Chapter 2
Application Layer

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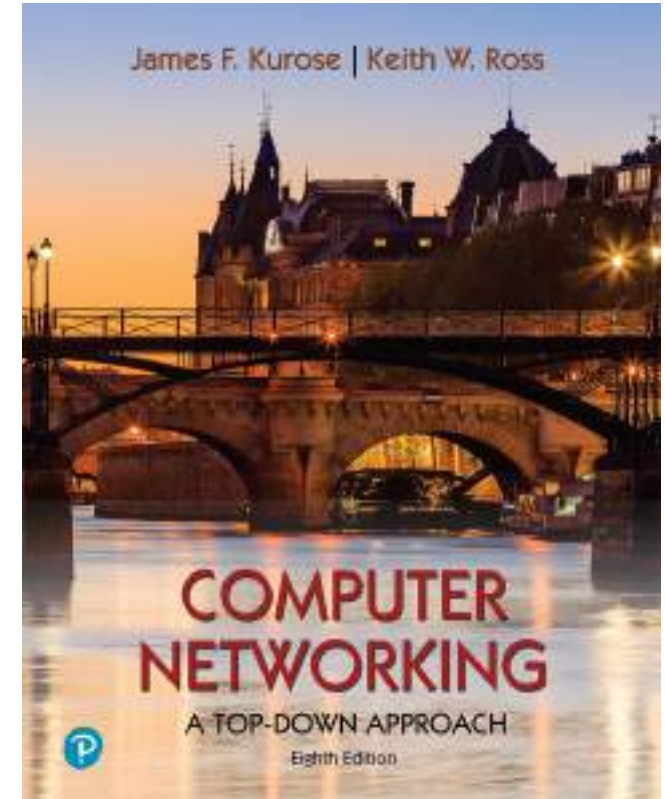
Computer Networking: A Top-Down Approach
8th edition   n
Jim Kurose, Keith Ross
Pearson, 2020

Application layer: overview

- Principles of network applications
- Web and HTTP
- E-mail, SMTP, IMAP
- The Domain Name System DNS

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

Application layer: overview

Our goals:

- conceptual *and* implementation aspects of application-layer protocols
  - transport-layer service models
  - client-server paradigm
  - peer-to-peer paradigm

- learn about protocols by examining popular application-layer protocols and infrastructure
  - HTTP
  - SMTP, IMAP
  - DNS
  - video streaming systems, CDNs
- programming network applications
  - socket API

Some network apps

- social networking

- Web

- text messaging

- e-mail

- multi-user network games

- streaming stored video (YouTube, Hulu, Netflix)

- P2P file sharing

- voice over IP (e.g., Skype)

- real-time video conferencing (e.g., Zoom)

- Internet search

- remote login

- ...

Q: your favorites?

Creating a network app

write programs that:

- run on (different) end systems

- communicate over network

- e.g., web server software communicates with browser software

no need to write software for network-core devices

- network-core devices do not run user applications

- applications on end systems allows for rapid app development, propagation
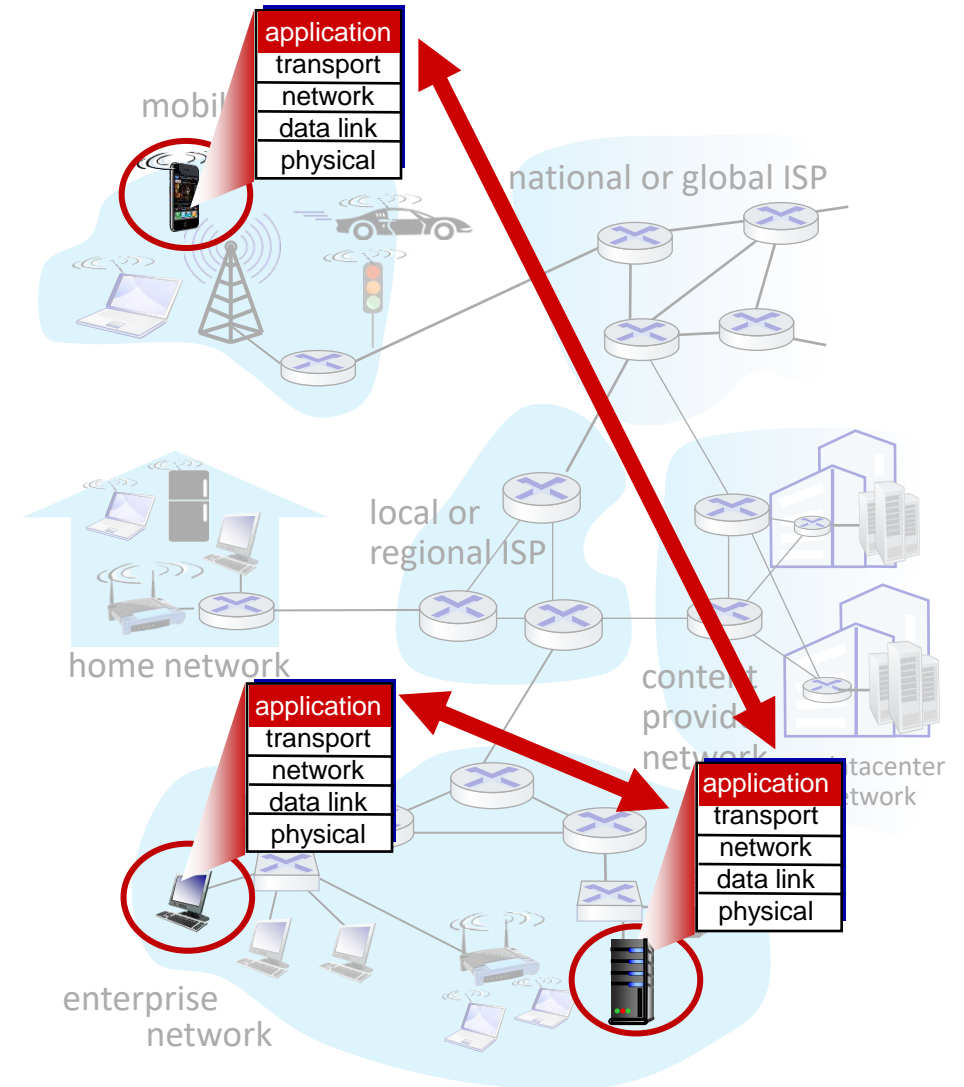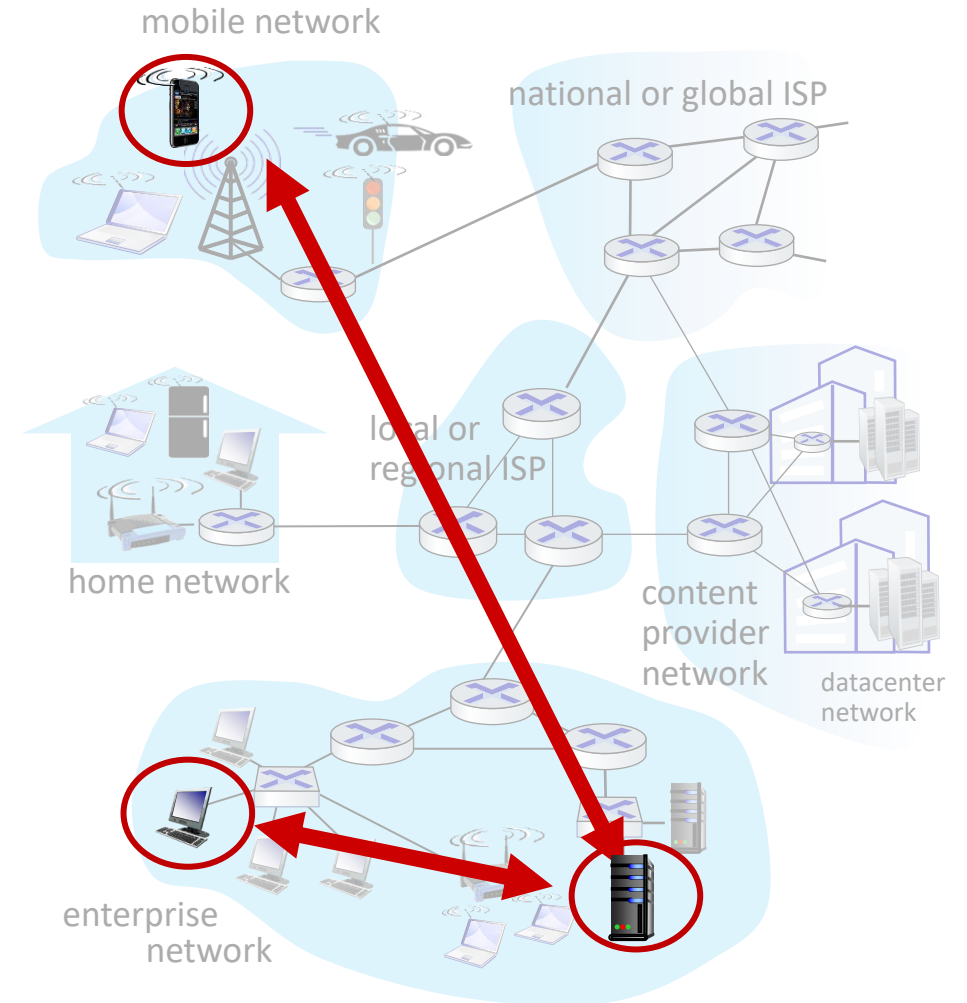
Client-server paradigm

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

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

Peer-peer architecture

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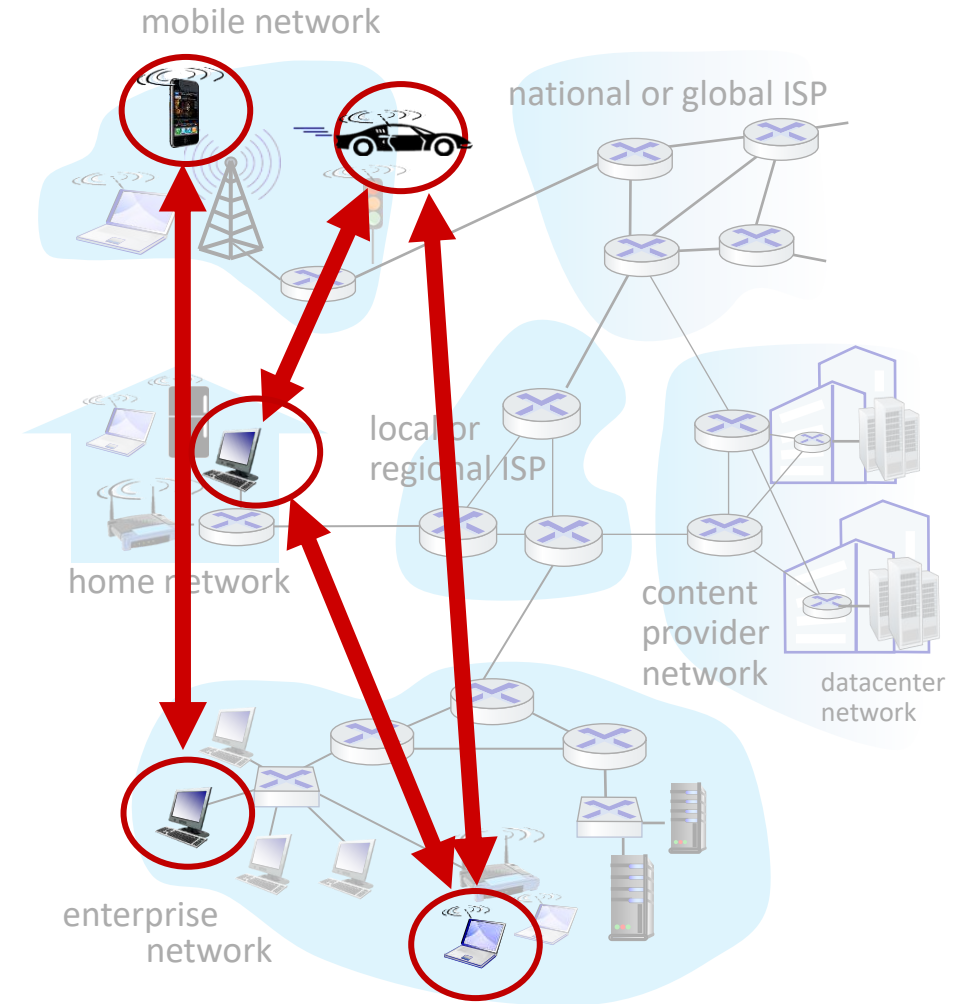
Processes communicating

process: program running within a host

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

clients, servers

client process: process that initiates communication

server process: process that waits to be contacted

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

Sockets

- process sends/receives messages to/from its socket

- socket analogous to door
  - sending process shoves message out door
  - sending process relies on transport infrastructure on other side of door to deliver message to socket at receiving process
  - two sockets involved: one on each side
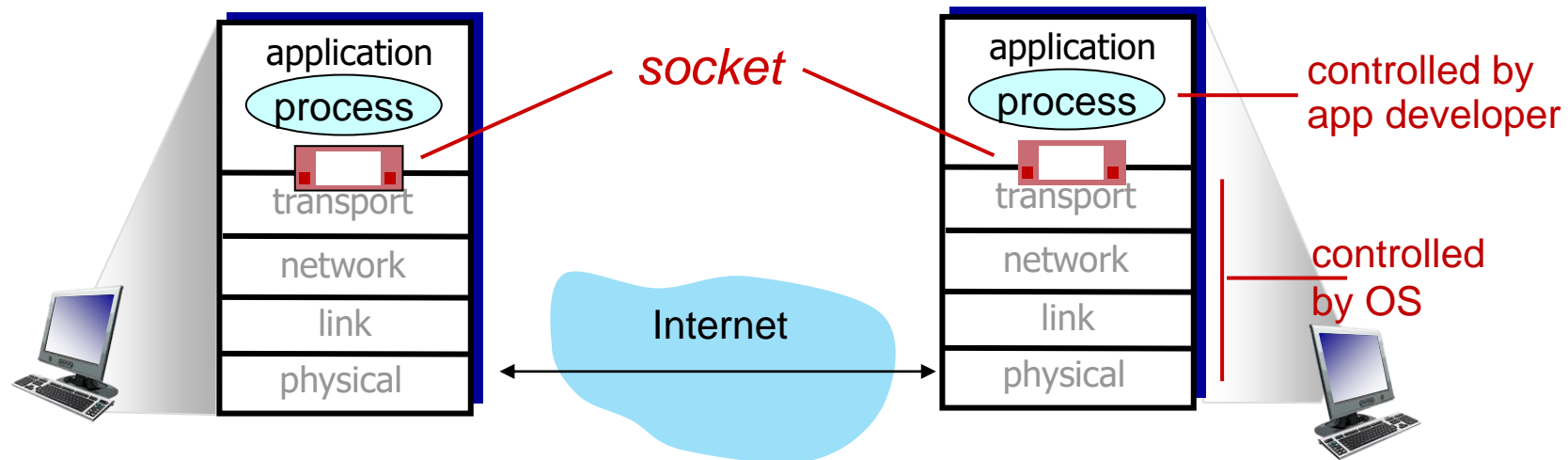
Addressing processes

- to receive messages, process must have *identifier*

- host device has unique 32-bit IP address

- *Q:* does IP address of host on which process runs suffice for identifying the process?

  - *A:* no, *many* processes can be running on same host

- *identifier* includes both IP address and port numbers associated with process on host.

- example port numbers:
  - HTTP server: 80
  - mail server: 25

- to send HTTP message to gaia.cs.umass.edu web server:
  - IP address: 128.119.245.12
  - port number: 80

- more shortly…

An application-layer protocol defines:

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

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

proprietary protocols:
- e.g., Skype, Zoom

What transport service does an app need?

data integrity

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

timing

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

throughput

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

security

- encryption, data integrity, ...

Transport service requirements: common apps

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

Internet transport protocols services

TCP service:

- *reliable transport* between sending and receiving process

- *flow control:* sender won't overwhelm receiver

- *congestion control:* throttle sender when network overloaded

- *connection-oriented:* setup required between client and server processes

- *does not provide:* timing, minimum throughput guarantee, security

UDP service:

- *unreliable data transfer* between sending and receiving process

- *does not provide:* reliability, flow control, congestion control, timing, throughput guarantee, security, or connection setup.

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

Internet applications, and transport protocols

application	application layer protocol	transport protocol
file transfer/download	FTP [RFC 959]	TCP
e-mail	SMTP [RFC 5321]	TCP
Web documents	HTTP 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

Securing TCP

Vanilla TCP & UDP sockets:

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

Transport Layer Security (TLS)

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

TSL implemented in application layer

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

Application layer: overview

- Principles of network applications

- **Web and HTTP**

- E-mail, SMTP, IMAP

- The Domain Name System DNS

- P2P applications

- video streaming and content distribution networks

- socket programming with UDP and TCP

Web and HTTP

First, a quick review...

- web page consists of *objects,* each of which can be stored on different Web servers

- object can be HTML file, JPEG image, Java applet, audio file,...

- web page consists of *base HTML-file* which includes *several referenced objects, each* addressable by a *URL,* e.g.,
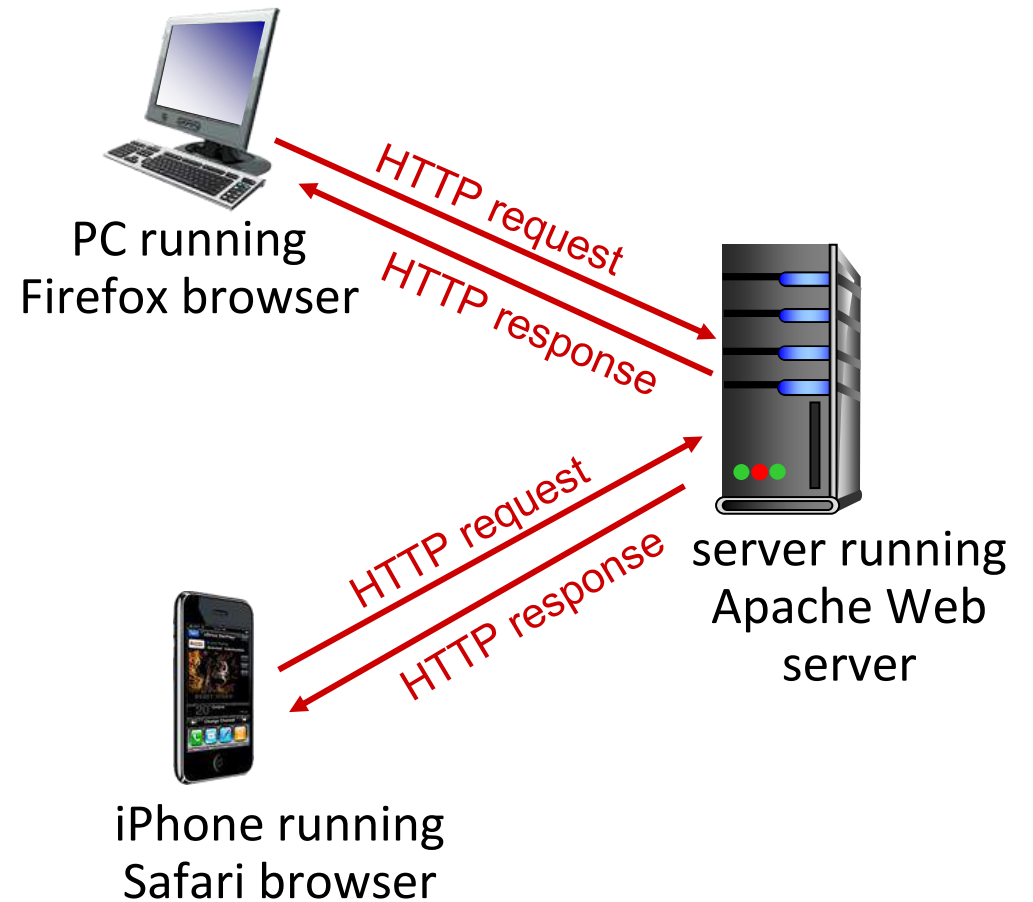
```
www.someschool.edu/someDept/pic.gif
```
    host name   path name

HTTP overview

HTTP: hypertext transfer protocol

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

PC running
Firefox browser

HTTP request
HTTP response

HTTP request
HTTP response

server running
Apache Web
server

iPhone running
Safari browser

HTTP overview (continued)

HTTP uses TCP:

- client initiates TCP connection (creates socket) to server, port 80

- server accepts TCP connection from client

- HTTP messages (application-layer protocol messages) exchanged between browser (HTTP client) and Web server (HTTP server)

- TCP connection closed

HTTP is "stateless"

- server maintains *no* information about past client requests

aside

protocols that maintain "state" are complex!

- past history (state) must be maintained

- if server/client crashes, their views of "state" may be inconsistent, must be reconciled

HTTP connections: two types

Non-persistent HTTP

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

downloading multiple objects required multiple connections

Persistent HTTP

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

Non-persistent HTTP: example

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

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

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

2. HTTP client sends HTTP *request message* (containing URL) into TCP connection socket. Message indicates that client wants object someDepartment/home.index
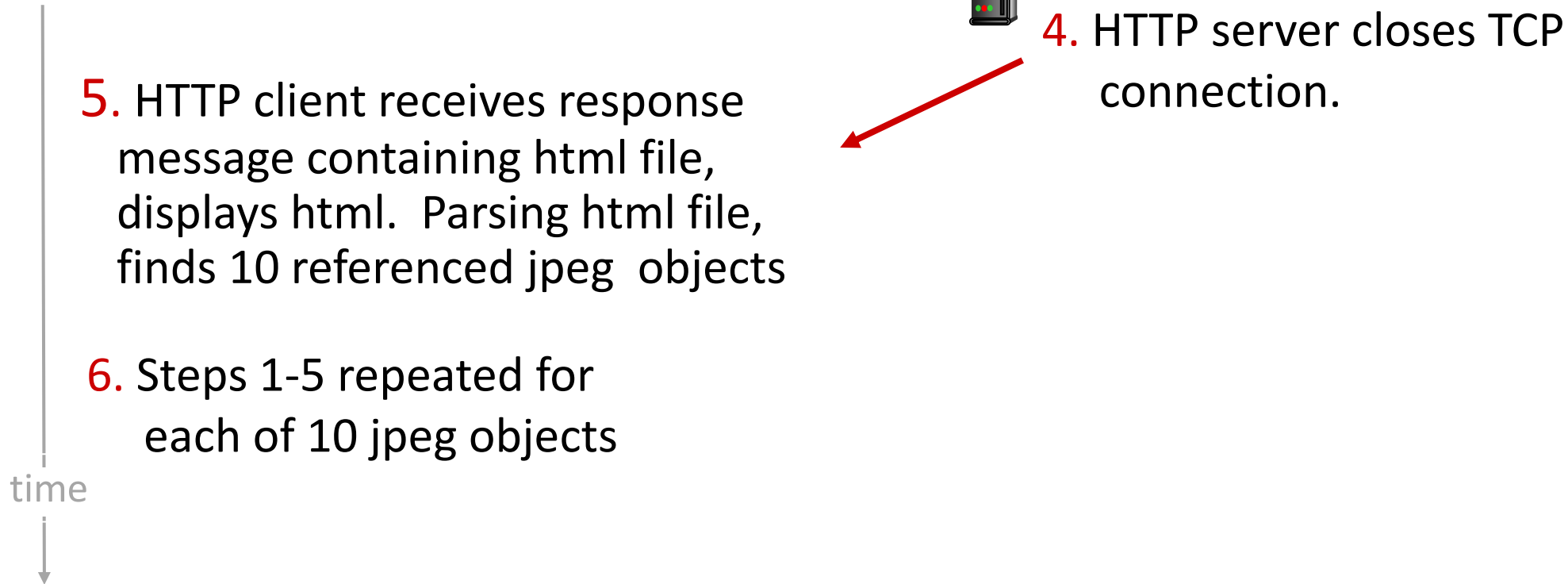
3. HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time

Non-persistent HTTP: example (cont.)

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

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
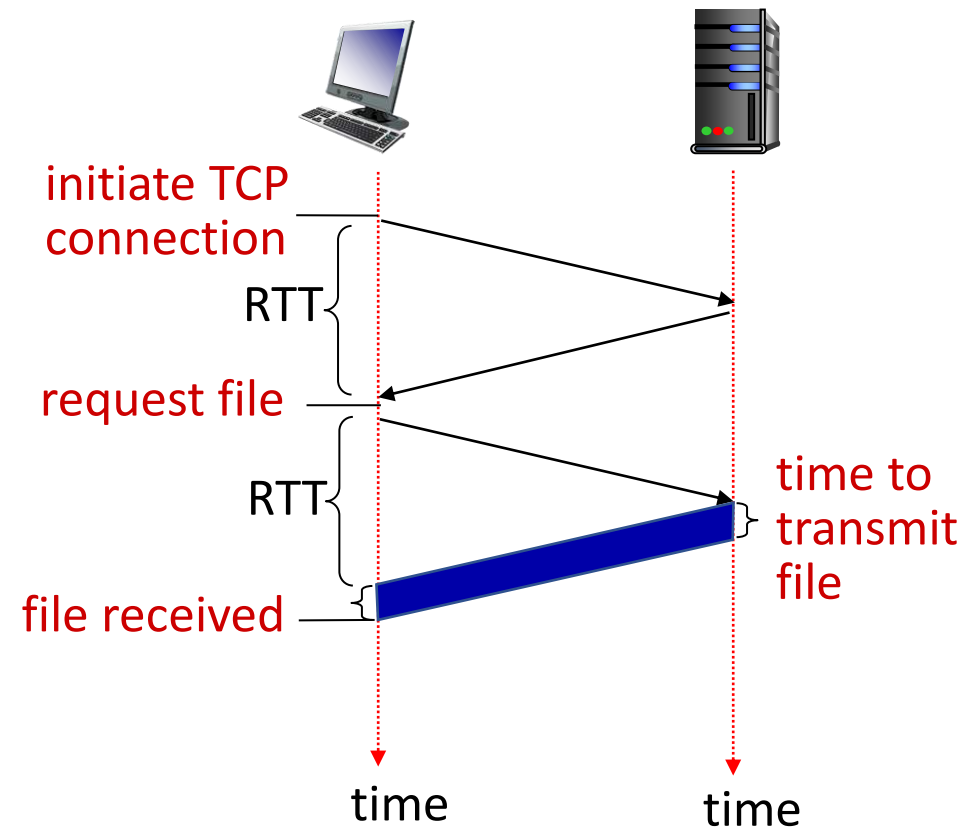
time

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*

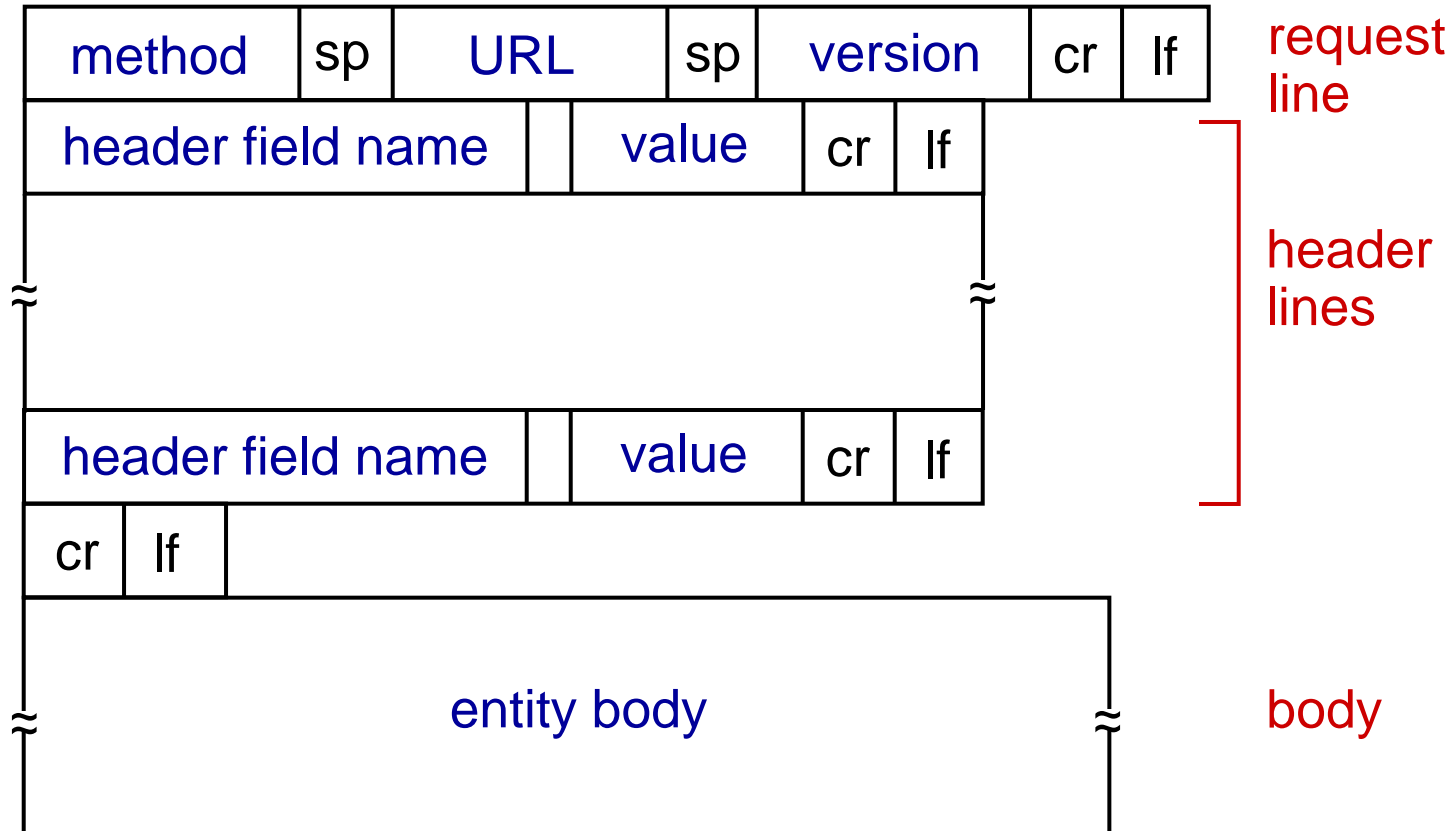- HTTP request message:
  - ASCII (human-readable format)

carriage return character
line-feed character

request line (GET, POST, HEAD commands)

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

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

HTTP request message: general format

method	sp	URL	sp	version	cr	lf	request line

header field name		value	cr	lf

~ ~

header field name		value	cr	lf

header lines

cr	lf

entity body

body

Other HTTP request messages

POST method:

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

GET method (for sending data to server):

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

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

HEAD method:

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

PUT method:

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

HTTP response message

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

HTTP response status codes

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

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

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

400 Bad Request
- request msg not understood by server

404 Not Found
- requested document not found on this server

505 HTTP Version Not Supported

Trying out HTTP (client side) for yourself

1. netcat to your favorite Web server:

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

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

2. type in a GET HTTP request:

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

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

3. look at response message sent by HTTP server!

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

Maintaining user/server state: cookies

Recall: HTTP GET/response interaction is *stateless*

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

a stateful protocol: client makes two changes to X, or none at all
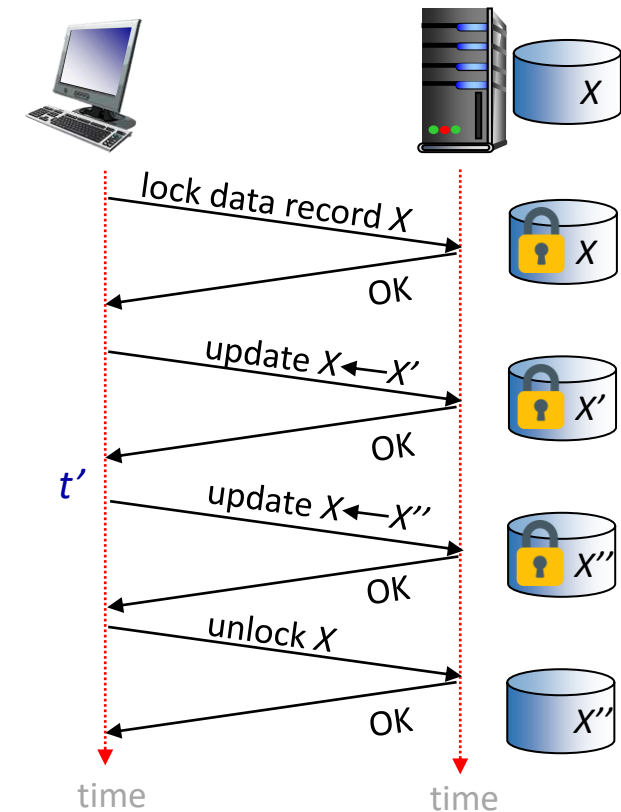
Q: what happens if network connection or client crashes at *t'* ?

Maintaining user/server state: cookies

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

four components:

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

Example:

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

Maintaining user/server state: cookies
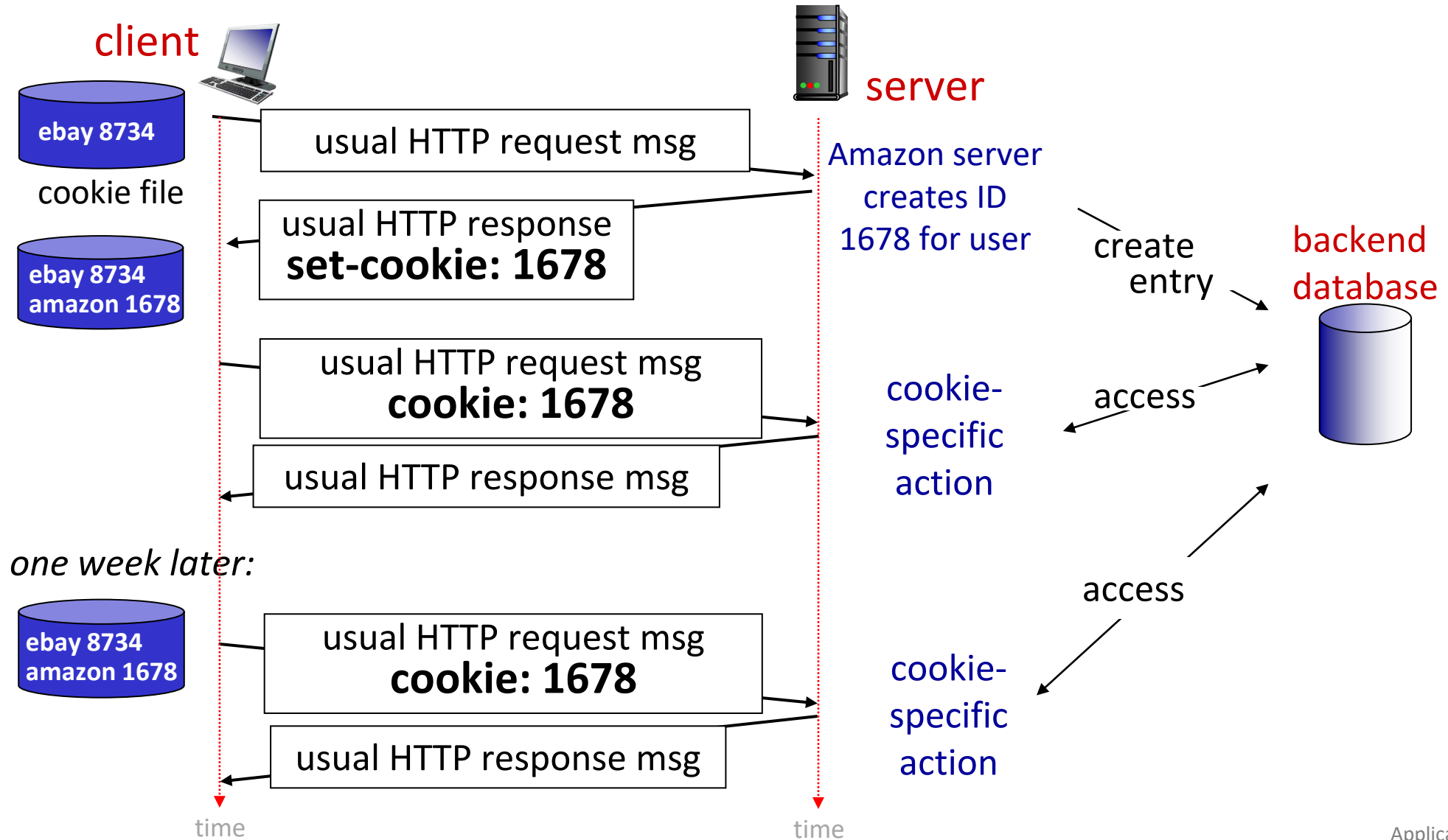
HTTP cookies: comments

What cookies can be used for:

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

Challenge: How to keep state?

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

cookies and privacy:

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

Web caches

Goal: satisfy client requests without involving origin server

- user configures browser to point to a (local) *Web cache*
- browser sends all HTTP requests to cache
  - *if* object in cache: cache returns object to client
  - *else* cache requests object from origin server, caches received object, then returns object to client
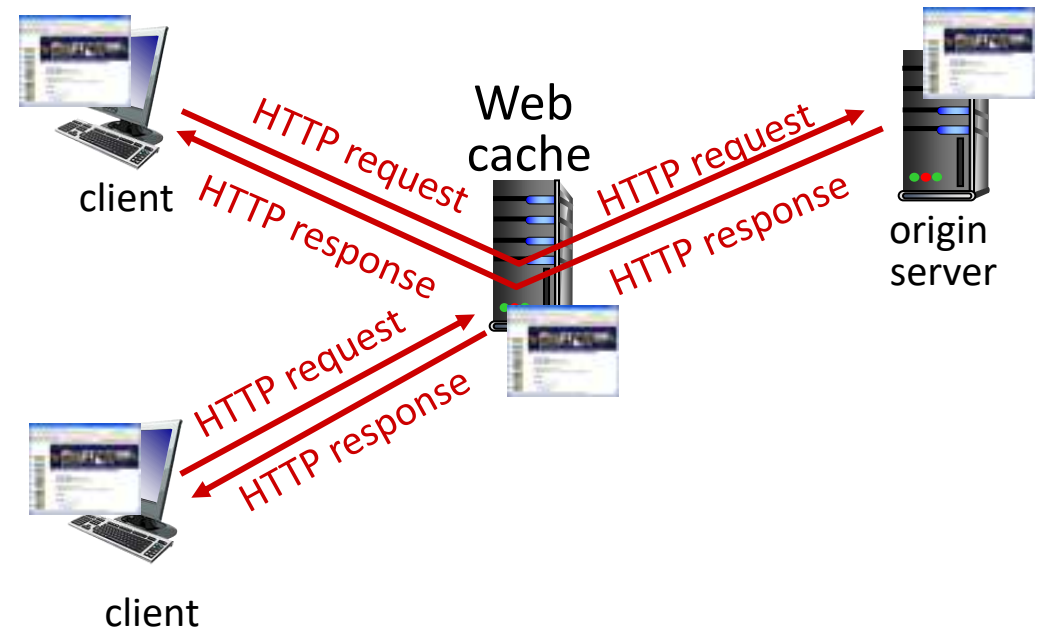
Web caches (aka proxy servers)

- Web cache acts as both client and server
  - server for original requesting client
  - client to origin server

- server tells cache about object's allowable caching in response header:

```
Cache-Control: max-age=<seconds>
```
```
Cache-Control: no-cache
```

Why Web caching?

- reduce response time for client request
  - cache is closer to client

- reduce traffic on an institution's access link

- Internet is dense with caches
  - enables "poor" content providers to more effectively deliver content
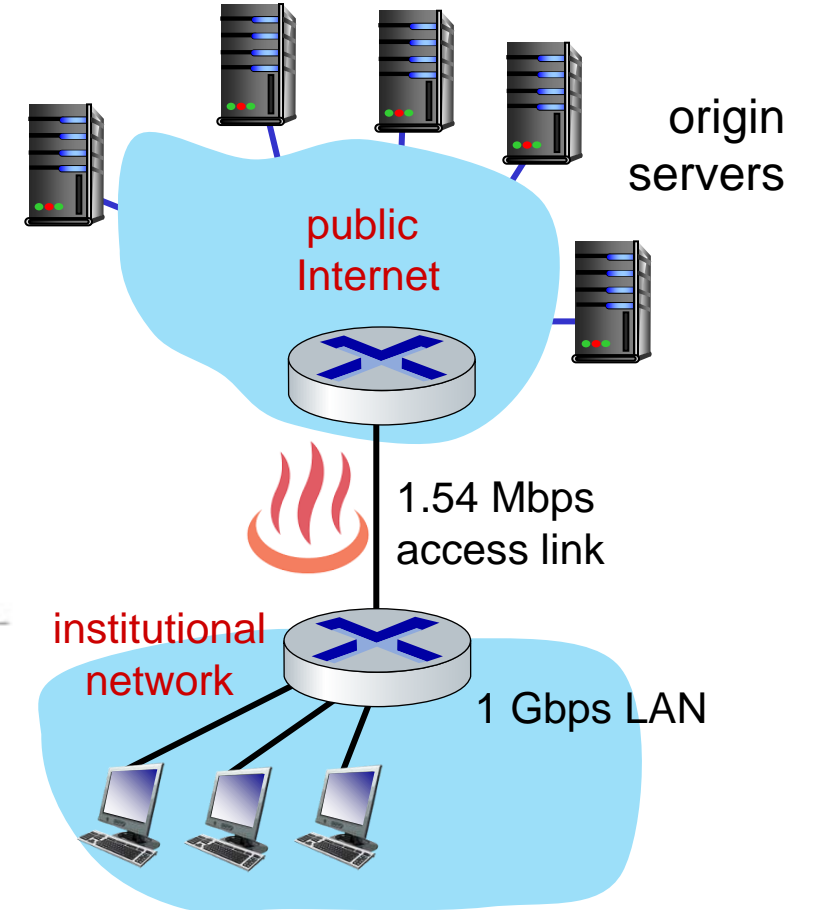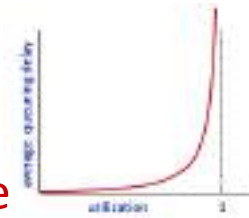
Caching example

Scenario:

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

Performance:

- access link utilization = .97   *problem:* large queueing delays at high utilization!
- LAN utilization: .0015
- end-end delay = Internet delay + access link delay + LAN delay
  = 2 sec + minutes + usecs

origin servers

public Internet

1.54 Mbps access link

institutional network

1 Gbps LAN

Option 1: buy a faster access link

Scenario:

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

Performance:

- access link utilization = ~~.97~~ → .0097
- LAN utilization: .0015
- end-end delay = Internet delay +
                    access link delay + LAN delay

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

Cost: faster access link (expensive!)

origin servers

public Internet

154 Mbps
1.54 Mbps
access link

institutional network

1 Gbps LAN

Option 2: install a web cache

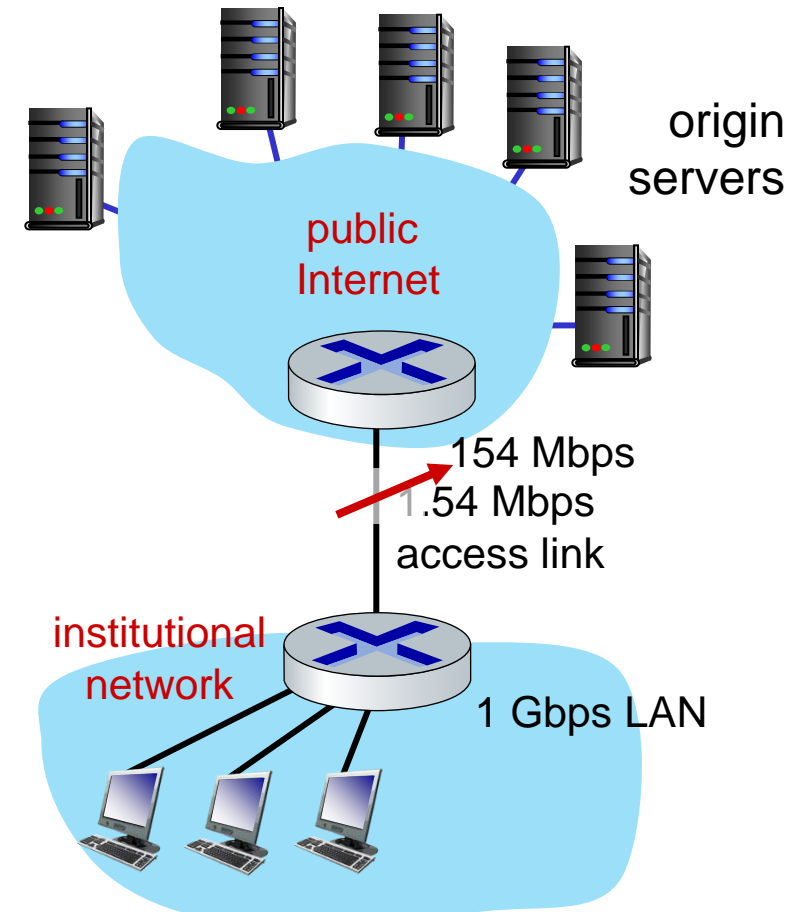*Scenario:*

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

Cost: web cache (cheap!)
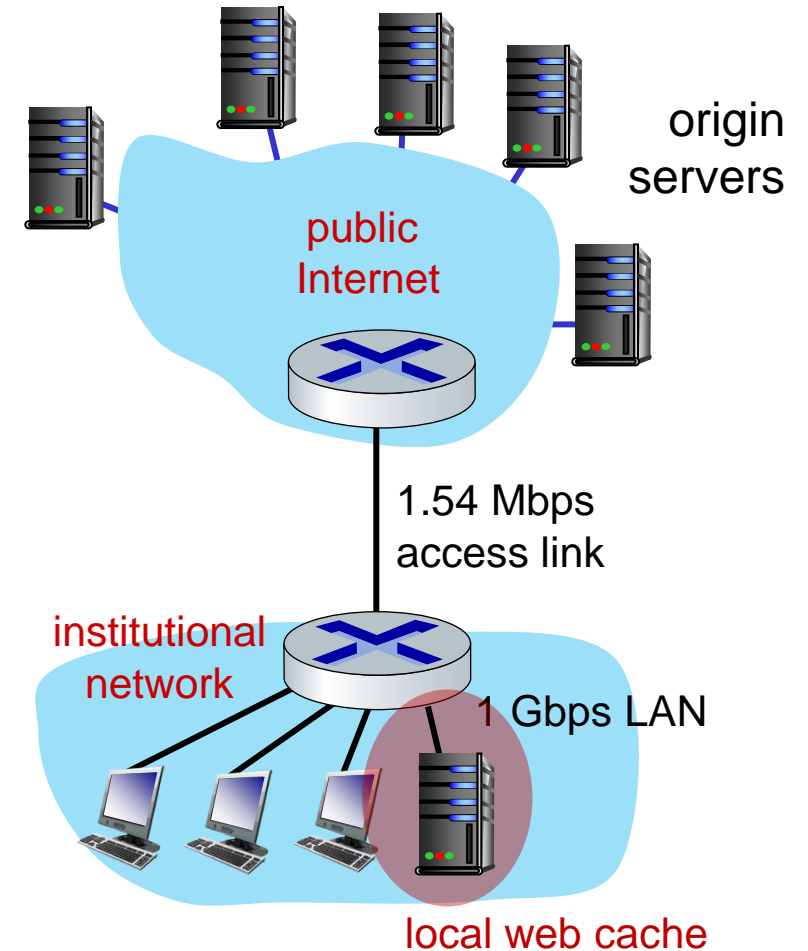
Performance:

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

How to compute link utilization, delay?

origin servers

public Internet

1.54 Mbps access link

institutional network

1 Gbps LAN

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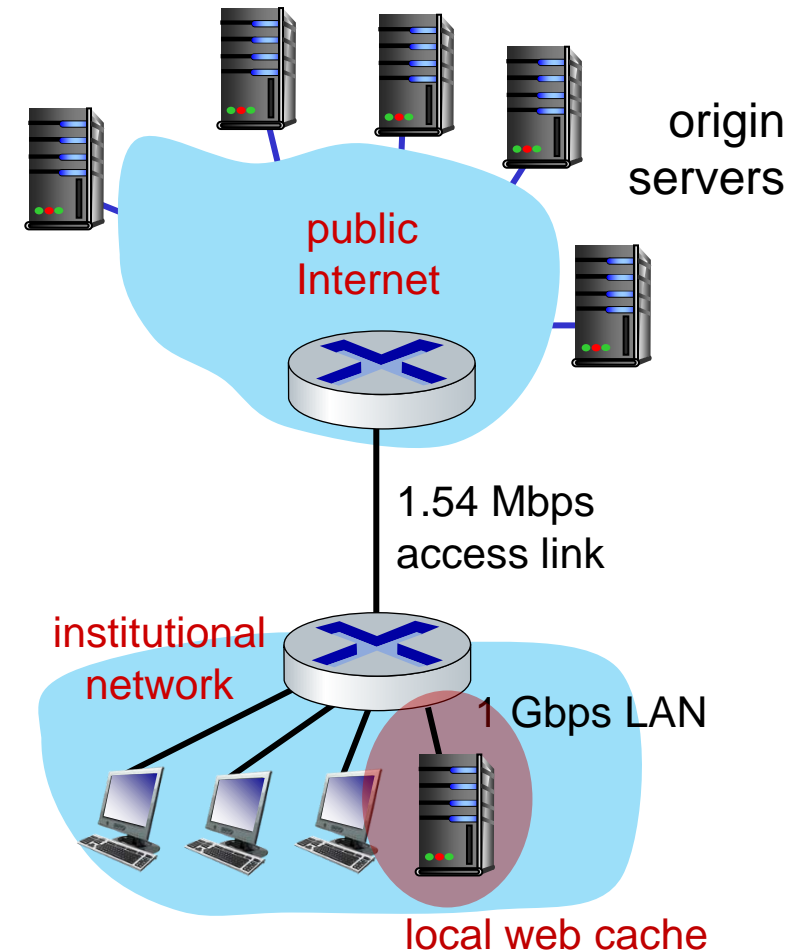
Calculating access link utilization, end-end delay with cache:

suppose cache hit rate is 0.4:

- 40% requests served by cache, with low (msec) delay

- 60% requests satisfied at origin

  - rate to browsers over access link

    = 0.6 * 1.50 Mbps = .9 Mbps

  - access link utilization = 0.9/1.54 = .58 means low (msec) queueing delay at access link

- average end-end delay:

  = 0.6 * (delay from origin servers)

      + 0.4 * (delay when satisfied at cache)

  = 0.6 (2.01) + 0.4 (~msecs) = ~ 1.2 secs

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

origin servers

public Internet

1.54 Mbps access link

institutional network

1 Gbps LAN

local web cache

Conditional GET

client   server

Goal: don't send object if cache has
up-to-date cached version
  - no object transmission delay (or use
    of network resources)

- *client:* specify date of cached copy
  in HTTP request
  If-modified-since: <date>

- *server:* response contains no
  object if cached copy is up-to-date:
  HTTP/1.0 304 Not Modified

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

object
not
modified
before
<date>

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

- -

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

object
modified
after
<date>

HTTP response
**HTTP/1.0 200 OK
<data>**
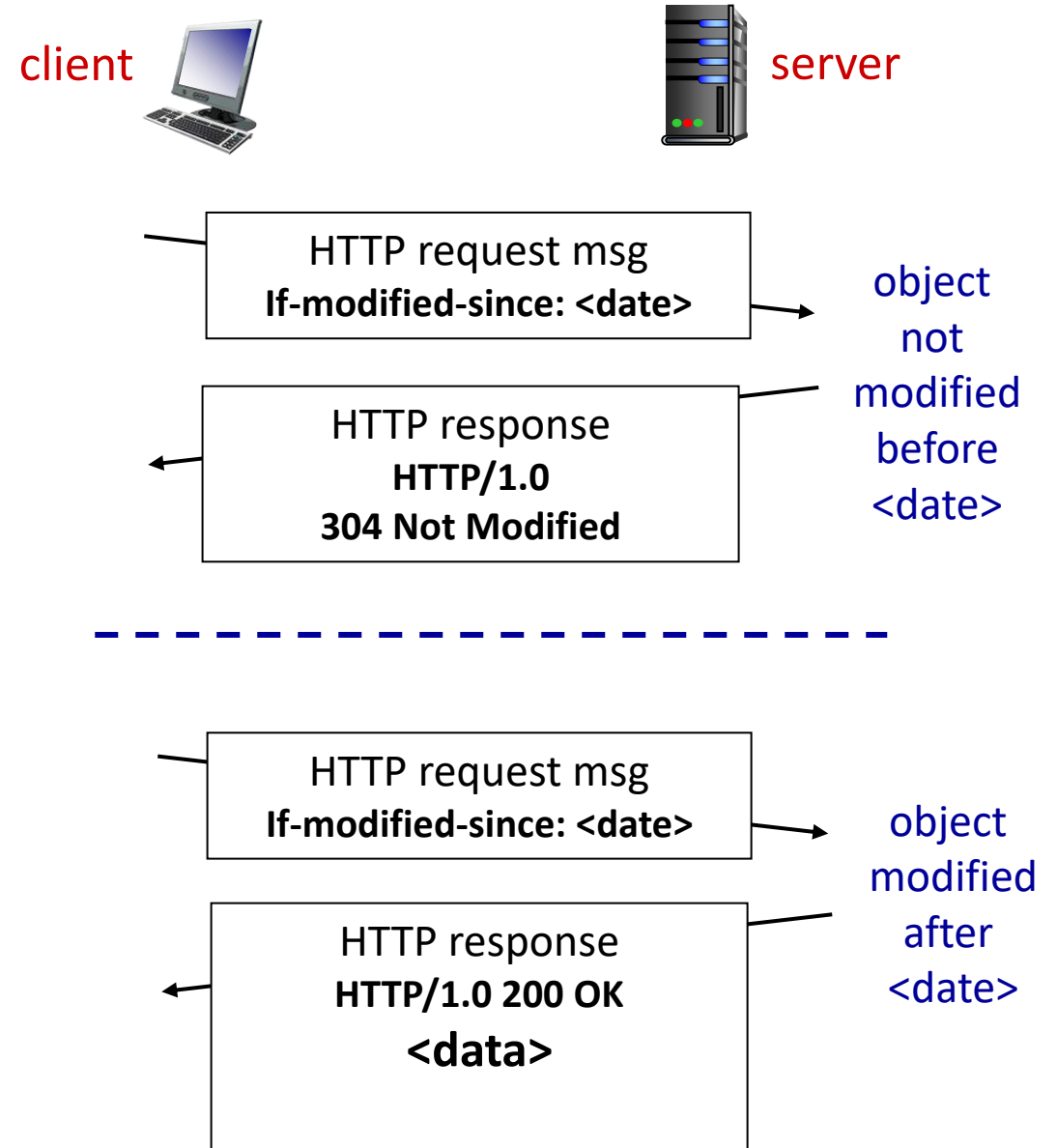
HTTP/2

Key goal: decreased delay in multi-object HTTP requests

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

- server responds *in-order* (FCFS: first-come-first-served scheduling) to GET requests

- with FCFS, small object may have to wait for transmission (head-of-line (HOL) blocking) behind large object(s)

- loss recovery (retransmitting lost TCP segments) stalls object transmission
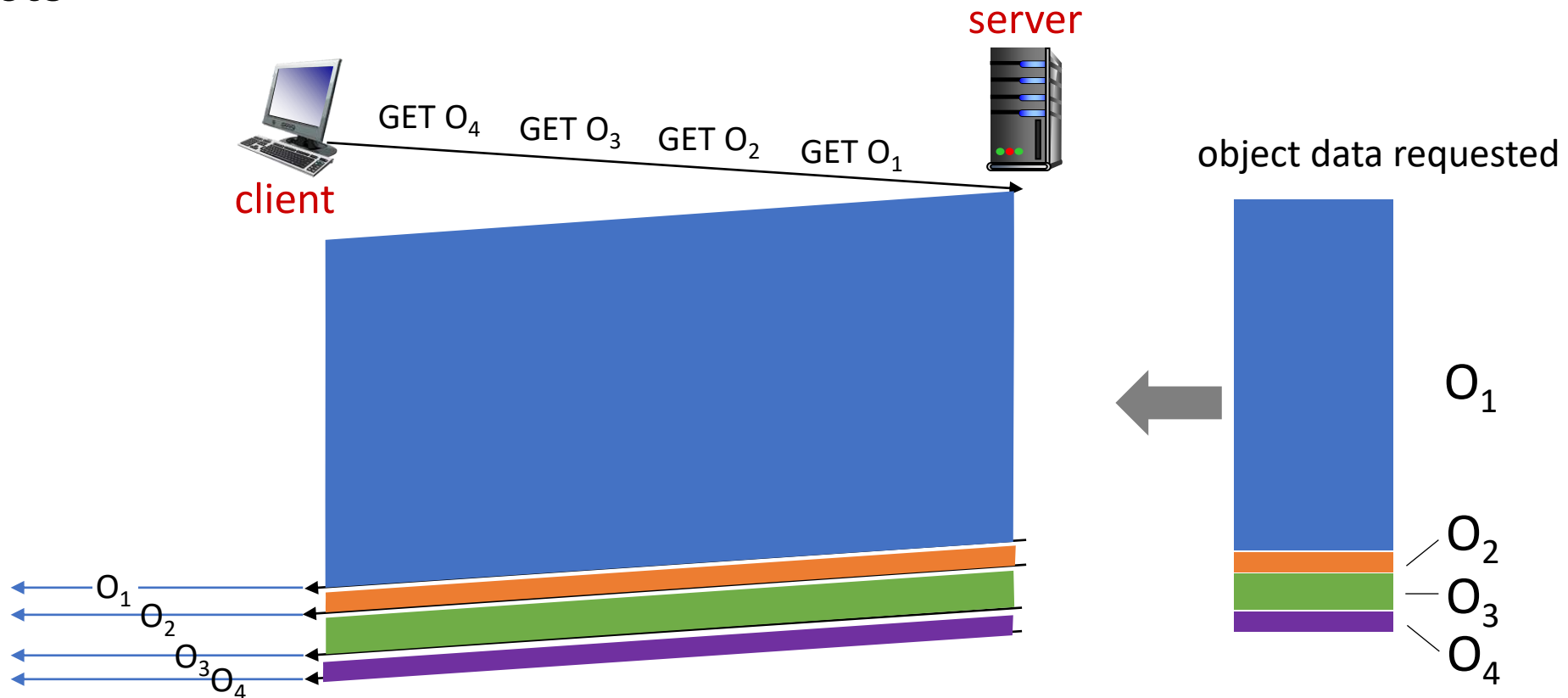
HTTP/2

Key goal: decreased delay in multi-object HTTP requests

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

- methods, status codes, most header fields unchanged from HTTP 1.1
- transmission order of requested objects based on client-specified object priority (not necessarily FCFS)
- *push* unrequested objects to client
- divide objects into frames, schedule frames to mitigate HOL blocking
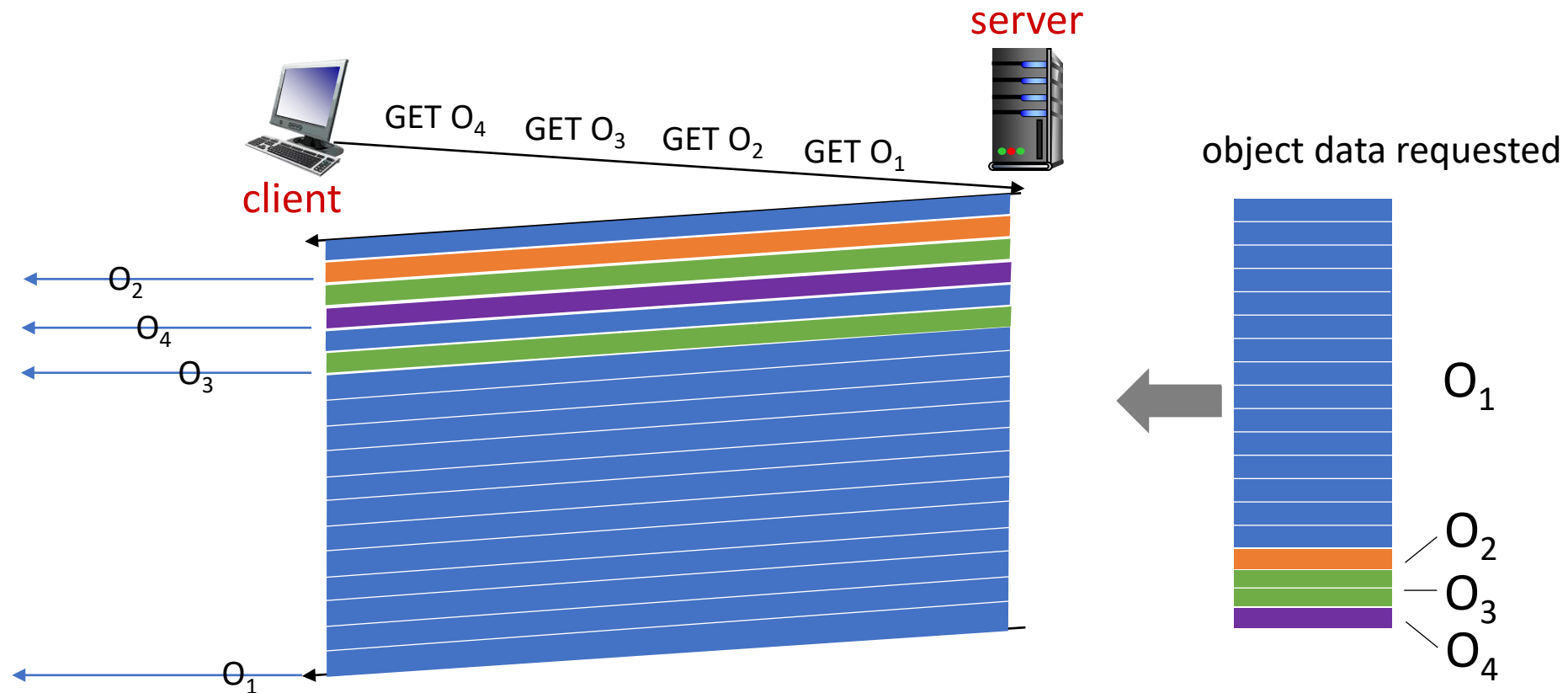
HTTP/2: mitigating HOL blocking

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

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

HTTP/2: mitigating HOL blocking

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

server

GET O_4 GET O_3 GET O_2 GET O_1

client

object data requested

O_2

O_4

O_3

O_1

O_2

O_3

O_4

O_1

O_2, O_3, O_4 delivered quickly, O_1 slightly delayed

HTTP/2 to HTTP/3

HTTP/2 over single TCP connection means:

- recovery from packet loss still stalls all object transmissions
  - as in HTTP 1.1, browsers have incentive to open multiple parallel TCP connections to reduce stalling, increase overall throughput

- no security over vanilla TCP connection

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

Application layer: overview

- Principles of network applications
- Web and HTTP
- **E-mail, SMTP, IMAP**
- The Domain Name System DNS

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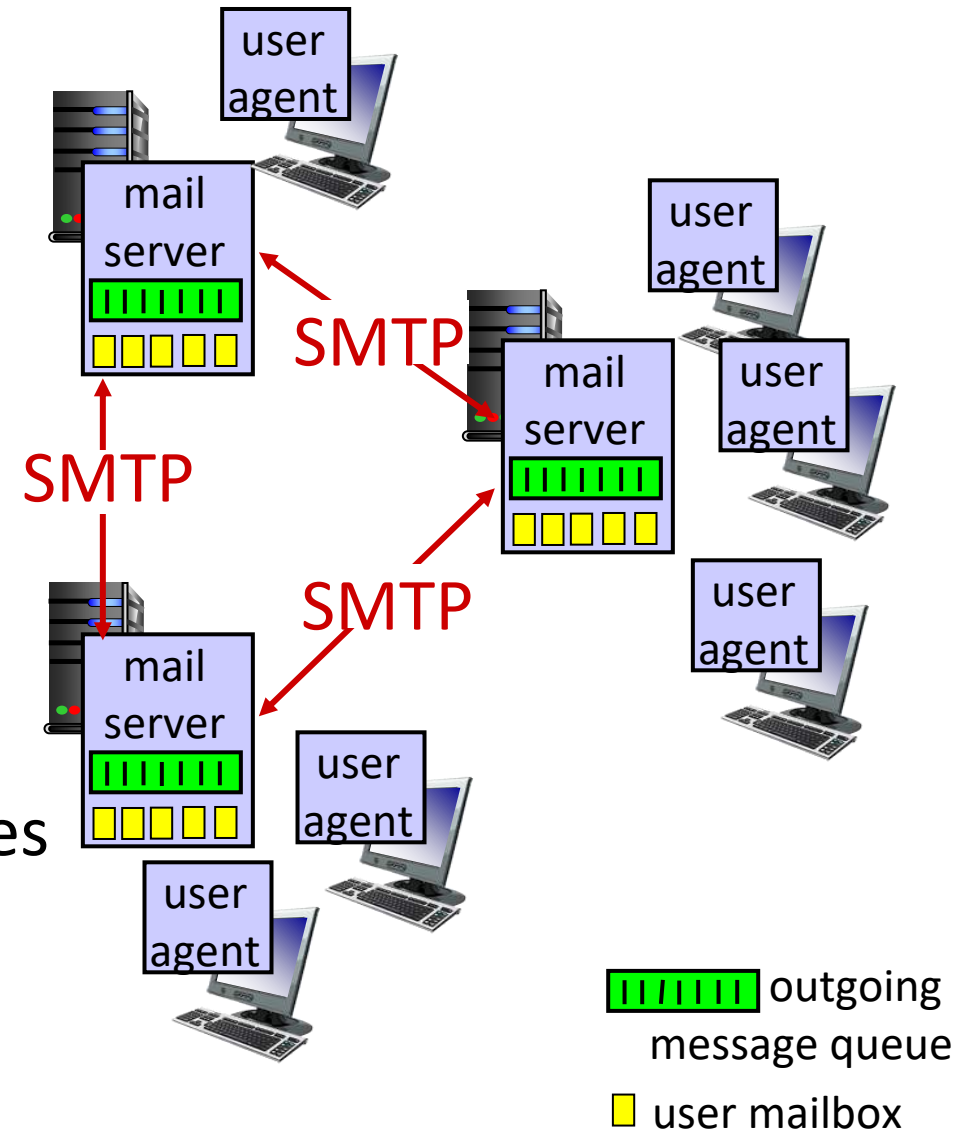- socket programming with UDP and TCP

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

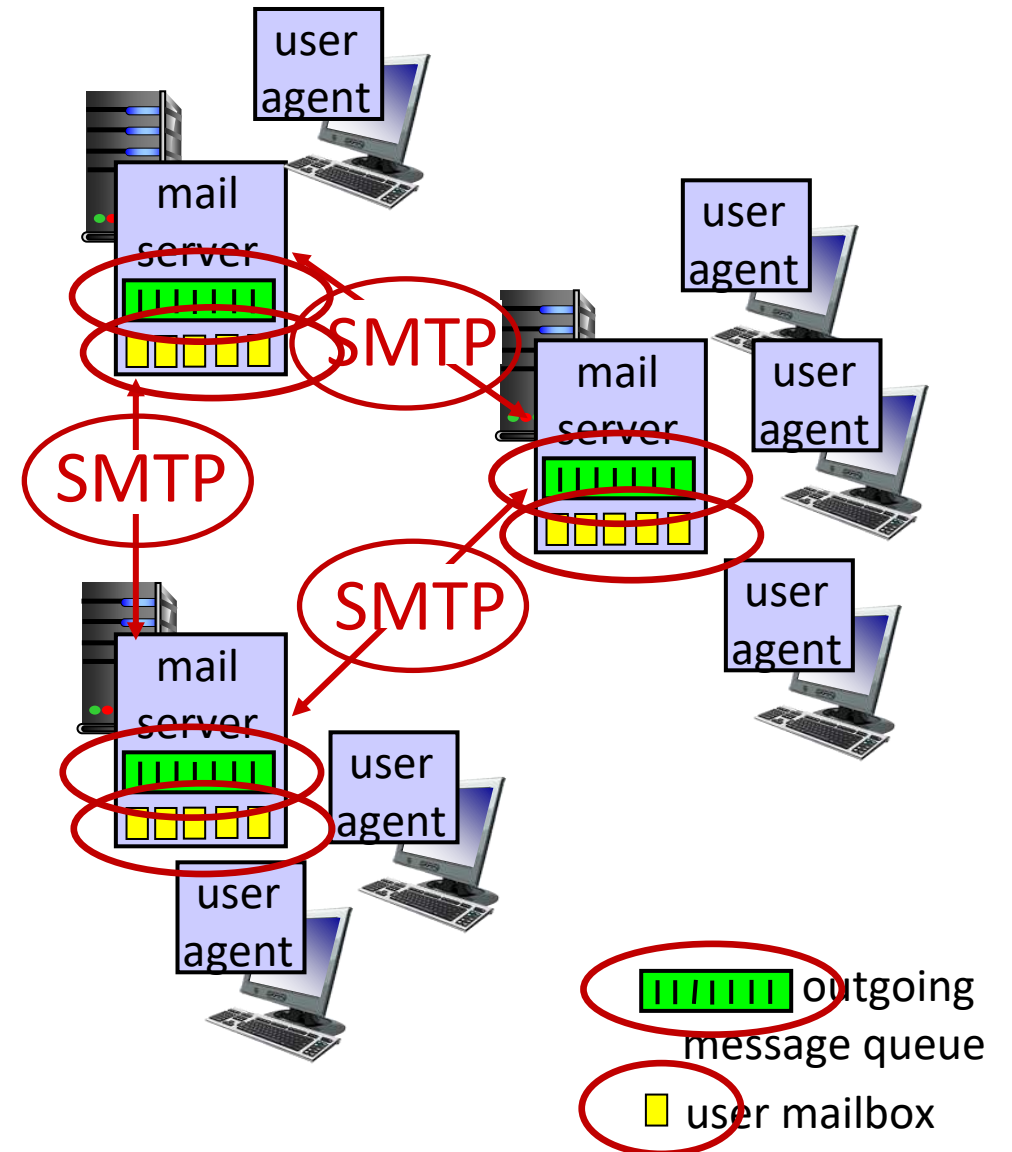outgoing message queue

user mailbox

E-mail: mail servers

mail servers:

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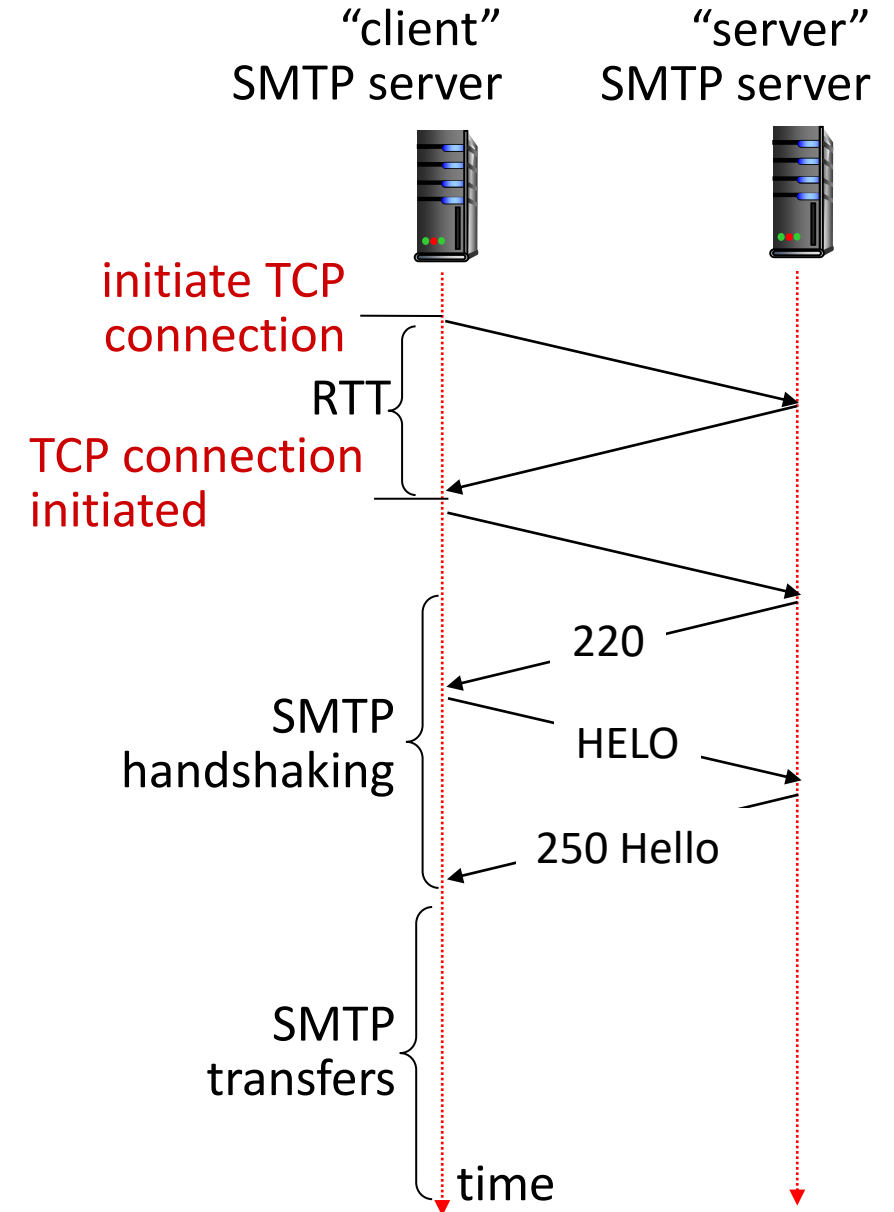
- *message queue* of outgoing (to be sent) mail messages

SMTP protocol between mail servers to send email messages

- client: sending mail server

- "server": receiving mail server

SMTP RFC (5321)

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

"client" SMTP server   "server" SMTP server

initiate TCP connection

RTT

TCP connection initiated

SMTP handshaking

220

HELO

250 Hello

SMTP transfers

time

Scenario: Alice sends e-mail to Bob

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

2) Alice's UA sends message to her mail server using SMTP; message placed in message queue

3) client side of SMTP at mail server opens TCP connection with Bob's mail server

4) SMTP client sends Alice's message over the TCP connection

5) Bob's mail server places the message in Bob's mailbox

6) Bob invokes his user agent to read message

Alice's mail server

Bob's mail server
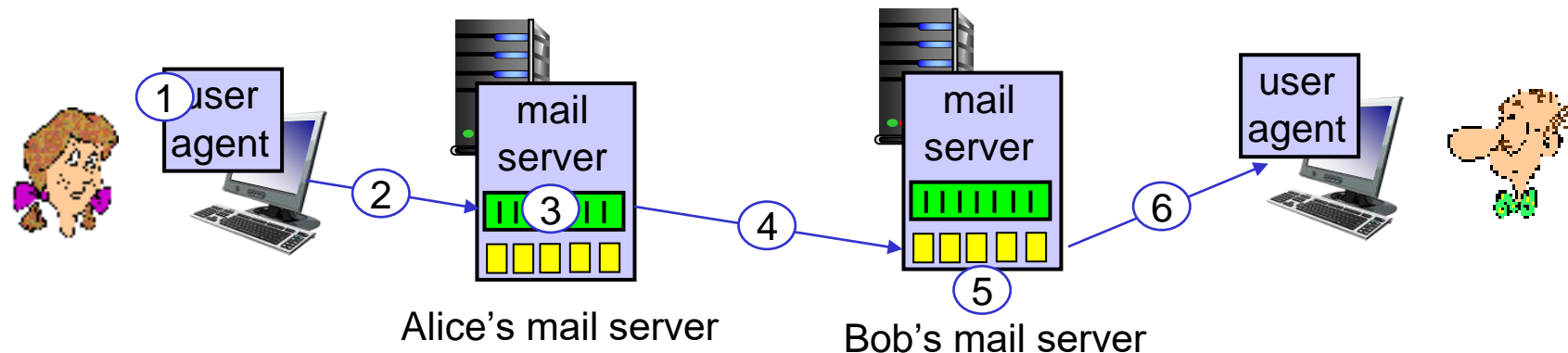
Sample SMTP interaction

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

SMTP: observations

*comparison with HTTP:*

- HTTP: client pull

- SMTP: client push

- both have ASCII command/response interaction, status codes

- HTTP: each object encapsulated in its own response message

- SMTP: multiple objects sent in multipart message

- SMTP uses persistent connections

- SMTP requires message (header & body) to be in 7-bit ASCII

- SMTP server uses CRLF.CRLF to determine end of message

Mail message format

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

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

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

  these lines, within the body of the email message area different from SMTP MAIL FROM:, RCPT TO: commands!

- Body: the "message" , ASCII characters only

header

blank line

body
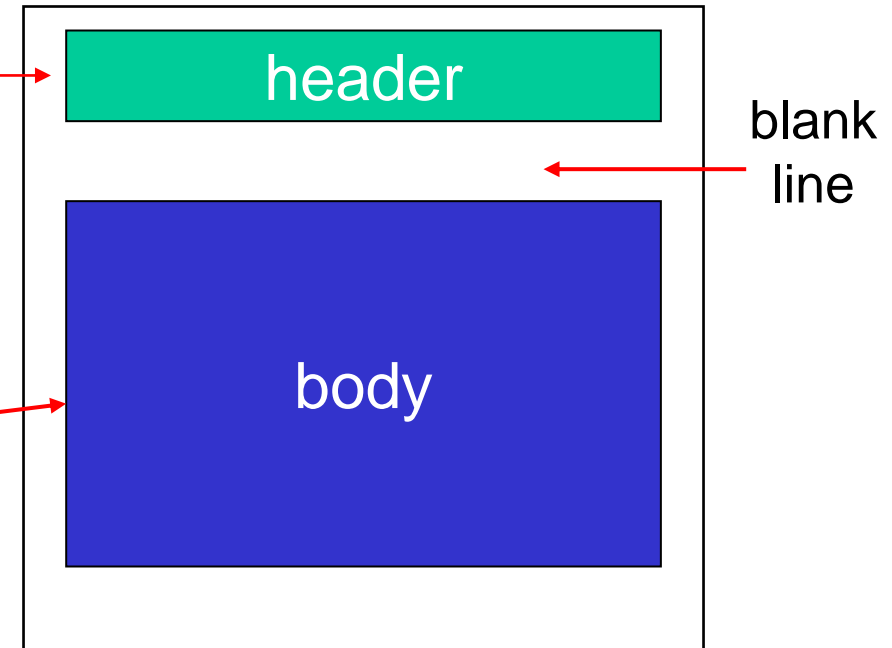
Retrieving email: mail access protocols
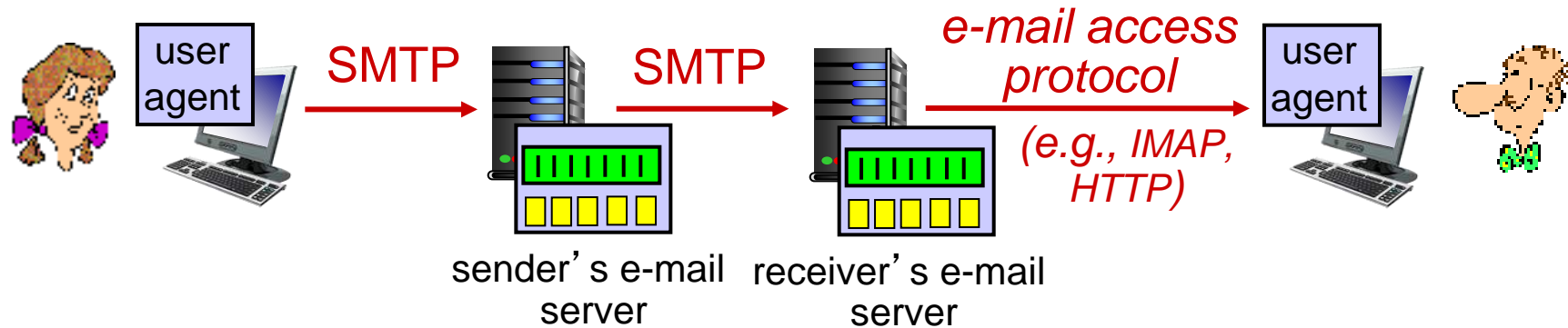
- **SMTP:** delivery/storage of e-mail messages to receiver's server

- **mail access protocol:** retrieval from server
  - **IMAP:** Internet Mail Access Protocol [RFC 3501]: messages stored on server, IMAP provides retrieval, deletion, folders of stored messages on server

- **HTTP:** gmail, Hotmail, Yahoo!Mail, etc. provides web-based interface on top of STMP (to send), IMAP (or POP) to retrieve e-mail messages

Application Layer: Overview

- Principles of network applications

- Web and HTTP

- E-mail, SMTP, IMAP

- **The Domain Name System DNS**

- P2P applications

- video streaming and content distribution networks

- socket programming with UDP and TCP

DNS: Domain Name System

people: many identifiers:

- SSN, name, passport #

Internet hosts, routers:

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

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

Domain Name System (DNS):

- *distributed database* implemented in hierarchy of many *name servers*

- *application-layer protocol:* hosts, DNS servers communicate to *resolve* names (address/name translation)

  - *note:* core Internet function, implemented as application-layer protocol

  - complexity at network's "edge"

DNS: services, structure

DNS services:

- hostname-to-IP-address translation

- host aliasing
  - canonical, alias names

- mail server aliasing

- load distribution
  - replicated Web servers: many IP addresses correspond to one name

Q: Why not centralize DNS?

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

A: doesn't scale!

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

Thinking about the DNS

humongous distributed database:
- ~ billion records, each simple

handles many *trillions* of queries/day:
- *many* more reads than writes
- *performance matters:* almost every Internet transaction interacts with DNS - msecs count!
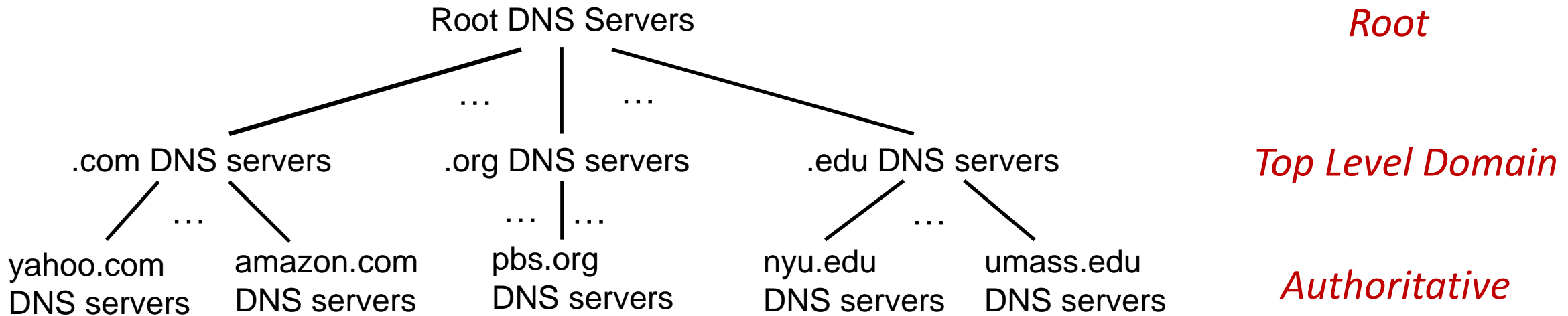
organizationally, physically decentralized:
- millions of different organizations responsible for their records

"bulletproof": reliability, security

DNS: a distributed, hierarchical database

Root DNS Servers   *Root*

.com DNS servers   .org DNS servers   .edu DNS servers   *Top Level Domain*

yahoo.com   amazon.com   pbs.org   nyu.edu   umass.edu   *Authoritative*
DNS servers   DNS servers   DNS servers   DNS servers   DNS servers
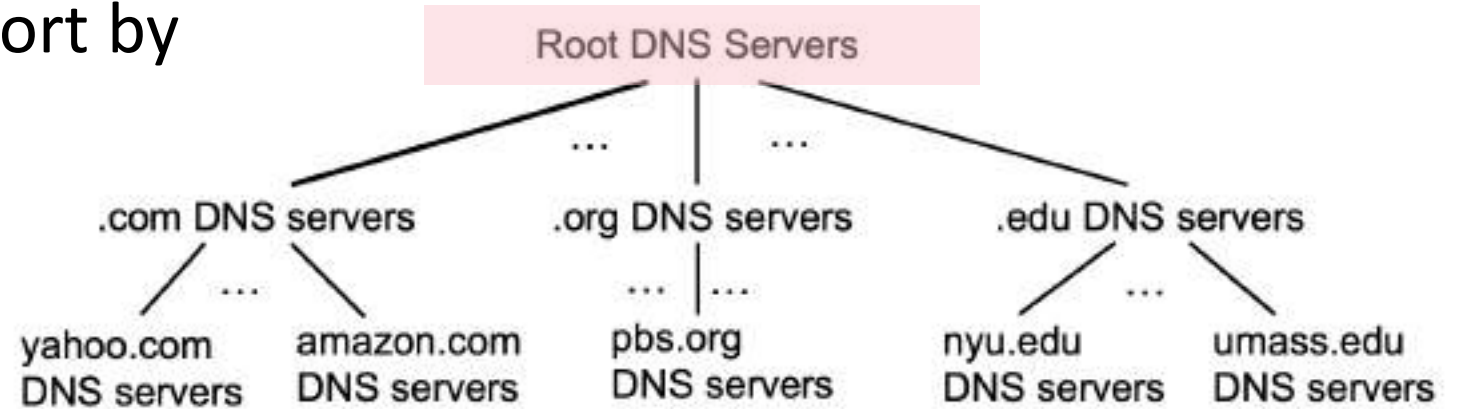
Client wants IP address for www.amazon.com; 1ˢᵗ approximation:

- 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

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

DNS: root name servers

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

- *incredibly important* Internet function
  - Internet couldn't function without it!
  - DNSSEC – provides security (authentication, message integrity)

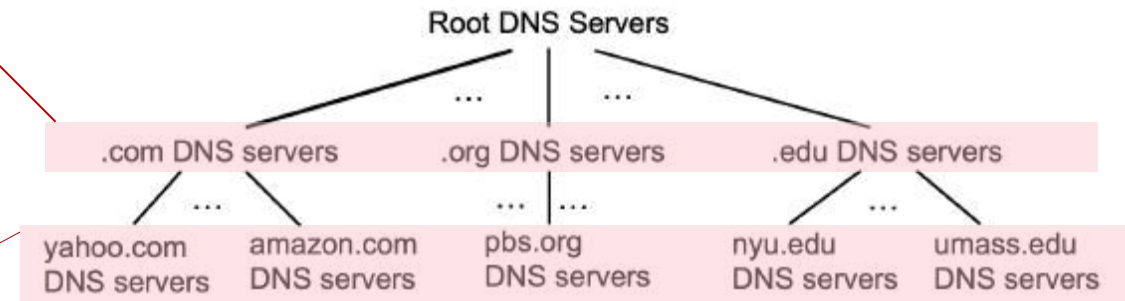- ICANN (Internet Corporation for Assigned Names and Numbers) manages root DNS domain

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

Key:
- ☐ 0 Servers
- ☐ 1–10 Servers
- ☐ 11–20 Servers
- ☐ 21+ Servers

Top-Level Domain, and authoritative servers

Top-Level Domain (TLD) servers:

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

Root DNS Servers

.com DNS servers   .org DNS servers   .edu DNS servers

yahoo.com   amazon.com   pbs.org   nyu.edu   umass.edu
DNS servers   DNS servers   DNS servers DNS servers DNS servers

authoritative DNS servers:

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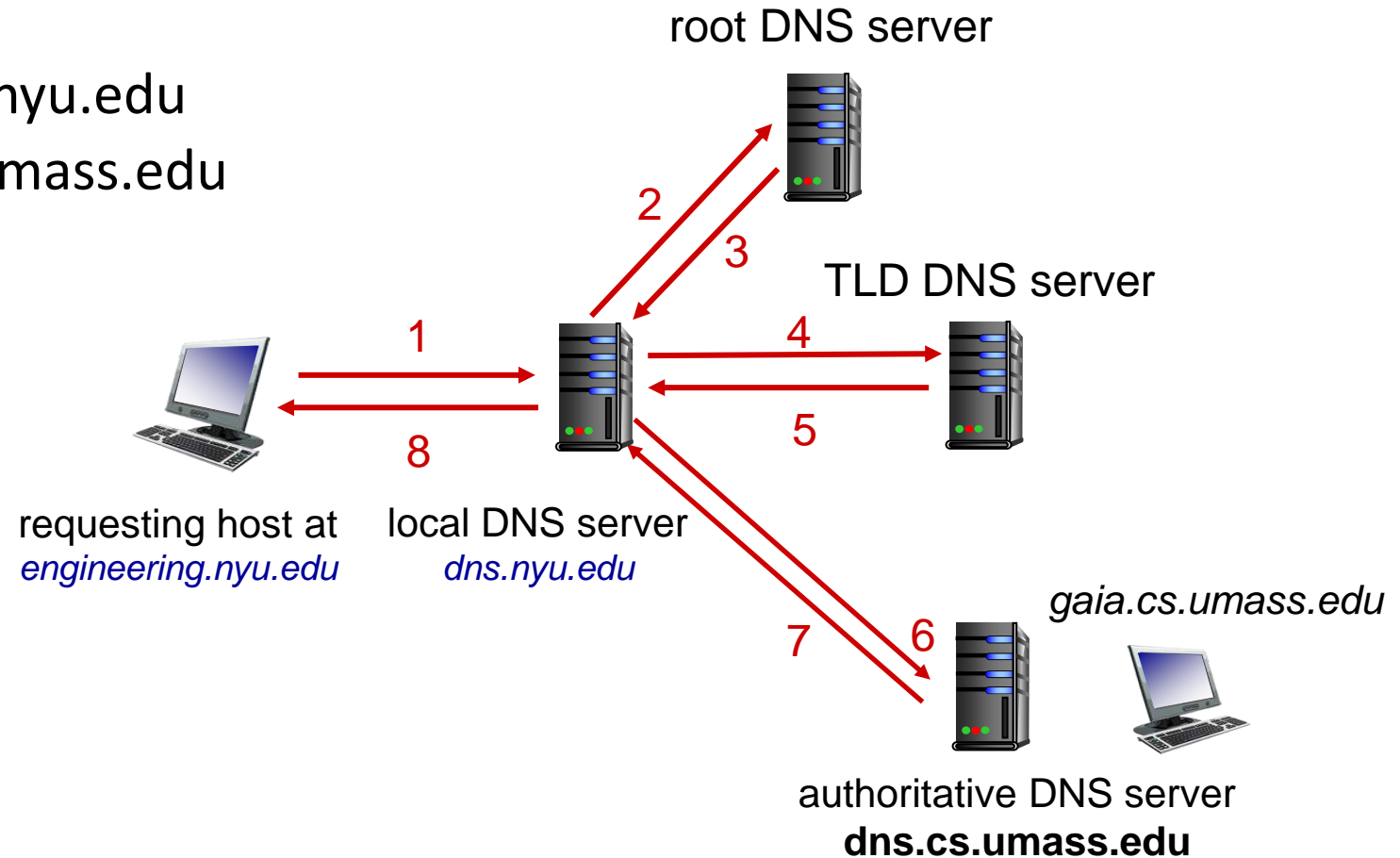
Local DNS name servers

- when host makes DNS query, it is sent to its *local* DNS server
  - Local DNS server returns reply, answering:
    - from its local cache of recent name-to-address translation pairs (possibly out of date!)
    - forwarding request into DNS hierarchy for resolution
  - each ISP has local DNS name server; to find yours:
    - MacOS: % scutil --dns
    - Windows: >ipconfig /all

- local DNS server doesn't strictly belong to hierarchy

DNS name resolution: iterated query

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

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

root DNS server

2

3

TLD DNS server

1

4

8

5

requesting host at
engineering.nyu.edu

local DNS server
dns.nyu.edu

gaia.cs.umass.edu
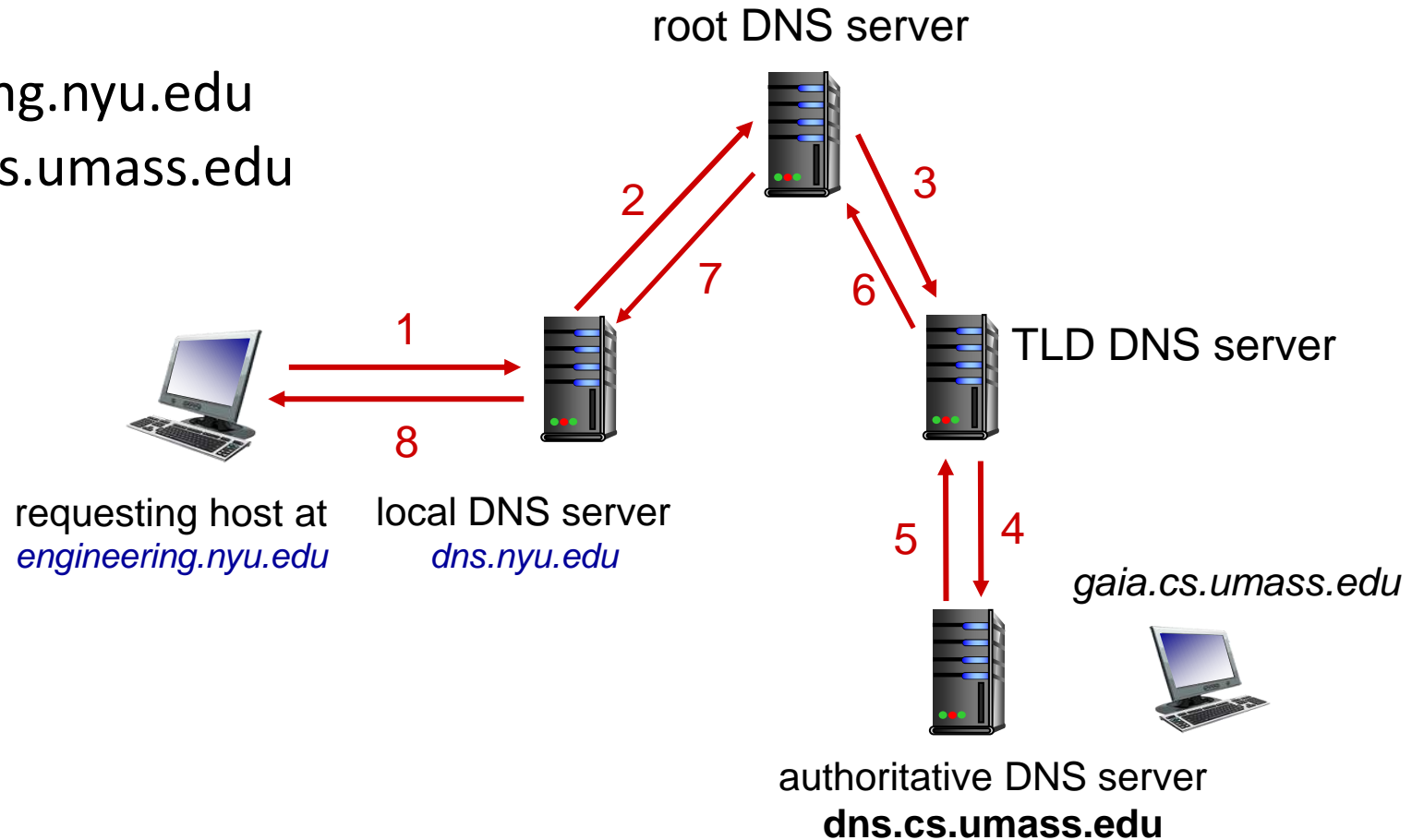
7

6

authoritative DNS server
dns.cs.umass.edu

DNS name resolution: recursive query

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

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

root DNS server

2   3
7   6

1
requesting host at
engineering.nyu.edu

8
local DNS server
dns.nyu.edu

TLD DNS server

5   4

gaia.cs.umass.edu

authoritative DNS server
dns.cs.umass.edu

Caching DNS Information

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

DNS records

DNS: distributed database storing resource records (RR)

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

type=A
- name is hostname
- value is IP address

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

type=CNAME
- name is alias name for some "canonical" (the real) name
- www.ibm.com is really servereast.backup2.ibm.com
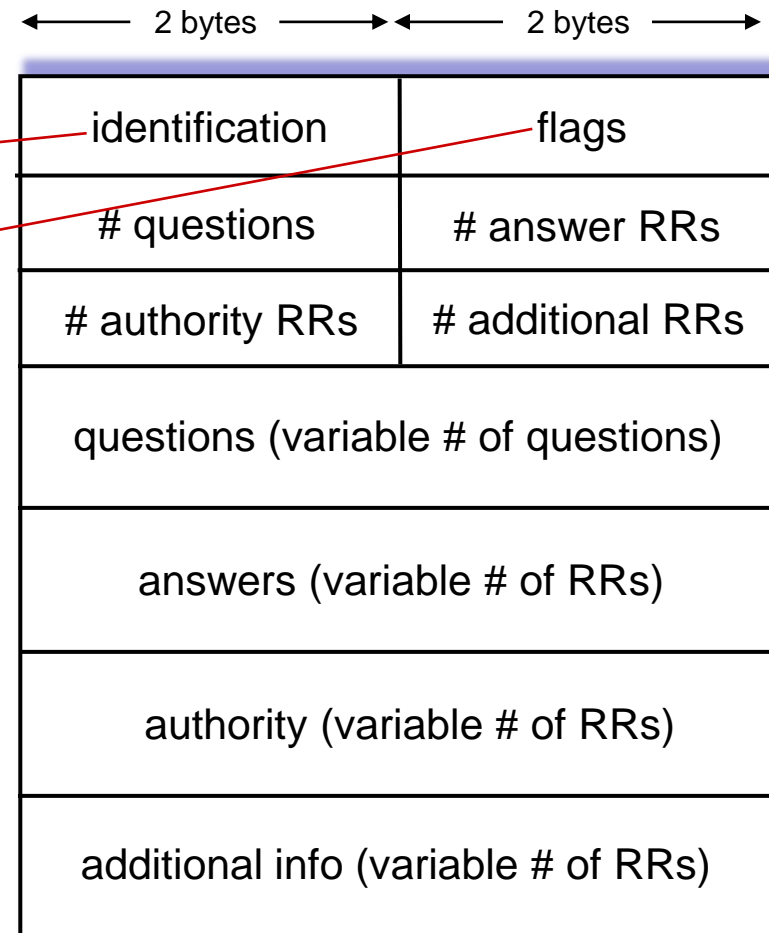- value is canonical name

type=MX
- value is name of SMTP mail server associated with name

DNS protocol messages

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

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

← 2 bytes →	← 2 bytes →
identification	flags
# questions	# answer RRs
# authority RRs	# additional RRs
questions (variable # of questions)	
answers (variable # of RRs)	
authority (variable # of RRs)	
additional info (variable # of RRs)	

DNS protocol messages

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

← 2 bytes →	← 2 bytes →
identification	flags
# questions	# answer RRs
# authority RRs	# additional RRs
questions (variable # of questions)	
answers (variable # of RRs)	
authority (variable # of RRs)	
additional info (variable # of RRs)	

name, type fields for a query ——— questions (variable # of questions)

RRs in response to query ——— answers (variable # of RRs)

records for authoritative servers ——— authority (variable # of RRs)

additional " helpful" info that may be used ——— additional info (variable # of RRs)

Getting your info into the DNS

example: new startup "Network Utopia"

- register name networkuptopia.com at *DNS registrar* (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts NS, A RRs into .com TLD server:
    (networkutopia.com, dns1.networkutopia.com, NS)
    (dns1.networkutopia.com, 212.212.212.1, A)

- create authoritative server locally with IP address 212.212.212.1
  - type A record for www.networkuptopia.com
  - type MX record for networkutopia.com

DNS security

DDoS attacks

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

- **bombard TLD servers**
  - potentially more dangerous

Spoofing attacks

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

Application Layer: Overview

- Principles of network applications
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- **P2P applications**
- video streaming and content distribution networks
- socket programming with UDP and TCP
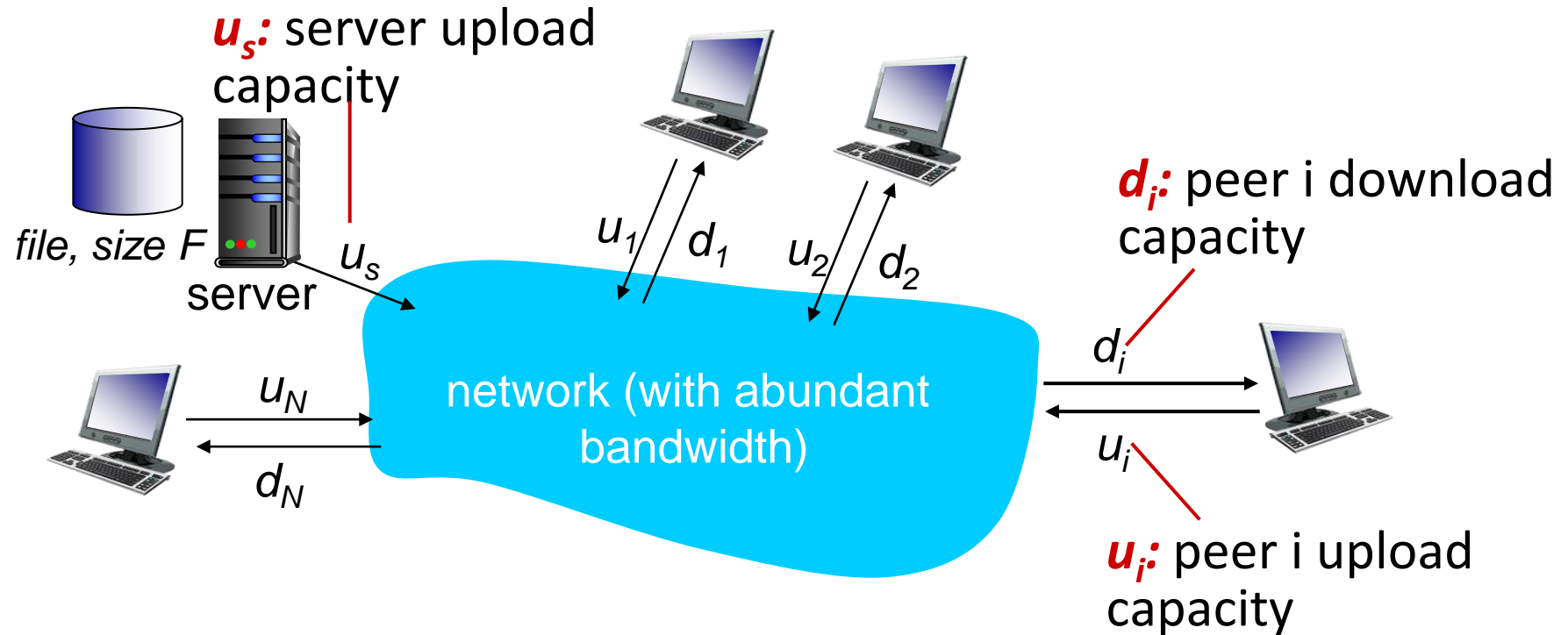
Peer-to-peer (P2P) architecture

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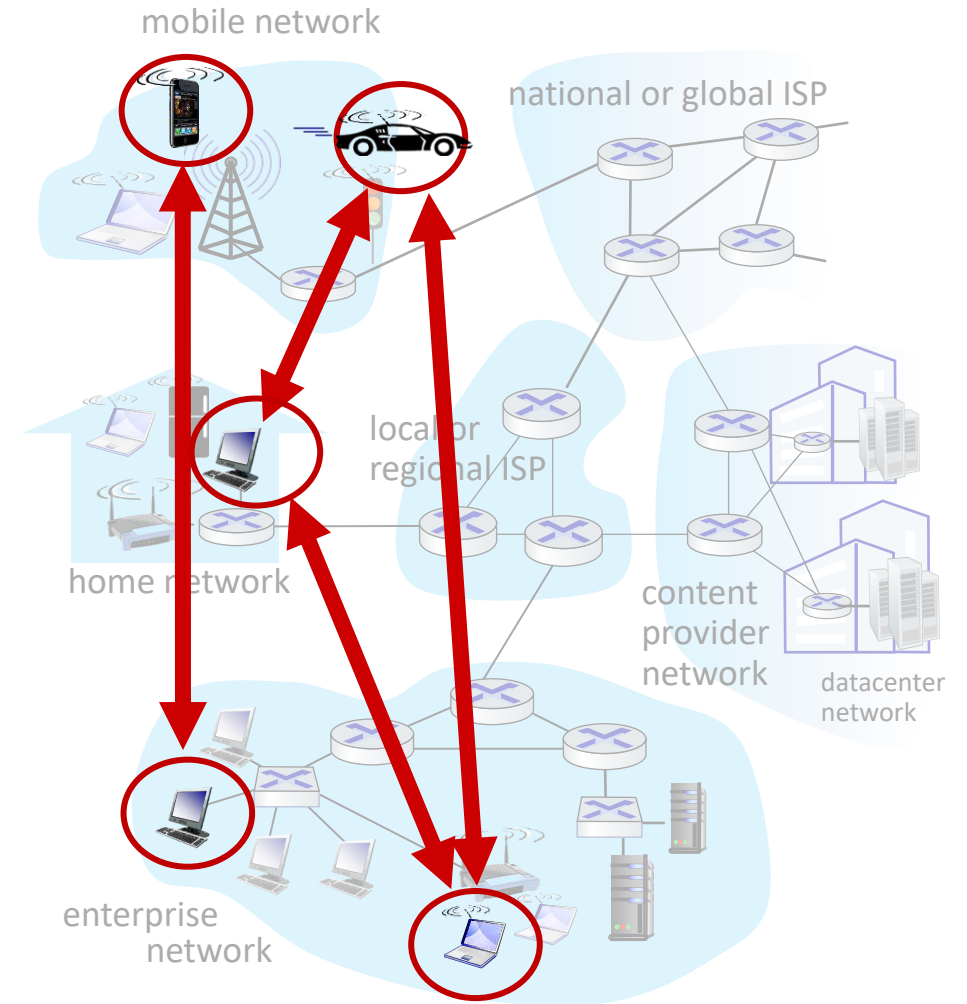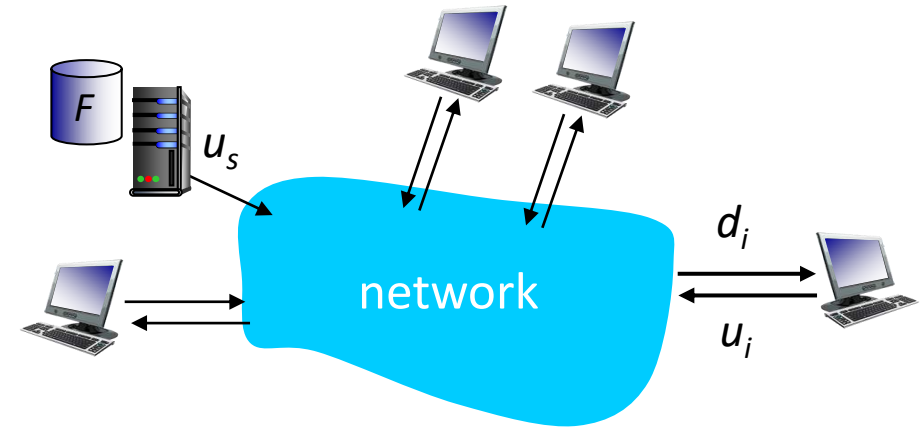
File distribution: client-server vs P2P

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

- peer upload/download capacity is limited resource

u_s: server upload capacity

d_i: peer i download capacity

u_i: peer i upload capacity

file, size F

server

network (with abundant bandwidth)

File distribution time: client-server

- *server transmission:* must sequentially send (upload) N file copies:
  - time to send one copy: F/u_s
  - time to send N copies: NF/u_s

- *client:* each client must download file copy
  - d_{min} = min client download rate
 - min client download time: F/d_{min}

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

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

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
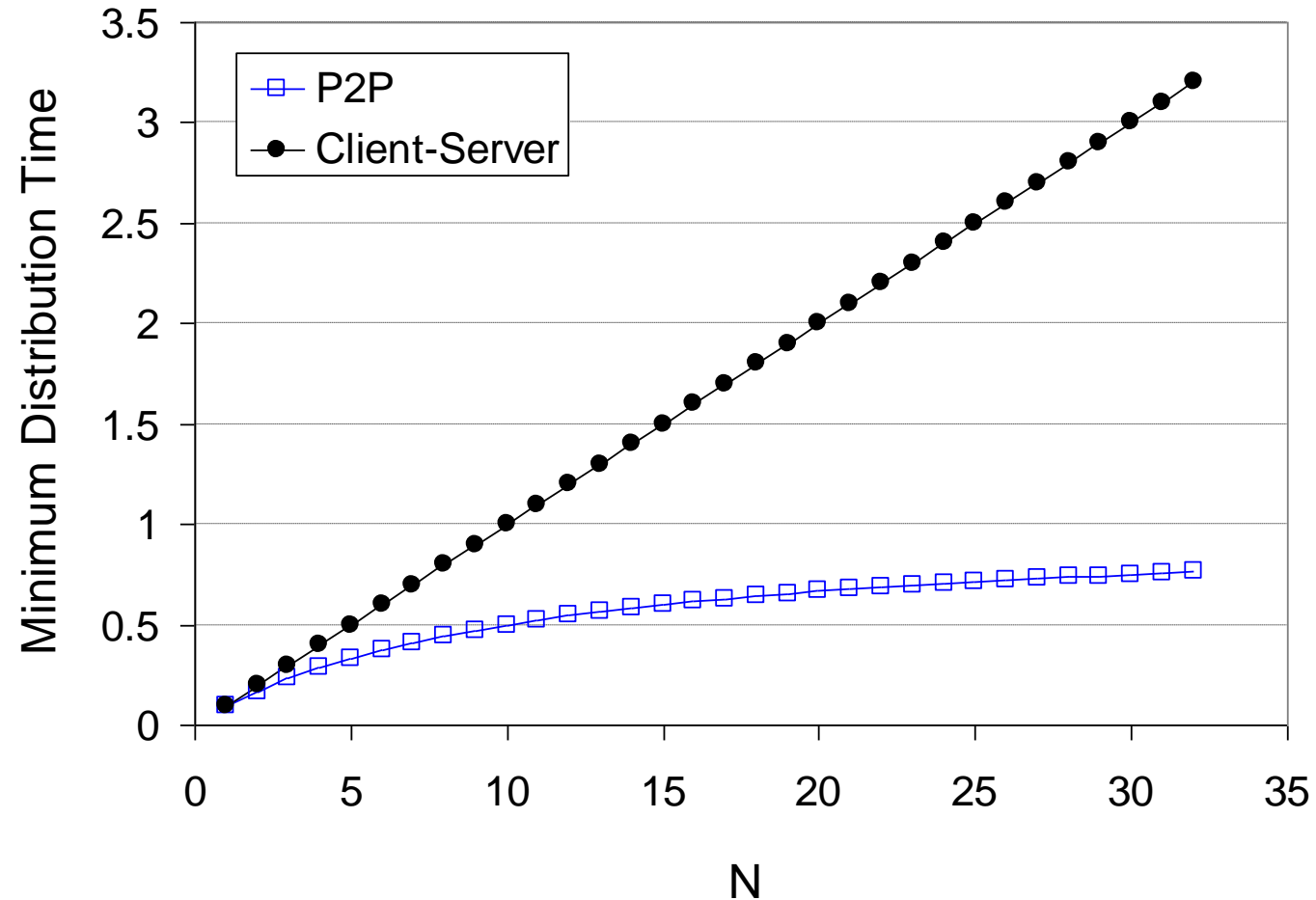 - max upload rate (limiting max download rate) is $u_s + \Sigma u_i$
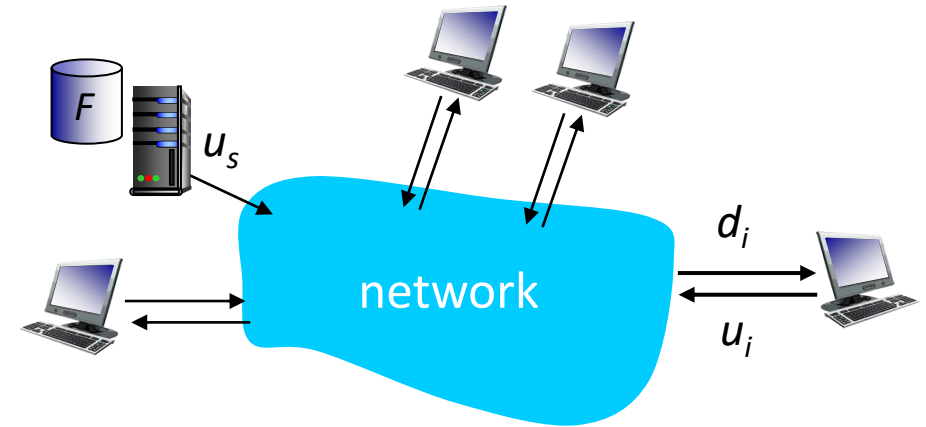
time to distribute F to N clients using P2P approach

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

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

Client-server vs. P2P: example

client upload rate = u, F/u = 1 hour, $u_s = 10u$, $d_{min} \geq u_s$
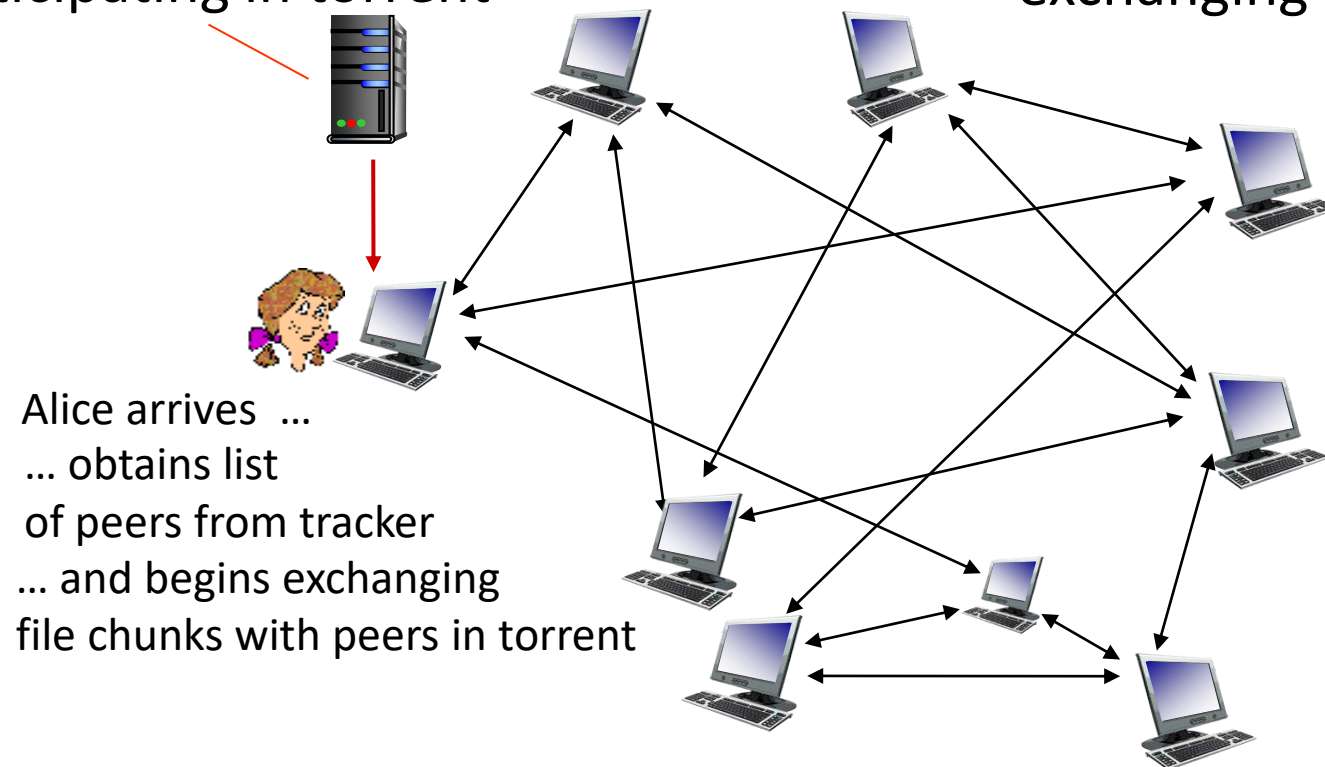
P2P file distribution: BitTorrent

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

tracker: tracks peers participating in torrent

torrent: group of peers exchanging chunks of a file

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
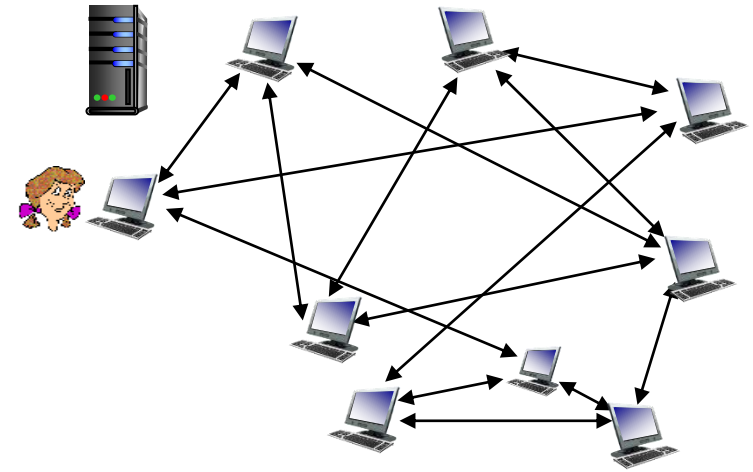
# BitTorrent: requesting, sending file chunks

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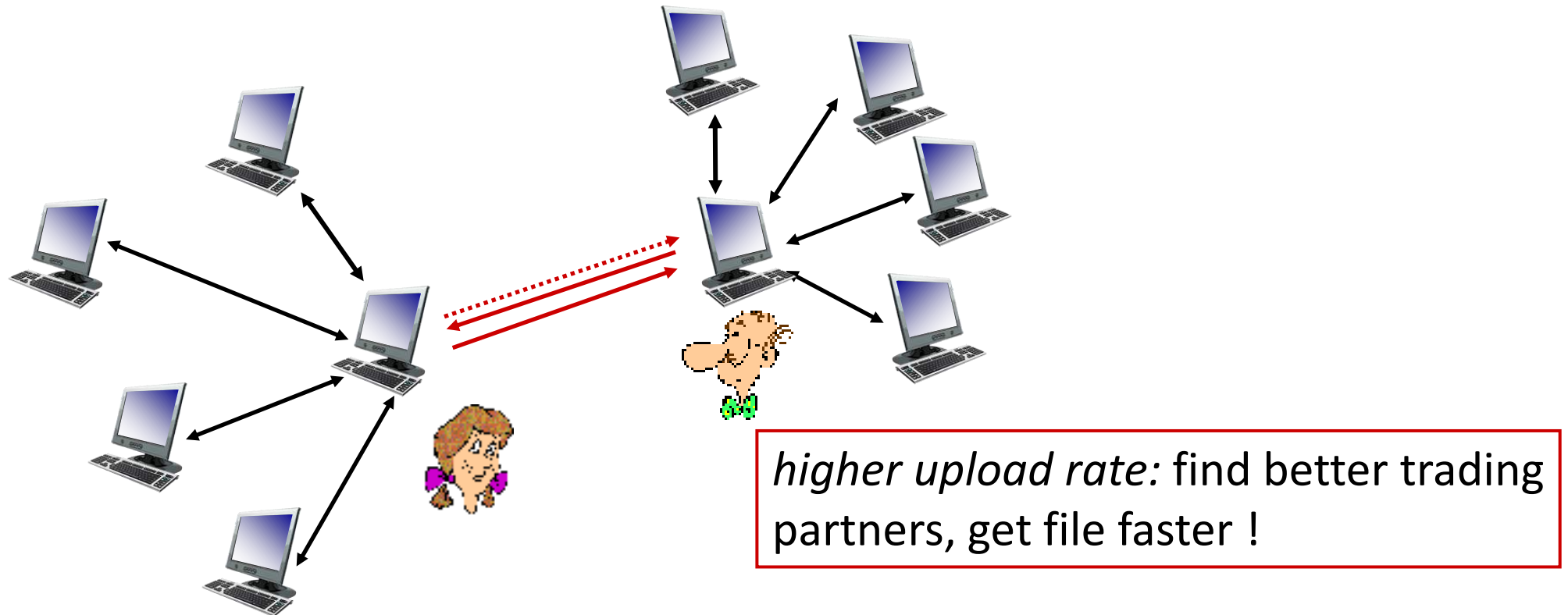
higher upload rate: find better trading partners, get file faster !

Application layer: overview

- Principles of network applications
- Web and HTTP
- E-mail, SMTP, IMAP
- The Domain Name System DNS

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

Video Streaming and CDNs: context

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

Multimedia: video

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

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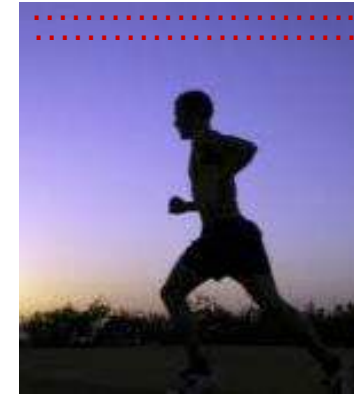
frame *i*

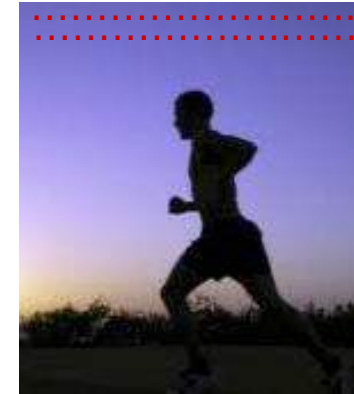*temporal coding example:* instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

Multimedia: video

- CBR: (constant bit rate): video encoding rate fixed

- VBR: (variable bit rate): video encoding rate changes as amount of spatial, temporal coding changes

- examples:
  - MPEG 1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, 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:

video server
(stored video)

client

Internet
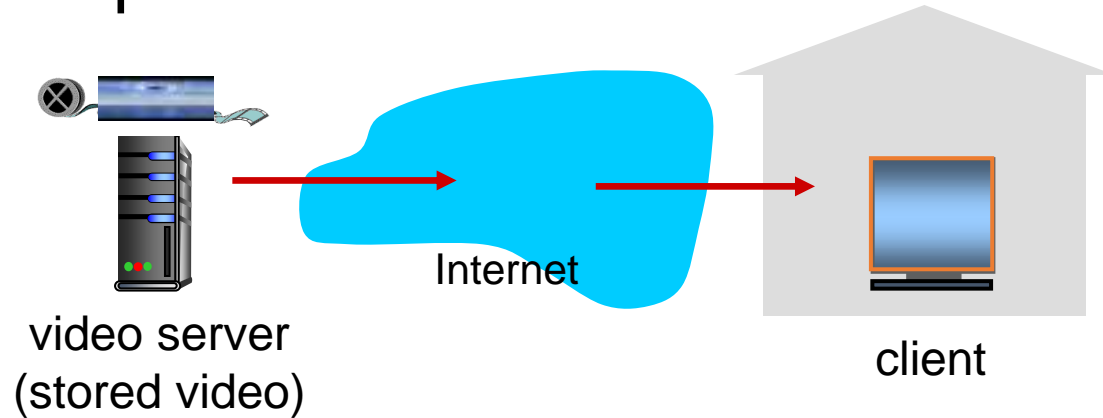
Main challenges:

- server-to-client bandwidth will *vary* over time, with changing network congestion levels (in house, access network, network core, video server)

- packet loss, delay due to congestion will delay playout, or result in poor video quality

Streaming stored video

Cumulative data

1. video recorded (e.g., 30 frames/sec)

2. video sent

3. video received, played out at client (30 frames/sec)

network delay (fixed in this example)

time

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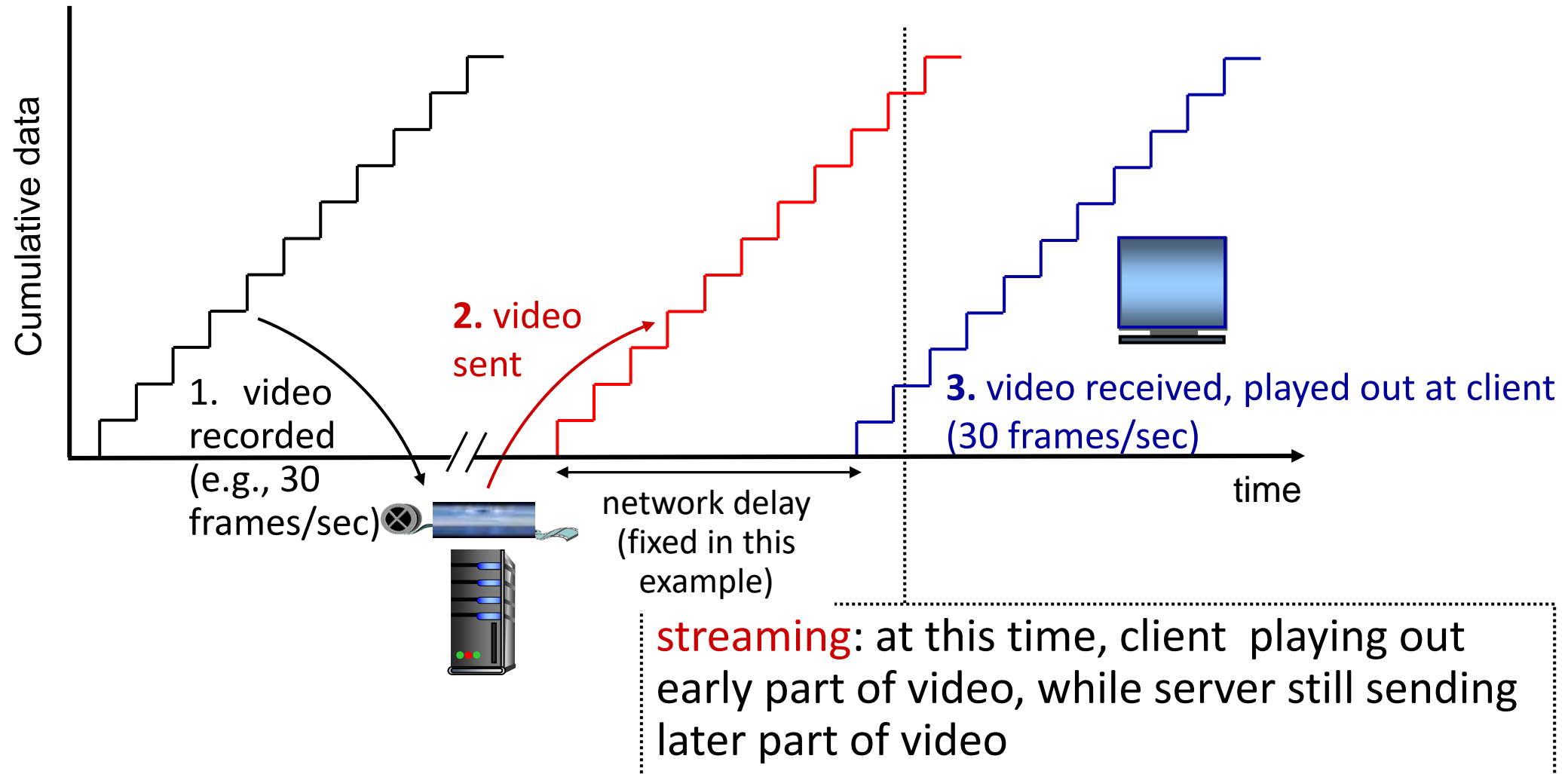
Streaming stored video: challenges

- continuous playout constraint: during client video playout, playout timing must match original timing
  - … but network delays are variable (jitter), so will need client-side buffer to match continuous playout constraint

- other challenges:
  - client interactivity: pause, fast-forward, rewind, jump through video
  - video packets may be lost, retransmitted
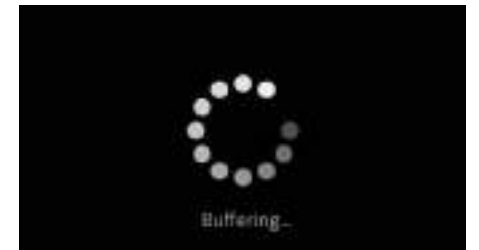
Streaming stored video: playout buffering
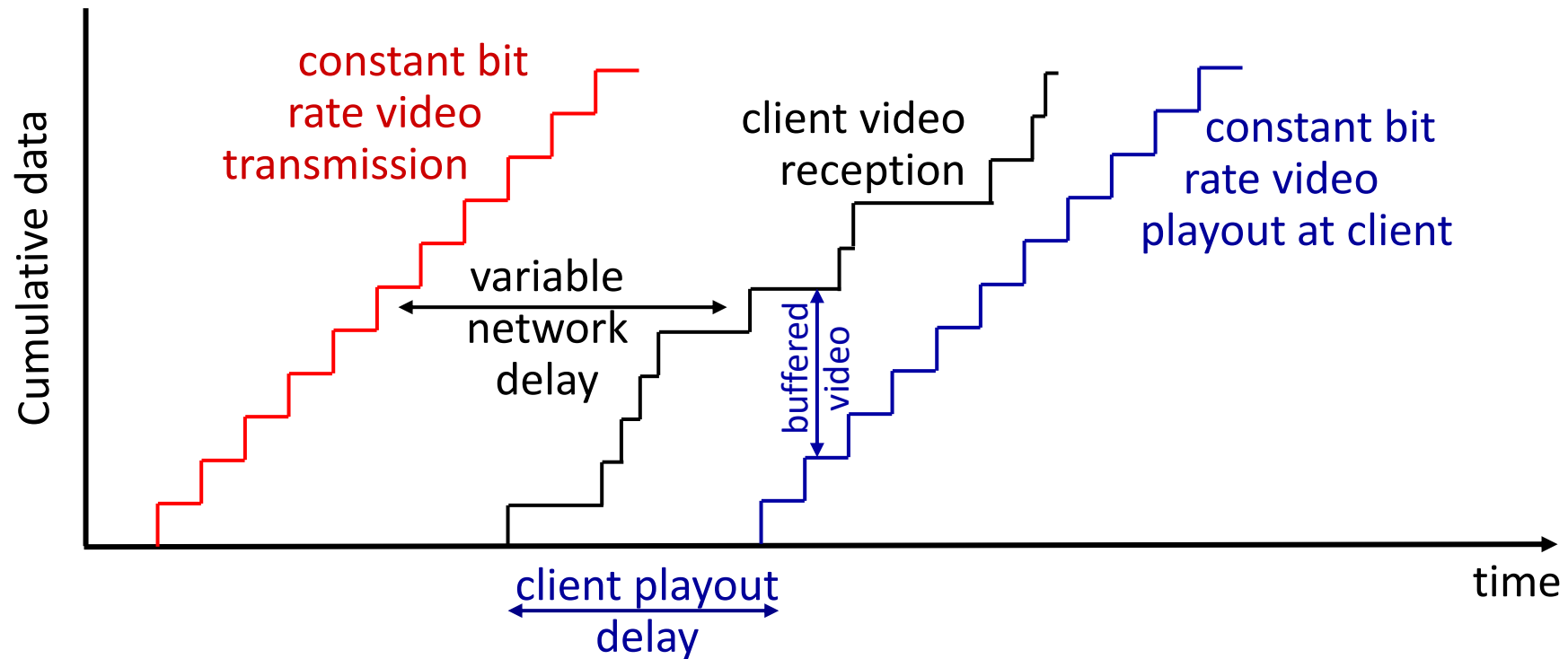
- *client-side buffering and playout delay:* compensate for network-added delay, delay jitter

Streaming multimedia: DASH

*D*ynamic, *A*daptive *S*treaming over *H*TTP

server:

- divides video file into multiple chunks
- each chunk encoded at multiple different rates
- different rate encodings stored in different files
- files replicated in various CDN nodes
- *manifest file:* provides URLs for different chunks
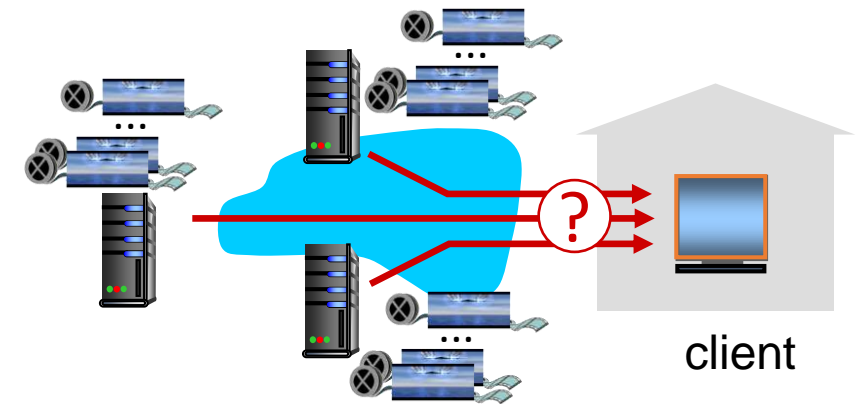
client

client:

- periodically estimates server-to-client bandwidth
- consulting manifest, requests one chunk at a time
  - chooses maximum coding rate sustainable given current bandwidth
  - can choose different coding rates at different points in time (depending on available bandwidth at time), and from different servers

Streaming multimedia: DASH

- *"intelligence"* at client: client determines
  - *when* to request chunk (so that buffer starvation, or overflow does not occur)
  - *what encoding rate* to request (higher quality when more bandwidth available)
  - *where* to request chunk (can request from URL server that is "close" to client or has high available bandwidth)
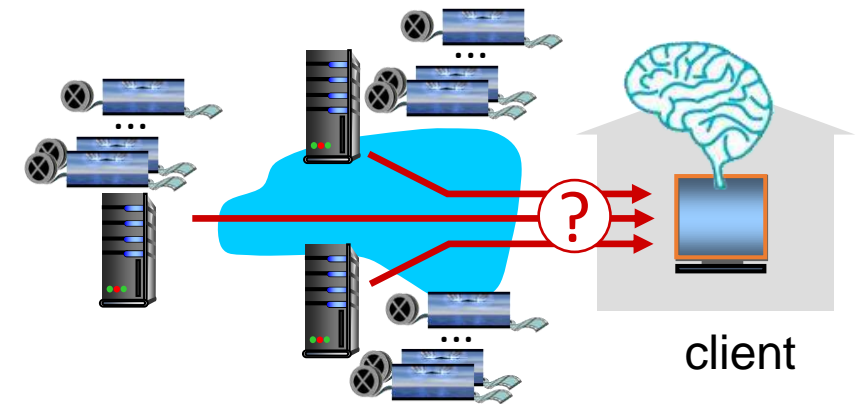
  Streaming video = encoding + DASH + playout buffering

Content distribution networks (CDNs)

challenge: how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?

- *option 1:* single, large "mega-server"
  - single point of failure
  - point of network congestion
  - long (and possibly congested) path to distant clients

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

Content distribution networks (CDNs)

challenge: how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?

- *option 2:* store/serve multiple copies of videos at multiple geographically distributed sites *(CDN)*
  - *enter deep:* push CDN servers deep into many access networks
    - close to users
    - Akamai: 240,000 servers deployed in > 120 countries (2015)
  - *bring home:* smaller number (10's) of larger clusters in POPs near access nets
    - used by Limelight

Content distribution networks (CDNs)

- CDN: stores copies of content (e.g. MADMEN) at CDN nodes

- subscriber requests content, service provider returns manifest
  - using manifest, client retrieves content at highest supportable rate
  - may choose different rate or copy if network path congested

Content distribution networks (CDNs)

OTT: "over the top"

Internet host-host communication as a service
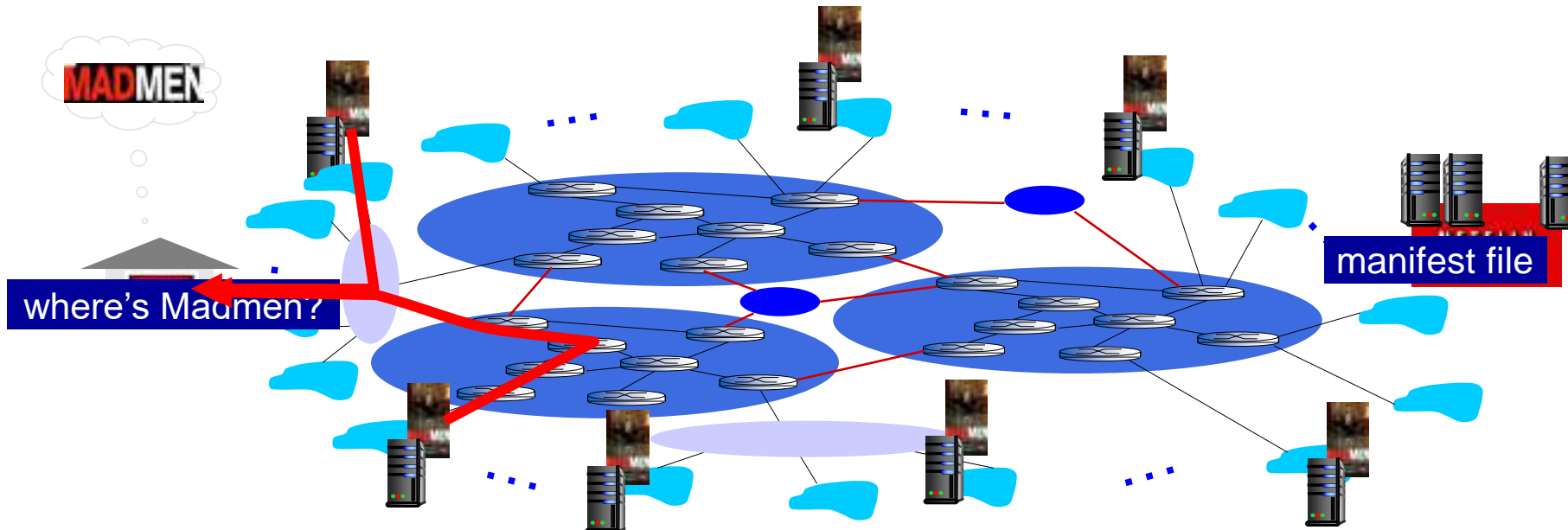
OTT challenges: coping with a congested Internet from the "edge"
- what content to place in which CDN node?
- from which CDN node to retrieve content? At which rate?

Application Layer: Overview

- Principles of network applications

- Web and HTTP

- E-mail, SMTP, IMAP

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- P2P applications

- video streaming and content distribution networks

- **socket programming with UDP and TCP**

Socket programming

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

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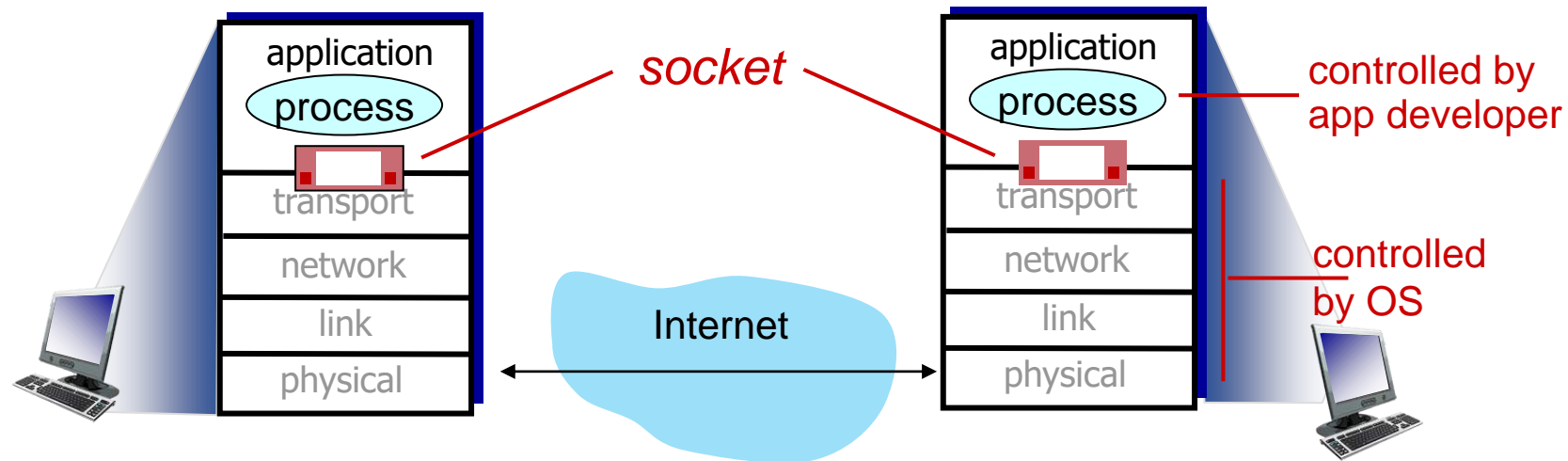
Socket programming

Two socket types for two transport services:

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

Application Example:

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

Socket programming with UDP

UDP: no "connection" between
  client and server:

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

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

Application viewpoint:
- UDP provides *unreliable* transfer of groups of bytes ("datagrams") between client and server processes

Client/server socket interaction: UDP

server (running on serverIP)

create socket, port= x:
serverSocket =
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 serverIP address
And port=x; send datagram via
clientSocket

read datagram from
clientSocket

close
clientSocket

Example app: UDP client

Python UDPClient

include Python's socket library ⟶ from socket import *

serverName = 'hostname'

serverPort = 12000

create UDP socket for server ⟶ clientSocket = socket(AF_INET,
SOCK_DGRAM)

get user keyboard input ⟶ message = raw_input('Input lowercase sentence:')

attach server name, port to message; send into socket ⟶ clientSocket.sendto(message.encode(),
(serverName, serverPort))

read reply characters from socket into string ⟶ modifiedMessage, serverAddress =
clientSocket.recvfrom(2048)

print out received string and close socket ⟶ print modifiedMessage.decode()

clientSocket.close()

Example app: UDP server

Python UDPServer

from socket import *
serverPort = 12000

create UDP socket ⟶ serverSocket = socket(AF_INET, SOCK_DGRAM)

bind socket to local port number 12000 ⟶ serverSocket.bind(('', serverPort))

print ("*The server is ready to receive*")

loop forever ⟶ while True:

Read from UDP socket into message, getting
client's address (client IP and port) ⟶   message, clientAddress = serverSocket.recvfrom(2048)

   modifiedMessage = message.decode().upper()

send upper case string back to this client ⟶   serverSocket.sendto(modifiedMessage.encode(),
                           clientAddress)

Socket programming with TCP

Client must contact server

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

Client contacts server by:

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

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

Application viewpoint

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

Client/server socket interaction: TCP
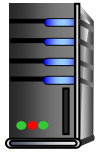
server (running on hostid)   **client**

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

↓

wait for incoming
connection request   TCP   create socket,
connectionSocket =   ←— connection setup —→   connect to **hostid**, port=**x**
serverSocket.accept()   clientSocket = socket()

↓   ↓

read request from   send request using
connectionSocket   clientSocket

↓

write reply to   read reply from
connectionSocket   clientSocket

↓   ↓

close   close
connectionSocket   clientSocket

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) →

Chapter 2: Summary

our study of network application layer is now complete!

- application architectures
  - client-server
  - P2P

- application service requirements:
  - reliability, bandwidth, delay

- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP

- specific protocols:
  - HTTP
  - SMTP, IMAP
  - DNS
  - P2P: BitTorrent

- video streaming, CDNs

- socket programming: TCP, UDP sockets

Chapter 2: Summary

Most importantly: learned about *protocols*!

- typical request/reply message exchange:
  - client requests info or service
  - server responds with data, status code

- message formats:
  - *headers*: fields giving info about data
  - *data:* info(payload) being communicated

important themes:
- centralized vs. decentralized
- stateless vs. stateful
- scalability
- reliable vs. unreliable message transfer
- "complexity at network edge"

Additional Chapter 2 slides

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
```

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

6. request video from
KINGCDN server,
streamed via HTTP

netcinema.com

3. netcinema's DNS returns CNAME for
http://KingCDN.com/NetC6y&B23V

netcinema's
authoratative DNS

Bob's
local DNS
server

KingCDN.com

KingCDN
authoritative DNS

Case study: Netflix

Netflix registration, accounting servers

Amazon cloud

upload copies of multiple versions of video to CDN servers

CDN server

CDN server

CDN server

Bob browses Netflix video

Manifest file, requested returned for specific video

① Bob manages Netflix account

② ③

④ DASH server selected, contacted, streaming begins