
University of Colorado Boulder

Fundamentals of Data Communications

Applications

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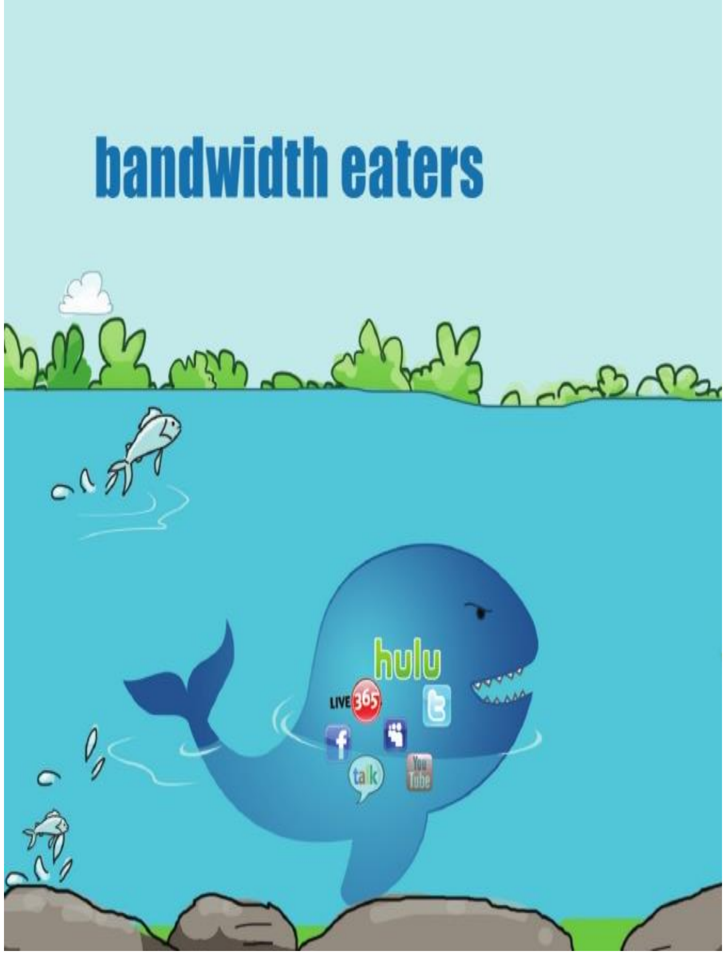
Review

Impact of User Applications on the Network

- **Interactive applications**
  – Inventory inquiries, database updates.
  – Human-to-machine interaction.
  – Because a human is waiting for a response, response time is important but not critical, unless the wait becomes excessive.

- **Real-time applications**
  – VoIP, video
  – Human-to-human interaction
  – End-to-end latency critical

- **Internet applications**
  – Social media
  – Streaming: audio & video



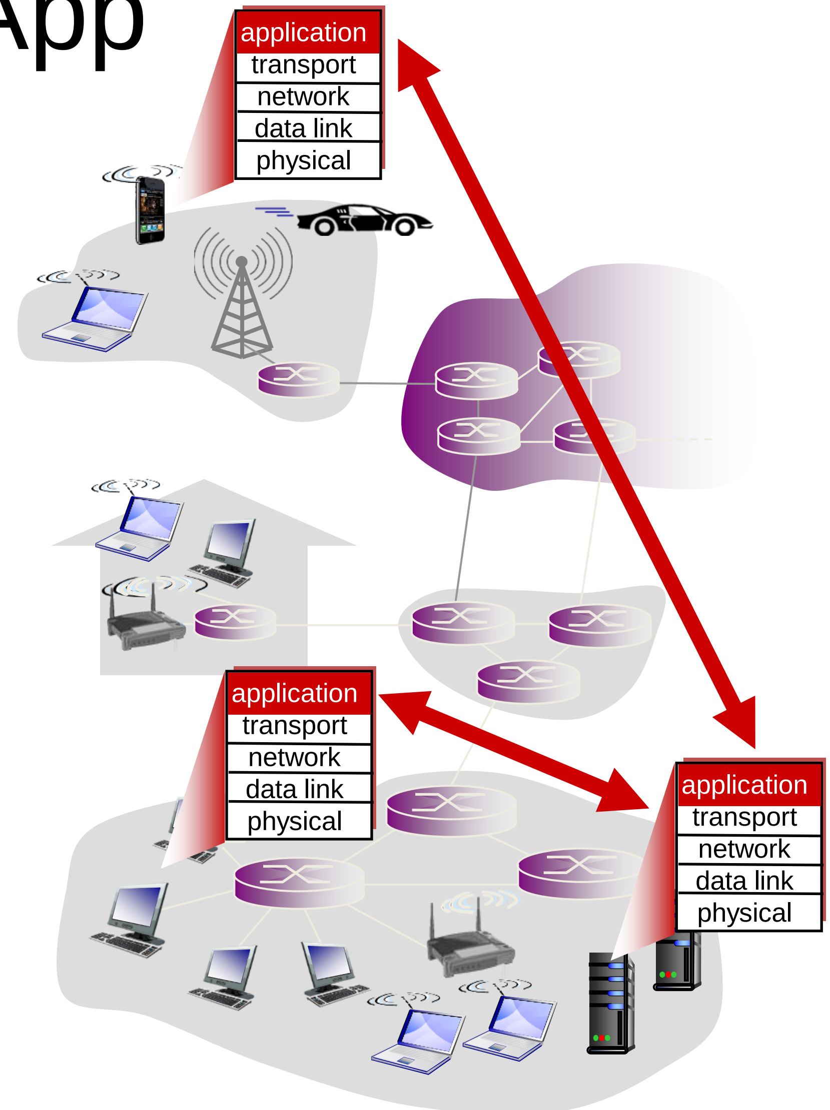
Creating a Network App

Write programs that:

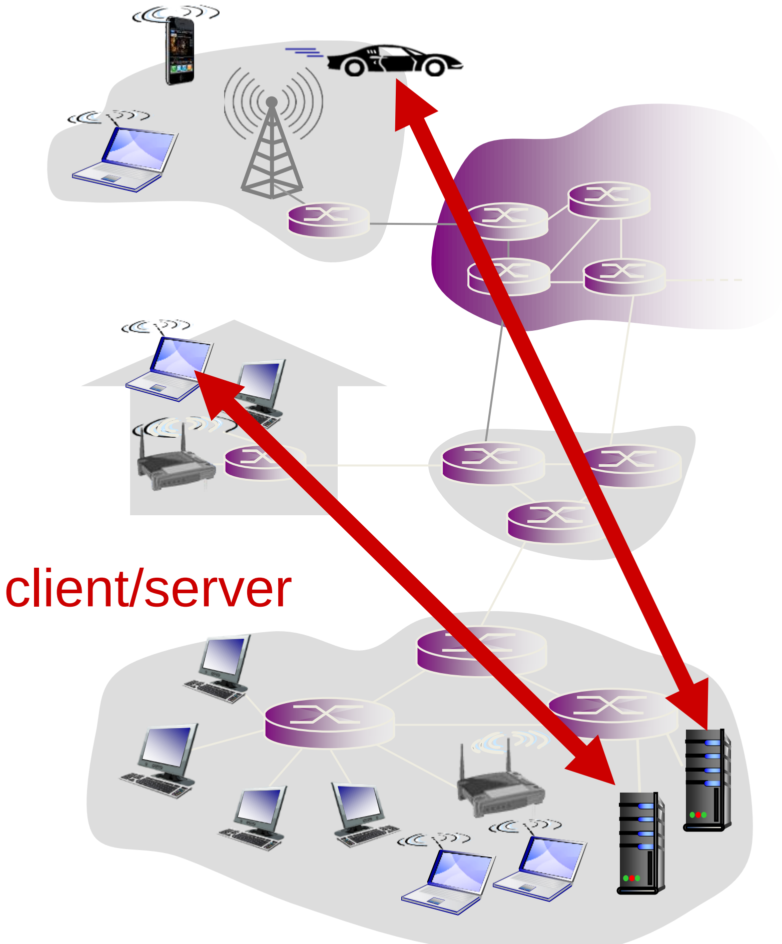
- run on (different) *end systems*
- communicate over network
- e.g., web server software communicates with browser software
  - Client/server or p2p

No need to write software for network-core devices

- network-core devices do not run user applications
  - This is changing!
- applications on end systems allows for rapid app development, propagation



Client-server Architecture



Server:

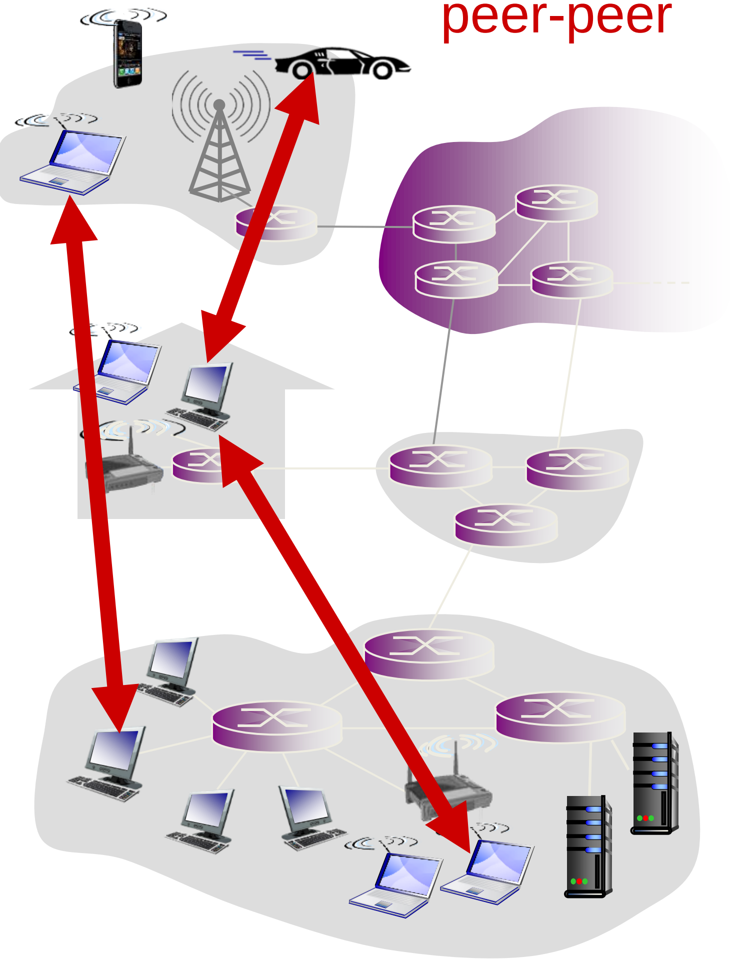
- always-on host
- “permanent” IP address
- data centers for scaling

Clients:

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

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



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

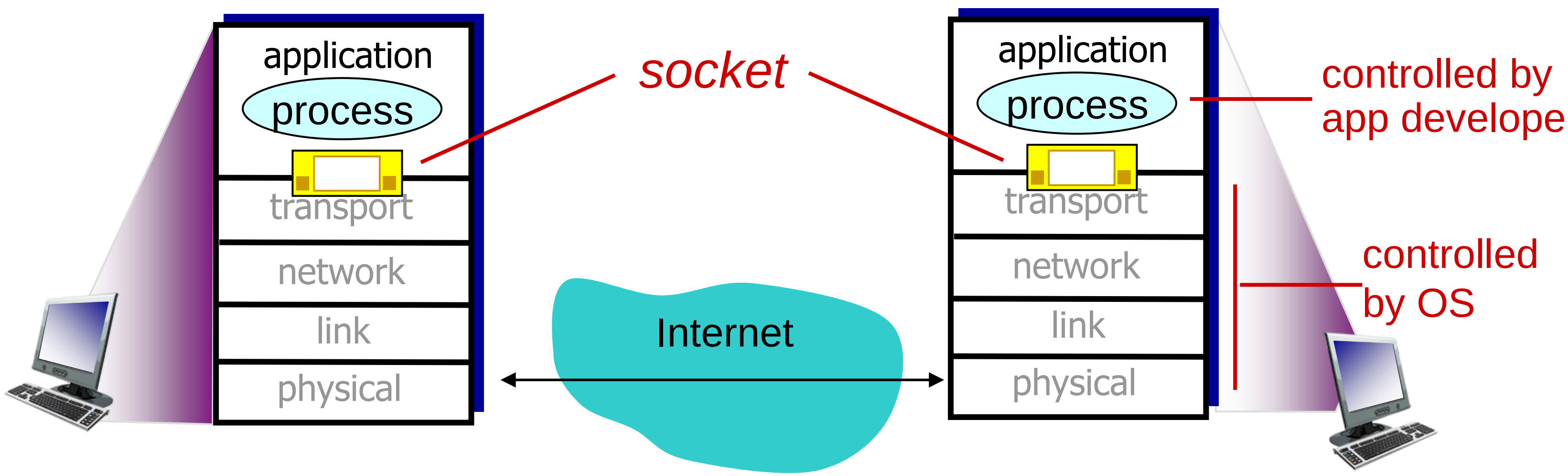
client process: process that initiates communication

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



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 cs.colorado.edu web server:
  - IP address: 128.119.245.12
  - port number: 80

App-layer Protocol Defines:

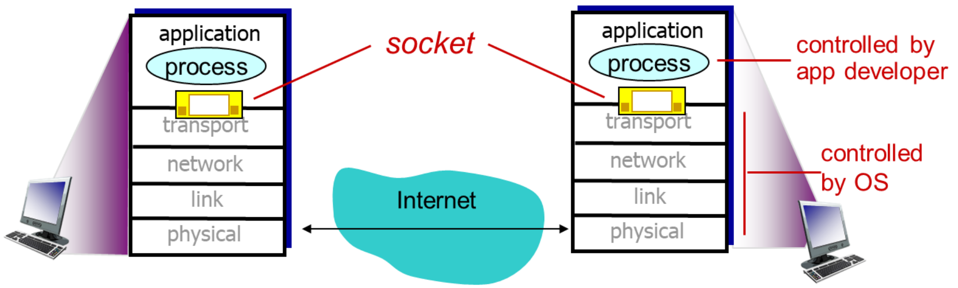
- Types of messages exchanged
  - e.g., request, response
- Message syntax:
  - what fields in messages & how fields are delineated
- Message semantics
  - meaning of information in fields
- Rules for when and how processes send & respond to messages

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
  - 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., VoIP, 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

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

Securing TCP

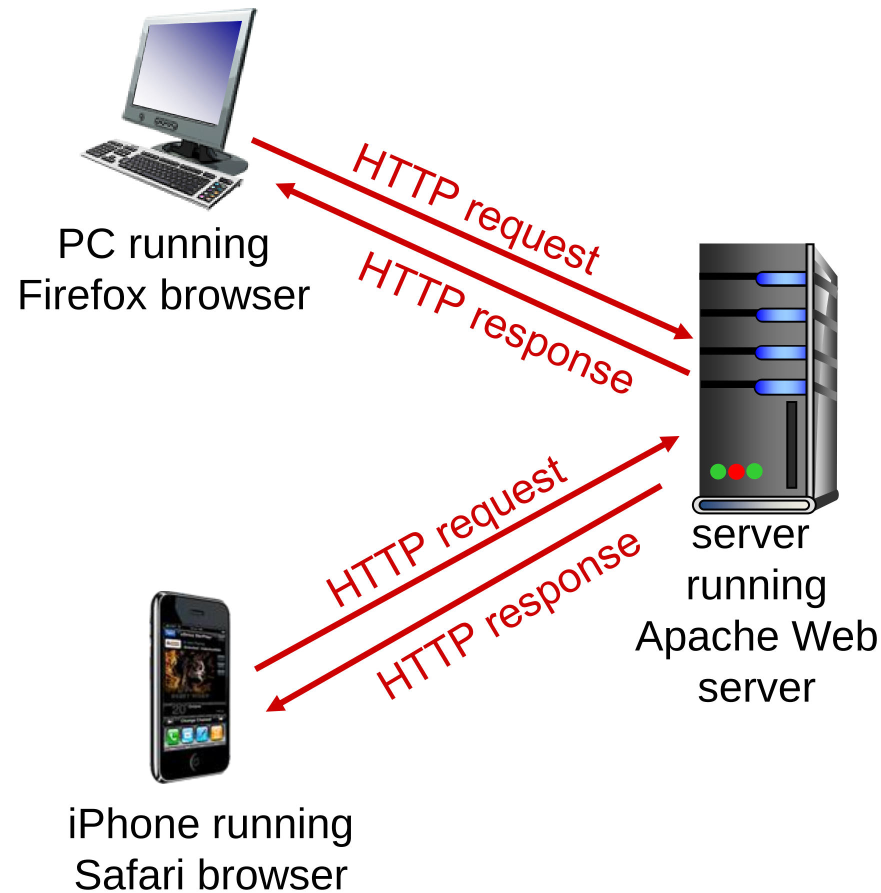
- **TCP & UDP**
  - no encryption
  - cleartext passwords sent into socket traverse Internet in cleartext
- **SSL**
  - provides encrypted TCP connection
  - data integrity
  - end-point authentication
  - SSL is at app layer
  - apps use SSL libraries, that “talk” to TCP
  - SSL socket API
    - ***cleartext passwords sent into socket traverse Internet encrypted***

Hypertext Transfer Protocol (HTTP)

HTTP Overview

HTTP: hypertext transfer protocol

- Web's <u>application layer</u> 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, typically 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 then closed
- downloading multiple objects required multiple connections

Persistent HTTP

- multiple objects can be sent over single TCP connection between client, server

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

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

carriage return character

line-feed character

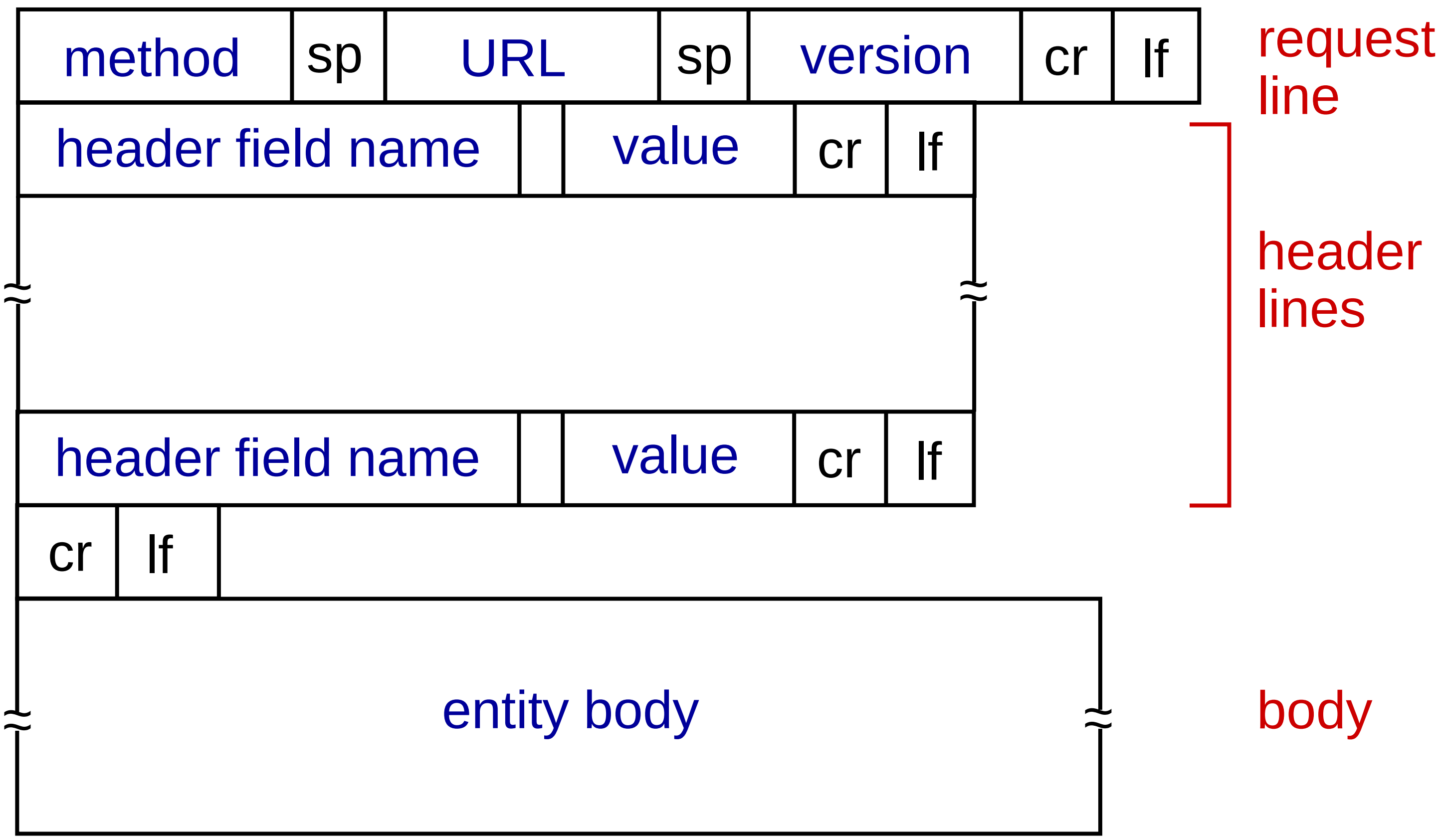
request line
(GET, POST,
HEAD commands)

header
lines

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

```
GET /index.html HTTP/1.1\r\n
Host: www-net.cs.colorado.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
```

HTTP Request Message: general format



Uploading Form Input

POST method:

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

URL method:

- uses GET method
- input is uploaded in URL field of request line:

www.somesite.com/animalsearch?monkeys&banana

HTTP Response Message

status line (protocol status code status phrase)

header lines

data, e.g., requested HTML file

```
HTTP/1.1 200 OK\r\n
Date: Sun, 26 Sep 2010 20:09:20 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=100\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 first 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 not found on this server

505 HTTP Version Not Supported

User-Server State: cookies

Many Web sites use cookies

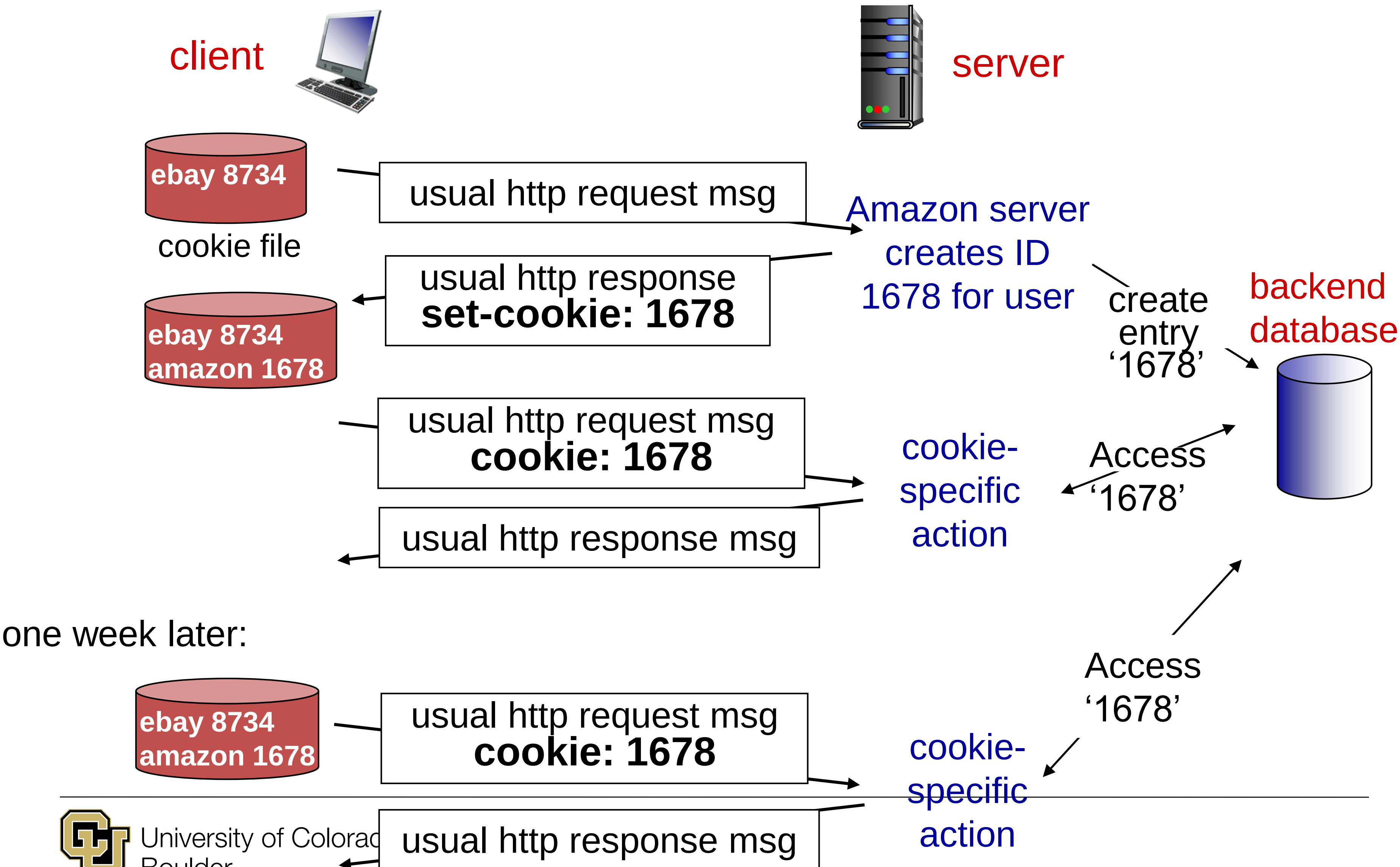
Four components:

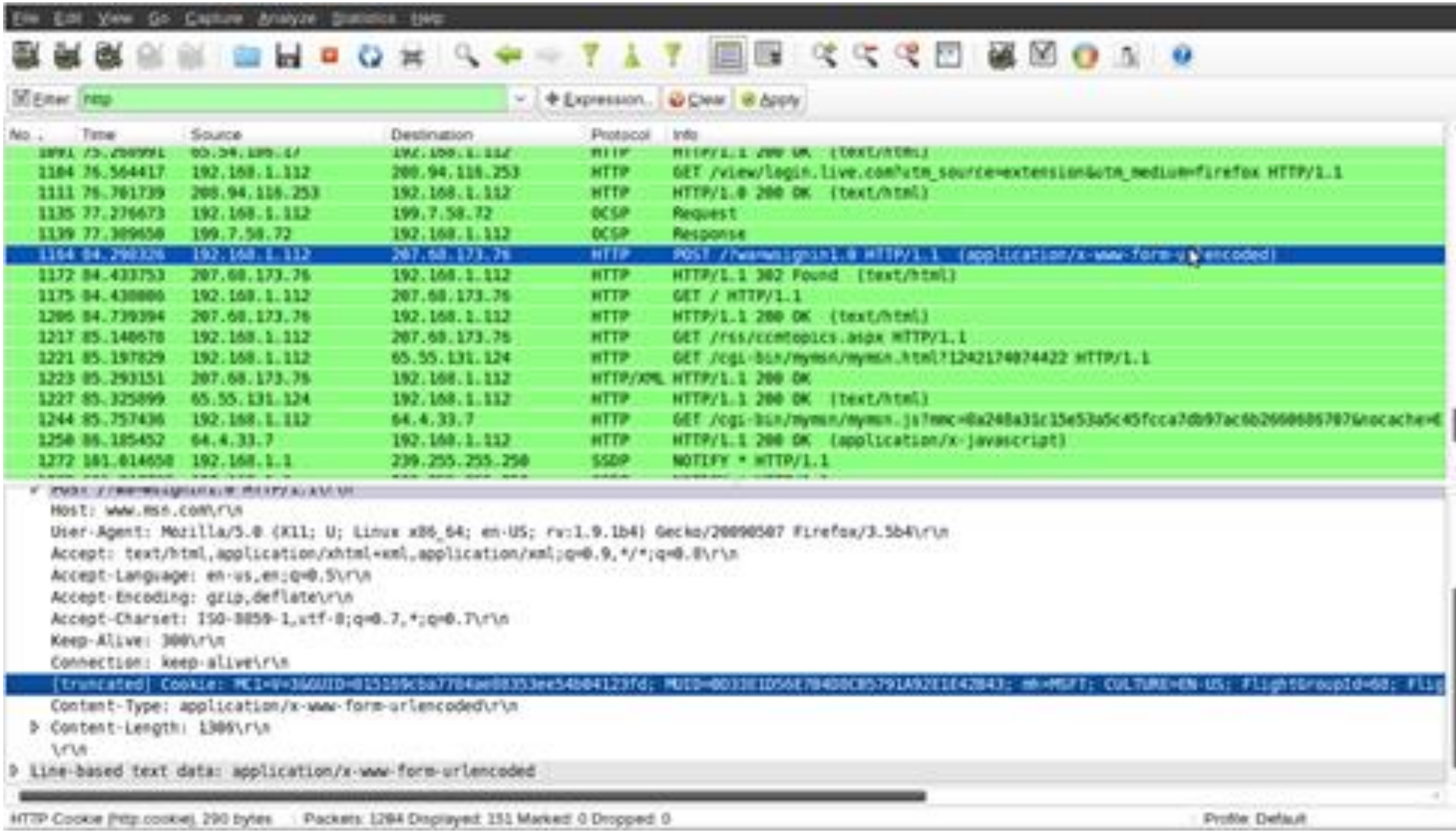
1) cookie header line of HTTP *response* message
2) cookie header line in next HTTP *request* message
3) cookie file kept on user's host, managed by user's browser
4) back-end database at Web site

Example:

- Sam always accesses 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.)

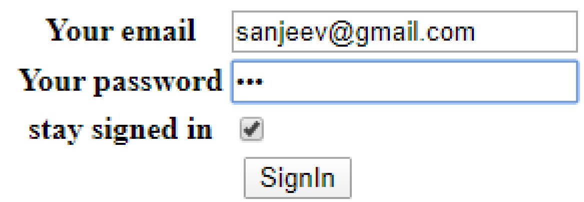




File Edit View Go Capture Analyze Statistics Help
Filter: http
Expression... Clear Apply
No. Time Source Destination Protocol Info
1104 76.564417 192.168.1.112 200.94.116.253 HTTP GET /view/login.live.com/utm_source=extension&utm_medium=firefox HTTP/1.1
1111 76.701739 200.94.116.253 192.168.1.112 HTTP HTTP/1.0 200 OK (text/html)
1135 77.276673 192.168.1.112 199.7.50.72 OCSP Request
1139 77.309650 199.7.50.72 192.168.1.112 OCSP Response
1172 84.433753 207.68.173.76 192.168.1.112 HTTP HTTP/1.1 302 Found (text/html)
1175 84.438806 192.168.1.112 207.68.173.76 HTTP GET / HTTP/1.1
1206 84.739394 207.68.173.76 192.168.1.112 HTTP HTTP/1.1 200 OK (text/html)
1217 85.140678 192.168.1.112 207.68.173.76 HTTP GET /rss/ccmtopics.aspx HTTP/1.1
1223 85.293151 207.68.173.76 192.168.1.112 HTTP/XML HTTP/1.1 200 OK
1227 85.325899 65.55.131.124 192.168.1.112 HTTP HTTP/1.1 200 OK (text/html)
1250 86.185452 64.4.33.7 192.168.1.112 HTTP HTTP/1.1 200 OK (application/x-javascript)
1272 101.014650 192.168.1.1 239.255.255.250 SSDP NOTIFY * HTTP/1.1
Host: www.msn.com\r\n
Accept-Language: en-us,en;q=0.5\r\n
Accept-Encoding: gzip,deflate\r\n
Keep-Alive: 300\r\n
Connection: keep-alive\r\n
Content-Type: application/x-www-form-urlencoded\r\n
Line-based text data: application/x-www-form-urlencoded
Profile: Default

Cookies

- Remembers stateful information (such as login) for stateless HTTP protocol



- Three main purposes
  - Session management
    - ***Logins, shopping carts, game scores, etc.***
  - Personalization
    - ***User preferences, themes, other settings***
  - Tracking
    - ***Recording and analyzing user behavior***

Cookie Tracking

- Websites can use cookies in questionable ways:
  - Privacy and safety

- Share long strings of information about what sites you've visited, and what you've done there
  - Data can be transmitted to other sites/parties without knowledge
    - ***Advertisers – allows them to build basic personal profiles about you, and serve relevant ads you're likely to buy***
      - What about smart homes?

- Don't contain name or email address

Cookies (continued)

What cookies can be used for:

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

aside

cookies and privacy:

- cookies permit sites to learn a lot about you
- you may supply name and e-mail to sites

- *How to keep "state":*
  - protocol endpoints: maintain state at sender/receiver over multiple transactions
  - cookies: http messages carry state

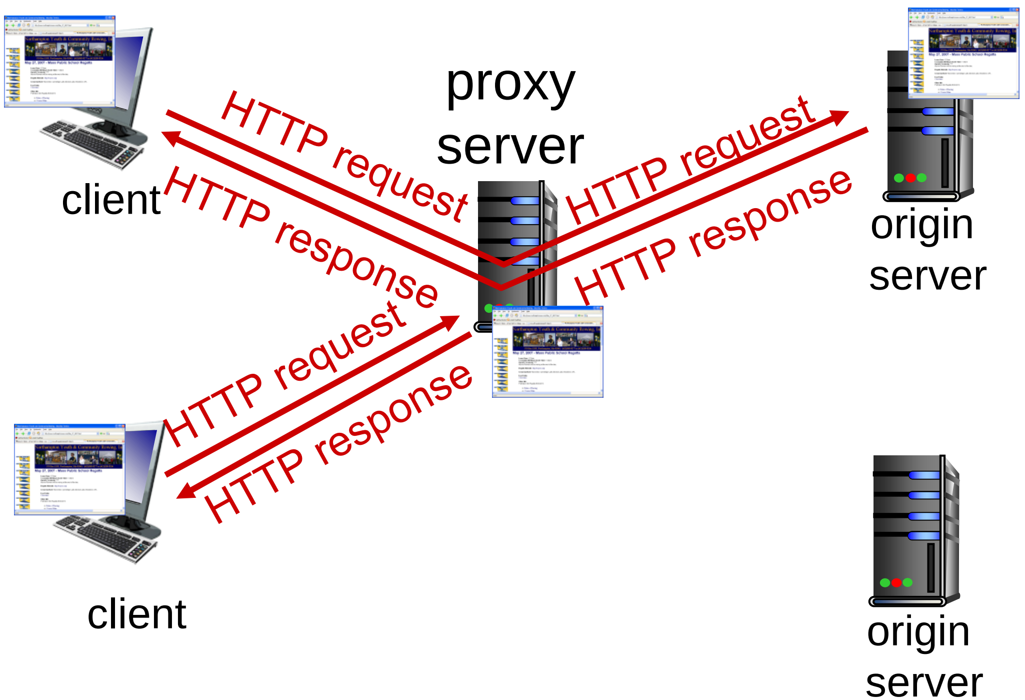
Digital Footprint

- **What does your digital footprint say about you?**

Web Caches (proxy server)

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
  – What are the benefits of this?



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?

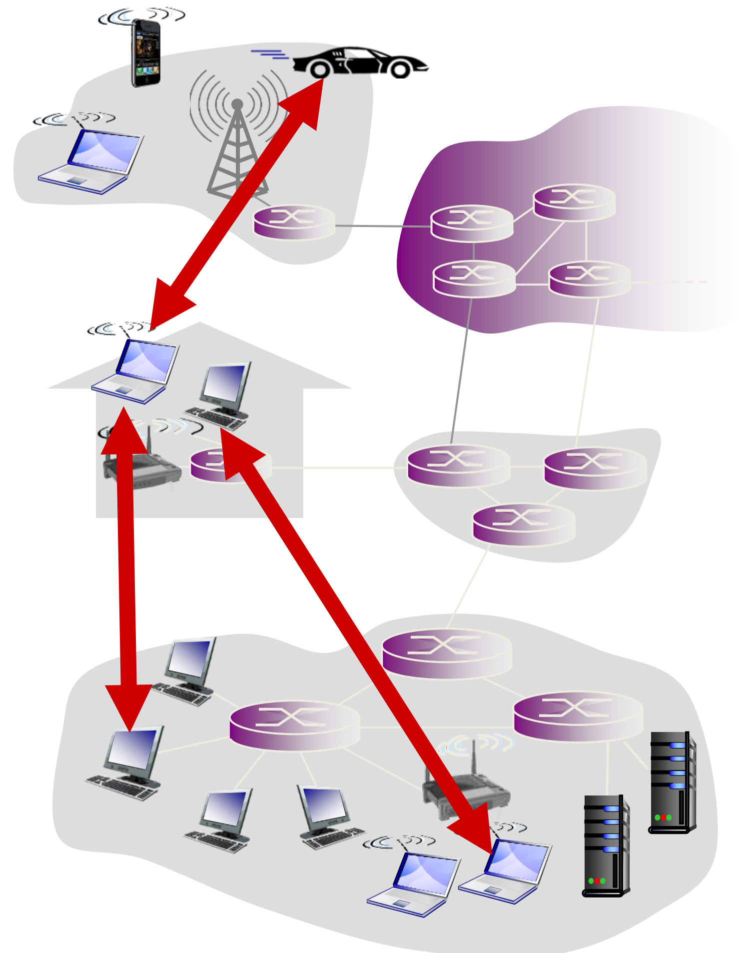
- reduce response time for client request
- reduce traffic on an institution's access link
- Internet dense with caches: enables "poor" content providers to effectively deliver content (so too does P2P file sharing)

Pure P2P Architecture

- *No* always-on server
- Arbitrary end systems directly communicate
- Peers are intermittently connected and change IP addresses

Examples:

- File distribution (BitTorrent)
- Streaming (Muvi)
- VoIP (Skype)

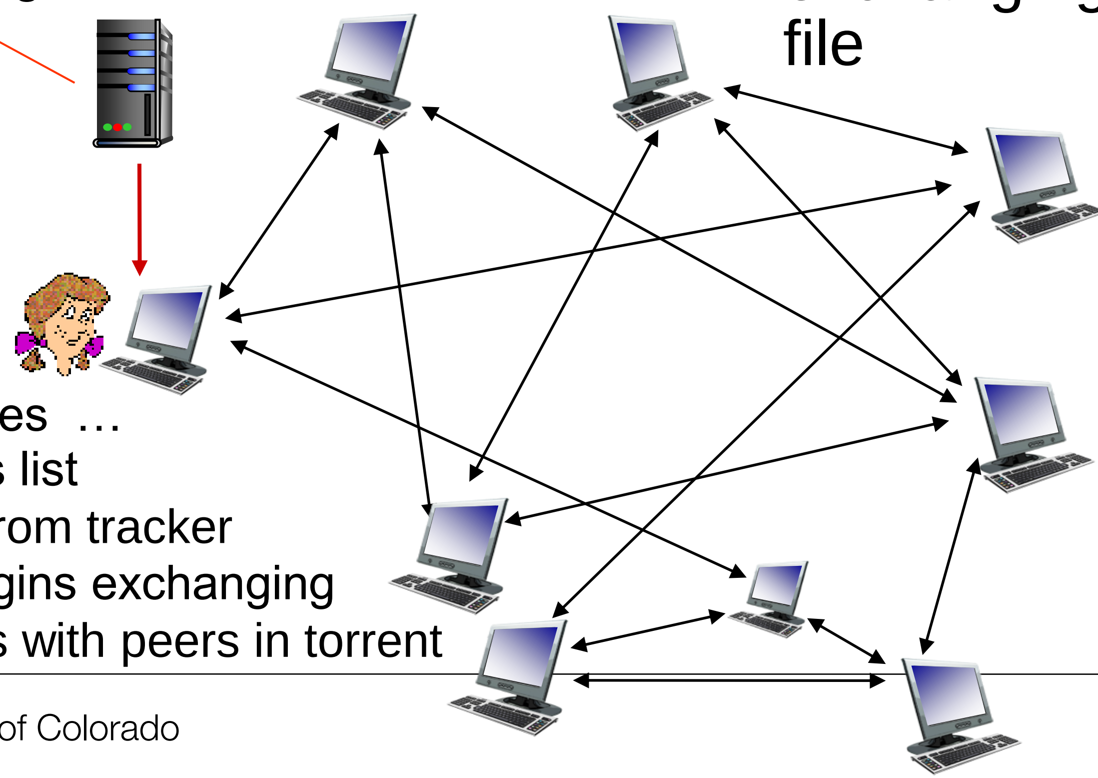


P2P File Distribution: BitTorrent

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

tracker: tracks peers participating in torrent

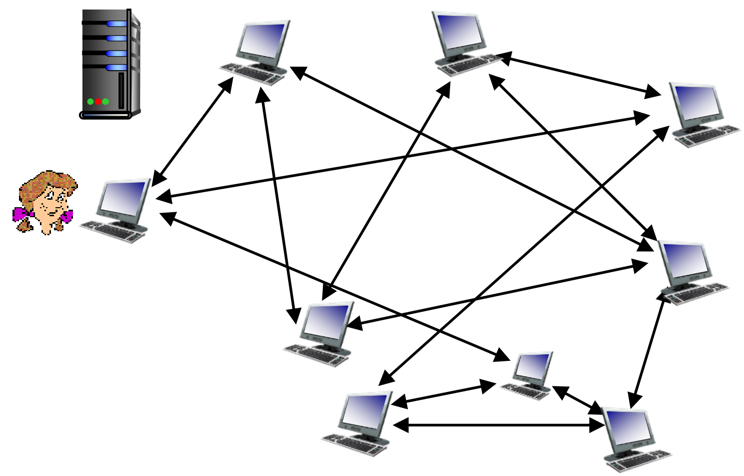
torrent: group of peers exchanging chunks of a file



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

P2P File Distribution: BitTorrent

- Peer joining torrent:
  - has no chunks, but will accumulate them over time from other peers
  - registers with tracker to get list of peers, connects to subset of peers ("neighbors")



- while downloading, peer uploads chunks to other peers
- peer may change peers with whom it exchanges chunks
- *churn:* peers may come and go
- once peer has entire file, it may (selfishly) leave or (altruistically) remain in torrent

BitTorrent: requesting, sending file chunks

- ***Requesting chunks:***
  - at any given time, different peers have different subsets of file chunks
  - periodically, Alice asks each peer for list of chunks that they have
  - Alice requests missing chunks from peers, rarest first
  - *What protocol does this sound like that we've already studied?*

Sending chunks:

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

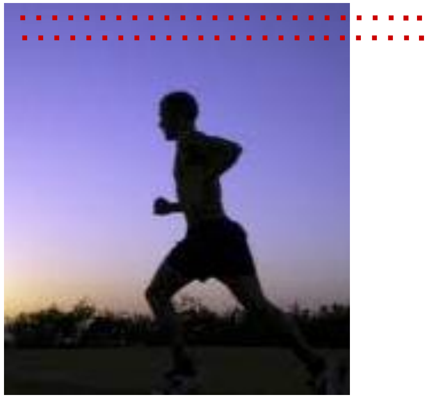
Video Streaming and CDNs: context

- **Video traffic: major consumer of Internet bandwidth**
  - Netflix, YouTube: 37%, 16% of downstream residential ISP traffic
  - ~2.25B YouTube users, ~75M Netflix users
- **Challenge: scale - how to reach ~2B users?**
  - single mega-video server won't work (why?)
- **Challenge: heterogeneity**
  - different users have different capabilities (e.g., wired versus mobile; bandwidth rich versus bandwidth poor; location)
- ***Solution:*** **distributed, application-level infrastructure**

Multimedia: video

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

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



frame *i*

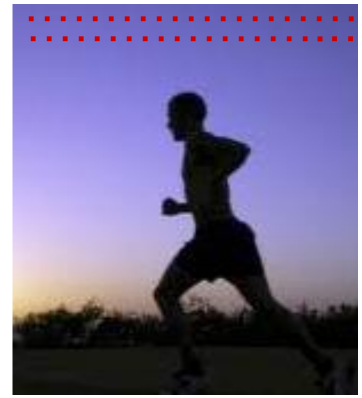
temporal coding example: instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

Multimedia: video

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



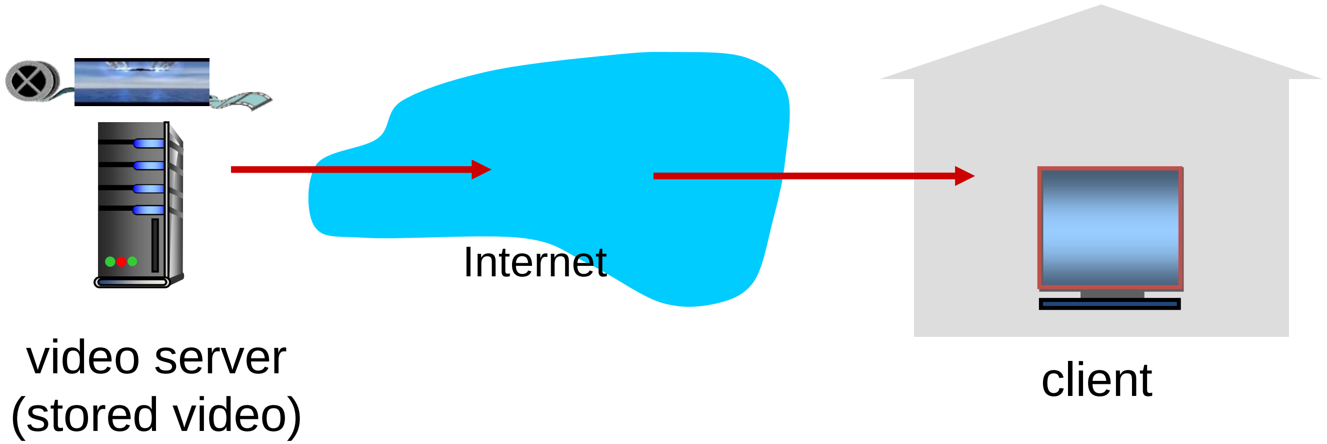
frame *i*

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

frame *i+1*

Streaming stored video:

simple scenario:



Streaming Multimedia: DASH

- *DASH: D*ynamic, *A*daptive *S*treaming over *H*TTP
- *Server:*
  - divides video file into multiple chunks
  - each chunk stored, encoded at different rates
  - *manifest file:* provides URLs for different chunks

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

Streaming Multimedia: DASH

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

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

Content Distribution Networks (CDN)

- *Challenge:* how to stream content (selected from millions of videos) to millions of *simultaneous* users?

- *Option 1:* single, large “mega-server”
  - single point of failure
  - point of network congestion
  - long path to distant clients
  - multiple copies of video sent over outgoing link
    - ***quite simply: this solution doesn't scale***

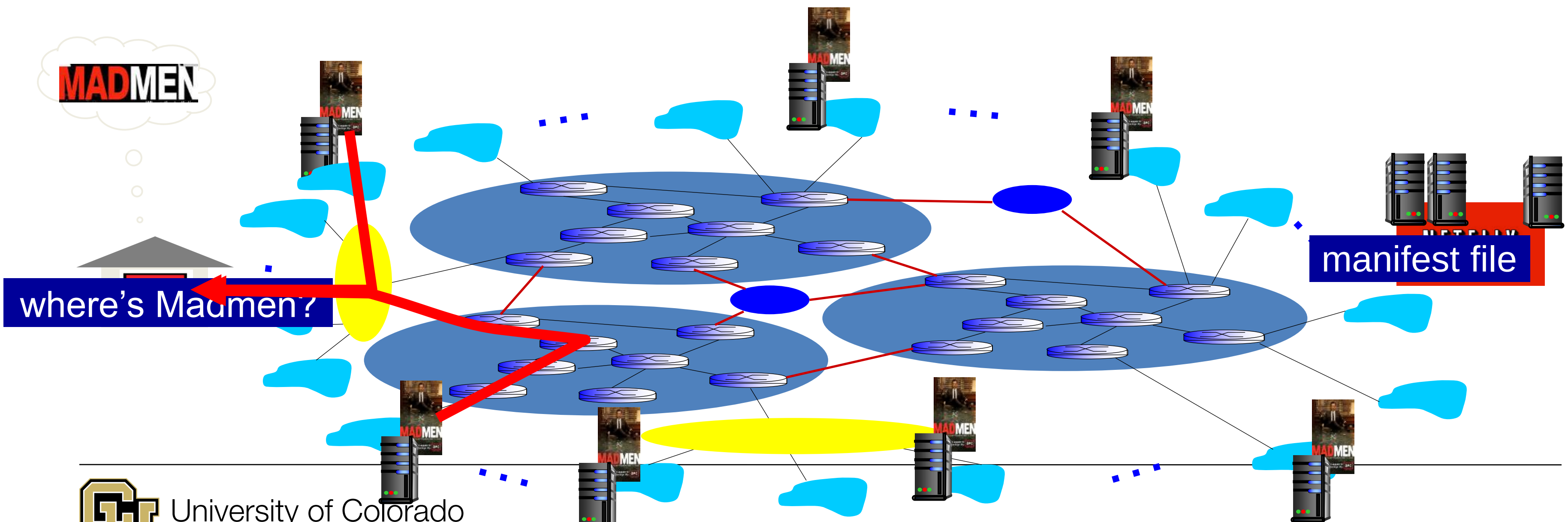
CDN

- *Challenge:* how to stream content (selected from millions of videos) to millions of simultaneous users?

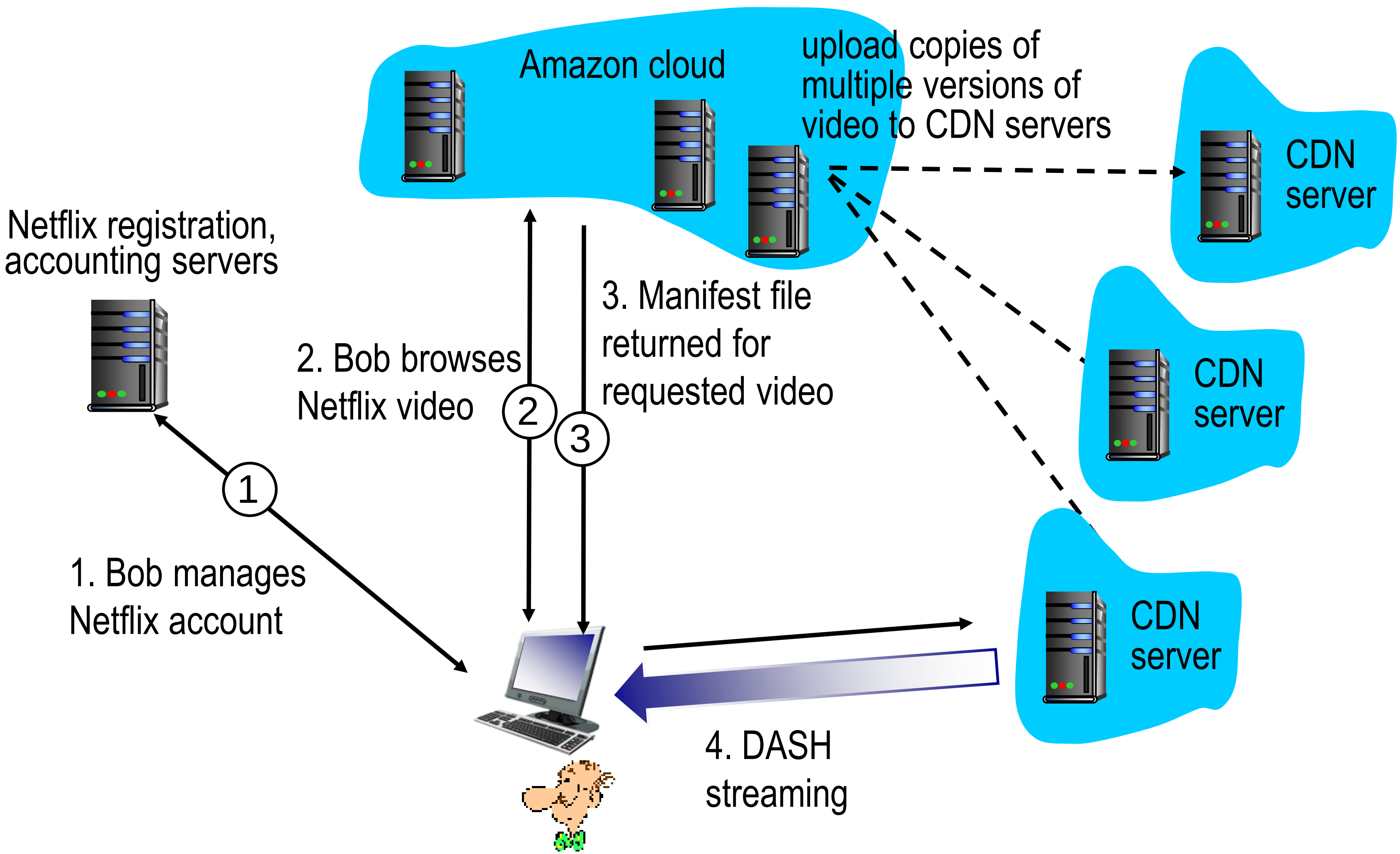
- *Option 2:* store/serve multiple copies of videos at multiple geographically distributed sites *(CDN)*
  - *enter deep:* push CDN servers deep into many access networks
    - ***close to users***
    - ***used by Akamai, 1700 locations***
  - *bring home:* smaller number (10's) of larger clusters in POPs near (but not within) access networks
    - ***used by Limelight***

Content Distribution Networks (CDNs)

- CDN: stores copies of content at CDN nodes
  - e.g. Netflix stores copies of Mad Men
- Subscriber requests content from CDN
  - – directed to nearby copy, retrieves content
  - – may choose different copy if network path congested (how could it know this?)



Case Study: Netflix



Questions?

Client can't connect to web server

Three Locations w/ single web server

Appendix

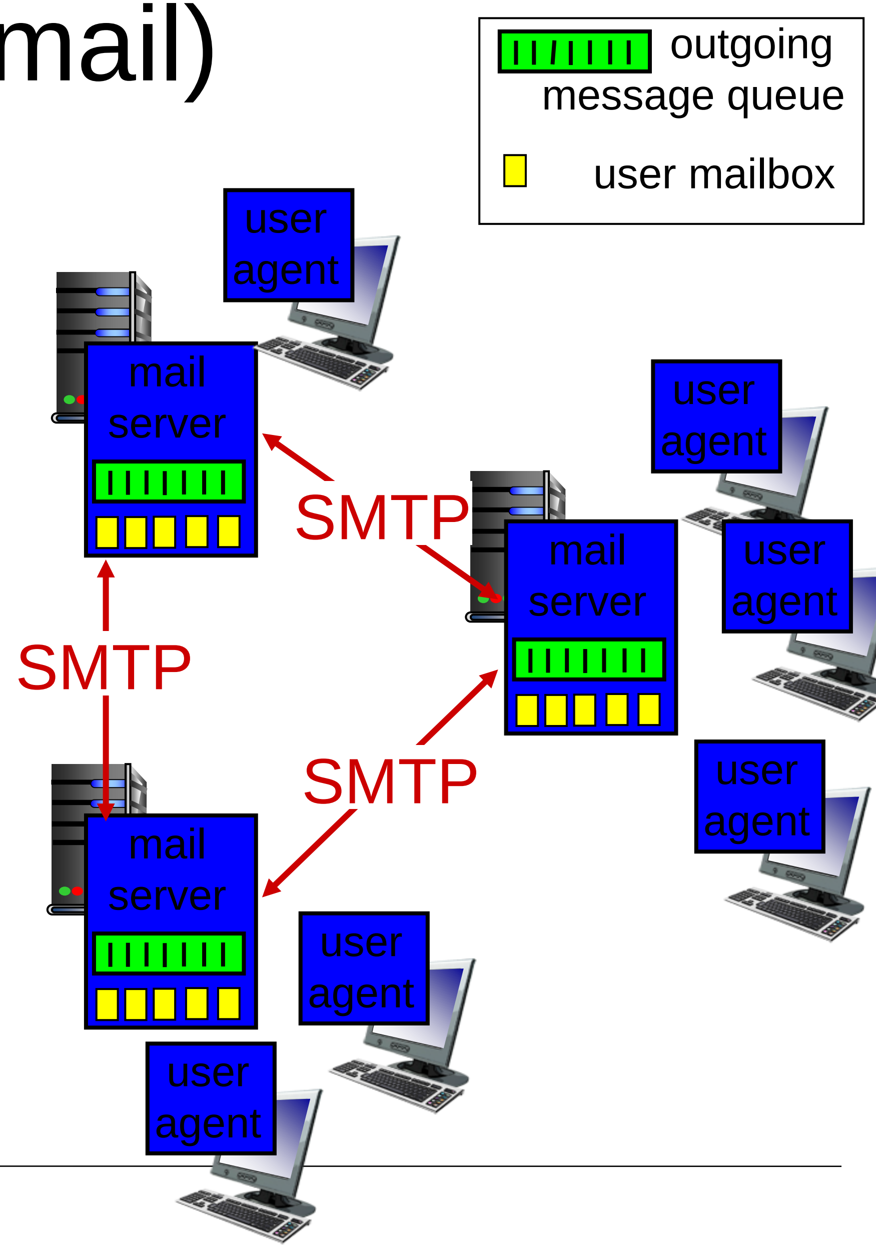
Electronic mail (e-mail)

Three major components:

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

User Agent

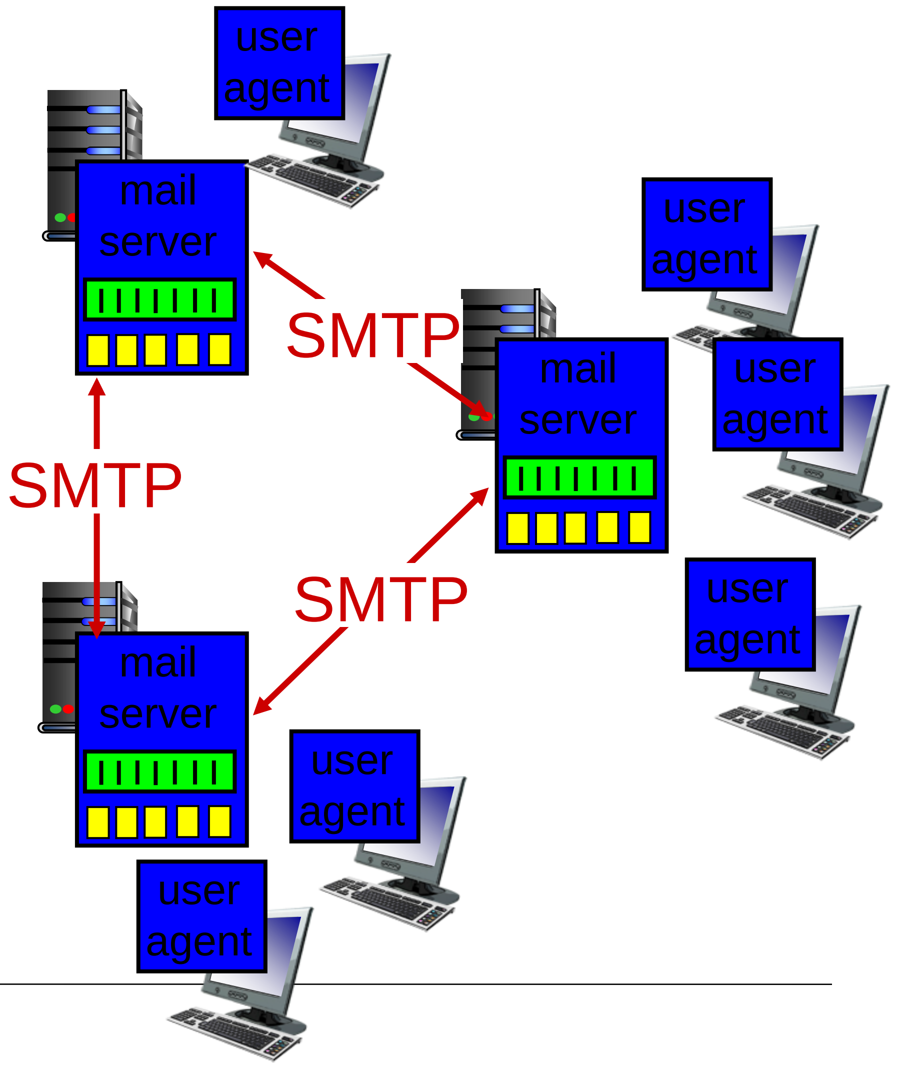
- **a.k.a. "mail reader"**
- **composing, editing, reading mail messages**
- **e.g., Outlook, Thunderbird, iPhone mail client**
- **outgoing, incoming messages stored on server**



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

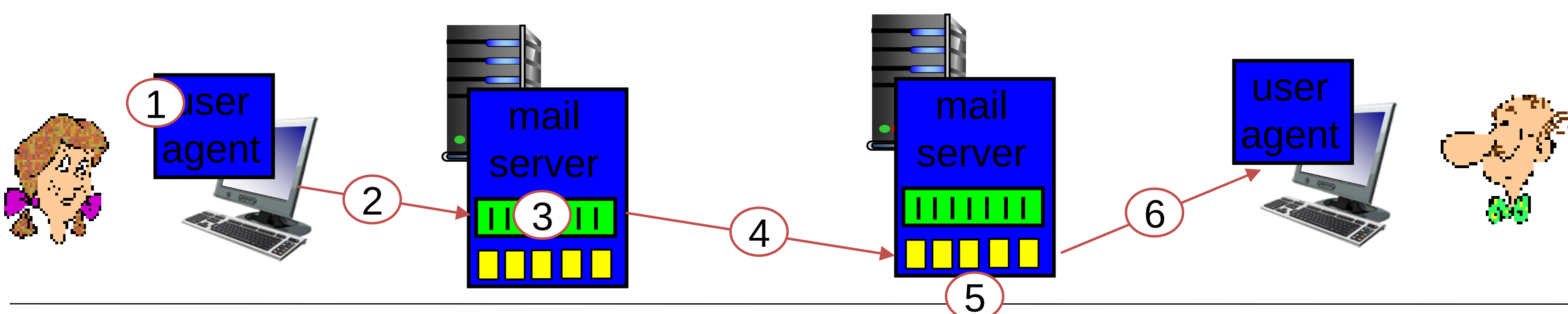


Electronic Mail: SMTP [RFC 2821]

- **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)**
  - commands: ASCII text
  - response: status code and phrase
- **messages must be in 7-bit ASCI**

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**



Alice's mail server

Bob's mail server

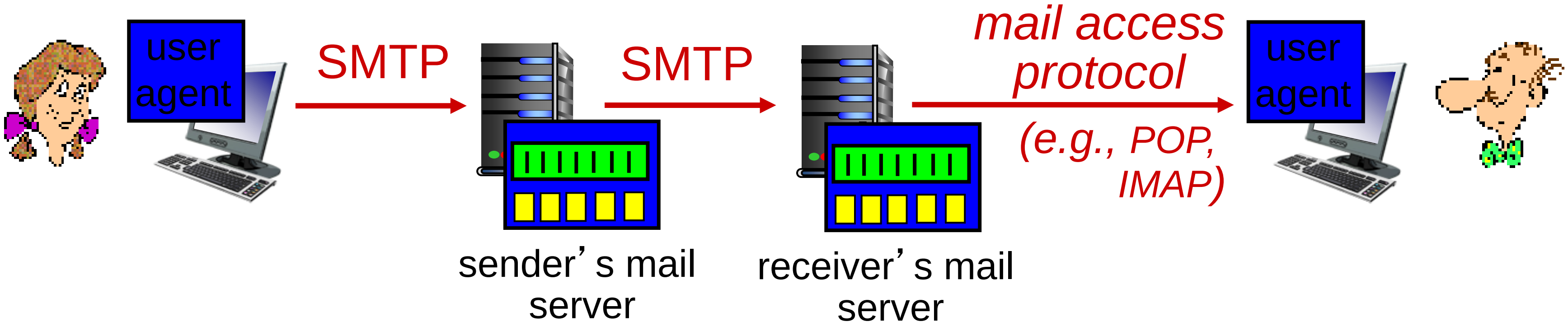
SMTP: Summary

- **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**

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**

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 messages on server
  - HTTP: gmail, Hotmail, Yahoo! Mail, etc.

POP3 protocol

authorization phase

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

***transaction phase,* client:**

- `list`: **list message numbers**
- `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
```

POP3 (more) and IMAP

more about POP3

- **previous example uses POP3 "download and delete" mode**
  - Bob cannot re-read e-mail if he changes client
- **POP3 "download-and-keep": copies of messages on different clients**
- **POP3 is stateless across sessions**

IMAP

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