Data Communication and Computer Networks

2. Application Layer
PART-A

Dr. Aiman Hanna

Department of Computer Science & Software Engineering
Concordia University, Montreal, Canada

These slides has mainly been extracted, modified and updated from original slides of :
Computer Networking: A Top Down Approach, 6th edition Jim Kurose, Keith Ross
Addison-Wesley, 2013

Additional materials have been extracted, modified and updated from:
Understanding Communications and Networking, 3e by William A. Shay 2005

Some network applications

- e-mail
- web
- text messaging
- remote login
- P2P file sharing
- multi-user network games
- streaming stored video (YouTube, Hulu, Netflix)
- E-commerce
- voice over IP (e.g., Skype)
- real-time video conferencing
- social networking
- search
- …
- …

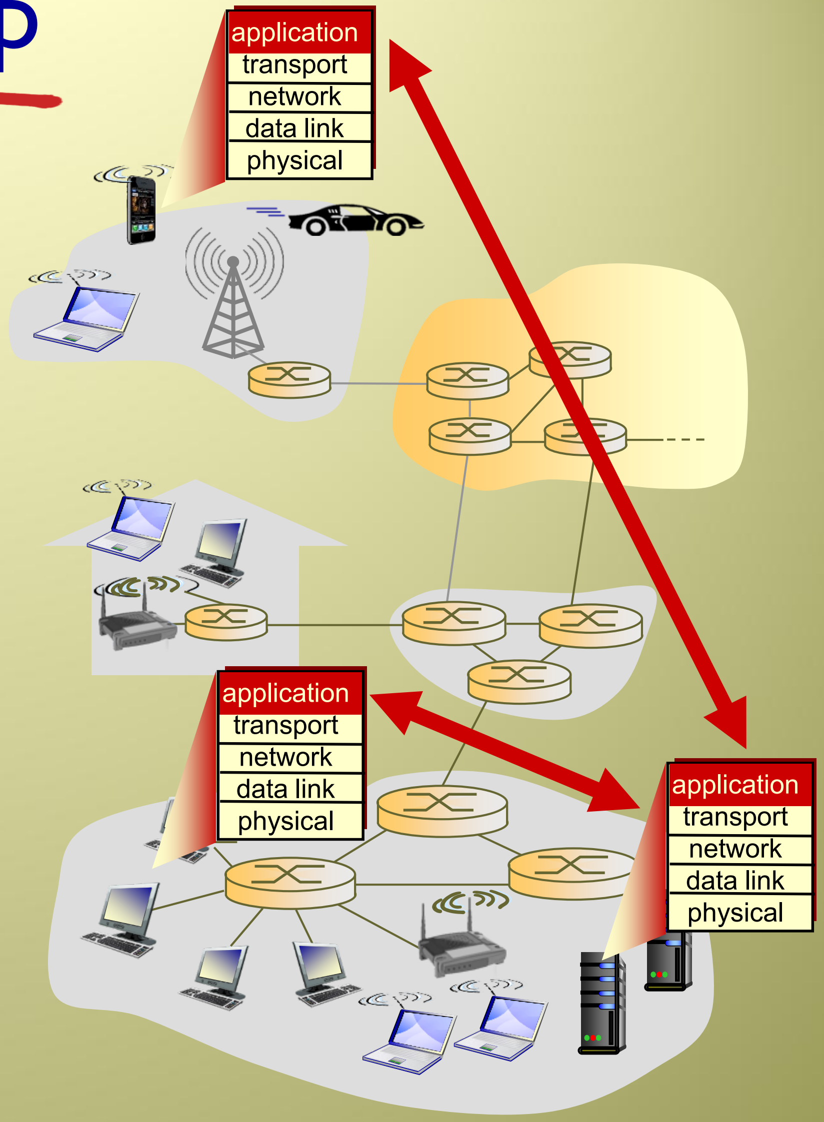
Creating a network app

write programs that:

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

no need to write software for network-core devices

- network-core devices do not run user applications. Why?
- applications on end systems allows for rapid app development, propagation

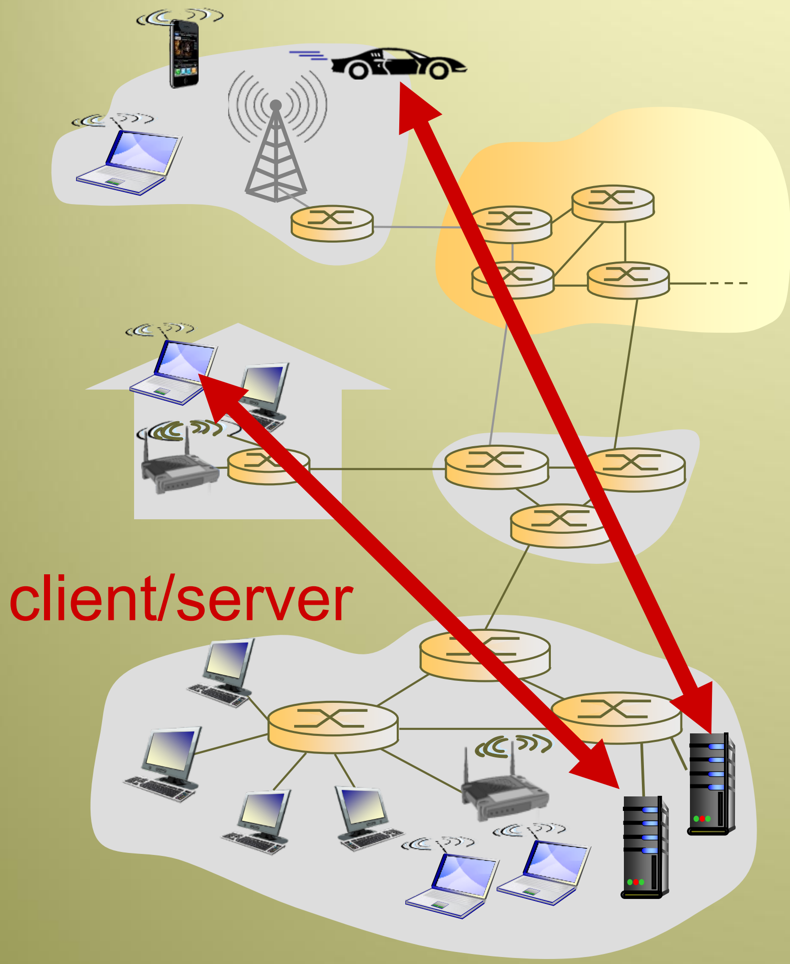


Application architectures

possible structure of applications:

- client-server
- peer-to-peer (P2P)

Client-server architecture



server:

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

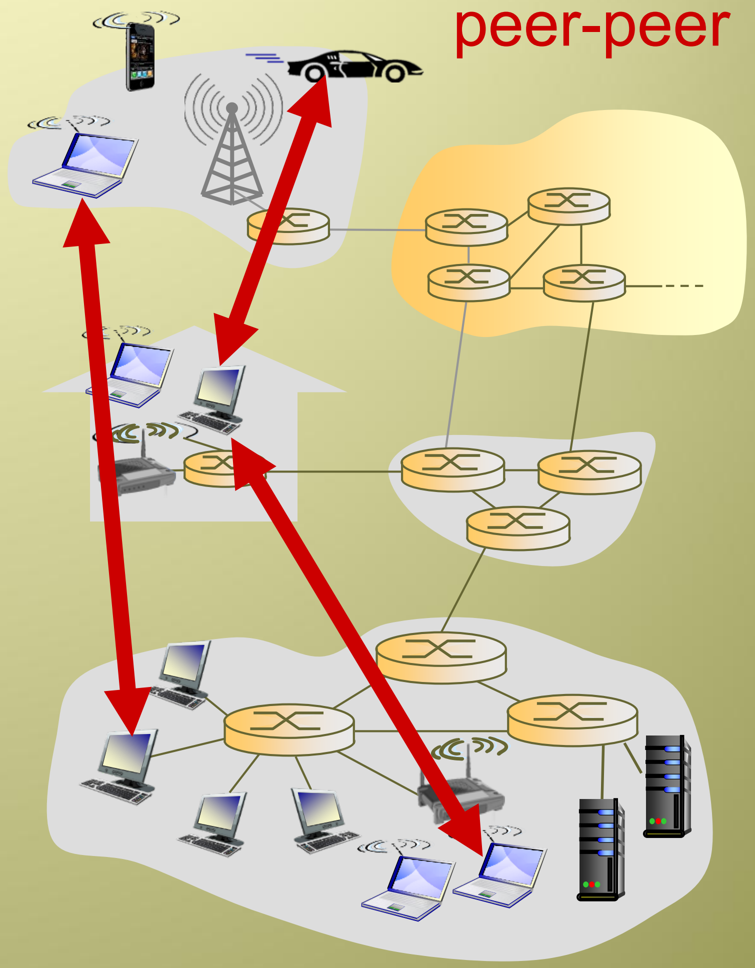
clients:

- communicate with server
- do not communicate directly with each other
- may be intermittently connected
- may have dynamic IP addresses

- famous client-server apps include Web, FTP, e-mail, Telnet, …

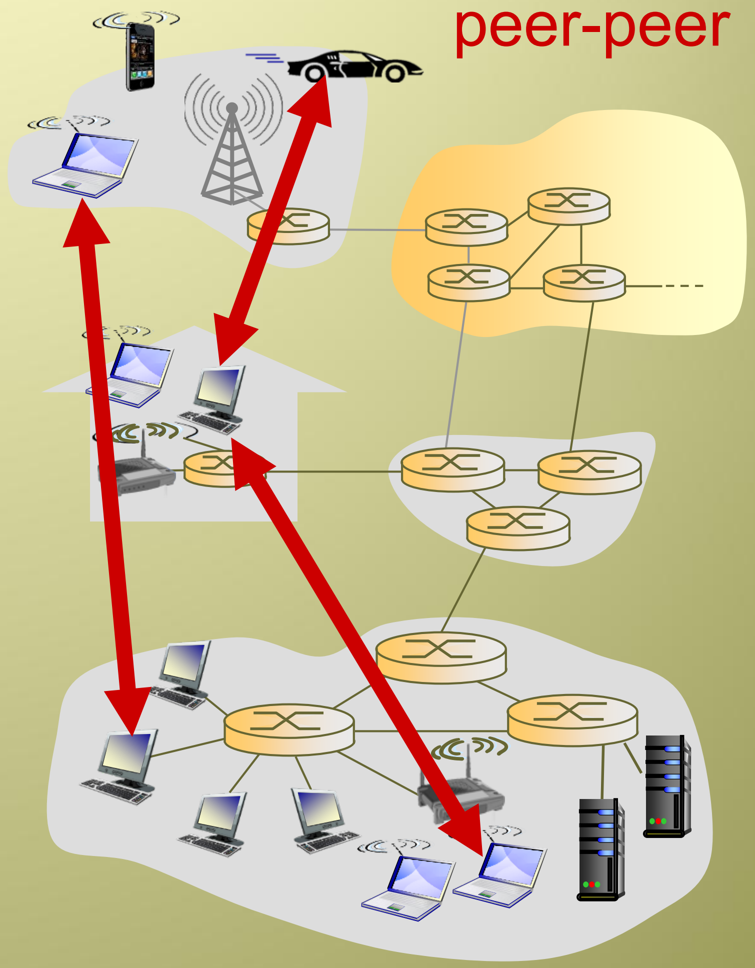
P2P architecture

- *no* always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, as well as new service demands
- peers are intermittently connected and change IP addresses
  - complex management
- examples of P2P applications include Skype, IPTV, BitTorrent,…



P2P architecture

- Cost-effective
  - no need for server infrastructure and server bandwidth
- However, future P2P applications face 3 major challenges:
  - *ISP-Friendly* : residential ISP (DSL, Cable, …) are asymmetric
  - *Security*: a challenge, since P2P apps are highly distributed and naturally open
  - *Incentive*: users must volunteer bandwidth, storage space and computational resources to P2P apps



Processes communicating!

process: program running within a host

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

clients, servers

client process: process that initiates communication

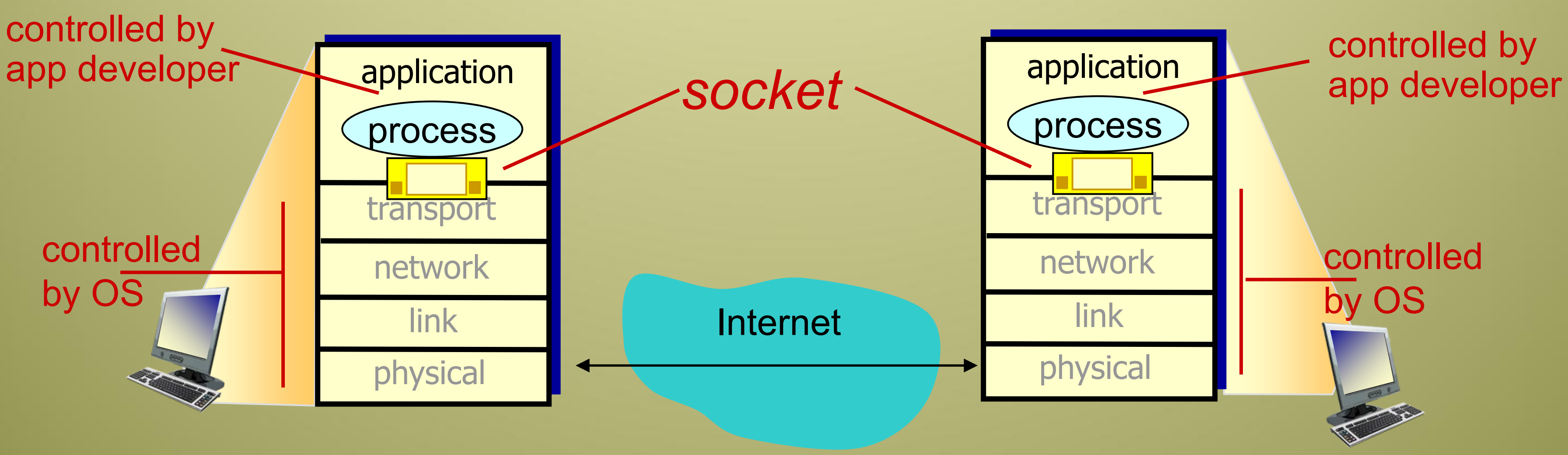
server process: process that waits to be contacted

- aside: applications with P2P architectures have **client** processes & **server** processes

Sockets

- process sends/receives messages to/from its socket (a software interface; an **API**)

- socket analogous to door
  - sending process shoves message out door
  - sending process relies on transport infrastructure on other side of door to deliver message to socket at receiving process



Addressing processes

- to receive messages, process must have *identifier*
- host device has unique 32-bit IP address
- *Q:* does IP address of host, on which process runs, suffice for identifying the receiving process (more precisely, the receiving socket)?
  - *A:* no, *many* network processes can be running on same host

- *identifier* includes both IP address and port numbers associated with process on host.
- example port numbers:
  - HTTP (web) server: 80
  - SMTP (mail) server: 25
- to send HTTP message to gaia.cs.umass.edu web server:
  - IP address: 128.119.245.12
  - port number: 80
- more shortly…

App-layer protocol defines

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

open protocols:

- defined in RFCs
- allows for interoperability
- e.g., HTTP, SMTP

proprietary protocols:

- e.g., Skype

What transport service does an app need?

data integrity / reliability

- 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) are **bandwidth-sensitive**; they require minimum amount of throughput to be "effective"
- other apps (e.g. file transfer, e-mail,) are "**elastic** apps"; they can make use of whatever throughput they get

security

- encryption, data integrity, end-to-end authentication, …

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 (few kbps)	No
Real-time audio/video (i.e. Internet telephony, videoconferencing)	Loss-tolerant	Audio: 5kbps-1Mbps Video: 10 Kbps – 5 Mbps	Yes; 100s ms
Streaming stored audio/video	Loss-tolerant	Same as above;	Yes; few seconds
Interactive games	Loss-tolerant	few kbps – 10 Kbps	Yes; 100s ms
Text/Instant messaging	No loss	Elastic	Yes and No

Internet transport protocols services

TCP service:

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

UDP service:

- *unreliable data transfer* between sending and receiving process
- *does not provide:* reliability, flow control, congestion control, timing, throughput guarantee, security, or connection setup

Q: why bother? Why is there a UDP?

Internet apps: application, transport protocols

Application	Application layer protocol	Underlying transport protocol
E-mail	SMTP [RFC 2821]	TCP
Remote terminal access	Telnet [RFC 854]	TCP
Web	HTTP [RFC 2616]	TCP
File transfer	FTP [RFC 959]	TCP
Streaming multimedia	HTTP (e.g., YouTube, Dailymotion, …)	TCP
Internet telephony	SIP [RFC 3261], RTP [RFC 3550], proprietary (e.g., Skype)	TCP or UDP (Why?)

Securing TCP

TCP & UDP

- no encryption
- cleartext passwords sent into socket traverse Internet in cleartext

Secure Socket Layer: **SSL**

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

SSL is at app layer

- Apps use SSL libraries, which "talk" to TCP

SSL socket API

- cleartext passwds sent into socket traverse Internet encrypted

- More details shortly…

Services **not** provided by Internet transport protocols

The services: 1) reliability, 2) throughput,
3) timing, 4) security

- Which of these services are provided by TCP and UDP?
  - 1) Reliability (by TCP),
  - 4) Security (by SSL-enhanced-TCP)
  - What about throughput and timing?!!!
- NO! these services are not provided by today's Internet transport protocols.
- Then, we cannot run time-sensitive applications (i.e. Internet telephony) over the Internet. Correct?
- No; that is incorrect! How then!

Application-layer protocols

- application-layer protocols define how application processes pass messages to each other
- in particular, they define:
  - Types of exchanged messages: i.e. *request* and *response* messages
  - Syntax of message types: i.e. what the different fields in the message are
  - Semantics of the fields: the meaning of the information in the fields
  - Rules of communication: i.e. when and how a process can send a message (or respond to a message)
- some public application-layer protocols are specified in RFCs; i.e. RFC 2616 for HTTP
  - for instance, if a browser developer follows the rules of RFC2616, the browser will be able to retrieve web pages from any server that followed the rules of HTTP RFC

Network Applications

- there are MANY network applications (possibly new ones are being written as you read these slides!)

- we will here look at 5 of the most important and pervasive network applications:
  - Web and HTTP
  - FTP
  - Electronic Mail
  - DNS
  - P2P

Web and HTTP

First, a review…

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

$$\underbrace{\texttt{www.someschool.edu}}_{\text{host name}}\underbrace{\texttt{/someDept/pic.gif}}_{\text{path name}}$$

HTTP overview

HTTP: hypertext transfer protocol

- the 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)

uses TCP:

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

HTTP is ***"stateless"***

- server maintains no information about past client requests

aside

protocols that maintain "state" are complex!

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

HTTP connections

non-persistent HTTP

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

persistent HTTP

- multiple objects can be sent over single TCP connection between client, server
- HTTP default mode uses persistent connection, but this can be re-configured

Non-persistent HTTP

suppose user enters URL:

`www.someSchool.edu/someDepartment/home.index`

(contains 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 (cont.)

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

time

6. Steps 1-5 repeated for each of 10 jpeg objects

Q: how these 10 jpeg objects were obtained? Have they been retrieved in a serial fashion, or using parallel connections?

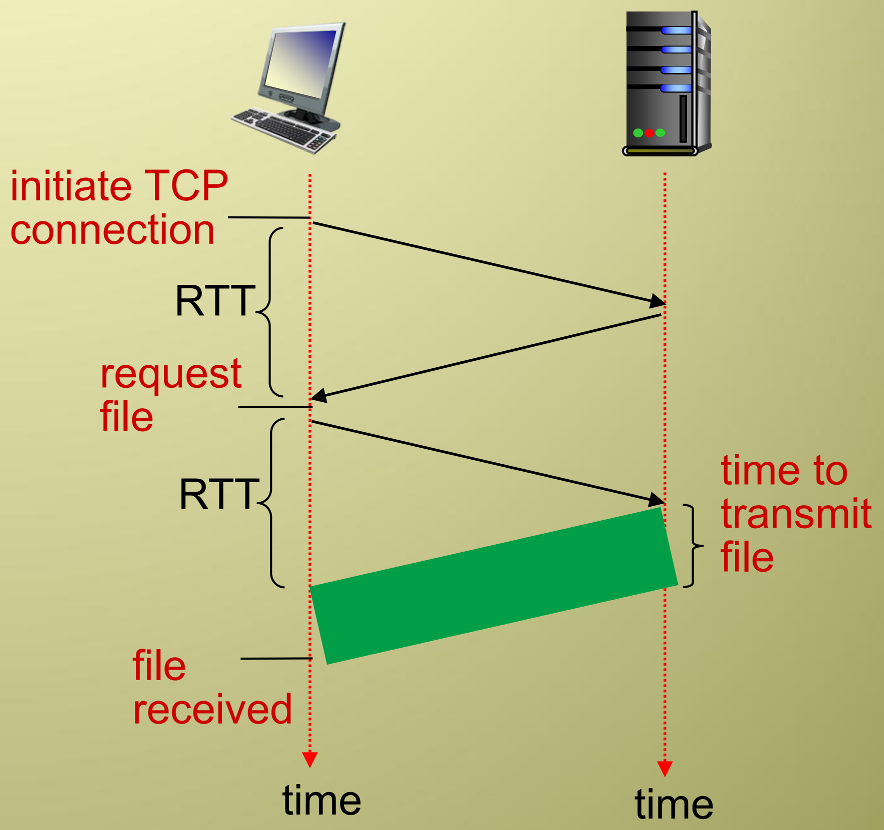
Non-persistent HTTP: response time

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

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

response time =

2RTT+ file transmission time



Persistent HTTP

non-persistent HTTP issues:

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

persistent HTTP:

- server leaves connection open after sending response (connection is only closed when it is not used for certain, configurable, amount of time)
- subsequent HTTP messages between same client/server sent over open connection
- client sends requests as soon as it encounters a referenced object
- as little as one RTT for all the referenced objects

HTTP request message

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

HTTP version #

carriage return character

line-feed character

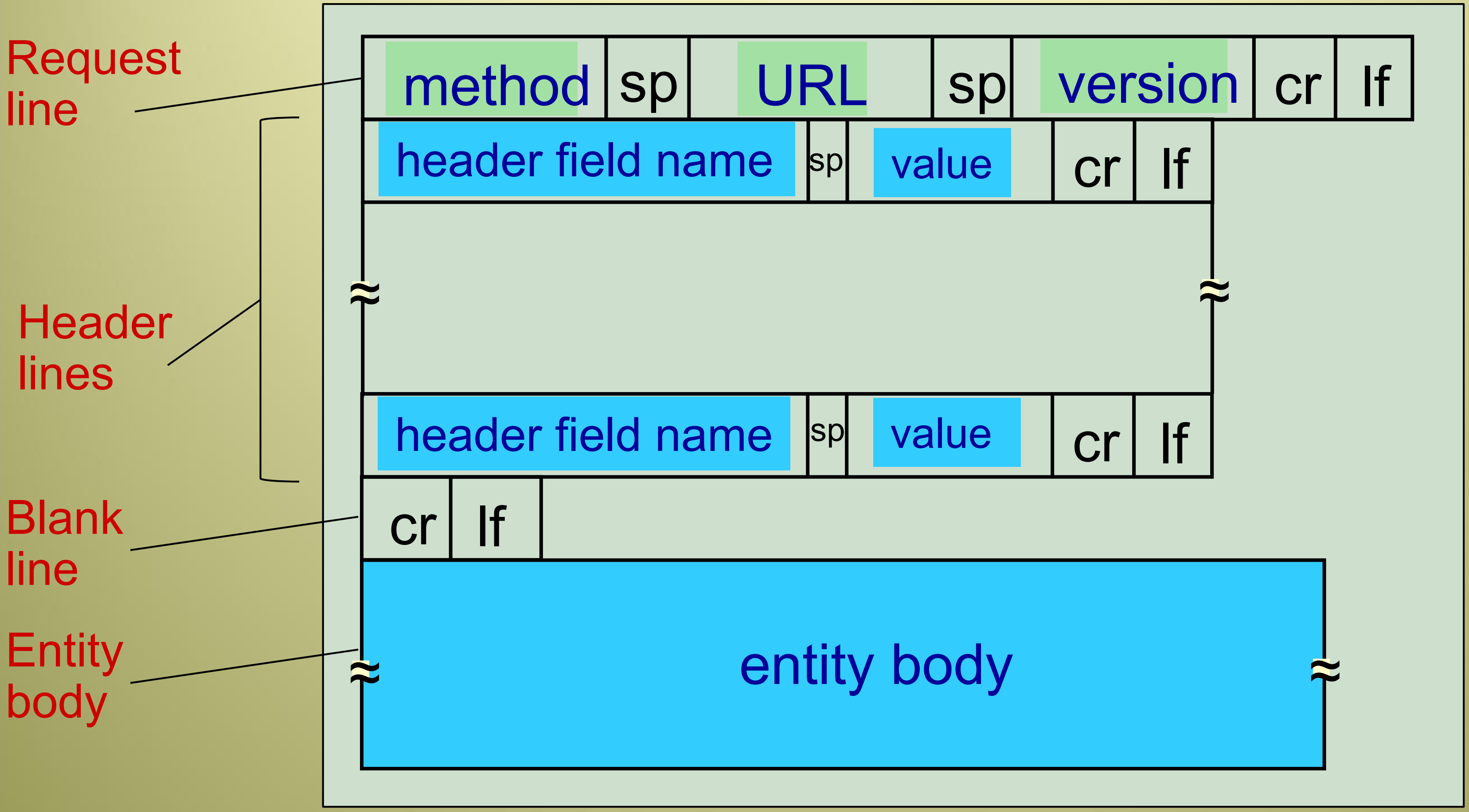
request line
(GET, POST,
HEAD, .. commands)

```
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
```

header
lines

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

HTTP request message: general format



General format of an HTP request message

Uploading form input

POST method:

- web page often includes form input
- input is uploaded to server in entity body

URL method:

- a request with a form does not necessary use POST
- GET method can be used with input data
- input is uploaded in URL field of request line:

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

Method types

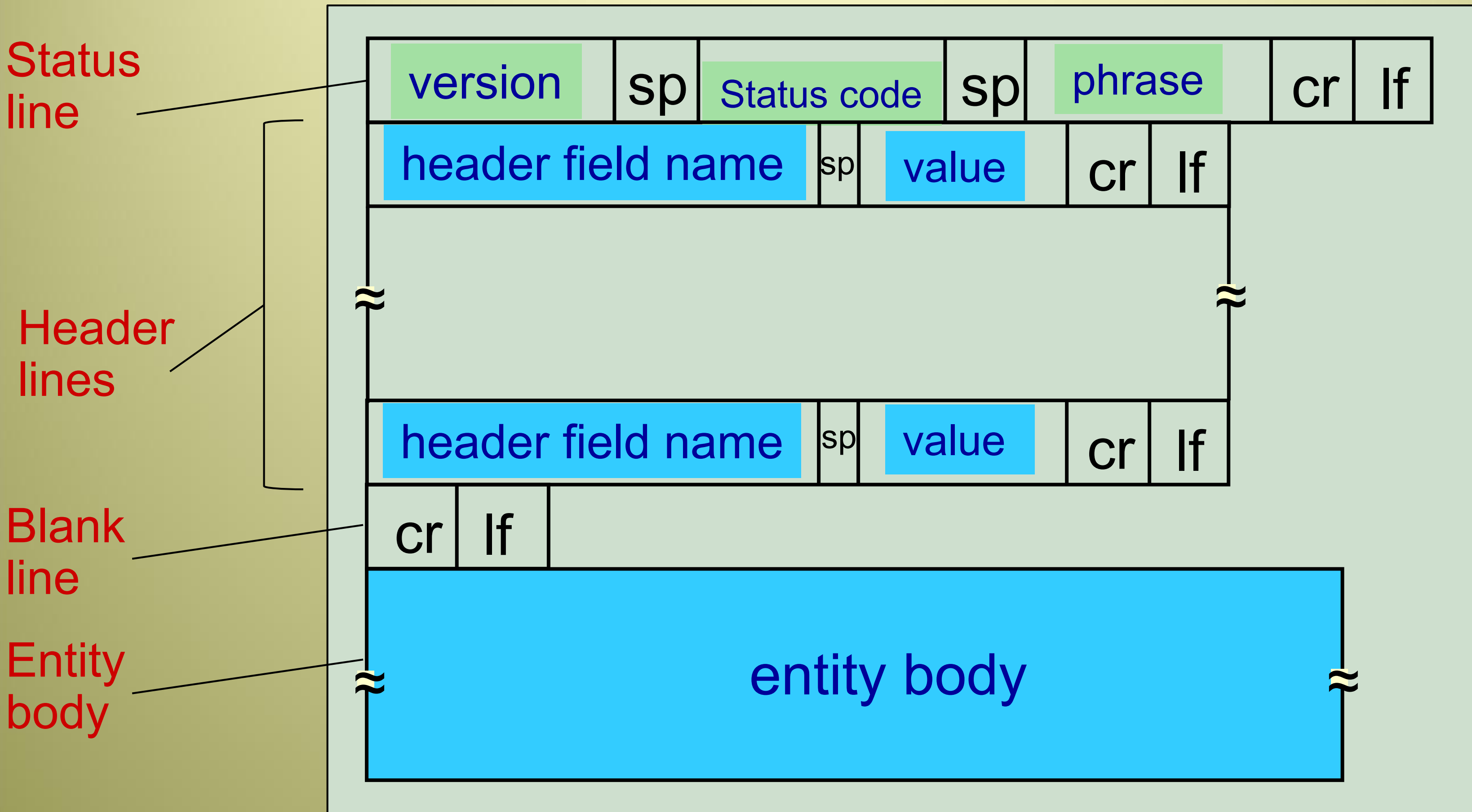
HTTP/1.0:

- GET
- POST
- HEAD
  - asks server to leave requested object out of response

HTTP/1.1:

- GET, POST, HEAD
- PUT
  - uploads file in entity body to path specified in URL field
- DELETE
  - deletes a web server object specified in the URL field

HTTP response message: general format



General format of an HTP response message

HTTP response message

status line

header lines

data, e.g., requested HTML file

```
HTTP/1.1 200 OK\r\n
Date: Sun, 14 Sep 2014 22:07:50 GMT\r\n
Server: Apache/2.0.52 (CentOS)\r\n
Last-Modified: Tue, 30 Oct 2007 17:00:02
   GMT\r\n
ETag: "17dc6-a5c-bf716880"\r\n
Accept-Ranges: bytes\r\n
Content-Length: 2652\r\n
Keep-Alive: timeout=10, max=50\r\n
Connection: Keep-Alive\r\n
Content-Type: text/html; charset=ISO-8859-
   1\r\n
\r\n
data data data data data ...
```

HTTP response status codes

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

`200 OK`

- request succeeded, requested object later in this msg

`301 Moved Permanently`

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

`400 Bad Request`

- request msg not understood by server

`404 Not Found`

- requested document does not exist on this server

`505 HTTP Version Not Supported`

- requested HTTP version is not supported by the server

Trying out HTTP (client side) for yourself

1. Telnet to your favorite Web server:

```
telnet cis.poly.edu 80
```

opens TCP connection to port 80 (default HTTP server port) at cis.poly.edu. anything typed in sent to port 80 at cis.poly.edu

2. type in a GET HTTP request:

```
GET /~ross/ HTTP/1.1
Host: cis.poly.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!

Trying out HTTP (client side) for yourself

Telnet cis.poly.edu

```
HTTP/1.1 404 File Not Found
Date: Sun, 08 Sep 2013 05:12:05 GMT
Server: Apache/1.2.5
Transfer-Encoding: chunked
Content-Type: text/html
```

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.01 Transitional//EN">
                                                              <html>
                                                                    <head>
                                                                          <titl
e>FILE NOT FOUND</title>
                            <link rel="stylesheet" type="text/css" href="/templa
te/css/cis_style.css">
                          <meta http-equiv="Content-Type" content="text/html; ch
arset=ISO-8859-1">
                      </head>
                             <body class="std">

                                               <table width="650" cellpadding="0
```

```
<font color="#ff0000">

<p>You are here because the URL you are looking for does not exist.  We are sorr
y for this
inconvenience.  Please <a href="/webmaster/">contact the webmaster</a> so that t
his problem can be
corrected.</p>

<p>Note: Course pages are maintained by faculty members teaching those courses;
comments/concerns relating to course pages should be directed to them.</p>

</font>

        </td>

                                </tr>

                                     </table>
```

User-server state: cookies

- HTTP servers are stateless
  - simplifies server design
  - increases performance
  - However, it is often desirable for a website to identify users

- many Web sites use cookies

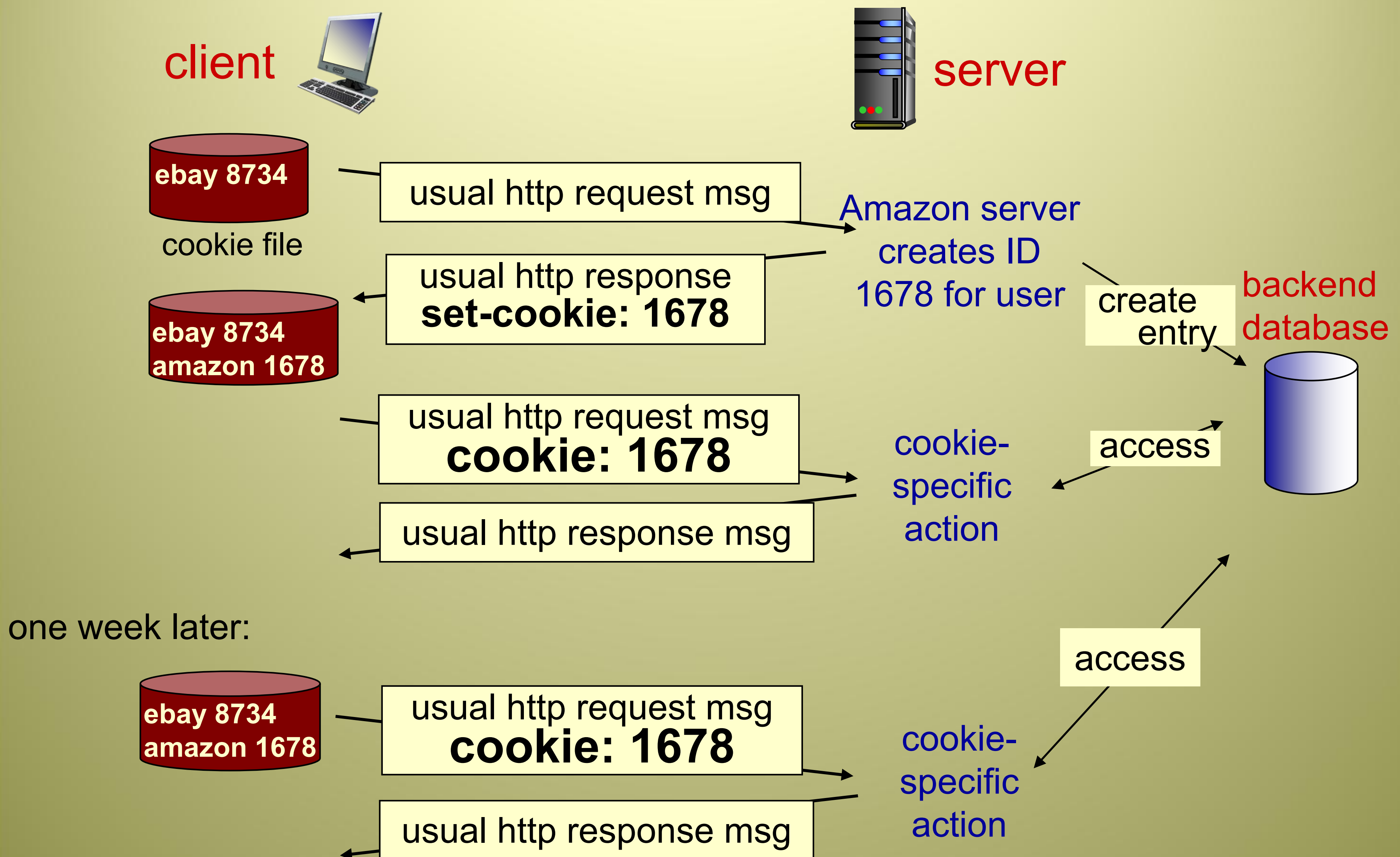
four components:

1) cookie header line in 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 the Web site

example:

- Susan always access Internet from PC
- visits specific e-commerce site for first time
- when initial HTTP requests arrives at site, site creates:
  - unique ID
  - entry in backend database for ID

Cookies: keeping "state" (cont.)



Cookies (continued)

what cookies can be used for:

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

aside

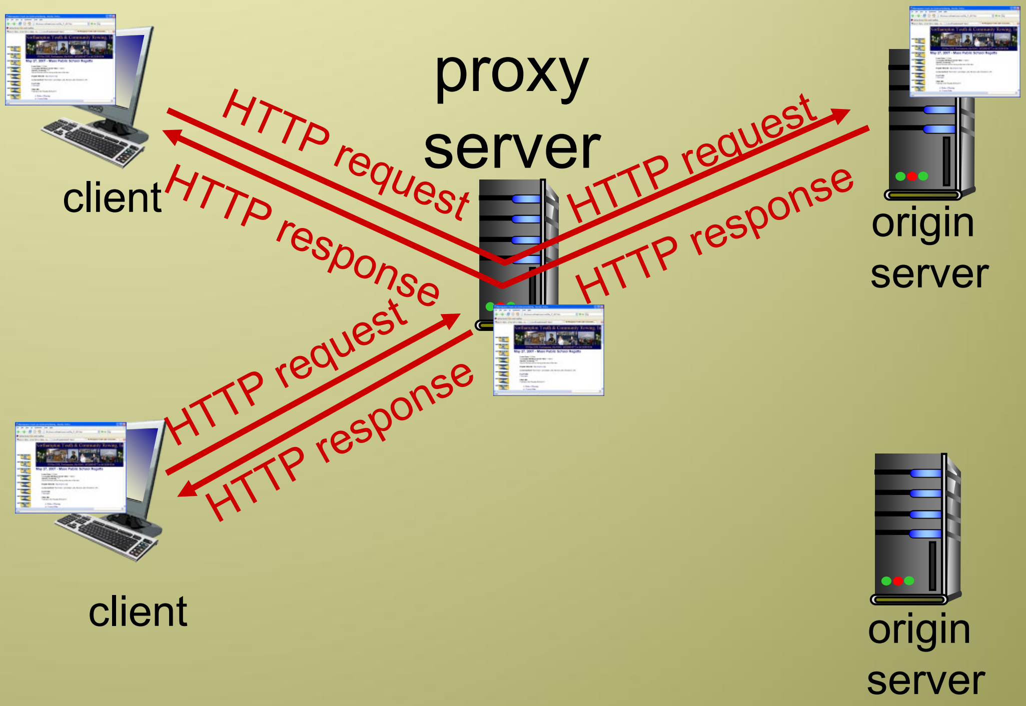
cookies and privacy:

- cookies are somehow controversial
- cookies permit sites to learn a lot about you
- you may supply name, e-mail, …. to sites

Web caches (proxy servers)

goal: satisfy client request without involving origin server

- user sets browser: Web accesses via cache
- browser sends all HTTP requests to cache
  - object in cache: cache returns object
  - else: cache requests object from origin server, then returns object to client



More about Web caching

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

why Web caching?

- reduce response time for client request
- reduce traffic on an institution's access link
- reduce traffic in the Internet as a whole
- Internet dense with caches: enables "poor" content providers to effectively deliver content (so too does P2P file sharing)

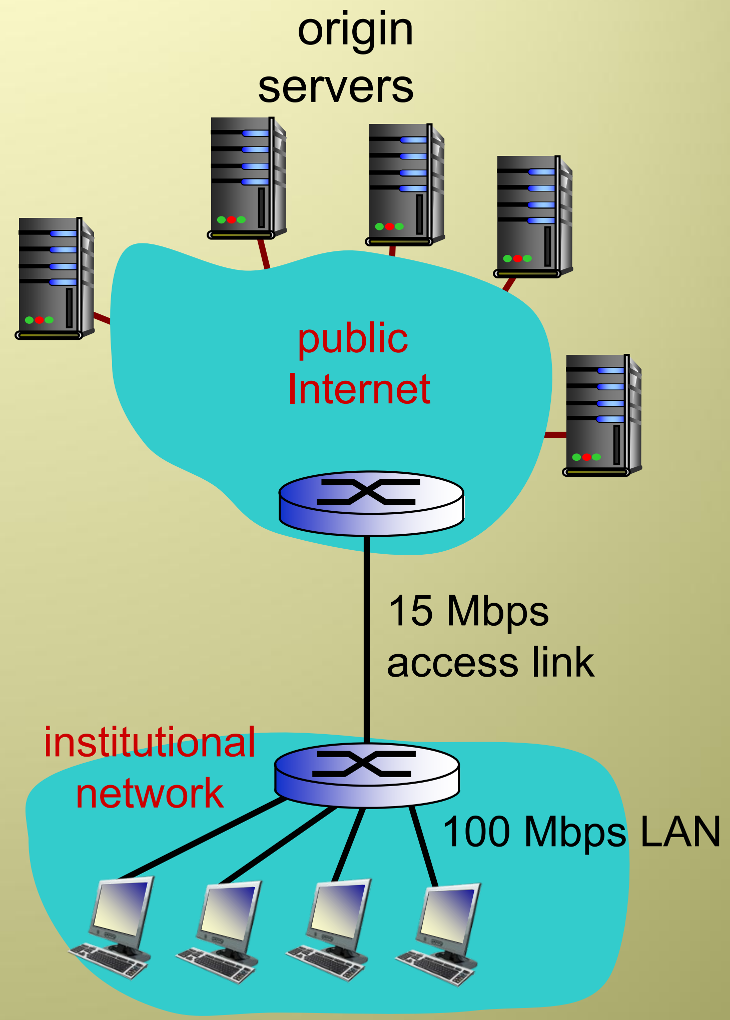
Caching example:

assumptions:

- **100 Mbps** LAN
- **15 Mbps** access between institution router and Internet router

- avg object size: **1 Mbits**
- avg request rate from browsers to origin servers: **15 request/sec**

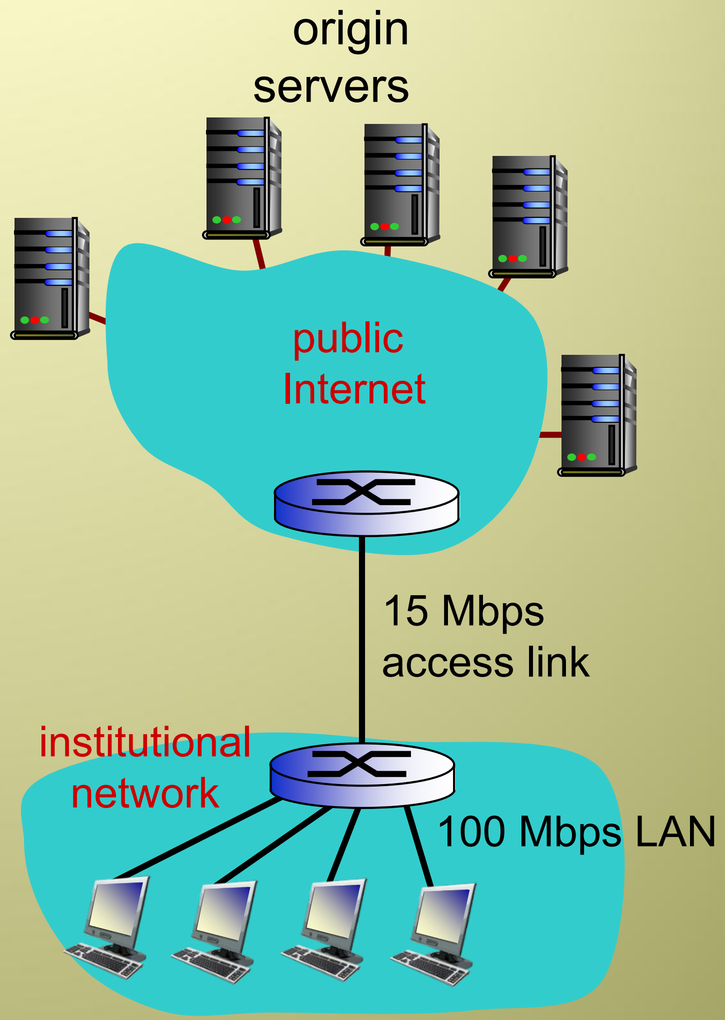
- HTTP requests are too small; hence represent **negligible** load on both institutional and public links
- Internet delay (RTT from Internet-side router to origin servers) is, in avg: **2 sec**



Caching example:

- Total response time (from time browser requests an object and it receives it) is:
  - LAN delay
    +
  - access delay between the two routers
    +
  - Internet delay

Q: what is the total response time of this network?



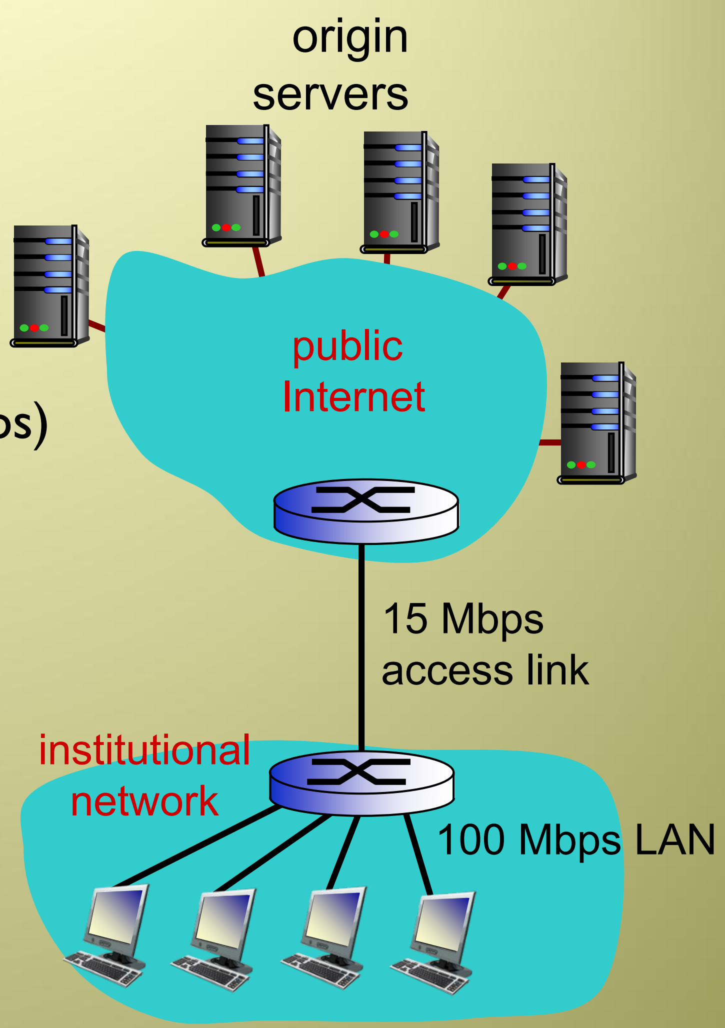
Caching example:

traffic intensity (La/R) on the LAN is:

(15 requests/sec) . (1 Mbits/request) / (100 Mbps) = 0.15

traffic intensity on access link (between the two routers) is:

(15 requests/sec) . (1 Mbits/request) / (15 Mbps) = 1



- traffic intensity of 15% on LAN
  ➔ small delay (µsecs to10s of msec)
- traffic intensity of 1 on access link
  ➔ delay grows without bound
  order of minutes, if not more!
- **total delay** = Internet delay + access delay + LAN delay
  = 2 sec + minutes + µsecs ➔ TERRIBLE!

Caching example:

Solution 1 (expensive solution):

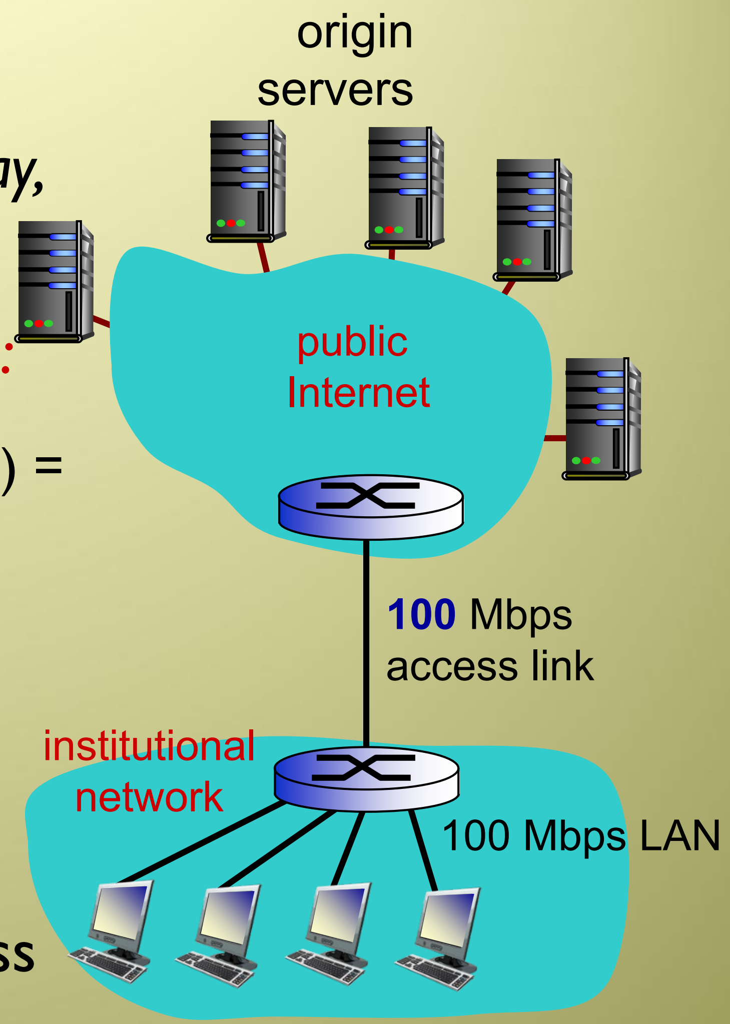
- *Increase access rate from 15 Mbps to, say, 100 Mbps*

  traffic intensity on LAN and access link is:

(15 requests/sec) . (1 Mbits/request) / (100 Mbps) = 0.15

- traffic intensity of 15%
  ➔ small delay (µsecs to10s of msec)

- **total delay** = Internet delay + access delay + LAN delay
  = 2 sec + msecs + µsecs
  ≈ **2 seconds**

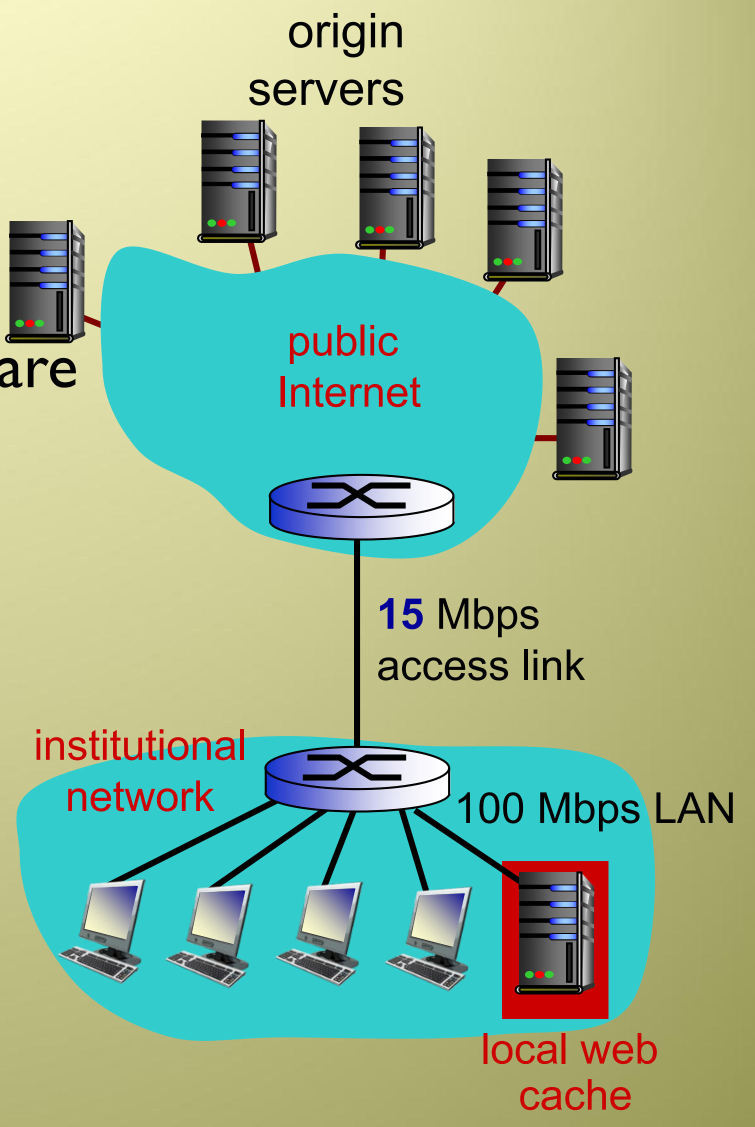


Caching example:

Solution 2 (more cost-effective solution):

- keep access link at 15 Mbps
- install a web cache
- ***hit-rate:*** the fraction of request that are satisfied by the cache
  - typically range from 20% to 70%
- for illustration, assume
  - 40% hit rate, and
  - requests from cache server take an average of **10 msec**

Q: what is the total response time of this network?



Caching example:

Solution 2 (more cost-effective solution):

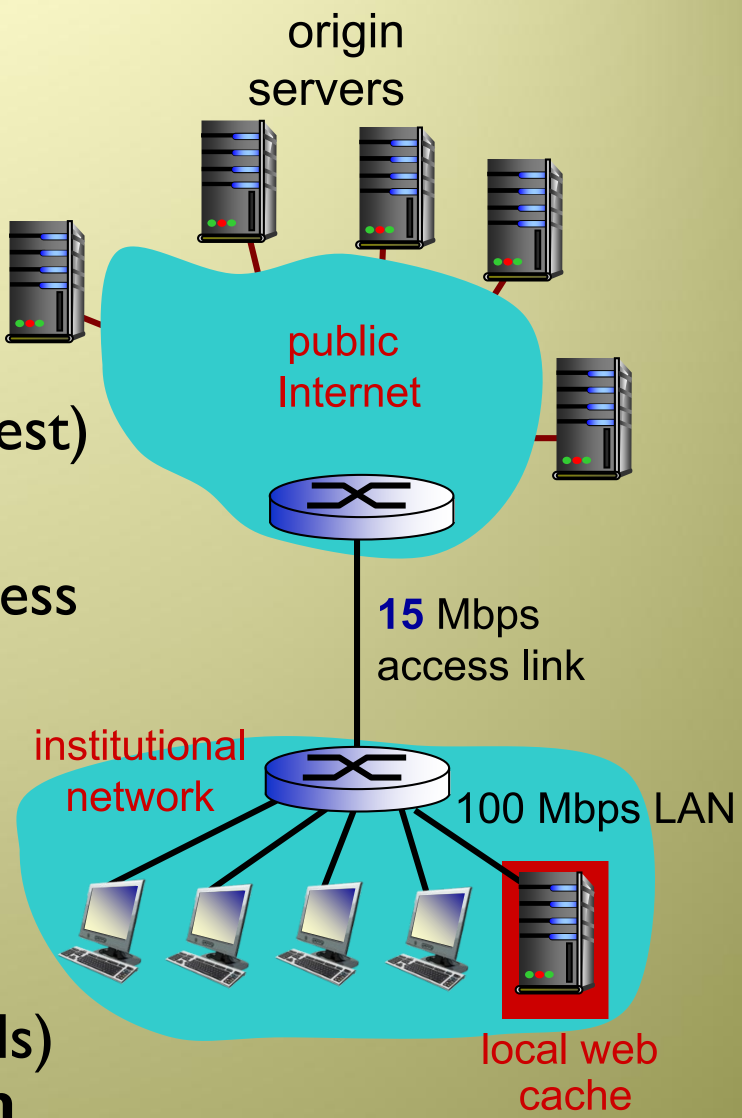
- 40% hits → 60% misses
- traffic intensity between two routers is:

  0.6 . [(15 requests/sec) . (1 Mbits/request) / (15Mbps)] = 0.6

  → 60% traffic intensity (often 80% or less is okay) results in a negligible delay compared to the 2 seconds internet delay

- **total delay** =

  0.4 . (0.01 seconds) + 0.6 (2.01 seconds) **≈ 1.2 seconds → even better than the expensive Solution 1**



Caching

- although caching has clear and obvious advantages, it introduced a very serious problem!

- what if the copy in the cache is stale?
  - cached copy may have been modified in the web server after being cached by the proxy server

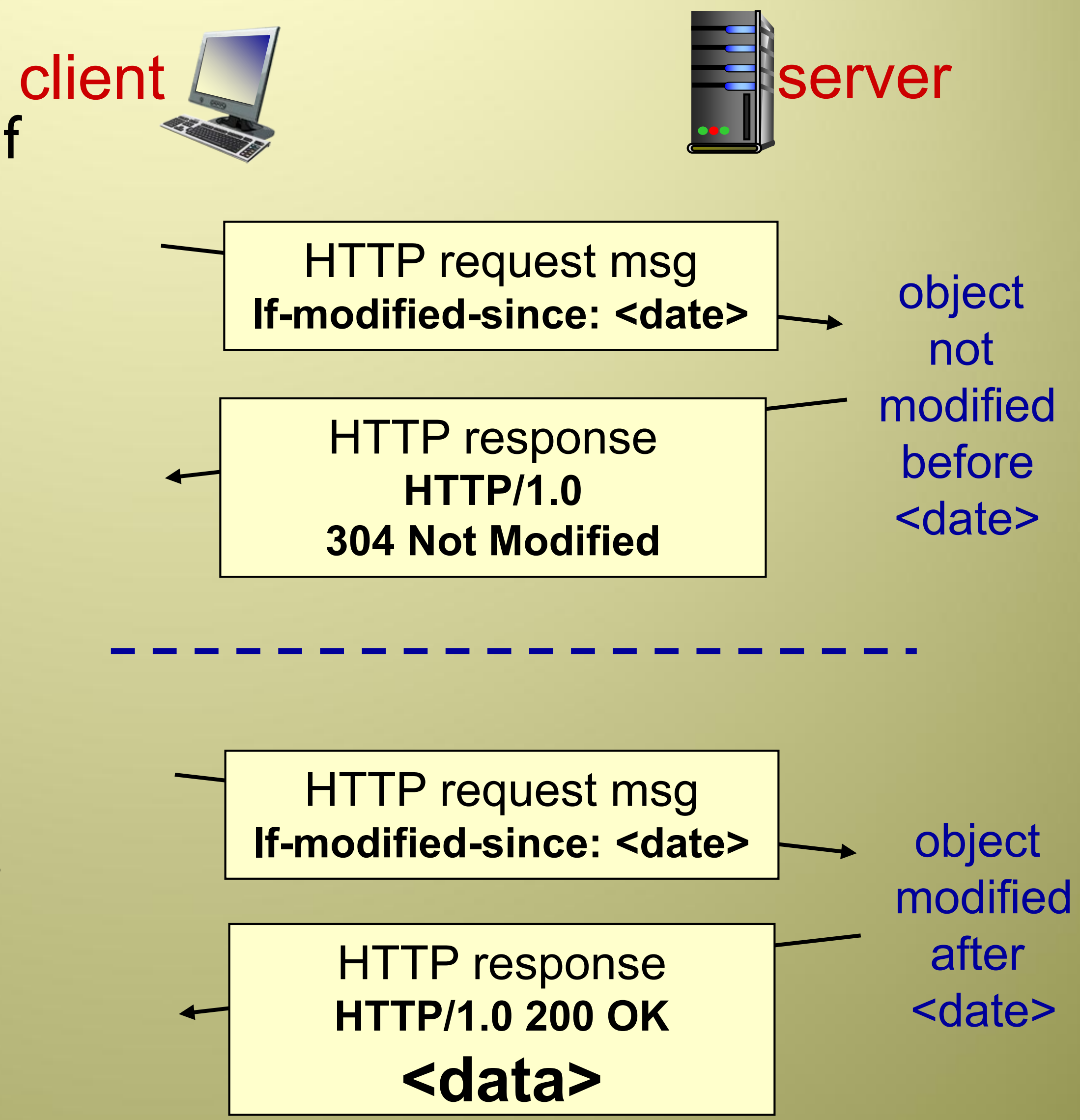
- a mechanism is hence needed by HTTP to verify against that
  - the **conditional GET**

Conditional GET

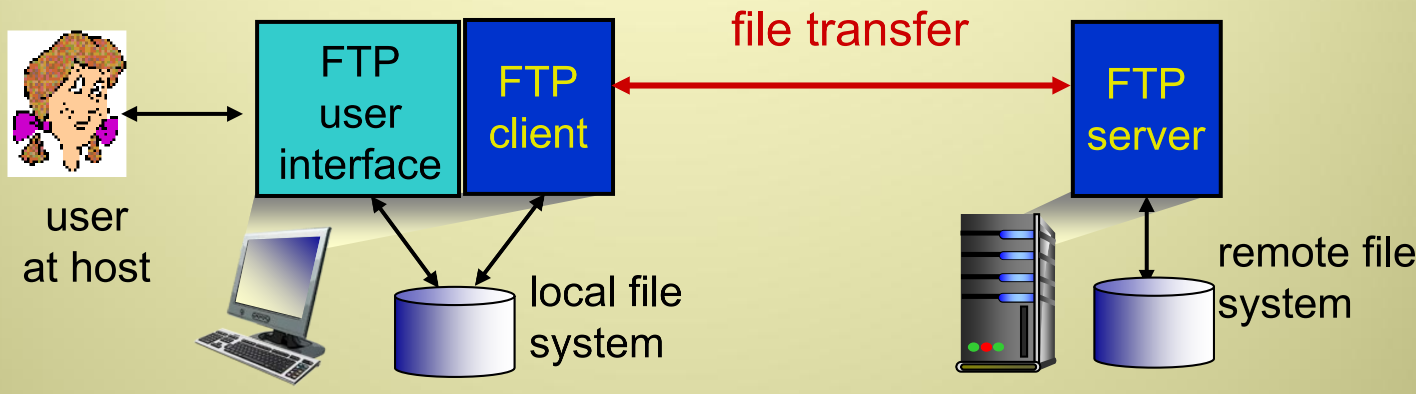
- *Goal:* don't send object if cache has up-to-date cached version
  - no object transmission delay
  - lower link utilization
- *cache:* specify date of cached copy in HTTP request

  `If-modified-since: <date>`
- *server:* response contains no object if cached copy is up-to-date:

  `HTTP/1.0 304 Not Modified`



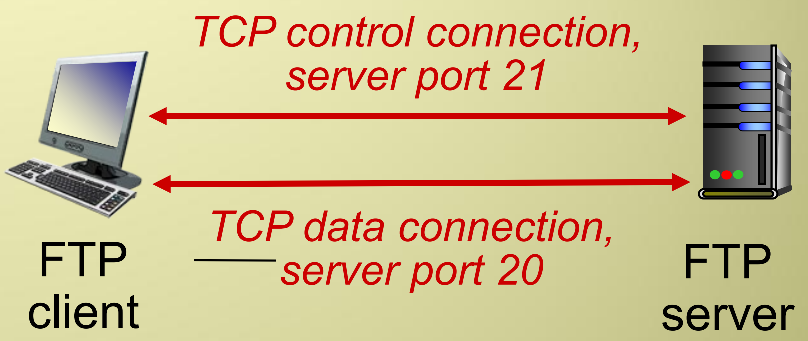
FTP: the file transfer protocol



- transfer file to/from remote host
- client/server model
  - *client:* side that initiates transfer (either to/from remote)
  - *server:* remote host
- ftp: RFC 959
- ftp server: port 21

FTP: separate control, data connections

- FTP client contacts FTP server at port 21, using TCP
- client authorized over **control connection**
- client browses remote directory, sends commands over control connection
- when server receives file transfer command, *server* opens 2nd **parallel** TCP **data connection** (for file) *to* client
- after transferring one file, server closes data connection



- server opens another TCP **data connection** to transfer another file
- control connection: *"out of band"*
- FTP server maintains "state": current directory, earlier authentication

FTP commands, responses

sample commands:

- sent as ASCII text over control channel

- **`USER`** ***`username`***
- **`PASS`** ***`password`***
- **`LIST`** return list of file in current directory
- **`RETR filename`** retrieves (gets) file
- **`STOR filename`** stores (puts) file onto remote host

sample return codes

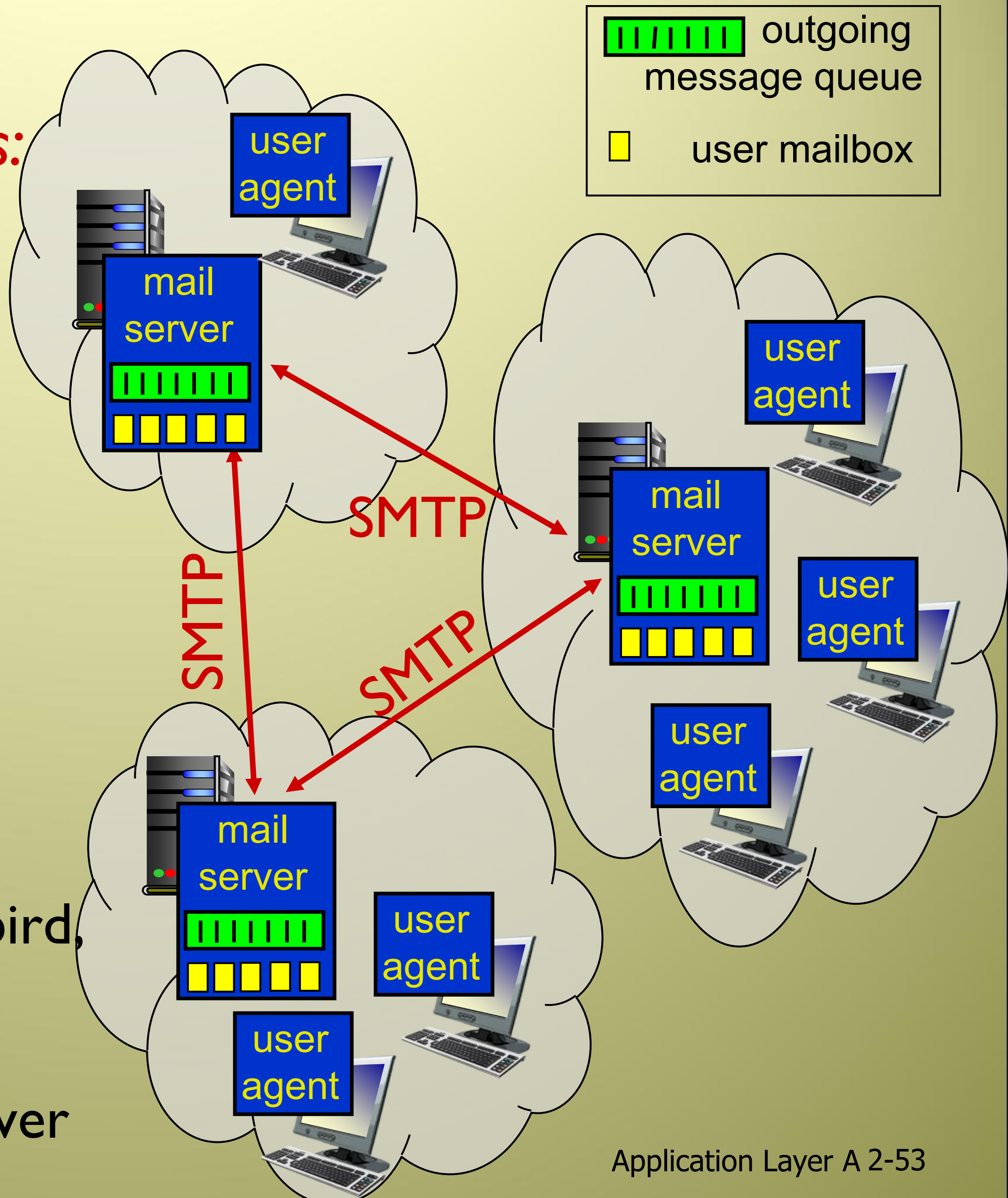
- status code and phrase (as in HTTP)

- **`331 Username OK, password required`**
- **`125 data connection already open; transfer starting`**
- **`425 Can't open data connection`**
- **`452 Error writing file`**

Electronic mail

Three major components:

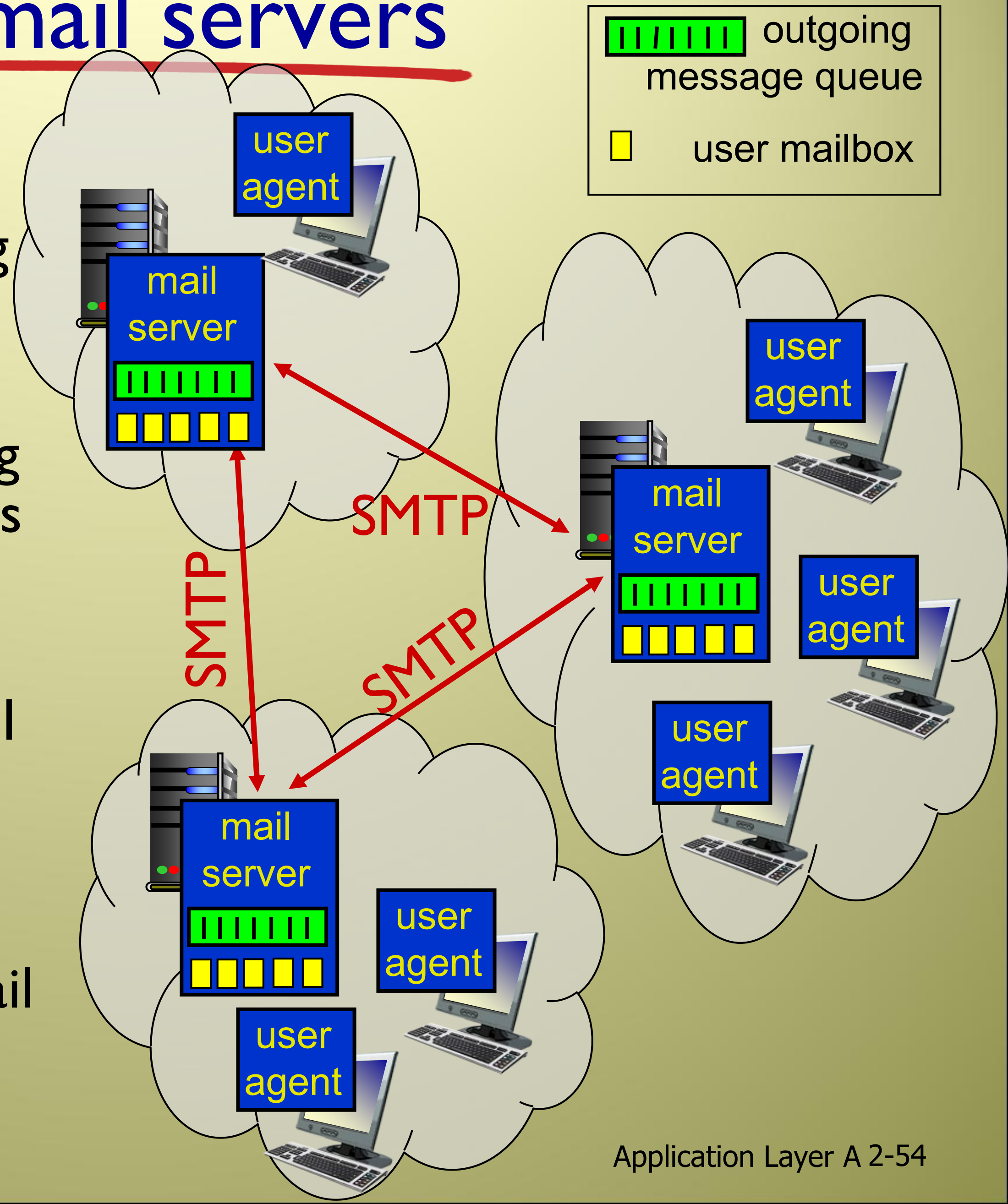
- user agents
- mail servers
- simple mail transfer protocol: SMTP



User Agent

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

Electronic mail: mail servers



mail servers:

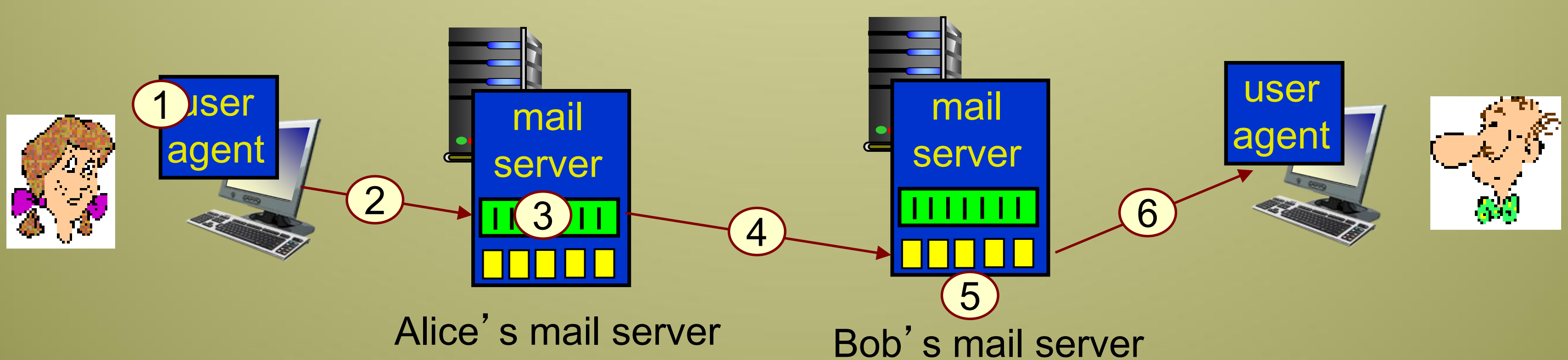
- *mailbox* contains incoming messages for user
- *message queue* of outgoing (to be sent) mail messages
- *SMTP protocol* between mail servers to send email messages
  - client: sending mail server
  - "server": receiving mail server

Simple Mail Transfer Protocol: SMTP [RFC 5321]

- the principle application-layer protocol for e-mail
- uses TCP to reliably transfer email message from client to server, port 25
- **direct transfer**: sending server to receiving server
- three phases of transfer
  - handshaking (greeting)
  - transfer of messages
  - closure
- command/response interaction (like HTTP, FTP)
  - commands: ASCII text
  - response: status code and phrase
- messages must be in **7-bit ASCII**

Scenario: Alice sends message to Bob

1) Alice uses UA to compose message "to" `bob@someschool.edu`
2) Alice's UA sends message to her mail server; message placed in message queue
3) client side of SMTP opens TCP connection with Bob's mail server
4) SMTP client sends Alice's message over the TCP connection
5) Bob's mail server places the message in Bob's mailbox
6) Bob invokes his user agent to read message



Sample SMTP interaction

```
S: 220 sunset.edu
C: HELO jupiter.fr
S: 250  Hello jupiter.fr, pleased to meet you
C: MAIL FROM: <alice@jupiter.fr>
S: 250 alice@jupiter.fr... Sender ok
C: RCPT TO: <bob@sunset.edu>
S: 250 bob@sunset.edu ... Recipient ok
C: DATA
S: 354 Enter mail, end with "." on a line by itself
C: Hi Bob,
C: How is it in beautiful Paris?
C: .
S: 250 Message accepted for delivery
C: QUIT
S: 221 sunset.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

These above steps lets you send email without using email client (reader)

Click here for another example

Click here to view SMTP codes

SMTP vs. HTTP

SMTP	HTTP
File transfer: mail server to mail server	File transfer: from a web server to a web client
Persistent TCP connection	Either persistent or non-persistent TCP connection
Push protocol	**Pull** protocol
Messages (headers & body) must be in ASCII i.e. special French characters, images, etc. must be encoded into ASCII	No such restriction
All objects (i.e. text and images) are placed in one message (multi-parts of the message)	Each object has its own HTTP response message

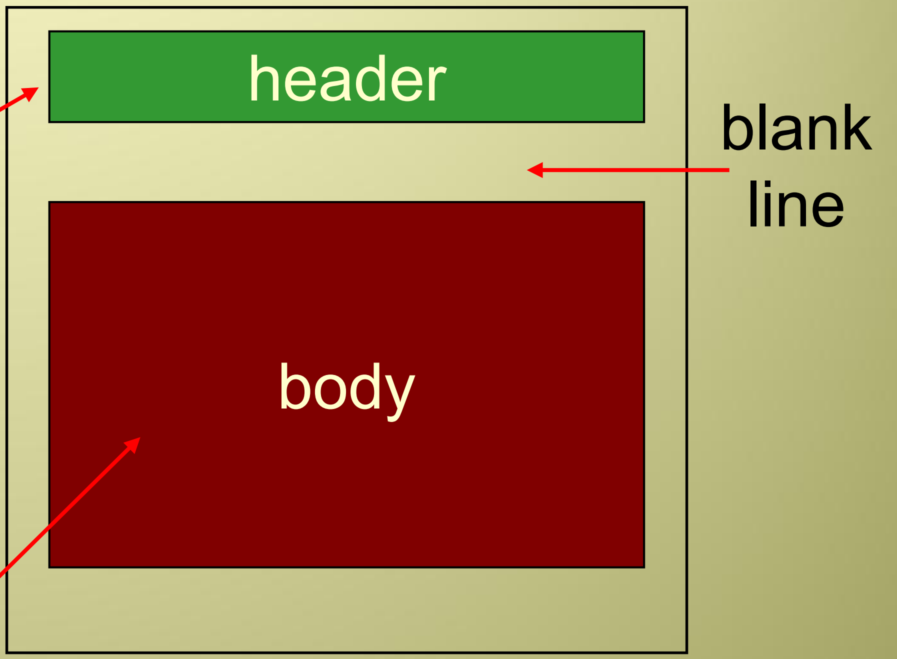
Mail message format

SMTP: protocol for exchanging email msgs

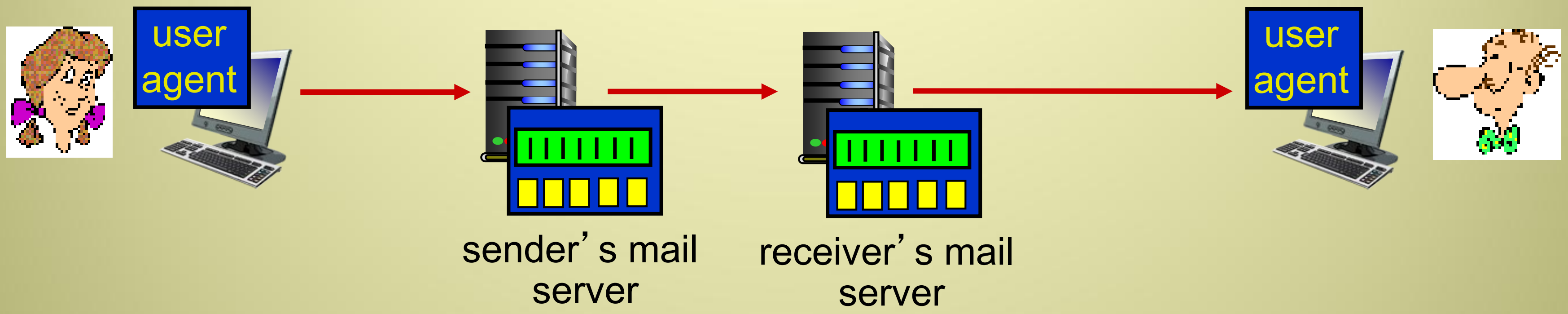
RFC 822: standard for text message format:

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

  different from SMTP MAIL **FROM**, RCPT **TO**: commands!
- Body: the "message"
  - ASCII characters only



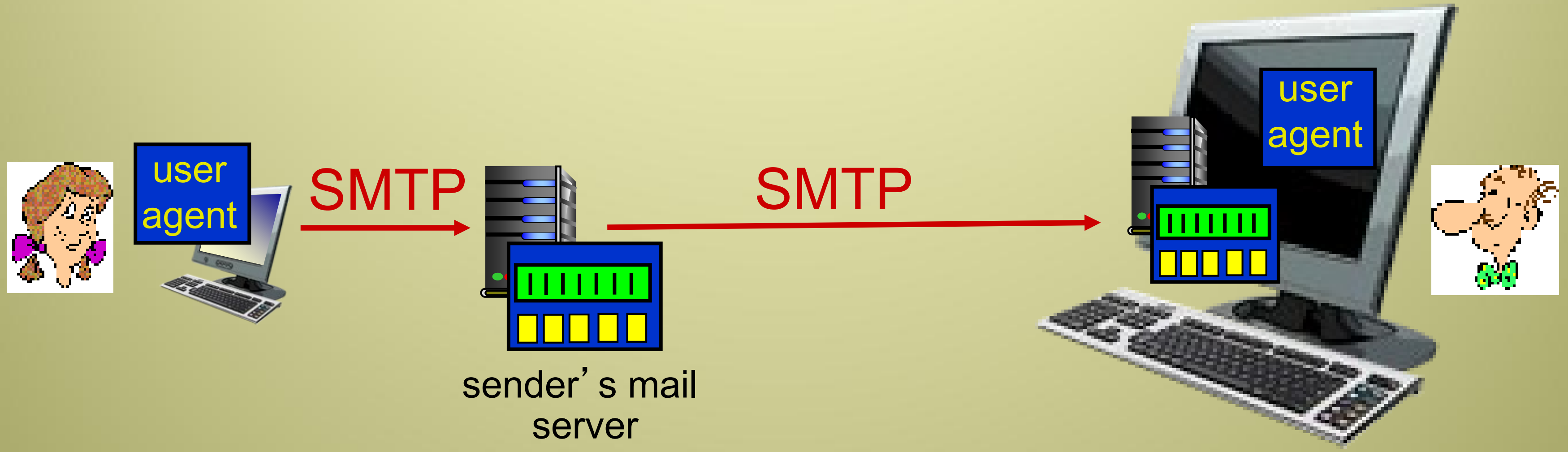
Mail access protocols



- Q: Why the two-step procedure?

Mail access protocols

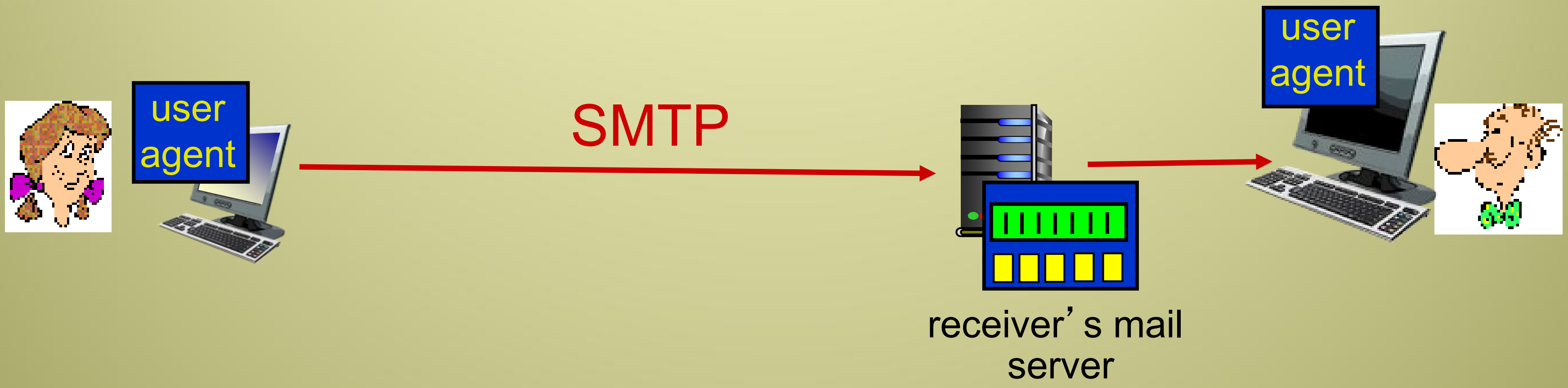
- Q: Why have a receiver server?
  Just install it in the receiver's local PC, where receiver executes his e-mail agent anyways!



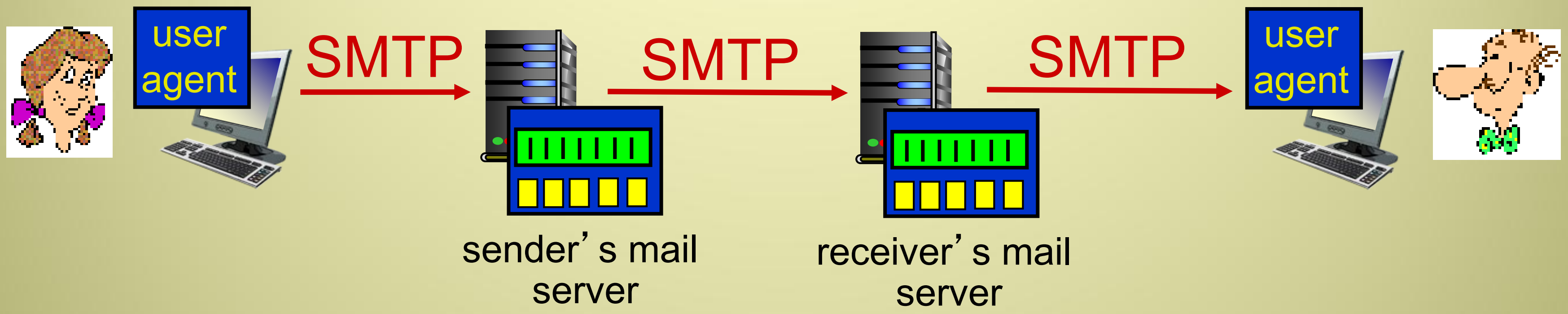
Mail access protocols

- Q: Why have a sender server?

  Just let the sender's user agent place the message directly on the receiver mail server

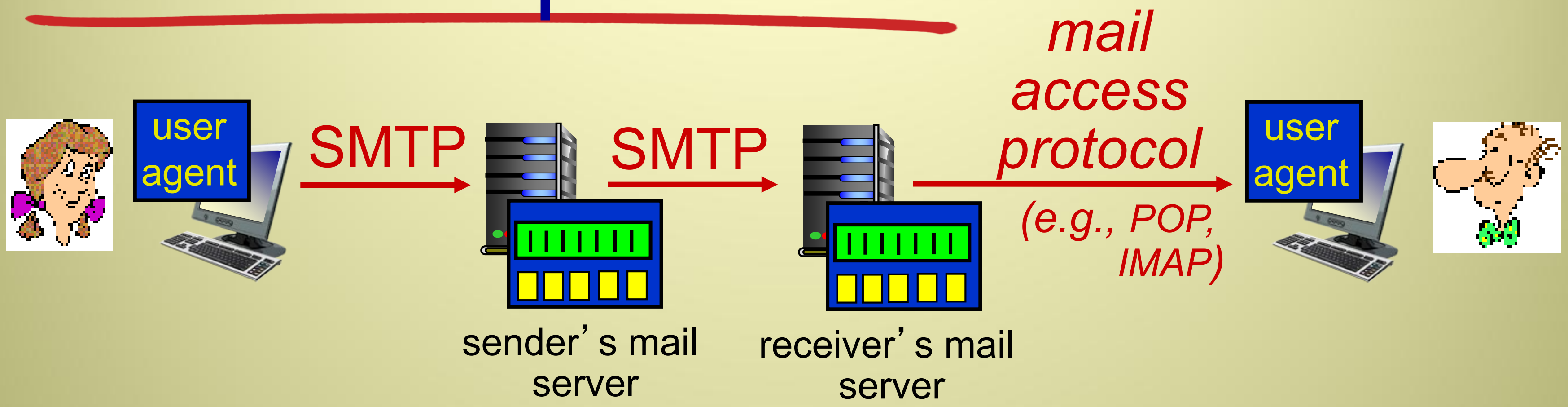


Mail access protocols



- OK: We need both of them, but will it work?

Mail access protocols



- SMTP: delivery/storage to receiver’s server
- mail access protocol: retrieval from server
  - POP: Post Office Protocol [RFC 1939]: authorization, download
  - IMAP: Internet Mail Access Protocol [RFC 1730]: more features, including manipulation of stored msgs on server
  - HTTP: gmail, Hotmail, Yahoo! Mail, etc.

POP3 protocol

- extremely simple mail access protocol, but
- limited !
  - User agent opens a TCP connection with the mail server on port 110
  - User progress through 3 phases:
    - authorization
      - Sends username/password
    - transaction, and
      - retrieves & manipulate message (i.e. mark message for deletion, obtain statistics, …)
    - update
      - after clients "quits", server updates what is needed (i.e. delete messages that were marked for deletion).

POP3 protocol

authorization phase

- client commands:
  - **user**: declare username
  - **pass**: password
- server responses
  - **+OK**
  - **-ERR**

transaction phase, client:

- **list**: list message numbers and there sizes
- **retr**: retrieve message by number
- **dele**: delete
- **quit**

```
S: +OK POP3 server ready
C: user bob
S: +OK
C: pass hungry
S: +OK user successfully logged on
```

```
C: list
S: 1 498
S: 2 912
S: .
C: retr 1
S: <message 1 contents>
S: .
C: dele 1
C: retr 2
S: <message 1 contents>
S: .
C: dele 2
C: quit
S: +OK POP3 server signing off
```

IMAP

- with POP3 user can manage downloaded messages into folders in local machine
- search can be done on that file system
- This hierarchy however is on the local machine only
  - cannot be seen on the server, or from different machines, which may be very inconvenient

IMAP

- keeps all messages in one place: at server
- allows user to create folders and organize messages in them
- keeps user state across sessions:
  - names of folders and mappings between message IDs and folder name

IMAP

- messages are assigned into folders
  - new messages are associated with INBOX folder
- Protocol provide commands to
  - allow user to create folders and move messages to them,
  - remotely, search folders for messages matching some criteria
  - delete, manipulate messages, …
- unlike, POP3, IMAP maintains state
  - i.e. created folders keep their names across multiple IMAP sessions
- permits user to obtain components of a message
  - i.e. obtain only the header or just a part of a multipart **MIME** message
  - this is useful, especially under low bandwidth connections

Webmail via HTTP

- users can access e-mail through web browsers
  - Hotmail introduced web-based e-mails in mid 1990s

- user agent is an ordinary web browser
- browsers communicate with their remote mailboxes via HTTP

- when a user accesses his/her mailbox, the e-mail messages are sent from the server to the browser via HTTP **instead of POP3 or IMAP**

- when a user wishes to send an e-mail, the e-mail is sent from the browser to the user's mail server through HTTP **instead of SMTP**