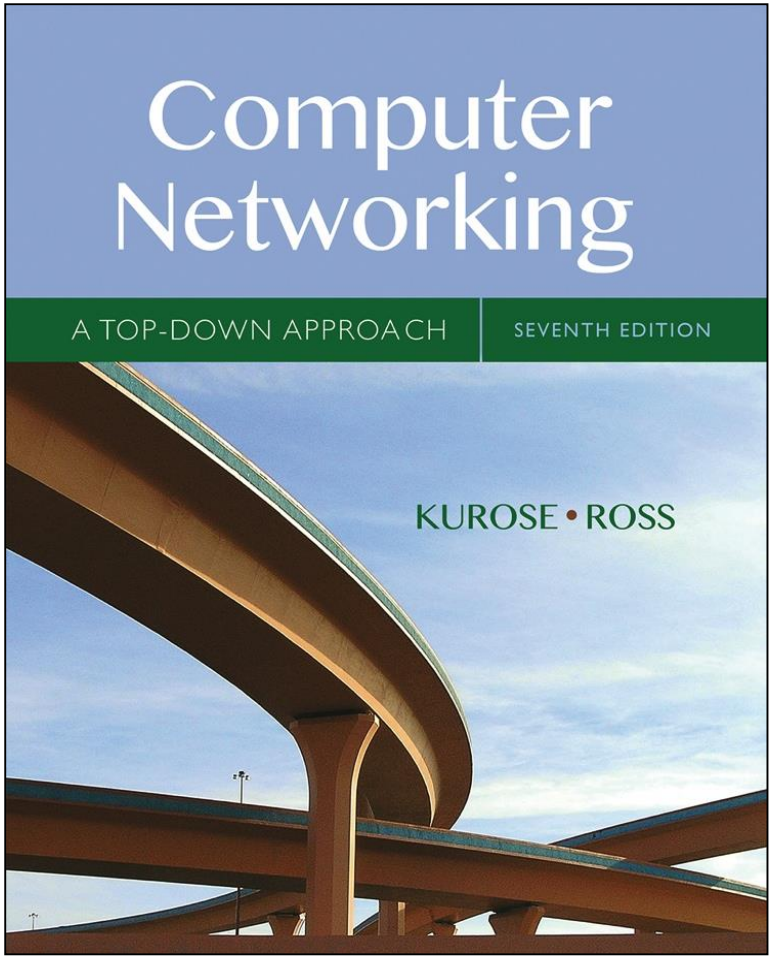
Computer Networking: A Top Down Approach

Seventh Edition



Chapter 2

Application Layer

Learning Objectives (1 of 7)

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

Application Layer

our goals:

- conceptual, implementation aspectsa 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

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
- …
- …

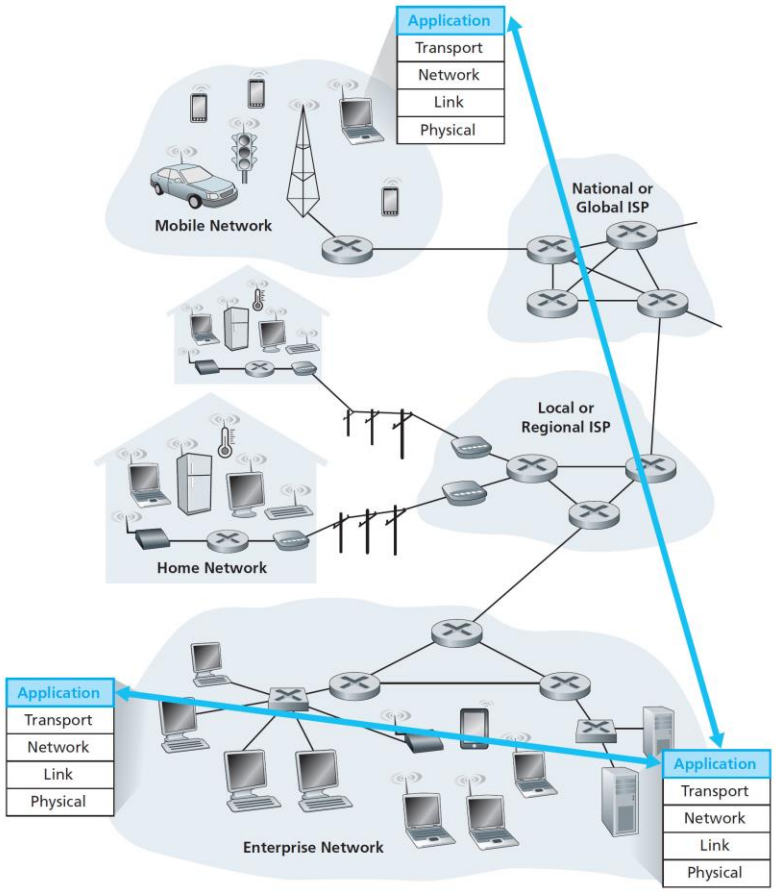
Creating a Network App

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)

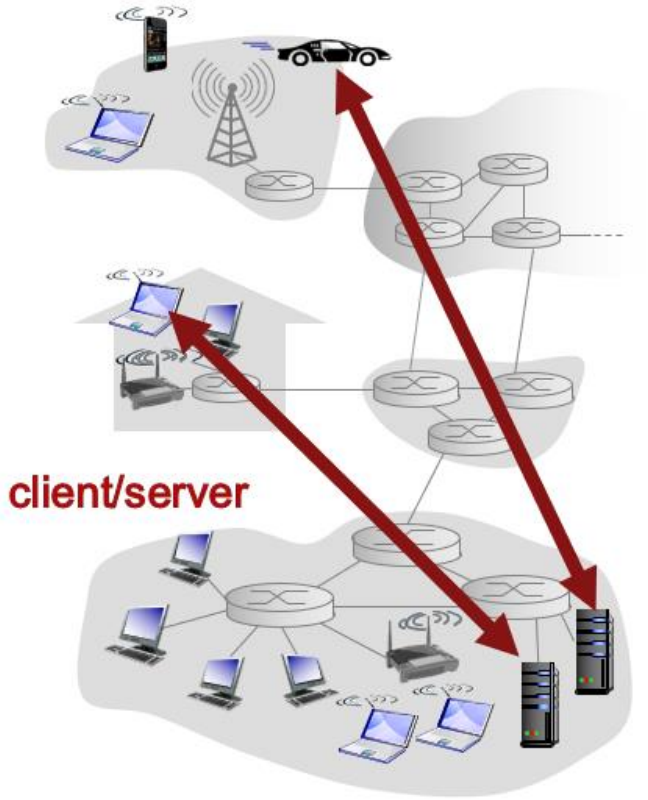
Client-Server Architecture

server:

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

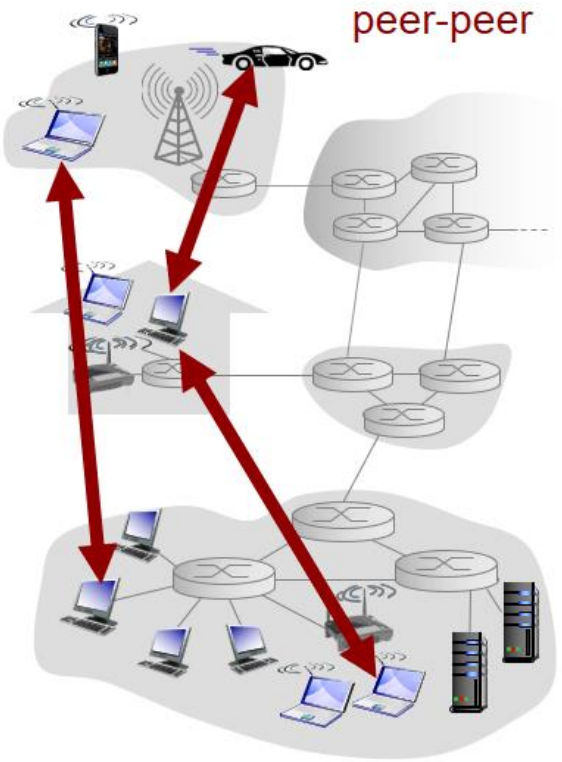
clients:

- 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

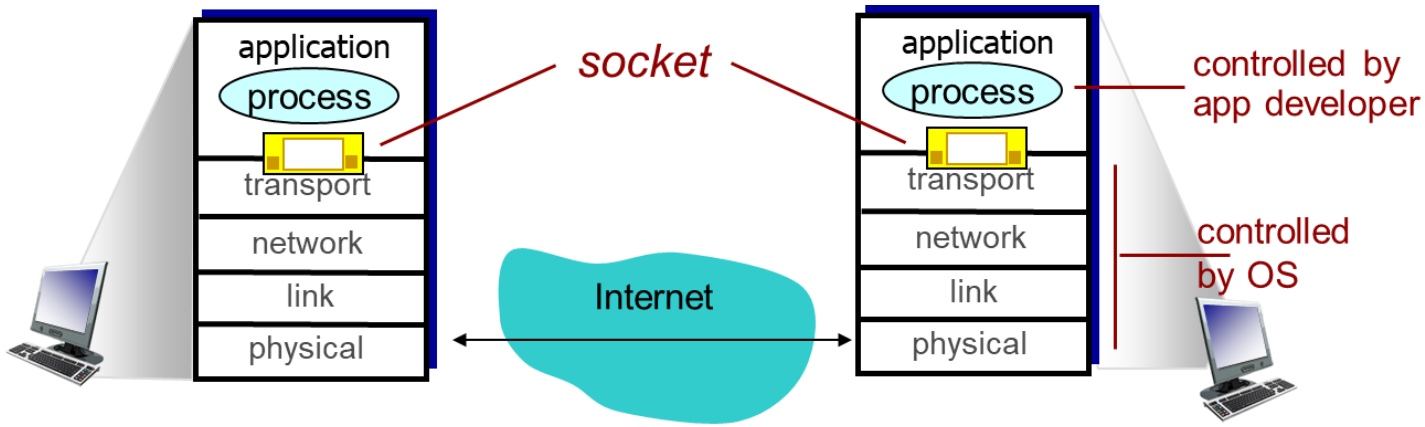
client process: process that initiates communication

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
- 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	yes, few secs
interactive games	loss-tolerant	few kbps up	yes, 100’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
- **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

Application	Application layer protocol	Underlying transport protocol
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 A P I

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

Learning Objectives (2 of 7)

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

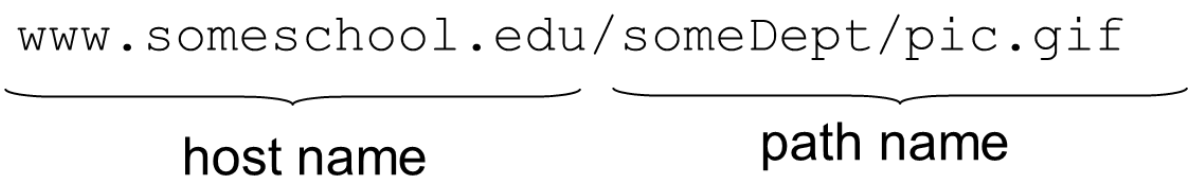
2.6 video streaming and content distribution networks

2.7 socket programming with UDP and TCP

Web and HTTP

First, a review…

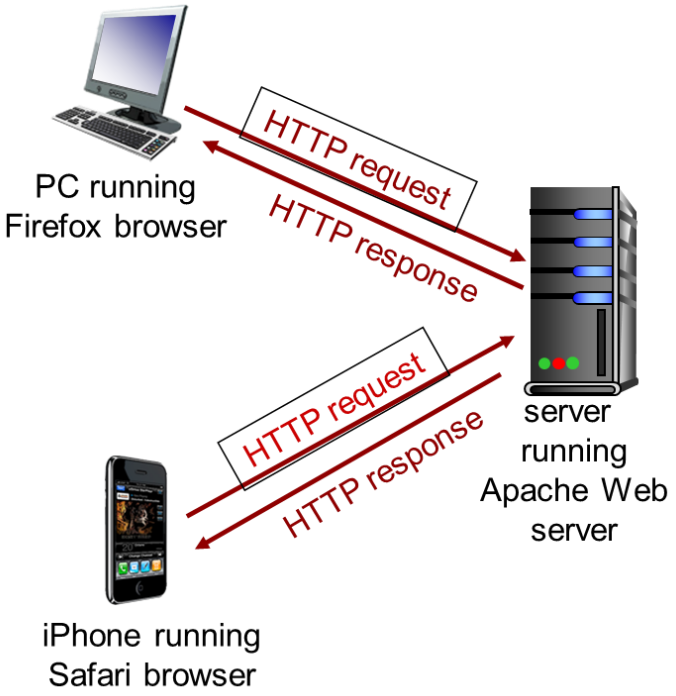
- **web page** consists of **objects**
- object can be HTML file, JPEG image, Java applet, audio file,…
- web page consists of **base HTML-file** which includes **several referenced objects**
- each object is addressable by a **URL,** e.g.,



HTTP Overview (1 of 2)

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 (2 of 2)

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

non-persistent HTTP

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

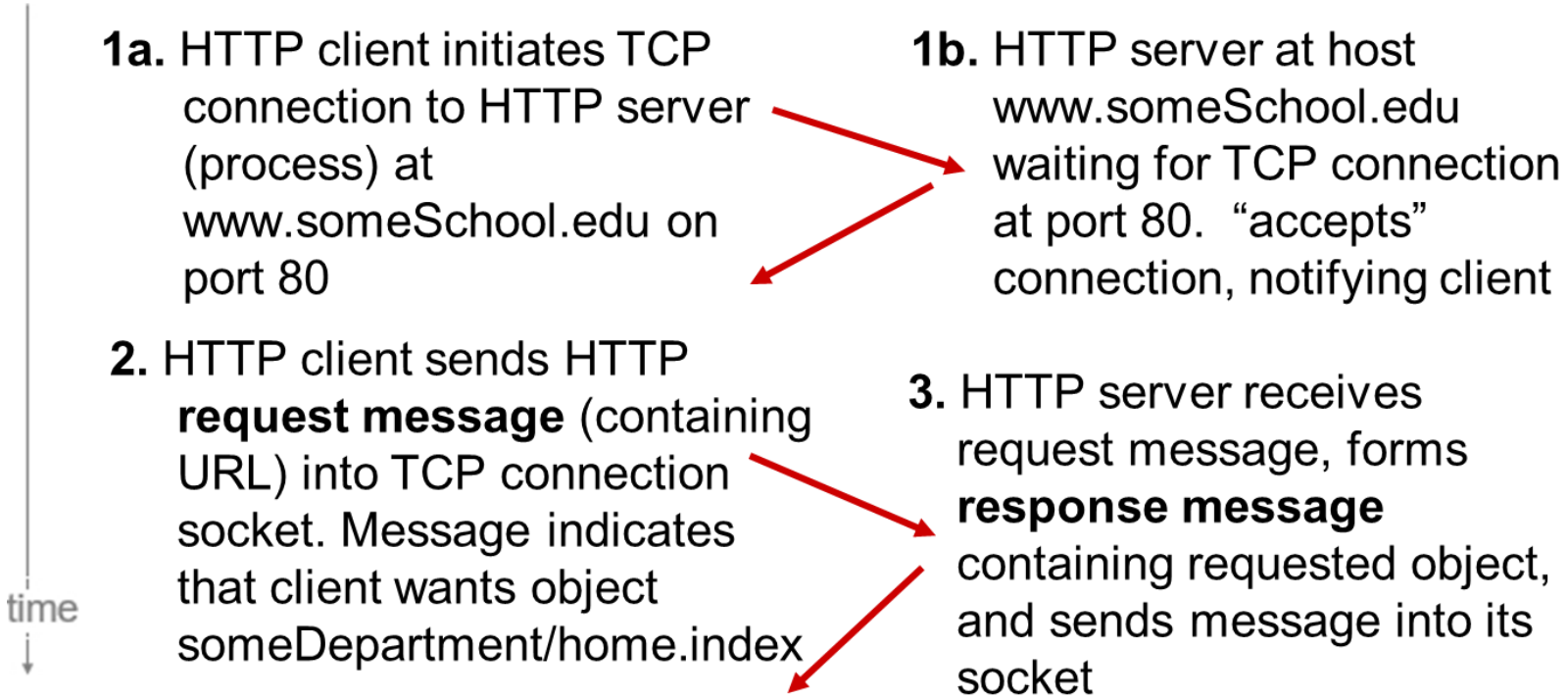
persistent HTTP

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

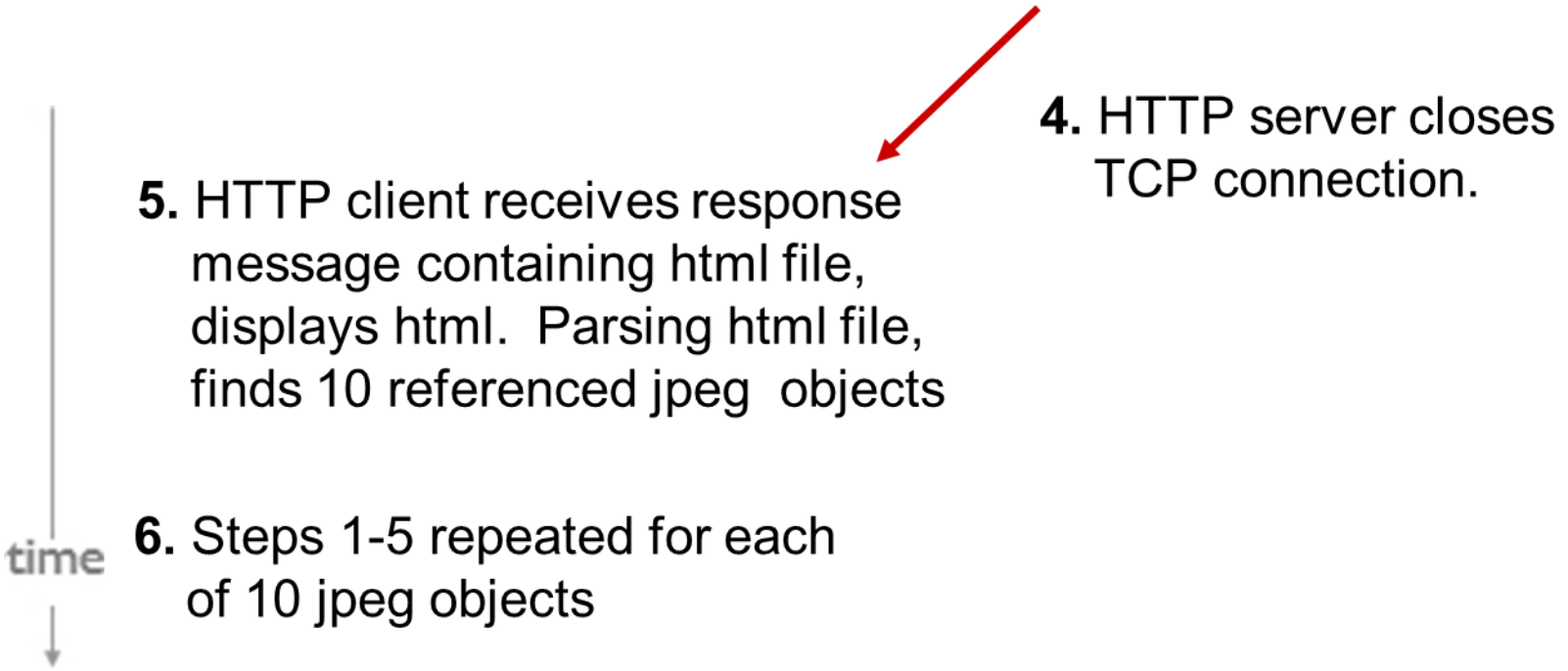
Non-Persistent HTTP (1 of 2)

suppose user enters URL:

www.someSchool.edu/someDepartment/home.index



Non-Persistent HTTP (2 of 2)

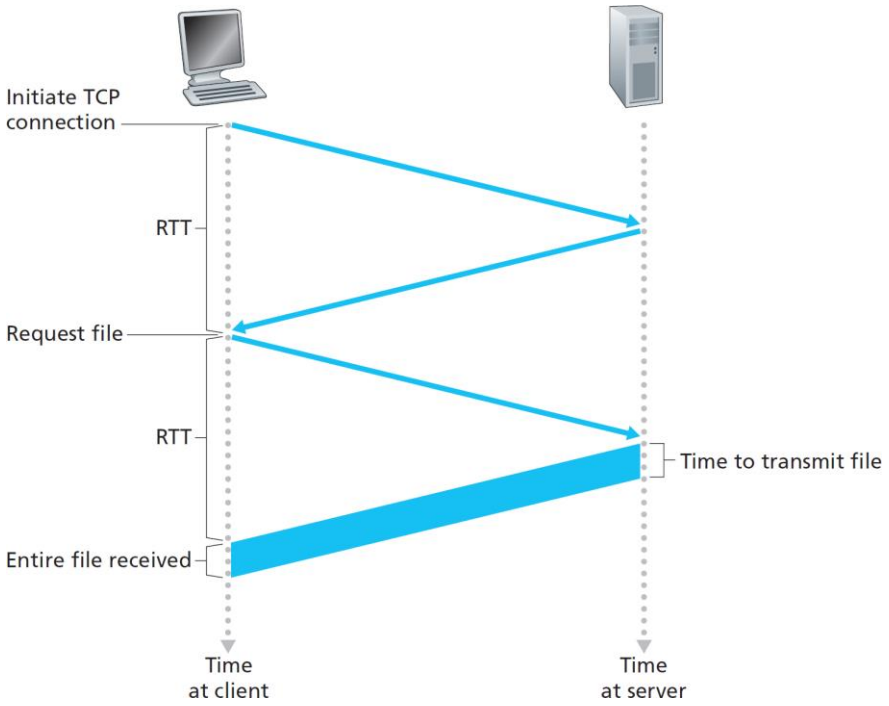


Non-Persistent HTTP: Response Time

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:

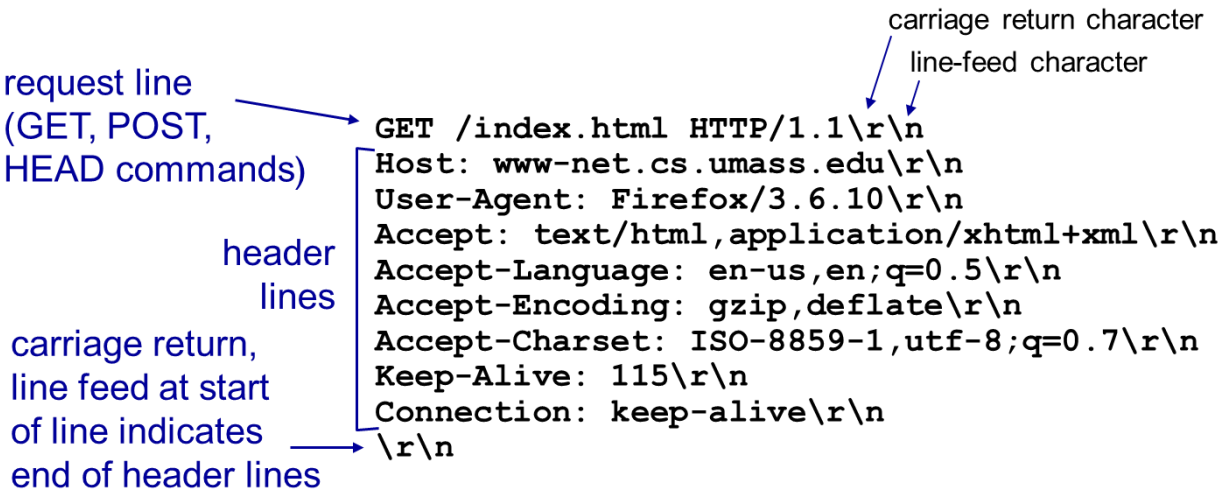
- requires 2 RTT s per object
- OS overhead for **each** TCP connection
- browsers often open parallel TCP connections to fetch referenced objects

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

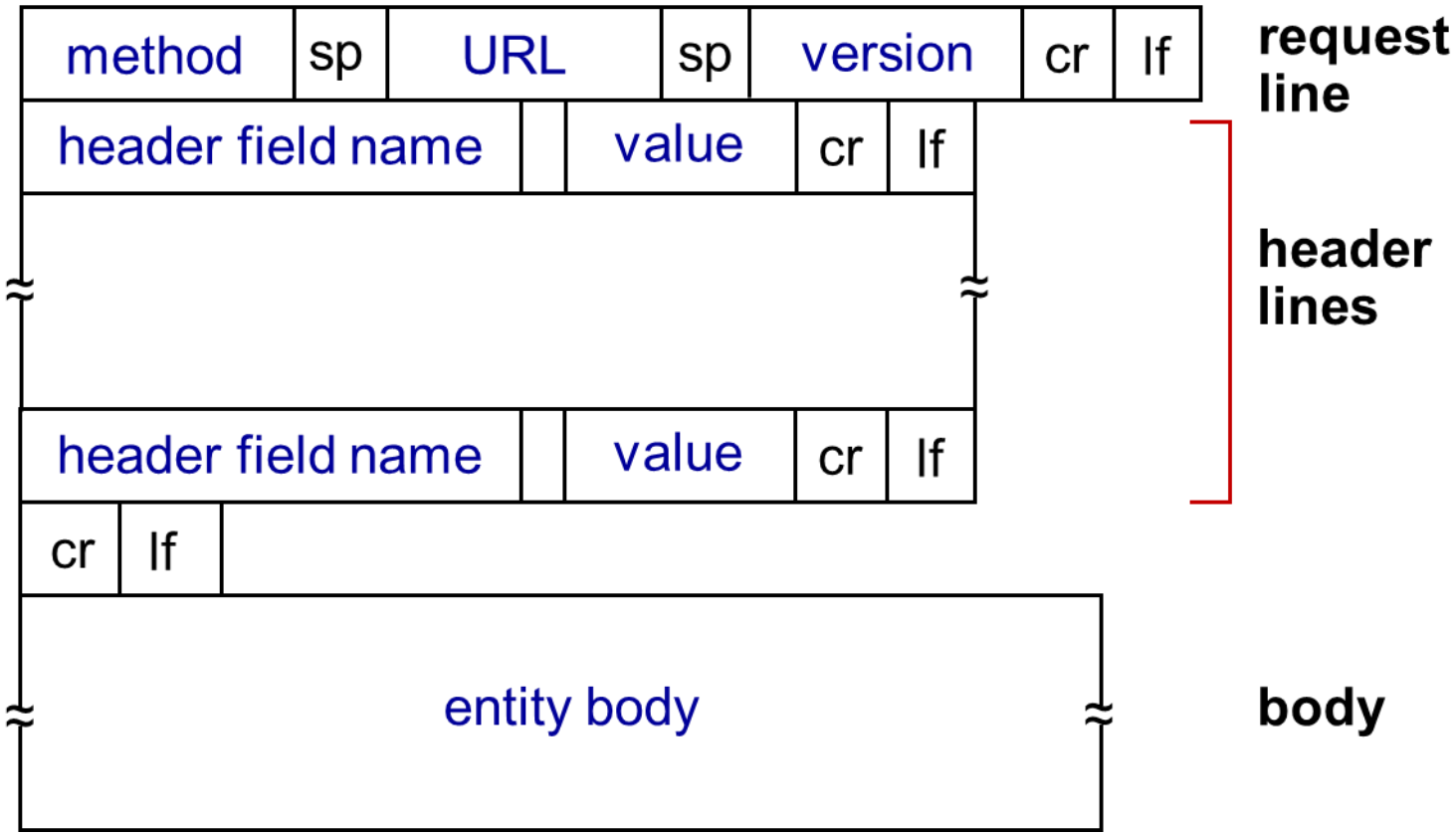
HTTP Request Message

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



* Check out the online interactive exercises for more examples: 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

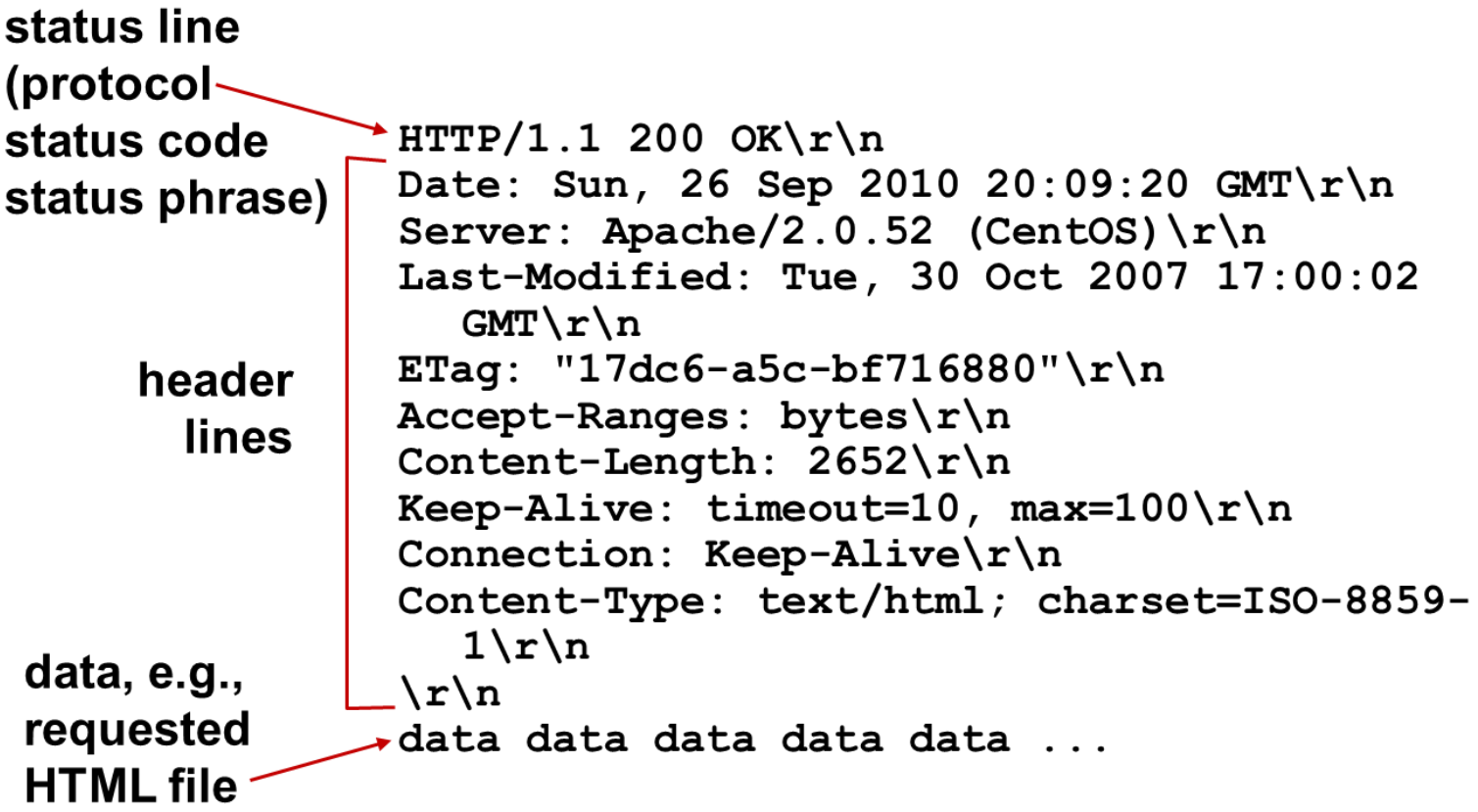
HTTP/1.0:

- 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



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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:

```
telnetgaia.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

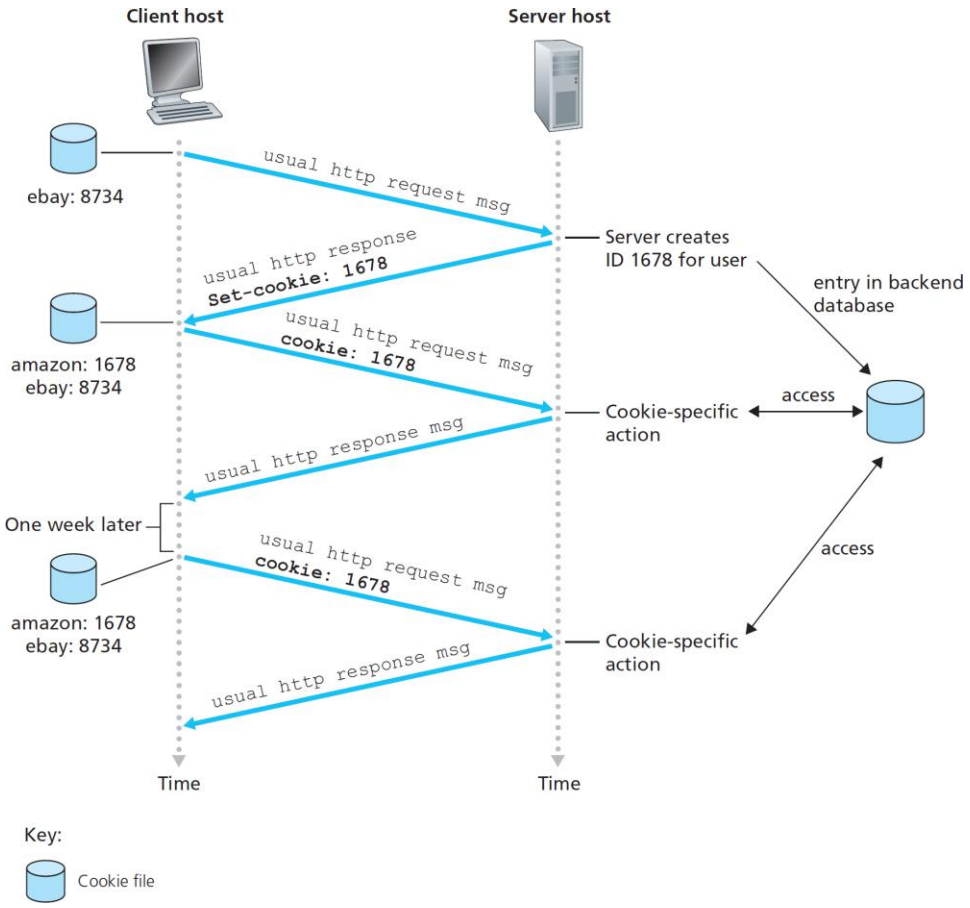
four components:

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"



Cookies

what cookies can be used for:

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

how to keep "state":

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

aside

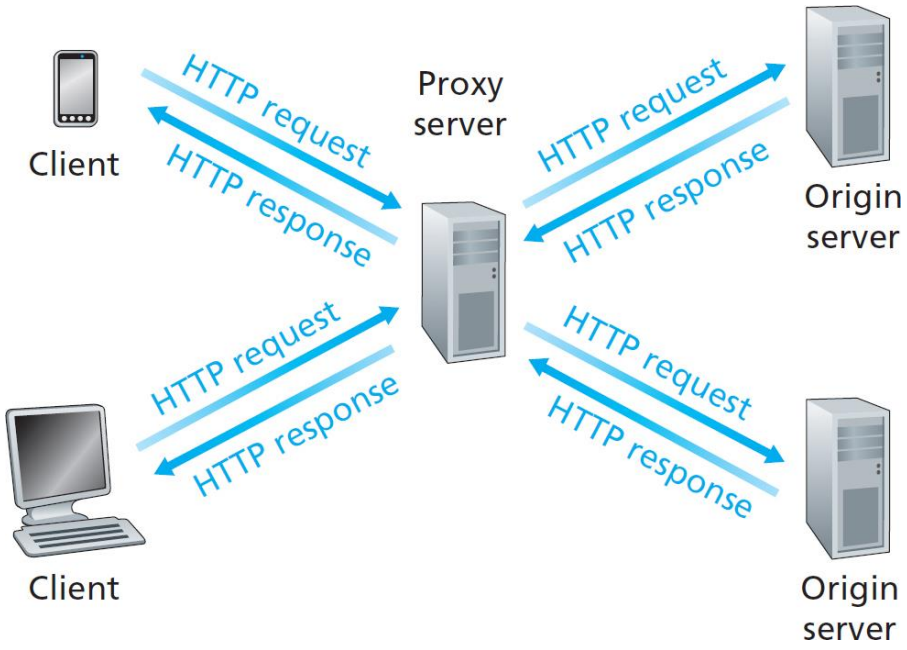
cookies and privacy:

- cookies permit sites to learn a lot about you
- you may supply name and e-mail to sites

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)

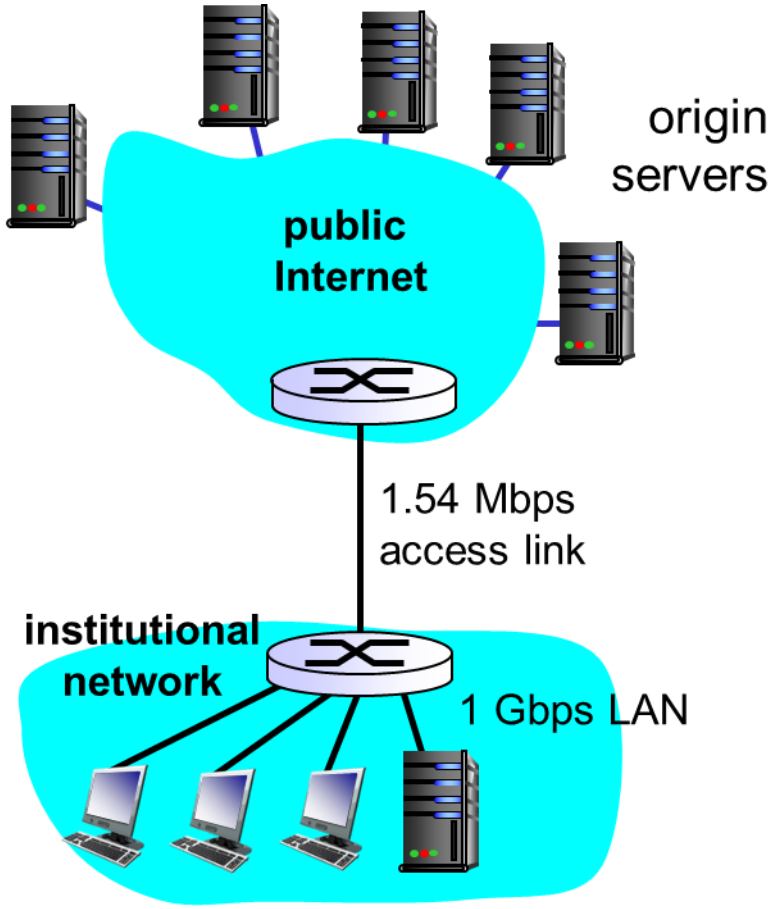
why Web caching?

- 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: (1 of 2)

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



Caching Example: (2 of 2)

consequences:

- LAN utilization: 15%
- access link utilization = 99%

problem!

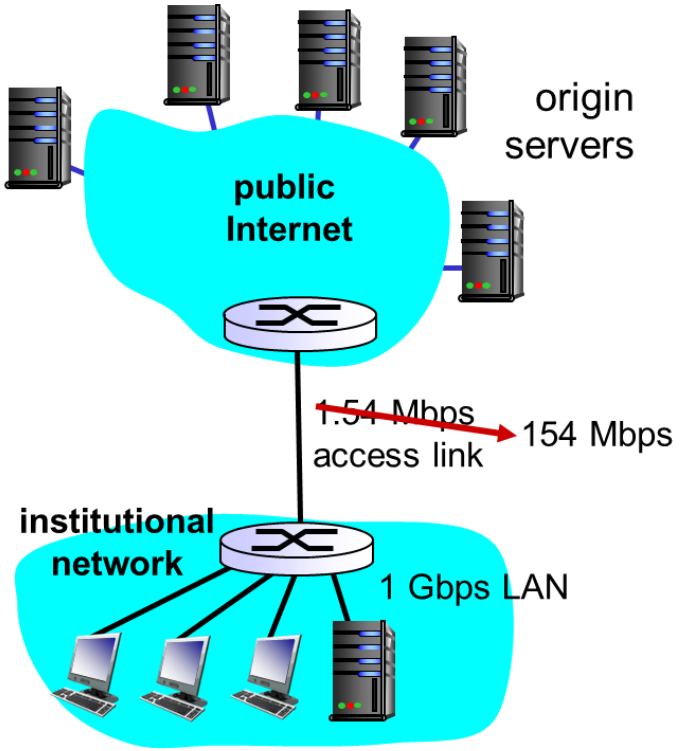
- total delay = Internet delay + access delay + LAN delay

  = 2 sec + minutes + usecs

Caching Example: Fatter Access Link (1 of 2)

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 154 Mbps



Caching Example: Fatter Access Link (2 of 2)

consequences:

- LAN utilization: 15%
- access link utilization = ~~99%~~ 9.9%
- total delay = Internet delay + access delay + LAN delay

  = 2 sec + ~~minutes~~ msecs + usecs

Cost: increased access link speed (not cheap!)

Caching Example: Install Local Cache (1 of 3)

assumptions:

- avg object size: 100K bits
- avg request rate from browsers to origin servers:15/sec
- avg data rate to browsers: 1.50 Mbps
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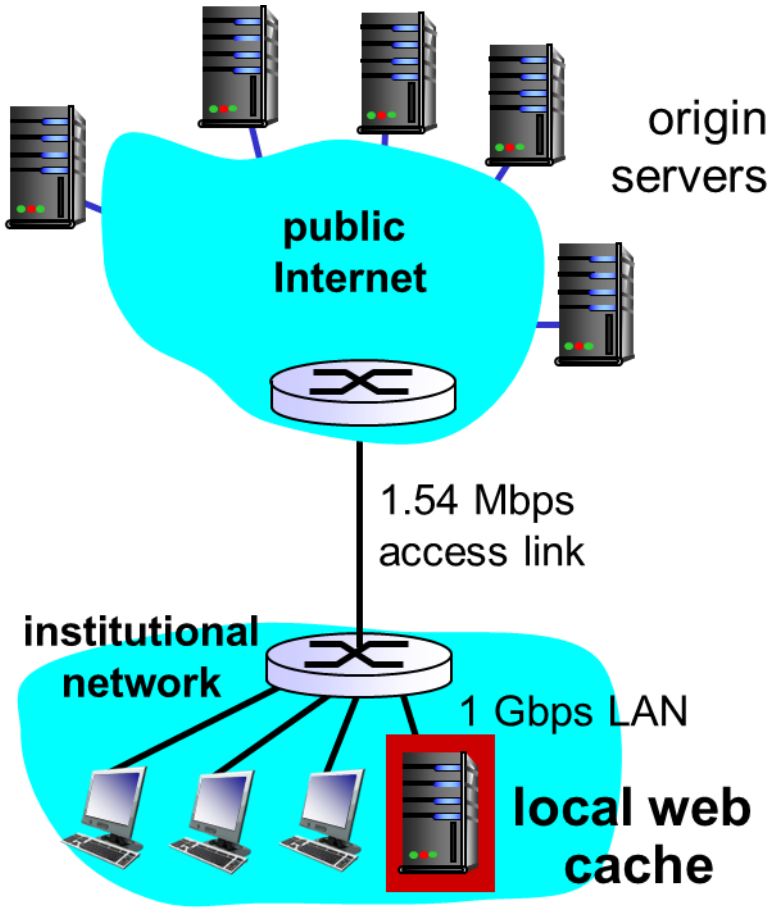


Caching Example: Install Local Cache (2 of 3)

consequences:

- LAN utilization: 15%
- access link utilization = **100?**
- total delay = Internet delay + access delay + LAN delay 2 sec + minutes + usecs

How to compute link utilization, delay?

Cost: web cache (cheap!)

Caching Example: Install Local Cache (3 of 3)

Calculating access link utilization, delay with cache:

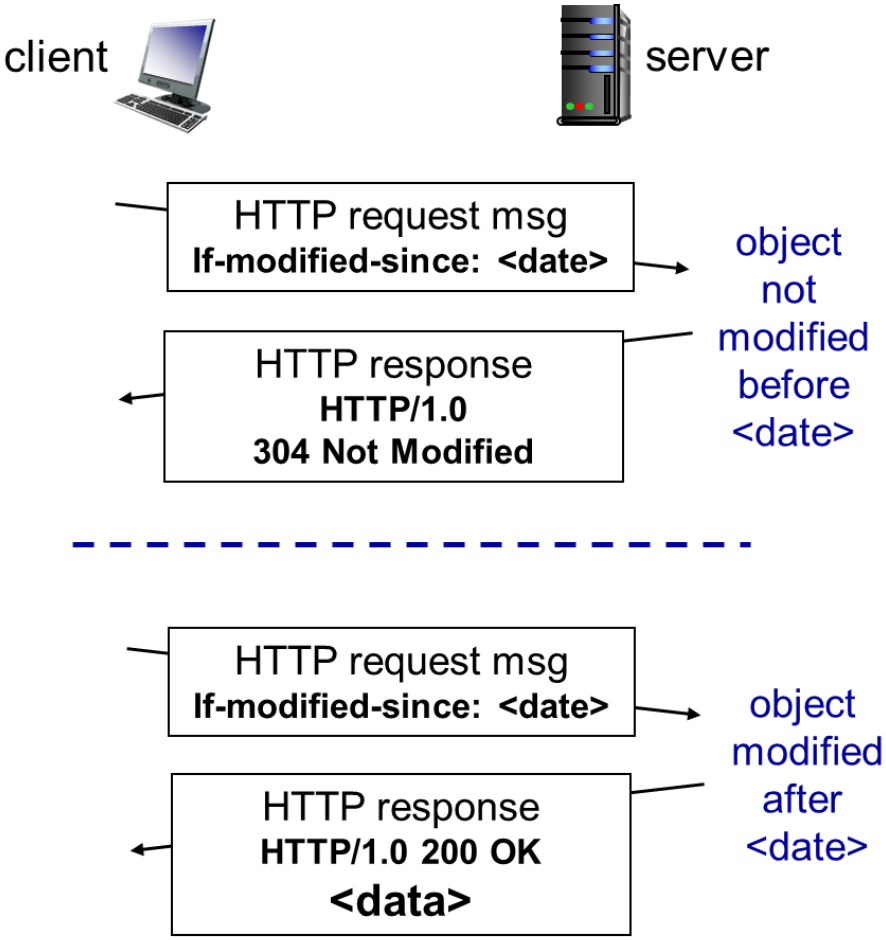
- suppose cache hit rate is 0.4
  - 40% requests satisfied at cache, 60% requests satisfied at origin
- access link utilization:
  - 60% of requests use access link
- data rate to browsers over access link $= 0.6 * 1.50 \text{ Mbps} = .9 \text{ Mbps}$
  - utilization $= \frac{0.9}{1.54} = .58$
- total delay
  - $= 0.6 * (\text{delay from origin servers}) + 0.4 * (\text{delay when satisfied at cache})$
  - $= 0.6 (2.01) + 0.4 (\sim \text{millisecs}) = \sim 1.2 \text{ secs}$
  - less than with 154 M b p s 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



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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

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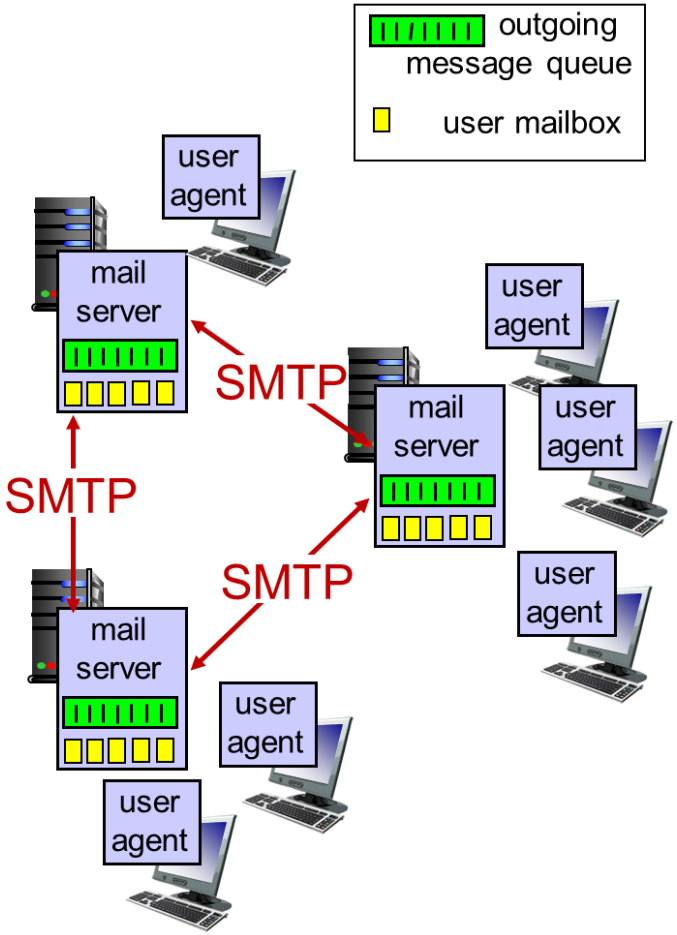
Electronic Mail

Three major components:

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

User Agent

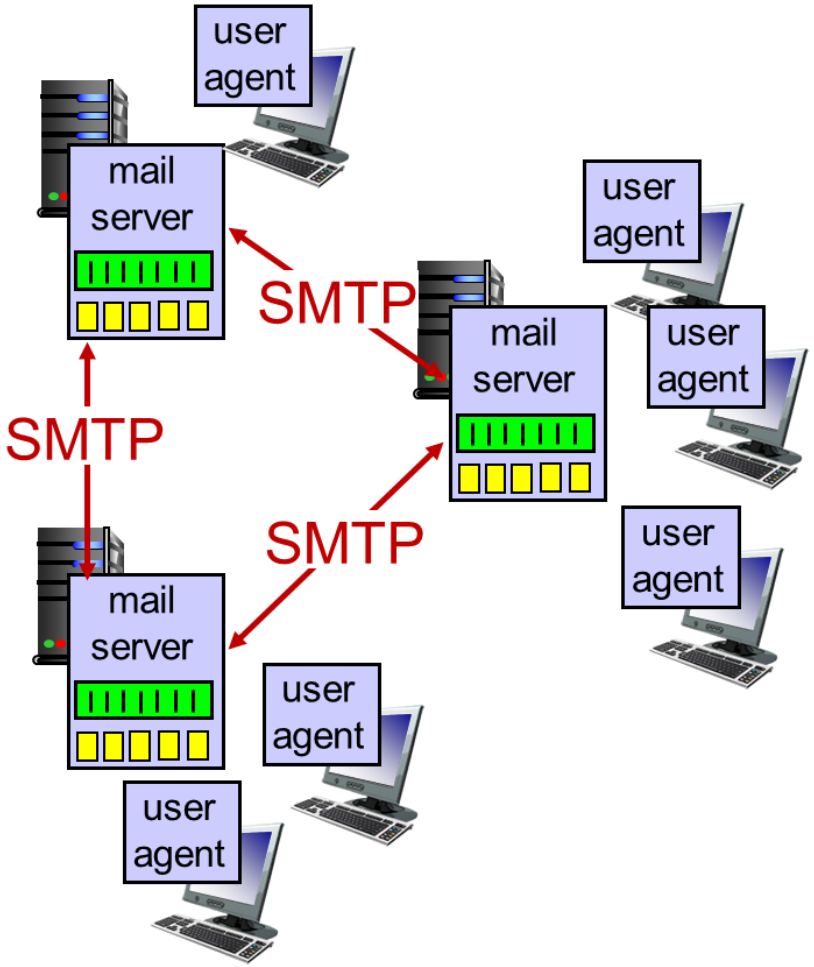
- a.k.a. “mail reader”
- composing, editing, reading mail messages
- e.g., Outlook, Thunderbird, iPhone mail client
- outgoing, incoming messages stored on server



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 ASCI

Scenario: Alice Sends Message to Bob

1) Alice uses UA to compose message “to” bob@someschool.edu

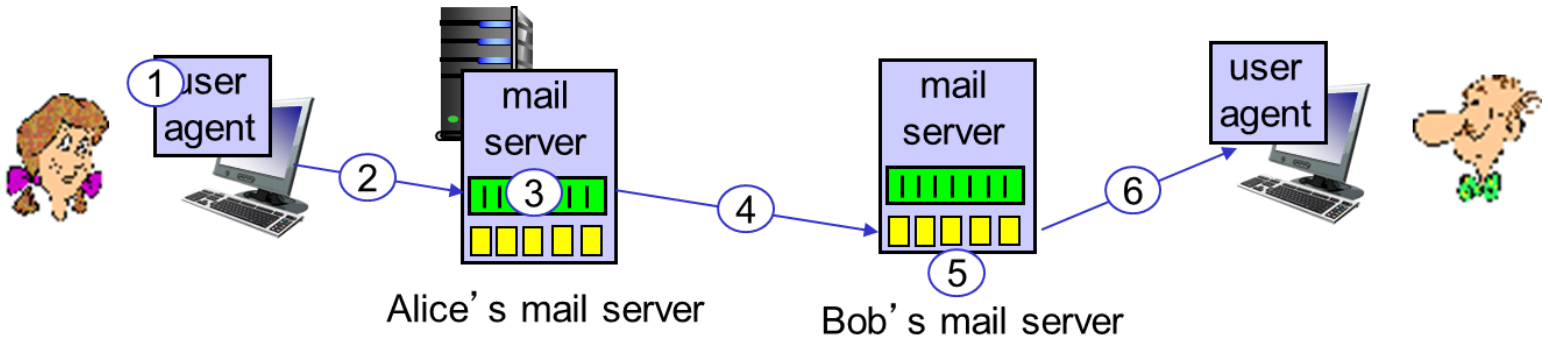
2) Alice’s UA sends message to her mail server; message placed in message queue

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

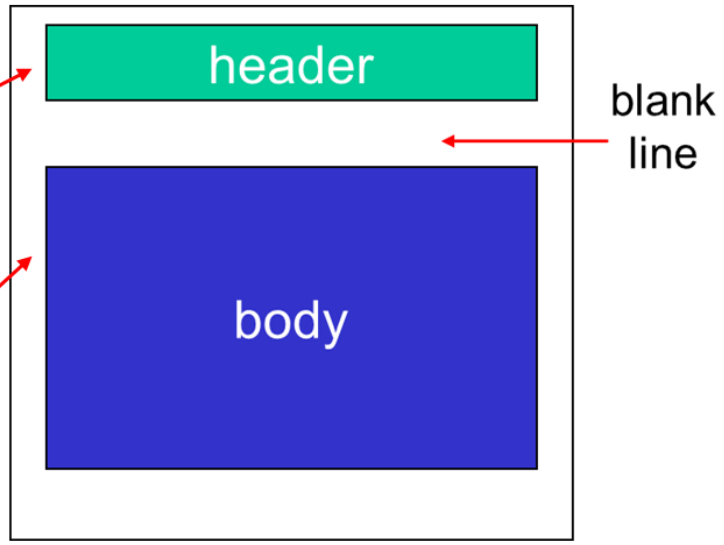
SMTP: protocol for exchanging email messages

RFC 822: standard for text message format:

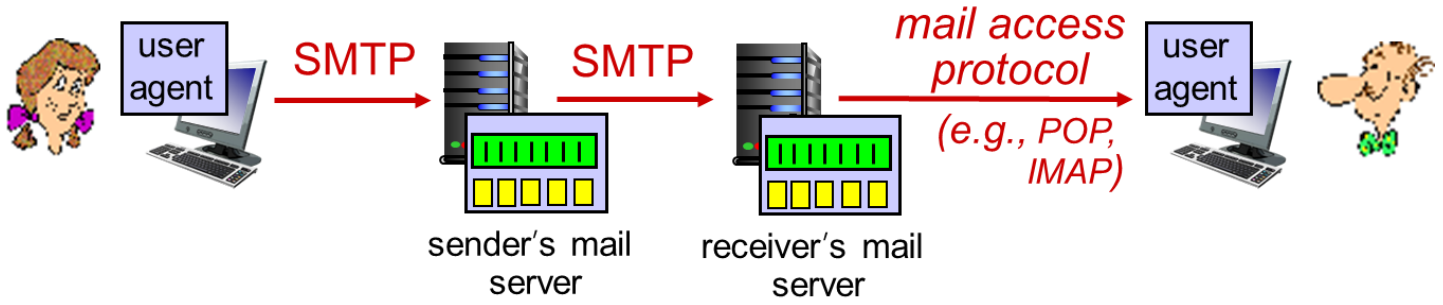
- header lines, e.g.,
  - To:
  - From:
  - Subject:

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

Learning Objectives (4 of 7)

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

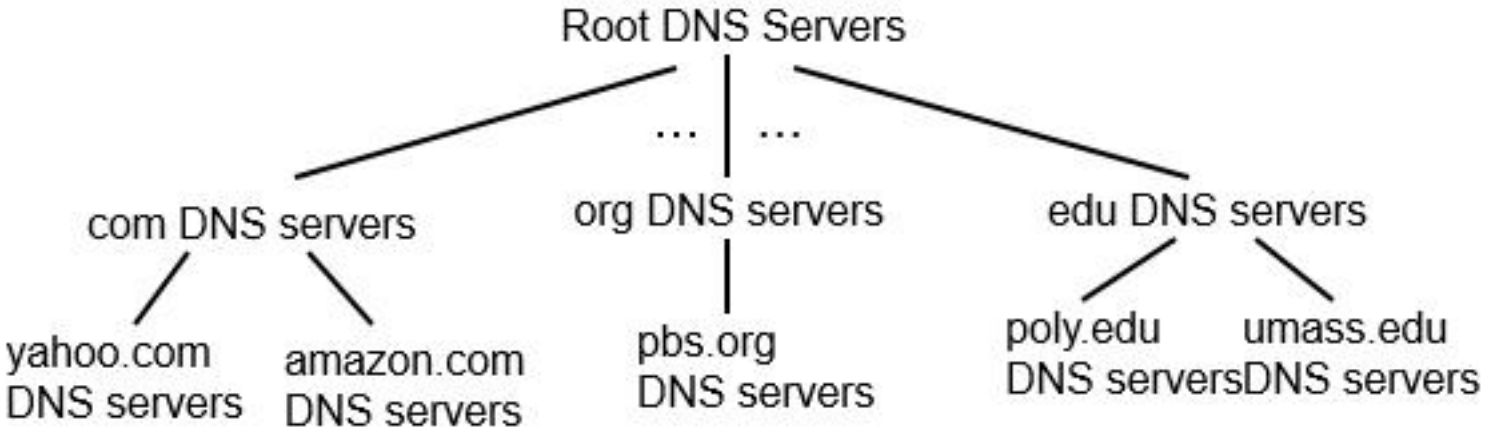
- hostname to IP address translation
- host aliasing
  - canonical, alias names
- mail server aliasing
- load distribution
  - replicated Web servers: many IP addresses correspond to one name

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; 1st approximation:

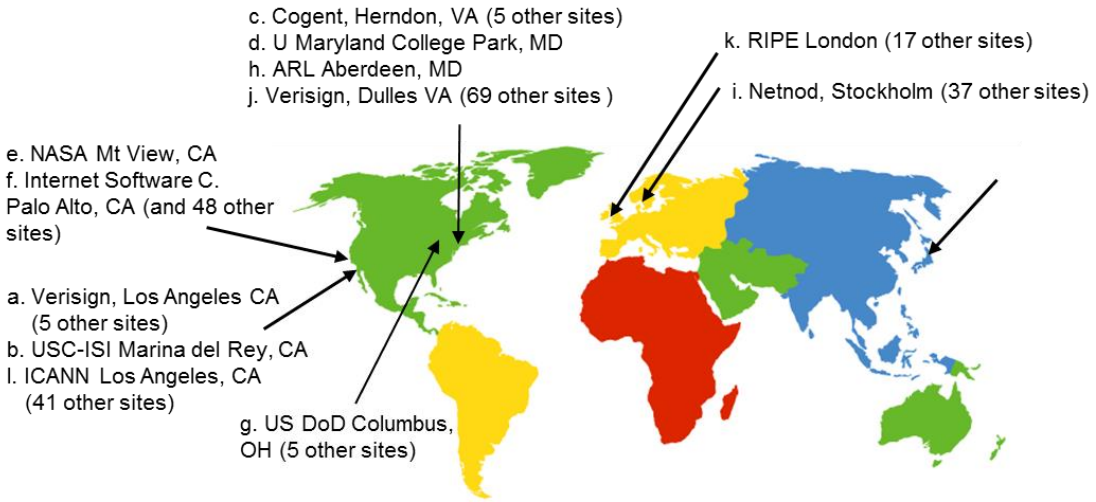
- client queries root server to find com DNS server
- client queries .com DNS server to get amazon.com DNS server
- client queries amazon.com DNS server to get IP address for www.amazon.com

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

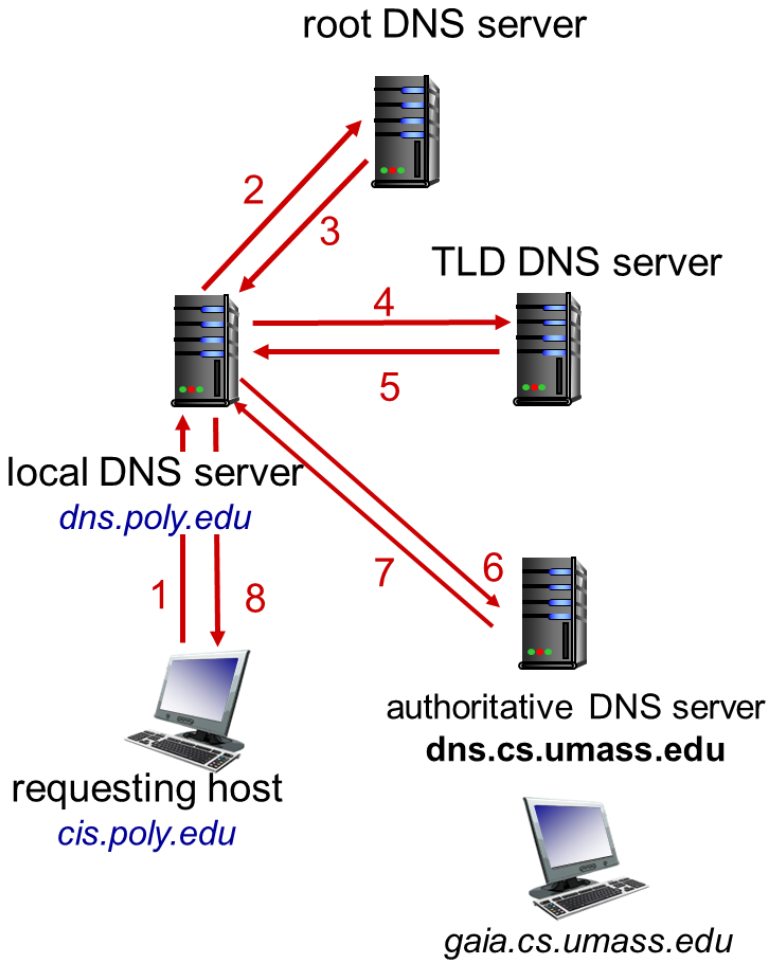
- does not strictly belong to hierarchy
- each ISP (residential ISP, company, university) has one
  - also called “default name server”
- when host makes DNS query, query is sent to its local DNS server
  - has local cache of recent name-to-address translation pairs (but may be out of date!)
  - acts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

DNS Name Resolution Example (1 of 2)

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

iterated query:

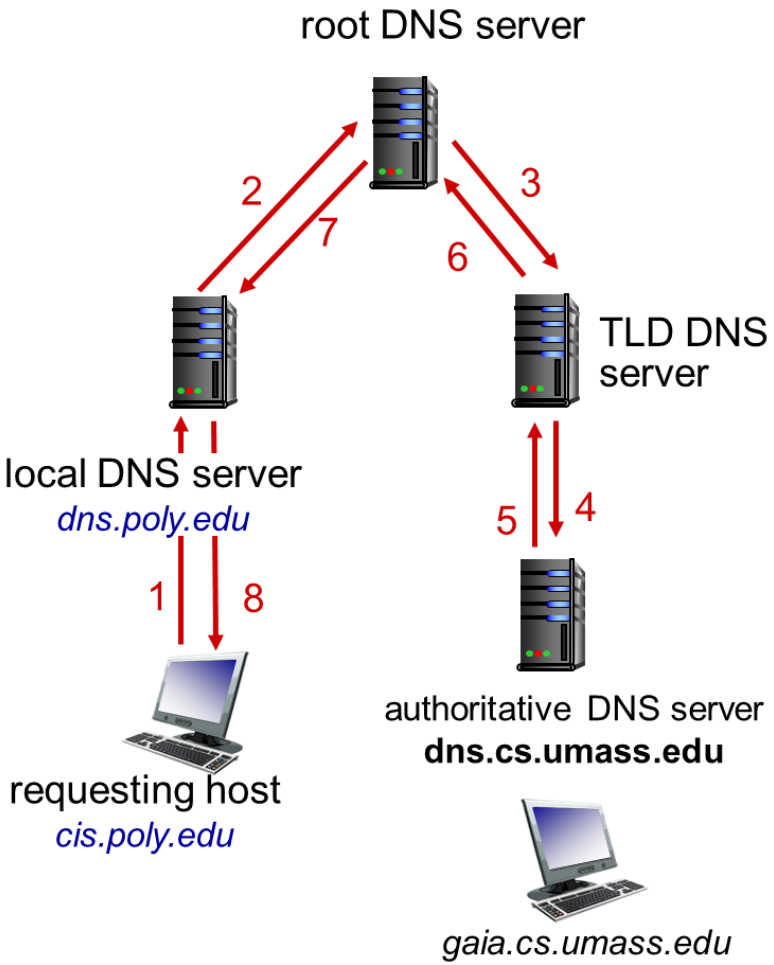
- contacted server replies with name of server to contact
- "I don't know this name, but ask this server"



DNS Name Resolution Example (2 of 2)

recursive query:

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



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 TTL s 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

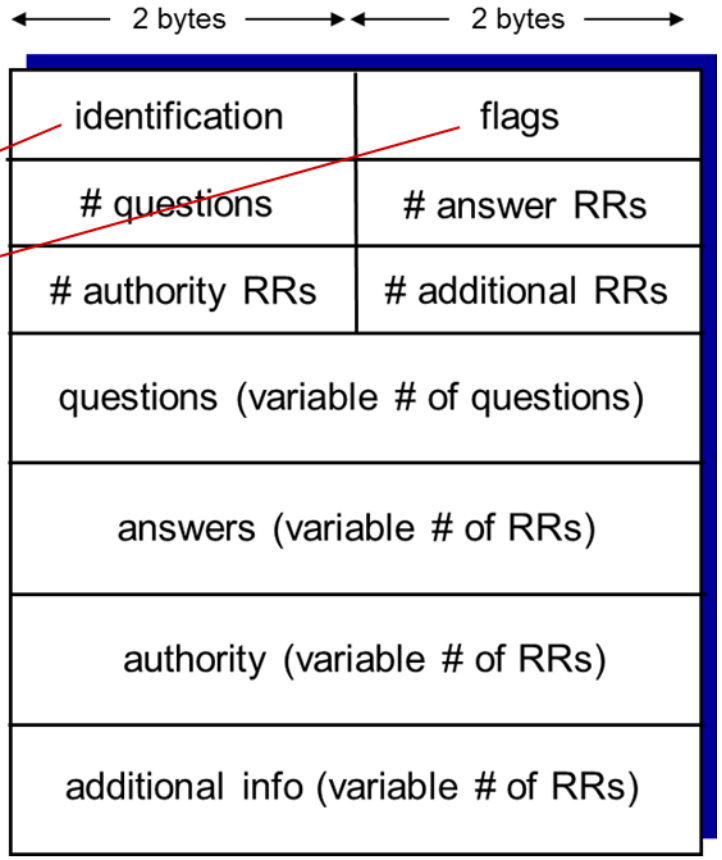
- **`value`** is name of mailserver associated with **`name`**

DNS Protocol, Messages (1 of 2)

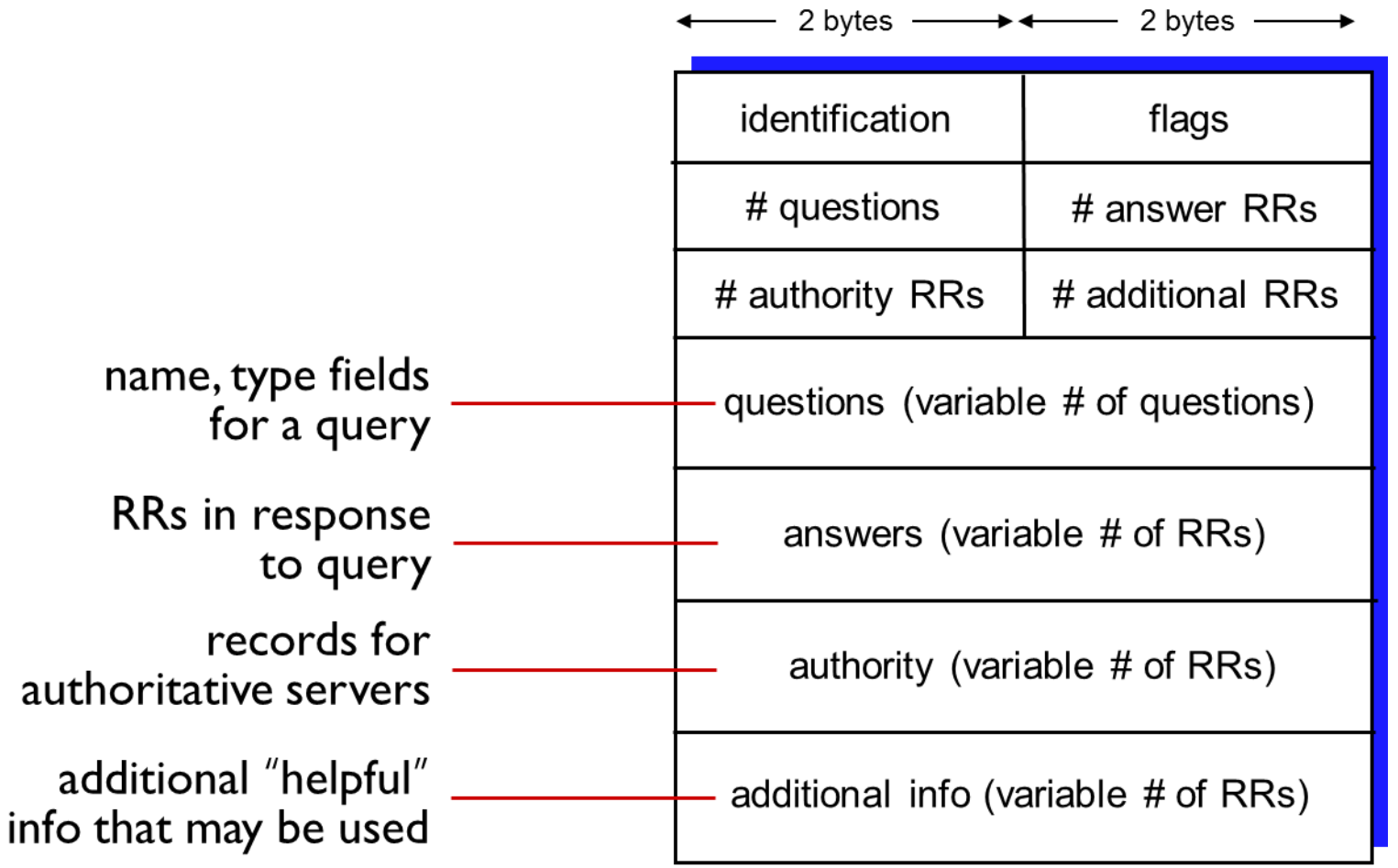
- **query** and **reply** messages, both with same **message format**

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 (2 of 2)



Inserting Records into DNS

- example: new startup “Network Utopia”
- register name networkuptopia.com at **DNS registrar** (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts 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.networkuptopia.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 relies to DNS server, which caches

exploit DNS for DDoS

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

Learning Objectives (5 of 7)

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

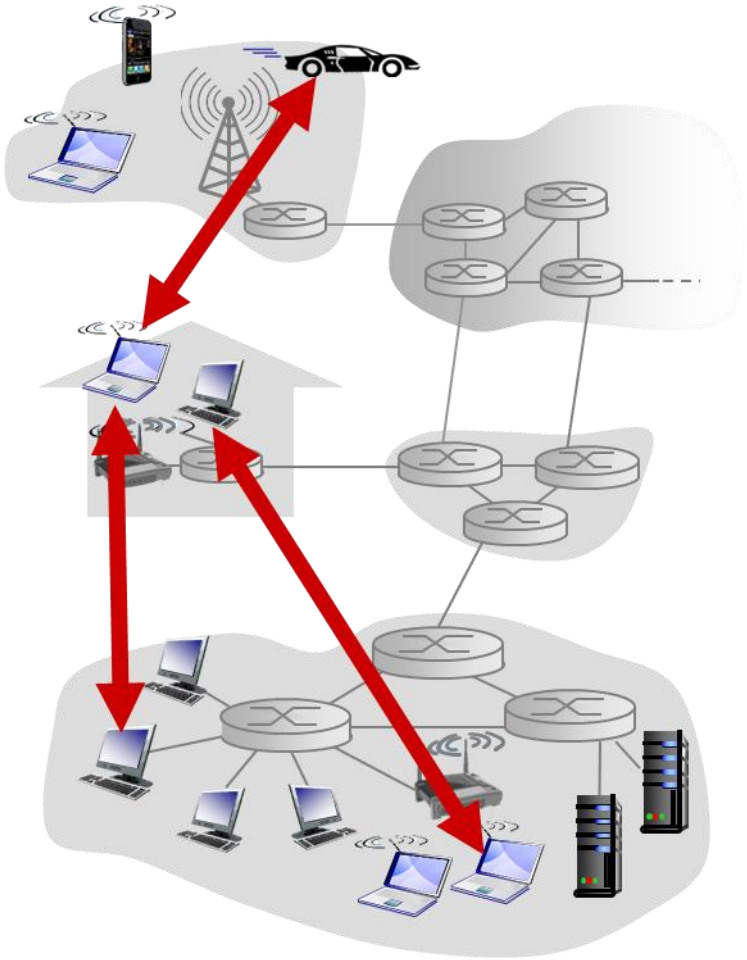
2.7 socket programming with UDP and TCP

Pure P2P Architecture

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

examples:

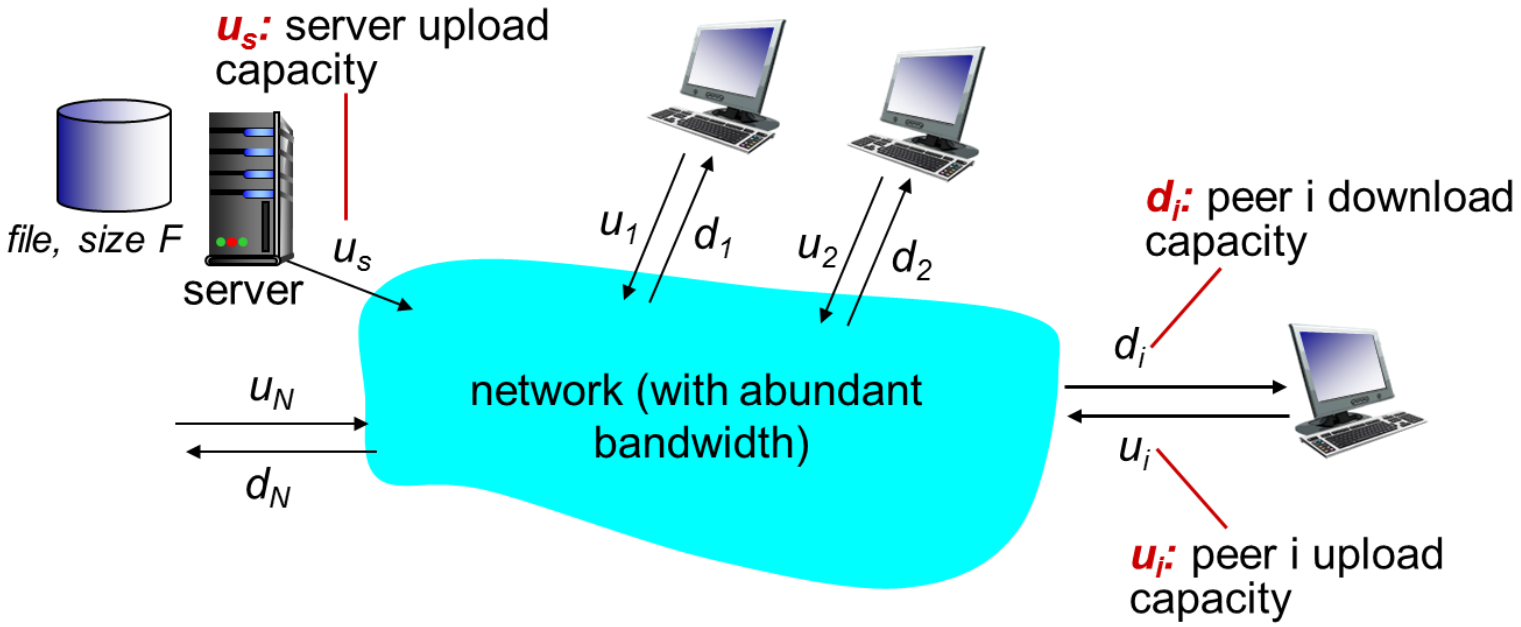
  - file distribution (BitTorrent)
  - Streaming (KanKan)
  - VoIP (Skype)



File Distribution: Client-Server vs P2P

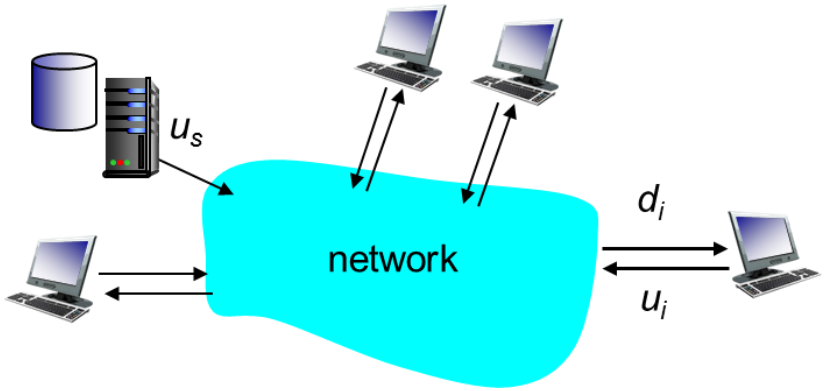
Question: how much time to distribute file (size *F*) from one server to *N* **peers**?

– 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: $\frac{F}{u_s}$
  - time to send *N* copies: $\frac{NF}{u_s}$
- **client:** each client must download file copy
  - d_{min} = min client download rate
  - min client download time: $\frac{F}{d_{min}}$



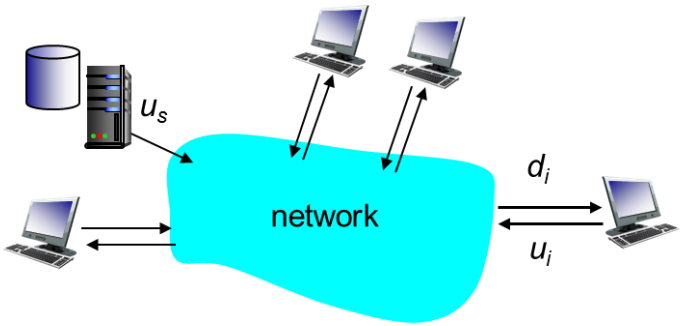
time to distribute F to N clients using client-server approach

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

increases linearly in N

File Distribution Time: P2P

- **server transmission:** must upload at least one copy
  - time to send one copy: $\frac{F}{u_s}$
- **client:** each client must download file copy
  - min client download time: $\frac{F}{d_{min}}$
- **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

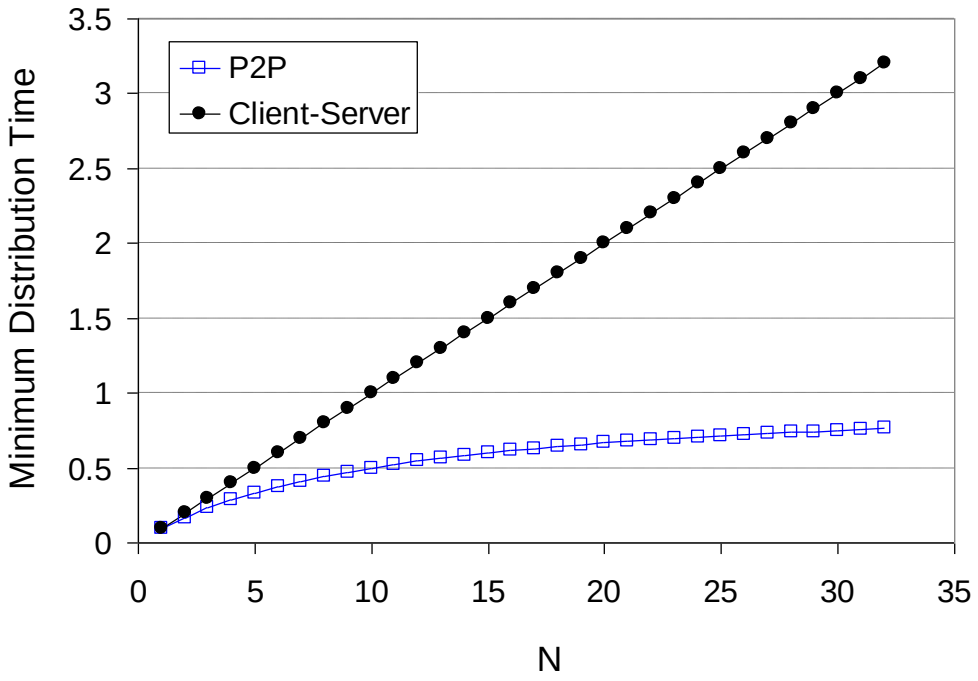
$$D_{P2P} \geq max\{F/u_s, F/d_{min}, NF/(u_s + \Sigma u_i)\}$$

increases linearly in N …

… but so does this, as each peer brings service capacity

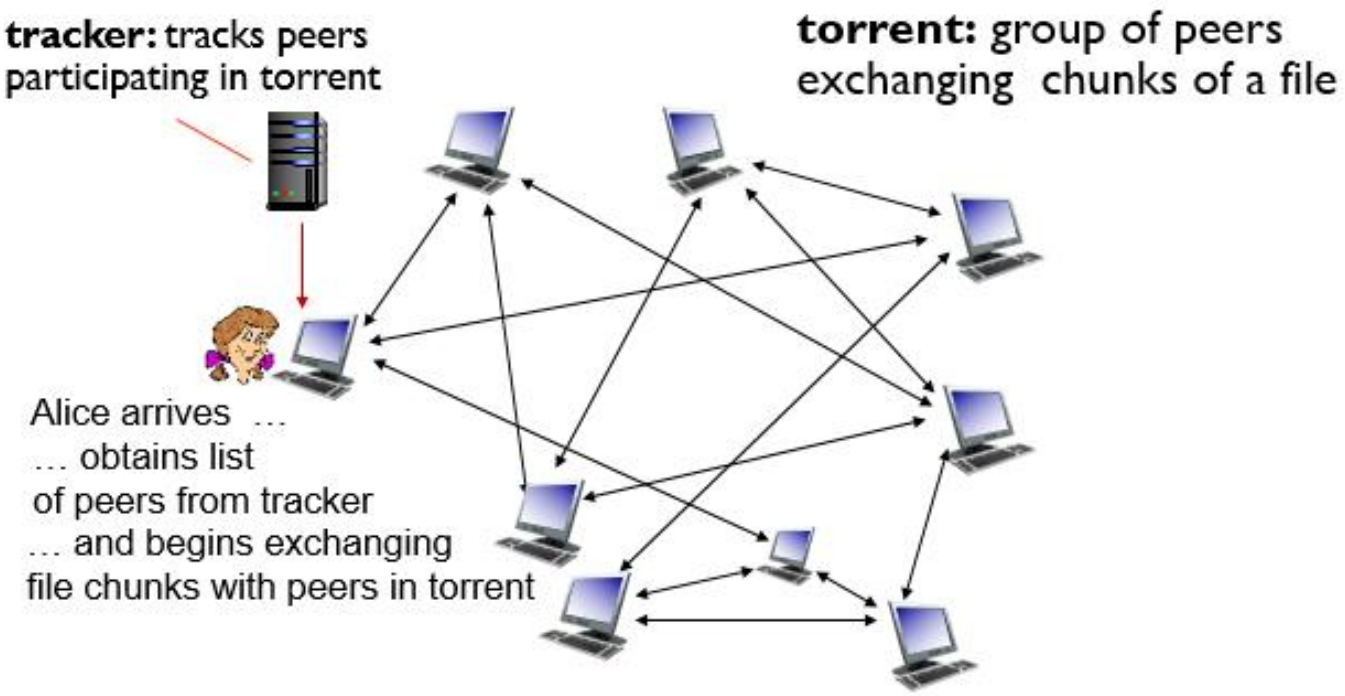
Client-Server vs P2P: Example

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



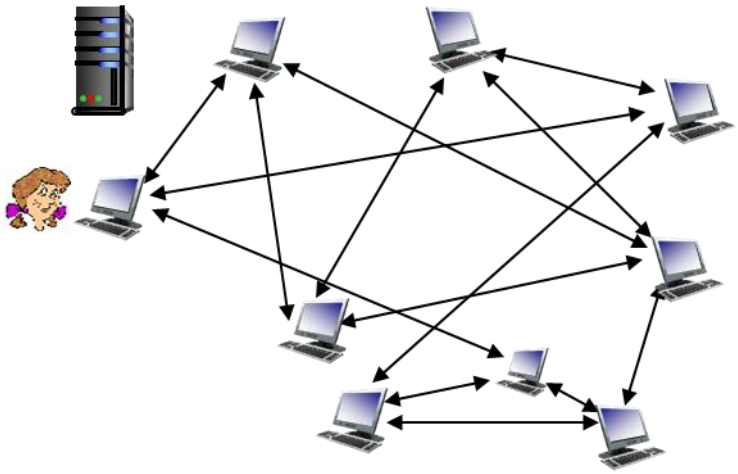
P2P File Distribution: BitTorrent (1 of 2)

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



P2P File Distribution: BitTorrent (2 of 2)

- 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

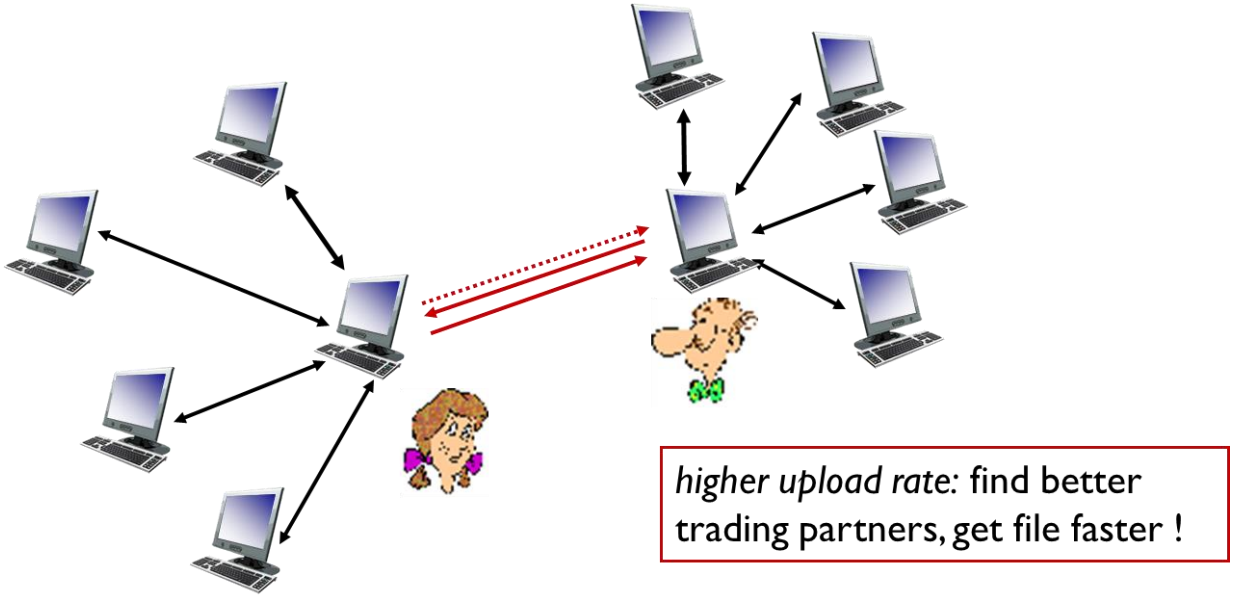
- Alice sends chunks to those four peers currently sending her chunks **at highest rate**
  - other peers are choked by Alice (do not receive chunks from her)
  - re-evaluate top 4 every10 secs
- every 30 secs: randomly select another peer, starts sending chunks
  - "optimistically unchoke" this peer
  - 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



Learning Objectives (6 of 7)

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)**

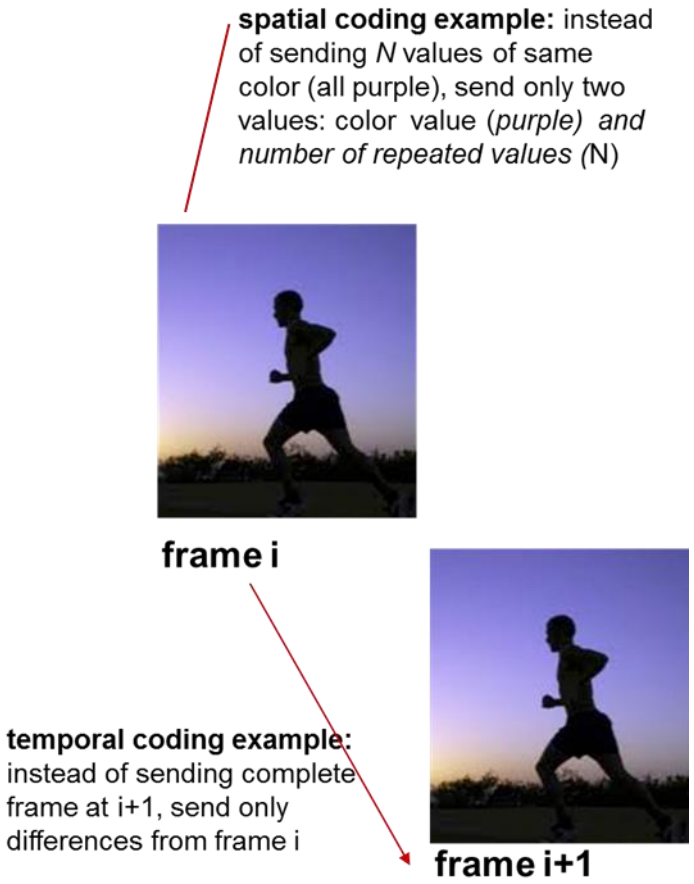
2.7 socket programming with UDP and TCP

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

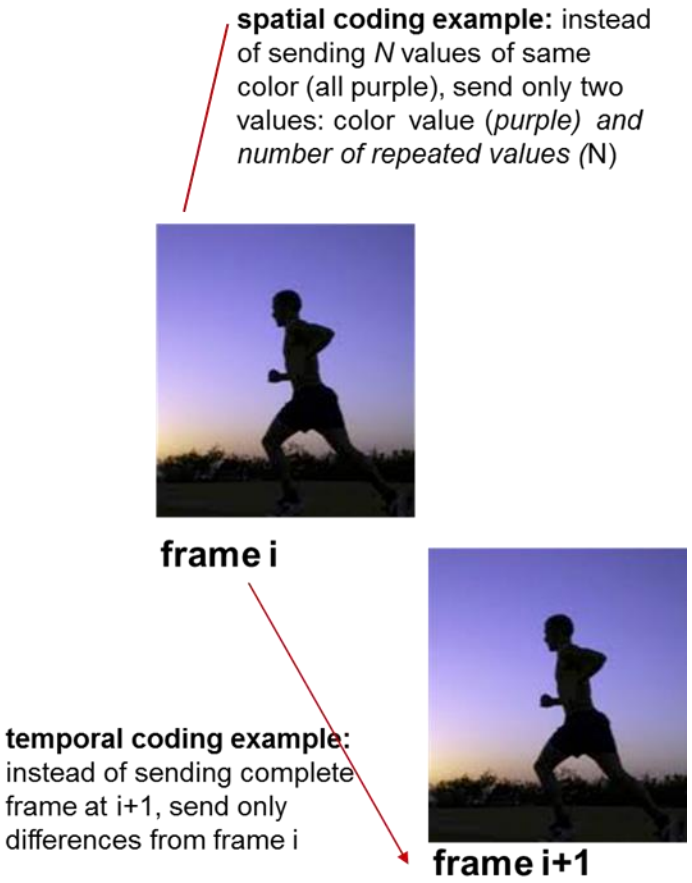
Multimedia: Video (1 of 2)

- 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)



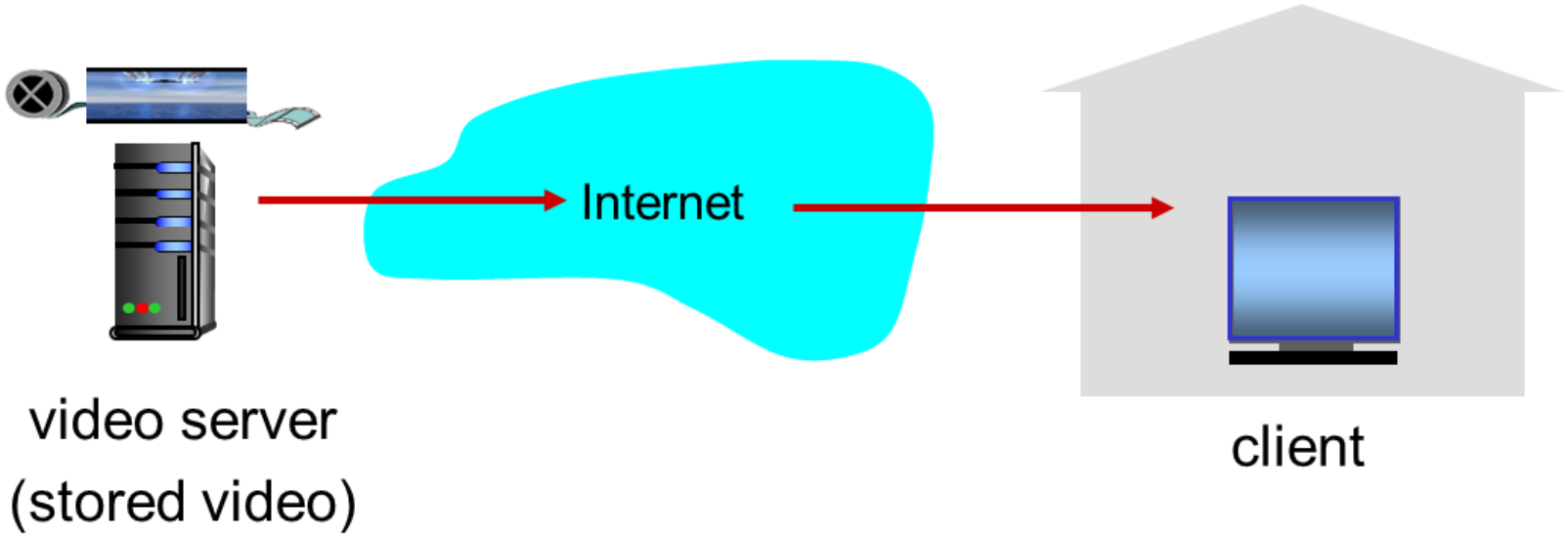
Multimedia: Video (2 of 2)

- **CBR: (constant bit rate):** video encoding rate fixed
- **VBR: (variable bit rate):** video encoding rate changes as amount of spatial, temporal coding changes
- **examples:**
  - MPEG1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, < 1 Mbps)



Streaming Stored Video

simple scenario:



Streaming Multimedia: DASH (1 of 2)

- **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 (2 of 2)

- **"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 (1 of 2)

- **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

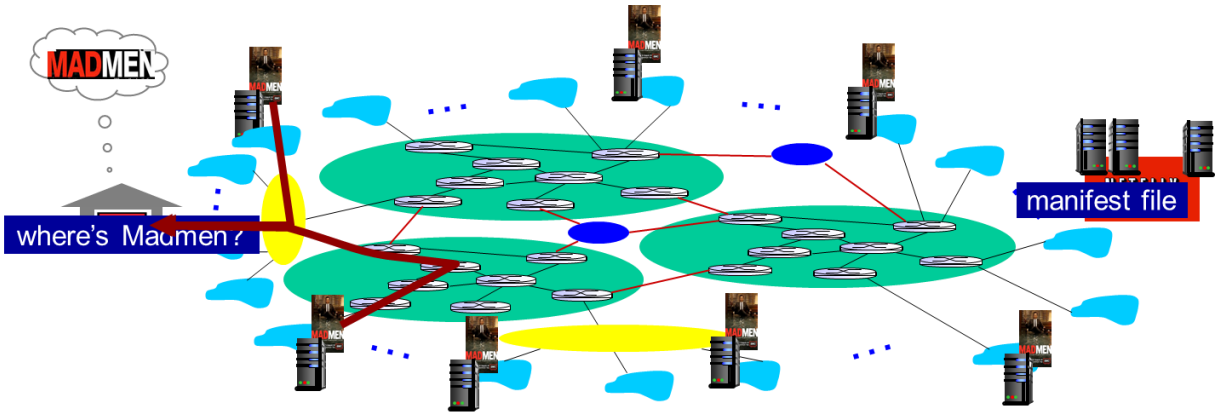
….quite simply: this solution **doesn't scale**

Content Distribution Networks (2 of 2)

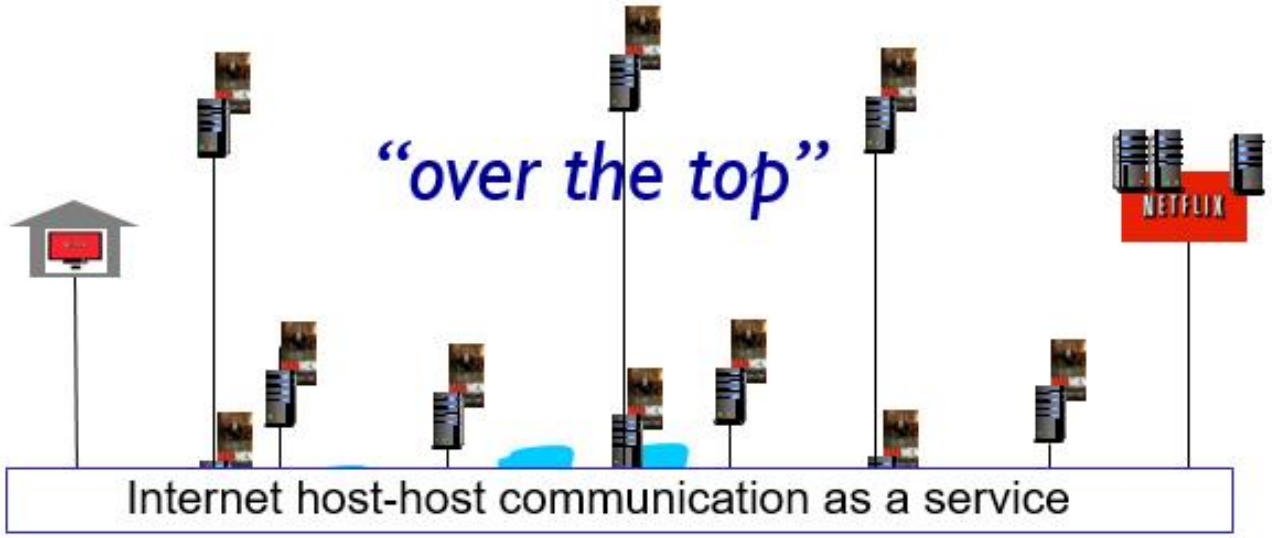
- **option 2:** store/serve multiple copies of videos at multiple geographically distributed sites **(CDN)**
  - **enter deep:** push CDN servers deep into many access networks
    - close to users
    - used by Akamai, 1700 locations
  - **bring home:** smaller number (10's) of larger clusters in POPs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

Content Distribution Networks (CDNs) (1 of 2)

- 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) (2 of 2)



OTT challenges: coping with a congested Internet

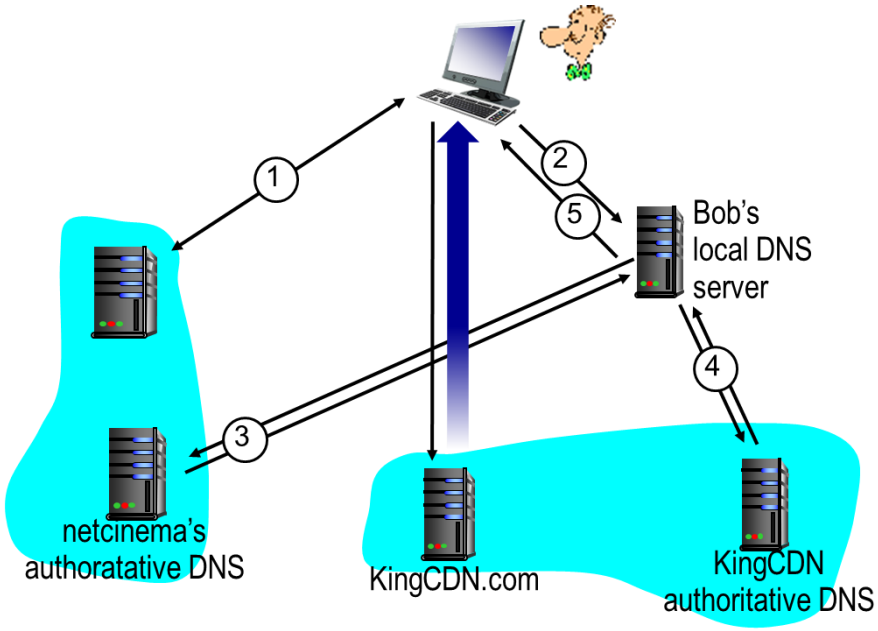
- from which CDN node to retrieve content?
- viewer behavior in presence of congestion?
- what content to place in which CDN node?

CDN Content Access: A Closer Look

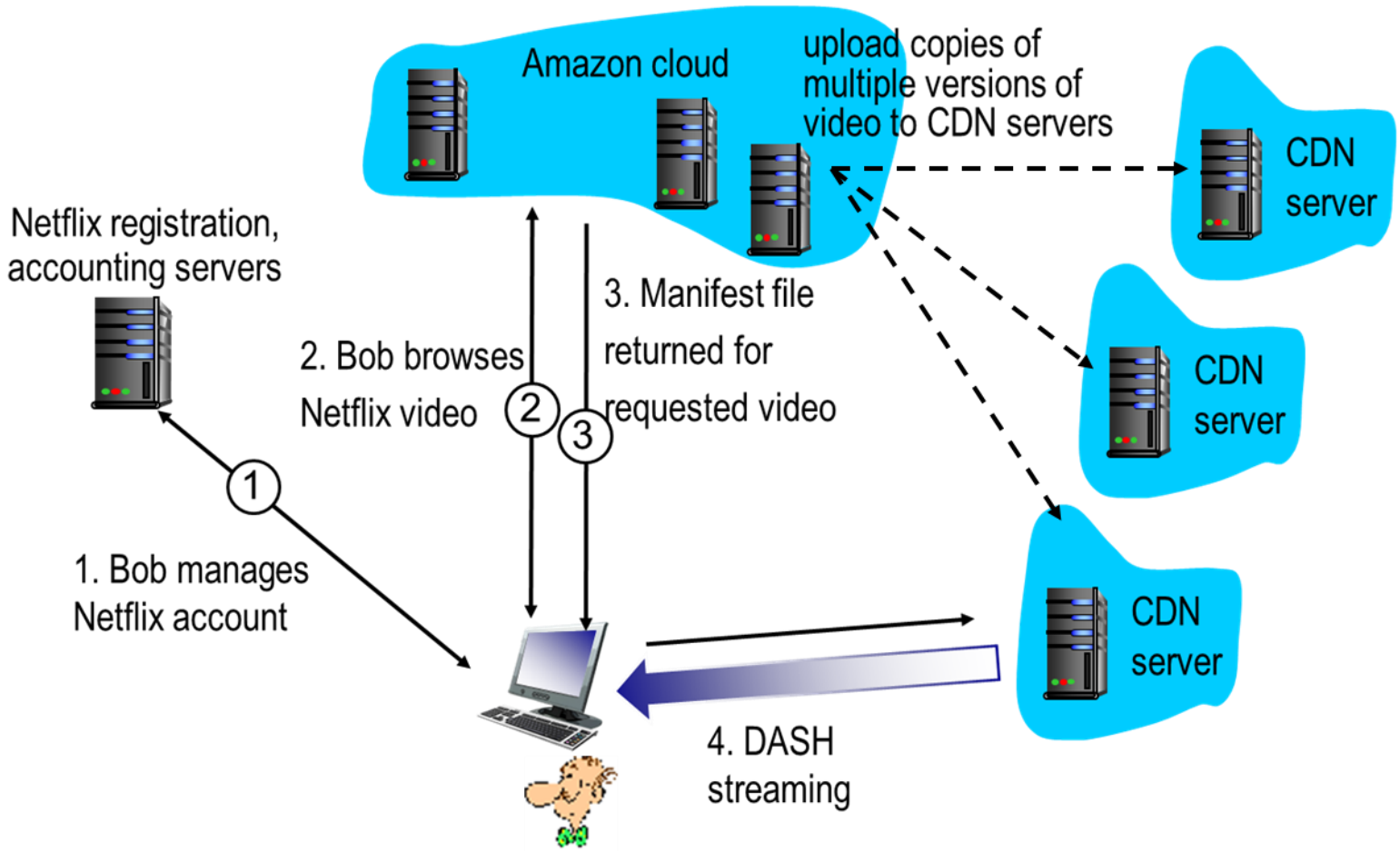
Bob (client) requests video http://netcinema.com/6Y7B23V

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

1. Bob gets URL for video http://netcinema.com/6Y7B23V from netcinema.com web page
2. resolve http://netcinema.com/6Y7B23V via Bob's local DNS
3. netcinema's DNS returns URL http://KingCDN.com/NetC6y&B23V
4&5. Resolve http://KingCDN.com/NetC6y&B23 via KingCDN's authoritative DNS, which returns IP address of KingCDN server with video



Case Study: Netflix



Learning Objectives (7 of 7)

2.1 Principles of network applications

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2.3 electronic mail

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2.4 DNS

2.5 P2P applications

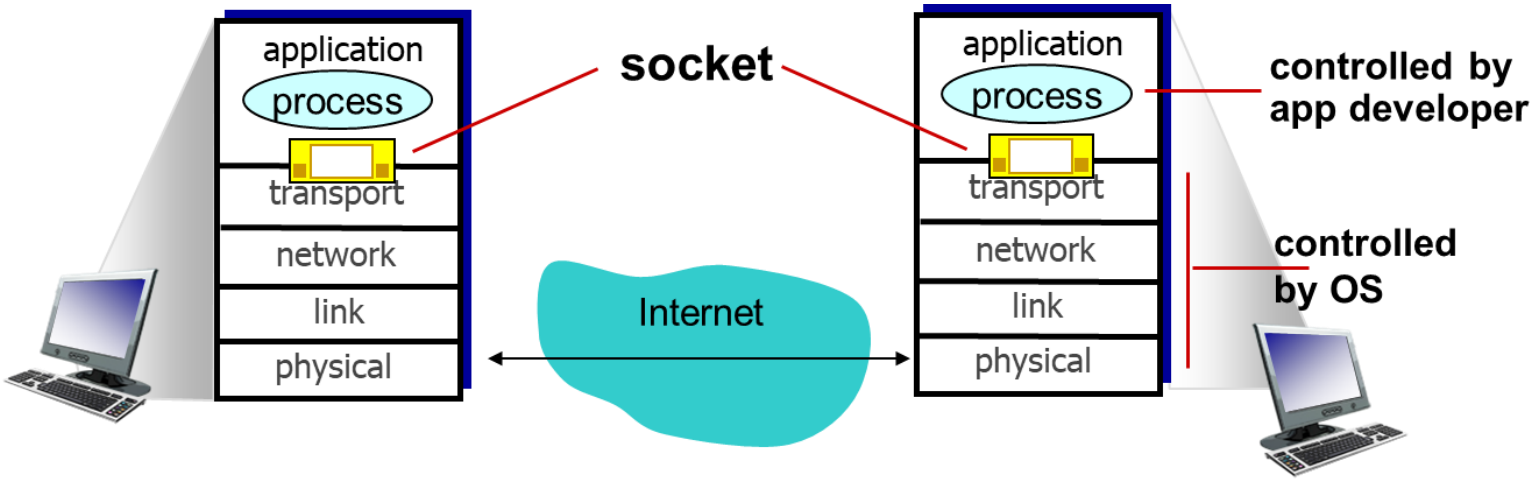
2.6 video streaming and content distribution networks

2.7 **socket programming with UDP and TCP**

Socket Programming (1 of 2)

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

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



Socket Programming (2 of 2)

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

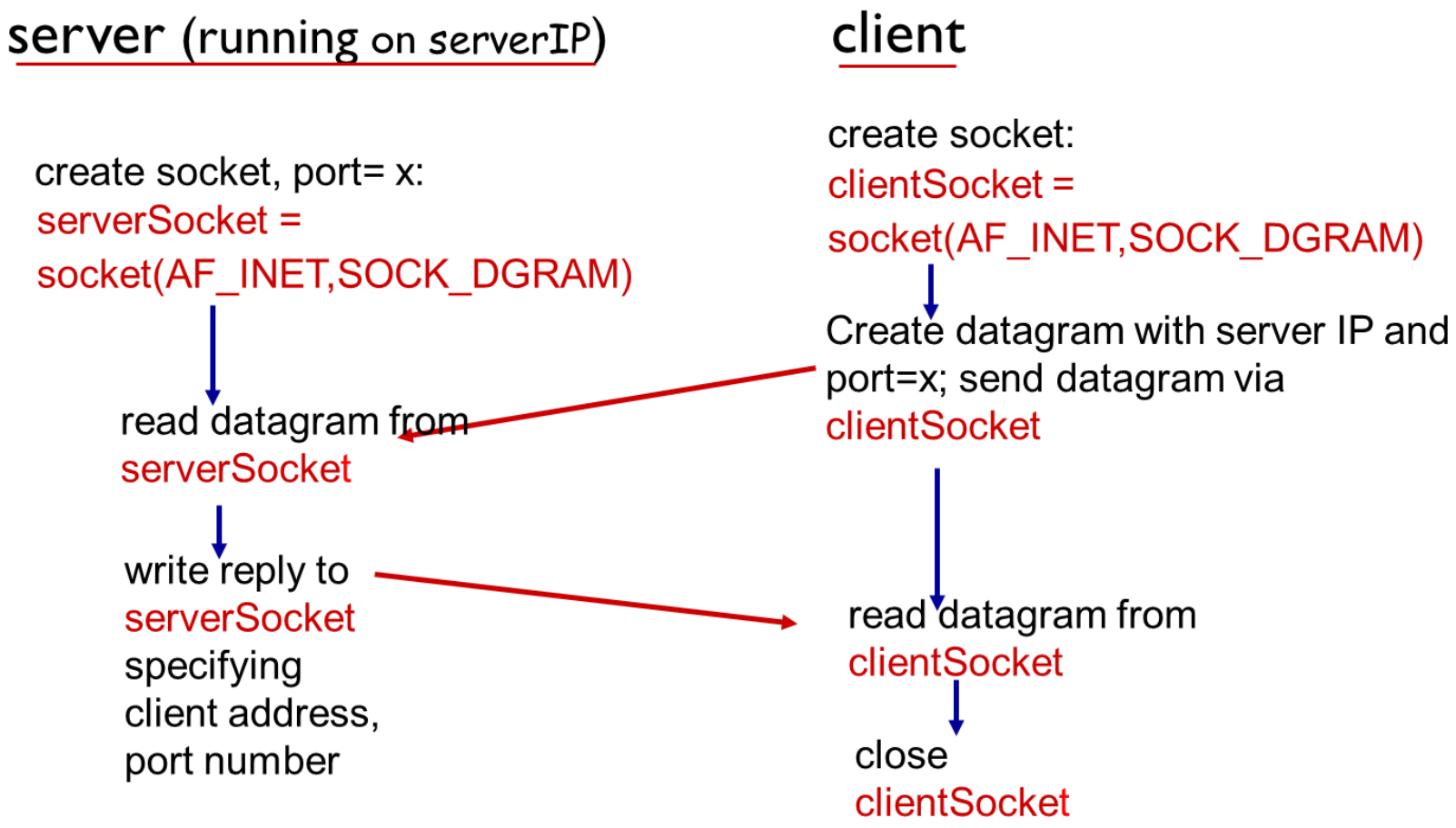
- no handshaking before sending data
- sender explicitly attaches IP destination address and port # to each packet
- receiver extracts sender IP address and port# from received packet

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



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))
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
serverSocket = socket(AF_INET, SOCK_DGRAM)
serverSocket.bind(('', serverPort))
print ("The server is ready to receive")
while True:
    message, clientAddress = serverSocket.recvfrom(2048)
    modifiedMessage = message.decode().upper()
    serverSocket.sendto(modifiedMessage.encode(),
                        clientAddress)
```

create UDP socket

bind socket to local port number 12000

loop forever

Read from UDP socket into message, getting client's address (client IP and port)

send upper case string back to this client

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

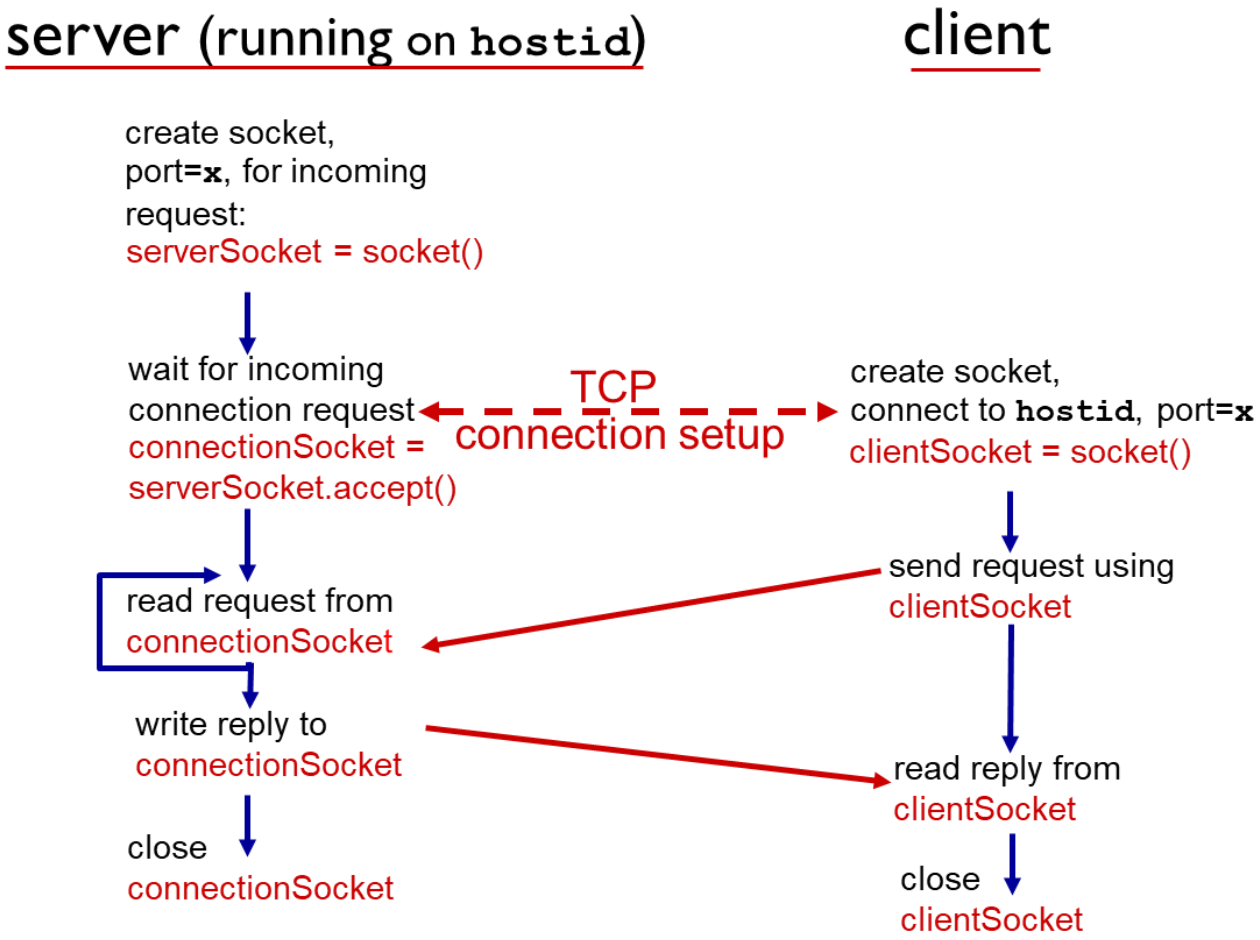
client contacts server by:

- 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



Example App: TCP Client

Python TCP Client

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

create TCP socket for server, remote port 12000

No need to attach server name, port

Example App: TCP Server

Python TCP Server

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind(('',serverPort))
serverSocket.listen(1)
print 'The server is ready to receive'
while True:
    connectionSocket, addr = serverSocket.accept()

    sentence = connectionSocket.recv(1024).decode()
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence.
                                        encode())
    connectionSocket.close()
```

create TCP welcoming socket

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)

Chapter 2: Summary (1 of 2)

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 (2 of 2)

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”

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