



# Introduction to Computer Networks (SWE3022)

Jaehoon (Paul) Jeong

Department of Computer Science and Engineering

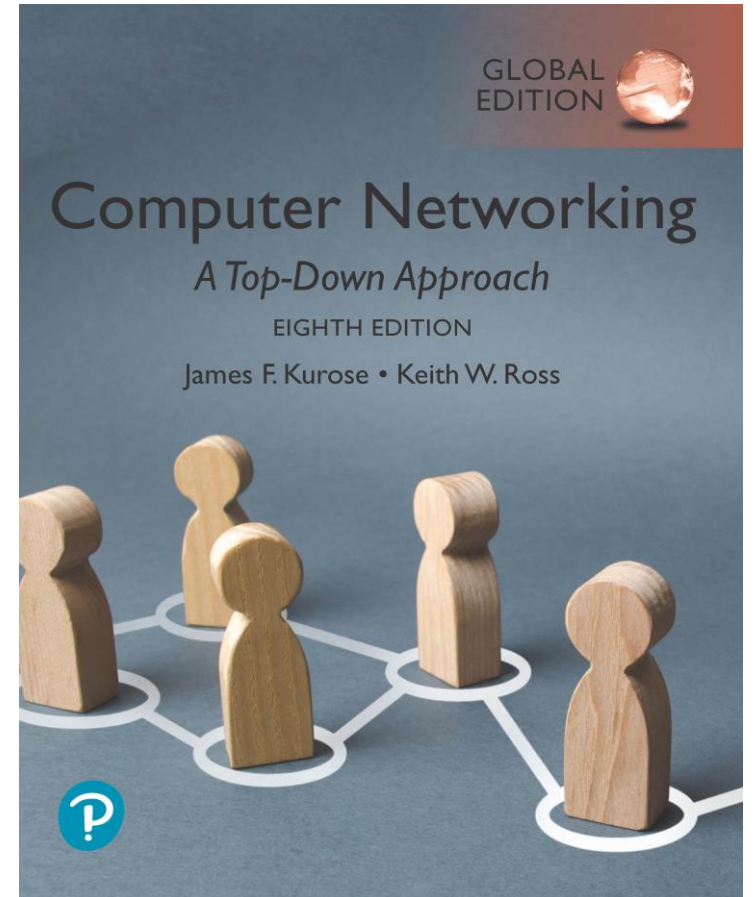
Sungkyunkwan University

Email: [pauljeong@skku.edu](mailto:pauljeong@skku.edu)

Note: The slides are adapted from the slides of Pearson Education Ltd.

# Chapter 2.

## Application Layer: Part 1



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

8<sup>th</sup> Edition, Global Edition

Jim Kurose, Keith Ross

Copyright © 2022 Pearson Education  
Ltd

# 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
  - HTTP
  - SMTP, IMAP
  - DNS
- 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
  - Internet search
  - remote login
  - ...
- Q: *your* favorites?

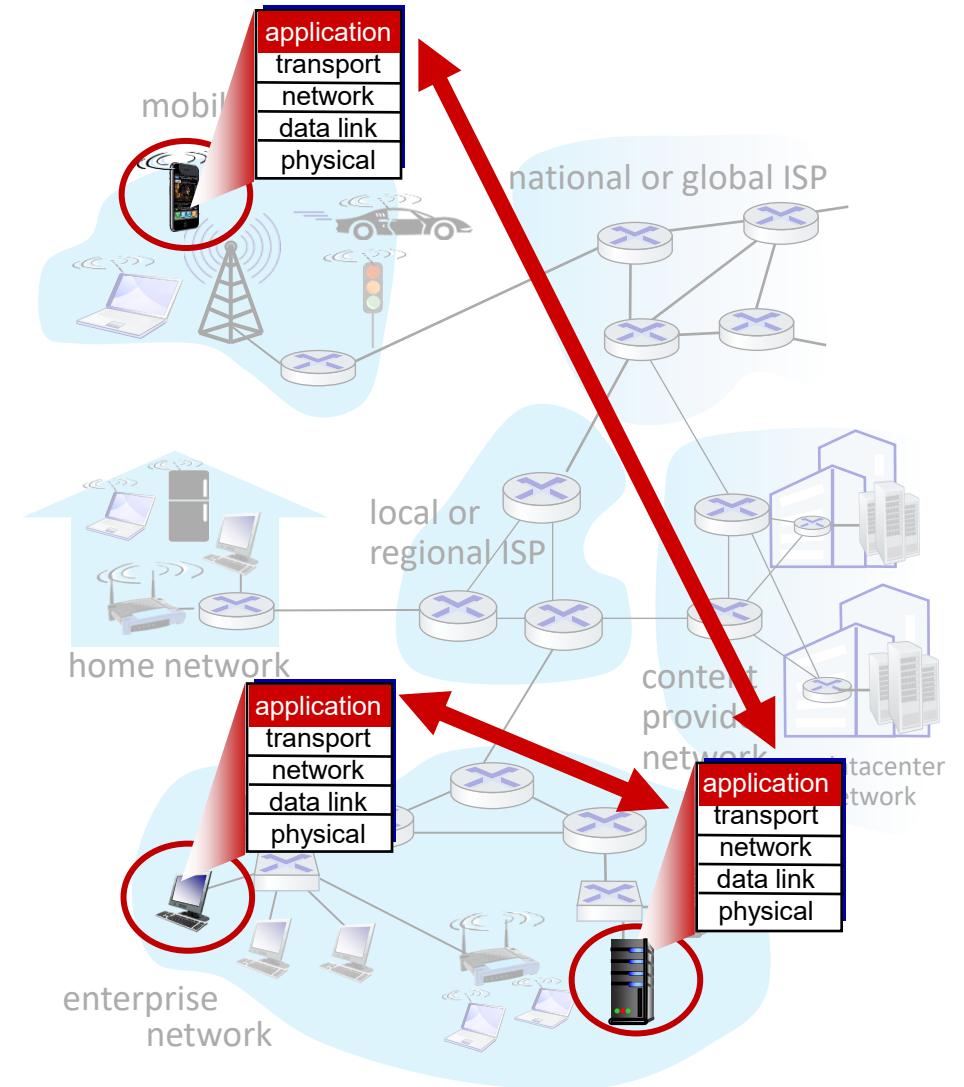
# Creating a network app

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



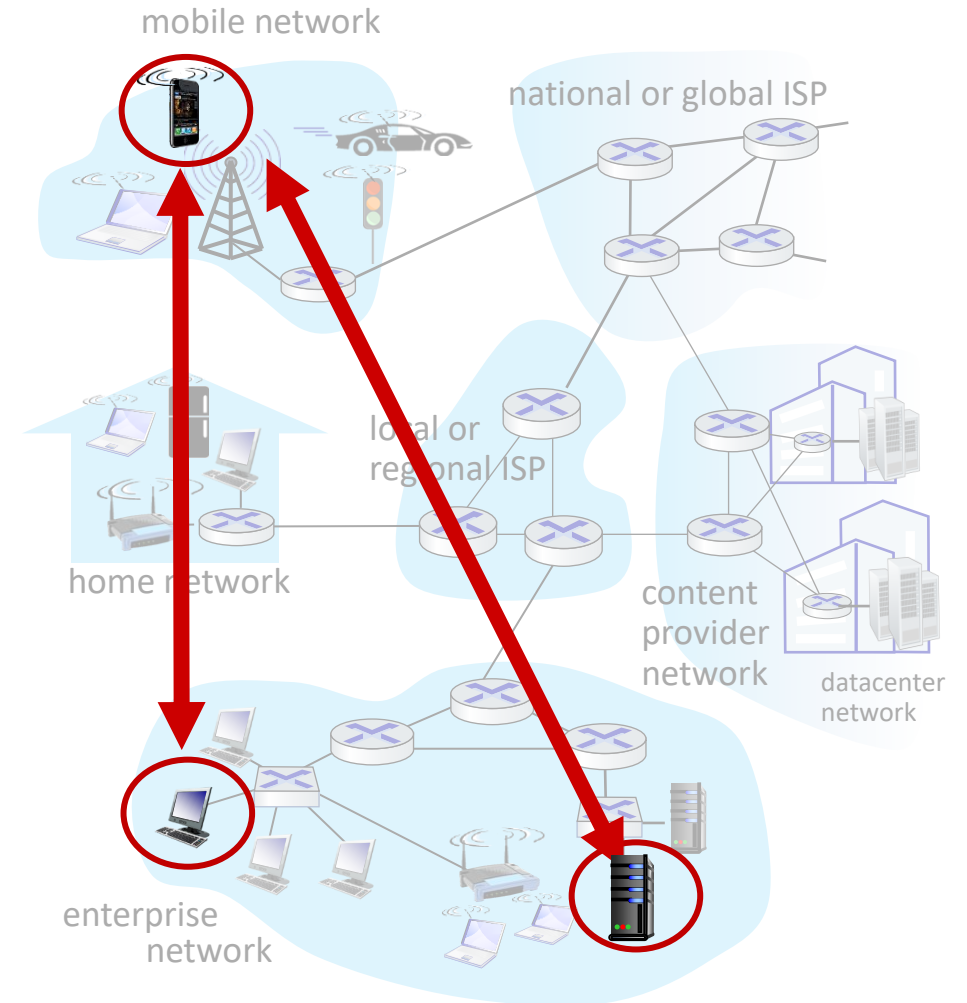
# Client-server paradigm

## server:

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

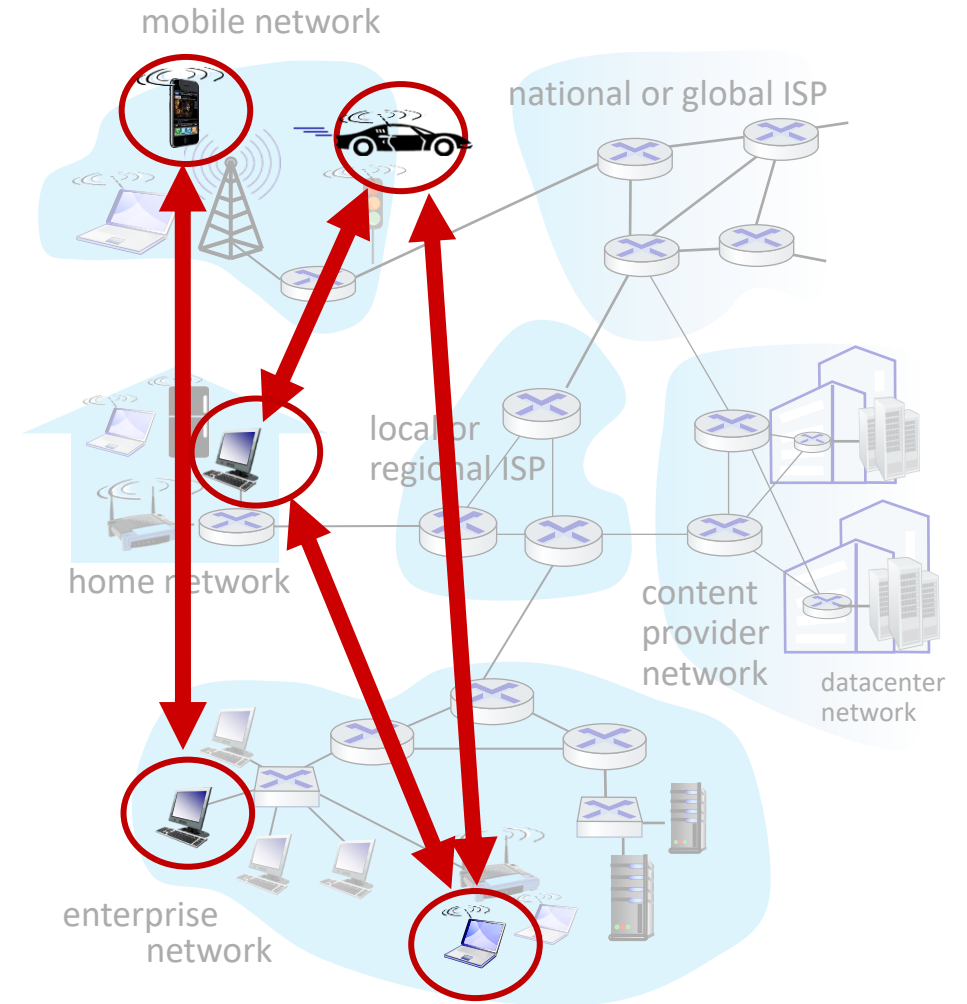
## clients:

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

clients, servers

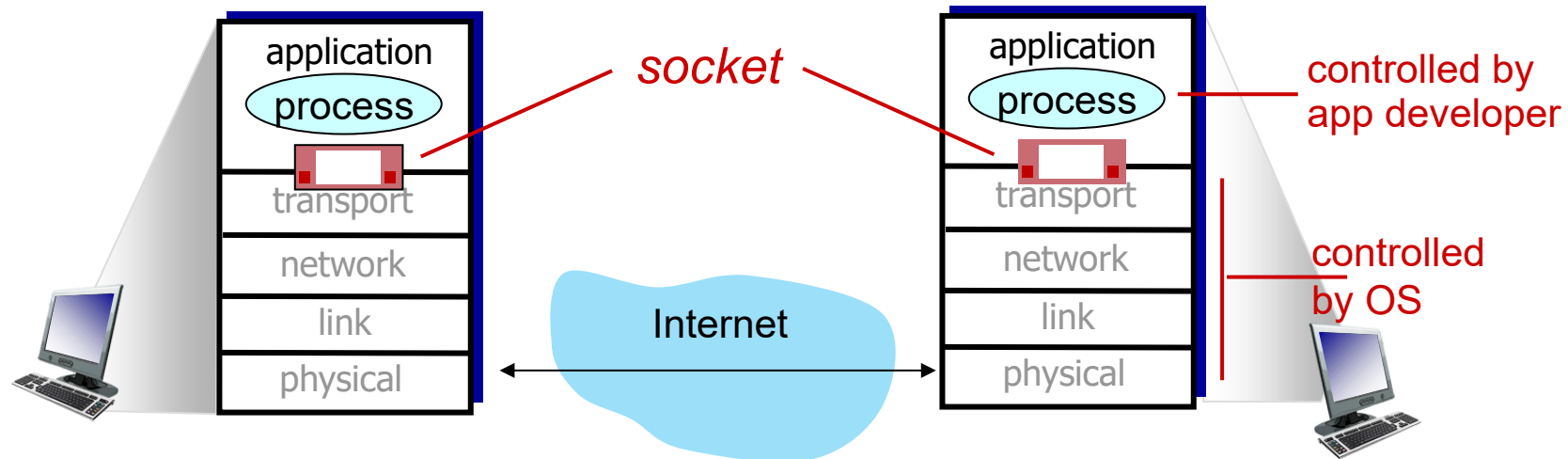
*client process*: process that initiates communication

*server process*: process that waits to be contacted

- note: 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 of 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 number** 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 (i.e., standards), 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 TSL libraries, that use TCP in turn

## TLS socket API

- cleartext sent into socket traverse Internet *encrypted*
- see 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`

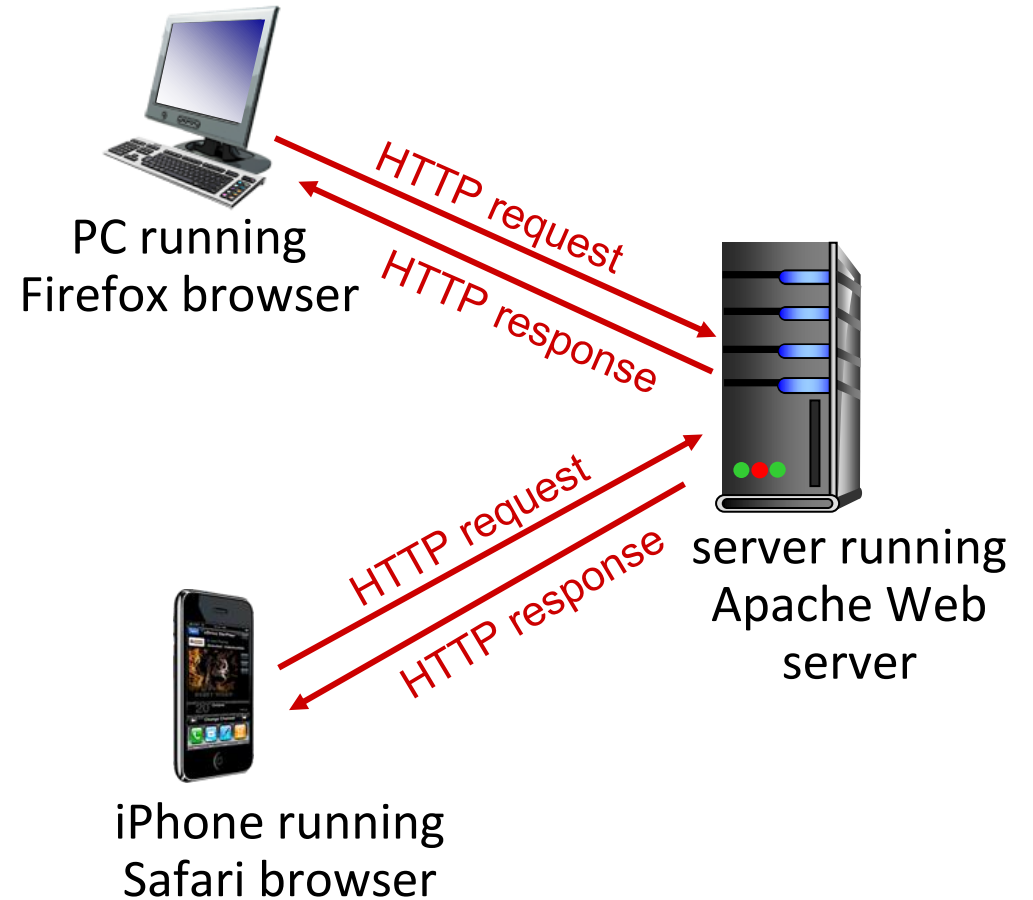
host name

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



# 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`

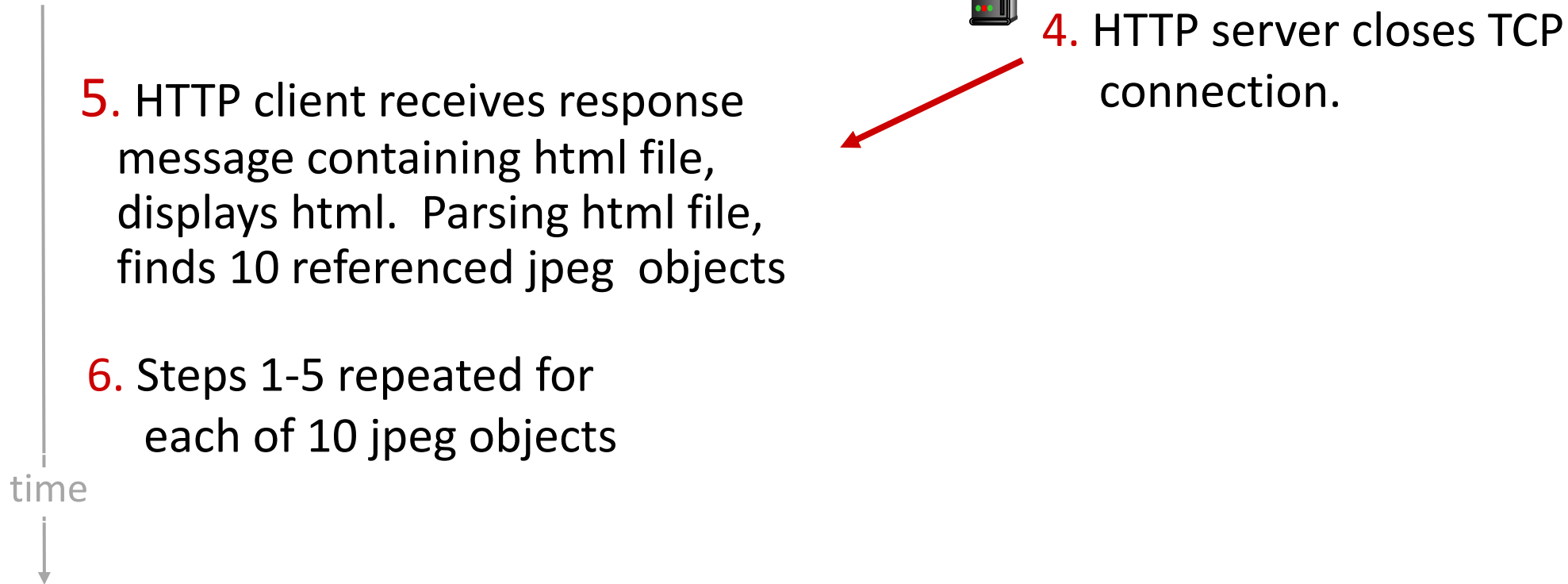
**3.** HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time



# Non-persistent HTTP: example (cont.)

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



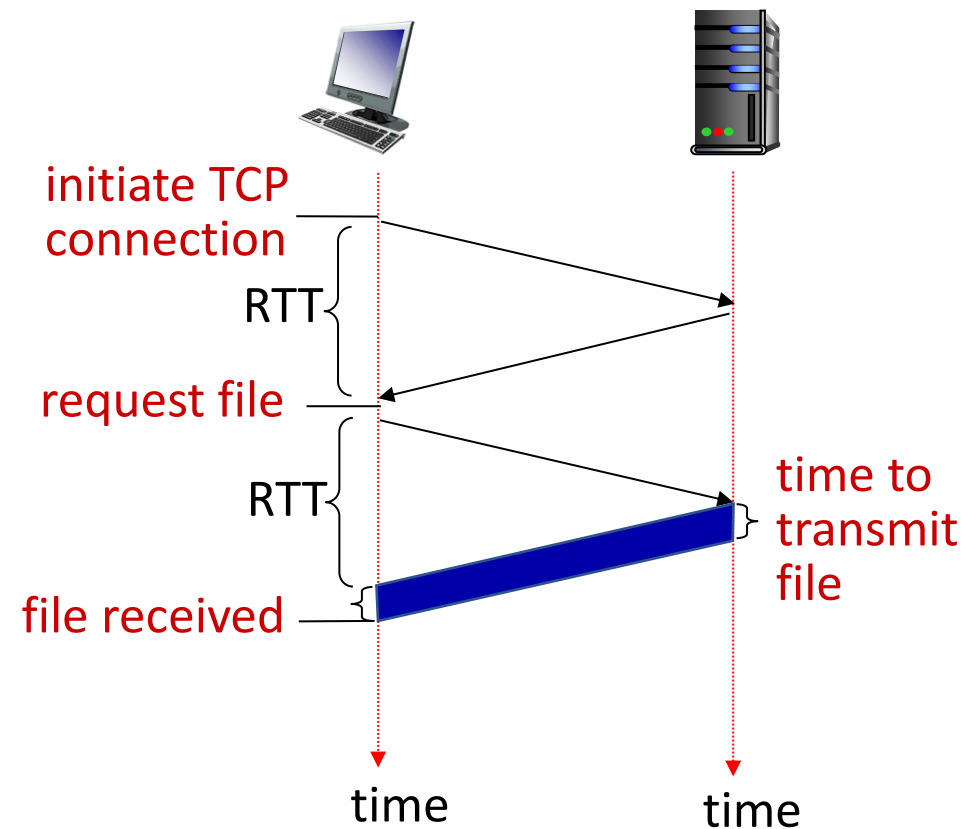


# Non-persistent HTTP: response time

**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://gaia.cs.umass.edu/kurose_ross/interactive/)

# HTTP request message: Carriage Return vs. Line Feed

- **Carriage return:** The cursor (as carriage) moves to the 1<sup>st</sup> column of the line.
- **Line feed:** The cursor moves to the next line.
- **Combination of carriage return and line feed:** It lets the cursor move the start of the next line.

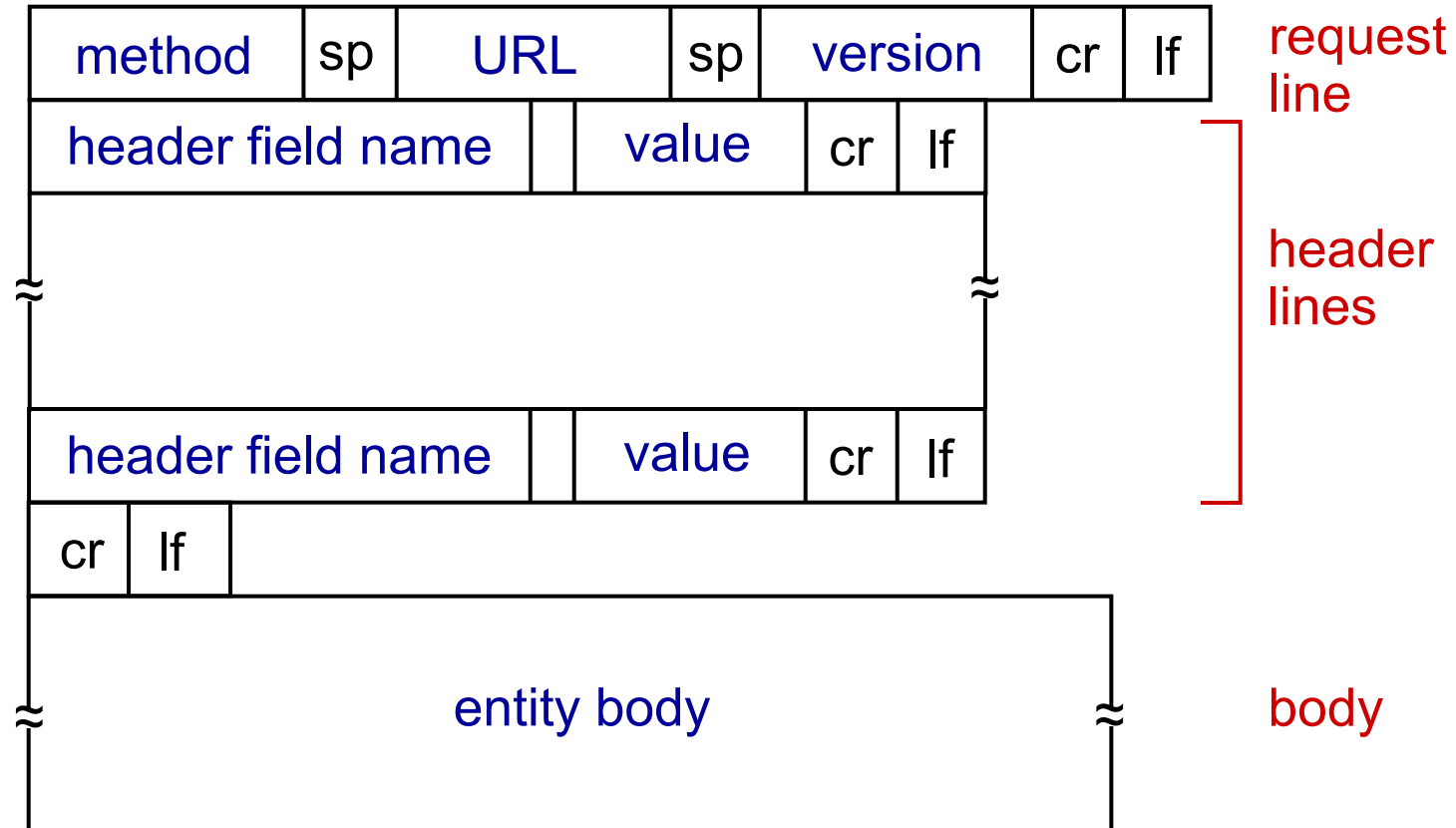


[Source] <https://jw910911.tistory.com/90>



[Source] <https://youtu.be/FkUXn5bOwzk>

# 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`

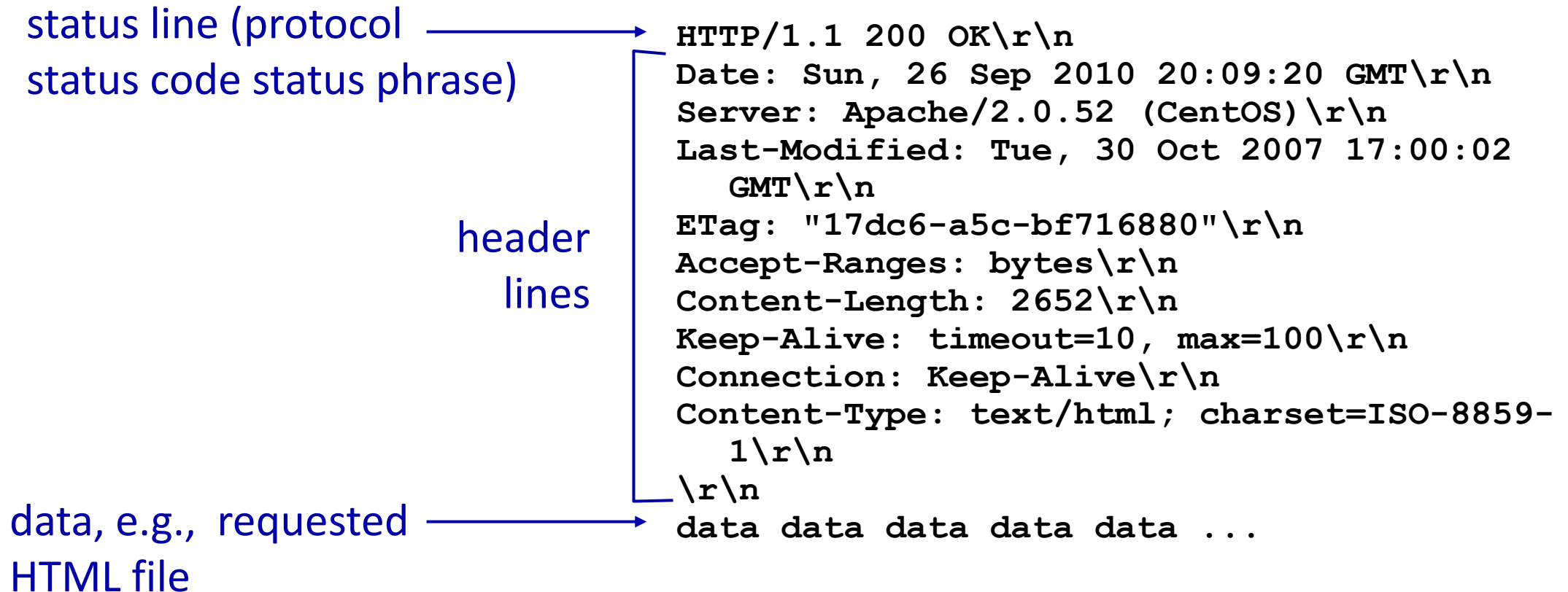
## HEAD method:

- 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://gaia.cs.umass.edu/kurose_ross/interactive/)

# HTTP response status codes

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

## 200 OK

- request succeeded, requested object later in this message

## 301 Moved Permanently

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

## 400 Bad Request

- request msg not understood by server

## 404 Not Found

- requested document not found on this server

## 505 HTTP Version Not Supported



# Trying out HTTP (client side) for yourself

## 1. Telnet to your favorite Web server:

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

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

## 2. type in a GET HTTP request:

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

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

## 3. look at response message sent by HTTP server!

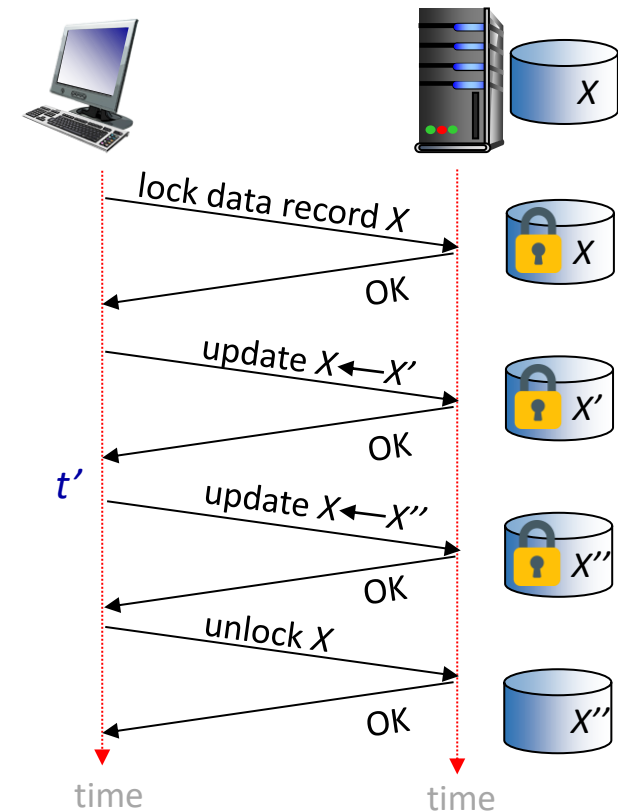
(or use Wireshark to look at captured HTTP request/response)

# 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

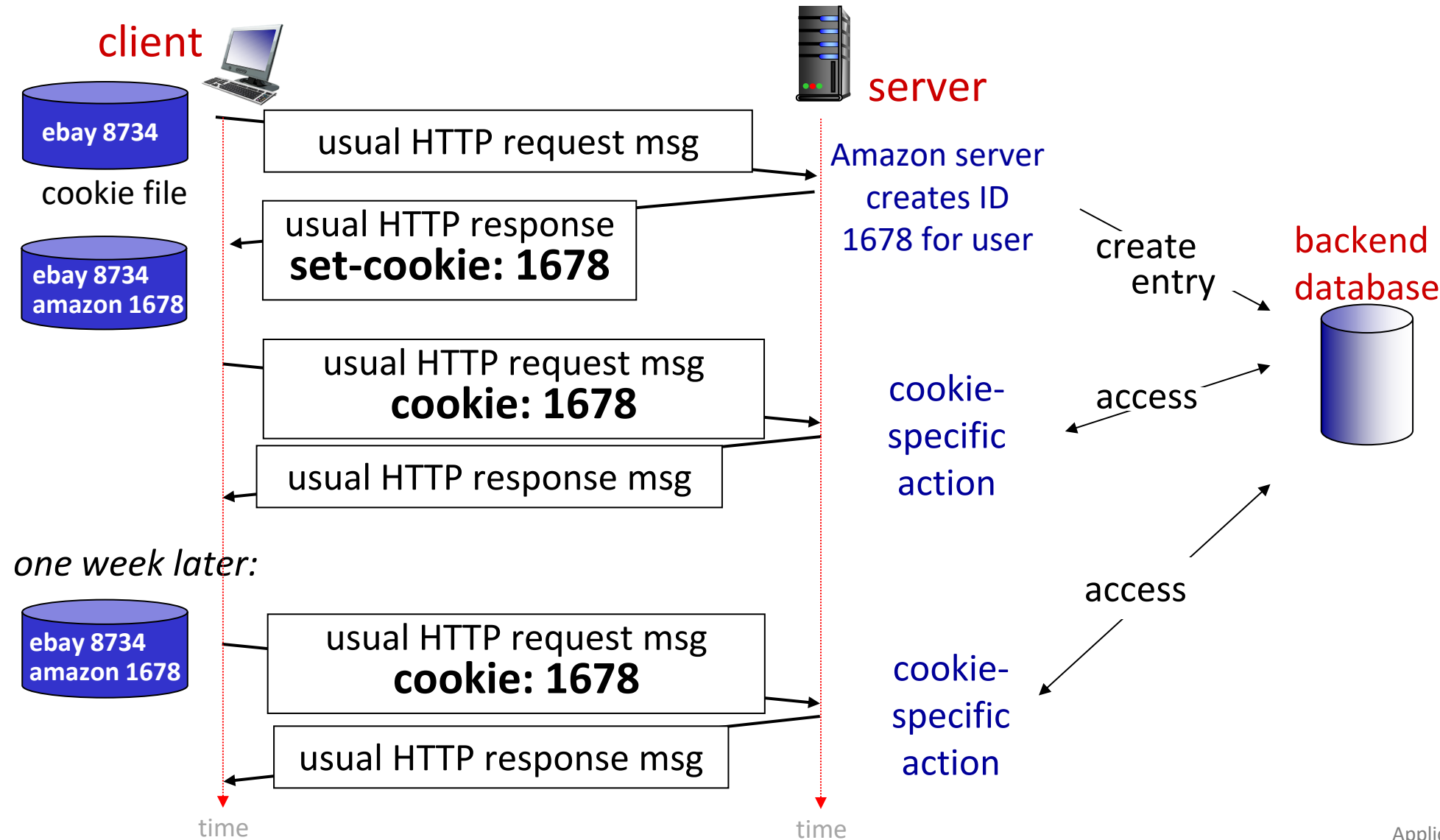
## *four components:*

- 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:*

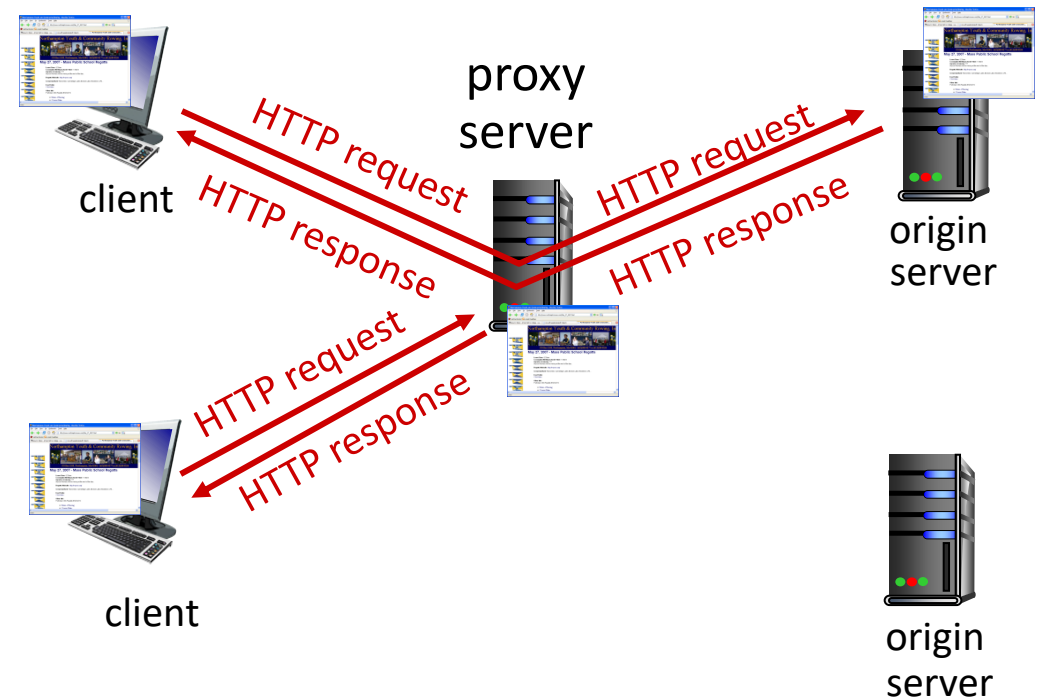
- protocol endpoints: maintain state at sender/receiver over multiple transactions
- cookies: HTTP messages carry state

- 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

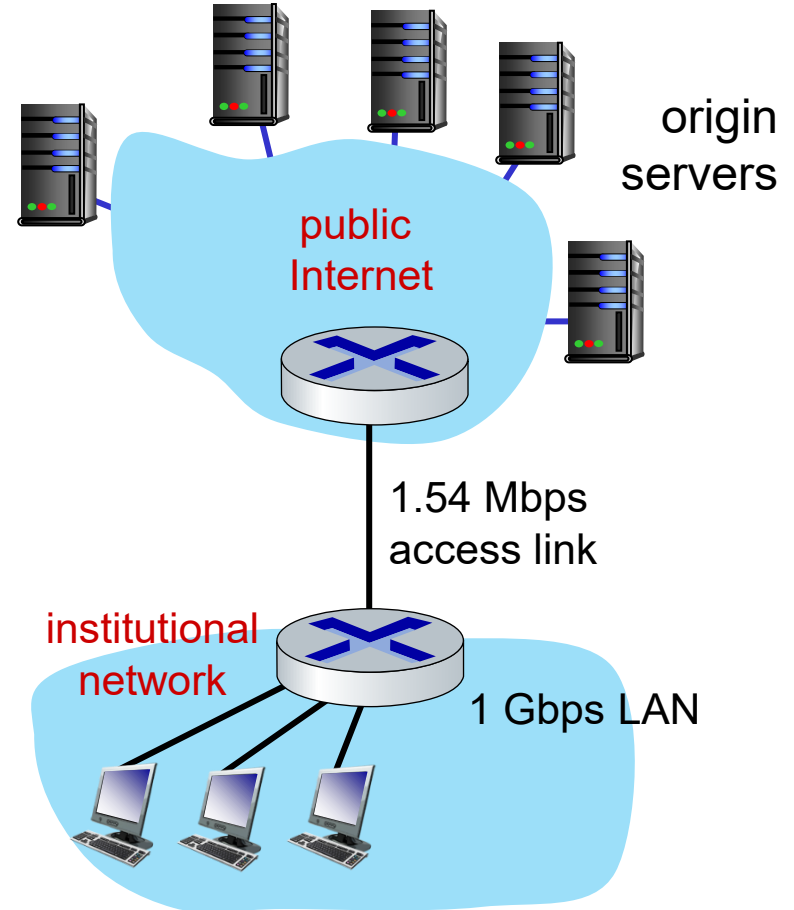
## Scenario:

- 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

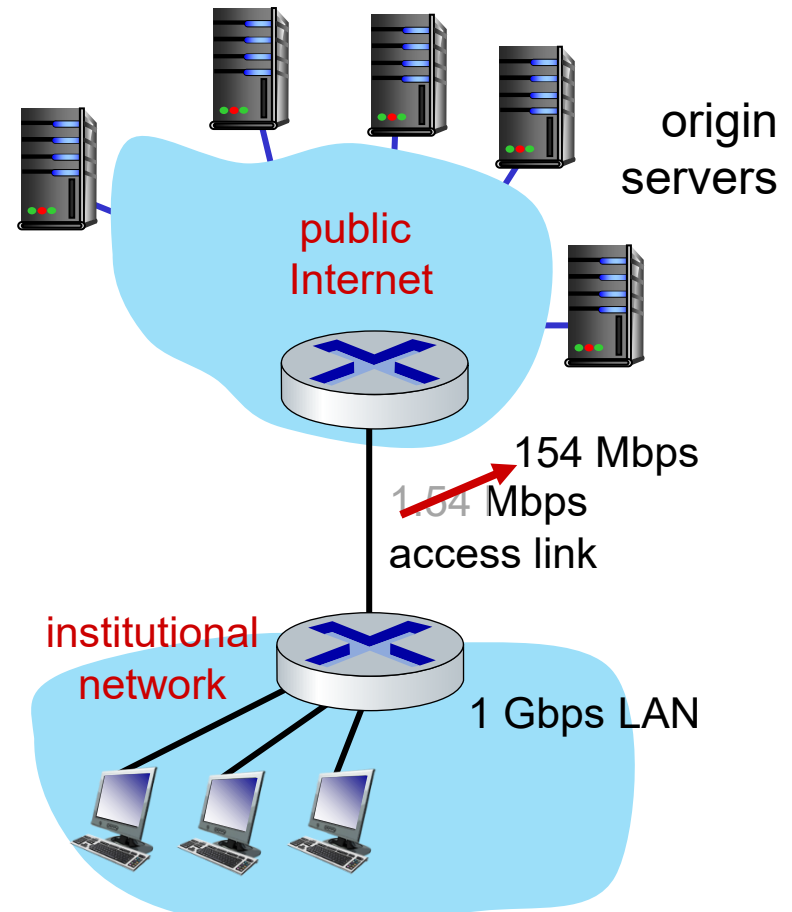
## Scenario:

- 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

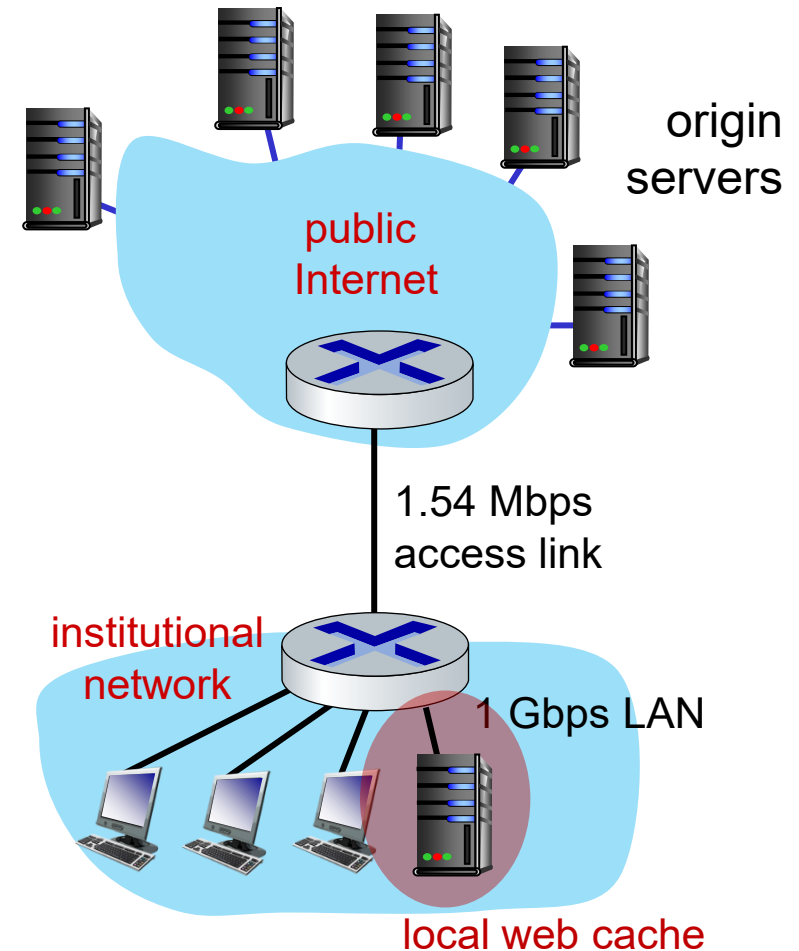
## Scenario:

- 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?*

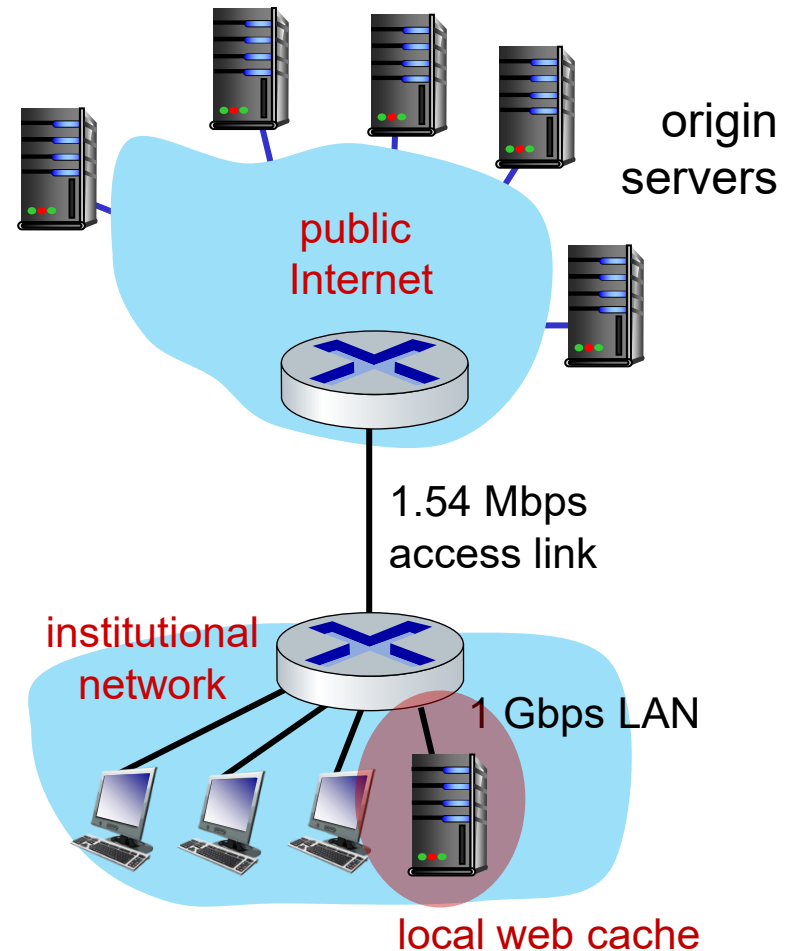
*Cost:* web cache (cheap!)



# 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

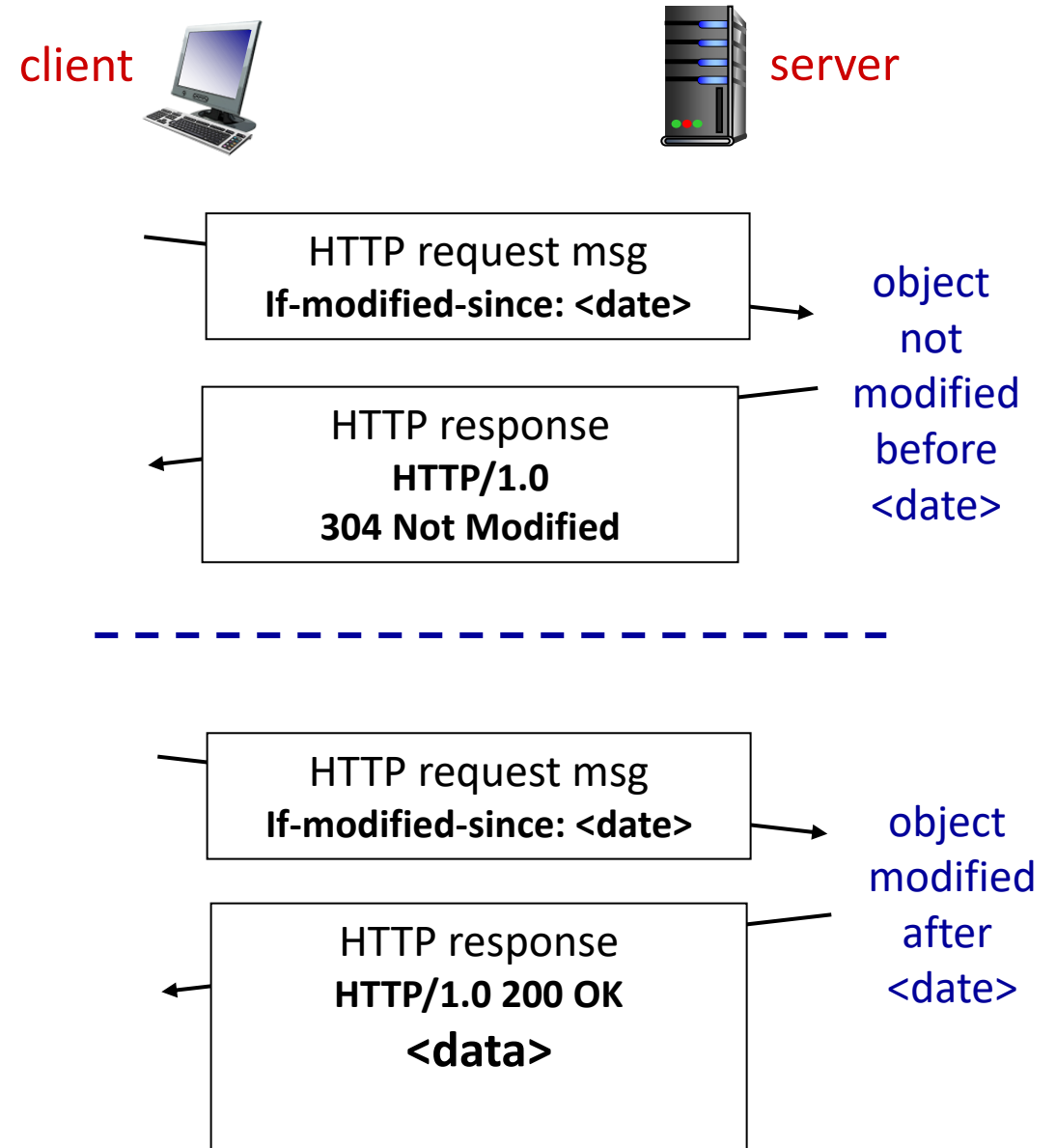
**Goal:** don't send object if cache has up-to-date cached version

- 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

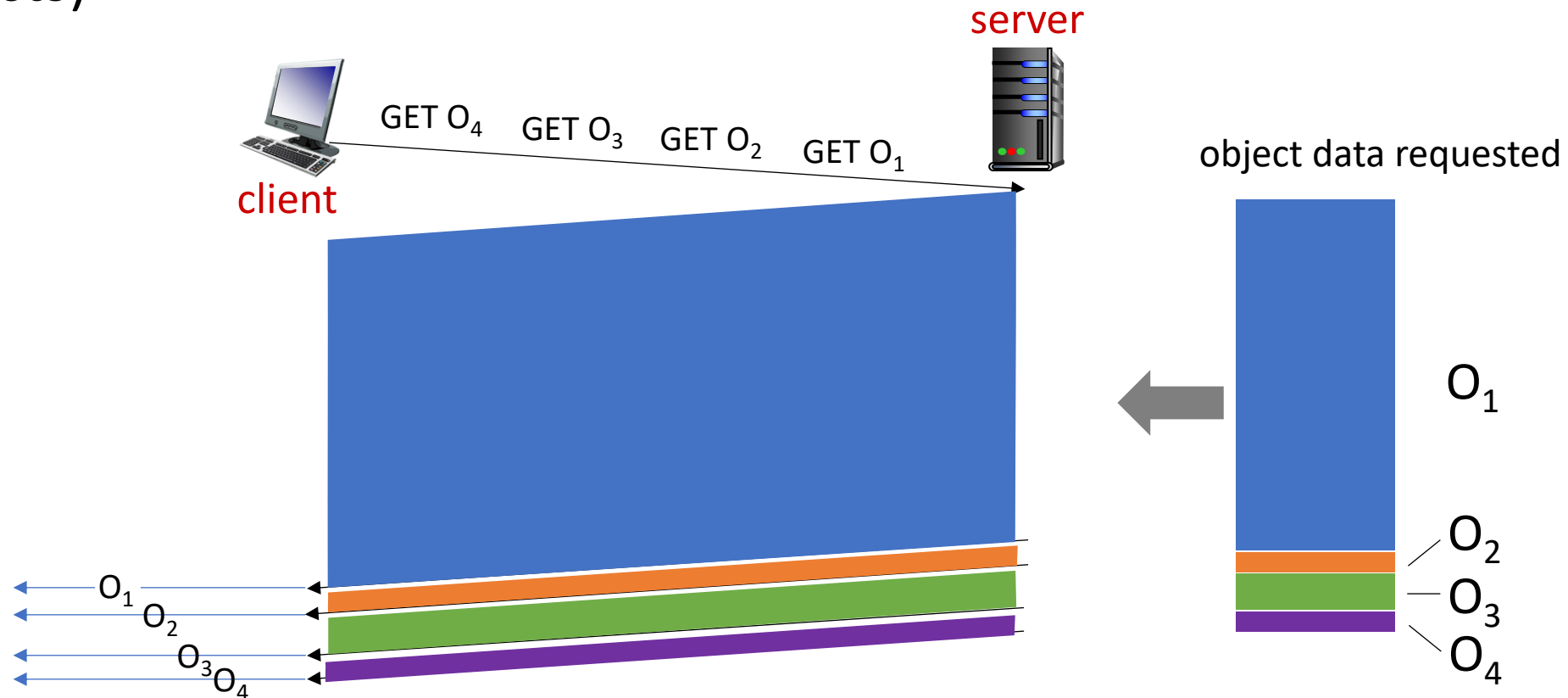
*Key goal:* decreased delay in multi-object HTTP requests

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

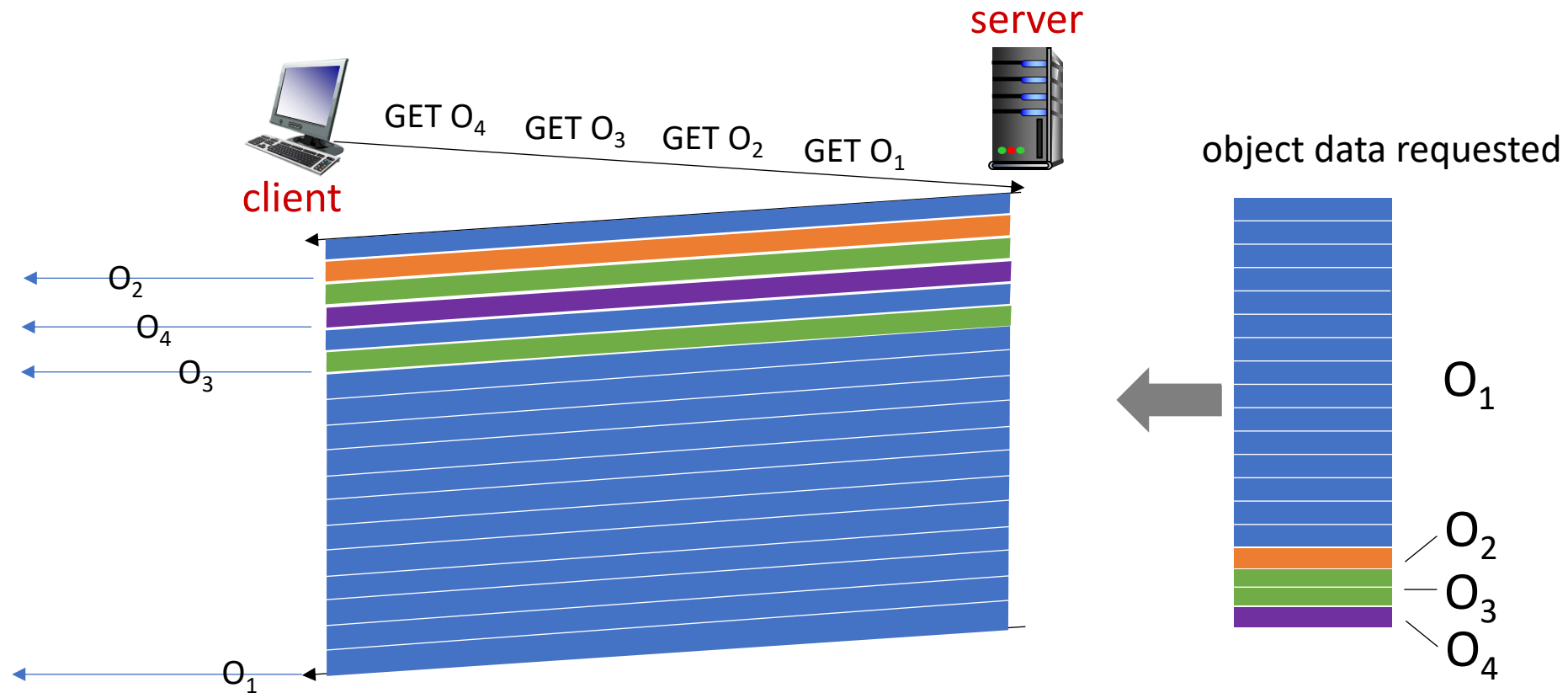
HTTP 1.1: client requests 1 large object (e.g., video file, and 3 smaller objects)



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

# HTTP/2: mitigating HOL blocking

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



*O<sub>2</sub>, O<sub>3</sub>, O<sub>4</sub> delivered quickly, O<sub>1</sub> slightly delayed*



# HTTP/2 to HTTP/3

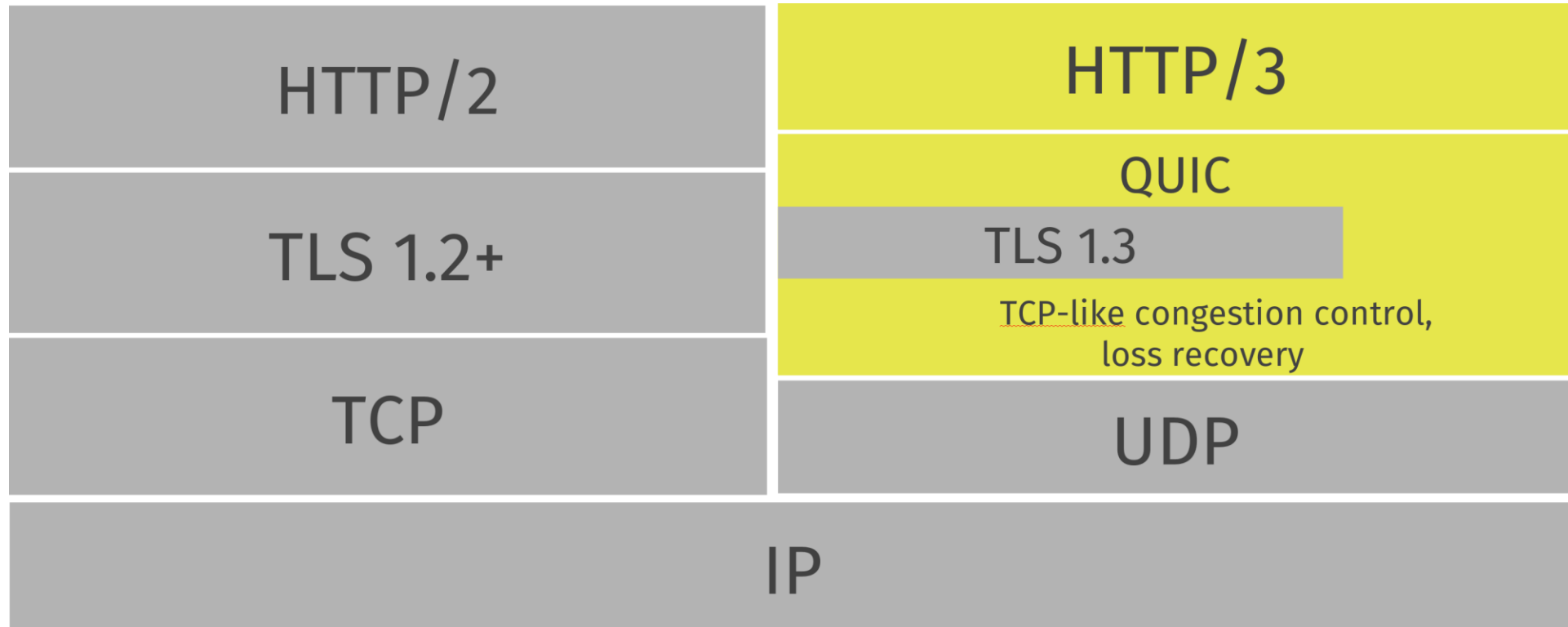
*Key goal:* decreased delay in multi-object HTTP requests

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 (i.e., QUIC over UDP)
  - QUIC: A UDP-Based Multiplexed and Secure Transport [RFC 9000]
    - It is a new reliable, secure transport protocol suitable for a protocol like HTTP.
    - URL: <https://datatracker.ietf.org/doc/html/rfc9000>
  - more on HTTP/3 in transport layer

# HTTP/2 to HTTP/3

## *Protocol Stacks for HTTP/2 and HTTP/3*



[Source] <https://http3-explained.haxx.se/en/the-protocol>

# 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



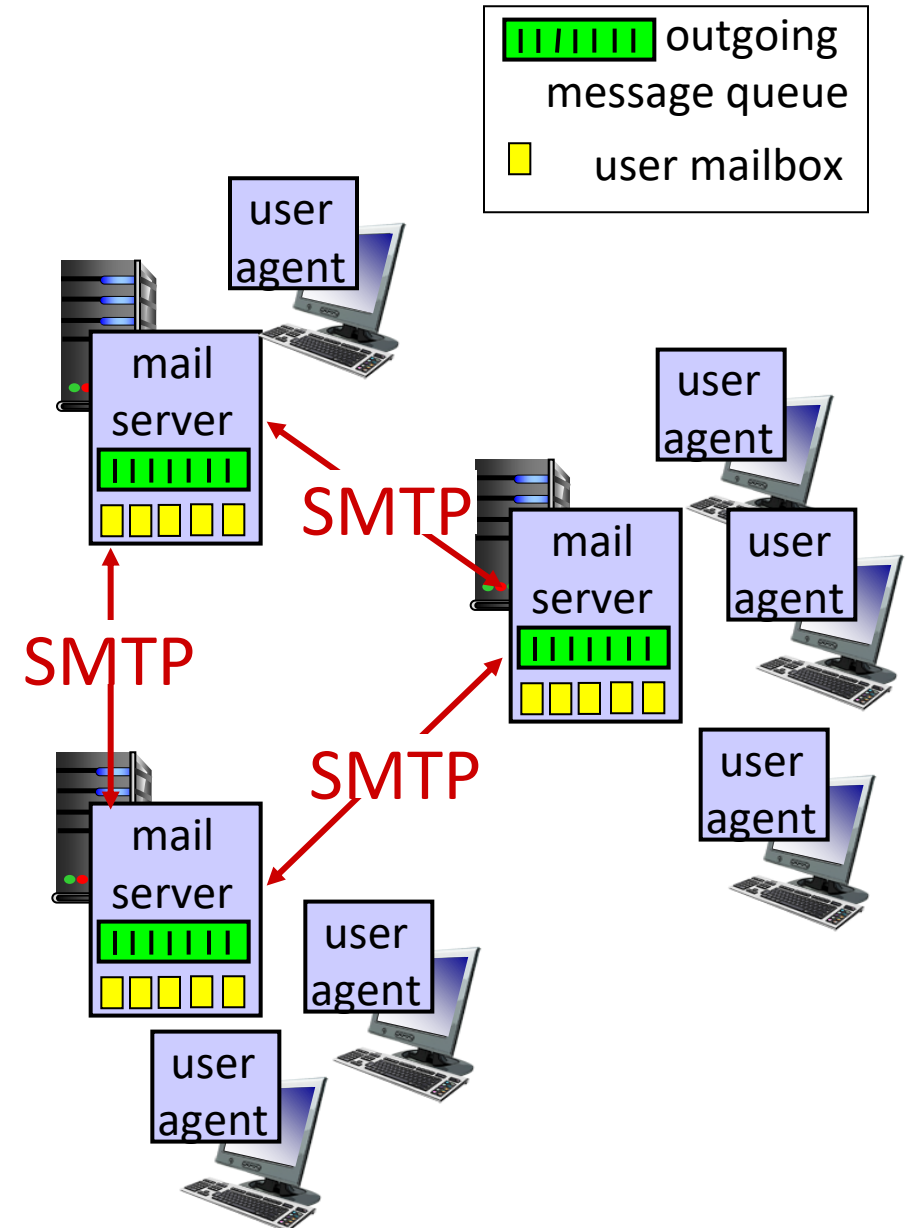
# E-mail

## Three major components:

- User agents
- Mail servers
- Simple Mail Transfer Protocol (SMTP)

## User Agent

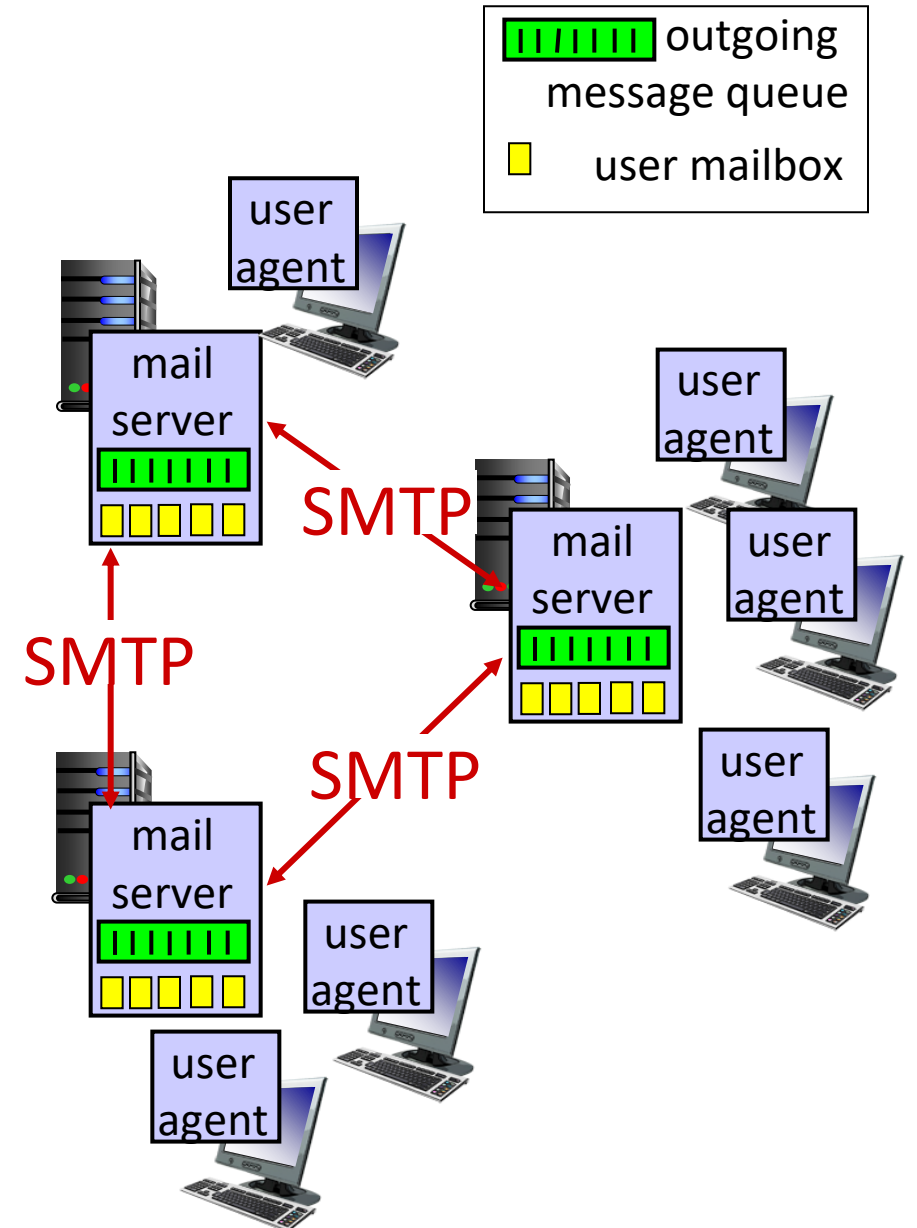
- a.k.a. “mail reader”
- composing, editing, reading mail messages
- e.g., Outlook, iPhone mail client
- outgoing, incoming messages stored on server



# 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

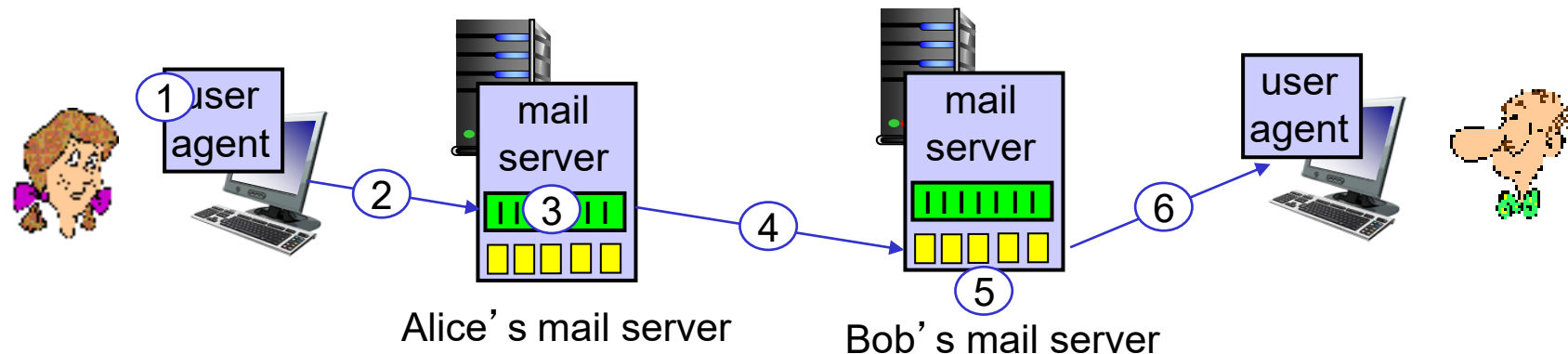


# E-mail: the RFC (5321)

- 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
```



# Try SMTP interaction for yourself:

telnet <servername> 25

- see 220 reply from server
- enter HELO, MAIL FROM:, RCPT TO:, DATA, QUIT commands

above lets you send email without using e-mail client (reader)

*Note: this will only work if <servername> allows telnet connections to port 25 (this is becoming increasingly rare because of security concerns)*

# SMTP: closing observations

## *comparison with HTTP:*

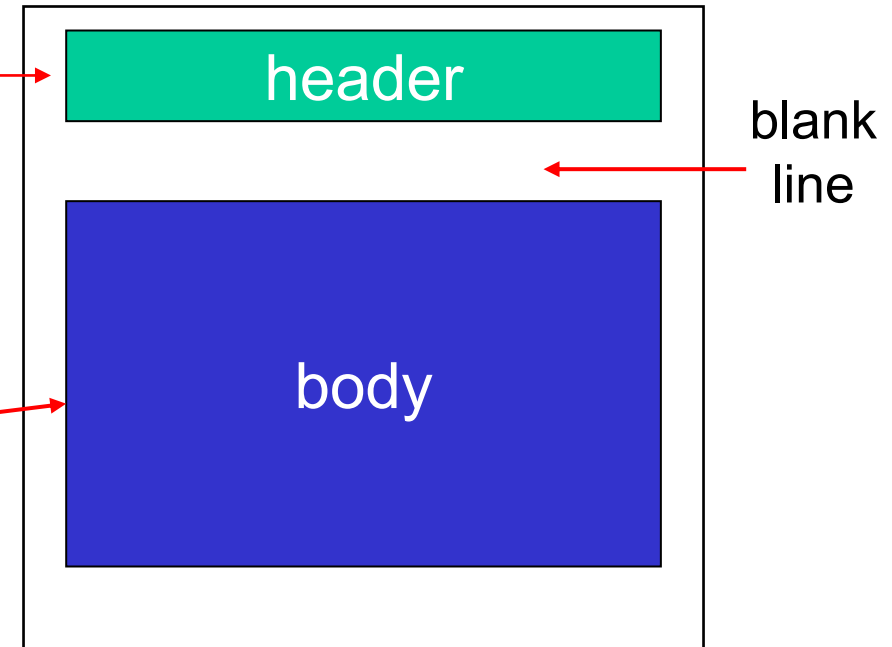
- HTTP: pull
- SMTP: push
- both have ASCII command/response interaction, status codes
- HTTP: each object encapsulated in its own response message
- SMTP: multiple objects sent in multipart message
- SMTP uses persistent connections
- SMTP requires message (header & body) to be in 7-bit ASCII
- SMTP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

# Mail message format

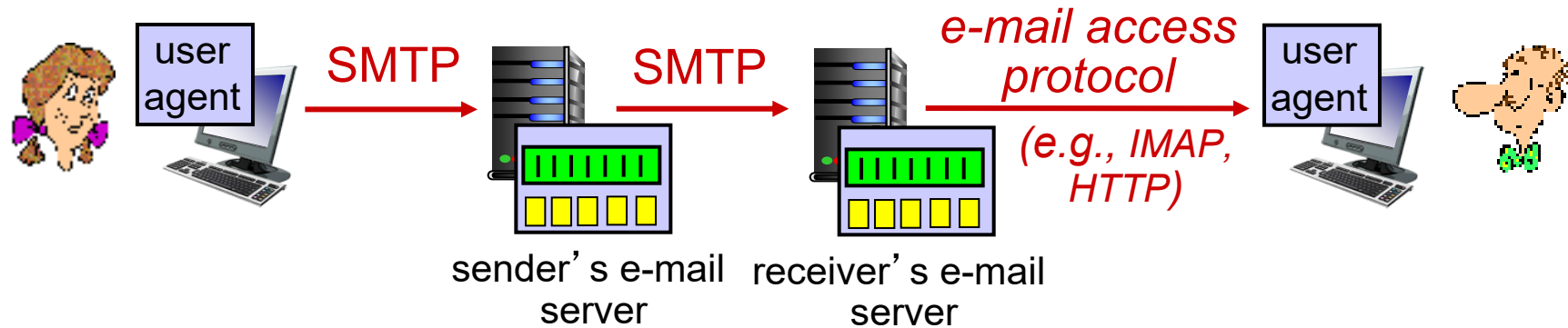
SMTP: protocol for exchanging e-mail messages, defined in RFC 531 (like HTTP)

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