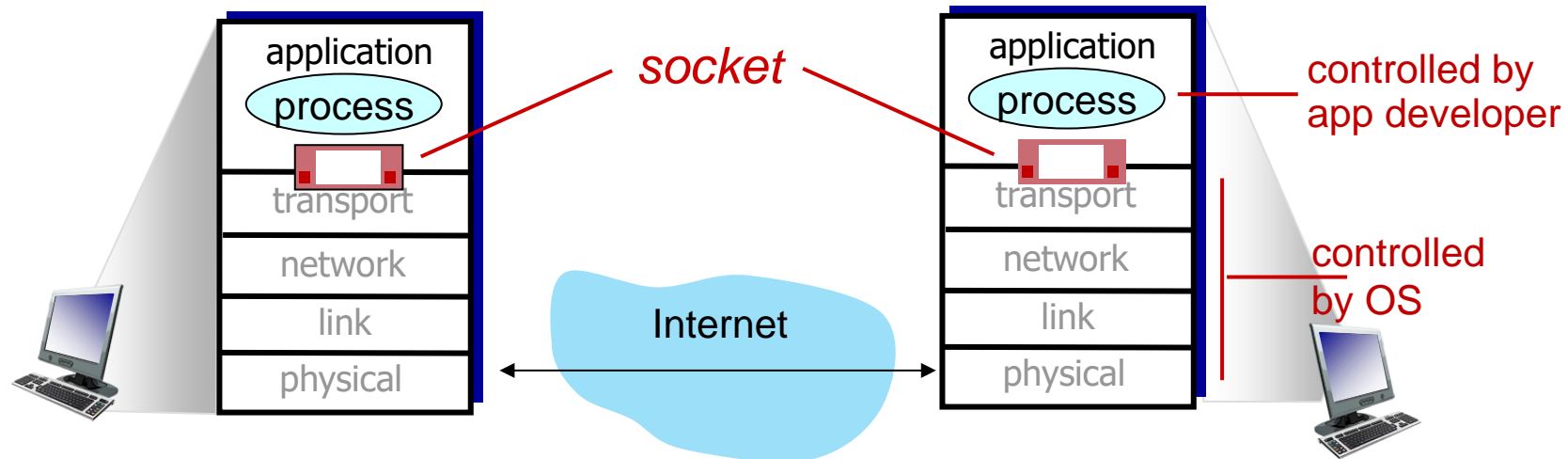
*client process*: process that initiates communication

*server process*: process that waits to be contacted

- note: applications with P2P architectures have client processes & server processes

# Sockets

- process sends/receives messages to/from its **socket**
- socket analogous to door
  - sending process shoves message out door
  - sending process relies on transport infrastructure on other side of door to deliver message to socket at receiving process
  - two sockets involved: one on each side



# Addressing processes

- to receive messages, process must have *identifier*
- host device has unique 32-bit IP address
- Q: does IP address of host on which process runs suffice for identifying the process?
  - A: no, *many* processes can be running on same host
- *identifier* includes both IP address and port numbers associated with process on host.
- example port numbers:
  - HTTP server: 80
  - mail server: 25
- to send HTTP message to gaia.cs.umass.edu web server:
  - IP address: 128.119.245.12
  - port number: 80
- more shortly...

# An application-layer protocol defines:

- **types of messages exchanged**,
  - e.g., request, response
- **message syntax**:
  - what fields in messages & how fields are delineated
- **message semantics**
  - meaning of information in fields
- **rules** for when and how processes send & respond to messages

## open protocols:

- defined in RFCs, everyone has access to protocol definition
- allows for interoperability
- e.g., HTTP, SMTP

## proprietary protocols:

- e.g., Skype, Zoom

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# What transport service does an app need?

## data integrity

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

## timing

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

## throughput

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

## security

- encryption, data integrity, ...



# Transport service requirements: common apps

application	data loss	throughput	time sensitive?
file transfer/download	no loss	elastic	no
e-mail	no loss	elastic	no
Web documents	no loss	elastic	no
real-time audio/video	loss-tolerant	audio: 5Kbps-1Mbps video:10Kbps-5Mbps	yes, 10's msec
streaming audio/video	loss-tolerant	same as above	yes, few secs
interactive games	loss-tolerant	Kbps+	yes, 10's msec
text messaging	no loss	elastic	yes and no

# Internet transport protocols services

## *TCP service:*

- *reliable transport* between sending and receiving process
- *flow control*: sender won't overwhelm receiver
- *congestion control*: throttle sender when network overloaded
- *connection-oriented*: setup required between client and server processes
- *does not provide*: timing, minimum throughput guarantee, security

## *UDP service:*

- *unreliable data transfer* between sending and receiving process
- *does not provide*: reliability, flow control, congestion control, timing, throughput guarantee, security, or connection setup.

Q: why bother? *Why* is there a UDP?

# Internet applications, and transport protocols

application	application layer protocol	transport protocol
file transfer/download	FTP [RFC 959]	TCP
e-mail	SMTP [RFC 5321]	TCP
Web documents	HTTP [RFC 7230, 9110]	TCP
Internet telephony	SIP [RFC 3261], RTP [RFC 3550], or proprietary	TCP or UDP
streaming audio/video	HTTP [RFC 7230], DASH	TCP
interactive games	WOW, FPS (proprietary)	UDP or TCP

# Securing TCP

## Vanilla TCP & UDP sockets:

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

## Transport Layer Security (TLS)

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

## TLS implemented in application layer

- apps use TLS libraries, that use TCP in turn
- cleartext sent into “socket” traverse Internet *encrypted*
- more: Chapter 8

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# Web and HTTP

*First, a quick review...*

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

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

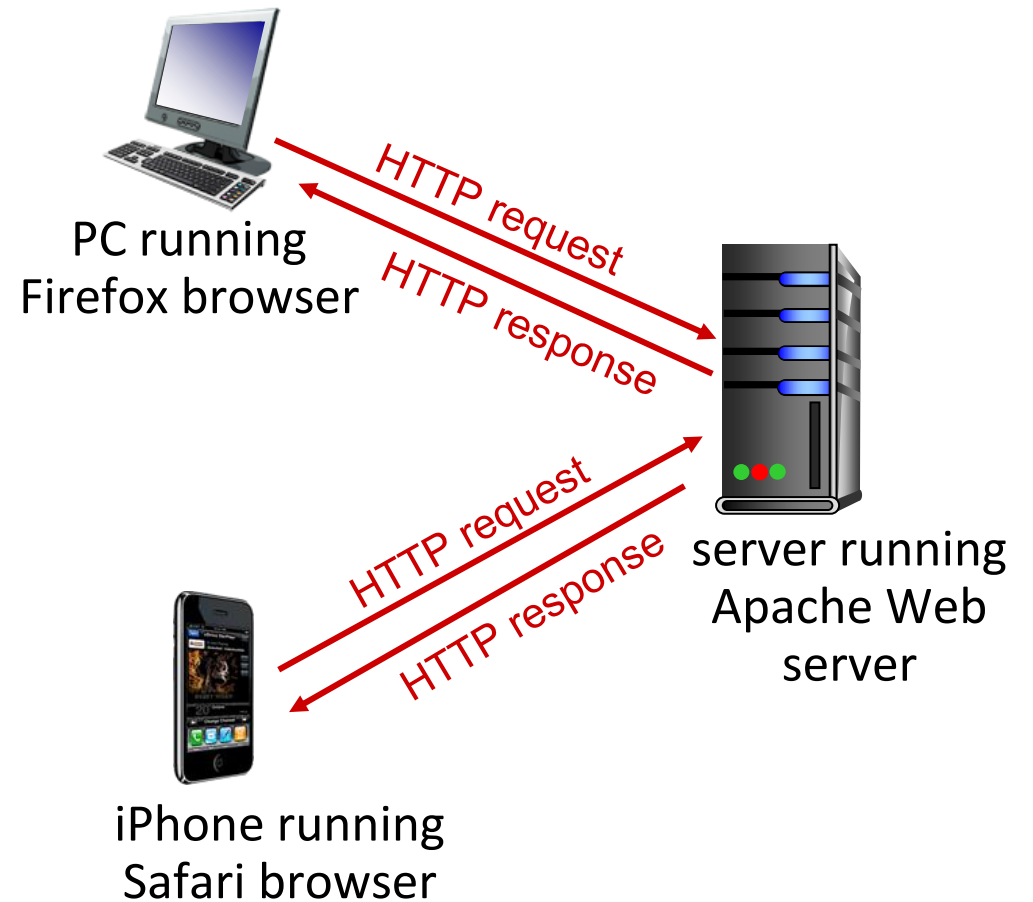
host name

path name

# HTTP overview

## HTTP: hypertext transfer protocol

- Web's application-layer protocol
- client/server model:
  - *client*: browser that requests, receives, (using HTTP protocol) and “displays” Web objects
  - *server*: Web server sends (using HTTP protocol) objects in response to requests





# HTTP overview (continued)

## *HTTP uses TCP:*

- client initiates TCP connection (creates socket) to server, port 80
- server accepts TCP connection from client
- HTTP messages (application-layer protocol messages) exchanged between browser (HTTP client) and Web server (HTTP server)
- TCP connection closed

## *HTTP is “stateless”*

- server maintains *no* information about past client requests

*aside*  
protocols that maintain  
“state” are complex!

- past history (state) must be maintained
- if server/client crashes, their views of “state” may be inconsistent, must be reconciled

# HTTP connections: two types

## *Non-persistent HTTP*

1. TCP connection opened
2. at most one object sent over TCP connection
3. TCP connection closed

downloading multiple objects required multiple connections

## *Persistent HTTP*

- TCP connection opened to a server
- multiple objects can be sent over *single* TCP connection between client, and that server
- TCP connection closed

# Non-persistent HTTP: example

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



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



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

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

**3.** HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time



# Non-persistent HTTP: example (cont.)

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



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

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

4. HTTP server closes TCP connection.

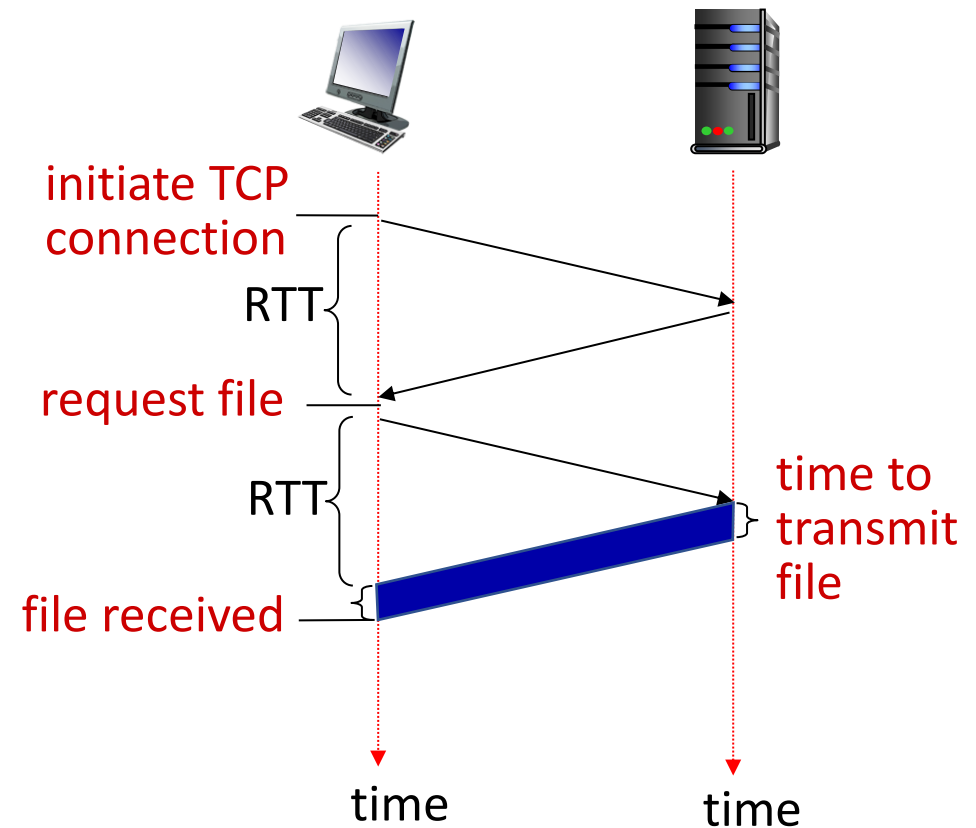


# Non-persistent HTTP: response time

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

**HTTP response time (per object):**

- one RTT to initiate TCP connection
- one RTT for HTTP request and first few bytes of HTTP response to return
- object/file transmission time



*Non-persistent HTTP response time = 2RTT + file transmission time*

# Persistent HTTP (HTTP 1.1)

## *Non-persistent HTTP issues:*

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

## *Persistent HTTP (HTTP1.1):*

- server leaves connection open after sending response
- subsequent HTTP messages between same client/server sent over open connection
- client sends requests as soon as it encounters a referenced object
- as little as one RTT for all the referenced objects (cutting response time in half)

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# HTTP request message

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

request line (GET, POST, HEAD commands) →

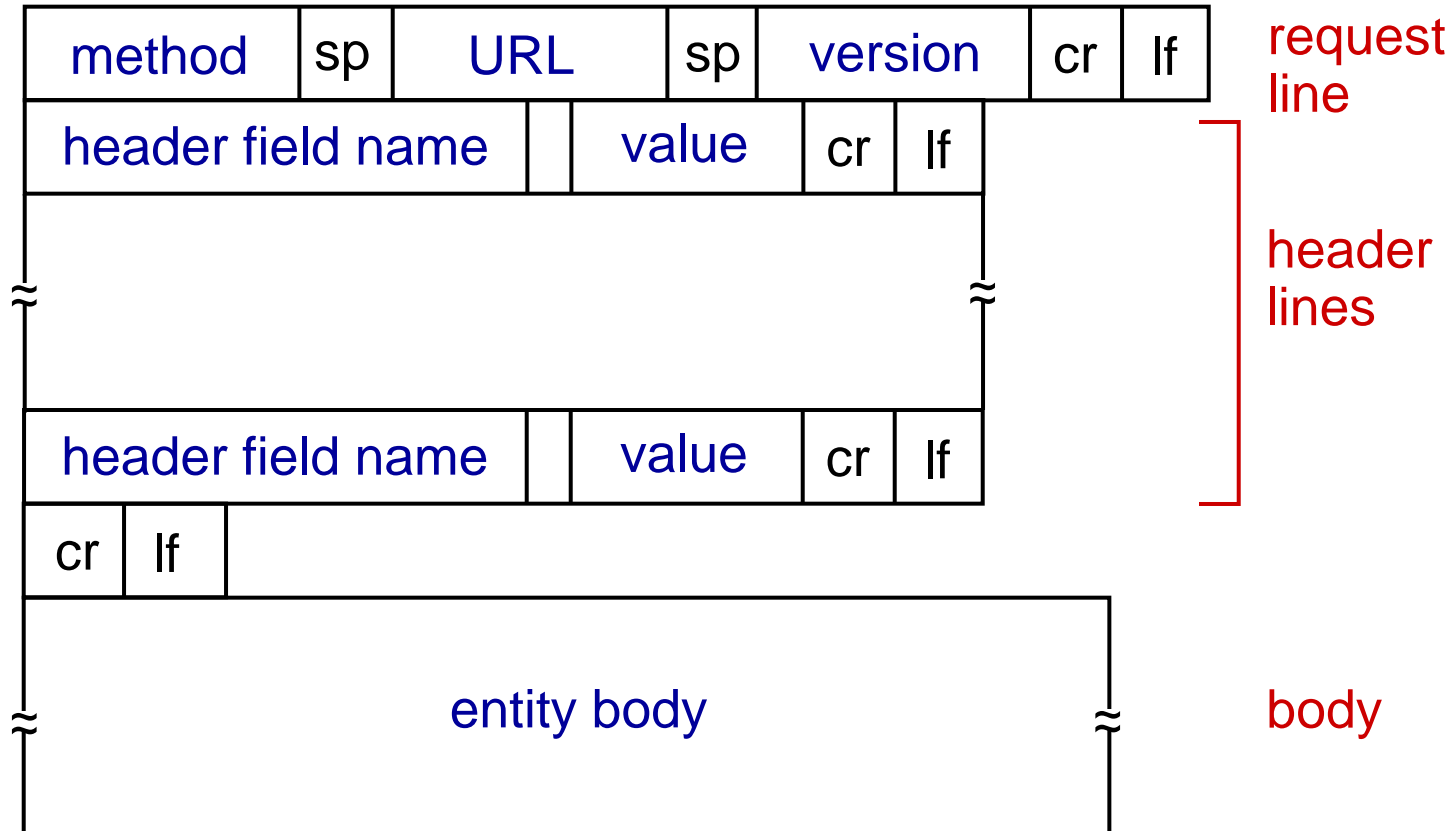
header lines

```
GET /index.html HTTP/1.1\r\n
Host: www-net.cs.umass.edu\r\n
User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X
10.15; rv:80.0) Gecko/20100101 Firefox/80.0 \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
Connection: keep-alive\r\n
\r\n
```

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

carriage return character  
line-feed character

# HTTP request message: general format



# Other HTTP request messages

## POST method:

- web page often includes form input
- user input sent from client to server in entity body of HTTP POST request message

## GET method (for sending data to server):

- include user data in URL field of HTTP GET request message (following a '?'):

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

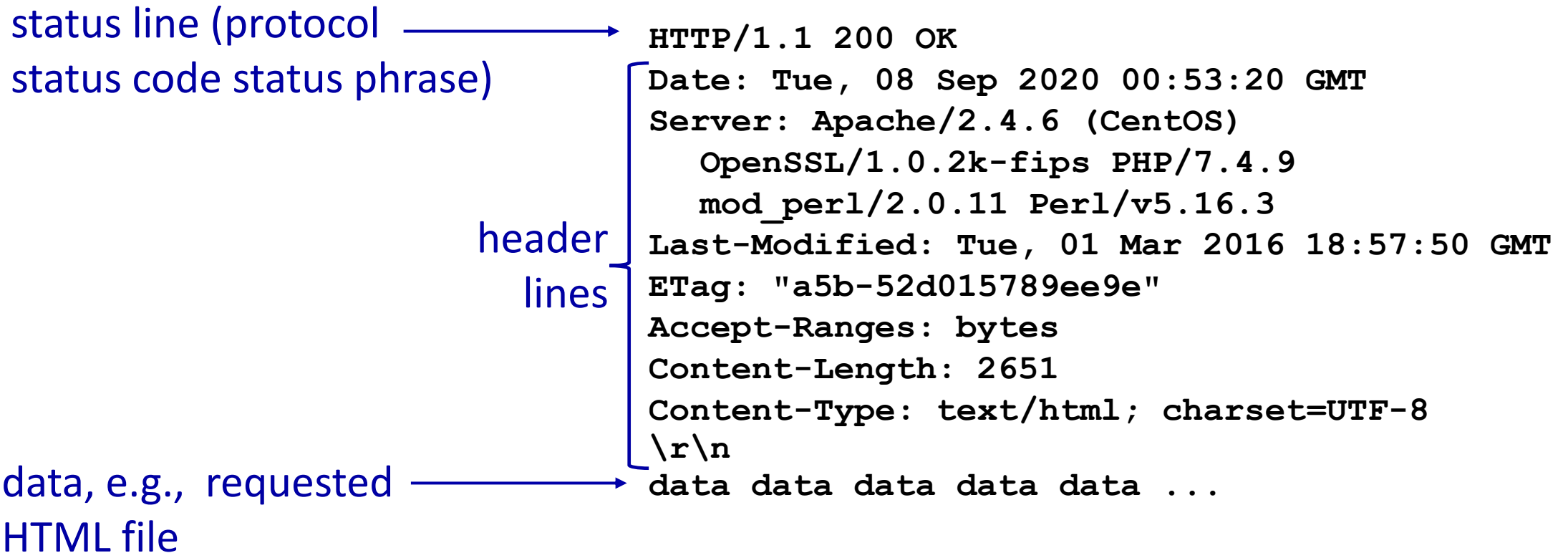
## HEAD method:

- requests headers (only) that would be returned *if* specified URL were requested with an HTTP GET method.

## PUT method:

- uploads new file (object) to server
- completely replaces file that exists at specified URL with content in entity body of POST HTTP request message

# HTTP response message



# HTTP response status codes

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

## 200 OK

- request succeeded, requested object later in this message

## 301 Moved Permanently

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

## 400 Bad Request

- request msg not understood by server

## 404 Not Found

- requested document not found on this server

## 505 HTTP Version Not Supported

# Trying out HTTP (client side) for yourself

## 1. netcat to your favorite Web server:

% nc -c -v gaia.cs.umass.edu 80 (for Mac)

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

~\$ nc -C gaia.cs.umass.edu 80 (for Linux)

- 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)

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# Maintaining user/server state: cookies

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

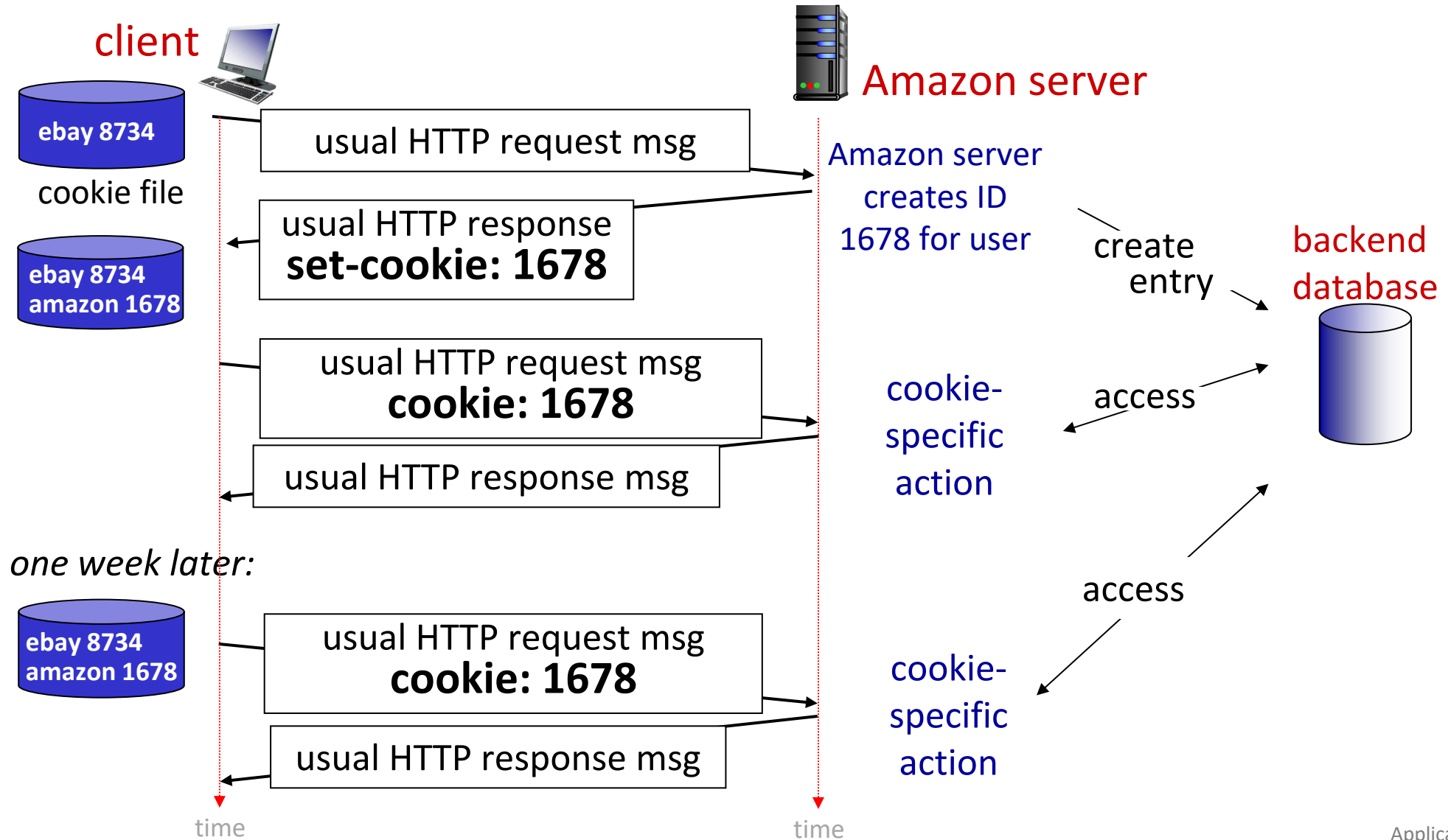
## *four components:*

- 1) cookie header line of HTTP *response* message
- 2) cookie header line in next HTTP *request* message
- 3) cookie file kept on user's host, managed by user's browser
- 4) back-end database at Web site

## Example:

- Susan uses browser on laptop, visits specific e-commerce site for first time
- when initial HTTP requests arrives at site, site creates:
  - unique ID (aka “cookie”)
  - entry in backend database for ID
- subsequent HTTP requests from Susan to this site will contain cookie ID value, allowing site to “identify” Susan

# Maintaining user/server state: cookies



# HTTP cookies: comments

## *What cookies can be used for:*

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

## *Challenge: How to keep state?*

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

aside

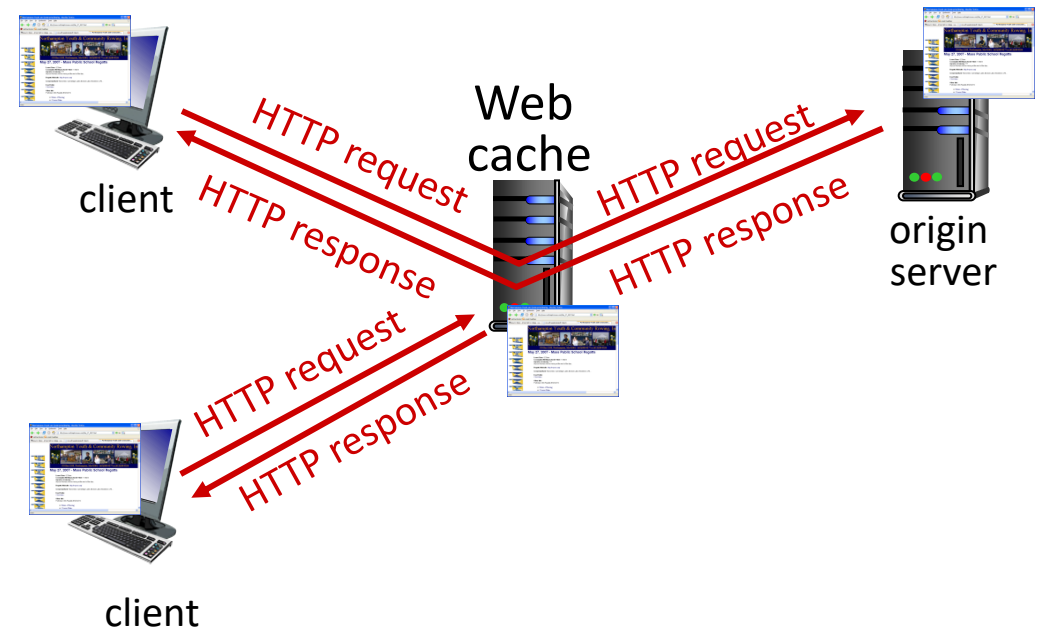
*cookies and privacy:*

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

# 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
```

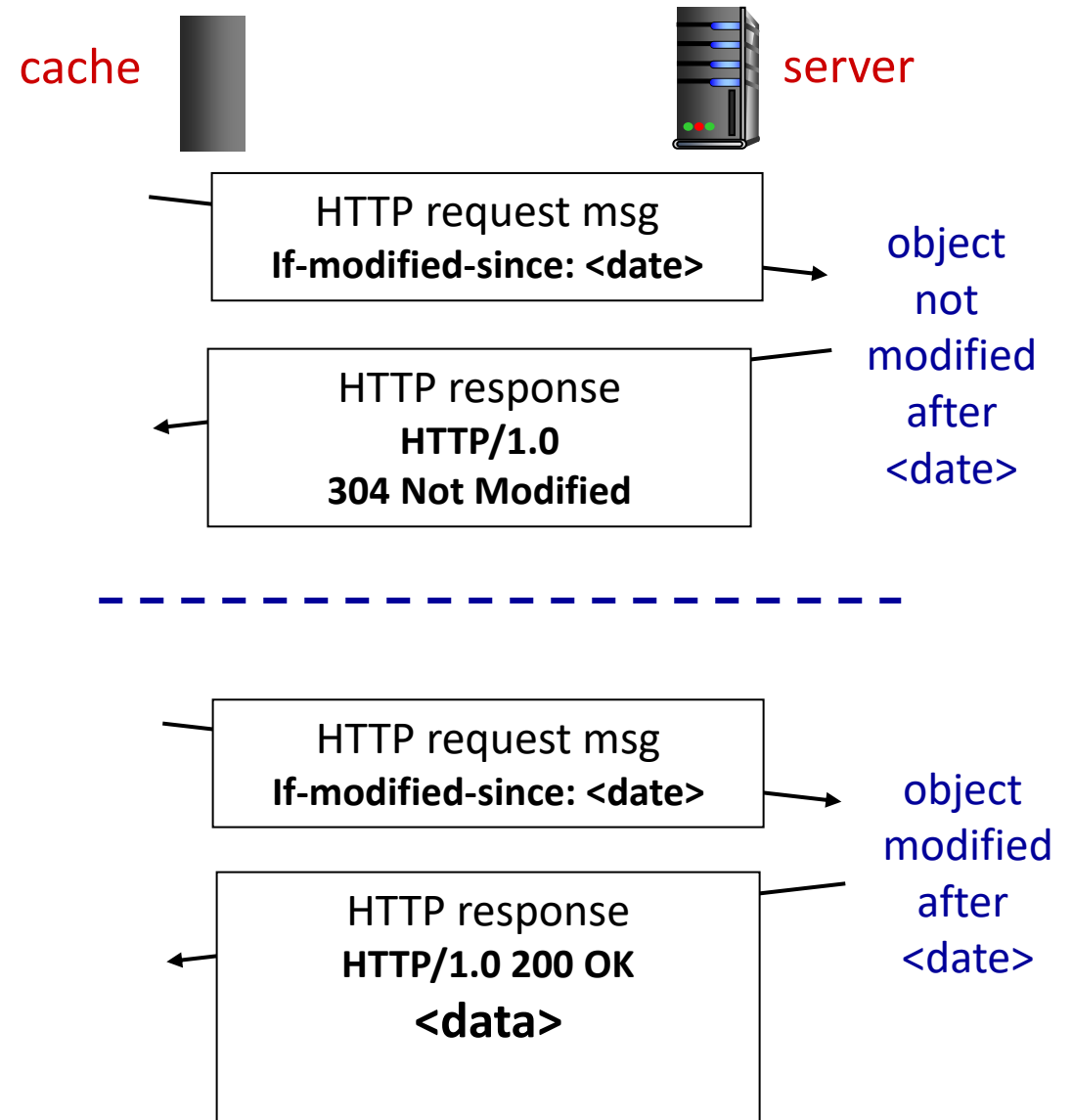
## *Why* Web caching?

- 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 via Conditional GET

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

- no object transmission delay (or use of network resources)
- **cache:** specify date of cached object 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**
- Browser can cache objects itself with the same mechanism



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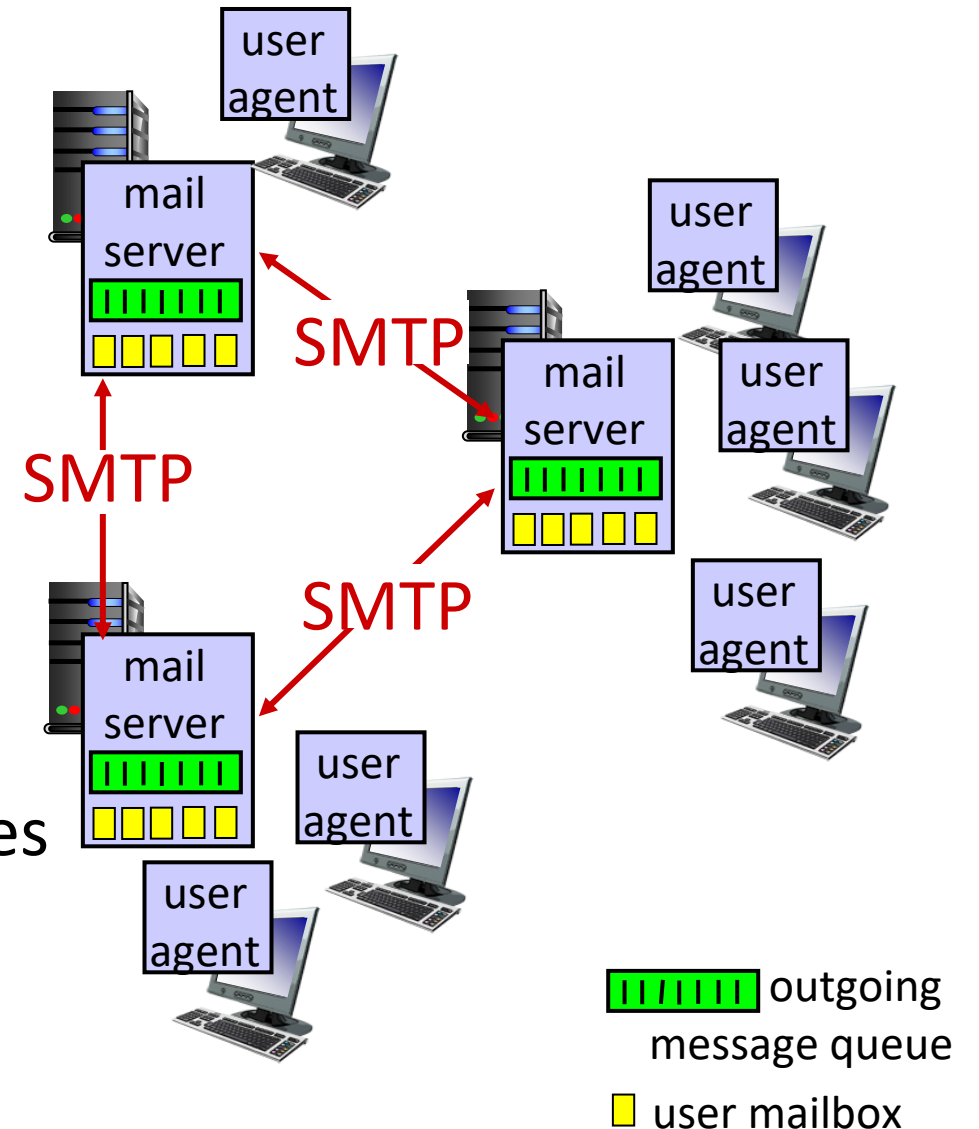
# E-mail

## Three major components:

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

## User Agent

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





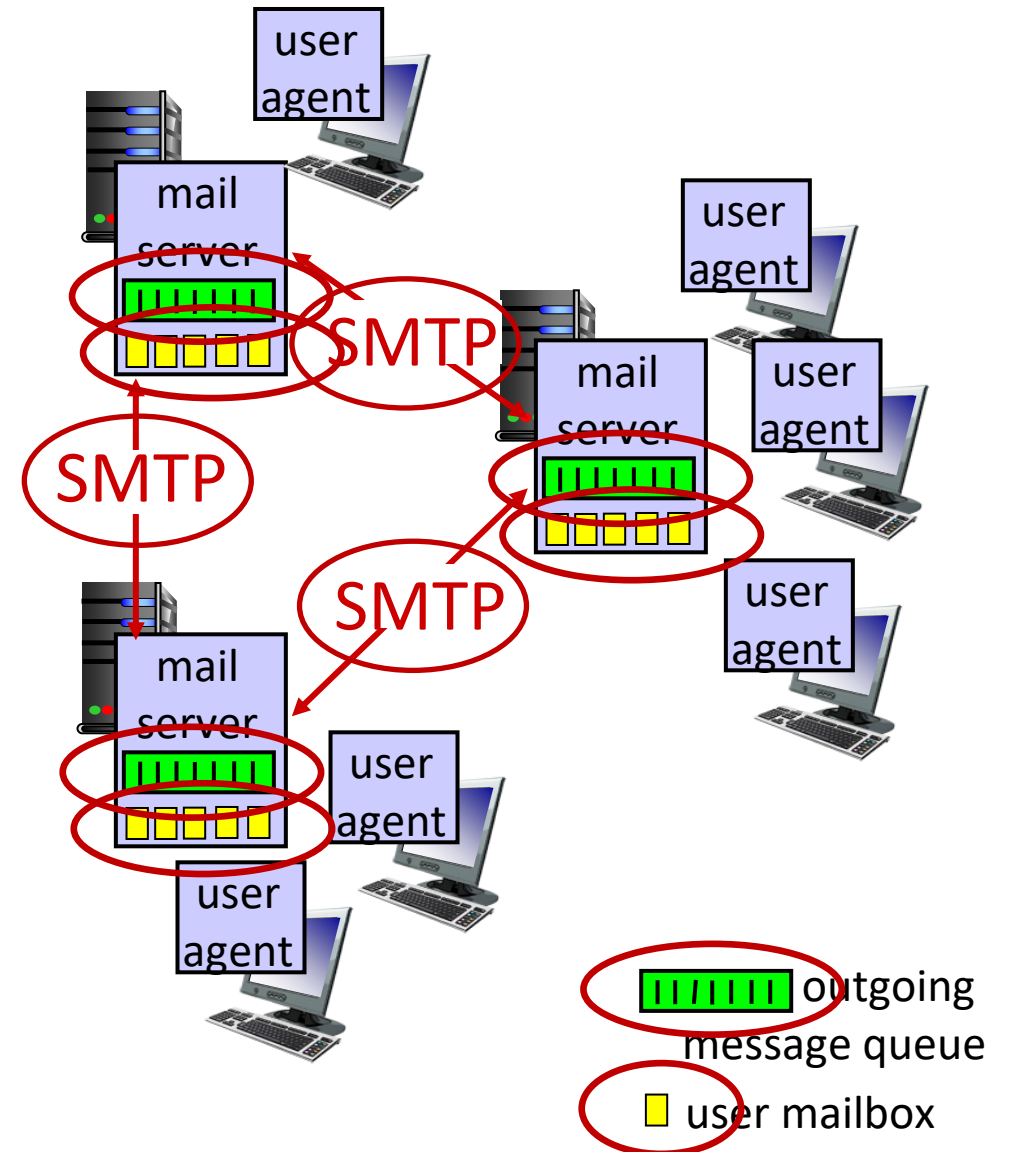
# E-mail: mail servers

## mail servers:

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

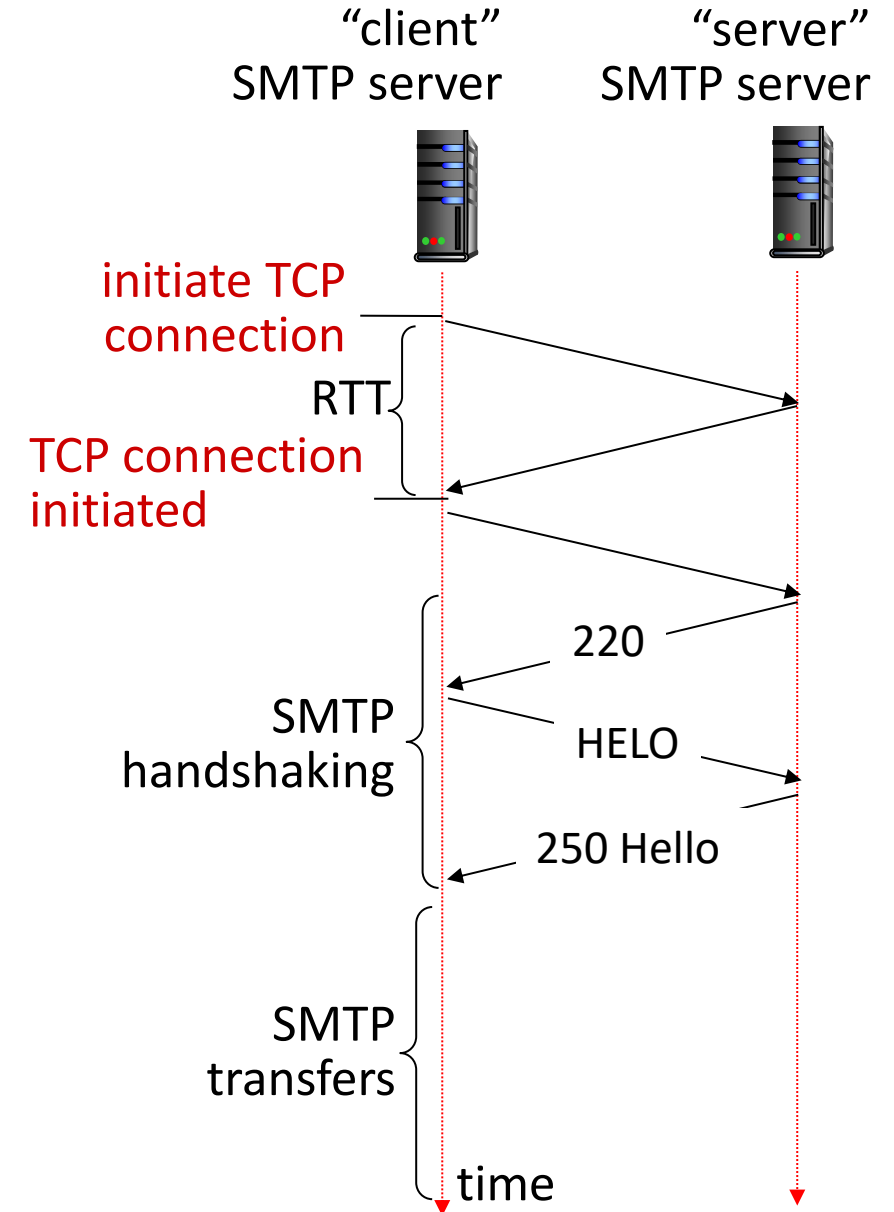
**SMTP protocol** between mail servers to send email messages

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



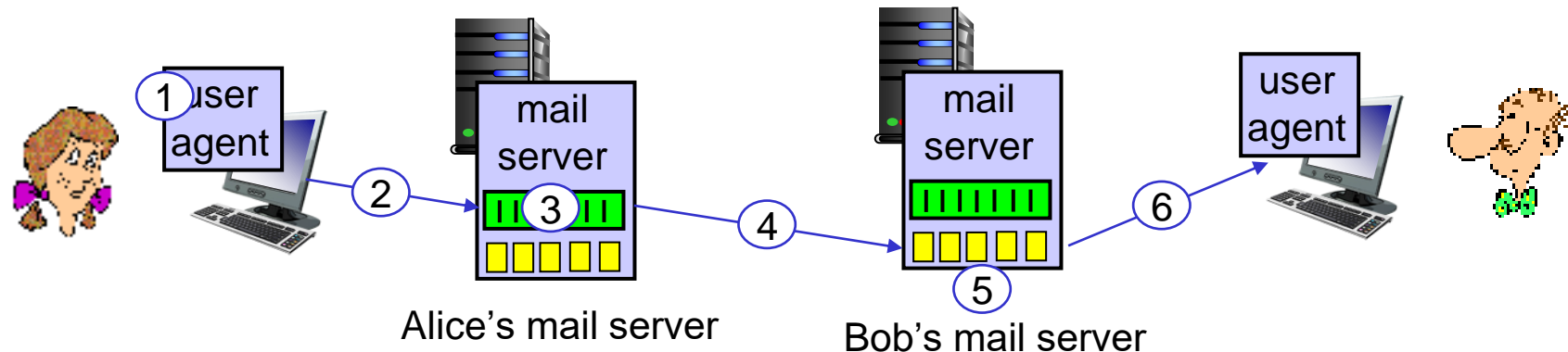
# SMTP RFC (5321)

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



# Scenario: Alice sends e-mail to Bob

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



# Sample SMTP interaction

```
S: 220 hamburger.edu
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:

`nc -c <servername> 25`

- see 220 reply from server
- enter HELO, MAIL FROM:, RCPT TO:, DATA, QUIT commands above lets you send email without using e-mail client (reader)

*Note: this will only work if <servername> allows netcat connections to port 25 (this is becoming increasingly rare because of security concerns; see lab instructions how to do this via MailCatcher)*

# SMTP: observations

## *comparison with HTTP:*

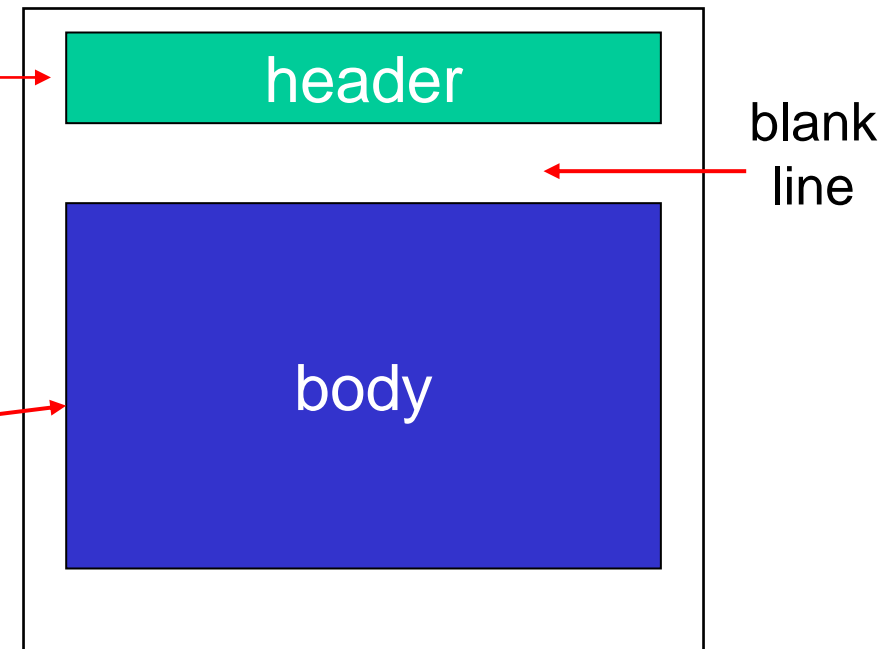
- HTTP: client pull
  - SMTP: client push
  - both have ASCII command/response interaction, status codes
  - HTTP: each object encapsulated in its own response message
  - SMTP: multiple objects sent in multipart message
- SMTP uses persistent connections
  - SMTP requires message (header & body) to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

# Mail message format

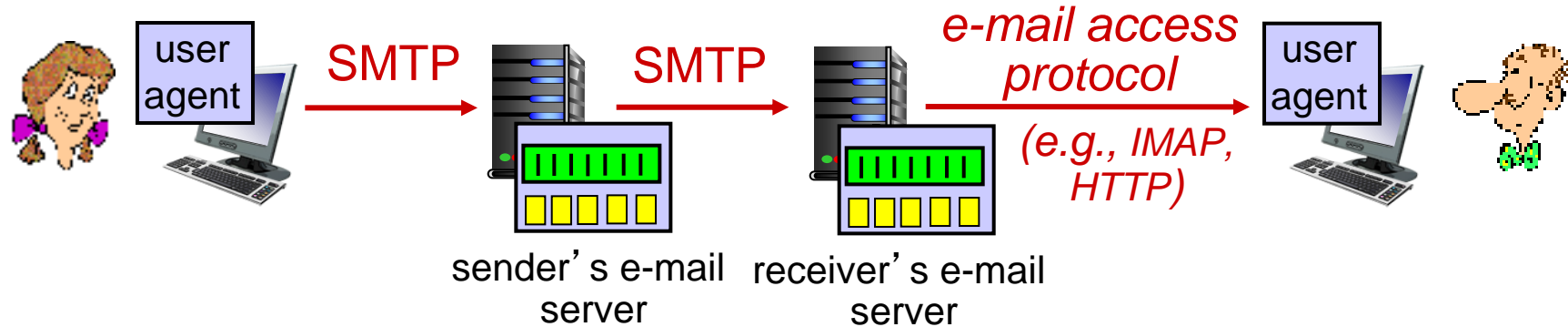
SMTP: protocol for exchanging e-mail messages, defined in RFC 5321 (like RFC 7231 defines HTTP)

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



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# DNS: Domain Name System

*people:* many identifiers:

- SSN, name, passport #

*Internet hosts, routers:*

- IP address (32 bit) - used for addressing datagrams
- “name”, e.g., cs.umass.edu - used by humans

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

## Domain Name System (DNS):

- *distributed database* implemented in hierarchy of many *name servers*
- *application-layer protocol*: hosts, DNS servers communicate to *resolve* names (address/name translation)
  - *note*: core Internet function, implemented as application-layer protocol
  - complexity at network’s “edge”

# DNS: services, structure

## DNS services:

- hostname-to-IP-address translation
- host aliasing
  - canonical, alias names
- mail server aliasing
- load distribution
  - replicated Web servers: many IP addresses correspond to one name

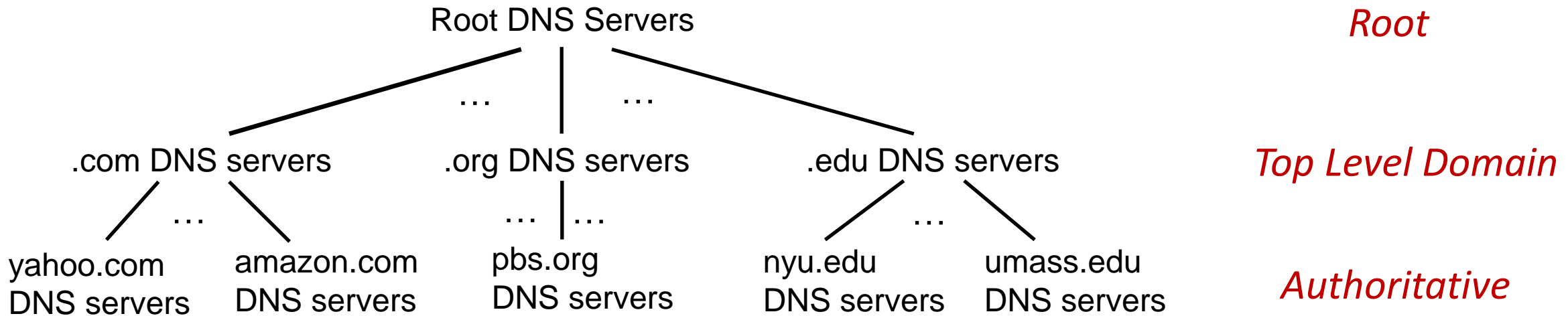
## *Q: Why not centralize DNS?*

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

## *A: doesn't scale!*

- Comcast DNS servers alone: 600B DNS queries/day
- Akamai DNS servers alone: 2.2T DNS queries/day

# DNS: a distributed, hierarchical database



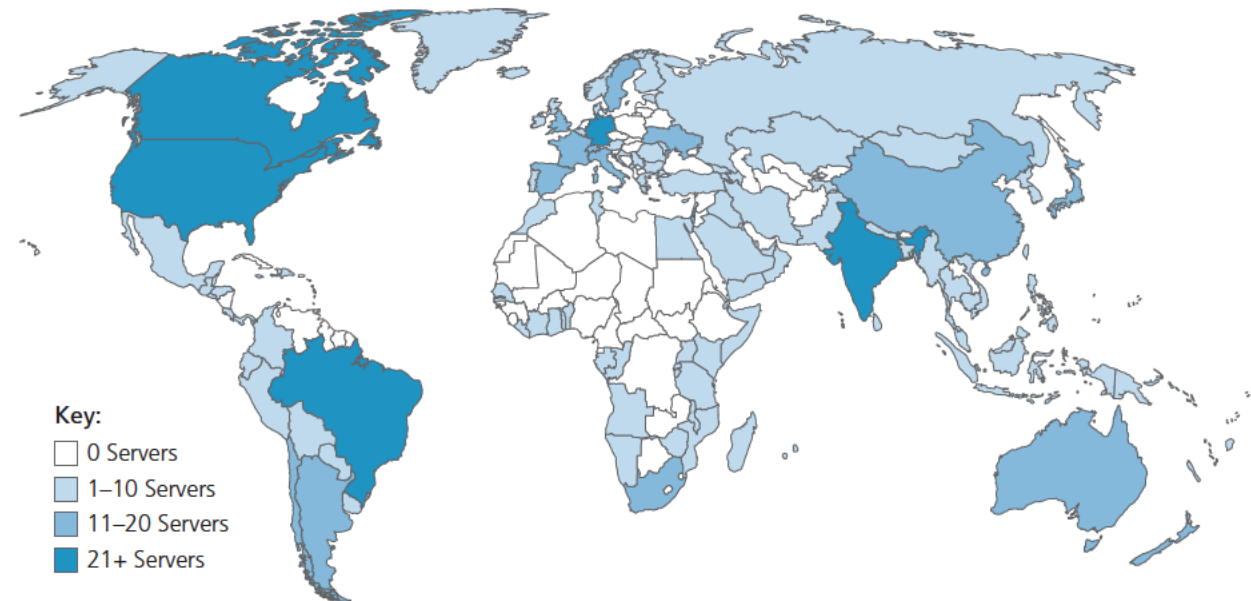
Client wants IP address for `www.amazon.com`; 1<sup>st</sup> approximation:

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

# DNS: root name servers

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

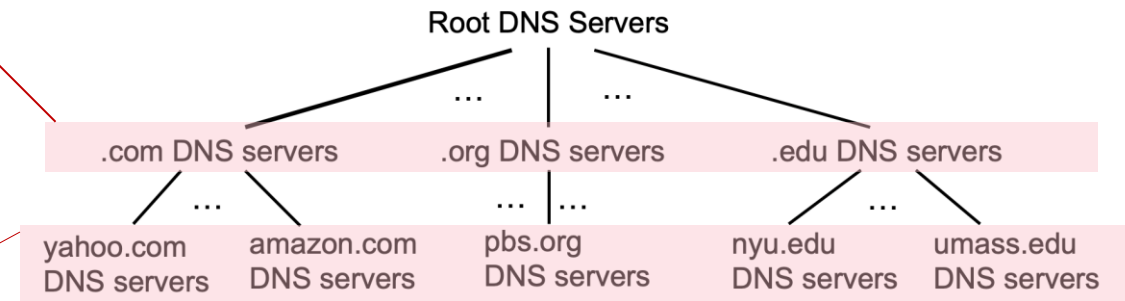
13 logical root name “servers”  
worldwide each “server” replicated  
many times (~200 servers in US)



# Top-Level Domain, and authoritative servers

## Top-Level Domain (TLD) servers:

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



## authoritative DNS servers:

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

# Local DNS name servers

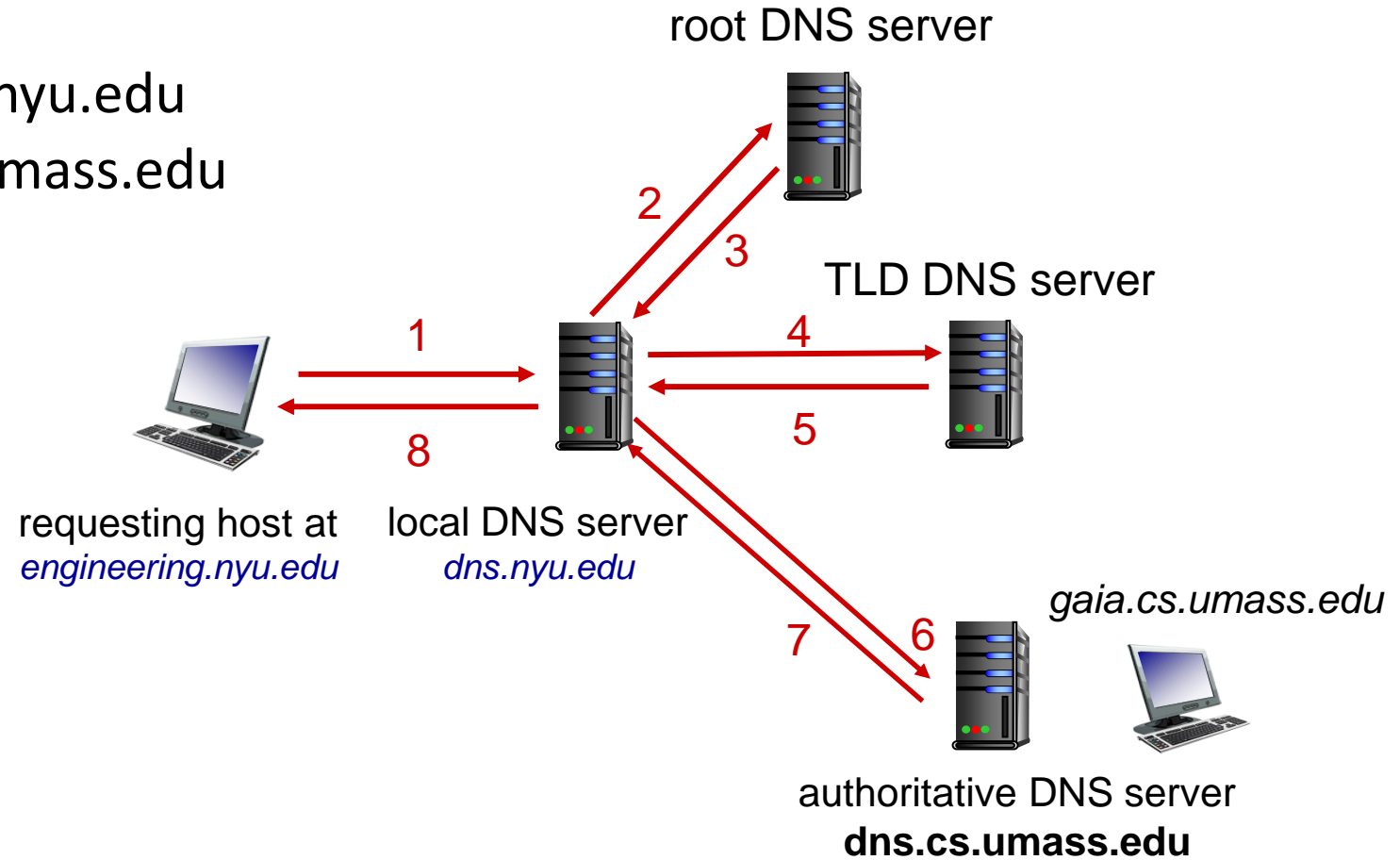
- when host makes DNS query, it is sent to its *local* DNS server
  - Local DNS server returns reply, answering:
    - from its local cache of recent name-to-address translation pairs (possibly out of date!)
    - forwarding request into DNS hierarchy for resolution
  - each ISP has local DNS name server; to find yours:
    - MacOS: `% scutil --dns`
    - Windows: `>ipconfig /all`
- local DNS server doesn't strictly belong to hierarchy

# DNS name resolution: iterated query

**Example:** host at `engineering.nyu.edu` wants IP address for `gaia.cs.umass.edu`

## Iterated query:

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



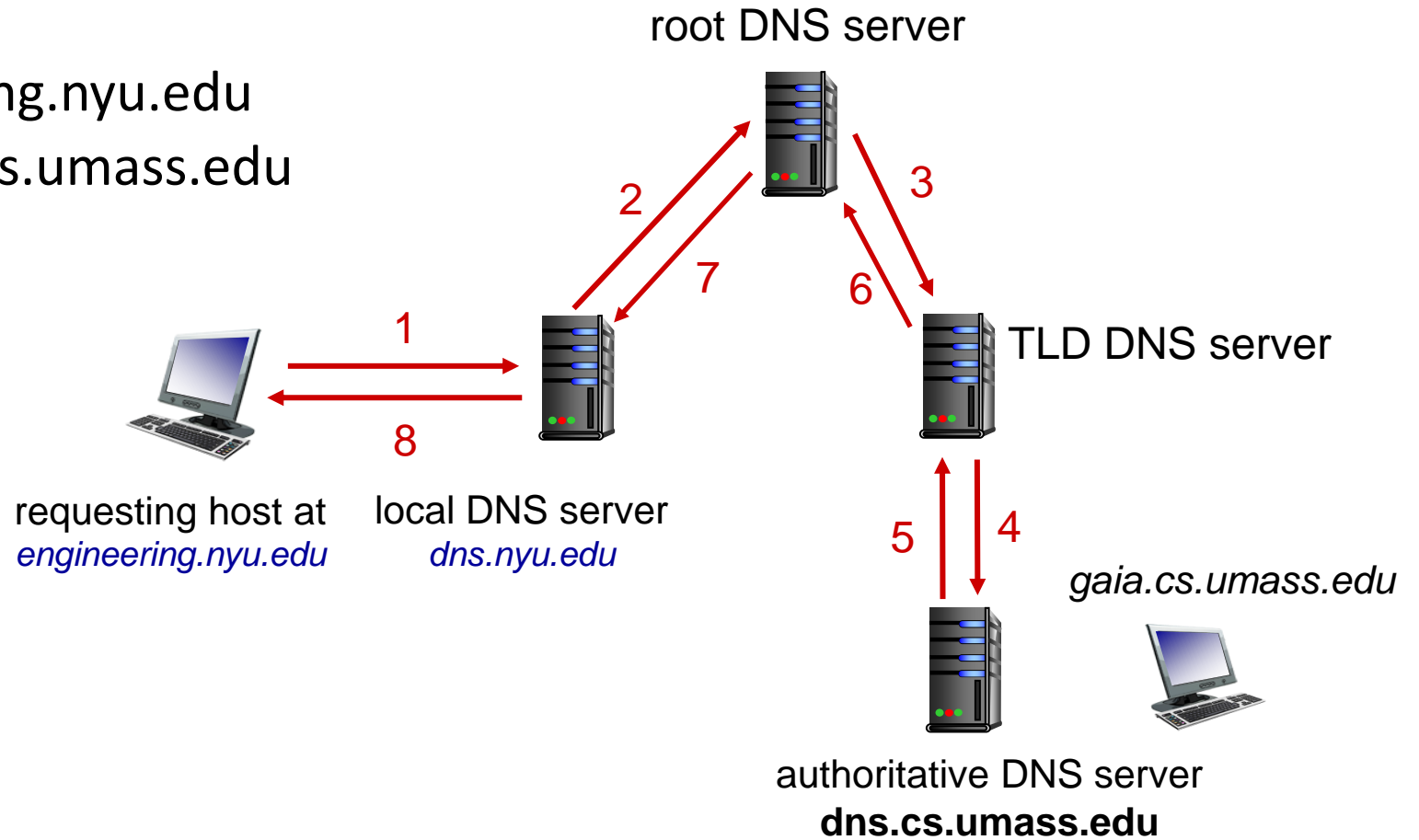


# DNS name resolution: recursive query

**Example:** host at `engineering.nyu.edu` wants IP address for `gaia.cs.umass.edu`

## Recursive query:

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



# Caching DNS Information

- once (any) name server learns mapping, it *cached* mapping, and *immediately* returns a cached mapping in response to a query
  - caching improves response time
  - cache entries timeout (disappear) after some time (TTL)
  - TLD servers typically cached in local name servers
- cached entries may be *out-of-date*
  - if named host changes IP address, may not be known Internet-wide until all TTLs expire!
  - *best-effort name-to-address translation!*

# DNS records

**DNS:** distributed database storing resource records (RR)

RR format: (name, value, type, ttl)

## type=A

- name is hostname
- value is IP address

## type=NS

- name is domain (e.g., foo.com)
- value is hostname of authoritative name server for this domain

## type=CNAME

- name is alias name for some “canonical” (the real) name
- www.ibm.com is really servereast.backup2.ibm.com
- value is canonical name

## type=MX

- value is name of SMTP mail server associated with name

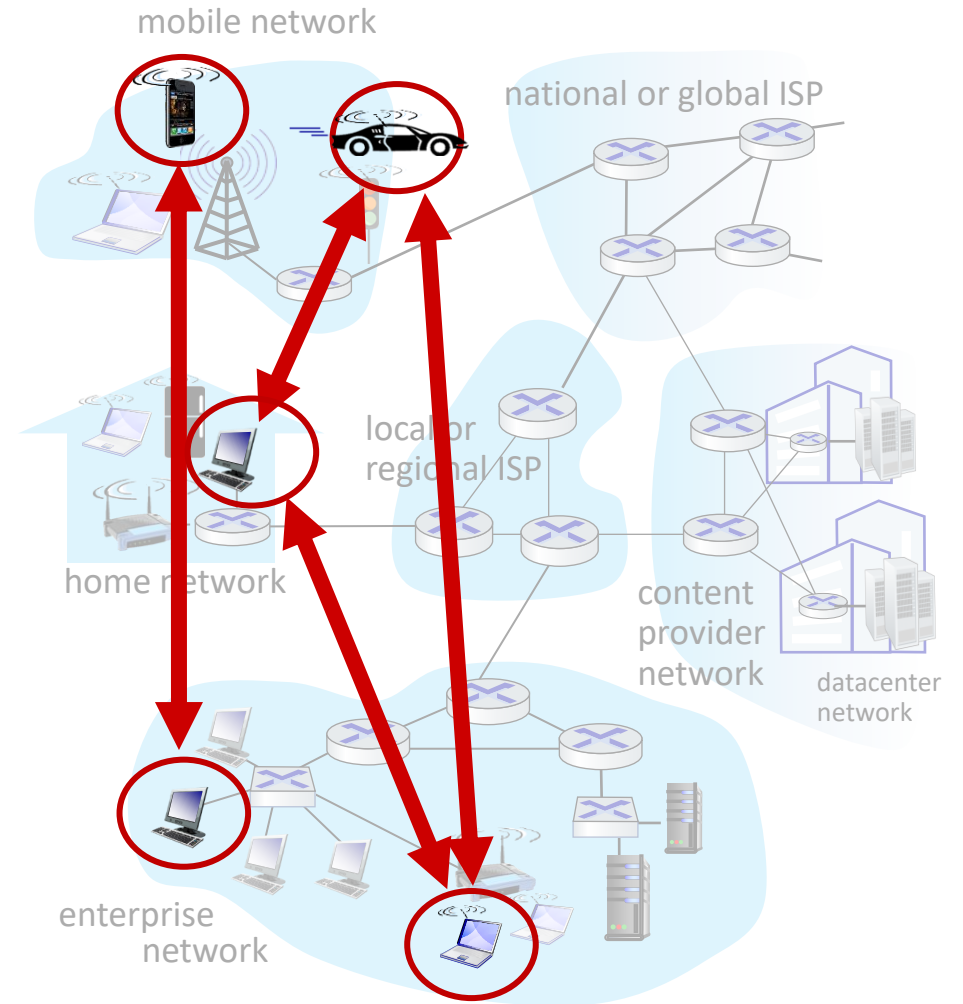
# Application Layer: Overview

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



# Peer-to-peer (P2P) architecture

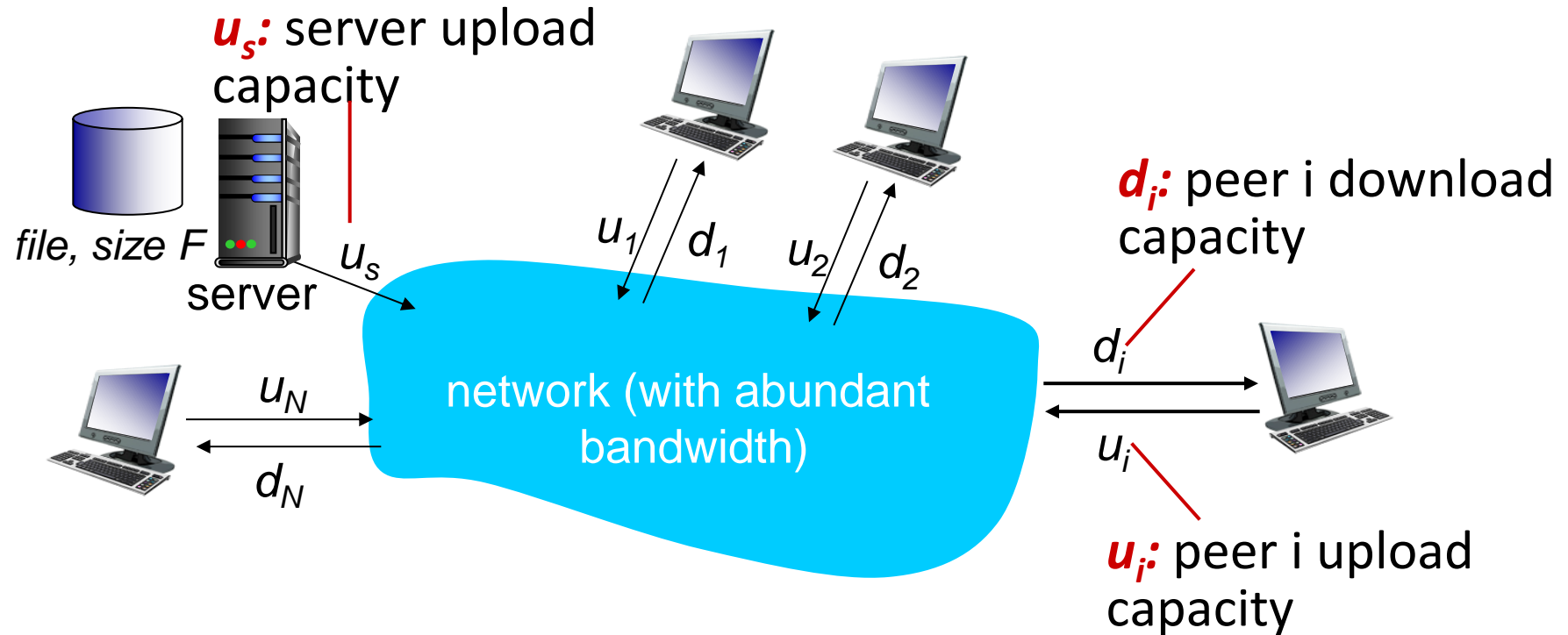
- *no* always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, and new service demands
- peers are intermittently connected and change IP addresses
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



# File distribution: client-server vs P2P

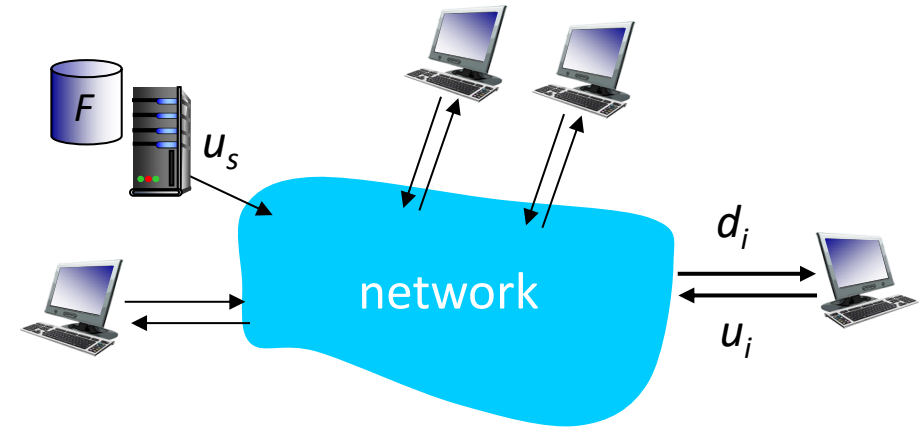
Q: how much time to distribute file (size  $F$ ) from one server to  $N$  peers?

- peer upload/download capacity is limited resource



# File distribution time: client-server

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



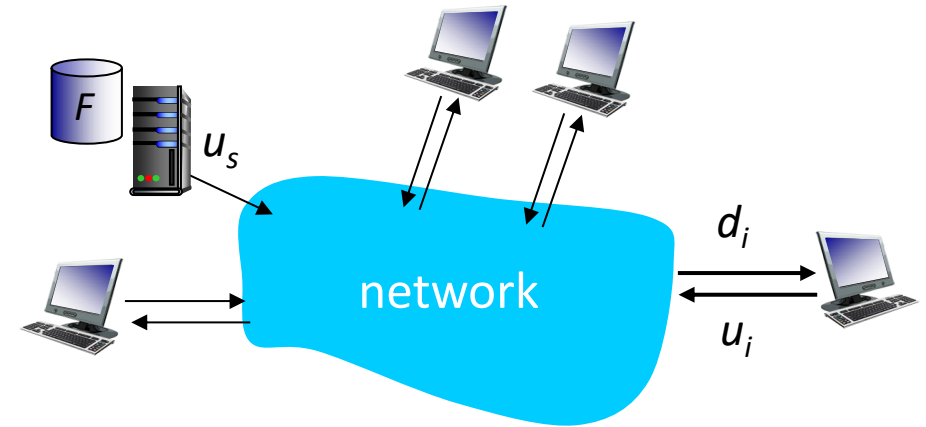
*time to distribute  $F$   
to  $N$  clients using  
client-server approach*

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

increases linearly in  $N$

# File distribution time: P2P

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



time to distribute  $F$   
to  $N$  clients using  
P2P approach

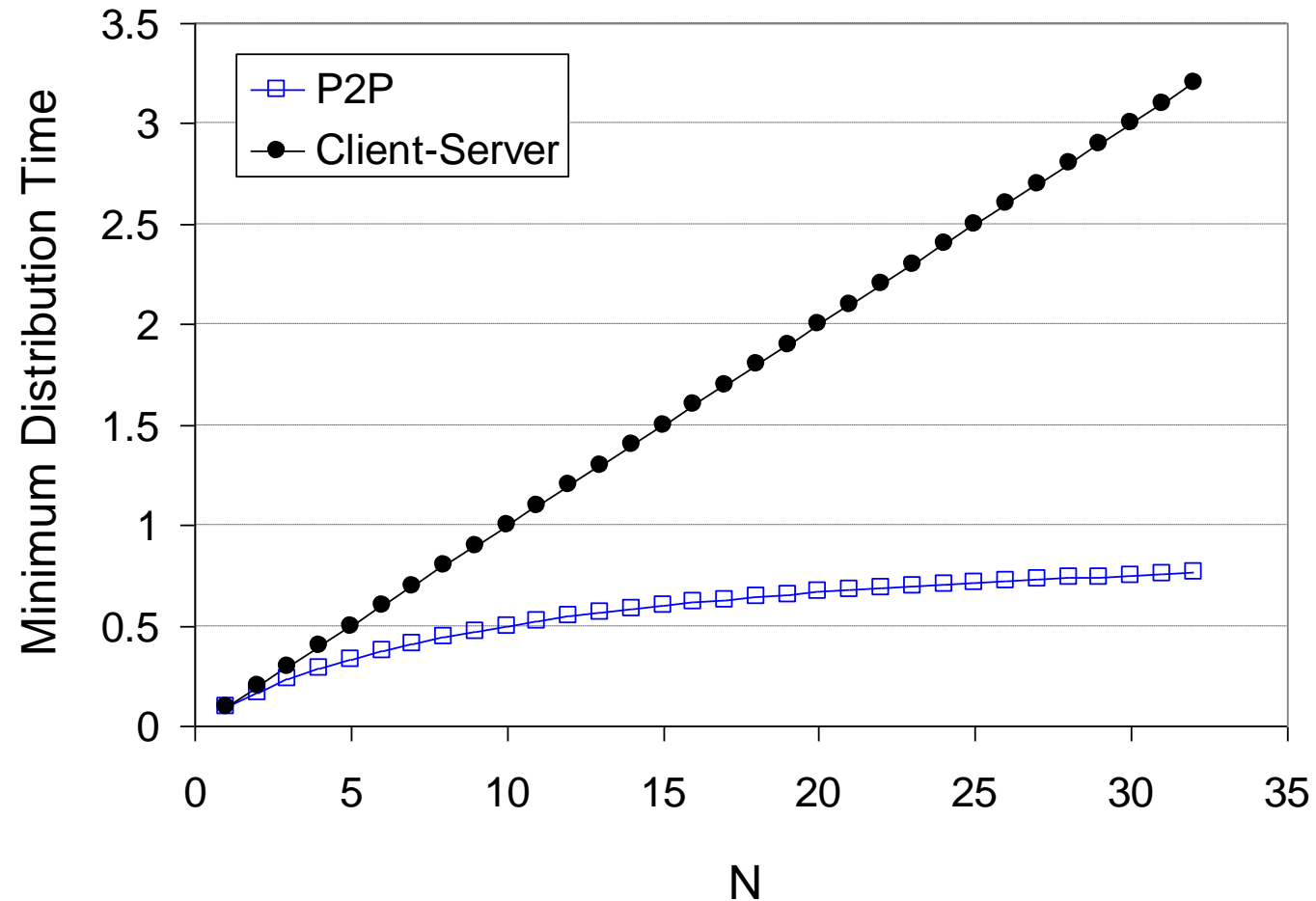
$$D_{P2P} \geq \max\{F/u_s, F/d_{min}, NF/(u_s + \sum u_i)\}$$

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



# Client-server vs. P2P: example

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

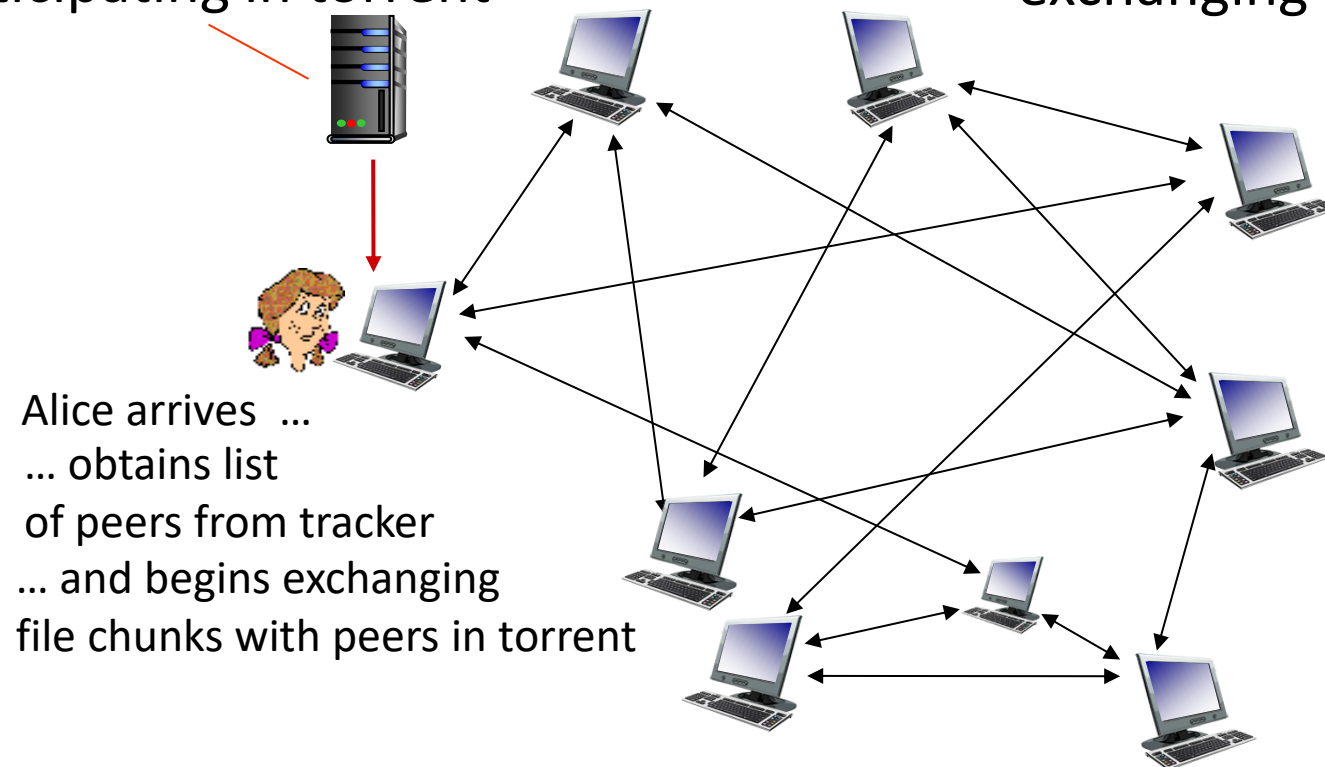


# P2P file distribution: BitTorrent

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

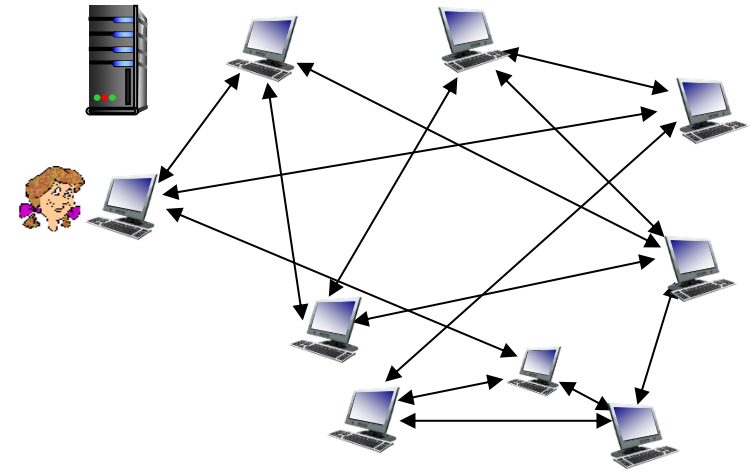
*tracker*: tracks peers  
participating in torrent

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



# P2P file distribution: BitTorrent

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



# BitTorrent: requesting, sending file chunks

## Requesting chunks:

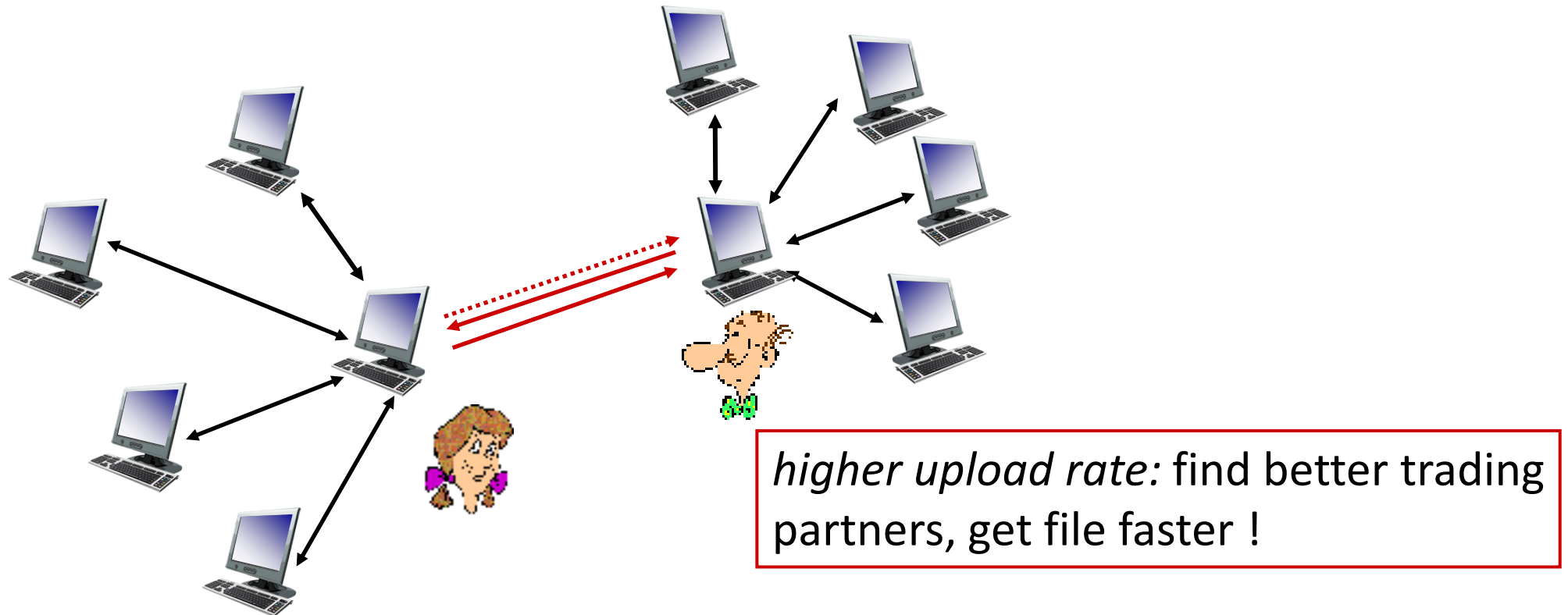
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

## Sending chunks: tit-for-tat

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

# BitTorrent: tit-for-tat

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



# Application layer: overview

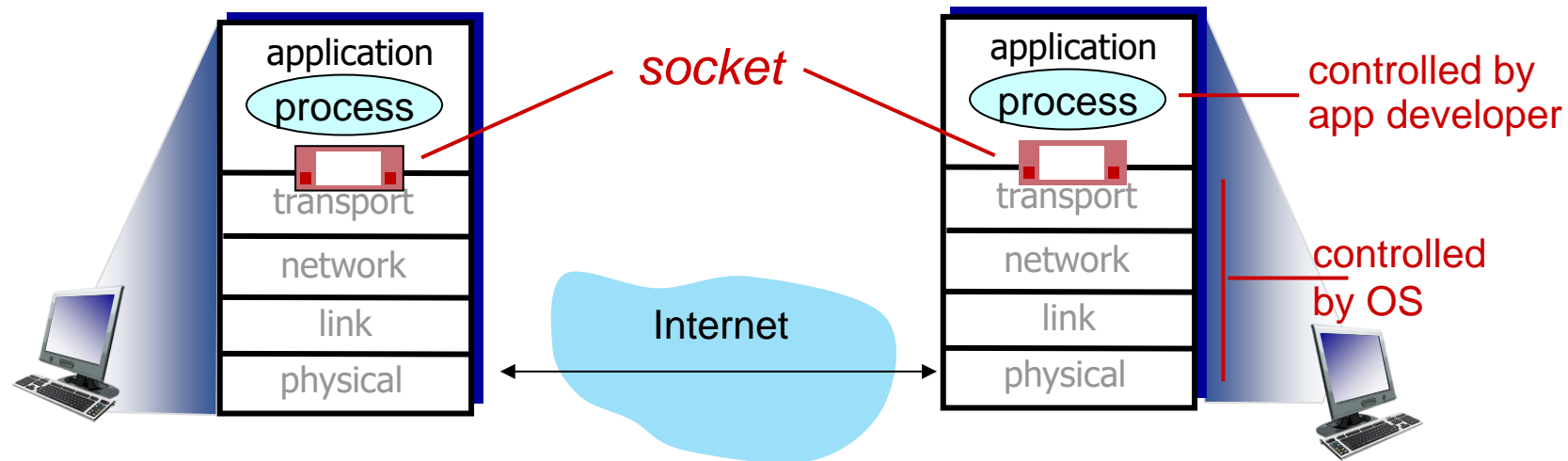
- Principles of network applications
- Web and HTTP
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- The Domain Name System DNS
- P2P applications
- socket programming with UDP and TCP



# Socket programming

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

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



# Socket programming

Two socket types for two transport services:

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

## Application Example:

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



# Socket programming with UDP

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

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

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

**Application viewpoint:**

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

# Client/server socket interaction: UDP



**server** (running on serverIP)

create socket, port= x:

`serverSocket =  
DatagramSocket()`

↓  
read datagram from  
`serverSocket`

↓  
write reply to  
`serverSocket`  
specifying  
client address,  
port number



**client**

create socket:

`clientSocket =  
DatagramSocket()`

↓  
Create datagram with server IP and  
port=x; send datagram via  
`clientSocket`

↓  
read datagram from  
`clientSocket`

↓  
close  
`clientSocket`

# Example: Java client (UDP)

```
import java.io.*;  
import java.net.*;
```

```
class UDPClient {  
    public static void main(String args[]) throws Exception  
    {
```

Create  
input stream



```
        BufferedReader inFromUser =  
            new BufferedReader(new InputStreamReader(System.in));
```

Create  
client socket



```
        DatagramSocket clientSocket = new DatagramSocket();
```

Translate  
hostname to IP  
address using DNS



```
        InetAddress IPAddress = InetAddress.getByName("hostname");
```

```
        byte[] sendData = new byte[1024];  
        byte[] receiveData = new byte[1024];
```

```
        String sentence = inFromUser.readLine();  
        sendData = sentence.getBytes();
```

# Example: Java client (UDP), cont.

Create datagram with  
data-to-send,  
length, IP addr, port

DatagramPacket sendPacket =  
new DatagramPacket(sendData, sendData.length, IPAddress, 9876);

Send datagram  
to server

clientSocket.send(sendPacket);

DatagramPacket receivePacket =  
new DatagramPacket(receiveData, receiveData.length);

Read datagram  
from server

clientSocket.receive(receivePacket);

String modifiedSentence =  
new String(receivePacket.getData());

System.out.println("FROM SERVER:" + modifiedSentence);  
clientSocket.close();

}

# Example: Java server (UDP)

```
import java.io.*;
import java.net.*;

class UDPServer {
    public static void main(String args[]) throws Exception
    {
        DatagramSocket serverSocket = new DatagramSocket(9876);

        byte[] receiveData = new byte[1024];
        byte[] sendData = new byte[1024];

        while(true)
        {
            DatagramPacket receivePacket =
                new DatagramPacket(receiveData, receiveData.length);
            serverSocket.receive(receivePacket);
```

Create datagram socket at port 9876

Create space for received datagram

Receive datagram

# Example: Java server (UDP), cont

```
String sentence = new String(receivePacket.getData());

Get IP addr  } InetAddress IPAddress = receivePacket.getAddress();
port #, of   }
sender       } int port = receivePacket.getPort();

String capitalizedSentence = sentence.toUpperCase();

Create datagram } sendData = capitalizedSentence.getBytes();
to send to client }
                } DatagramPacket sendPacket =
                }   new DatagramPacket(sendData, sendData.length, IPAddress, port);

Write out      } serverSocket.send(sendPacket);
datagram to socket }
                }
            }
        }

End of while loop,
loop back and wait for
another datagram
```

# Socket programming with TCP

## Client must contact server

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

## Client contacts server by:

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

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

## Application viewpoint

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

# Client/server socket interaction: TCP



**server** (running on `hostid`)

**client**



create socket,  
port=`x`, for incoming  
request:

`welcomeSocket = ServerSocket()`

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: Java client (TCP)

```
import java.io.*;
import java.net.*;
class TCPClient {
```

```
    public static void main(String argv[]) throws Exception
    {
```

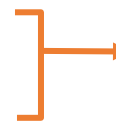
```
        String sentence;
        String modifiedSentence;
```

Create  
input stream



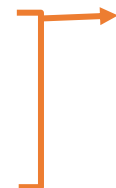
```
        BufferedReader inFromUser =
            new BufferedReader(new InputStreamReader(System.in));
```

Create  
client socket,  
connect to server



```
        Socket clientSocket = new Socket("hostname", 6789);
```

Create  
output stream  
attached to socket



```
        DataOutputStream outToServer =
            new DataOutputStream(clientSocket.getOutputStream());
```

# Example: Java client (TCP), cont.

Create input stream attached to socket	}]→	<pre>BufferedReader inFromServer =     new BufferedReader(new         InputStreamReader(clientSocket.getInputStream()));  sentence = inFromUser.readLine();</pre>
Send line to server	}]→	<pre>outToServer.writeBytes(sentence + '\n');</pre>
Read line from server	}]→	<pre>modifiedSentence = inFromServer.readLine();  System.out.println("FROM SERVER: " + modifiedSentence);  clientSocket.close();  } }</pre>

# Example: Java server (TCP)

```
import java.io.*;  
import java.net.*;
```

```
class TCPServer {
```

```
    public static void main(String argv[]) throws Exception  
    {
```

```
        String clientSentence;  
        String capitalizedSentence;
```

Create  
welcoming socket  
at port 6789

```
        ServerSocket welcomeSocket = new ServerSocket(6789);
```

Wait, on welcoming  
socket for contact  
by client

```
        while(true) {
```

```
            Socket connectionSocket = welcomeSocket.accept();
```

Create input  
stream, attached  
to socket

```
            BufferedReader inFromClient =  
                new BufferedReader(new  
                    InputStreamReader(connectionSocket.getInputStream()));
```

# Example: Java server (TCP), cont

Create output  
stream, attached  
to socket

```
DataOutputStream outToClient =  
    new DataOutputStream(connectionSocket.getOutputStream());
```

Read in line  
from socket

```
clientSentence = inFromClient.readLine();
```

```
capitalizedSentence = clientSentence.toUpperCase() + '\n';
```

Write out line  
to socket

```
outToClient.writeBytes(capitalizedSentence);
```

```
}  
}  
}
```

End of while loop,  
loop back and wait for  
another client connection

# Chapter 2: Summary

our study of network application layer is now complete!

- application architectures
  - client-server
  - P2P
- application service requirements:
  - reliability, bandwidth, delay
- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP
- specific protocols:
  - HTTP
  - SMTP, IMAP
  - DNS
  - P2P: BitTorrent
- socket programming:  
TCP, UDP sockets

# Chapter 2: Summary

Most importantly: learned about *protocols*!

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

important themes:

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