

Chapter 2

Application Layer

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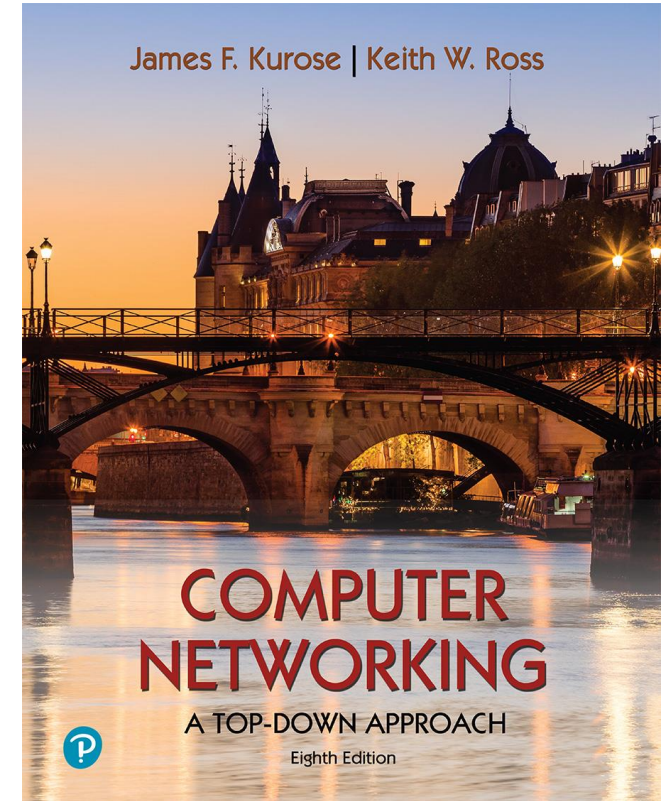
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Computer Networking: A Top-Down Approach

8th edition n
Jim Kurose, Keith Ross
Pearson, 2020

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
 - Internet search
 - remote login
 - ...
- Q: *your* favorites?

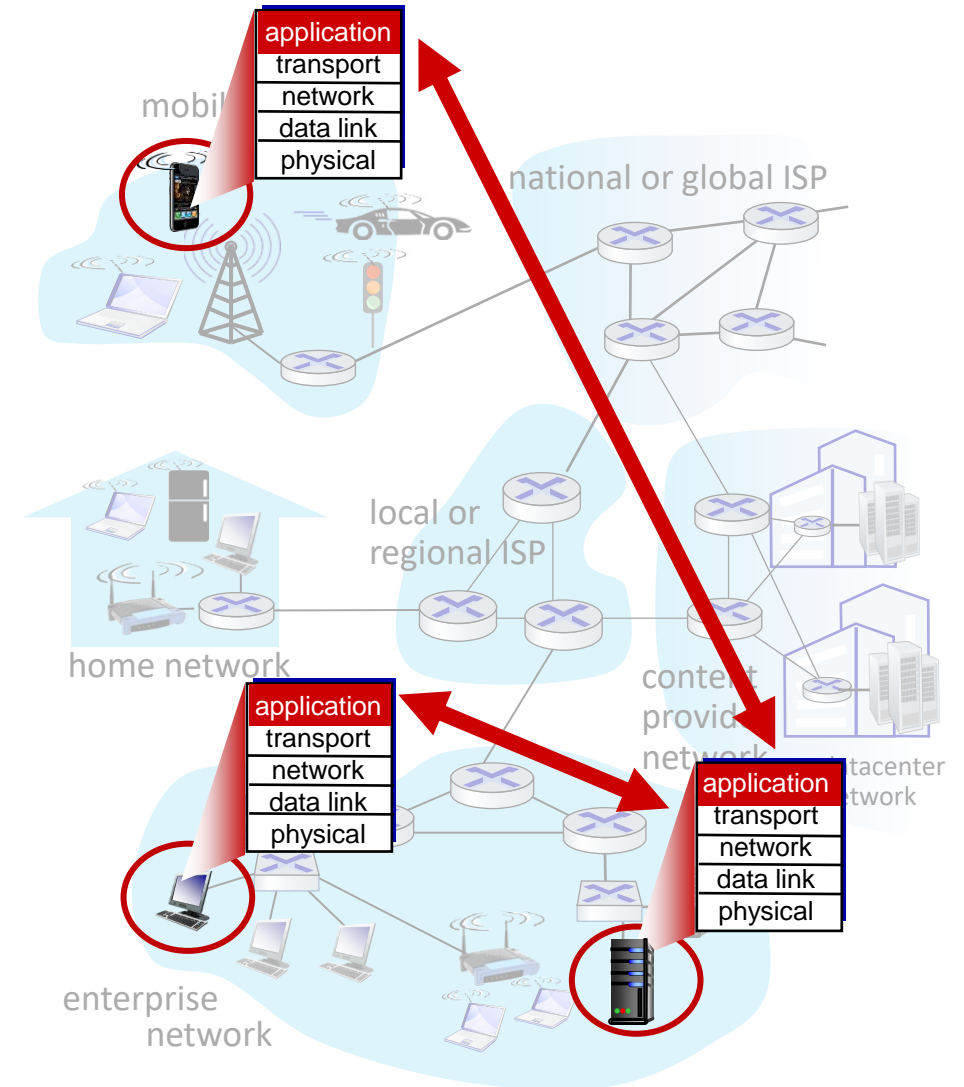
Creating a network app

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



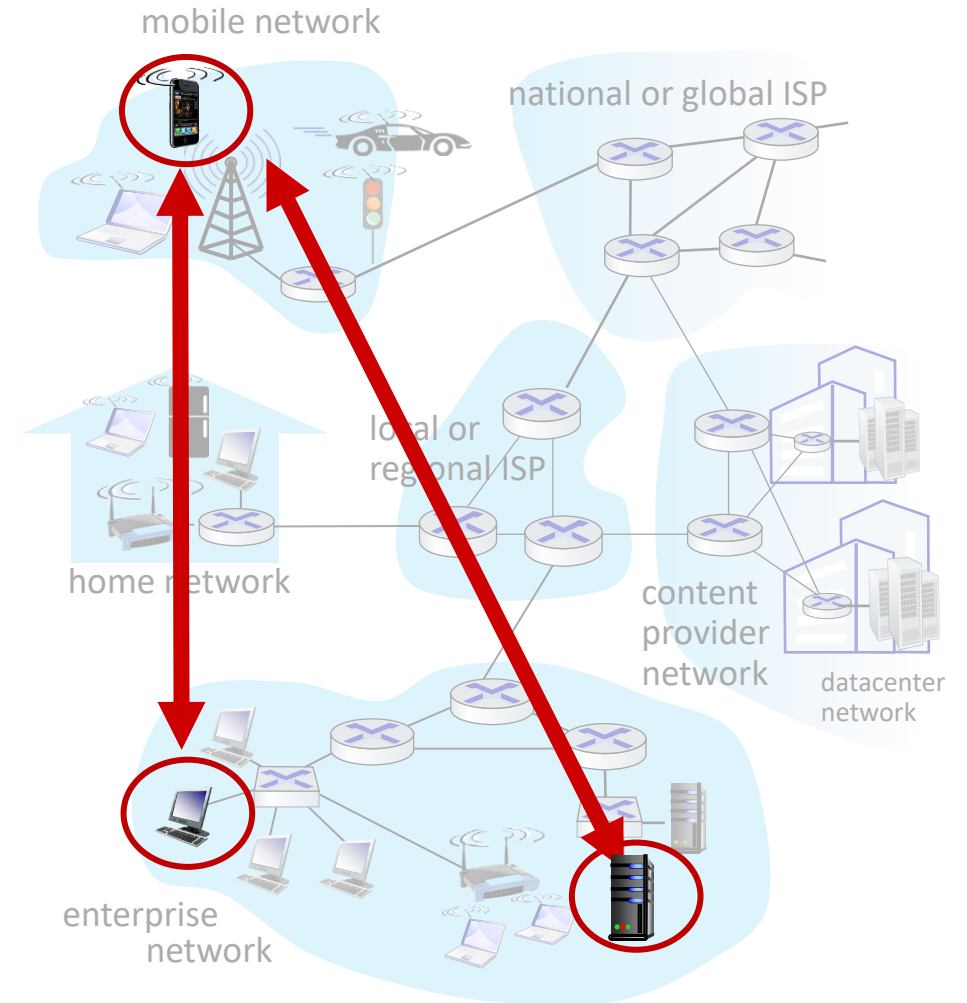
Client-server paradigm

server:

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

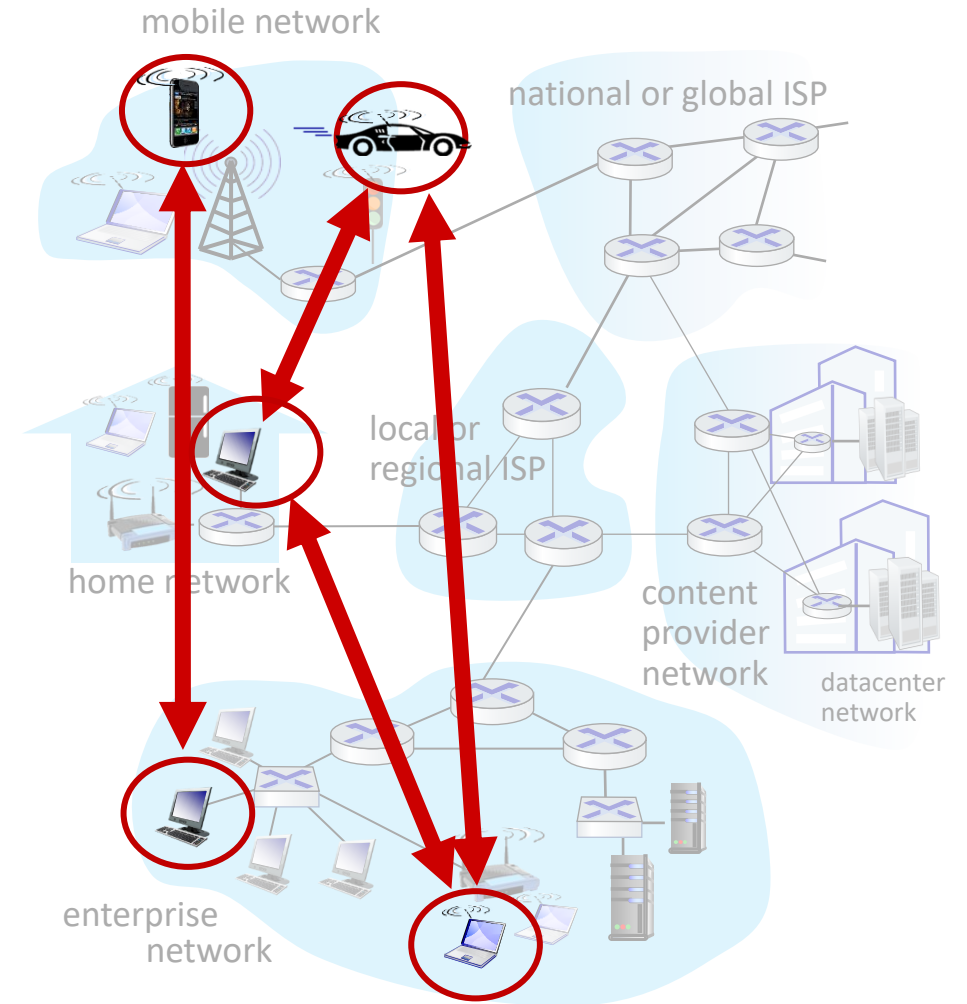
clients:

- 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

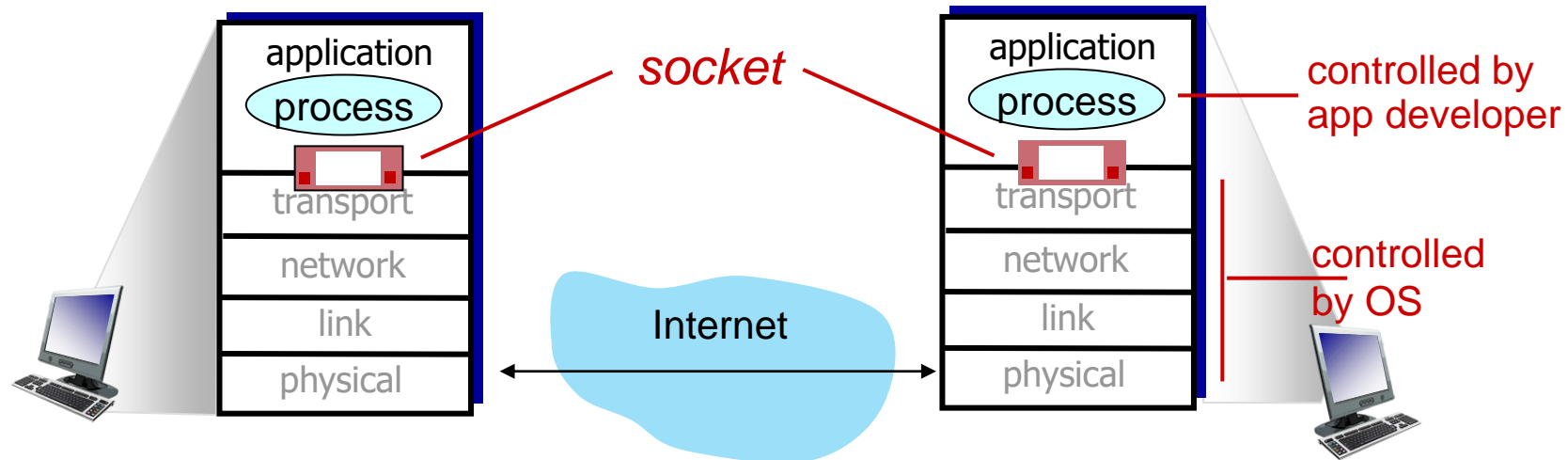
client process: process that initiates communication

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

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
- *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

Securing TCP

Vanilla TCP & UDP sockets:

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

Transport Layer Security (TLS)

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

TLS implemented in application layer

- apps use TLS libraries, that use TCP in turn

TLS socket API

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

Web and HTTP

First, a quick review...

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

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

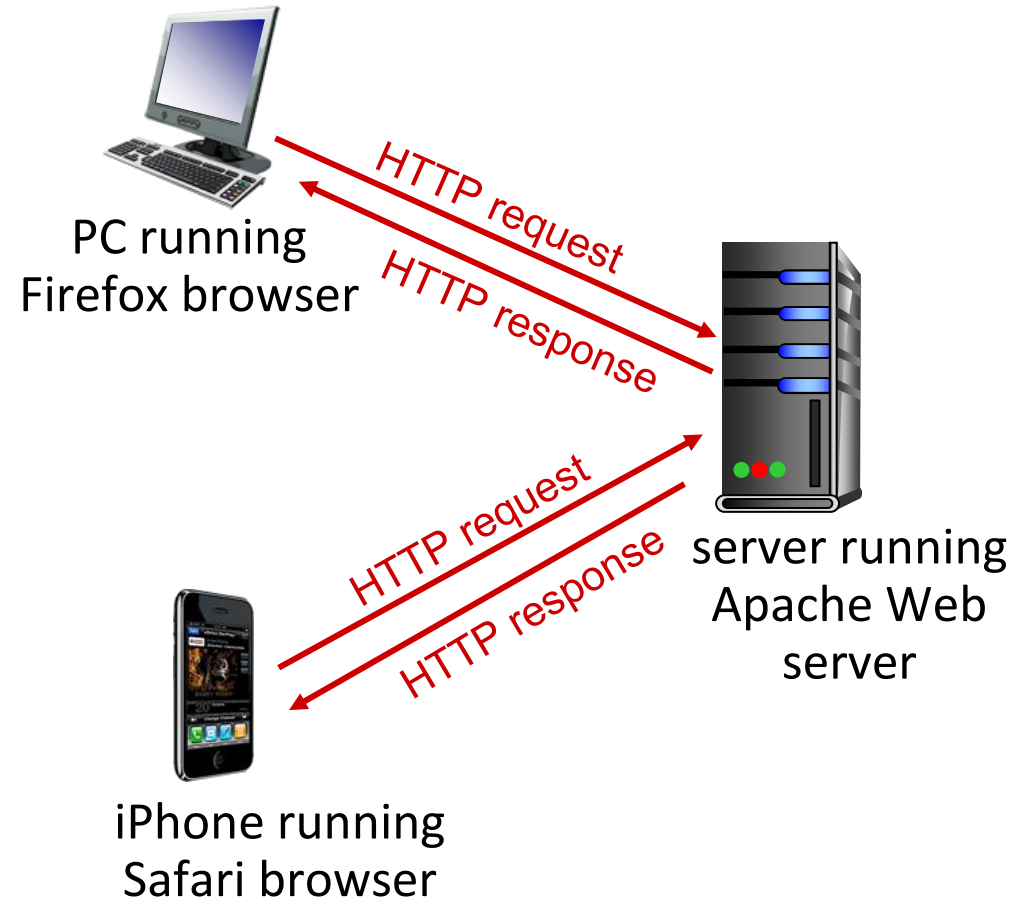
host name

path name

HTTP overview

HTTP: hypertext transfer protocol

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



HTTP overview (continued)

HTTP uses TCP:

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

HTTP is “stateless”

- server maintains *no* information about past client requests

aside
protocols that maintain “state” are complex!

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

HTTP connections: two types

Non-persistent HTTP

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

downloading multiple objects required multiple connections

Persistent HTTP

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

Non-persistent HTTP: example

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



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



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

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

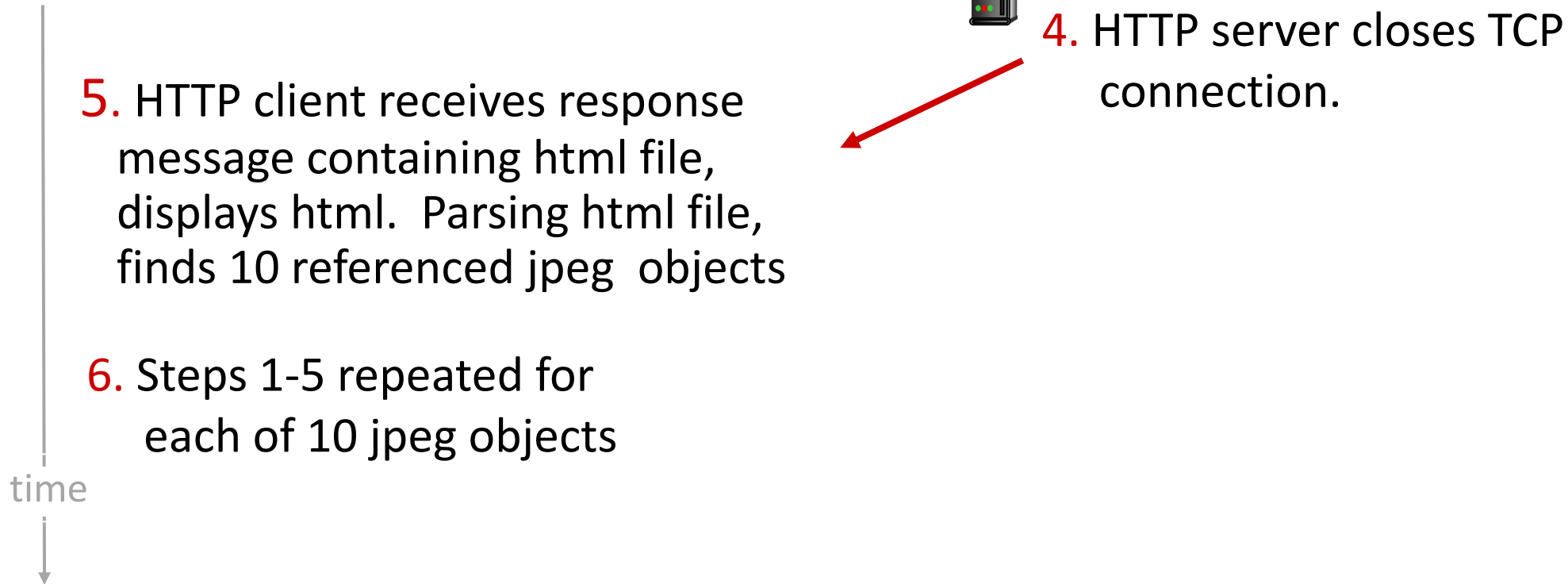
3. HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time



Non-persistent HTTP: example (cont.)

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

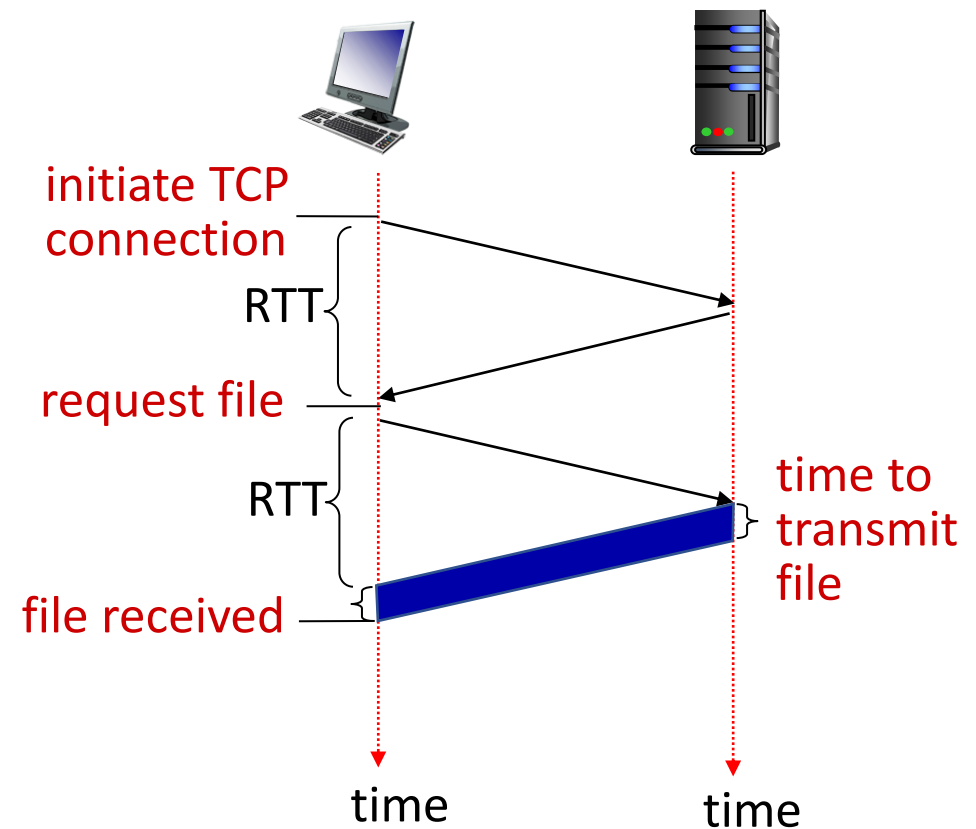


Non-persistent HTTP: response time

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

HTTP response time (per object):

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



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

Persistent HTTP (HTTP 1.1)

Non-persistent HTTP issues:

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

Persistent HTTP (HTTP1.1):

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

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

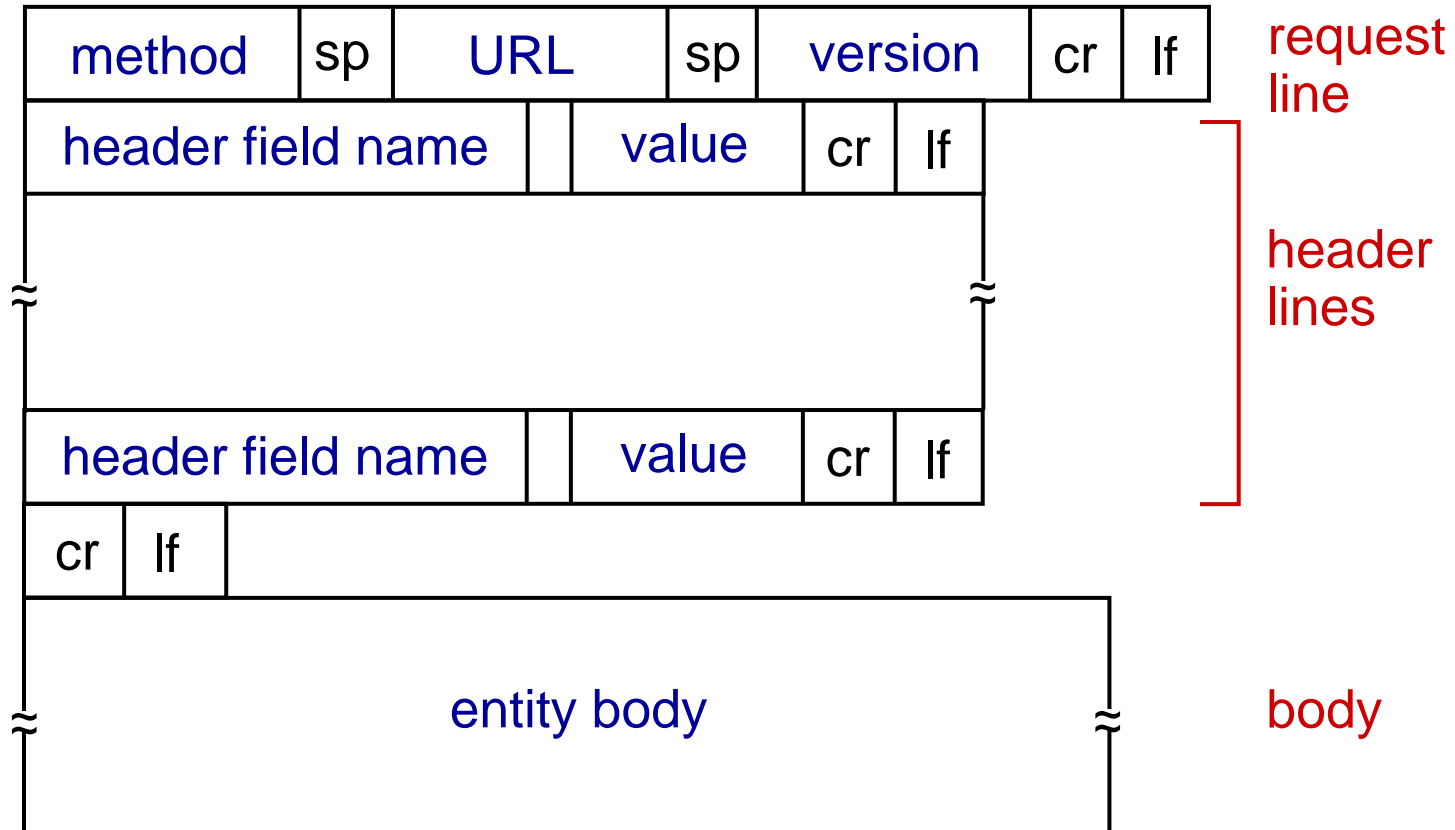
carriage return, line feed
at start of line indicates
end of header lines

carriage return character
line-feed character

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

* 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`

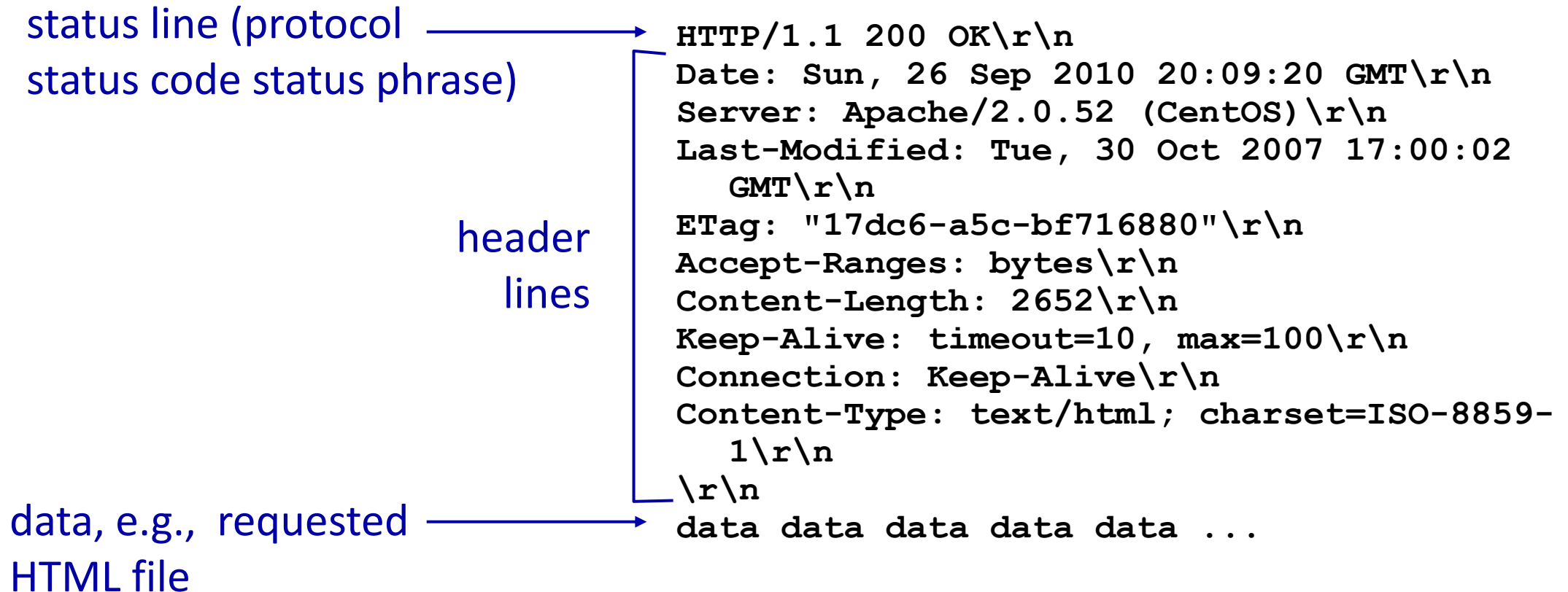
HEAD method:

- 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 POST 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

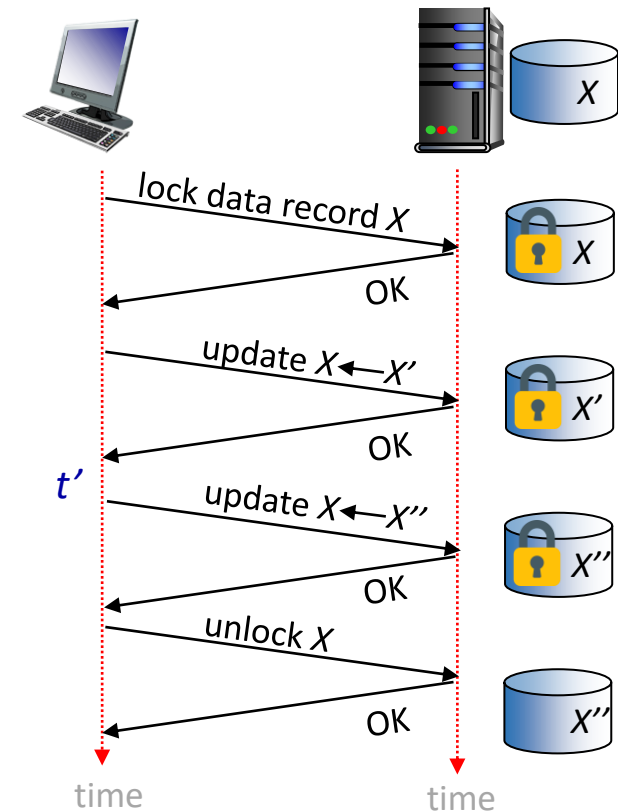
505 HTTP Version Not Supported

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

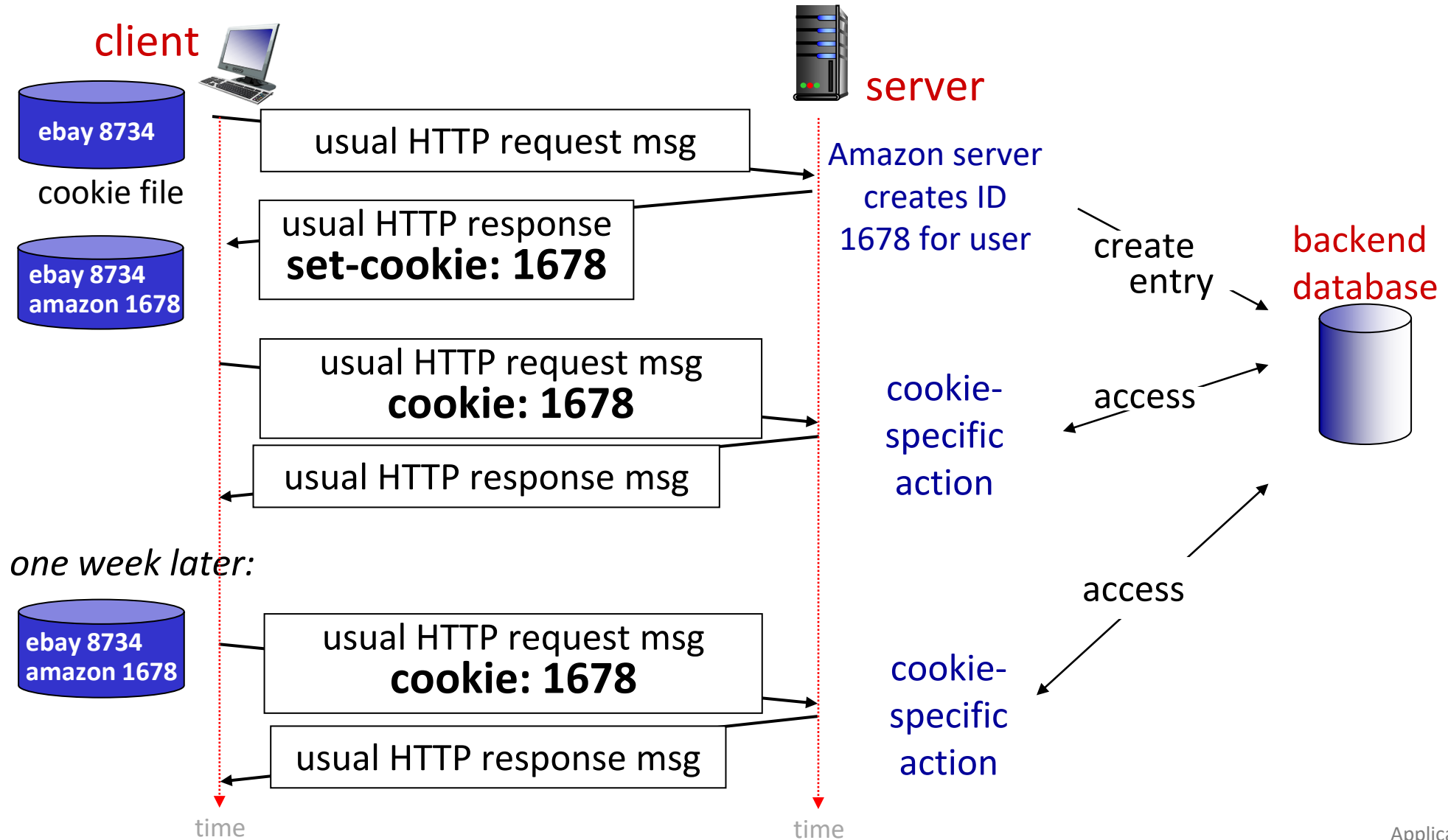
four components:

- 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:

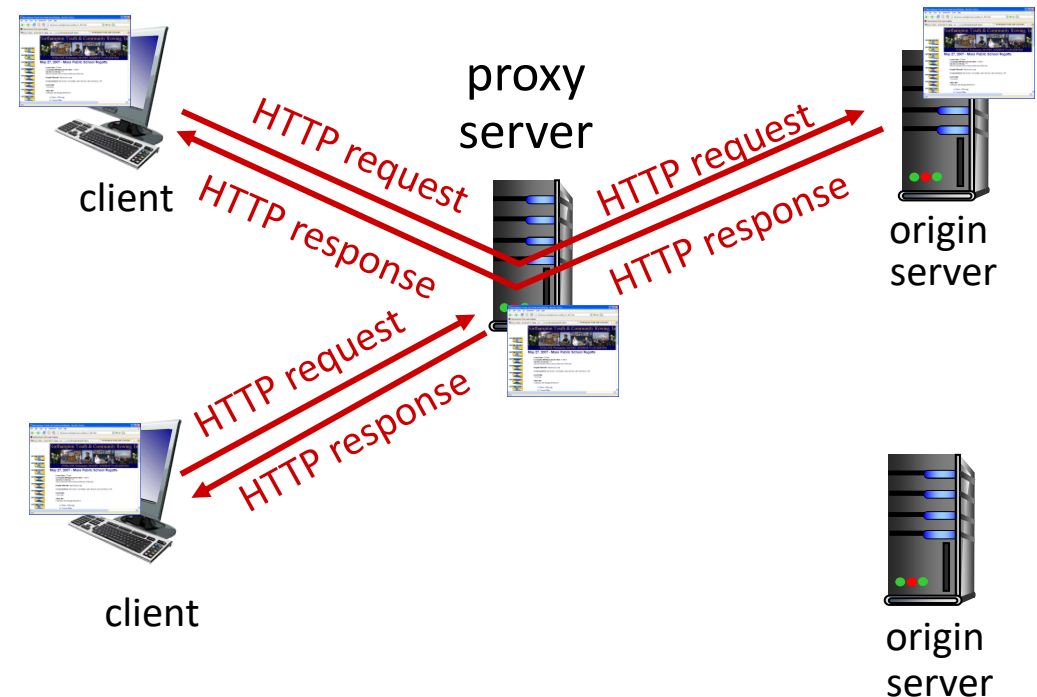
- protocol endpoints: maintain state at sender/receiver over multiple transactions
- cookies: HTTP messages carry state

- 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 (proxy servers)

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

Why Web caching?

- reduce response time for client request
 - 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

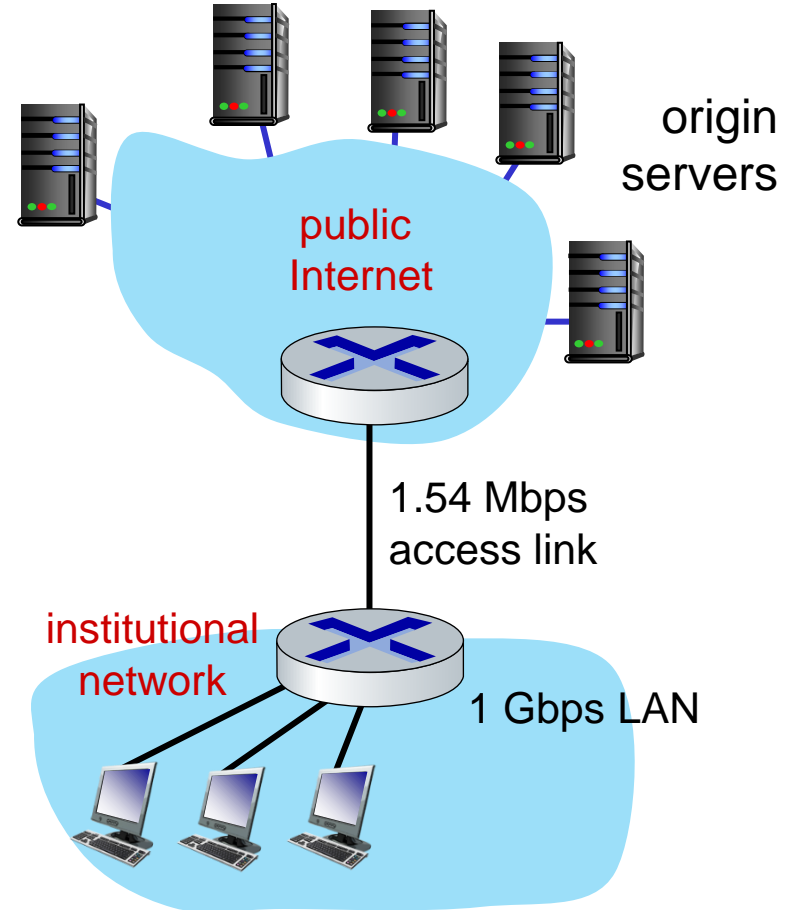
Scenario:

- 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
 - average data rate to browsers: 1.50 Mbps

Performance:

- LAN utilization: .0015
- access link utilization = .97
- end-end delay = Internet delay +
access link delay + LAN delay
= 2 sec + minutes + usecs

*problem: large
delays at high
utilization!*



Caching example: buy a faster access link

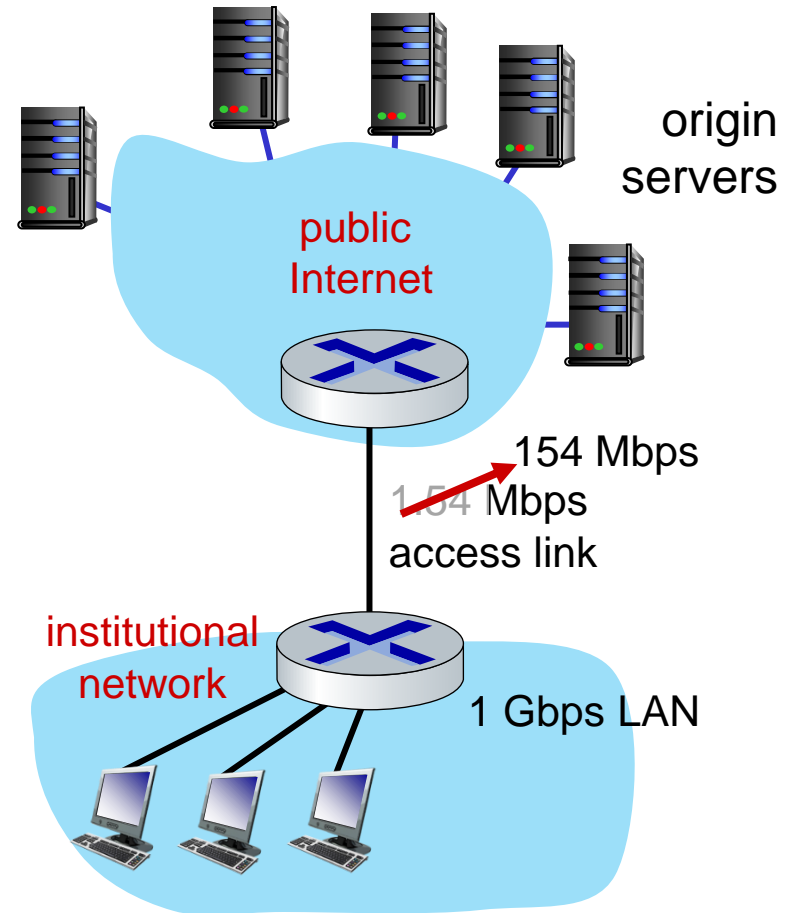
Scenario:

- 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: .0015
- access link utilization = ~~.97~~ .0097
- end-end delay = Internet delay +
access link delay + LAN delay
= 2 sec + ~~minutes~~ + usecs

Cost: faster access link (expensive!) → msec



Caching example: install a web cache

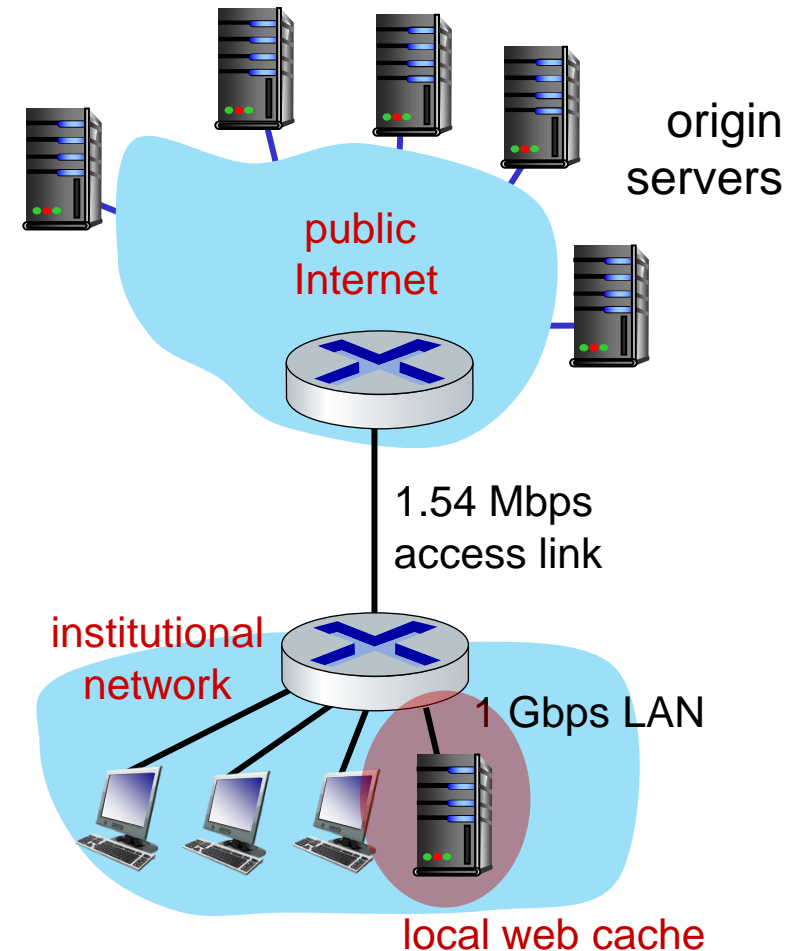
Scenario:

- 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?*

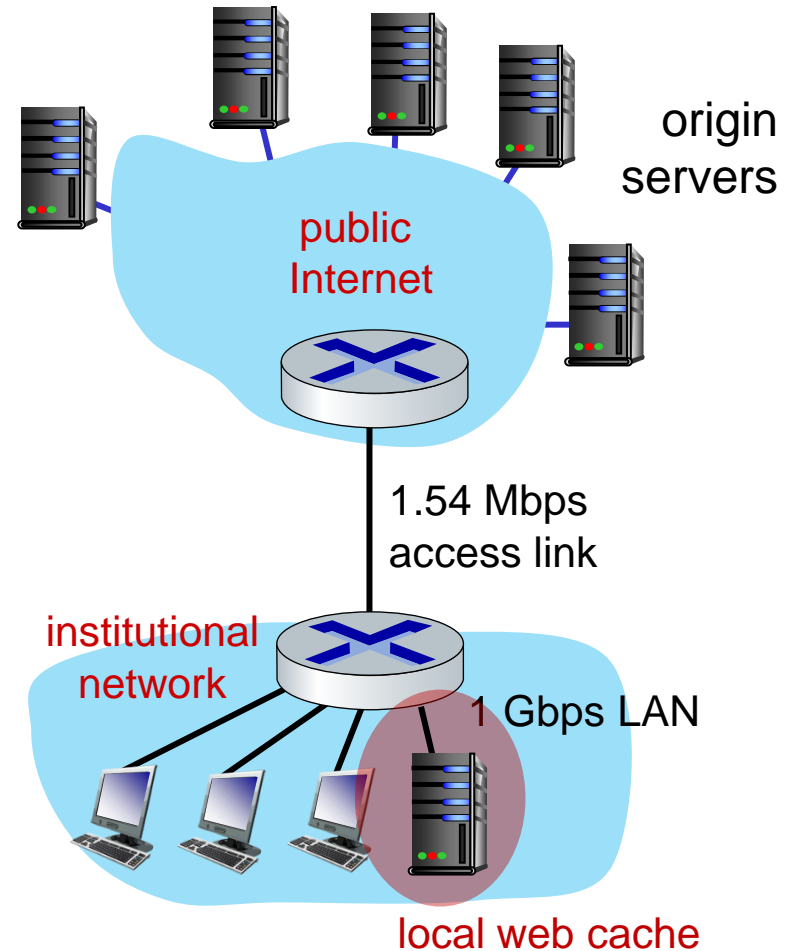
Cost: web cache (cheap!)



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

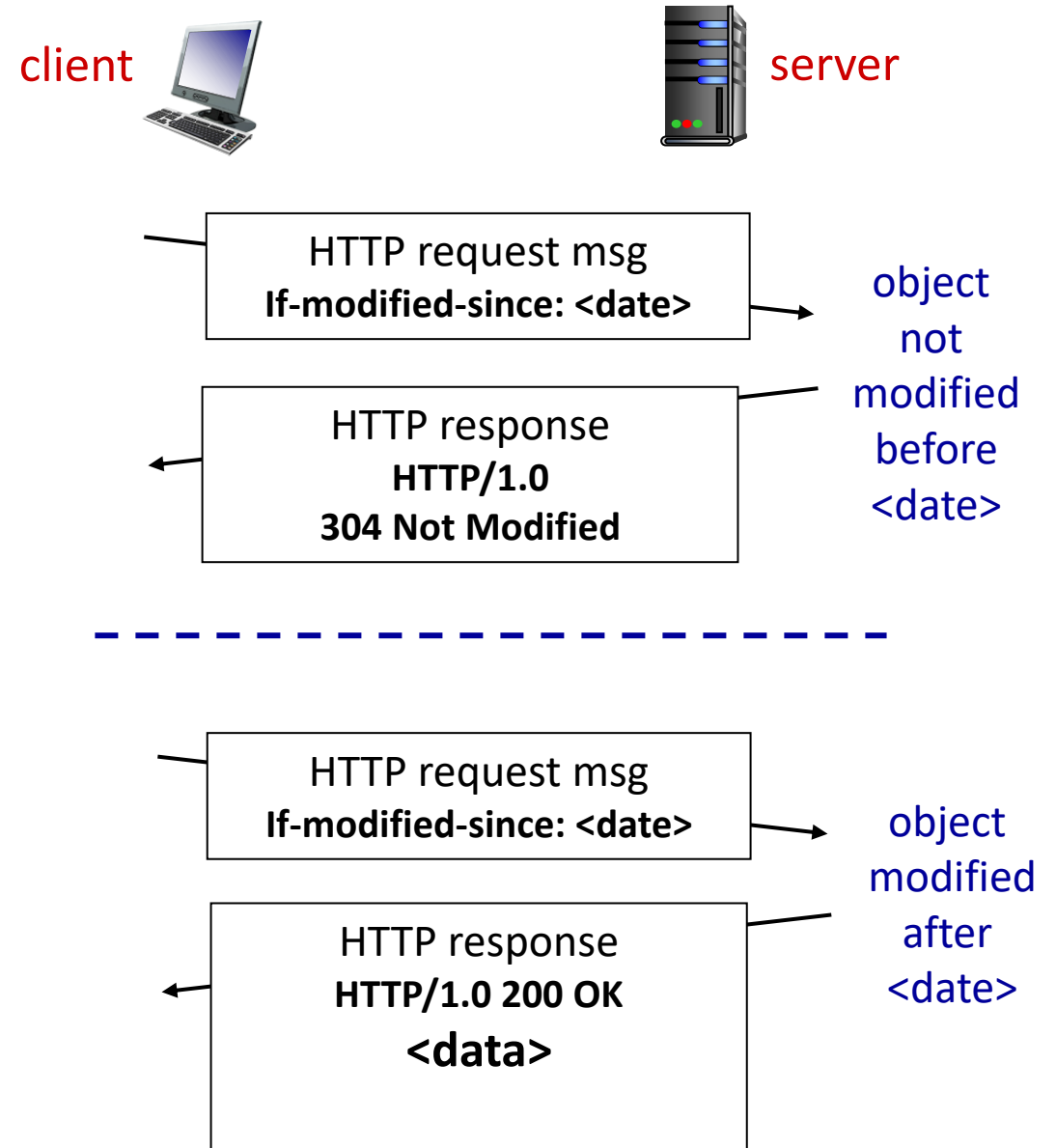


lower average end-end delay than with 154 Mbps link (and cheaper too!)

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

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

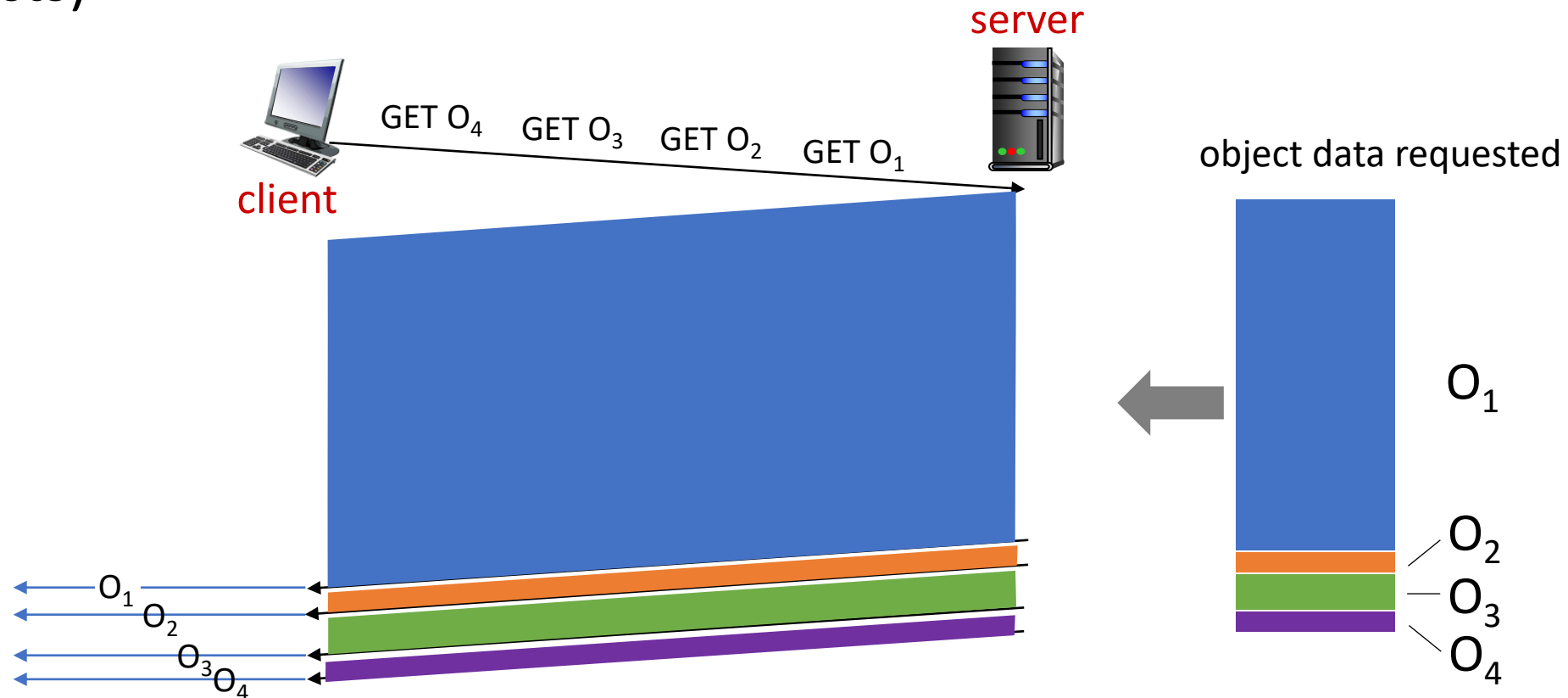
Key goal: decreased delay in multi-object HTTP requests

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

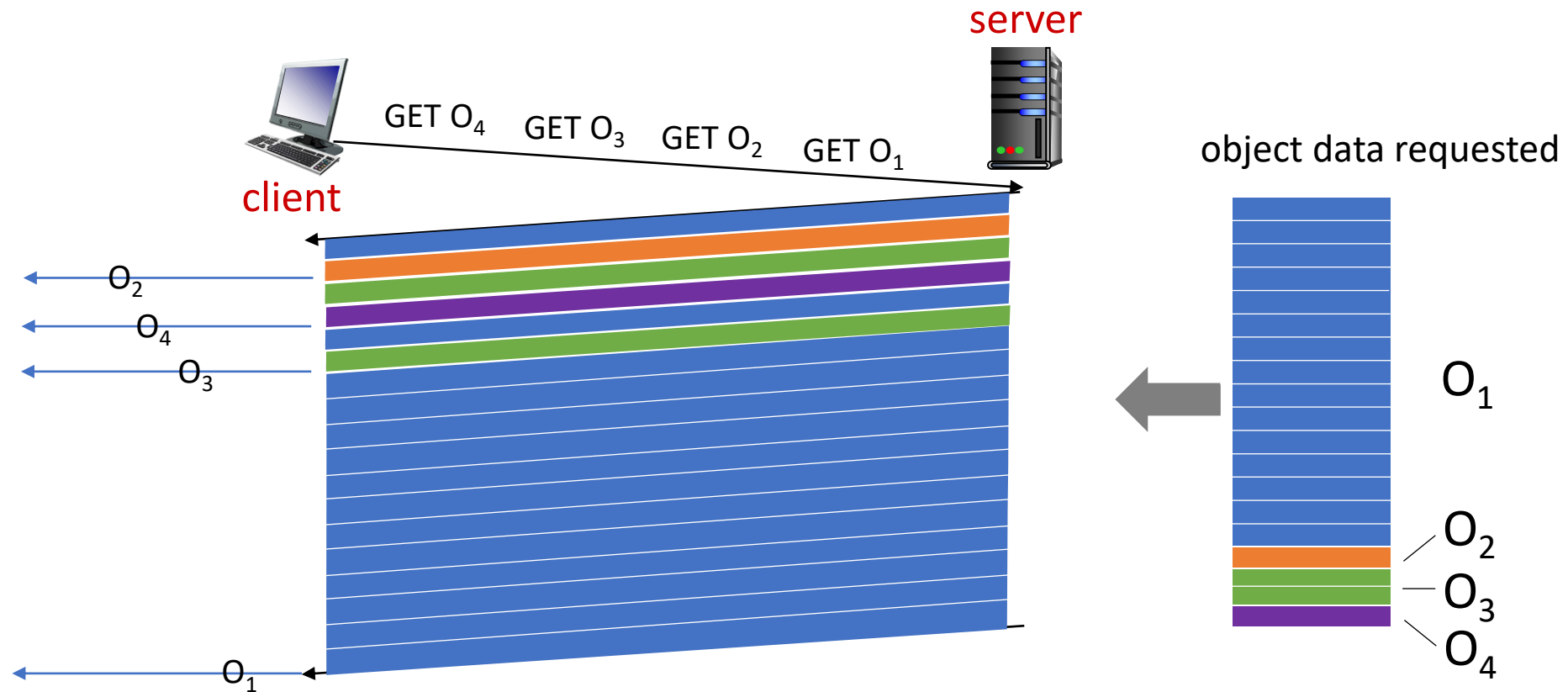
HTTP 1.1: client requests 1 large object (e.g., video file, and 3 smaller objects)



objects delivered in order requested: O₂, O₃, O₄ wait behind O₁

HTTP/2: mitigating HOL blocking

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



O₂, O₃, O₄ delivered quickly, O₁ slightly delayed

HTTP/2 to HTTP/3

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

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

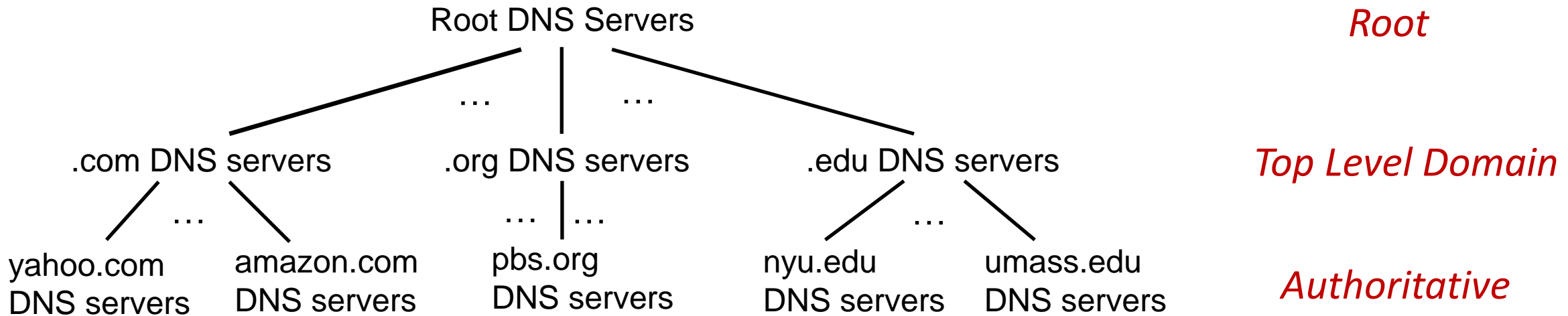
Q: Why not centralize DNS?

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

A: doesn't scale!

- Comcast DNS servers alone: 600B DNS queries per day

DNS: a distributed, hierarchical database



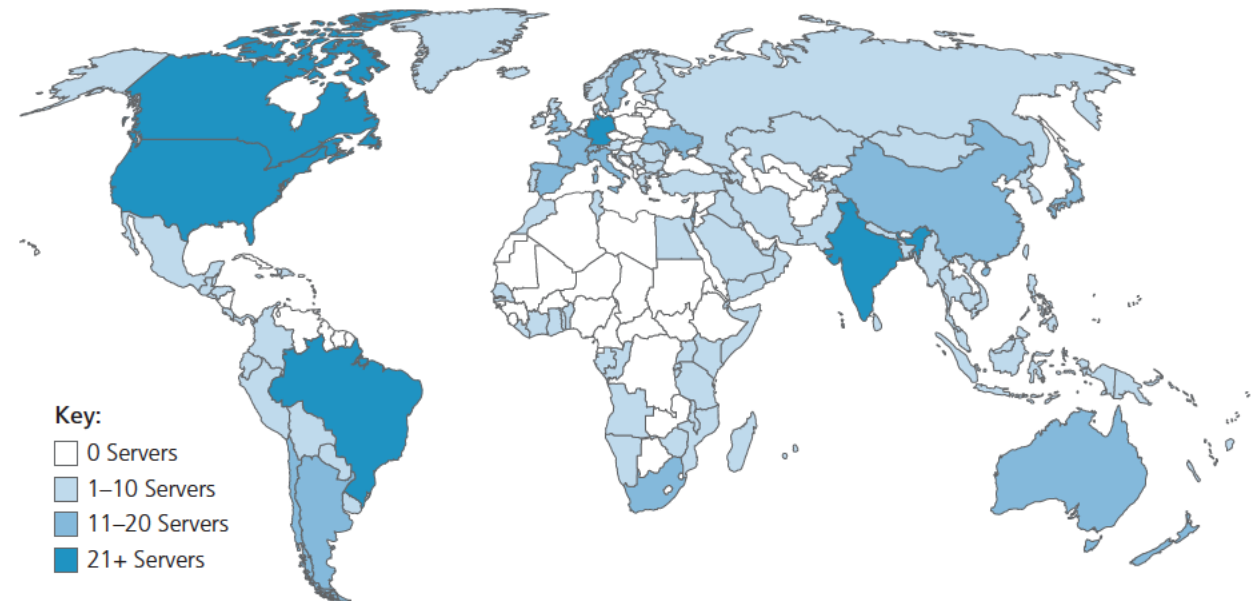
Client wants IP address for `www.amazon.com`; 1st approximation:

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



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
- Network Solutions: authoritative registry for .com, .net TLD
- Educause: .edu TLD

Authoritative DNS servers:

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

Local DNS name servers

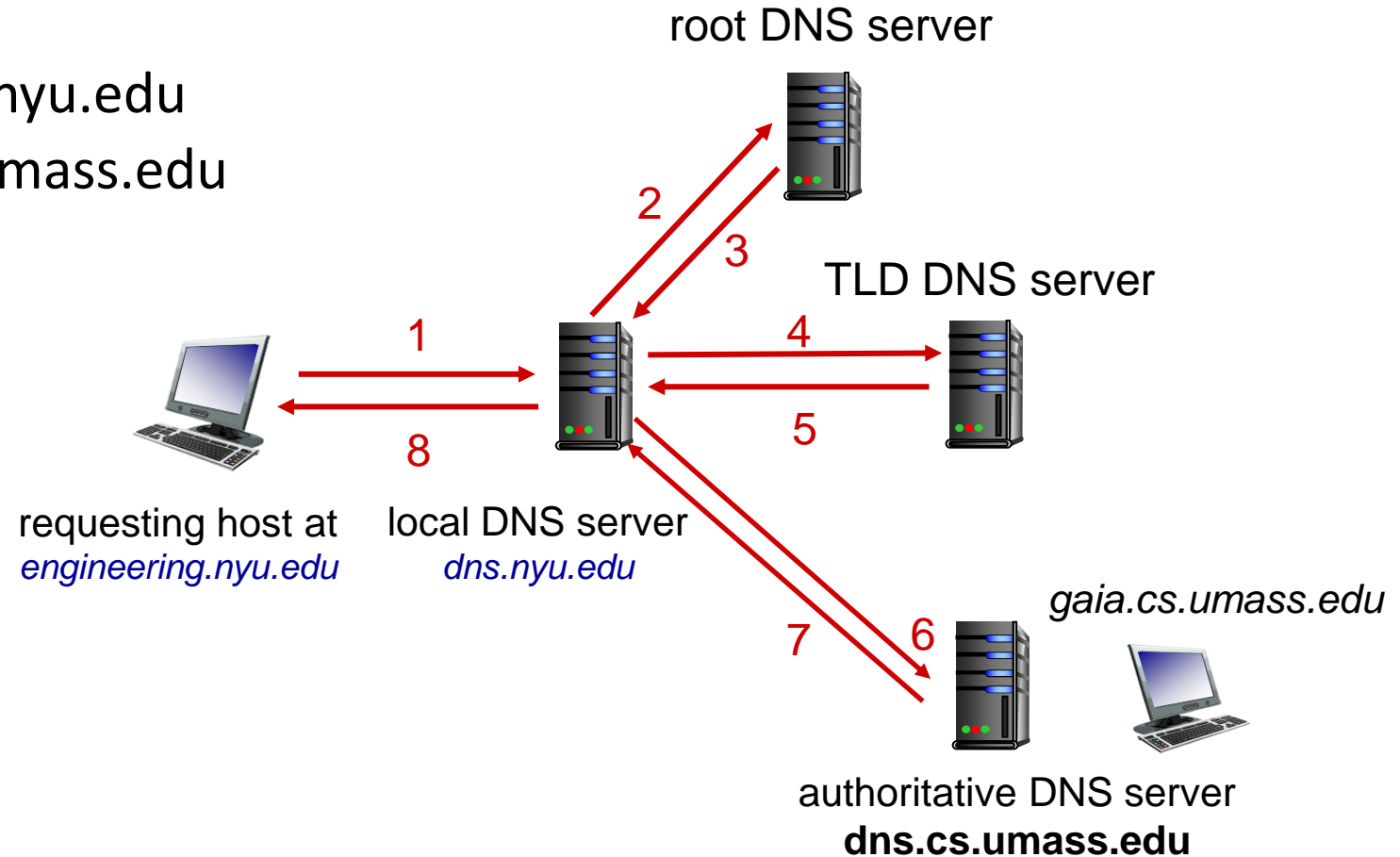
- does not strictly belong to hierarchy
- each ISP (residential ISP, company, university) has one
 - also called “default name server”
- when host makes DNS query, query is sent to its local DNS server
 - has local cache of recent name-to-address translation pairs (but may be out of date!)
 - acts as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

DNS name resolution: (not entirely) iterated query

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

Iterated query:

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

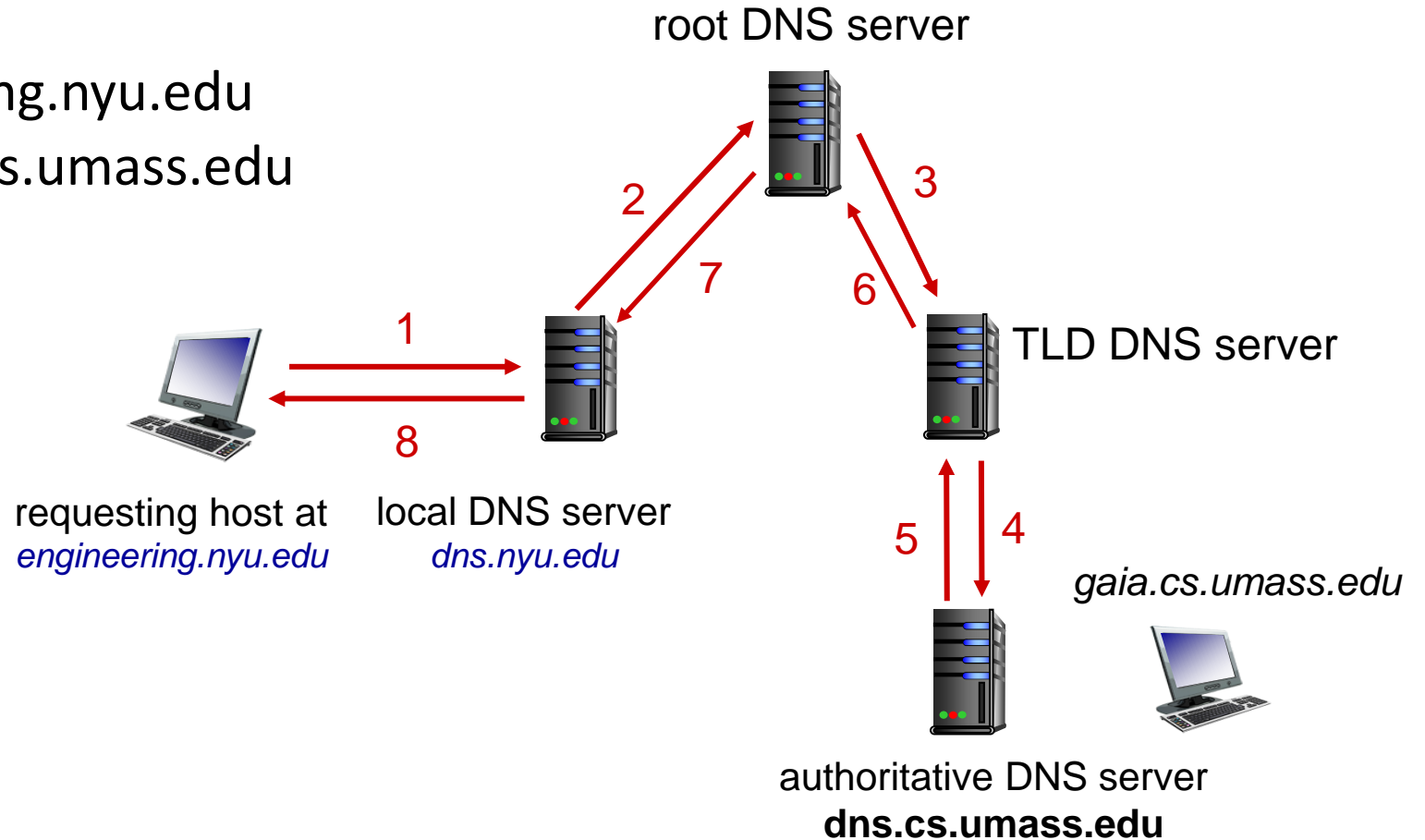


DNS name resolution: recursive query

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

Recursive query:

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



Caching, Updating DNS Records

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

DNS records

DNS: distributed database storing resource records (RR)

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

type=A

- name is hostname
- value is IP address

type=NS

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

type=CNAME

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

type=MX

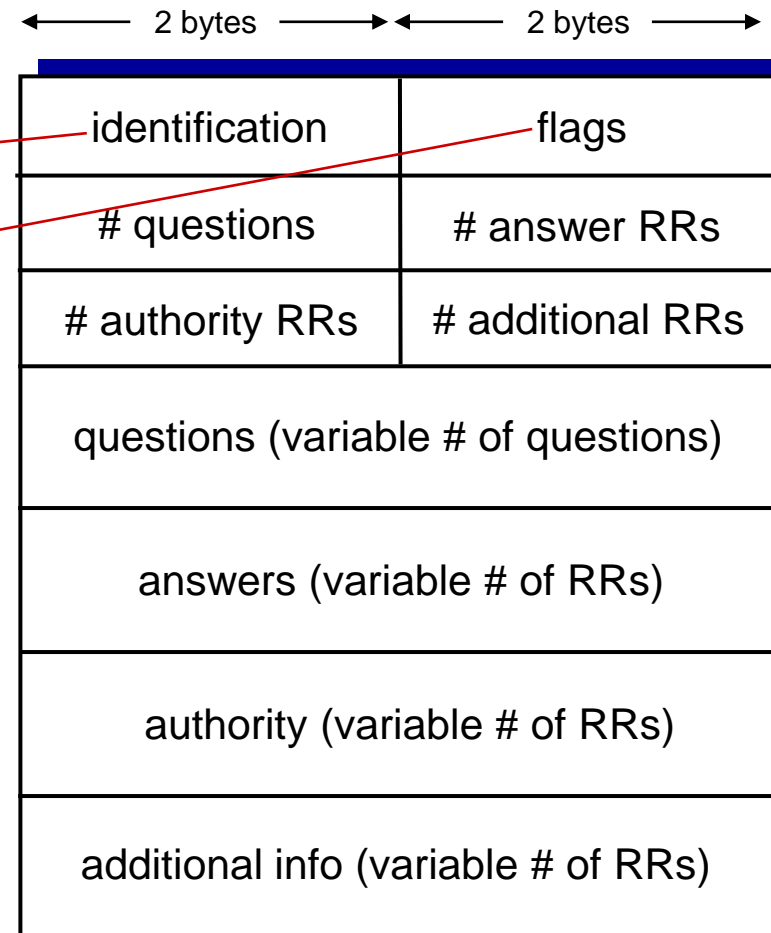
- value is name of mailserver associated with name

DNS protocol messages

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

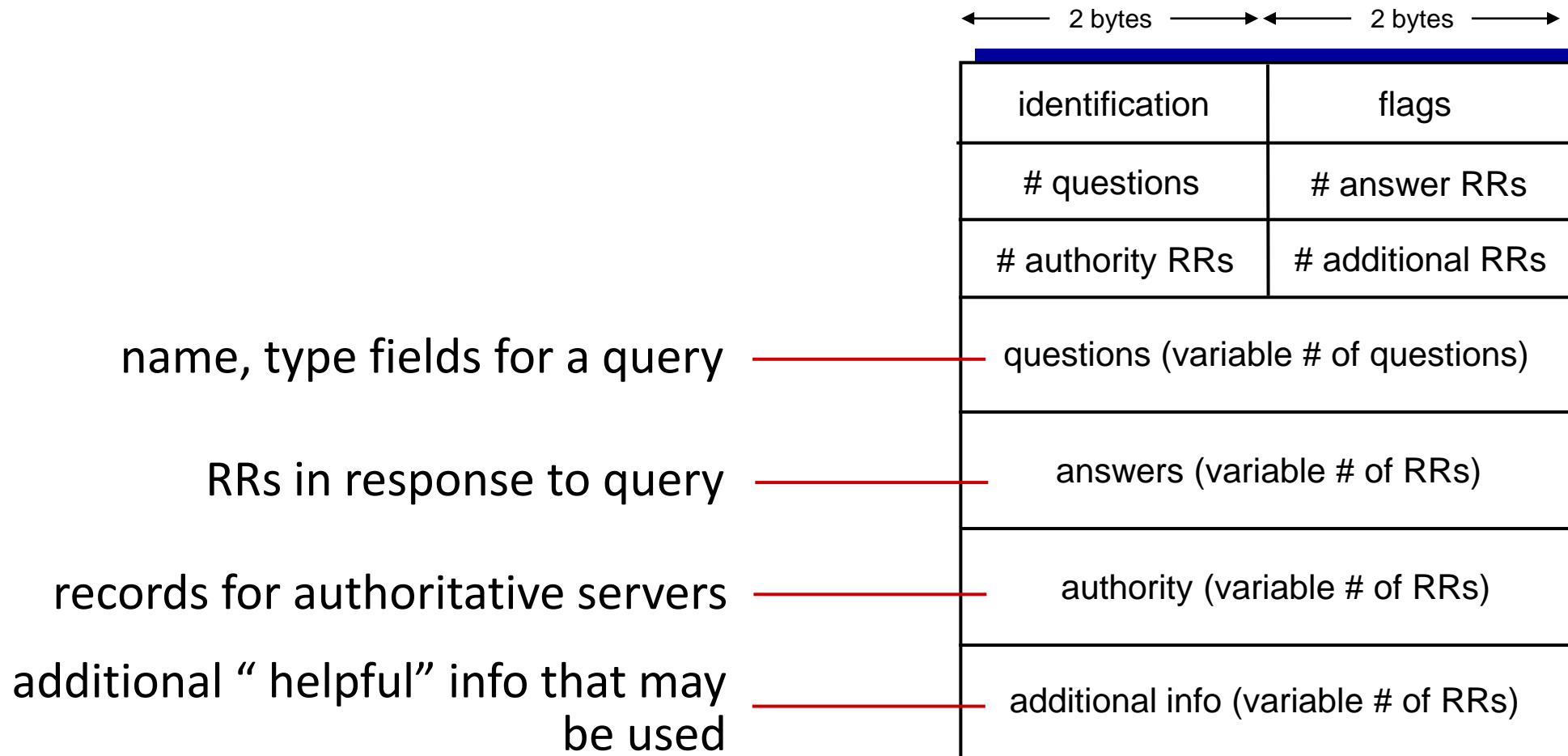
message header:

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



DNS protocol messages

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



Inserting records into DNS

Example: new startup “Network Utopia”

- register name networkutopia.com at *DNS registrar* (e.g., Network Solutions)
 - provide names, IP addresses of authoritative name server (primary and secondary)
 - registrar inserts 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.networkutopia.com`
 - type MX record for `networkutopia.com`

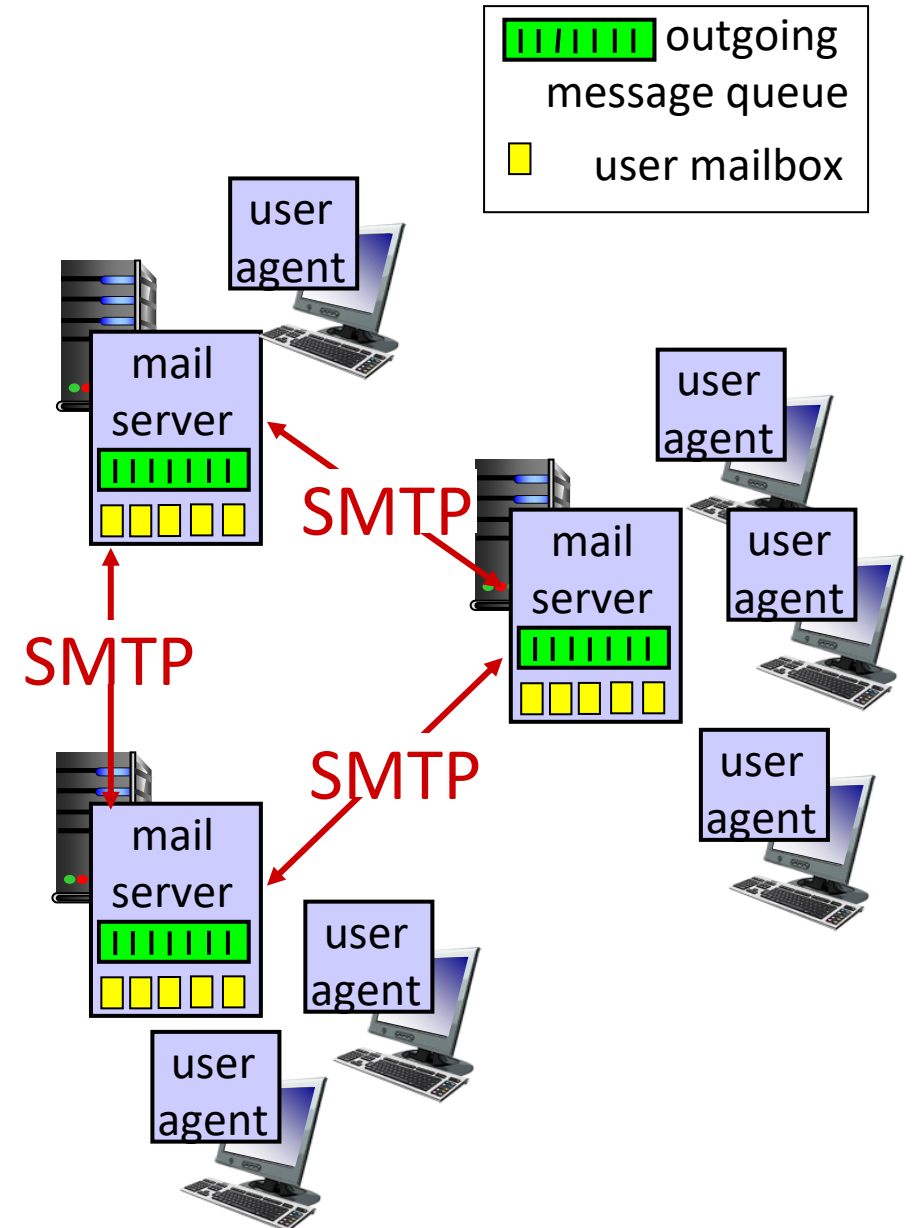
E-mail

Three major components:

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

User Agent

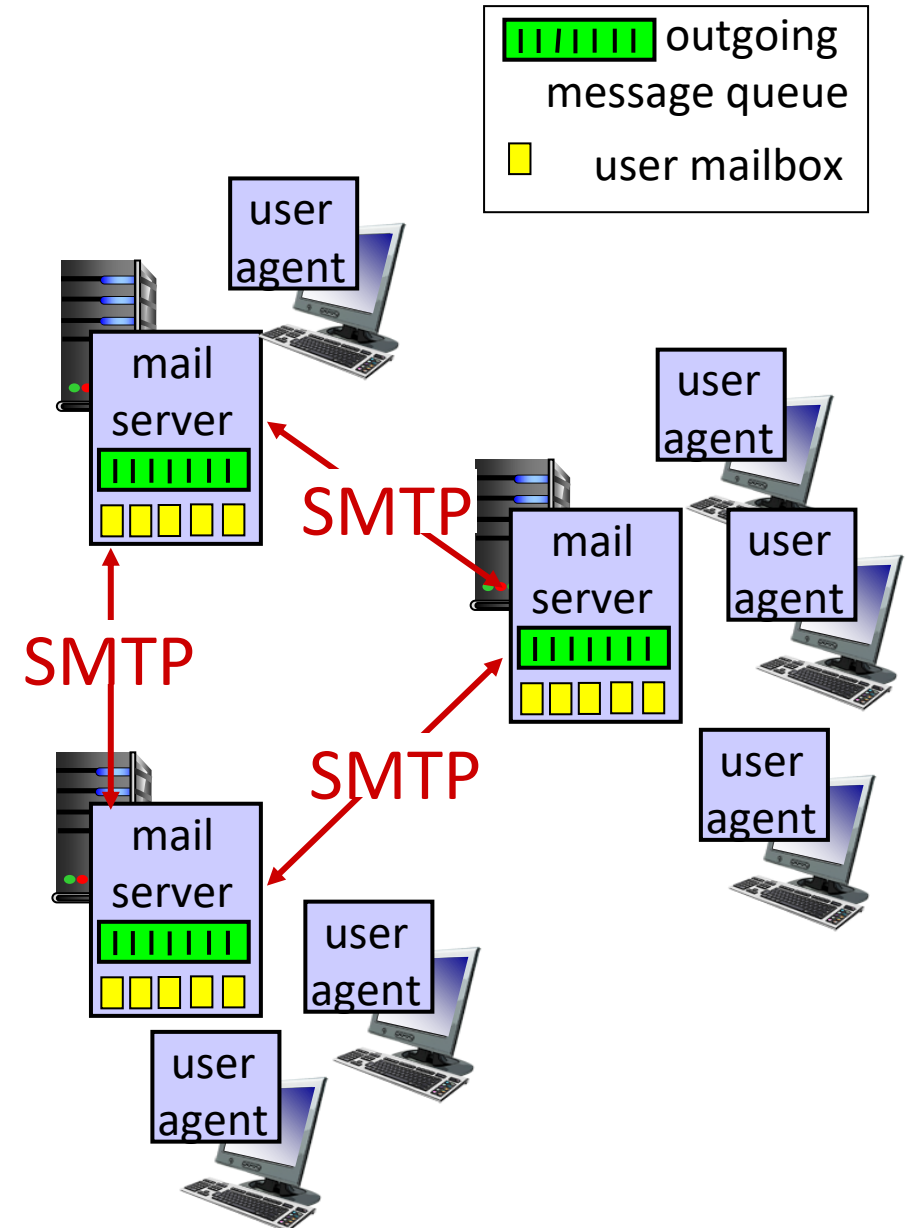
- a.k.a. “mail reader”
- composing, editing, reading mail messages
- e.g., Outlook, iPhone mail client
- outgoing, incoming messages stored on server



E-mail: mail servers

mail servers:

- *mailbox* contains incoming messages for user
- *message queue* of outgoing (to be sent) mail messages
- *SMTP protocol* between mail servers to send email messages
 - client: sending mail server
 - “server”: receiving mail server

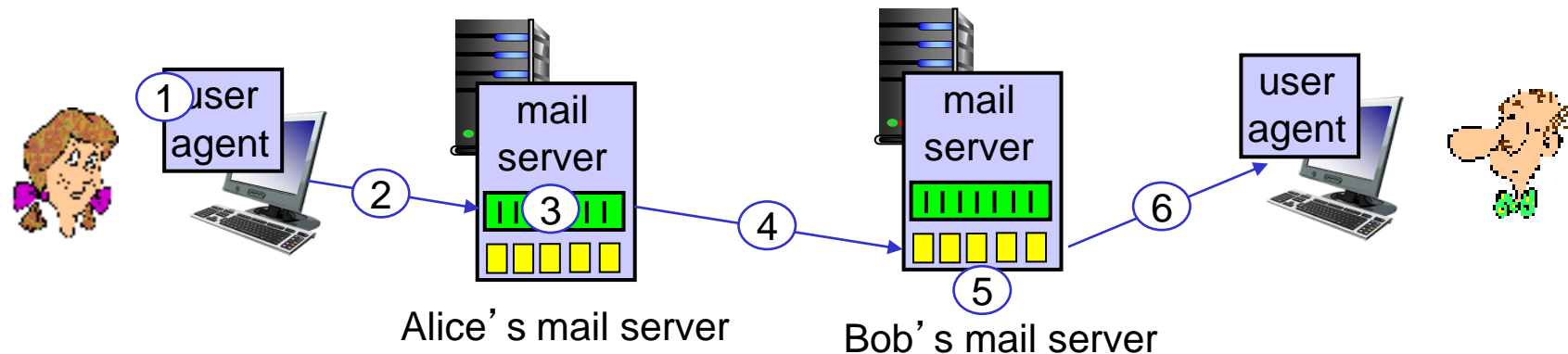


E-mail: the RFC (5321)

- 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 ASCII

Scenario: Alice sends e-mail to Bob

- 1) Alice uses UA to compose e-mail message "to" bob@some school.edu
- 2) Alice's UA sends message to her mail server; 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:

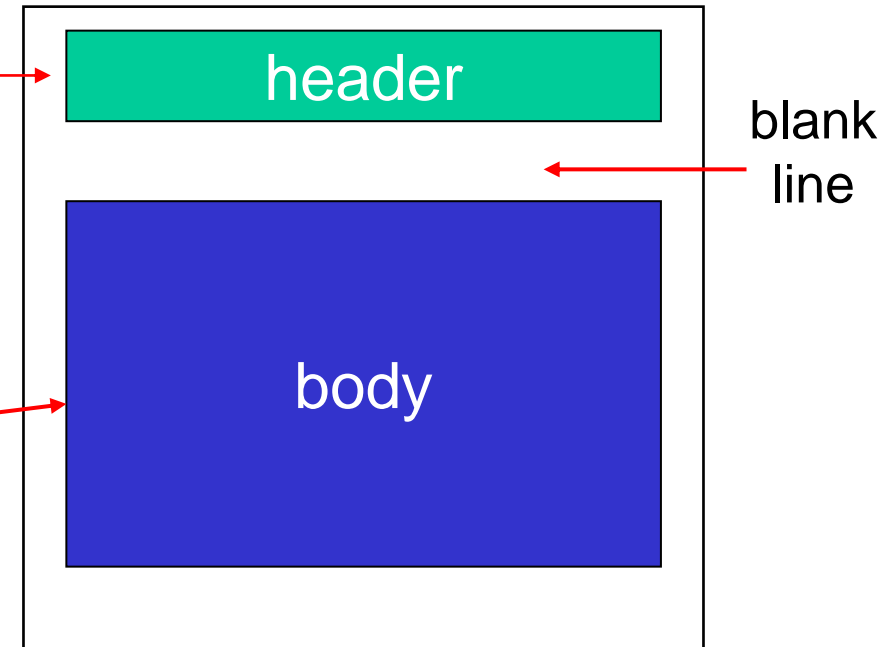
- HTTP: pull
- SMTP: push
- both have ASCII command/response interaction, status codes
- HTTP: each object encapsulated in its own response message
- SMTP: multiple objects sent in multipart message
- SMTP uses persistent connections
- SMTP requires message (header & body) to be in 7-bit ASCII
- SMTP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

Mail message format

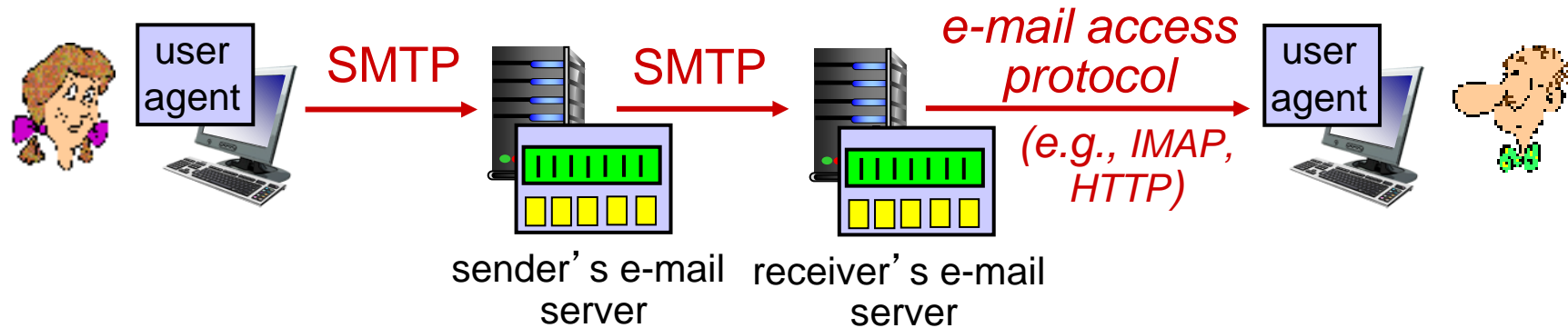
SMTP: protocol for exchanging e-mail messages, defined in RFC 531 (like HTTP)

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

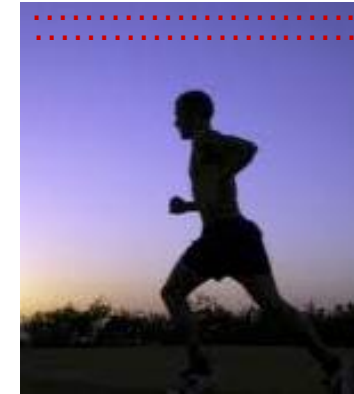


- **SMTP**: delivery/storage of e-mail messages to receiver's server
- mail access protocol: retrieval from server
 - **IMAP**: Internet Mail Access Protocol [RFC 3501]: messages stored on server, IMAP provides retrieval, deletion, folders of stored messages on server
- **HTTP**: gmail, Hotmail, Yahoo!Mail, etc. provides web-based interface on top of SMTP (to send), IMAP (or POP) to retrieve e-mail messages

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

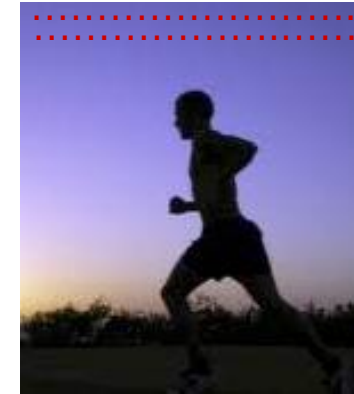


frame $i+1$

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

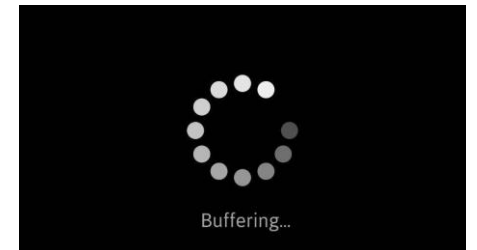
temporal coding example: instead of sending complete frame at $i+1$, send only differences from frame i



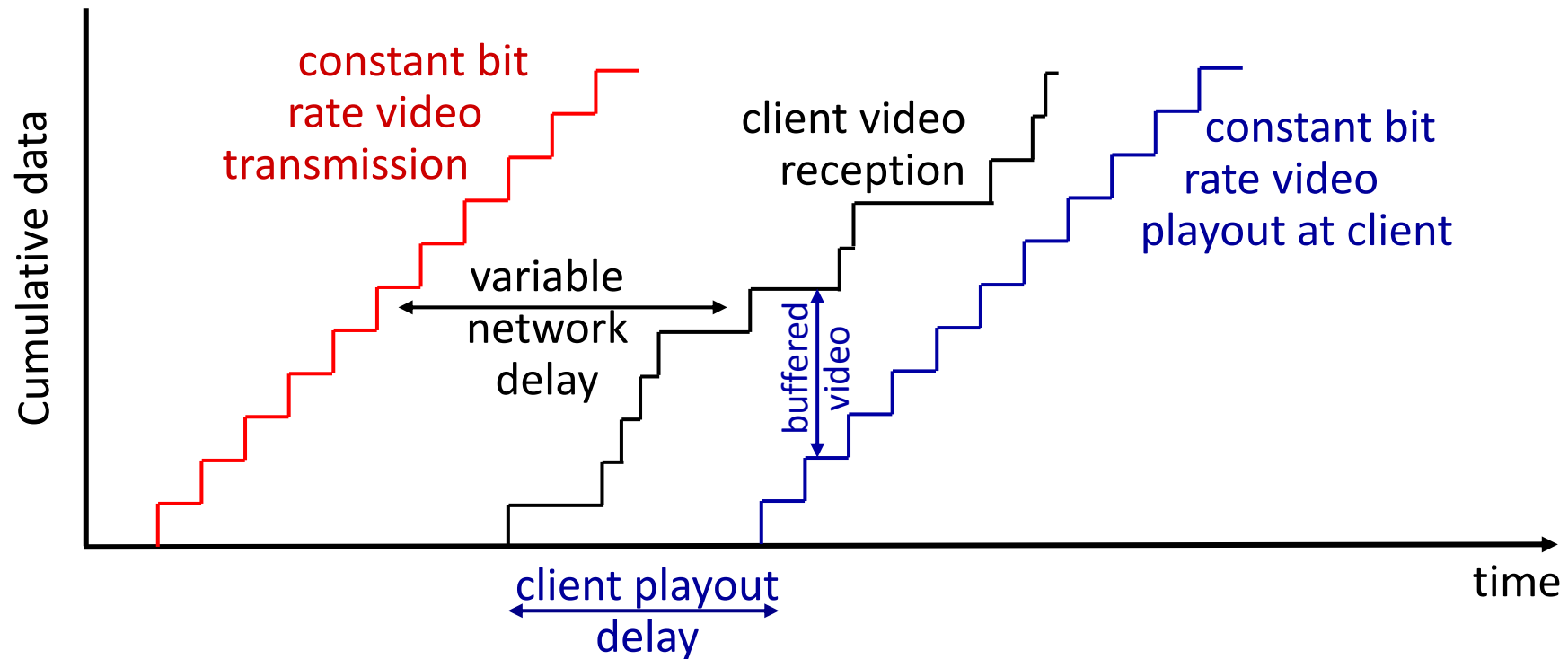
frame $i+1$

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