Networks (2IRR20)

Application Layer (02)

Dr. Tanir Ozcelebi

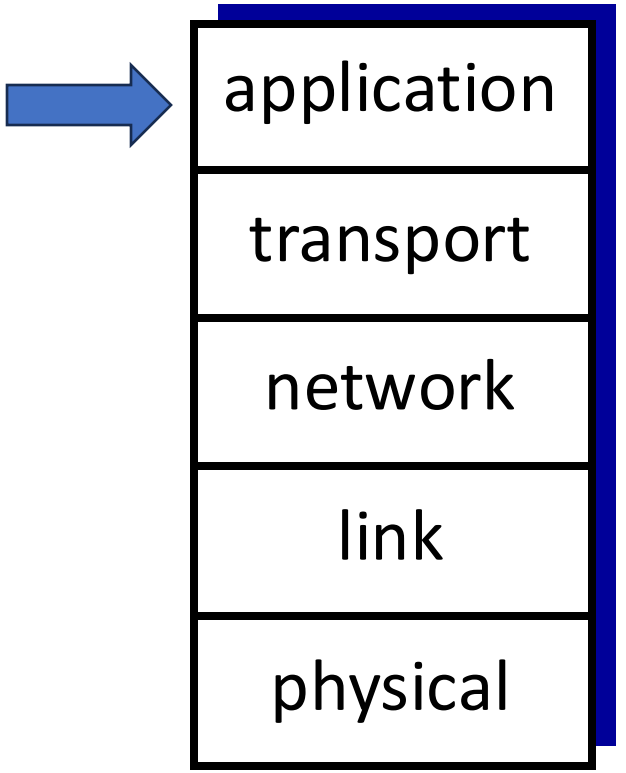
TU/e Computer Science

Interconnected Resource-aware Intelligent Systems (IRIS)

Slides adapted from the textbook:
Computer Networking: A Top-Down Approach
8th edition, Global Edition by Jim Kurose, Keith Ross

This slide set

- Principles of network applications
- Learn about protocols by examining application-layer protocols
  - HTTP
  - SMTP, IMAP
  - DNS
- P2P applications
- Video streaming and content distribution networks
- Socket programming with UDP and TCP



Some network apps

- e-mail
- World Wide Web
- instant messaging
- remote login
- file sharing
- online video games
- multimedia streaming
- voice calls
- interactive video conferencing
- cryptocurrencies

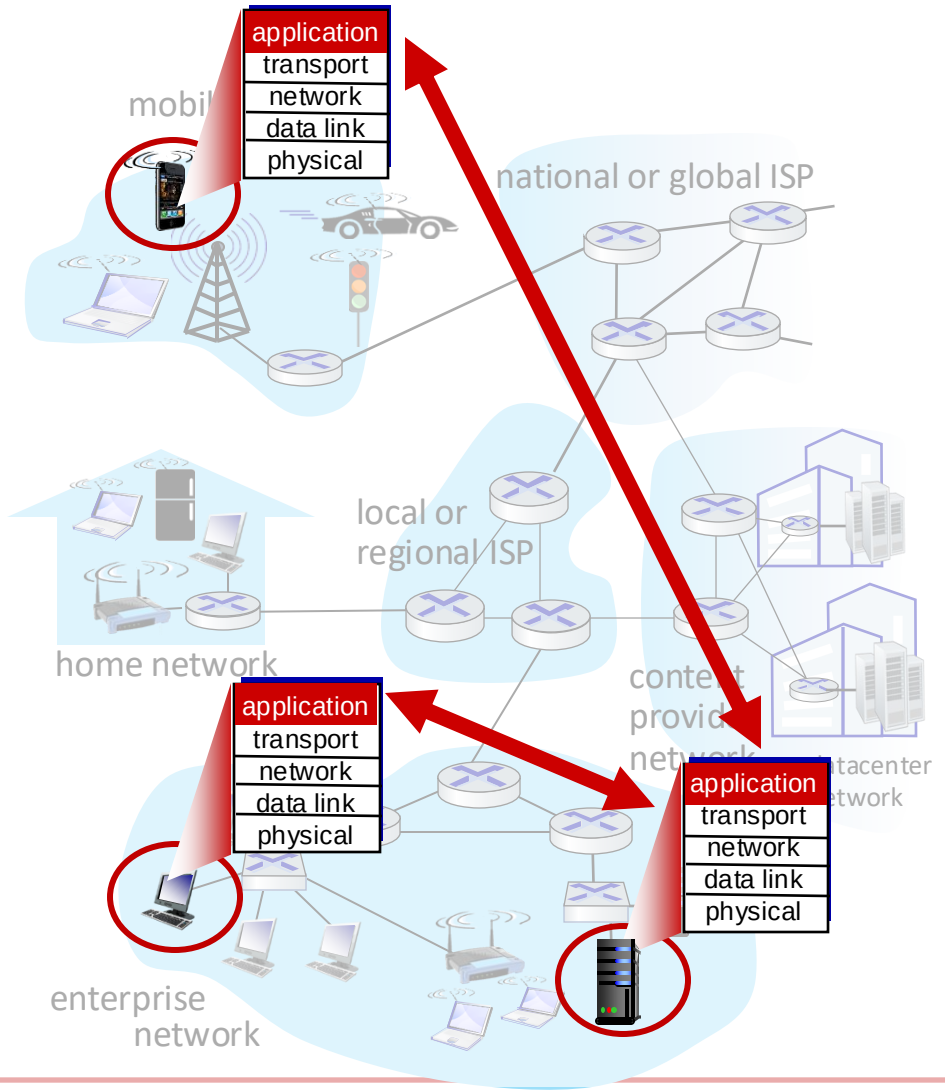
Creating a network application

Typical developer (e.g., for iOS) writes programs:

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

Network-core devices do not run such user applications

- However, they may run other (non-user) applications
  for debugging, experimenting, testing etc.



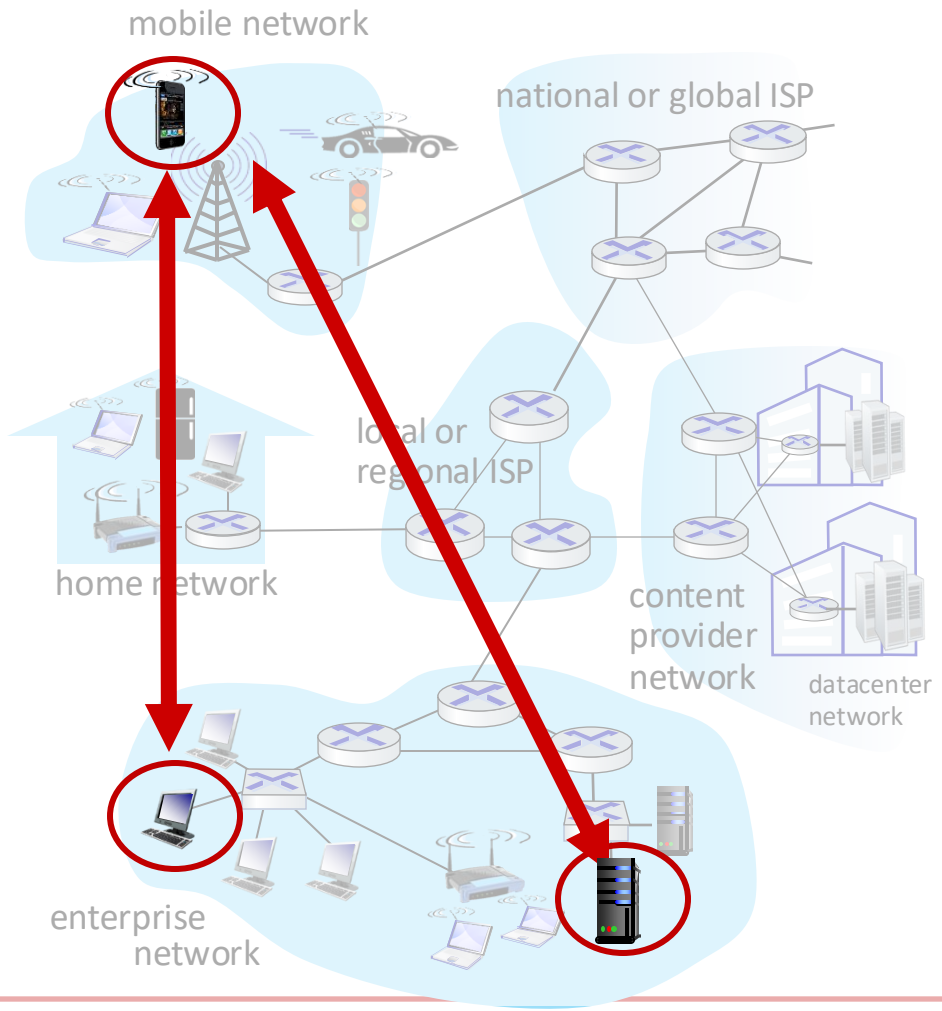
Client-server paradigm

Servers:

- always-on host
- permanent IP address

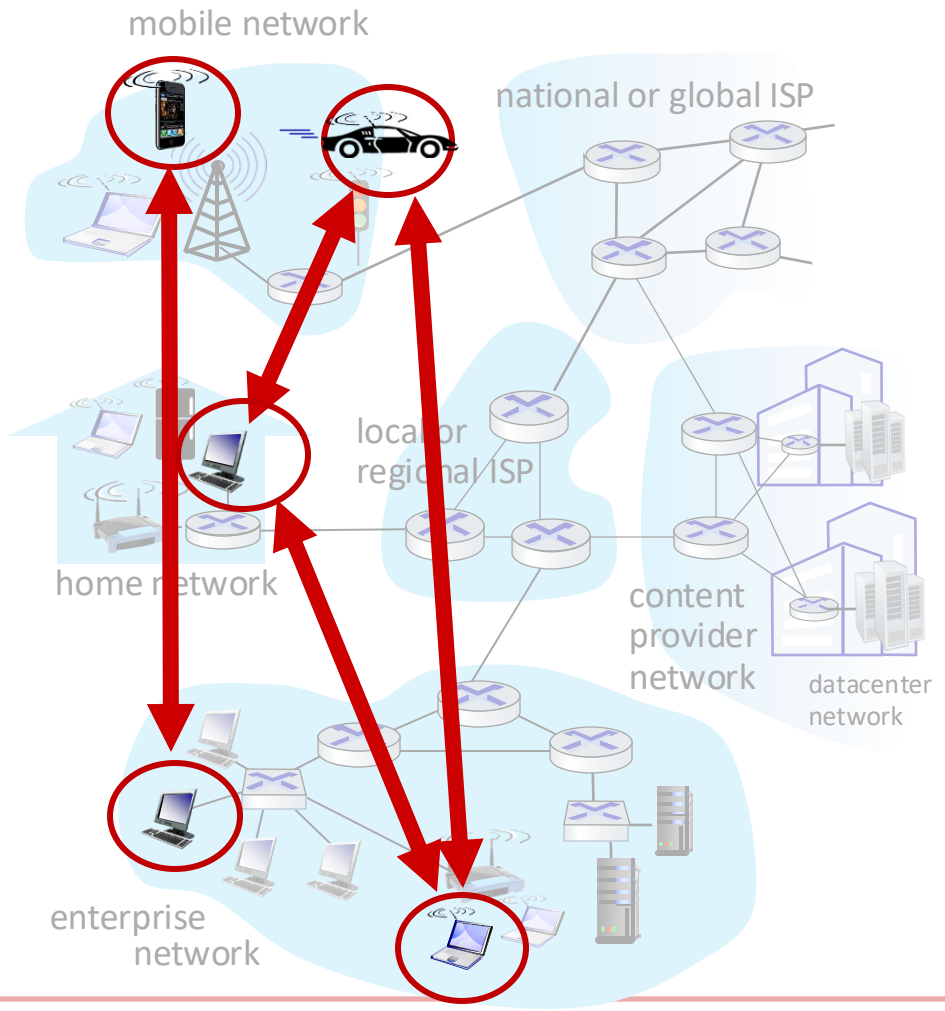
Clients:

- initiate contact with server
- may be on/off (connected from time to time)
- may have dynamic IP addresses
- do *not* communicate directly with each other



Pure peer-to-peer (P2P) architecture

- *No* always-on server in P2P
- Arbitrary end systems (peers) directly communicate
- Peers
  - may be on/off (connected from time to time)
  - may have dynamic IP addresses
- Highly scalable but difficult to manage!
  - *self scalability* – new peers bring new service capacity, as well as new service demands



Processes communicating

Process: a program in execution.

- Within the 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.

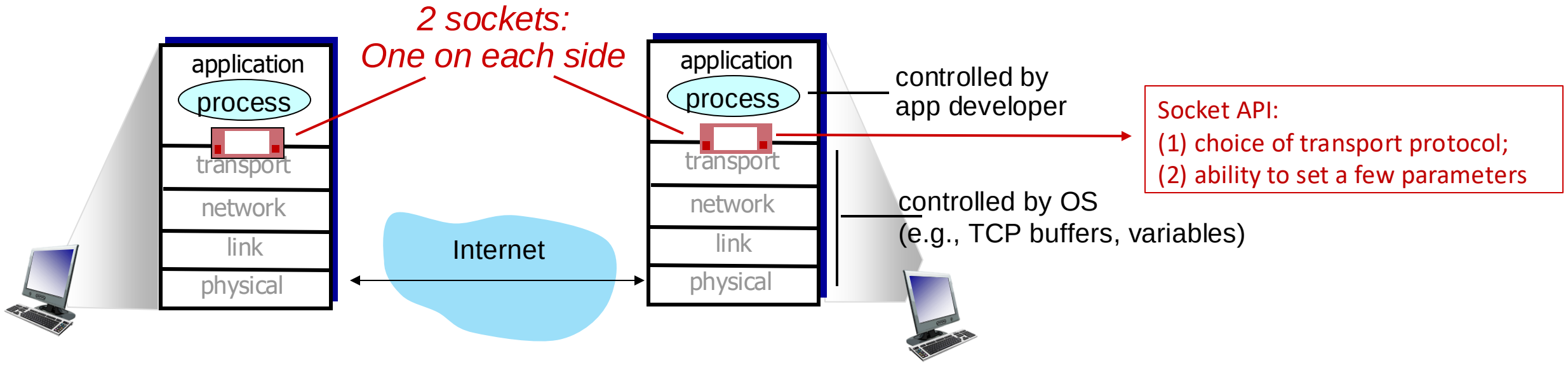
server process: process that waits to be contacted.

- **Note:** Even applications with P2P architectures have client processes & server processes.

Network sockets

- A process sends/receives messages through its sockets.
  - **Socket:** a data structure for maintaining connection data.

- It is like a door to the process.
  - sending process shoves message out the door and relies on transport infrastructure on other side of door to deliver message to the socket at receiving process.



Addressing processes

- To receive messages, process (or its door: the socket) must have an *identifier.*
- Host has unique 32-bit IP address (128-bit in IPv6)
  - In a way, IP address is the identifier for the host (network interface). But there may be many processes running on a host. So this is not enough to identify the process.
- *Process 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 formatted
- message semantics
  - meaning of info in fields
- rules for when and how processes send / respond to messages

open protocols:

- defined in IETF RFCs, everyone has access
  - RFC: Request for Comments
    e.g. RFC 2616 for HTTP
    e.g. RFC 2821 for SMTP
- allows for interoperability
- e.g., HTTP, SMTP

proprietary protocols:

- e.g., Skype, Facetime

What transport service may an app need?

reliable data transfer

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

throughput

- some apps (e.g., multimedia) require minimum amount of throughput to be “effective”

timing

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

security

- encryption, data integrity, …

Transport service requirements: common apps

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

Internet transport protocols services

TCP service:

- *reliable transport* between sending and receiving process
- *flow control:* sender won't overwhelm receiver
- *congestion control:* throttle sender when network overloaded
- *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 transport protocols services

application	application layer protocol	transport protocol
file transfer/download	FTP [RFC 959]	TCP
e-mail	SMTP [RFC 5321]	TCP
Web documents	HTTP 1.1 [RFC 7320]	TCP
Internet telephony	SIP [RFC 3261], RTP [RFC 3550], or proprietary	TCP or UDP
streaming audio/video	HTTP [RFC 7320], DASH	TCP
interactive games	WOW, FPS (proprietary)	UDP or TCP

Web and HTTP

Web and HTTP

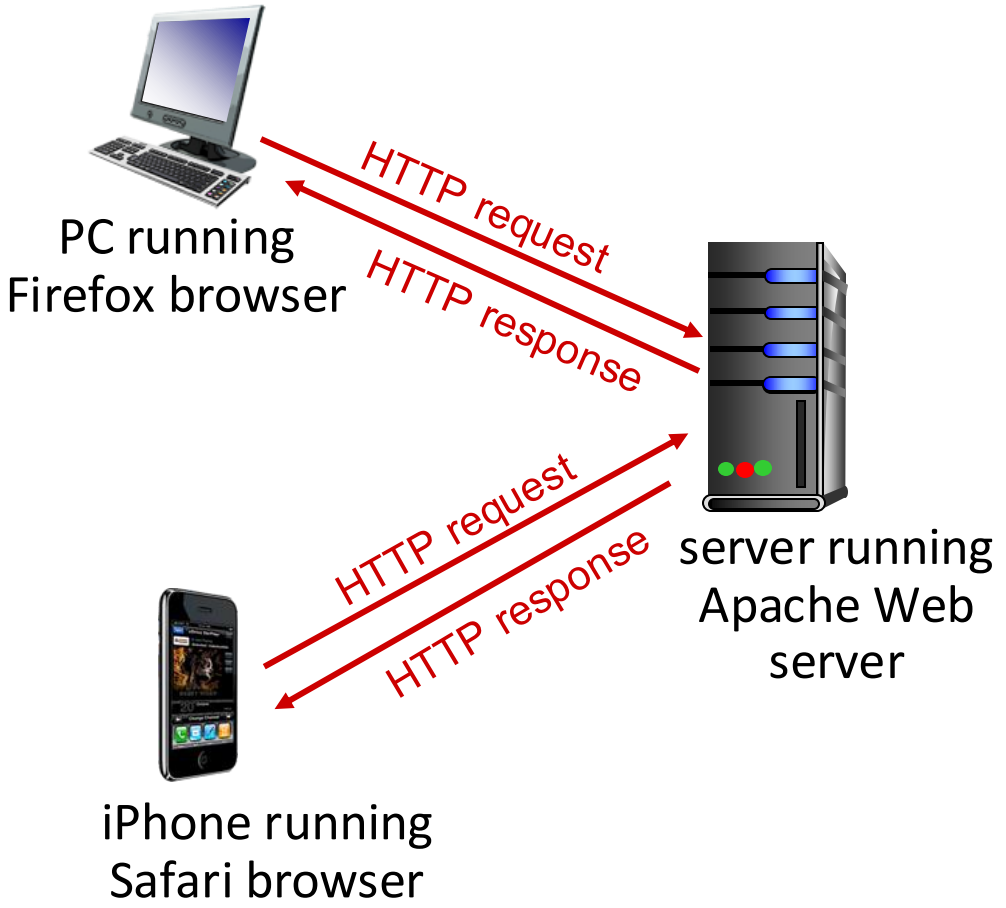
- Web page consists of *objects,* each of which can be stored on different Web servers.
- Object can be HTML file, JPEG image, audio file,…
- web page consists of *base HTML-file* which includes *several referenced objects, each* addressable by a *URL,* e.g.,

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

host name | path name

HTTP: 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 (continued)

HTTP uses TCP:

- Client initiates TCP connection (creates socket) to server, port 80.
- Server accepts TCP connection from client.
- HTTP messages exchanged between browser (HTTP client) and Web server (HTTP server).
- TCP connection is closed.

HTTP is "stateless"

- Server maintains *no* info. 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 (HTTP1.0):

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

[So downloading multiple objects requires multiple TCP connections.]

Persistent HTTP (HTTP1.1):

1. TCP connection opened.
2. Multiple objects (can be) sent over TCP connection.
3. 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)

4. HTTP server closes TCP connection.

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

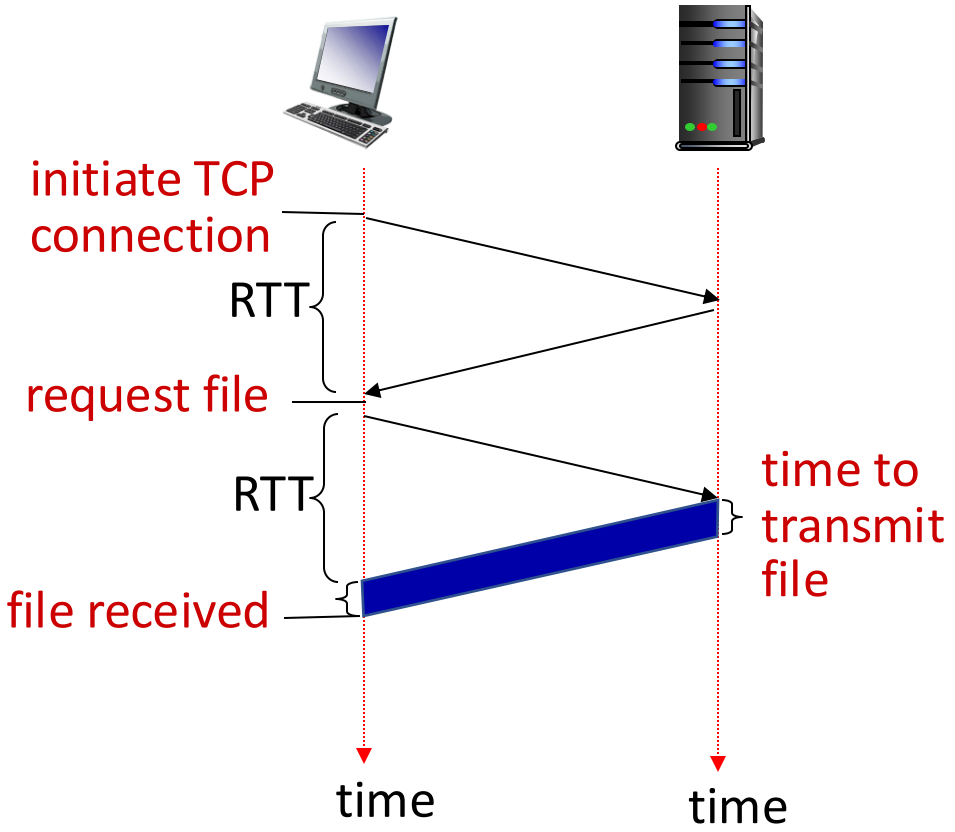
time

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
- obect/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)

HTTP request message

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

request line (GET, POST, HEAD commands)

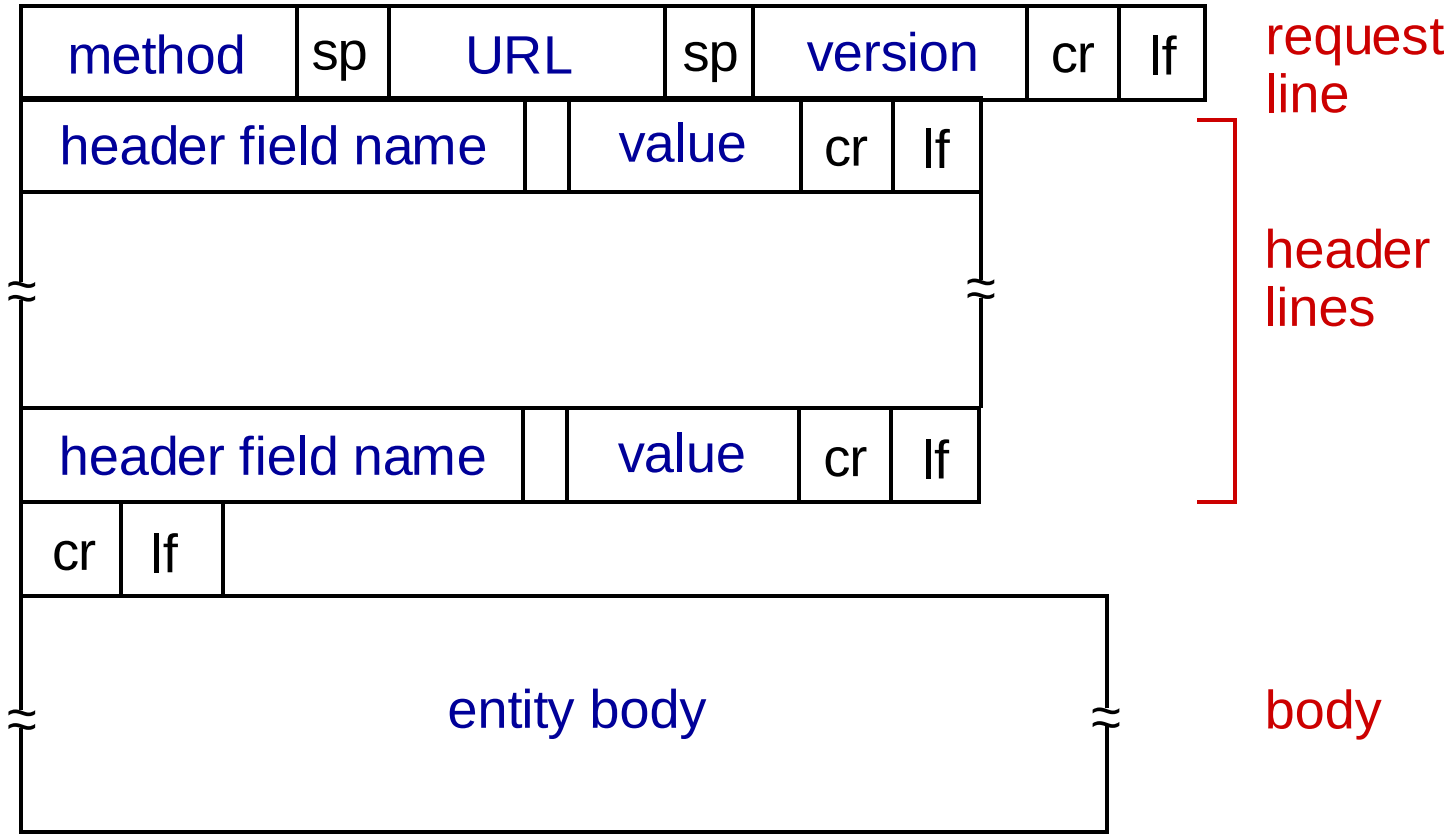
header lines

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

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

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

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
```

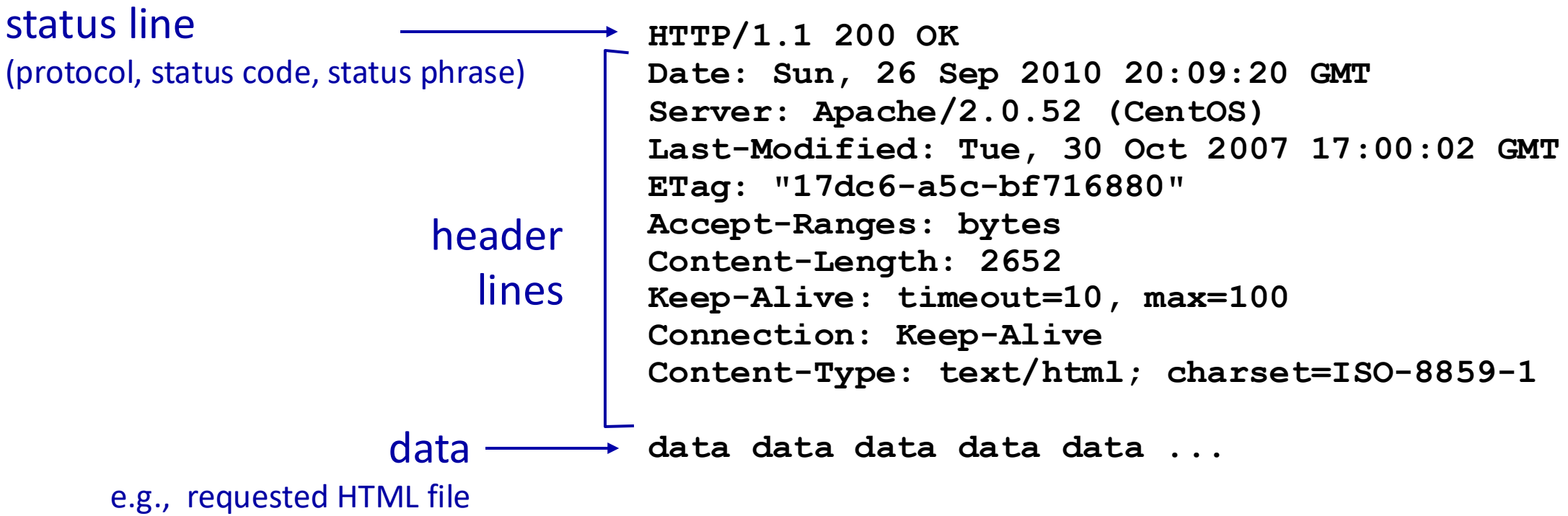
HEAD method:

- 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 HTTP request message

HTTP response message



* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

HTTP response status codes

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

200 OK
- request succeeded, requested object later in this message

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

400 Bad Request
- request msg not understood by server

404 Not Found
- requested document not found on this server

505 HTTP Version Not Supported

Trying out HTTP (client side) for yourself

1. Telnet to your favorite Web server on Command Prompt:

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

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

2. type in a GET HTTP request:

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

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

3. look at response message sent by HTTP server!

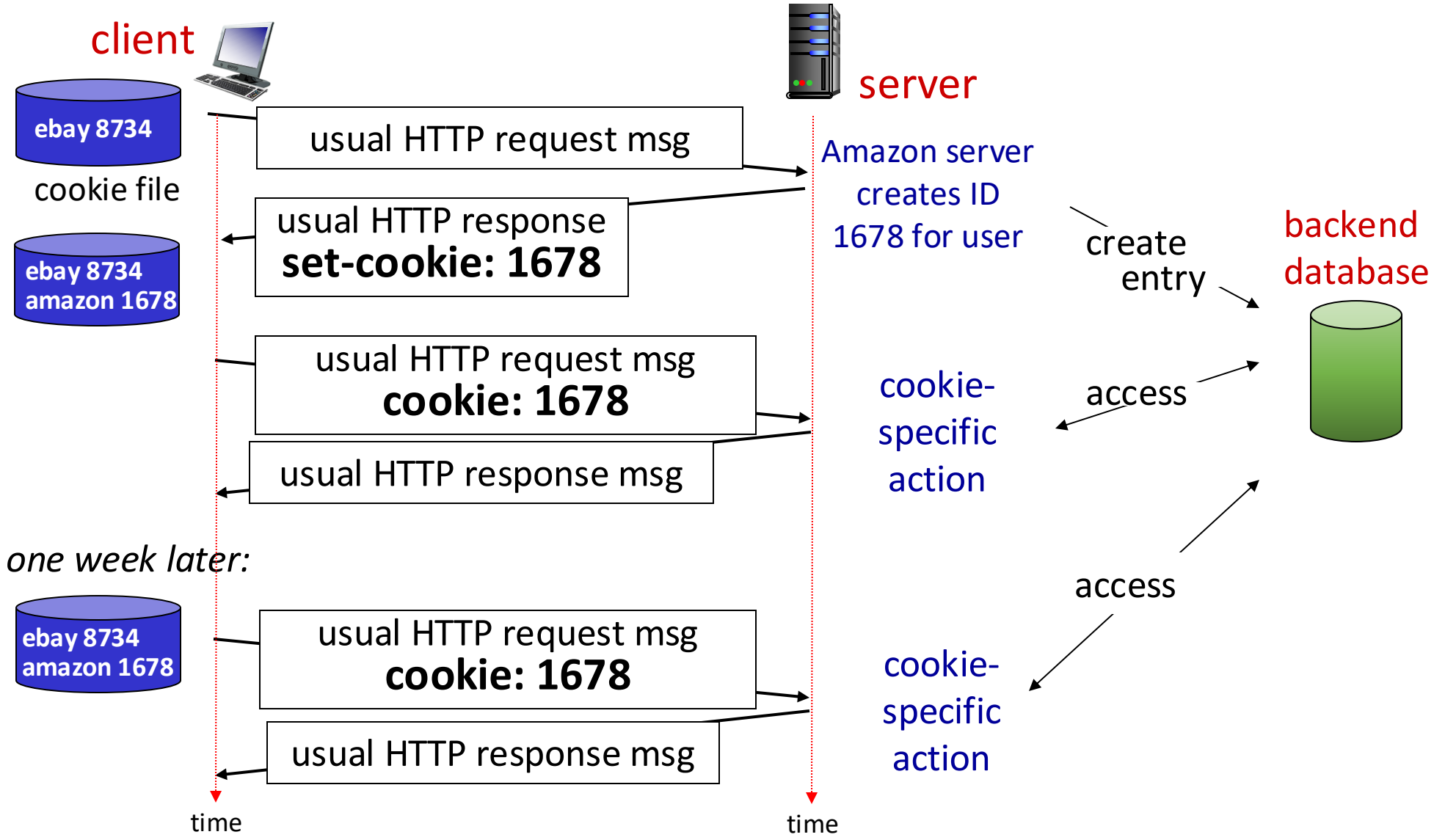
Maintaining user/server state: cookies

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

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:

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

aside

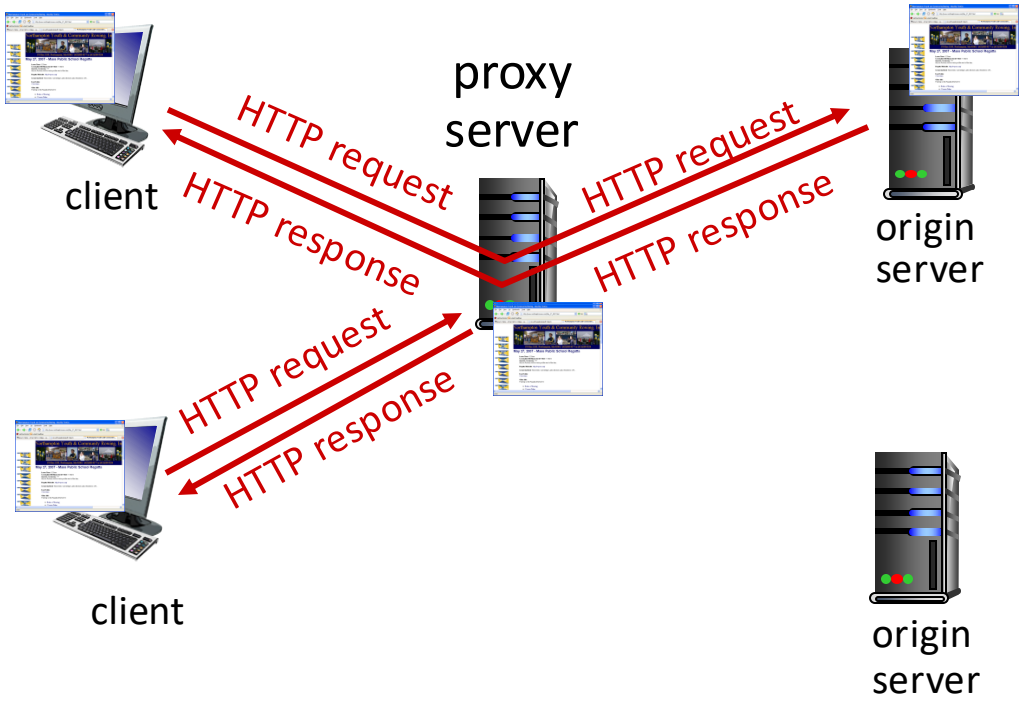
cookies and privacy:

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

Web caches (proxy servers)

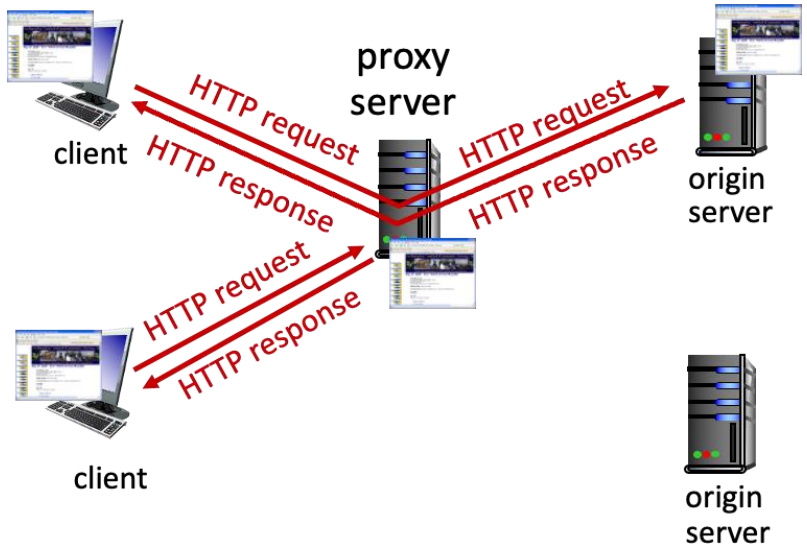
Goal: satisfy client request without involving origin server

- User configures browser to point to a *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 act as both client and server

Why Web caching?



- Reduced response time for client request.
  - Cache acts as a server that is closer to client.
- Reduced traffic on an institution's access link.
- Internet is dense with caches
  - enables "poor" content providers to more effectively deliver content

Caching example

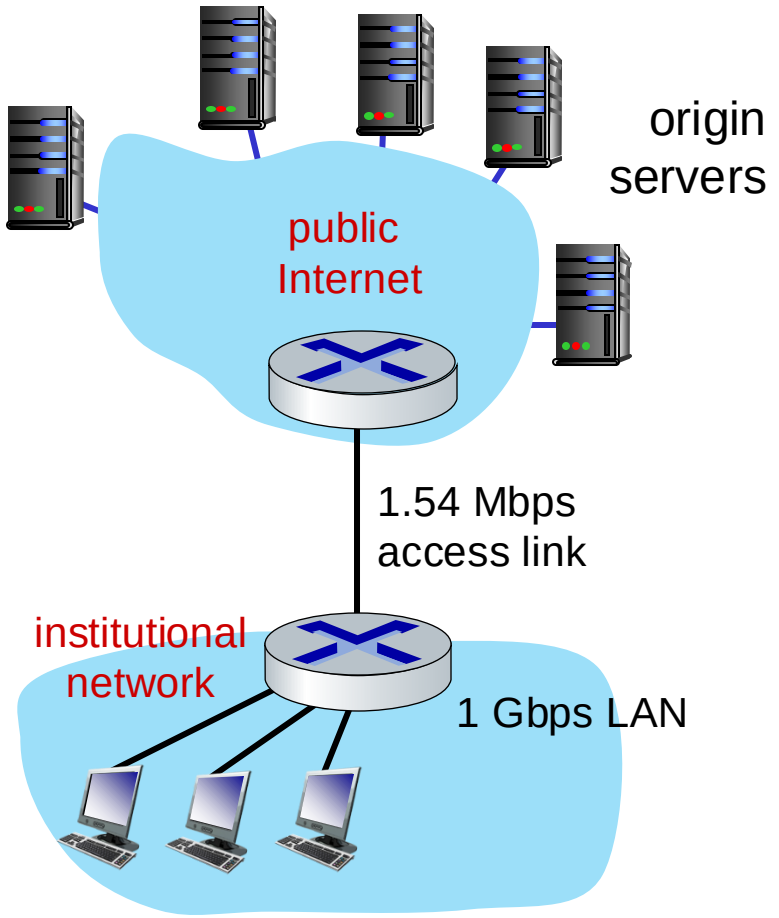
Scenario:

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

Performance:

- LAN utilization: 0.0015
- access link utilization = 0.97
- end-end delay = Internet delay + access link delay + LAN delay
  = 2 sec + minutes + usecs

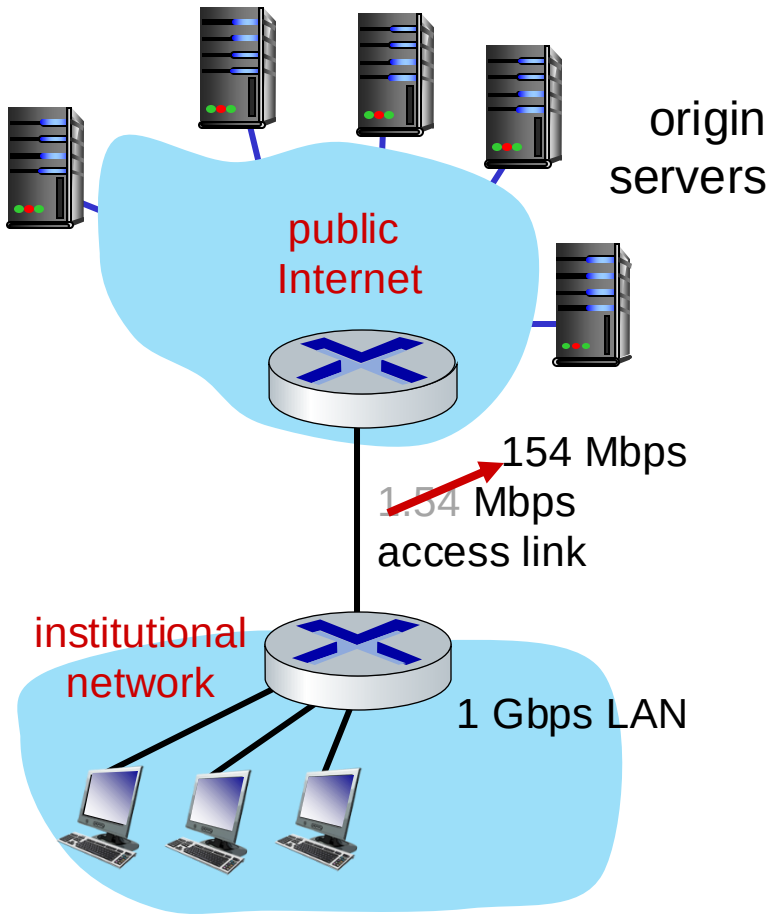
problem: large delays at high utilization!



A solution: buy a faster access link

Scenario:

- access link rate: ~~1.54~~ 154 Mbps
- RTT from institutional router to server: 2 sec
- Web object size: 100K bits
- Avg request rate from browsers to origin servers: 15/sec
  - avg data rate to browsers: 1.50 Mbps



Performance:

- LAN utilization: 0.0015
- access link utilization = ~~0.97~~ 0.0097
- end-end delay = Internet delay + access link delay + LAN delay
  = 2 sec + ~~minutes~~ + usecs

Cost: faster access link (expensive!) msecs

Cheaper solution: install a web cache

Scenario:

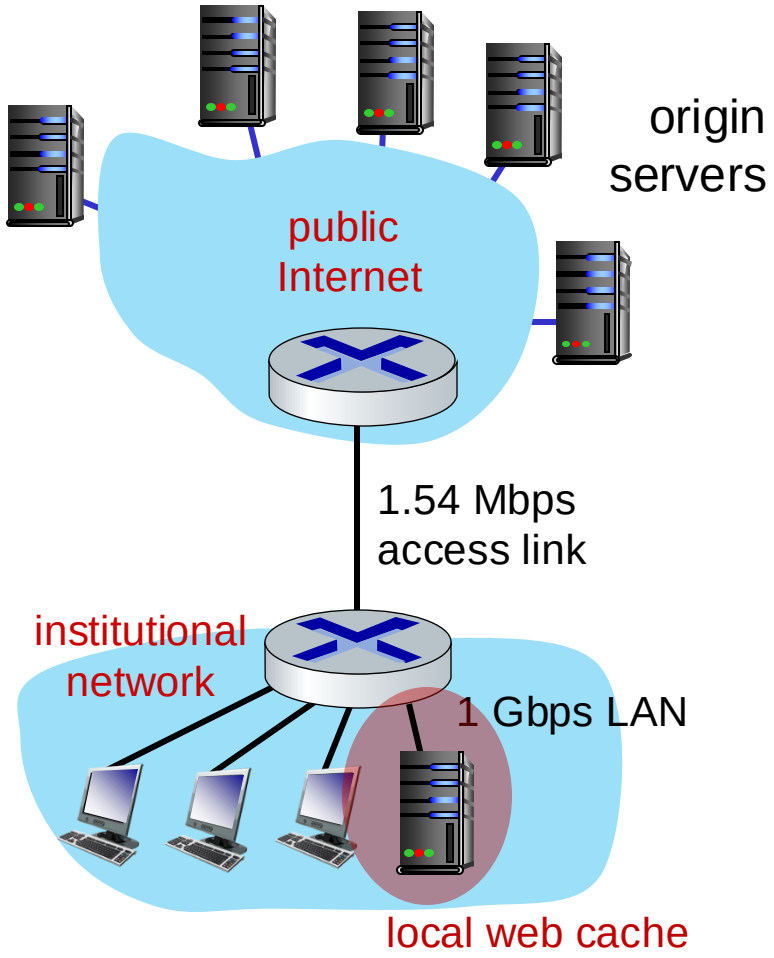
- access link rate: 1.54 Mbps
- RTT from institutional router to server: 2 sec
- Web object size: 100K bits
- Avg request rate from browsers to origin servers: 15/sec
  - avg data rate to browsers: 1.50 Mbps

Performance:

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

How to compute link utilization, delay?

Cost: web cache (cheap!)



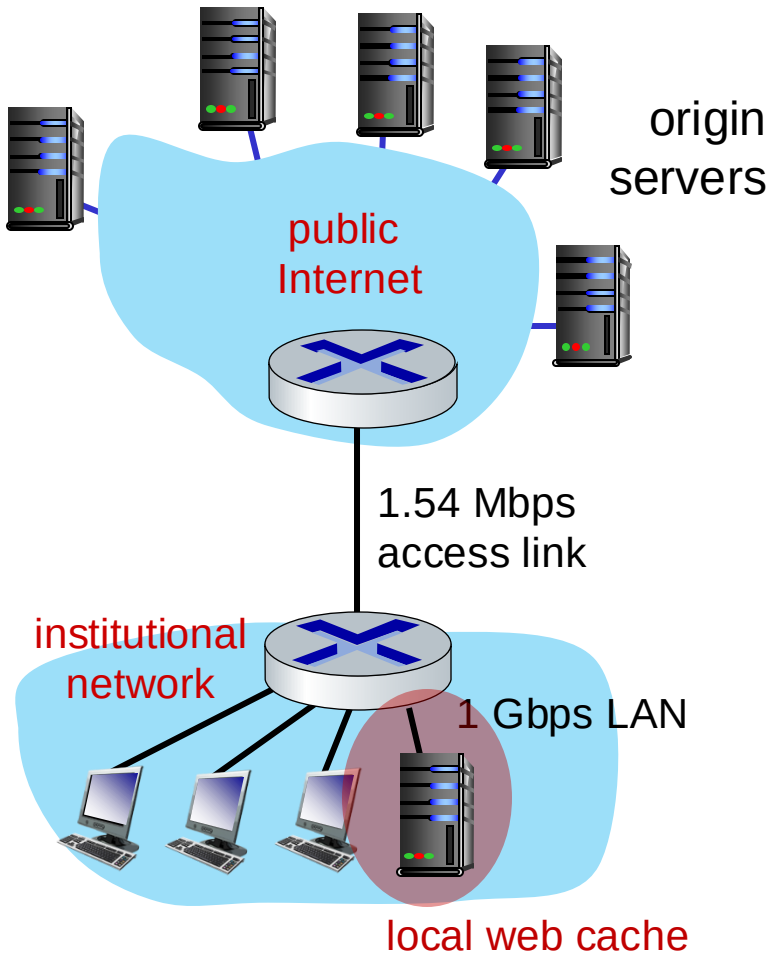
Caching example: install a web cache

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

- suppose **cache hit rate** is 0.4:
  - 40% requests satisfied at cache
  - 60% requests satisfied at origin (using access link)

- data rate to browsers over access link
  = 0.6 * 1.50 Mbps = 0.9 Mbps
  - So **access link utilization** = 0.9/1.54 = 0.58

- average end-end delay
  = 0.6 * (delay from origin servers)
  + 0.4 * (delay when satisfied at cache)
  = 0.6 (~2.01 secs) + 0.4 (~msecs) = ~ 1.2 secs



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

Conditional GET

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

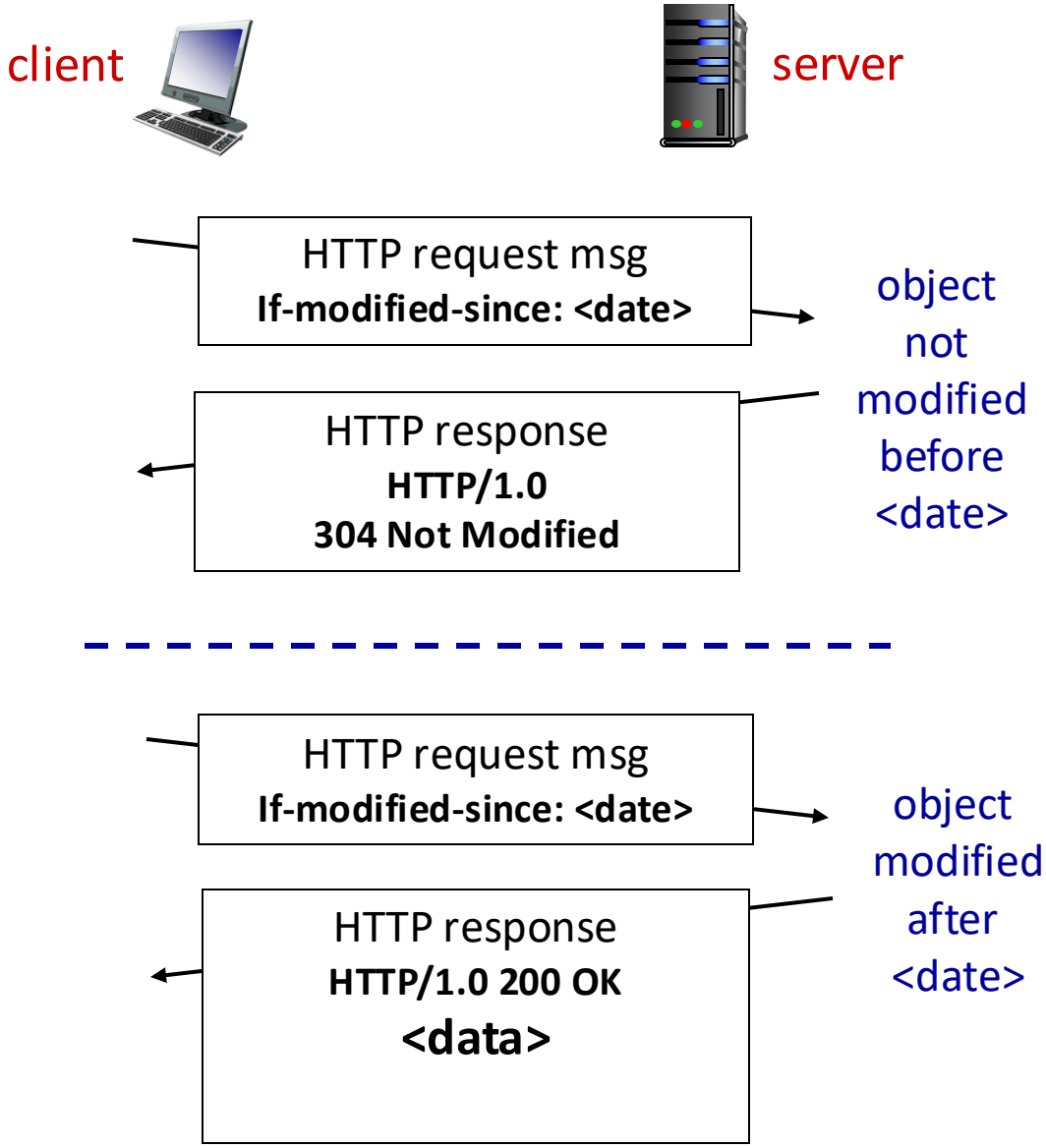
- no object transmission delay
- lower link utilization

- *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



HTTP/2 (RFC 9113)

Key goal: decreased delay in multi-object HTTP requests

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

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

HTTP/2 (RFC 9113)

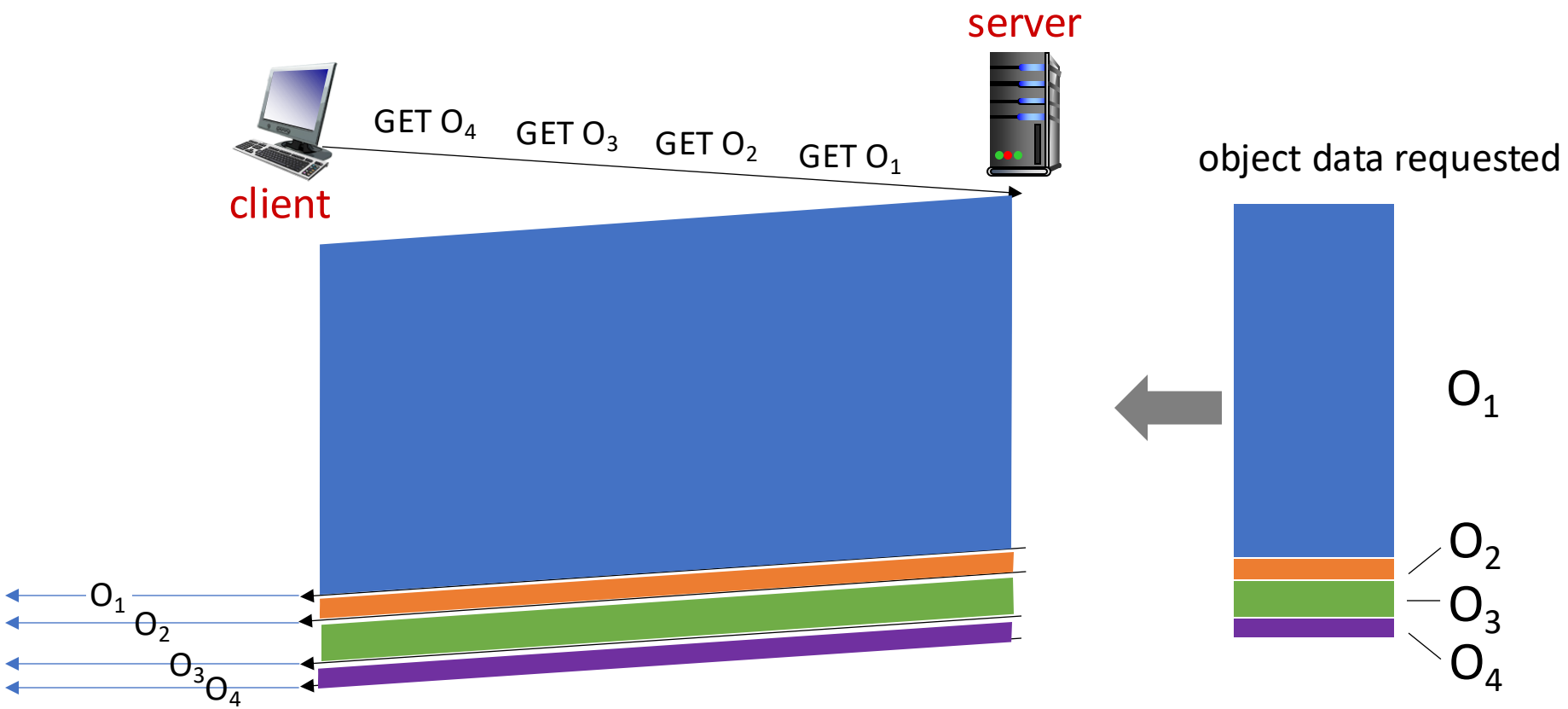
Key goal: decreased delay in multi-object HTTP requests

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

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

HTTP/2: mitigating HOL blocking

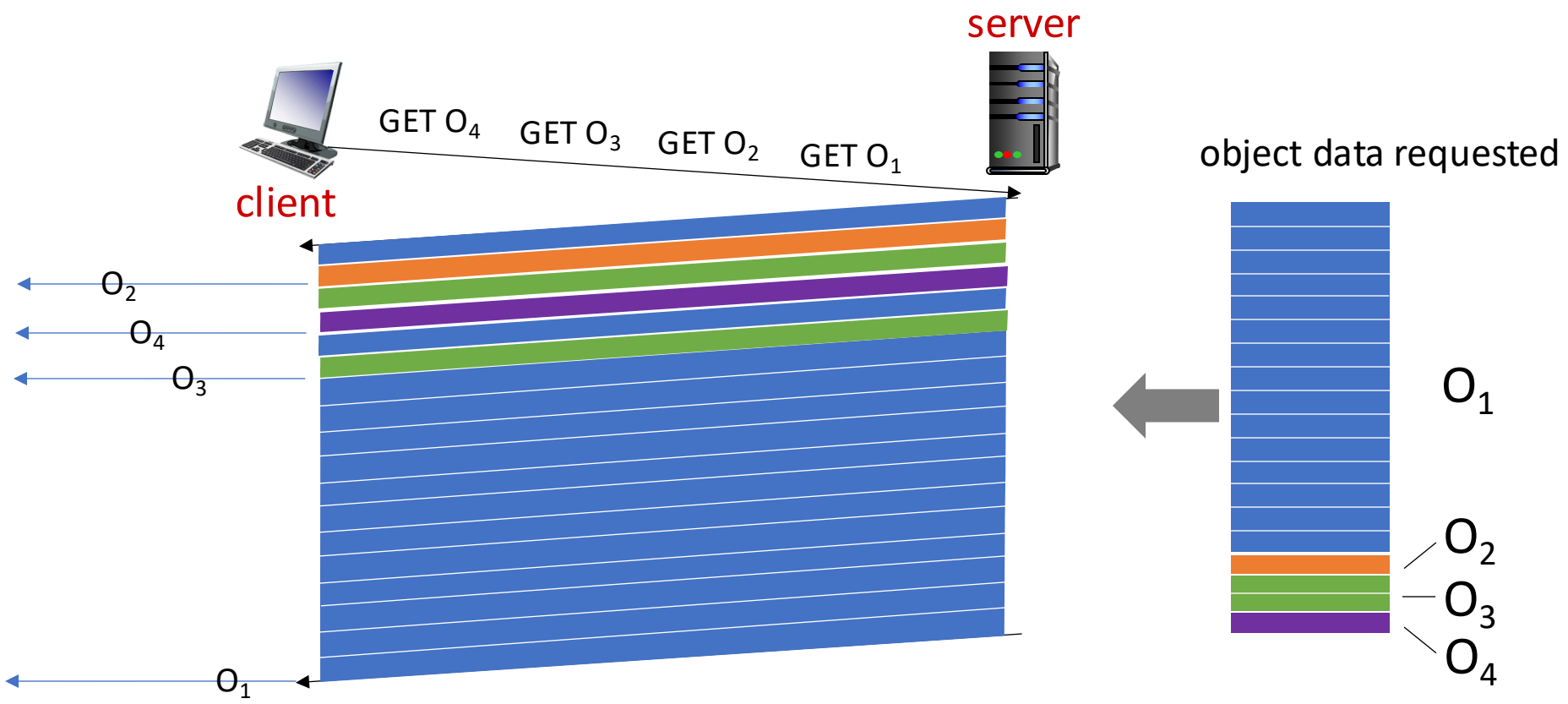
HTTP 1.1: client requests 1 large object (e.g., video file, and 3 smaller objects)



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

HTTP/2: mitigating HOL blocking

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



O_2, O_3, O_4 delivered quickly, O_1 slightly delayed

HTTP/2 to HTTP/3 (RFC 9114)

Key goal: decreased delay in multi-object HTTP requests

HTTP/2 over single TCP connection means:

- recovery from packet loss still stalls all object transmissions
  - as in HTTP 1.1, browsers have incentive to open multiple parallel TCP connections to reduce stalling, increase overall throughput
- no security over TCP connection

- HTTP/3: adds security, per object error-control and congestion-control (more pipelining) over UDP

E-mail, SMTP, IMAP

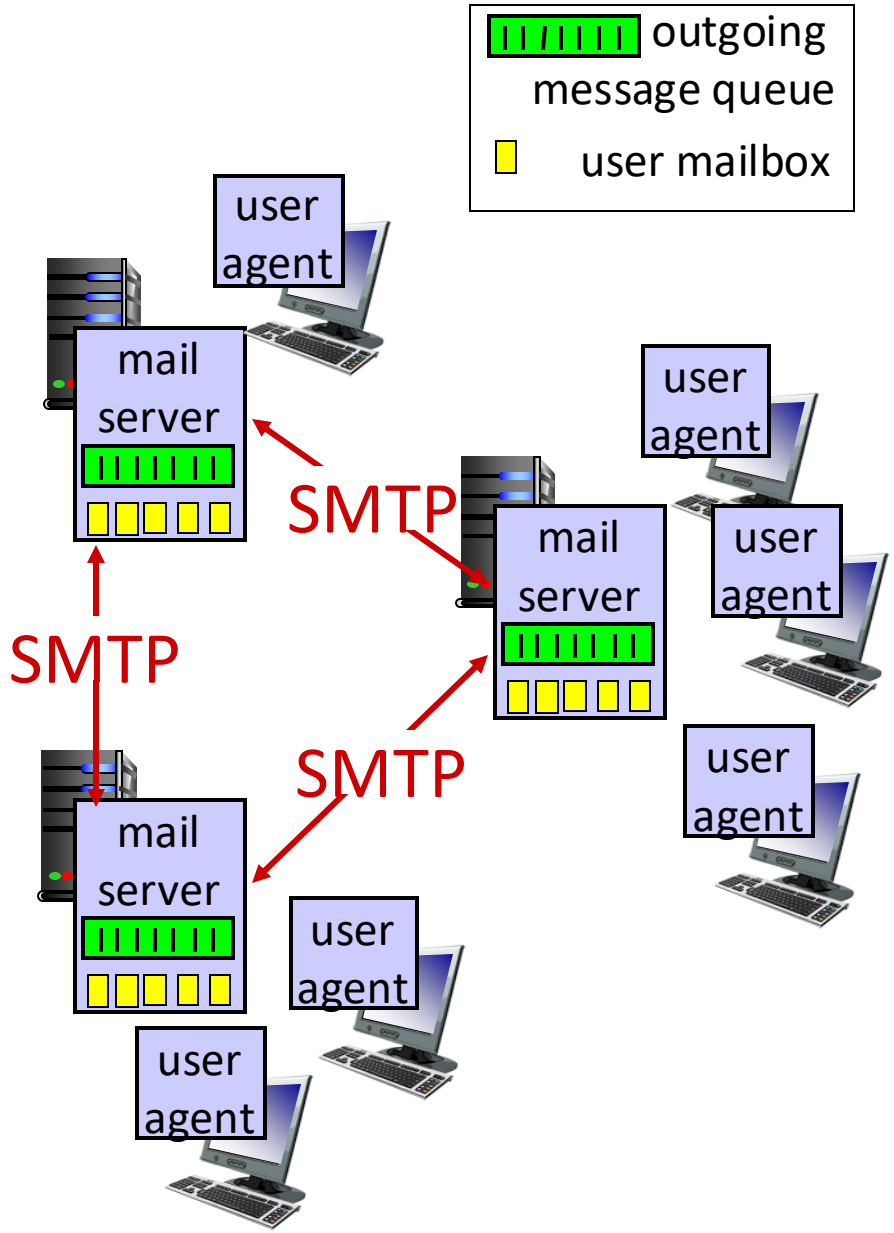
E-mail

Three major components:

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

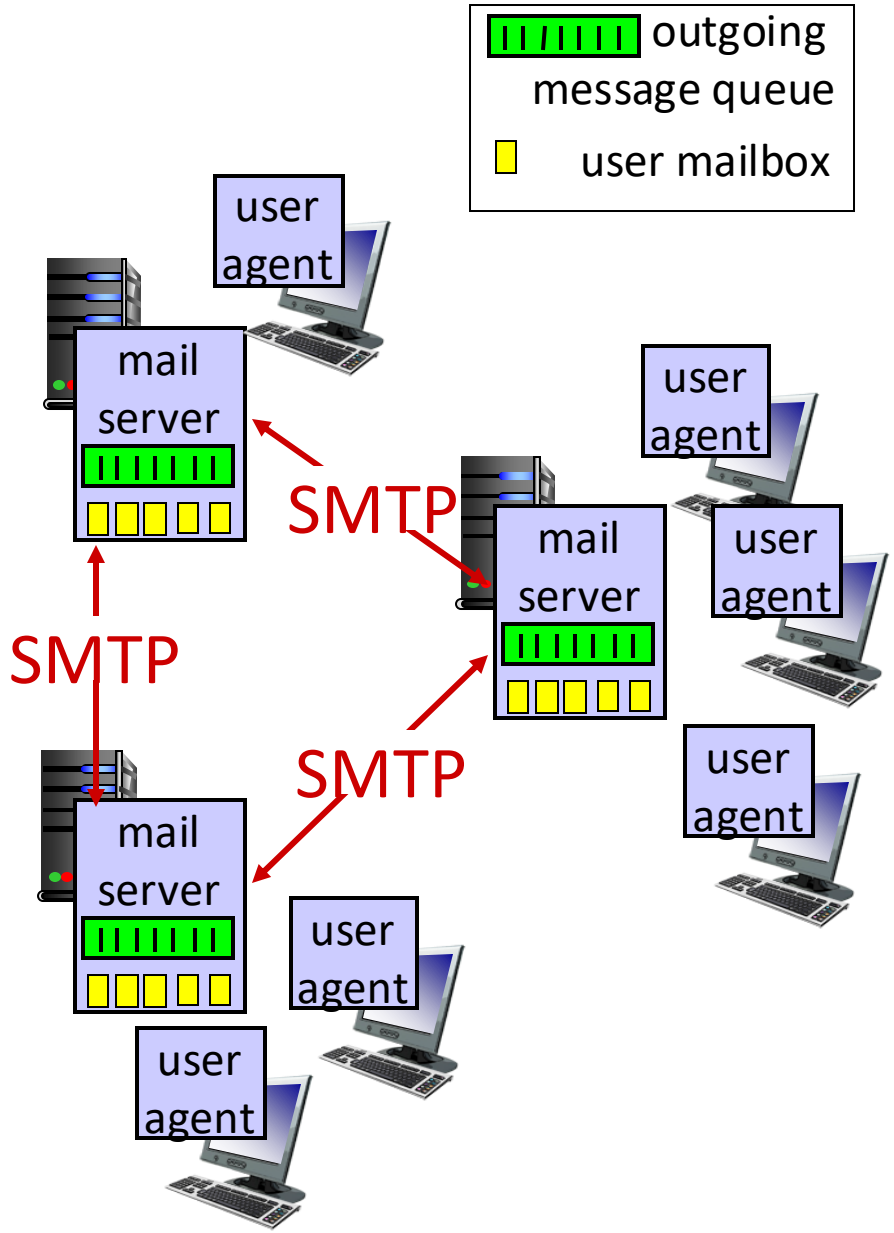
User Agent

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



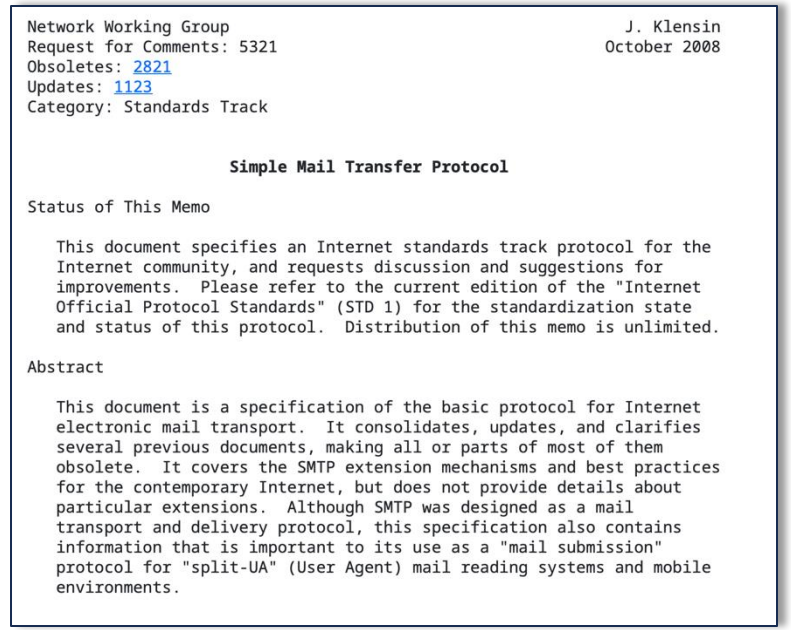
E-mail: mail servers

- *mailbox* contains incoming messages for user
- *message queue* of outgoing (to be sent) mail messages
- *Simple Mail Transfer Protocol (SMTP)* between mail servers to send email messages
  - client: sending mail server
  - "server": receiving mail server



E-mail: the 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
  - 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



Network Working Group J. Klensin
Request for Comments: 5321 October 2008
Obsoletes: 2821
Updates: 1123
Category: Standards Track

Simple Mail Transfer Protocol

Status of This Memo

This document specifies an Internet standards track protocol for the Internet community, and requests discussion and suggestions for improvements. Please refer to the current edition of the "Internet Official Protocol Standards" (STD 1) for the standardization state and status of this protocol. Distribution of this memo is unlimited.

Abstract

This document is a specification of the basic protocol for Internet electronic mail transport. It consolidates, updates, and clarifies several previous documents, making all or parts of most of them obsolete. It covers the SMTP extension mechanisms and best practices for the contemporary Internet, but does not provide details about particular extensions. Although SMTP was designed as a mail transport and delivery protocol, this specification also contains information that is important to its use as a "mail submission" protocol for "split-UA" (User Agent) mail reading systems and mobile environments.

Scenario: Alice sends e-mail to Bob

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

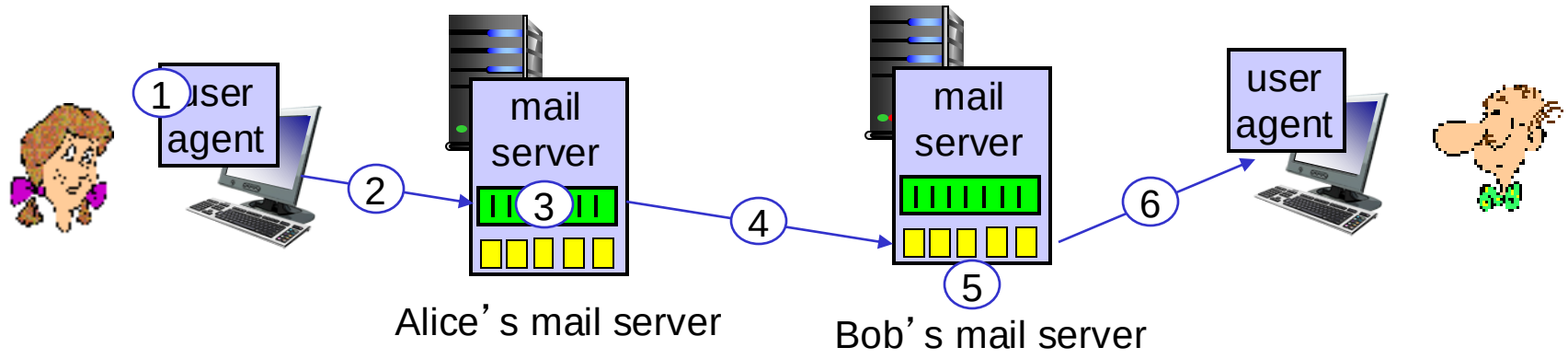
2) Alice’s UA sends message to her mail server; message placed in message queue

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
```

SMTP: closing observations

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

- 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

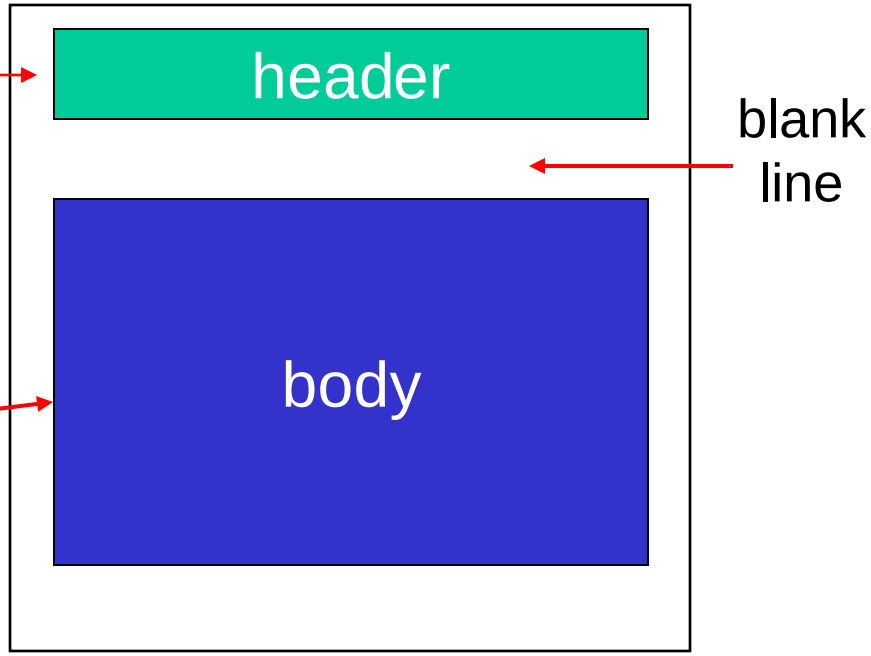
Mail message format

SMTP: protocol for exchanging e-mail messages, defined in RFC 531 (like HTTP)

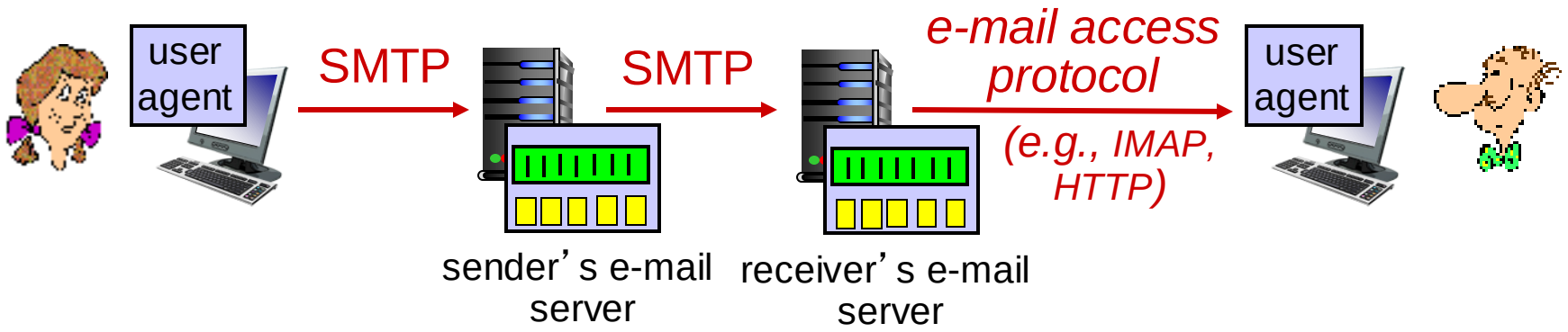
RFC 822 defines *syntax* for e-mail message itself (like HTML)

- 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



Mail access protocols



- SMTP: delivery/storage of e-mail messages to receiver's 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. provide web-based interface on top of STMP (to send), IMAP (or POP) to retrieve e-mail messages

DNS: Domain Name System

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:

- *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

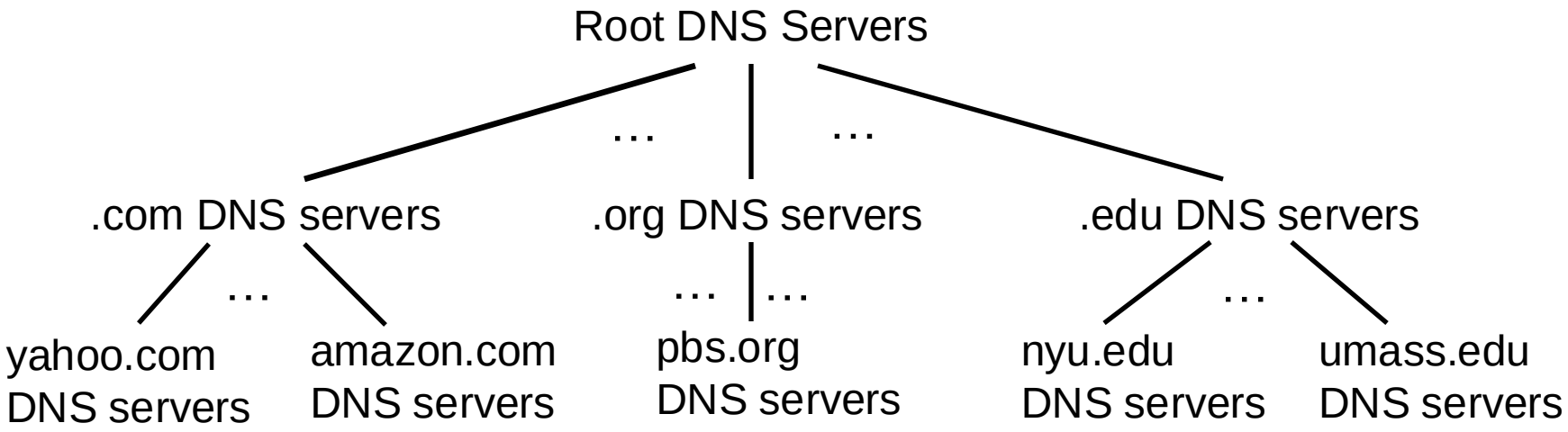
    e.g. www.gmail.com = mail.google.com
- load distribution
  - replicated Web servers: many IP addresses correspond to one name

Q: Why not centralize DNS?

A:

- single point of failure
- distant centralized database
  - delay!
- maintenance
- traffic volume: doesn't scale!
  - Comcast DNS servers alone: 600B DNS queries per day

DNS: a distributed, hierarchical database



Root

Top Level Domain

Authoritative

Client wants IP address for www.amazon.com; a 1st approach:

- 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

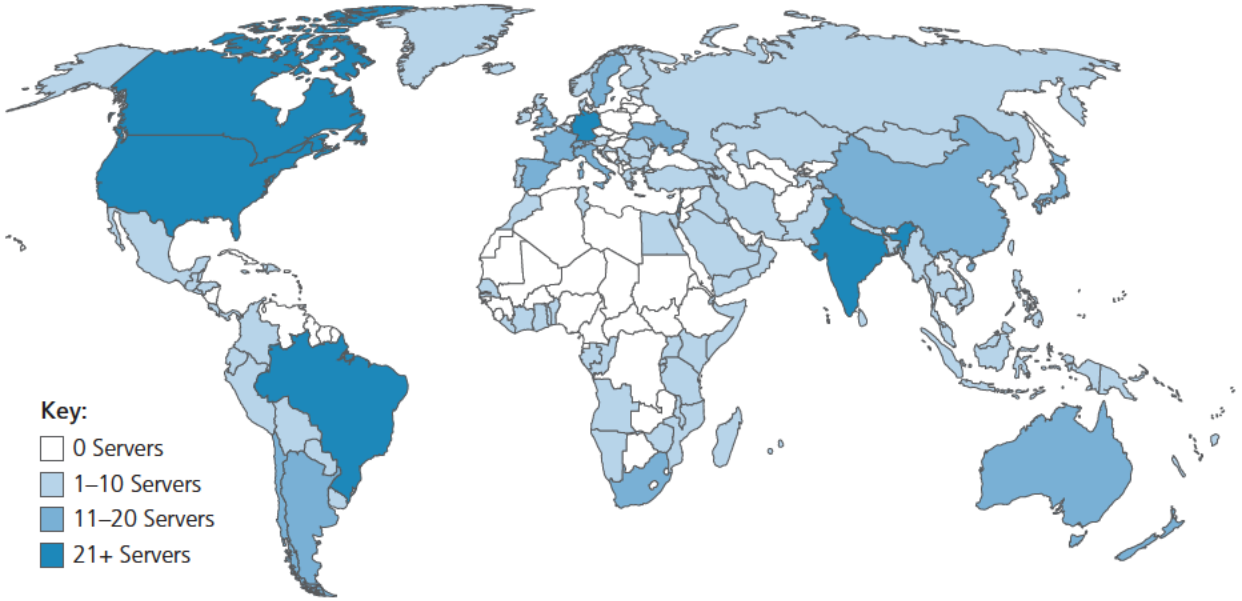
DNS: root name servers

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

- *important* Internet function
  - Internet couldn't function without it!

- 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)



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.: .cn, .uk, .fr, .ca, .jp

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 (user side!)

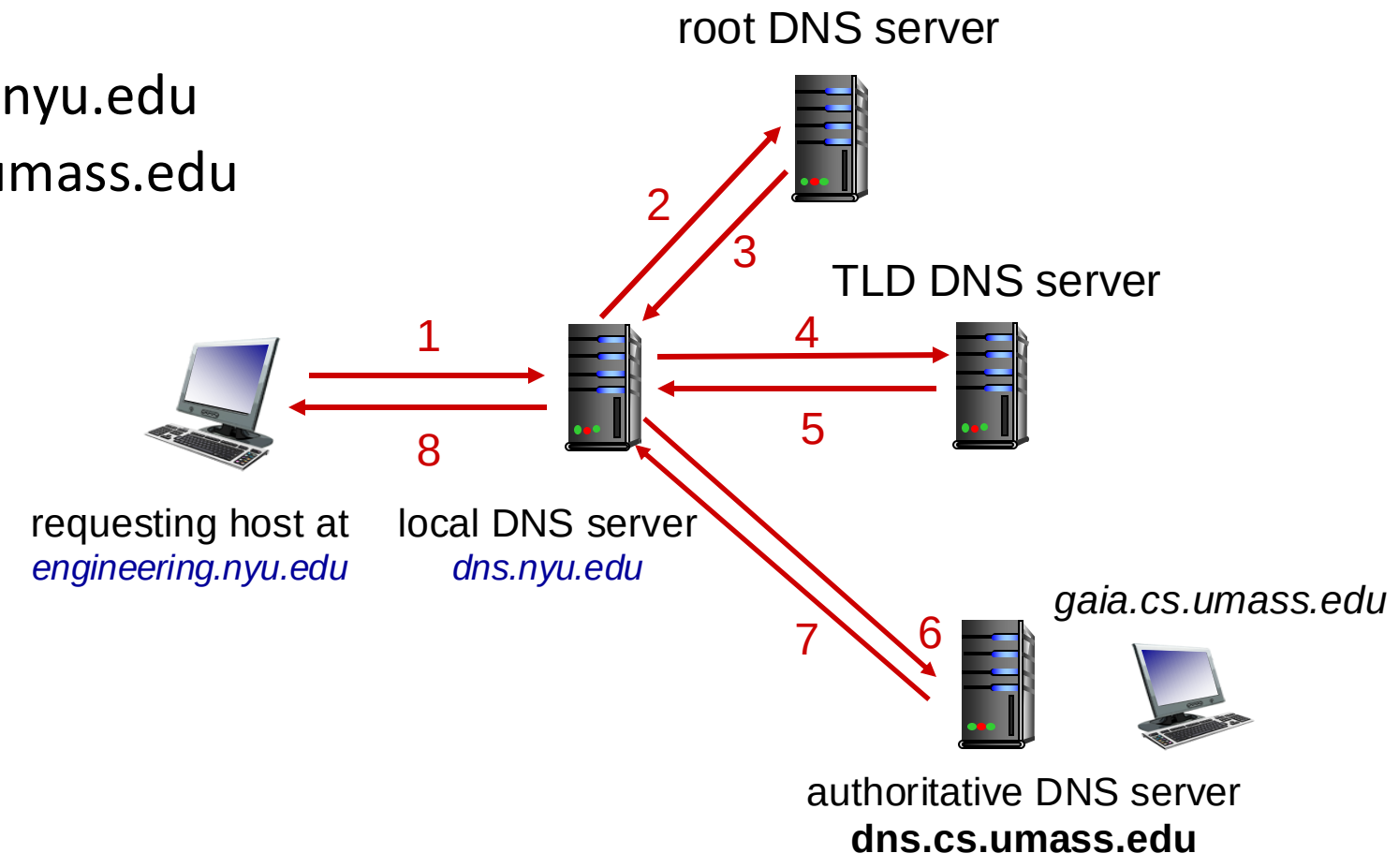
- does not strictly belong to hierarchy
- each ISP (residential ISP, company, university) has one
  - also called “default name server”
- when host makes DNS query, query is sent to its local DNS server first
  - has local cache of recent name-to-address translations (but may be out of date!)
  - acts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

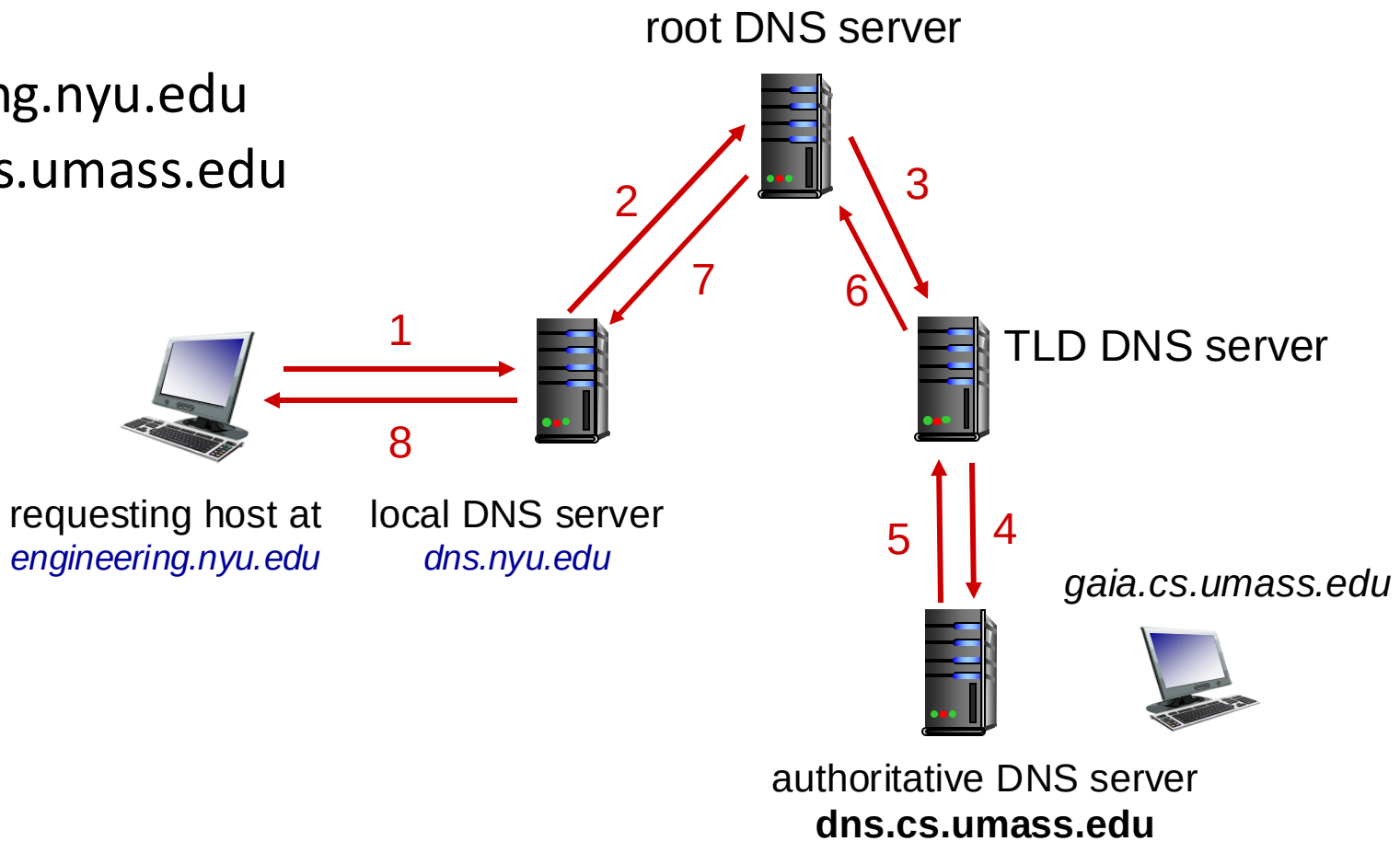


DNS name resolution: all queries recursive

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, Updating DNS 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*
  - if name host changes IP address, may not be known Internet-wide until all TTLs expire!

- update/notification mechanisms for dynamic updates in 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

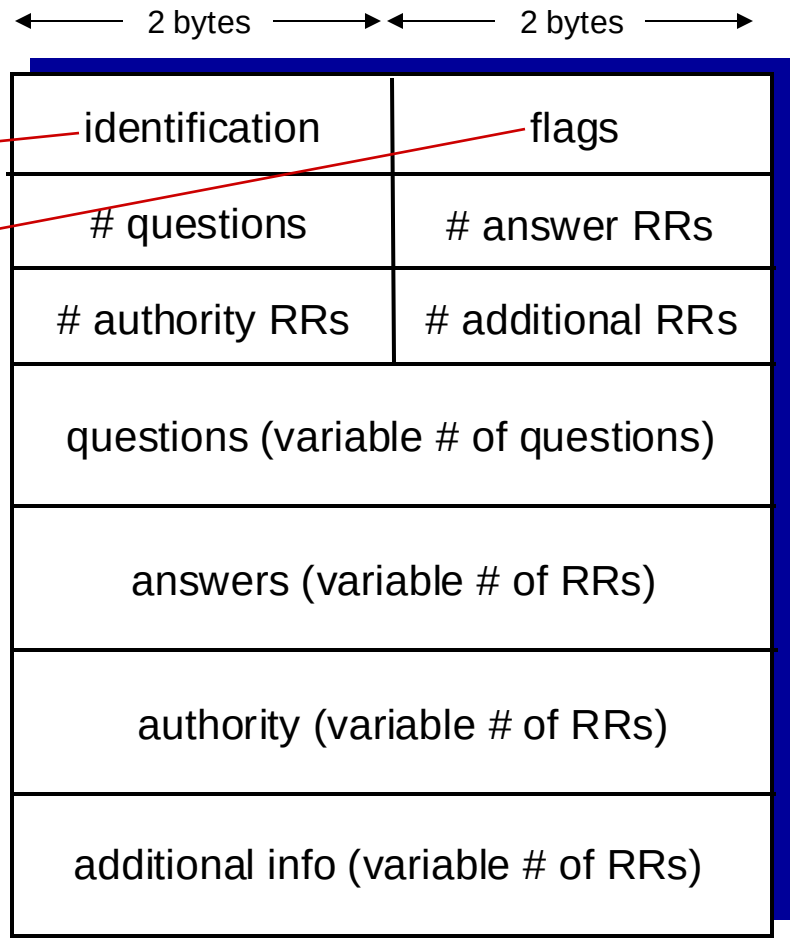
- `value` is name of mailserver associated with `name`

DNS protocol messages

DNS *query* and *reply* messages, both have the same *format:*

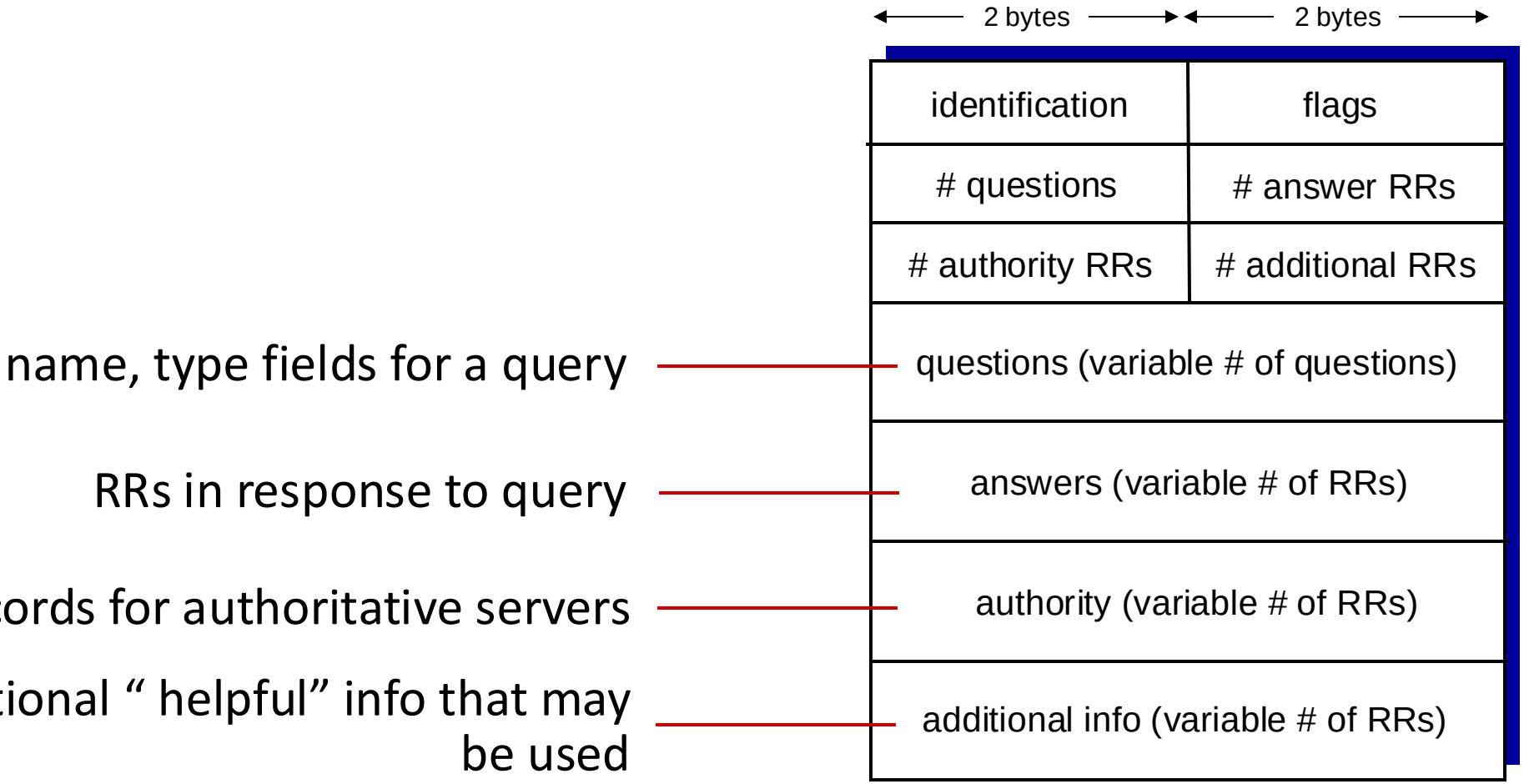
message header:

- identification: 16 bit # for query, reply to query uses same #
- flags:
  - query or reply
  - recursion desired
  - recursion available
  - reply is authoritative



DNS protocol messages

DNS *query* and *reply* messages, both have the same *format:*



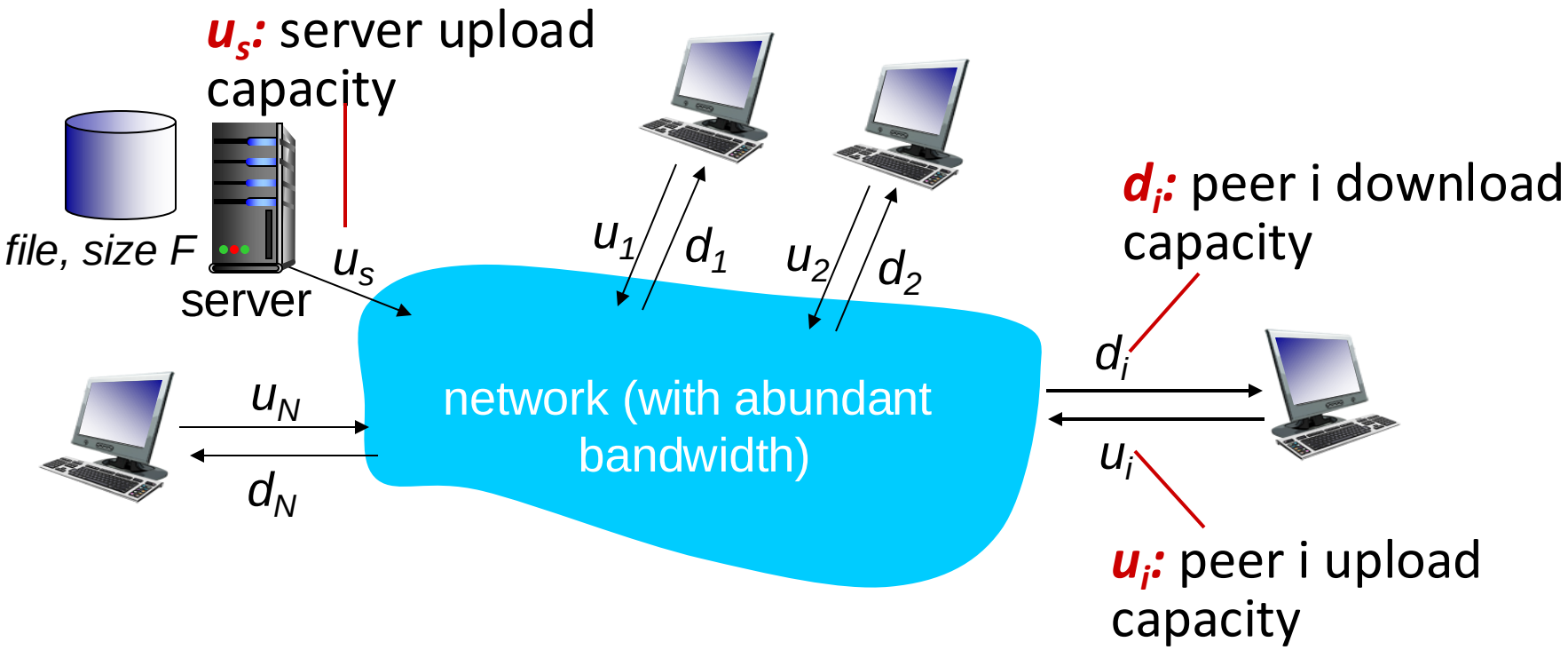
Peer-to-peer applications

Example: File distribution

File distribution: client-server vs P2P

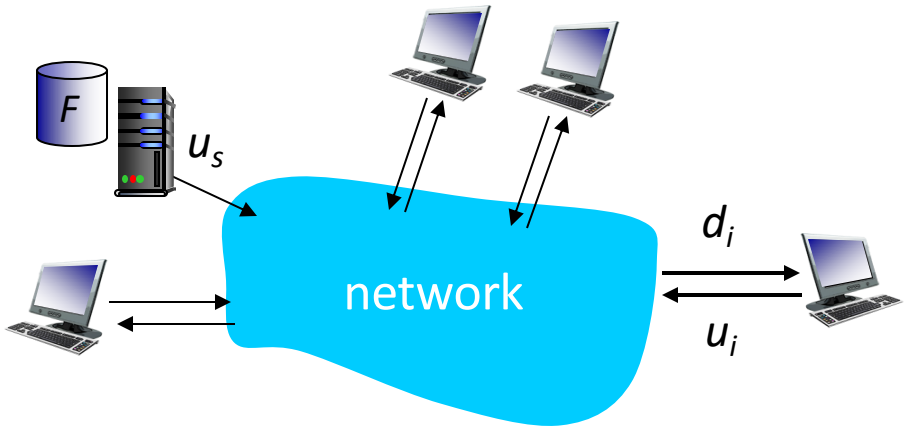
Q: how much time to distribute file (size *F*) from one server to *N peers*?

- 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 (slowest)
  - download time of the slowest client: F/d_{min}

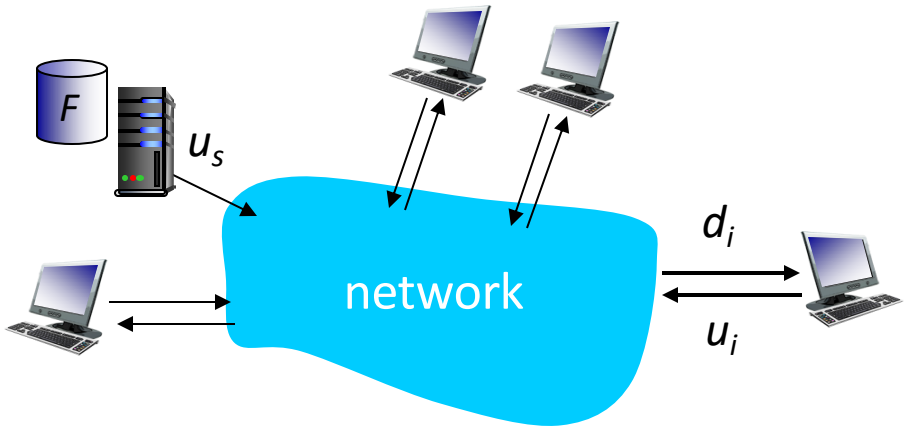
time to distribute F to N clients using client-server approach

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

increases linearly in N

File distribution time: P2P

- *server transmission:* must upload at least one copy:
  - time to send one copy: 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 $u_s + \Sigma u_i$



time to distribute F to N clients using P2P approach

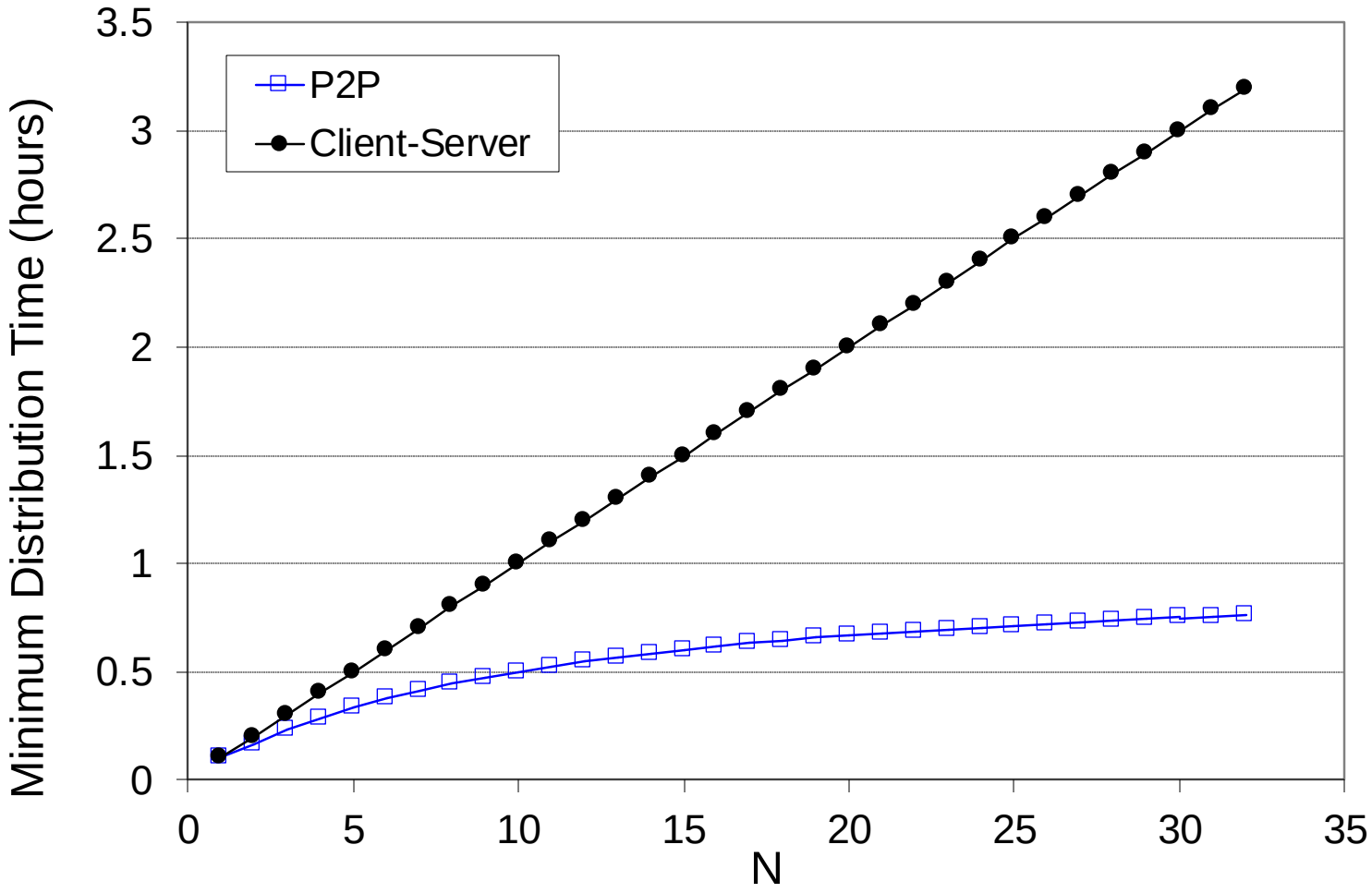
$$D_{P2P} \geq max\{F/u_s, F/d_{min}, NF/(u_s + \Sigma u_i)\}$$

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

Client-server vs. P2P: example

Client upload rate = u
Server upload rate = $u_s = 10u$

F/u = 1 hour
$d_{min} \geq u_s$

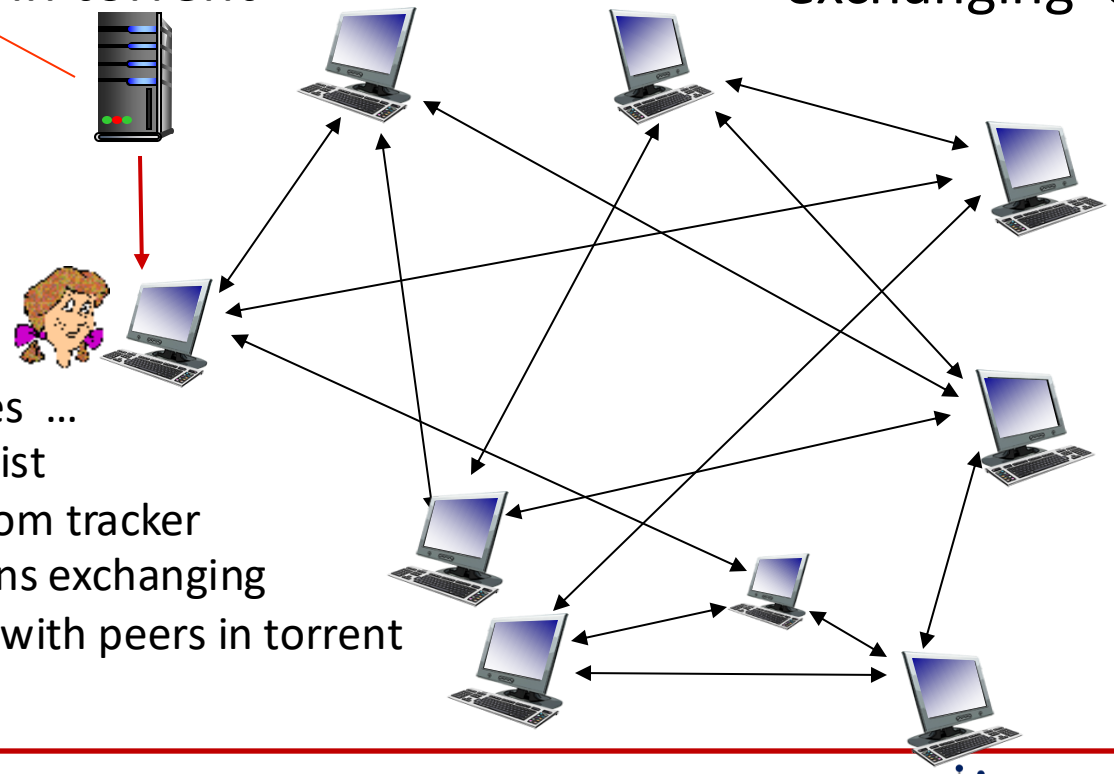


P2P file distribution: BitTorrent

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

tracker: tracks peers participating in torrent

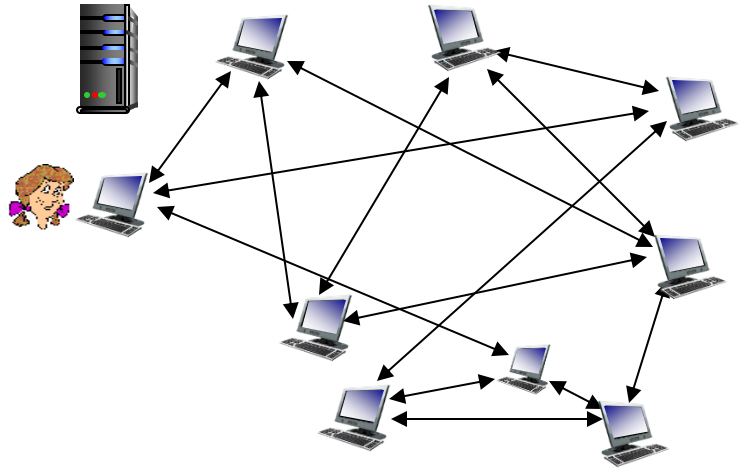
torrent: group of peers exchanging chunks of a file



Alice arrives …
… obtains list
of peers from tracker
… and begins exchanging
file chunks with peers in torrent

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

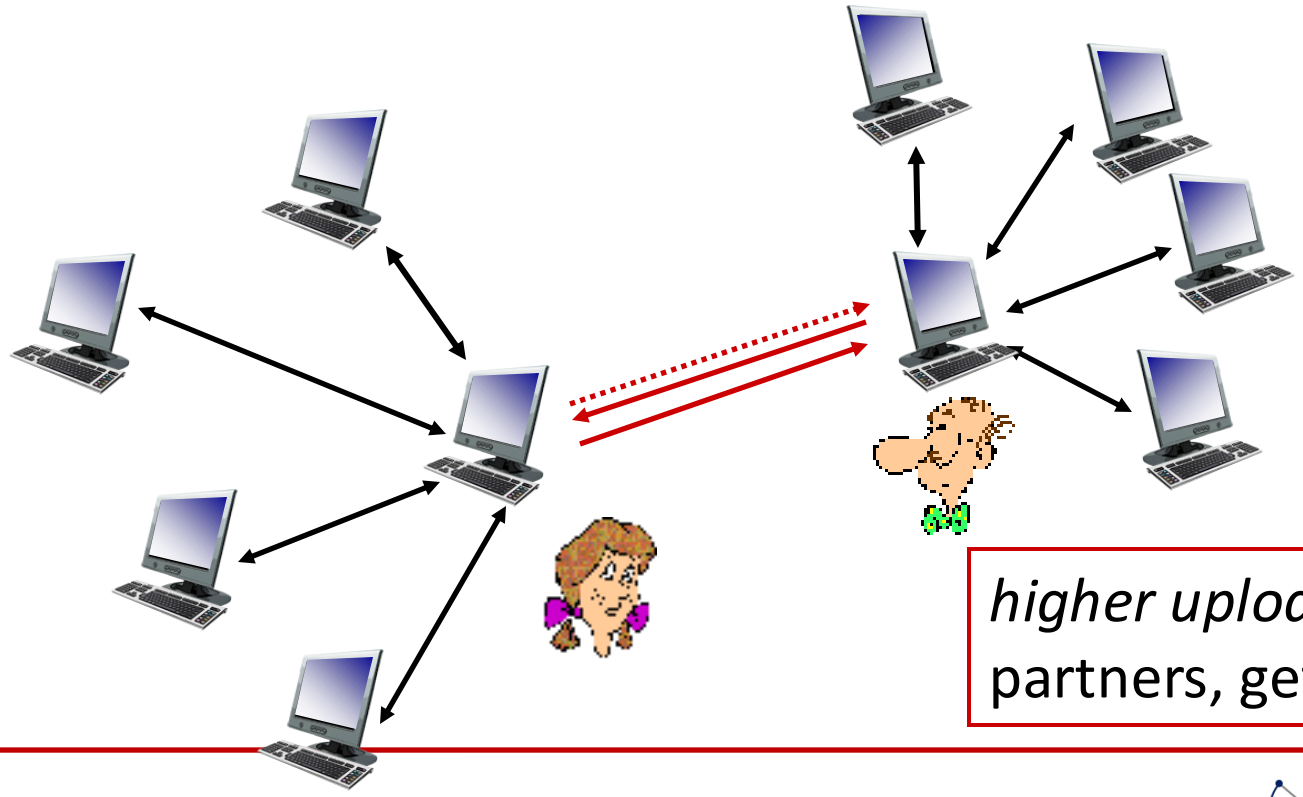
- Alice sends chunks to those four peers currently sending her chunks *at highest rate*
  - other peers are “choked” by Alice (do not receive chunks from her)
  - re-evaluate top 4 every10 secs
- every 30 secs: randomly selects another peer, starts sending chunks
  - “optimistically unchoke” this peer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

BitTorrent: reciprocate!

(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



higher upload rate: find better trading partners, get file faster !

Video streaming and CDNs

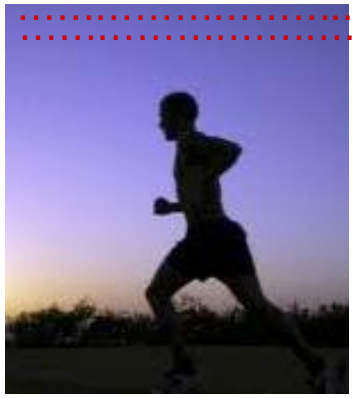
Video Streaming and CDNs: context

- stream video traffic: major consumer of Internet bandwidth
  - Netflix, YouTube, Amazon Prime: 80% of residential ISP traffic (2020)
- challenge: scale - how to reach ~1B users?
  - single mega-video server won't work (why?)
- challenge: heterogeneity
  - different users have different capabilities (e.g., wired versus mobile; bandwidth rich versus bandwidth poor)
- *solution: distributed, application-level infrastructure*

Multimedia: video

- video: sequence of images displayed at constant rate
  - e.g., 24 images/sec
- digital image: array of pixels
  - each pixel represented by bits
- coding: use redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)

spatial coding example: instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values* (N)



frame *i*

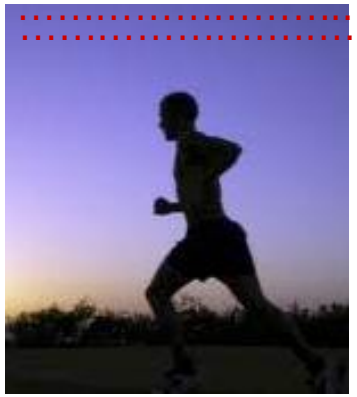
frame *i+1*

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

Multimedia: video

- CBR (constant bit rate): video encoding rate fixed
- VBR (variable bit rate): video encoding rate changes as amount of spatial, temporal coding changes
- examples:
  - MPEG 1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, 64Kbps – 12 Mbps)

spatial coding example: instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values* (N)



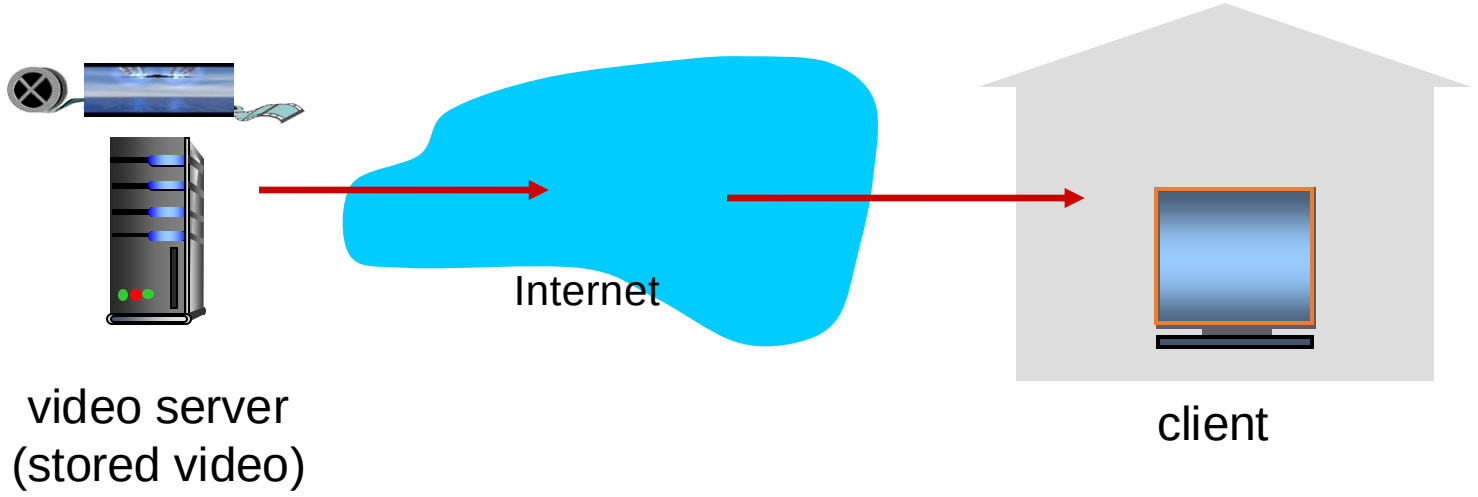
frame *i*

frame *i+1*

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

Streaming stored video

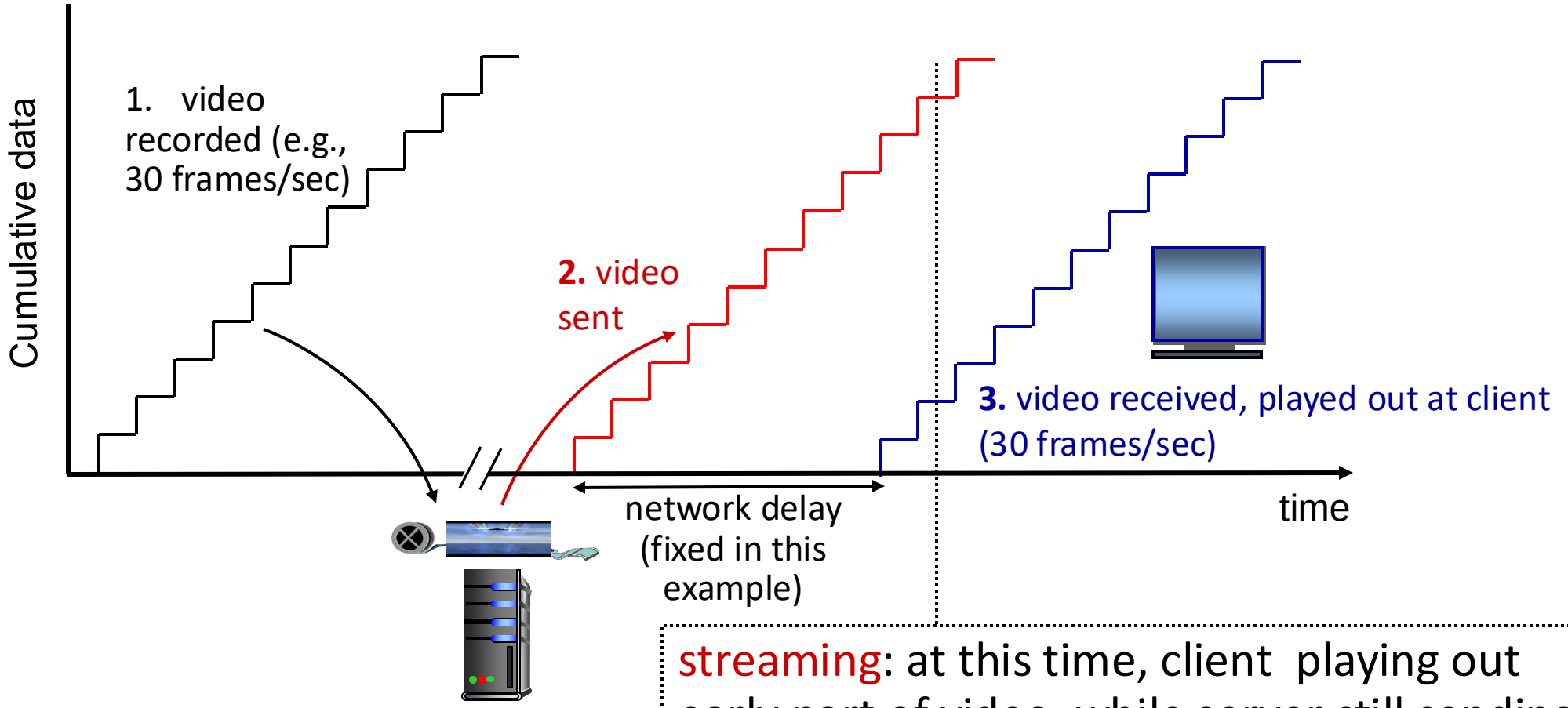
simple scenario:



Issues:

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

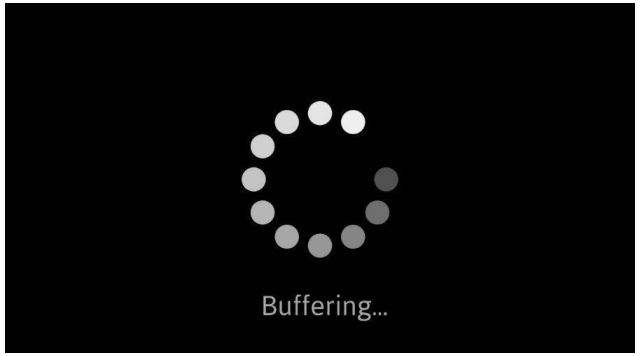
Streaming stored video



streaming: at this time, client playing out early part of video, while server still sending later part of video

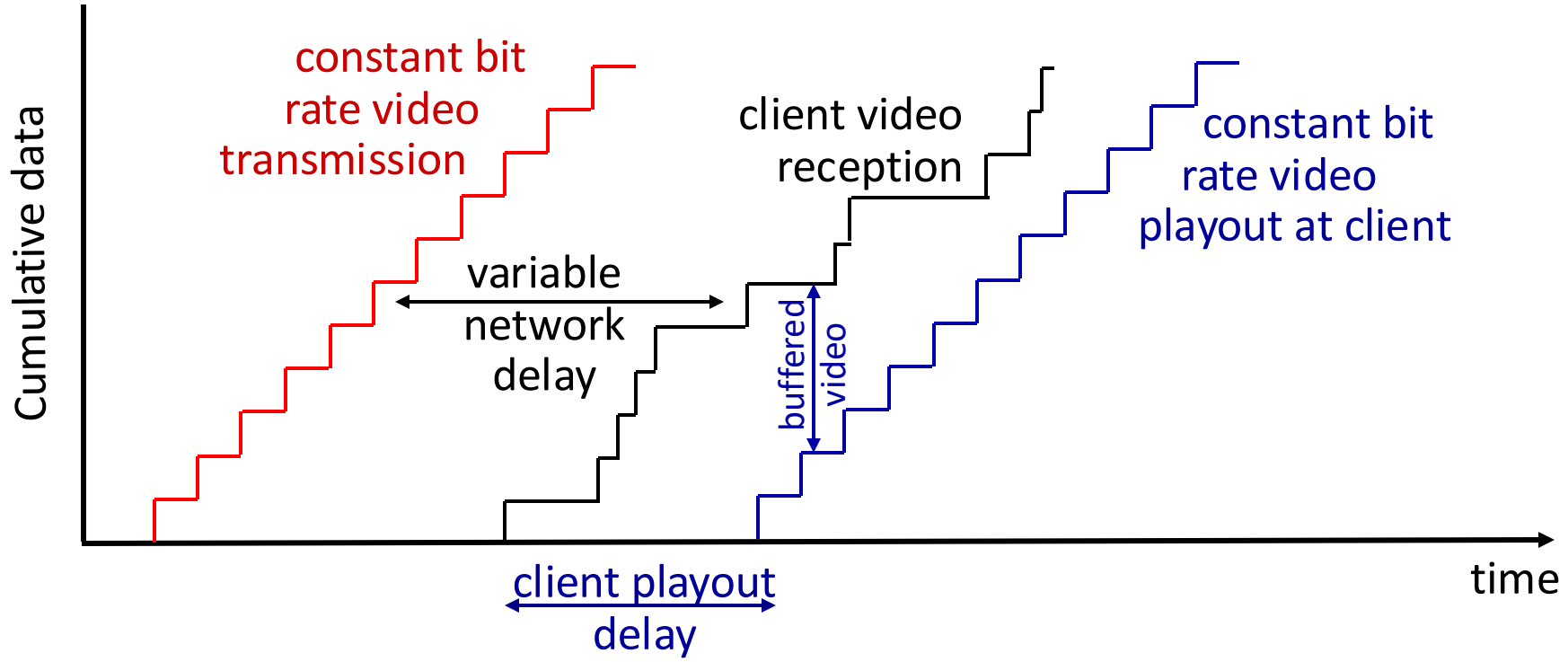
Streaming stored video: challenges

- Continuous playout constraint: once client playout begins, playback must match original timing
  - … but network delays are variable (**jitter**), so will need client-side buffer to match playout requirements



- Other challenges:
  - client interactivity: pause, fast-forward, rewind, jump through video
  - video packets may be lost, retransmitted

Streaming stored video: playout buffering

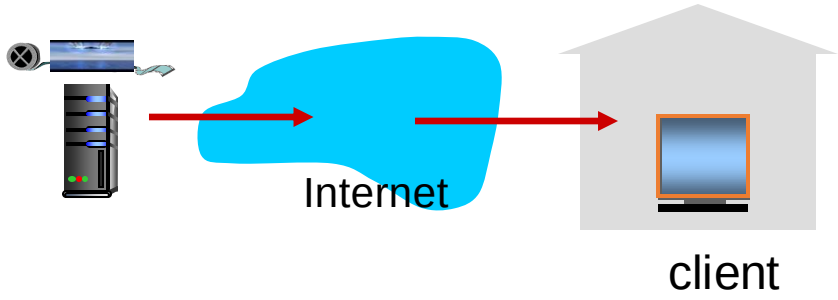


- *client-side buffering and playout delay:* compensate for network-added delay, delay jitter

Streaming multimedia: DASH

- *DASH: D*ynamic, *A*daptive *S*treaming over *H*TTP

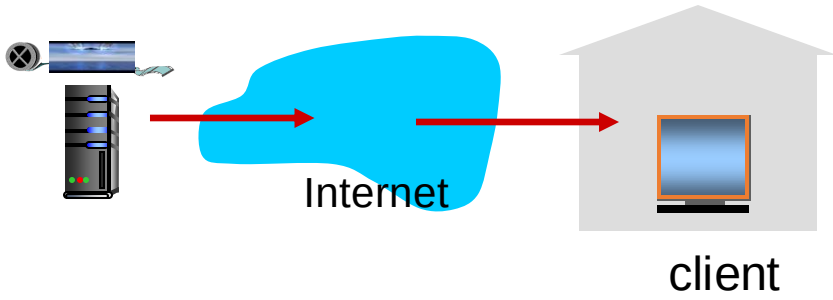
- *server:*
  - divides video file into multiple chunks
  - each chunk stored, encoded at different rates
  - *manifest file:* provides URLs for different chunks



- *client:*
  - periodically measures server-to-client bandwidth
  - consulting manifest, **requests one chunk at a time**
    - When bandwidth is high → request high coding rate (high-quality) chunks
    - When bandwidth is low → request low coding rate (low-quality) chunks

Streaming multimedia: DASH (client intelligence)

- Client determines
  - *when* to request chunk (so that buffer underflow, 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)



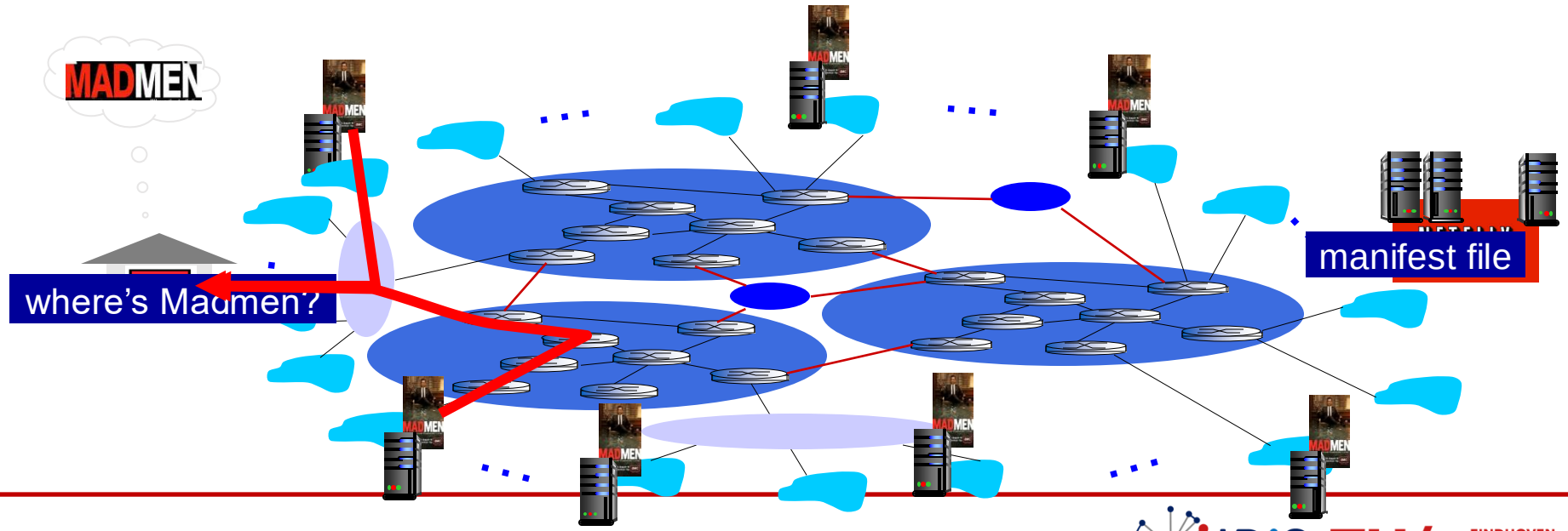
DASH was released after we published this paper:

Content distribution networks (CDNs)

- *challenge:* how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?
- store/serve multiple copies of videos at multiple geographically distributed sites *(called CDN)*
- 2 styles:
  - push CDN servers deep into many access networks
    - close to users: Akamai with 240,000 servers deployed in more than 120 countries (2015)
  - smaller number (10's) of larger clusters near (but not within) access networks
    - close to access networks: used by Limelight

Content distribution networks (CDNs)

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



Content distribution networks (CDNs)

OTT: "over the top" media service

Internet host-host communication as a service

Content distribution networks (CDNs)

OTT media service (a.k.a. streaming media service) challenges:

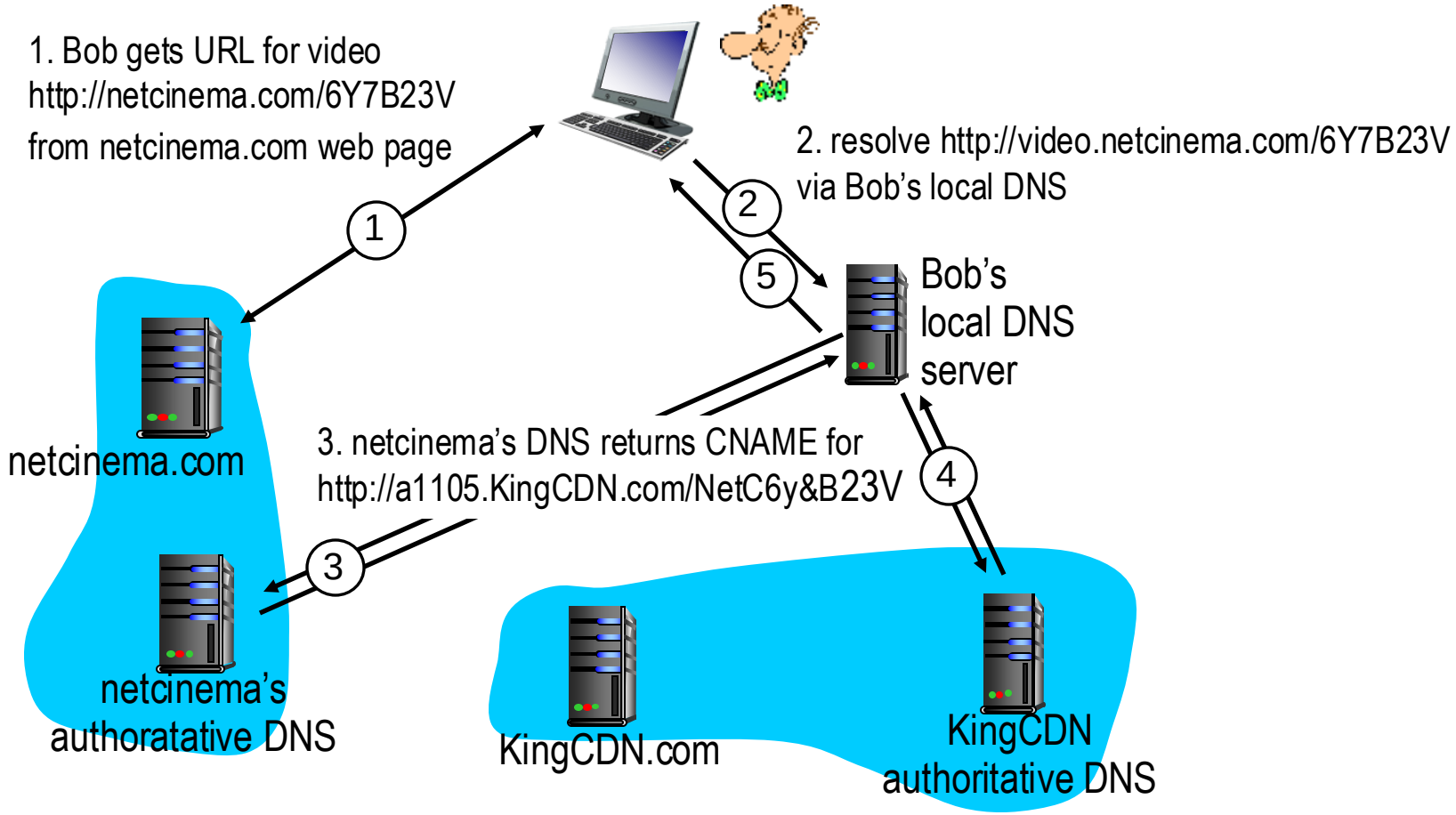
Coping with a congested Internet

- 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://video.netcinema.com/6Y7B23V

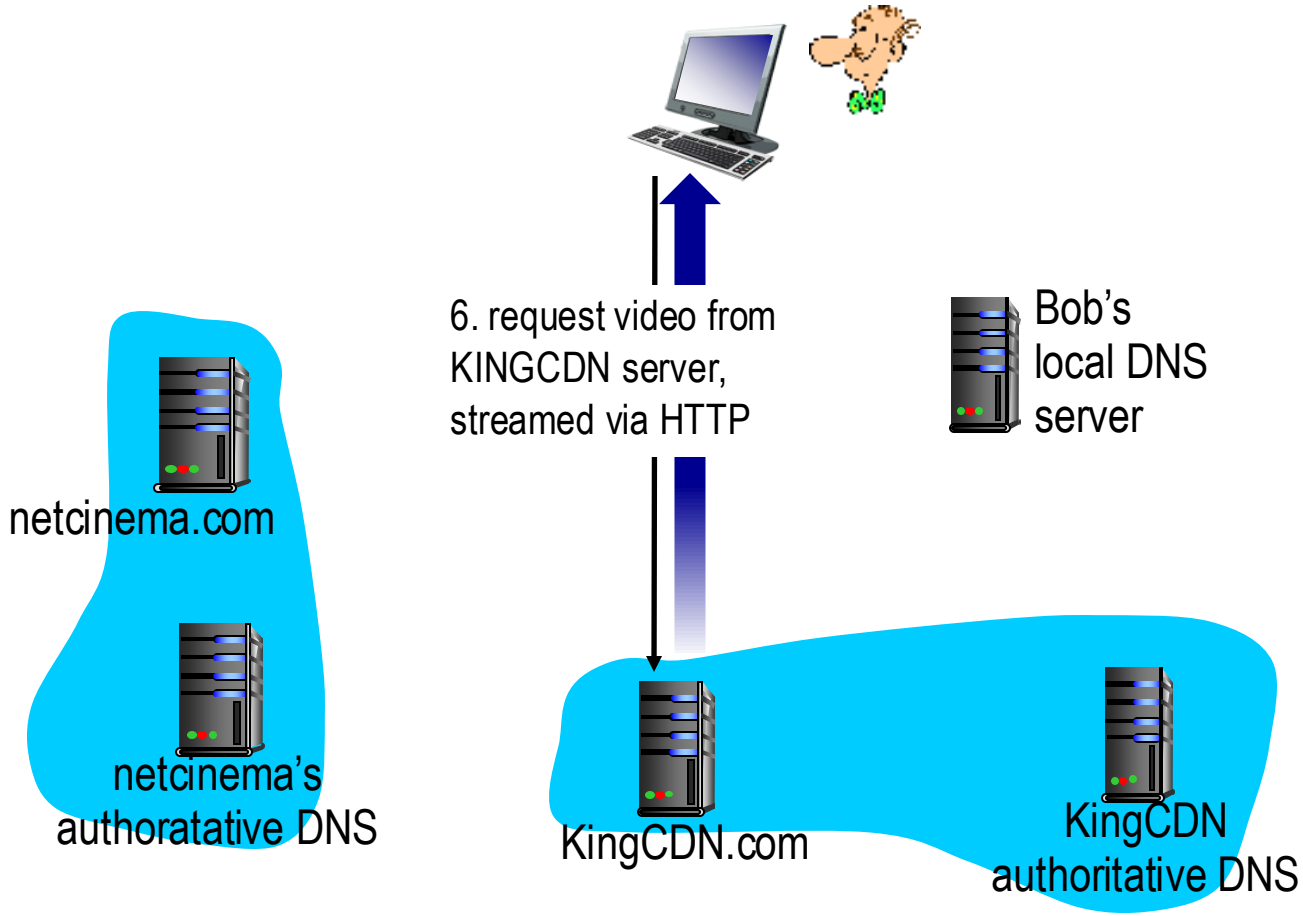
- video stored in CDN at http://a1105.kingCDN.com/NetC6yB23V



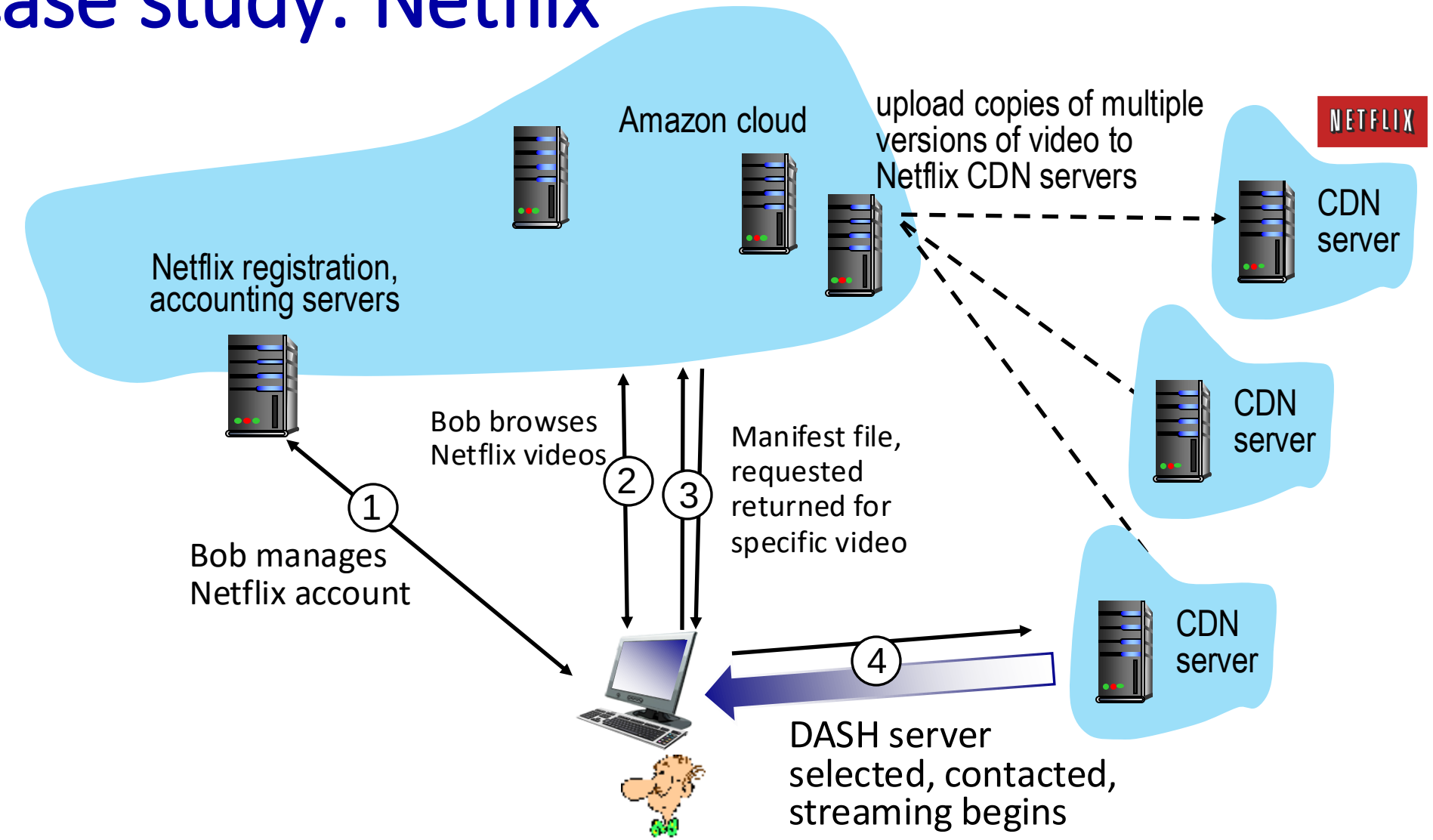
CDN content access: a closer look

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

- video stored in CDN at http://a1105.kingCDN.com/NetC6yB23V



Case study: Netflix

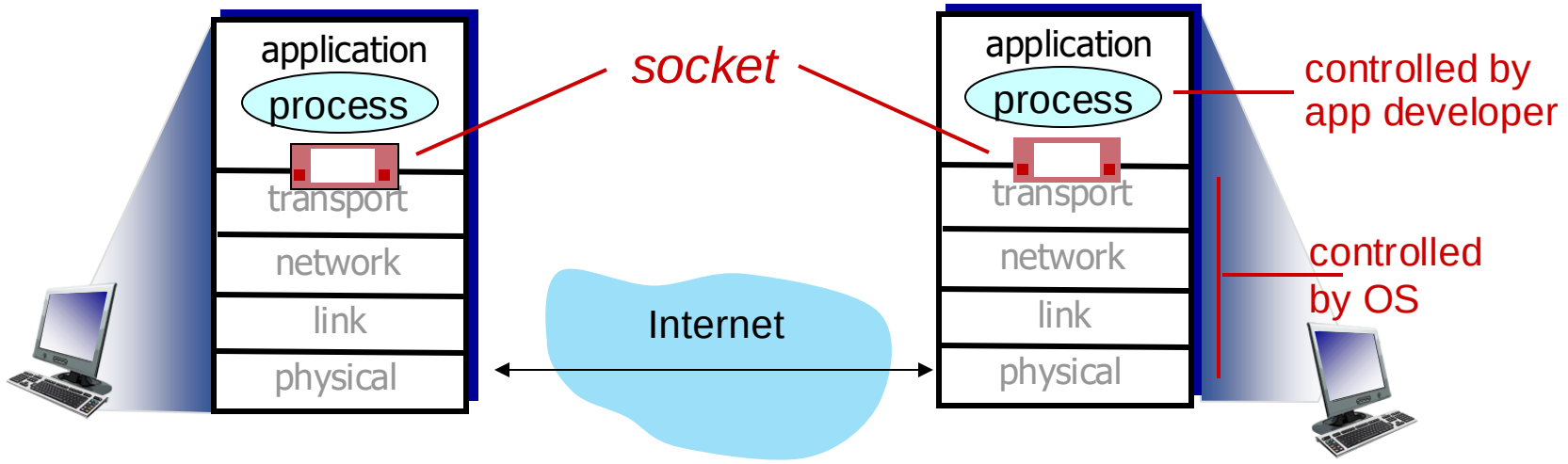


Socket programming

Socket programming

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

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



Socket programming

Two socket types for two transport services:

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

Application Example:

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

Socket programming with UDP

UDP: no “connection” between client & server

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

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

Application viewpoint:

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

Client/server socket interaction: UDP

server (running on serverIP)

create socket, port= x:
serverSocket =
socket(AF_INET,SOCK_DGRAM)

read datagram from
serverSocket

write reply to
serverSocket
specifying
client address,
port number

client

create socket:
clientSocket =
socket(AF_INET,SOCK_DGRAM)

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

read datagram from
clientSocket

close
clientSocket

Example app: UDP client

Python UDPClient

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

Example app: UDP server

Python UDPServer

```
from socket import *
serverPort = 12000
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:

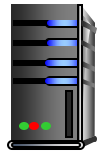
- Creating TCP socket, specifying IP address, port number of server process
- *when client creates socket:* client TCP establishes connection to server TCP

- 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

Application viewpoint

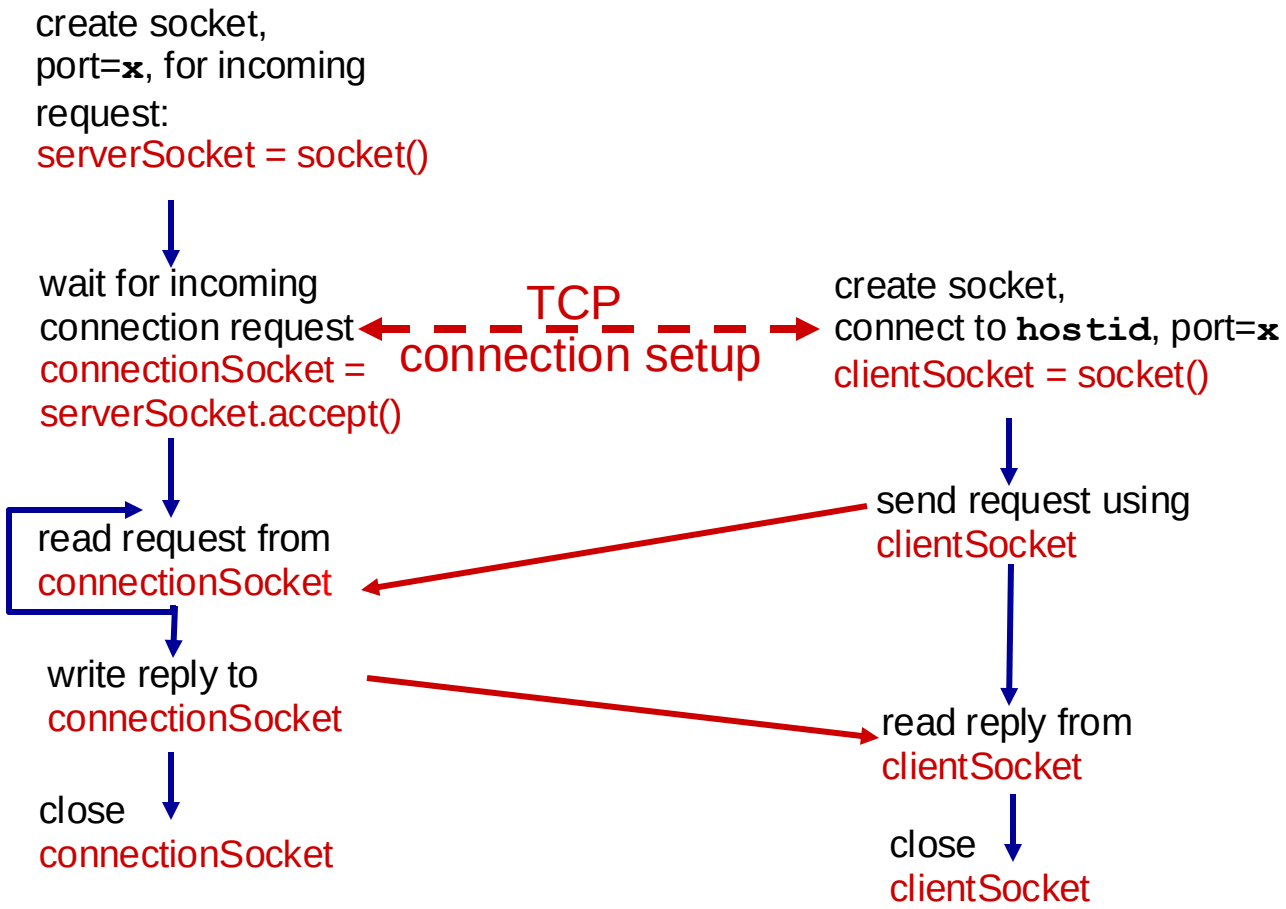
TCP provides reliable, in-order byte-stream transfer ("pipe") between client and server

Client/server socket interaction: TCP



server (running on hostid)

client 



Example app: TCP client

Python TCPClient

```
from socket import *
serverName = 'servername'
serverPort = 12000
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 TCPServer

```
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) →