

Chapter 2

Application Layer

Computer Networking: A Top Down Approach

6th edition

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Chapter 2: outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 FTP

2.4 electronic mail

- SMTP, POP3, IMAP

2.5 DNS

2.6 P2P applications

2.7 socket programming
with UDP and TCP

Chapter 2: application layer

our goals:

- ❖ conceptual, implementation aspects of network application protocols
 - transport-layer service models
 - client-server paradigm
 - peer-to-peer paradigm
- ❖ learn about protocols by examining popular application-level protocols
 - HTTP
 - FTP
 - SMTP / POP3 / IMAP
 - DNS
- ❖ creating network applications
 - socket API

Some network apps

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

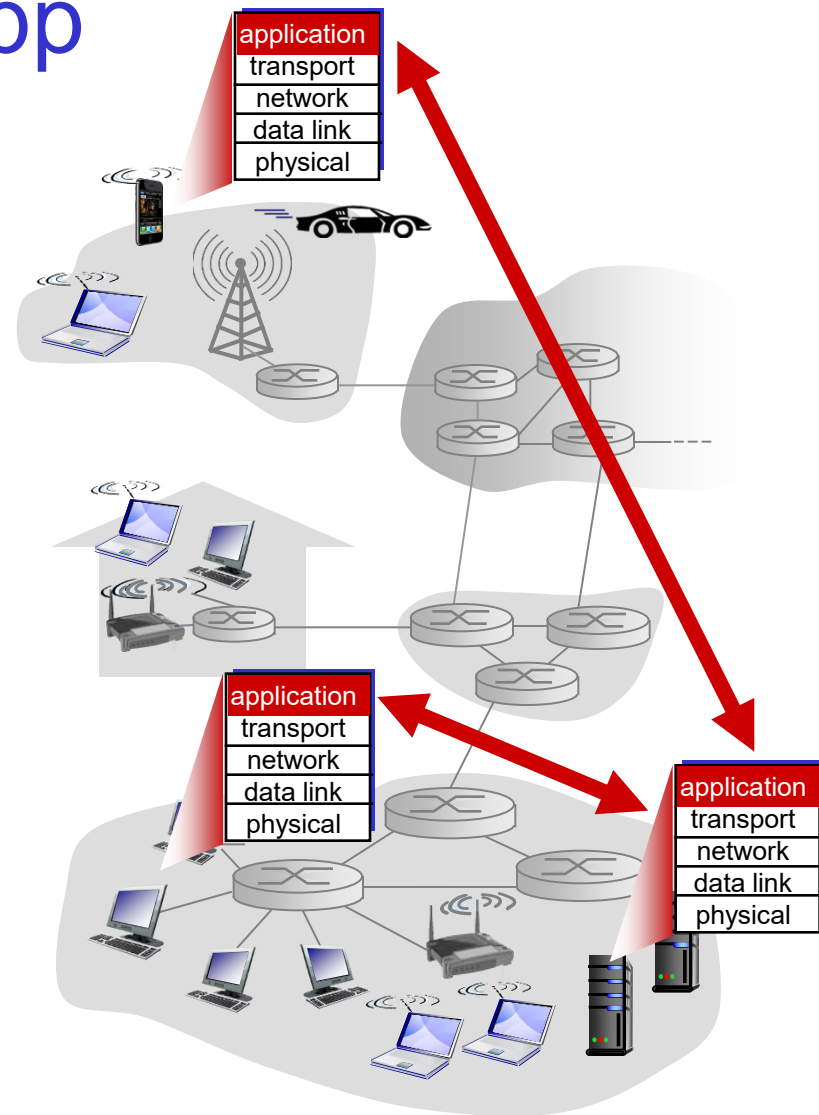
Creating a network app

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
- ❖ applications on end systems allows for rapid app development, propagation



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:

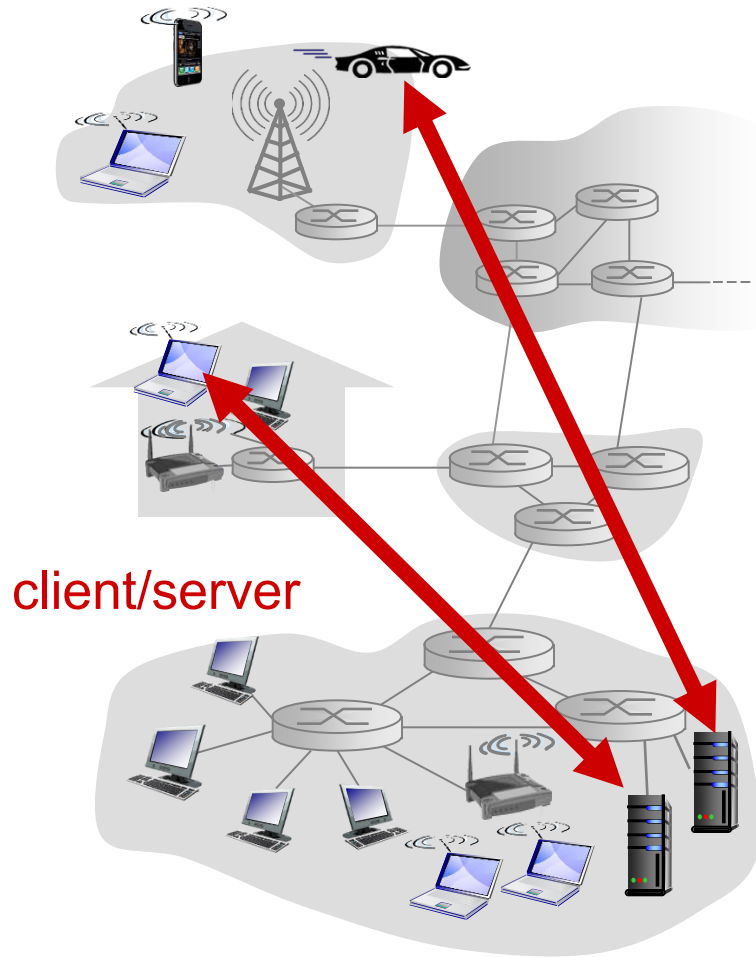
- ❖ e.g., Skype

Application architectures

possible structure of applications:

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

Client-server architecture



server:

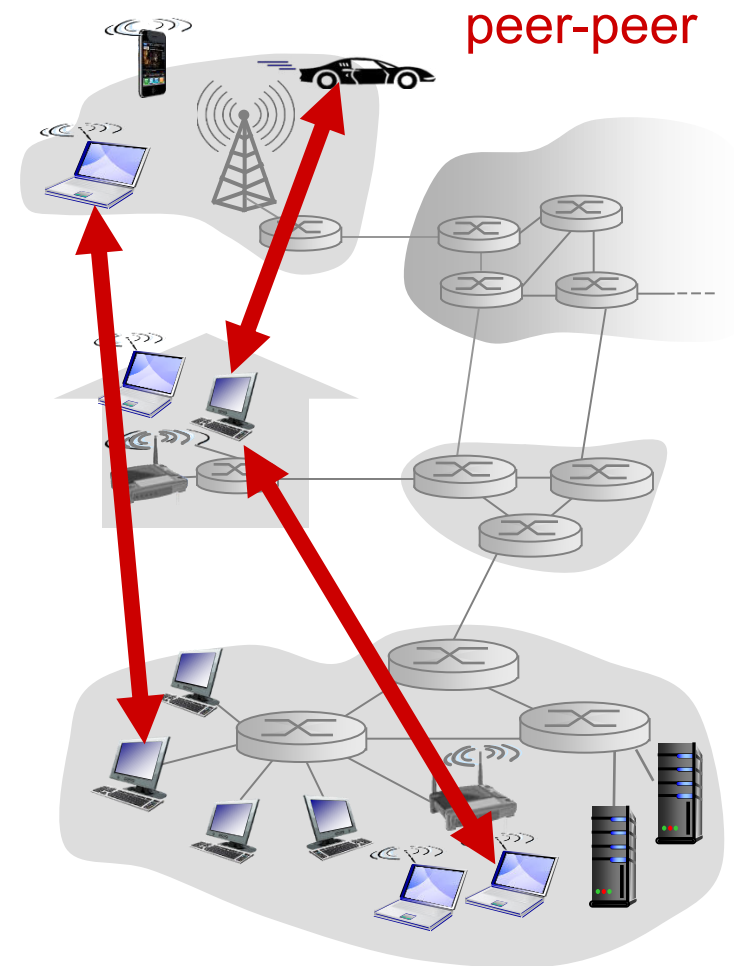
- ❖ always-on host
- ❖ permanent IP address
- ❖ data centers for scaling

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 clients, servers
within a host

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

client process: process that initiates communication

server process: process that waits to be contacted

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

How to identify a 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

What are the services generally required by an application?

Transport services required by an application

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	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, 100' s msec
stored audio/video	loss-tolerant	same as above	
interactive games	loss-tolerant	few kbps up	yes, few secs
text messaging	no loss	elastic	yes, 100' s msec 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
- ❖ *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,

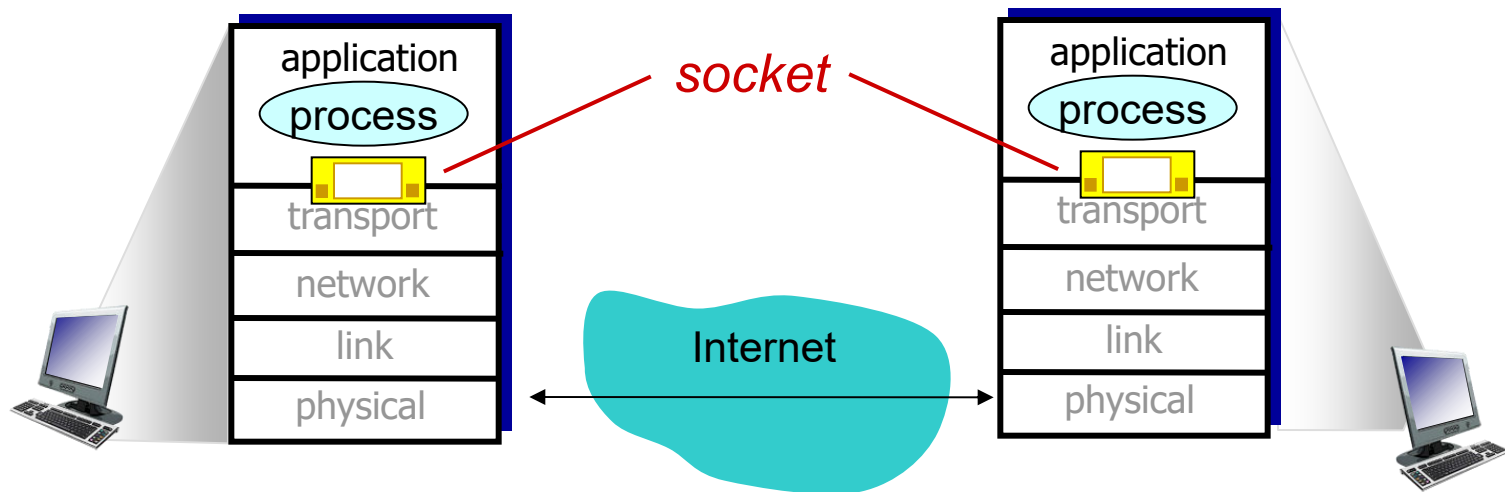
Q: why bother? Why is there a UDP?

Internet 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), RTP [RFC 1889]	TCP or UDP
Internet telephony		SIP, RTP, proprietary (e.g., Skype)	TCP or UDP

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



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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.,

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

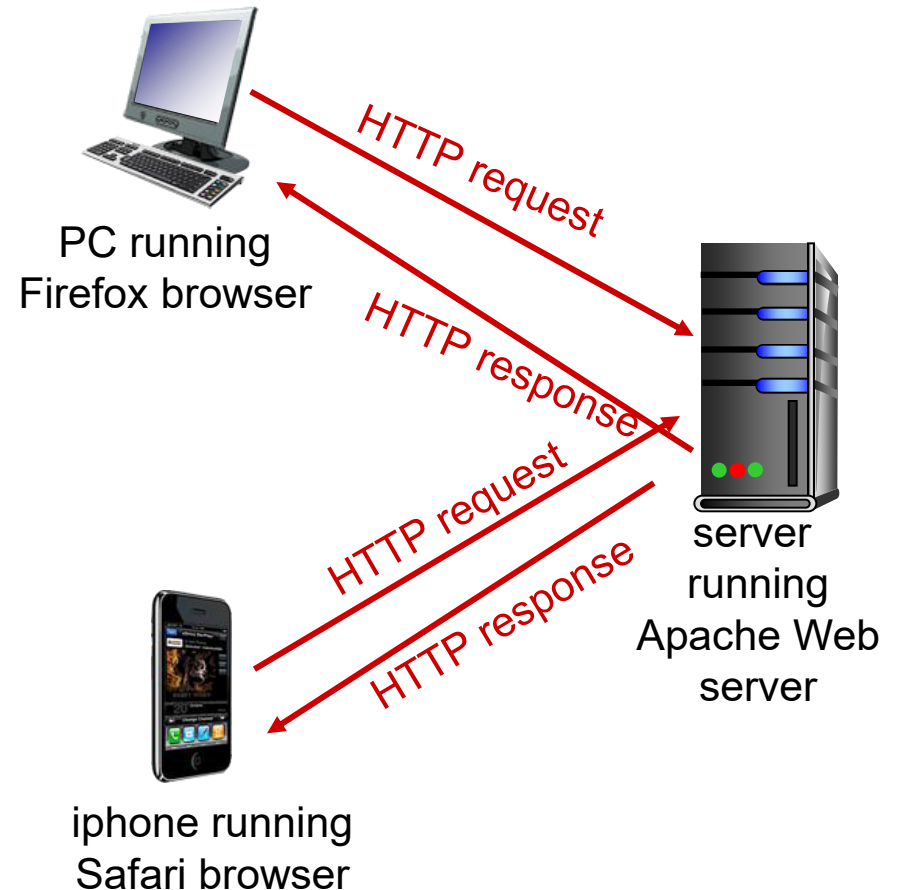
host name

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)

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 then closed
- ❖ downloading multiple objects required multiple connections

persistent HTTP

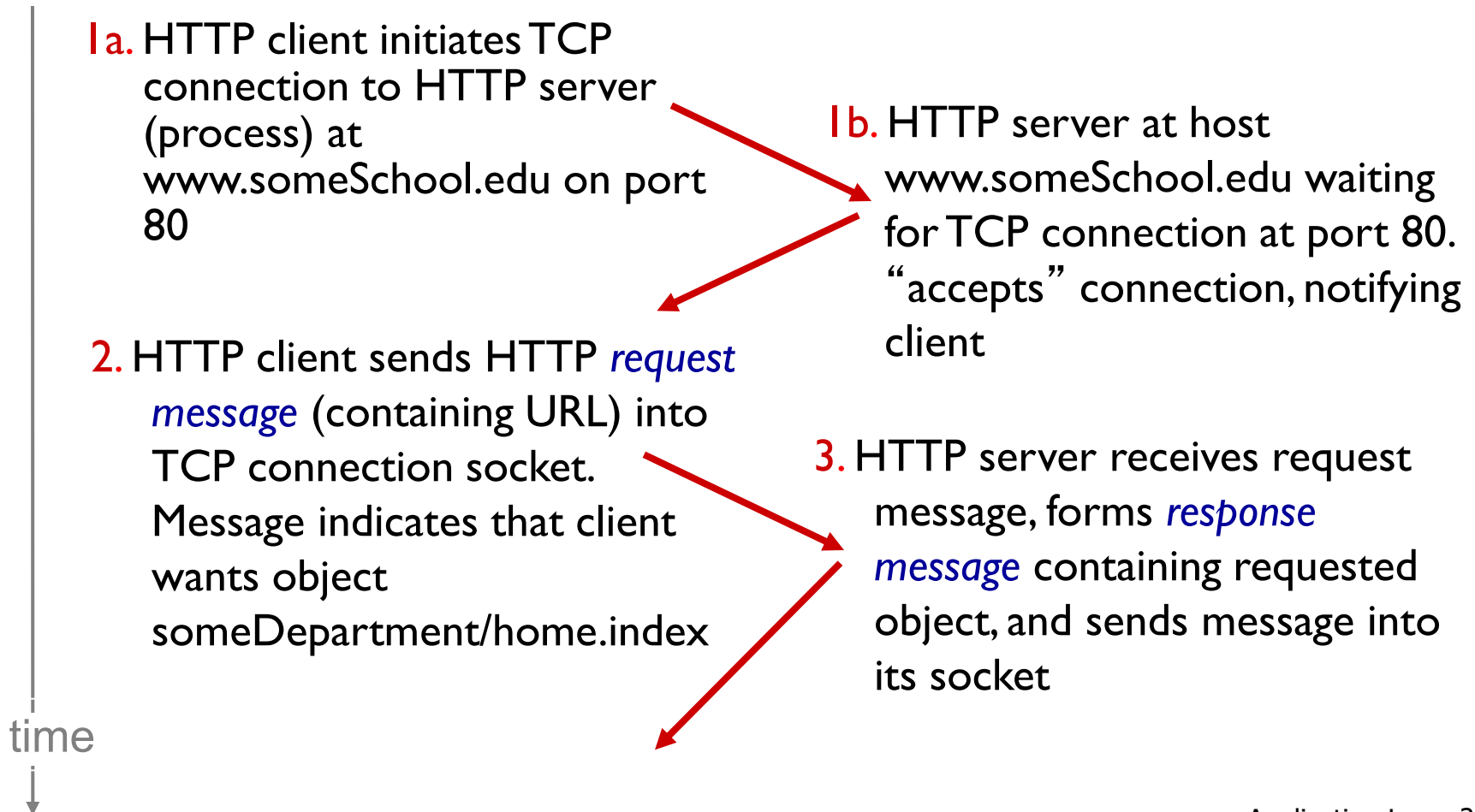
- ❖ multiple objects can be sent over single TCP connection between client, server

Non-persistent HTTP

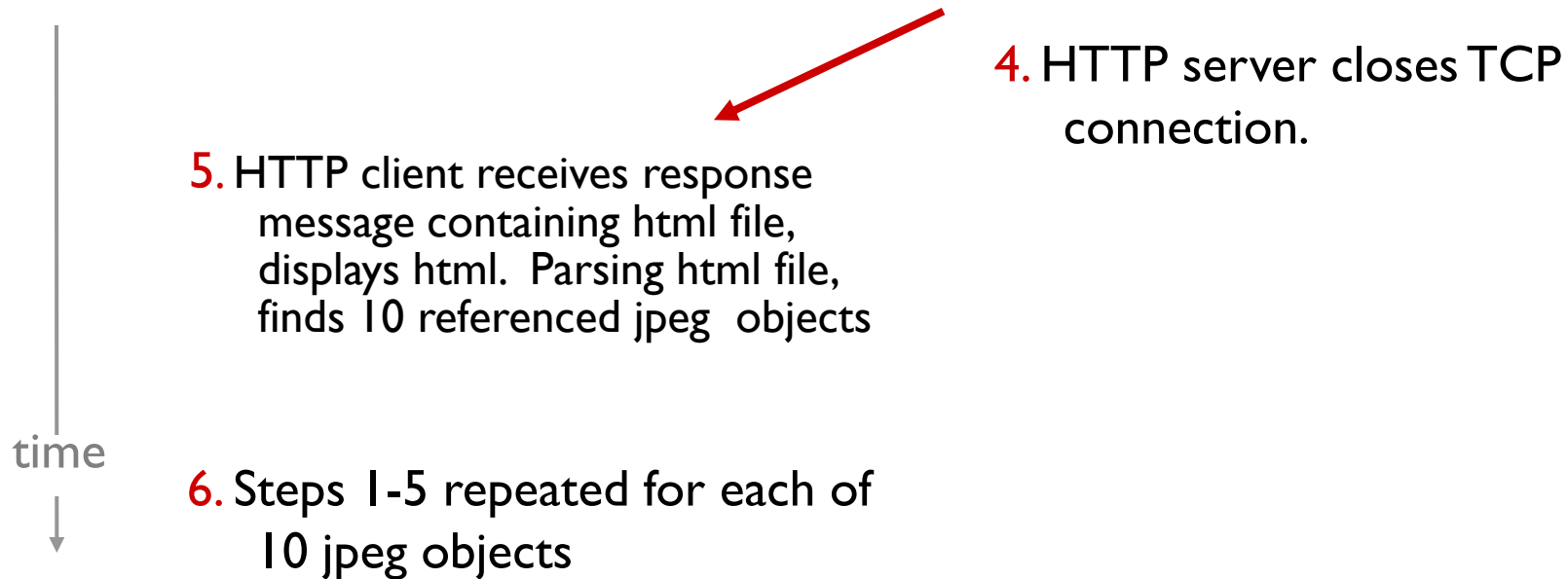
suppose user enters URL:

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

(contains text,
references to 10
jpeg images)



Non-persistent HTTP (cont.)

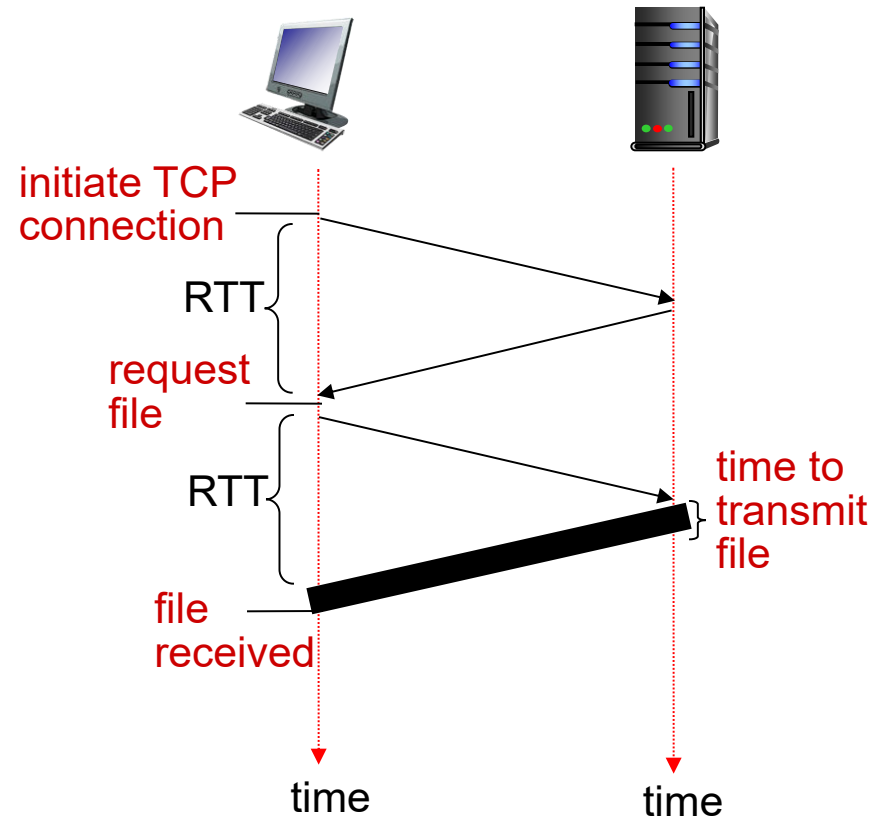


Non-persistent HTTP: response time

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 =
 $2\text{RTT} + \text{file transmission time}$



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
- ❖ 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)

request line
(GET, POST,
HEAD commands)

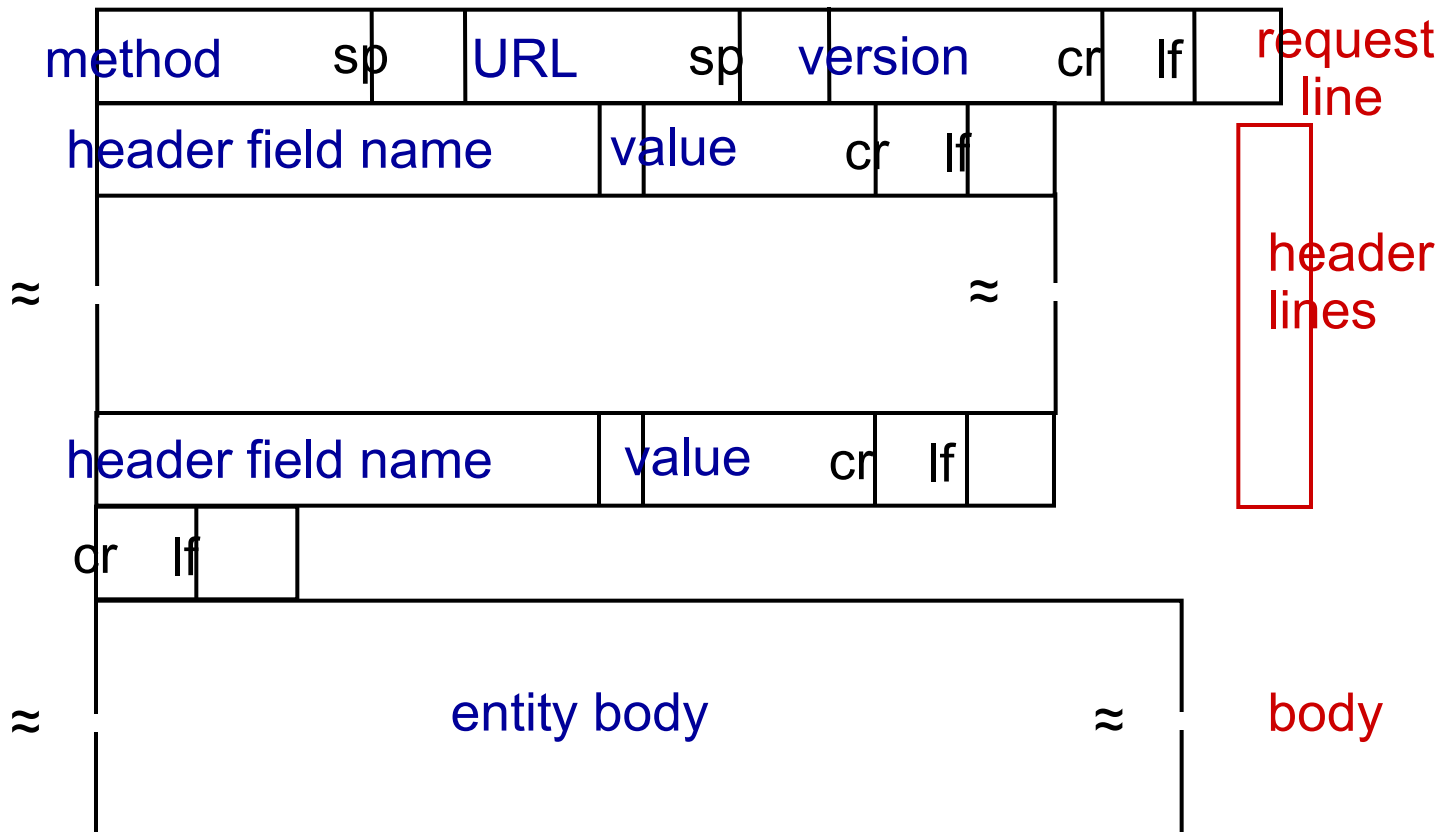
header
lines

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.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
```

carriage return character
line-feed character

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`

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 file specified in the URL field

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 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 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:

- ❖ 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.)

client



server



cookie file



ebay 8734
amazon 1678

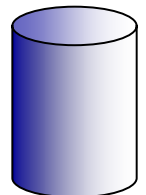
usual http request msg

Amazon server
creates ID
1678 for user

usual http response
set-cookie: 1678

create
entry

backend
database



usual http request msg
cookie: 1678

cookie-
specific
action

access

usual http response msg

access

cookie-
specific
action

one week later:



ebay 8734
amazon 1678

usual http request msg
cookie: 1678

usual http response msg

Cookies (continued)

what cookies can be used for:

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

cookies and privacy: aside

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

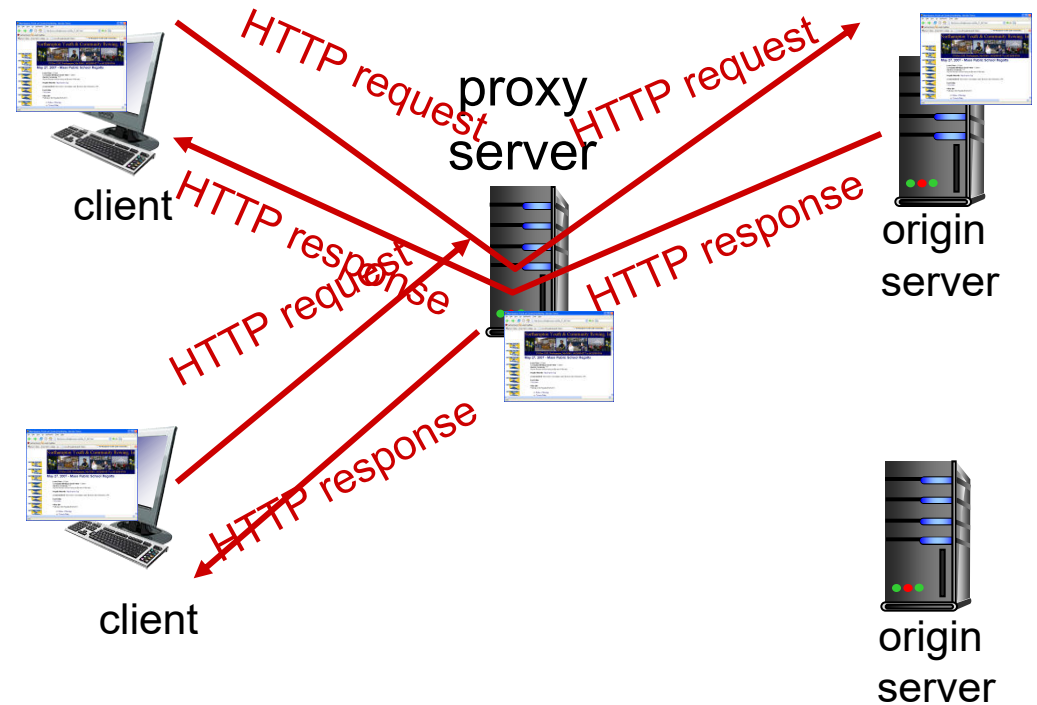
how to keep “state”:

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

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



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
- ❖ Internet dense with caches: enables “poor” content providers to effectively deliver content (so too does P2P file sharing)

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

client



server



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

object
not
modified
before
<date>

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

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

object
modified
after
<date>

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

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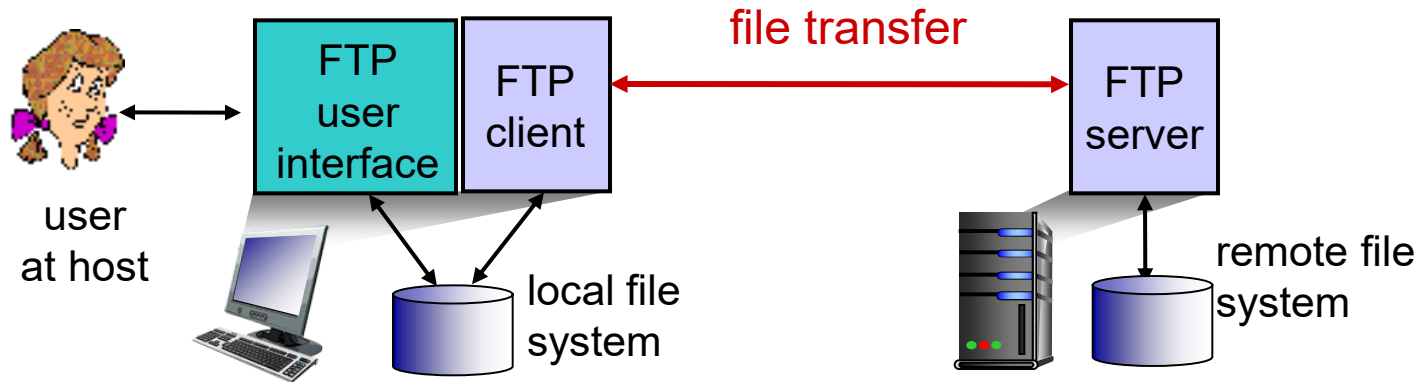
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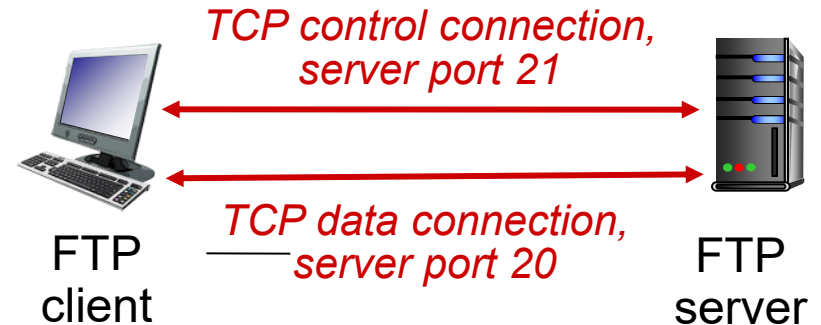
FTP: the file transfer protocol



- ❖ 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 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**

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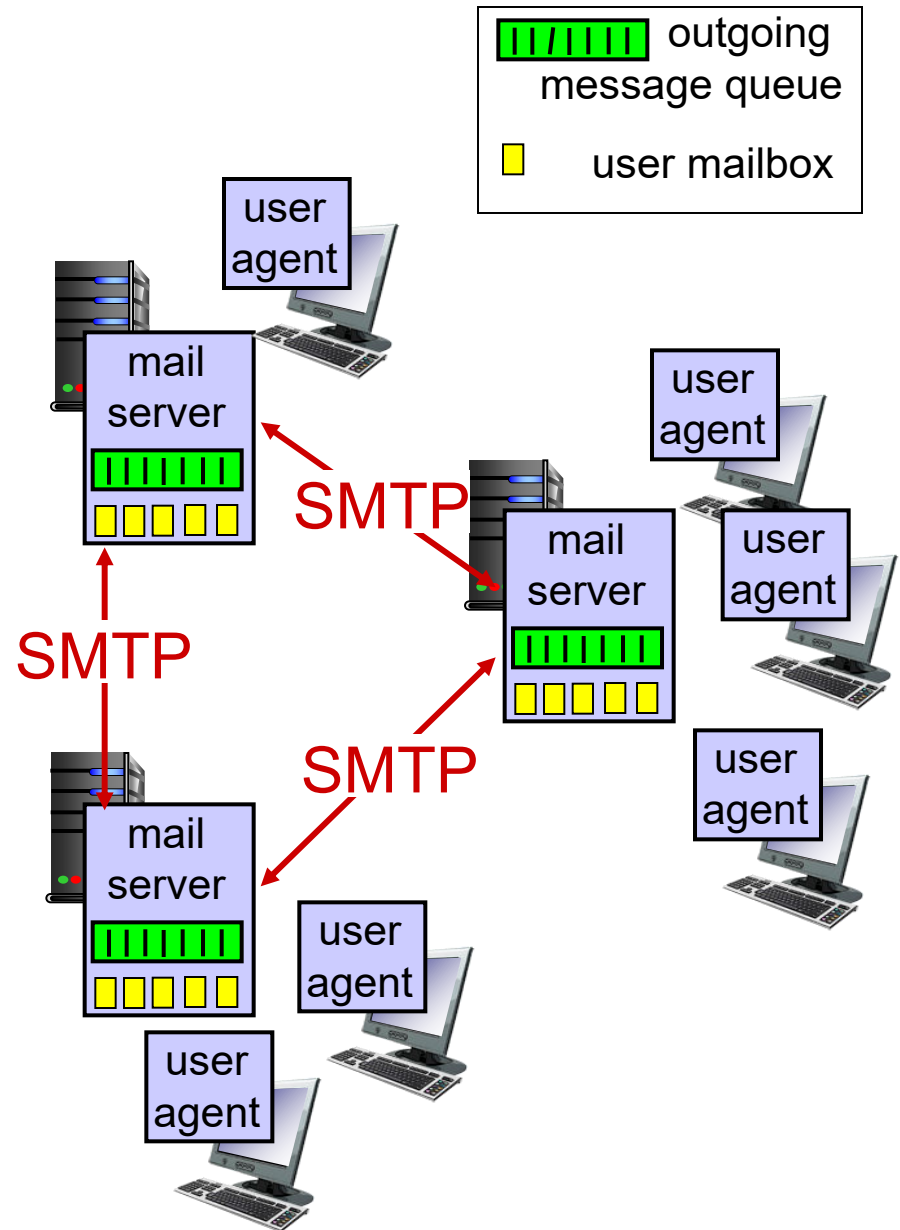
Electronic mail

Three major components:

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

User Agent

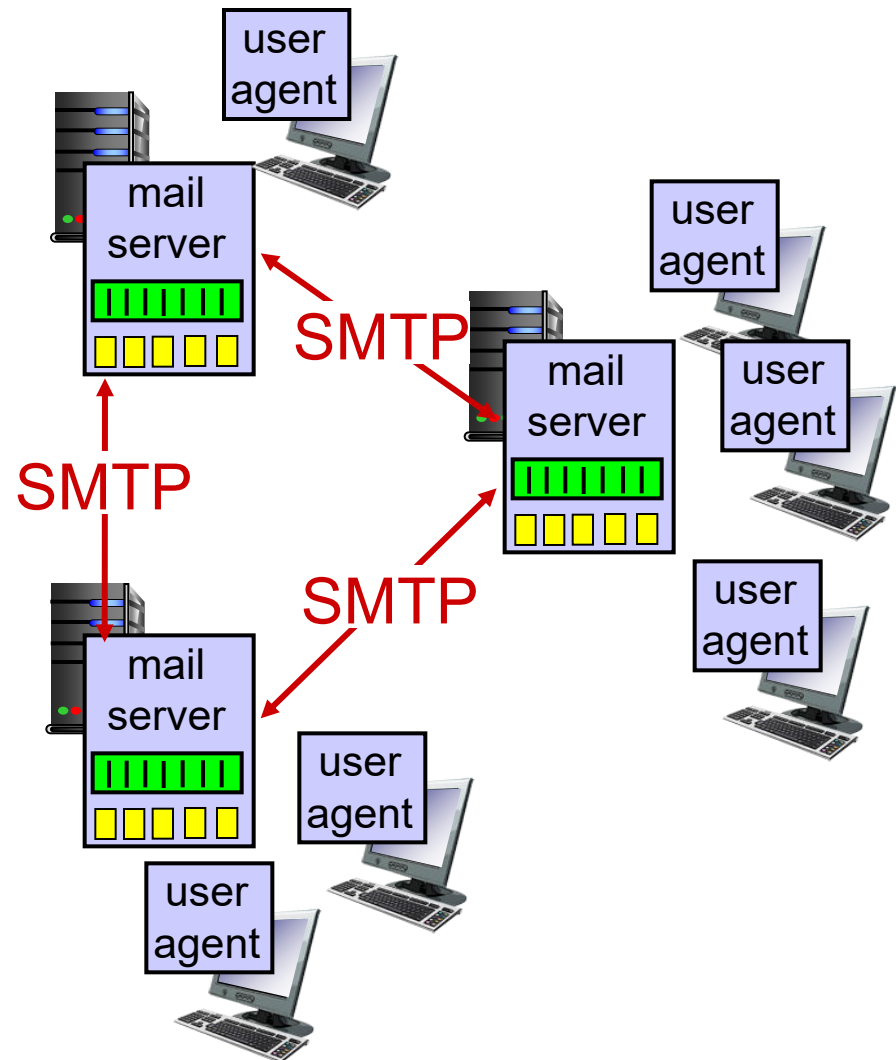
- ❖ a.k.a. “mail reader”
- ❖ composing, editing, reading mail messages
- ❖ e.g., Outlook, Thunderbird, iPhone mail client
- ❖ outgoing, incoming messages stored on server



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

- ❖ 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

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: final words

- ❖ 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 msg
- ❖ SMTP: multiple objects sent in multipart msg

Mail message format

SMTP: protocol for exchanging email msgs

RFC 822: standard for text message format:

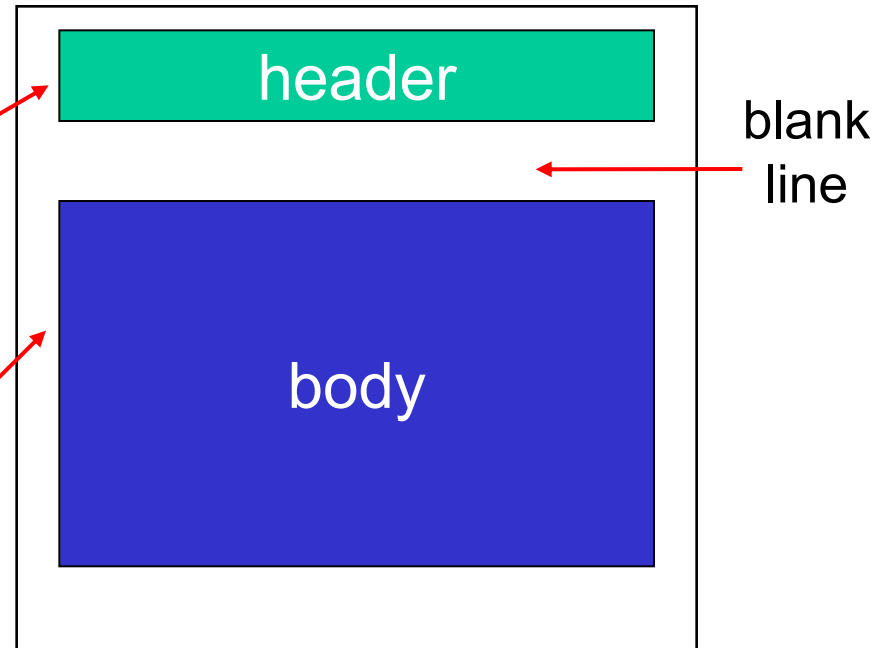
❖ header lines, e.g.,

- To:
- From:
- Subject:

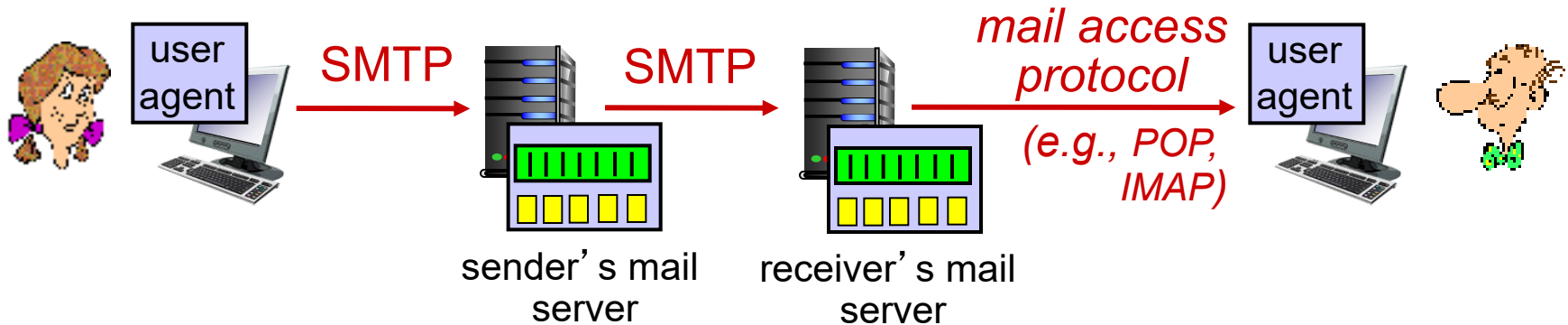
different from SMTP MAIL
FROM, RCPT TO:
commands!

❖ Body: the “message”

- ASCII characters only



Mail access protocols



- ❖ **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

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

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DNS: domain name system

people: many identifiers:

- SSN, name, passport #

Internet hosts, routers:

- IP address (32 bit) - used for addressing datagrams
- “name”, e.g., www.yahoo.com - 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

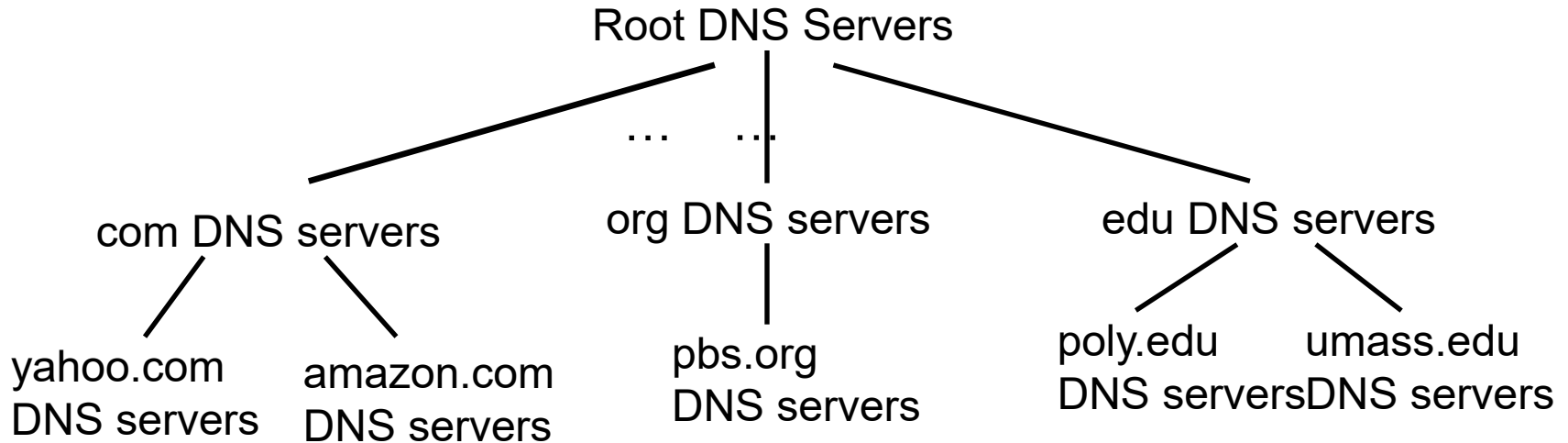
- ❖ hostname to IP address translation
- ❖ host aliasing
 - canonical, alias names
- ❖ mail server aliasing
- ❖ load distribution
 - replicated Web servers: many IP addresses correspond to one name

why not centralize DNS?

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

A: doesn't scale!

DNS: a distributed, hierarchical database

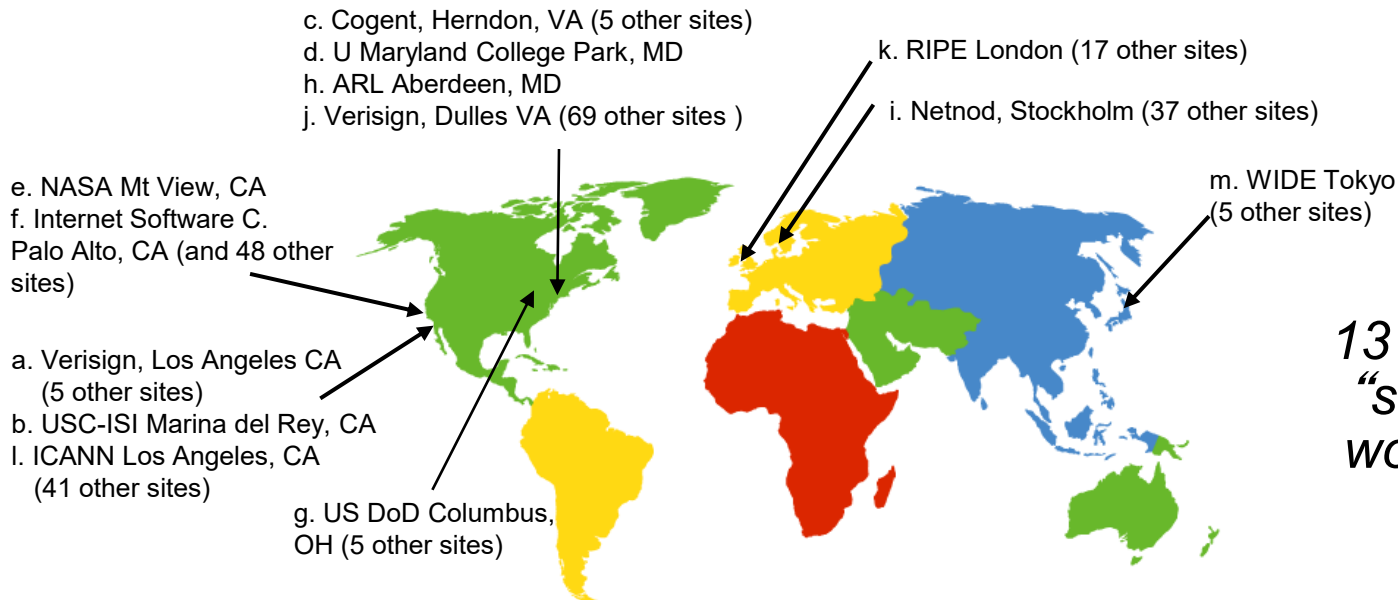


client wants IP for www.amazon.com; 1st approx:

- ❖ 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

- ❖ contacted by local name server that can not resolve name
- ❖ root name server:
 - contacts authoritative name server if name mapping not known
 - gets mapping
 - returns mapping to local name server



*13 root name
“servers”
worldwide*

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.: uk, fr, ca, jp
- Network Solutions maintains servers for .com TLD
- Educause for .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 server

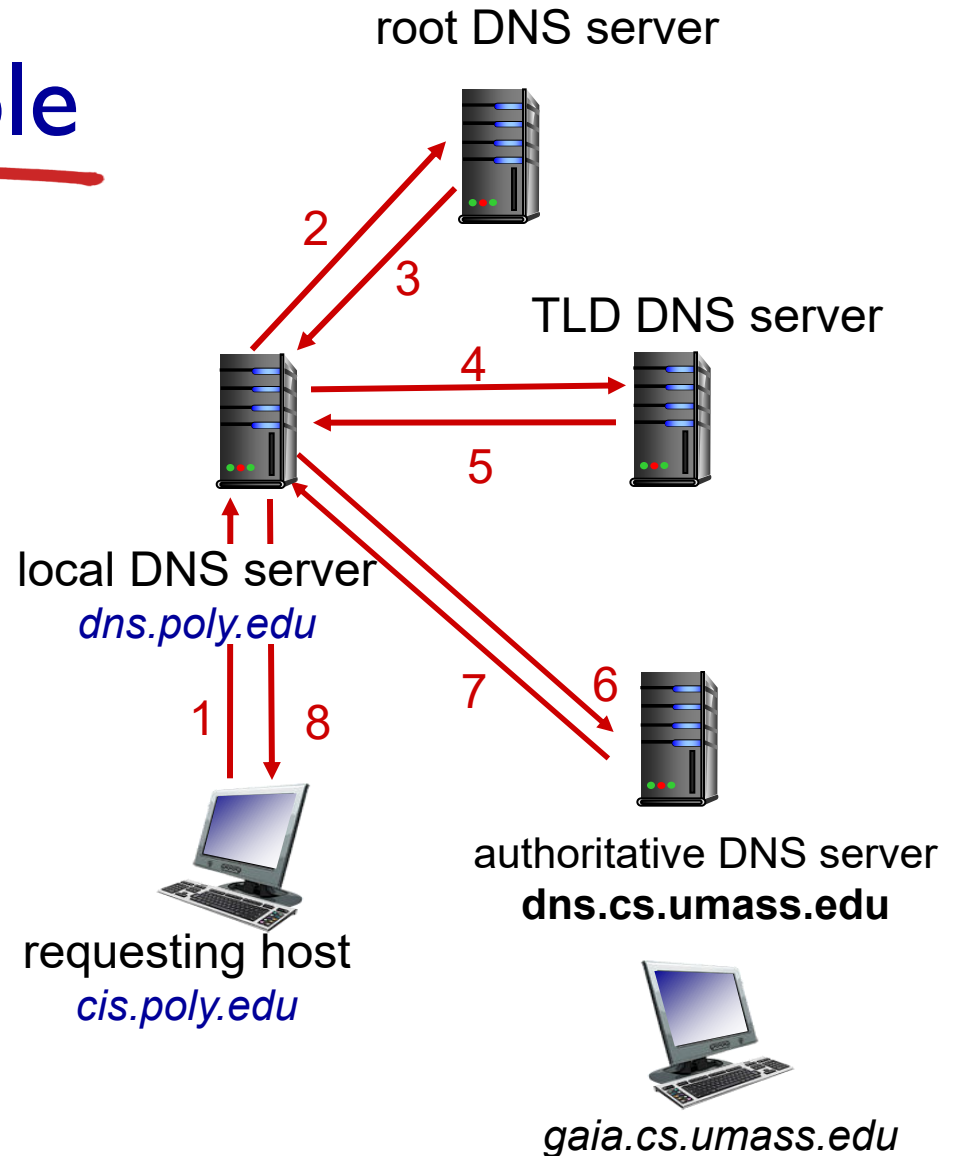
- ❖ does not strictly belong to hierarchy
- ❖ each ISP (residential ISP, company, university) has one
 - also called “default name server”
- ❖ when host makes DNS query, query is sent to its local DNS server
 - has local cache of recent name-to-address translation pairs (but may be out of date!)
 - acts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

DNS name resolution example

- ❖ host at cis.poly.edu wants IP address for gaia.cs.umass.edu

iterated query:

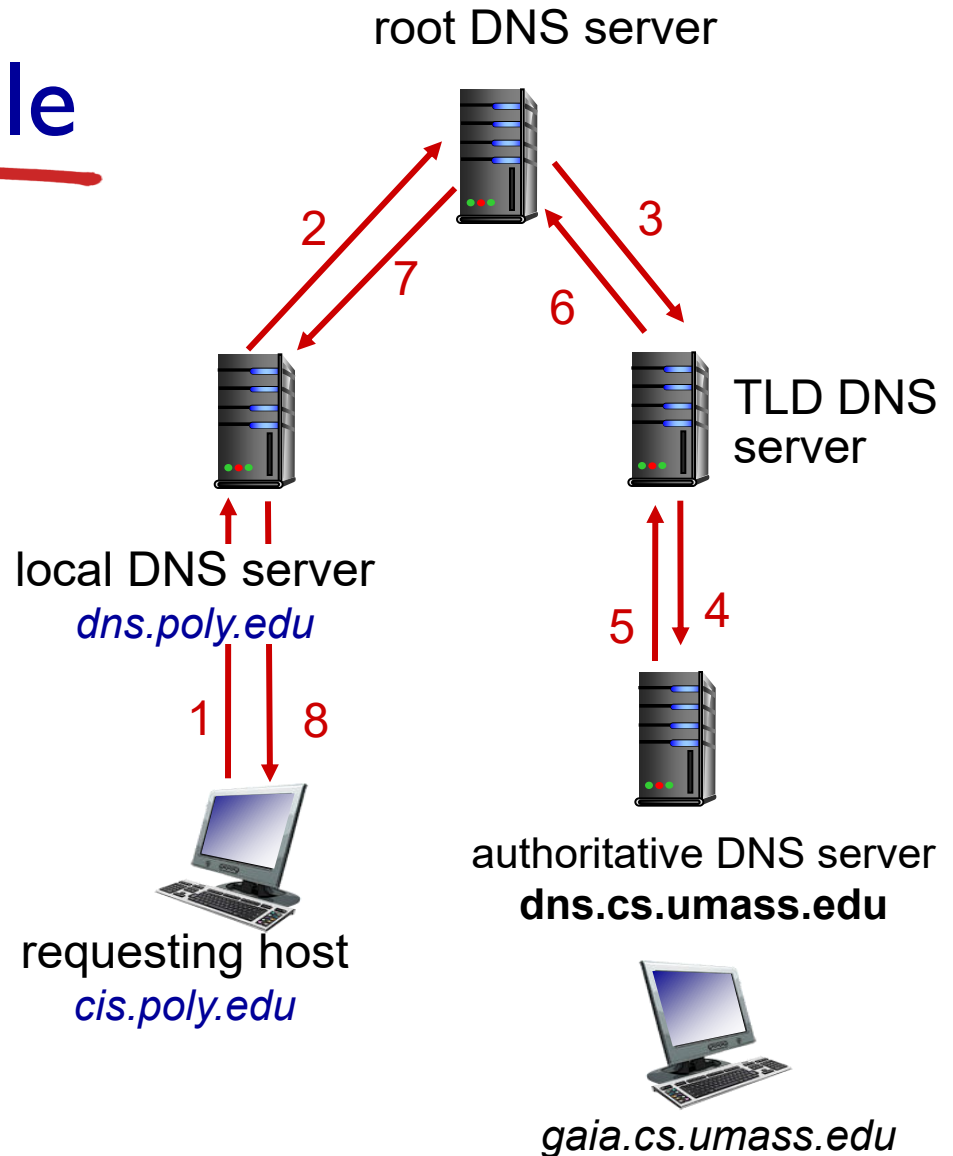
- ❖ contacted server replies with name of server to contact
- ❖ “I don’t know this name, but ask this server”



DNS name resolution example

recursive query:

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



DNS: caching, updating records

- ❖ once (any) name server learns mapping, it *caches* 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 db 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

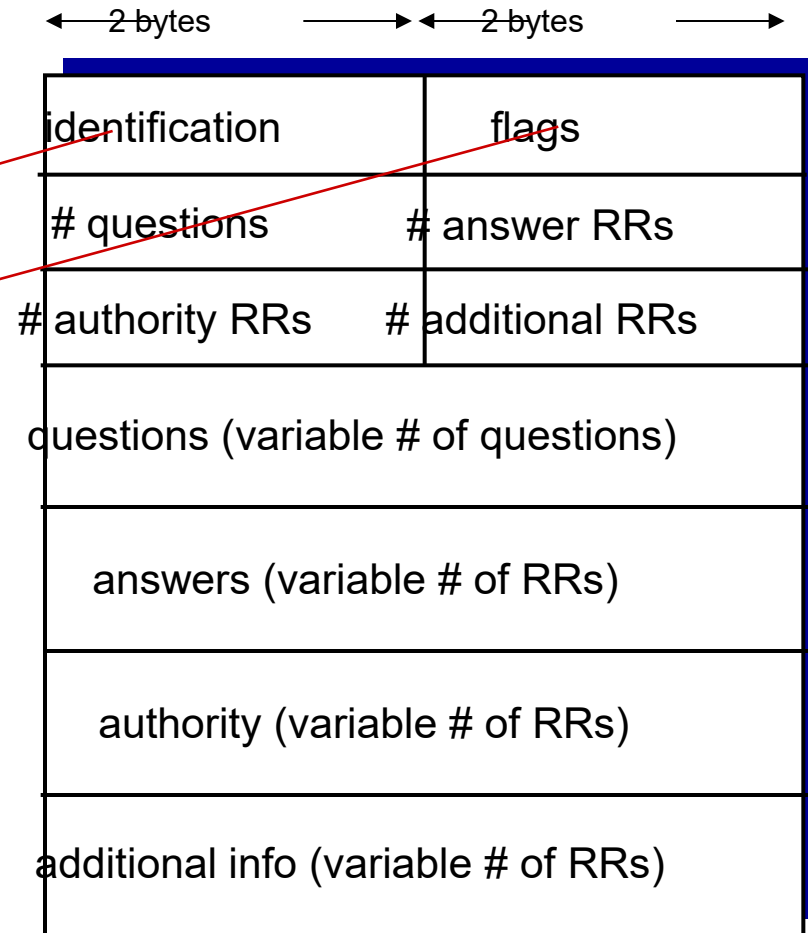
❖ *query* and *reply* messages, both with same *message format*

msg header

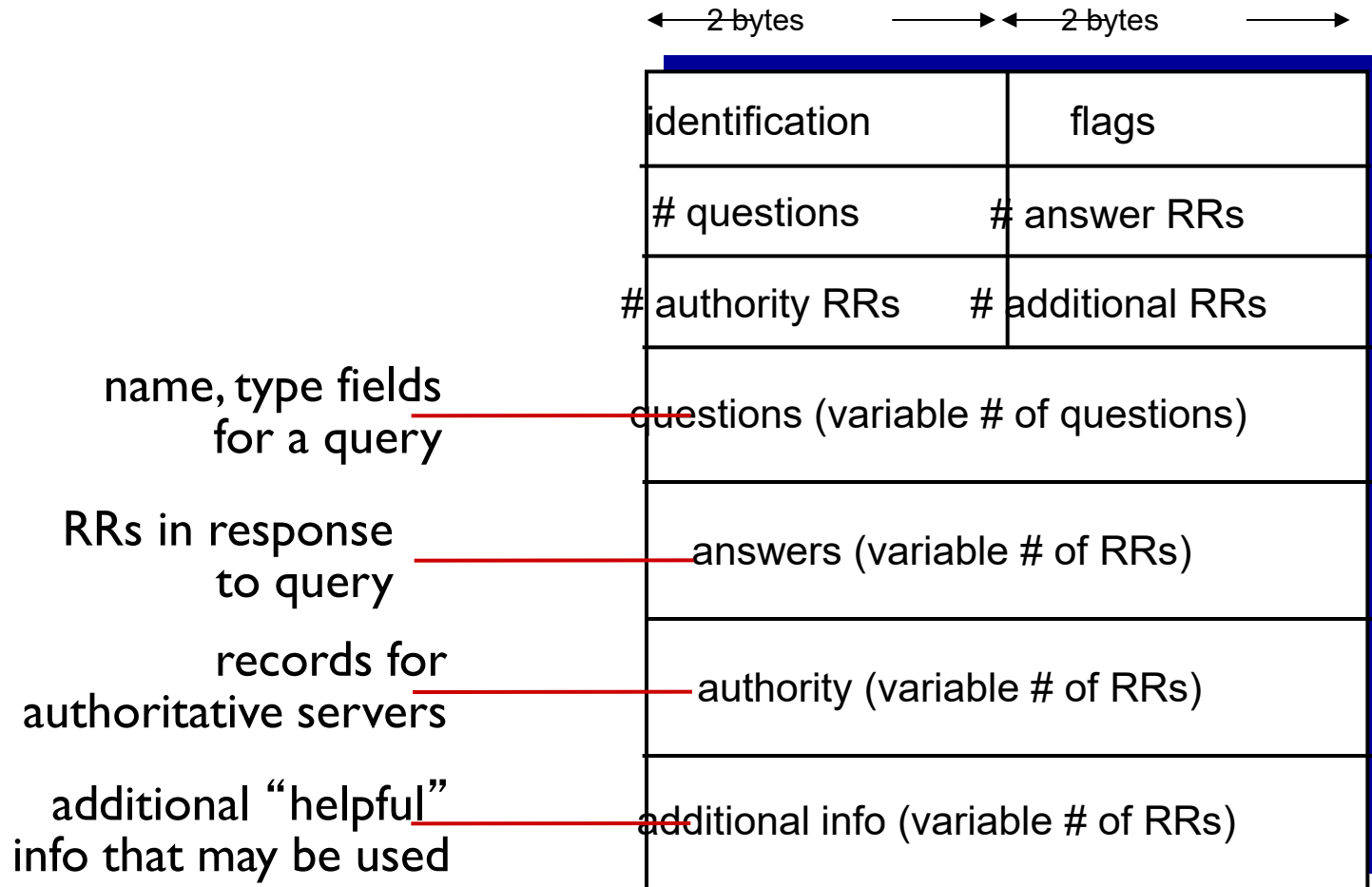
❖ **identification:** 16 bit # for query, reply to query uses same #

❖ **flags:**

- query or reply
- recursion desired
- recursion available
- reply is authoritative



DNS protocol, messages



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 two RRs into .com TLD server:
(networkutopia.com, dns1.networkutopia.com, NS)
(dns1.networkutopia.com, 212.212.212.1, A)

Attacking DNS

DDoS attacks

- ❖ Bombard root servers with traffic
 - Not successful to date
 - Traffic Filtering
 - Local DNS servers cache IPs of TLD servers, allowing root server bypass
- ❖ Bombard TLD servers
 - Potentially more dangerous

Redirect attacks

- ❖ Man-in-middle
 - Intercept queries
- ❖ DNS poisoning
 - Send bogus replies to DNS server, which caches

Exploit DNS for DDoS

- ❖ Send queries with spoofed source address: target IP
- ❖ Requires amplification