Chapter 2
Application Layer

© *The materials in these notes are adapted from Computer Networking: A Top Down Approach,* 6th edition, by Jim Kurose, Keith Ross

Chapter 2: outline

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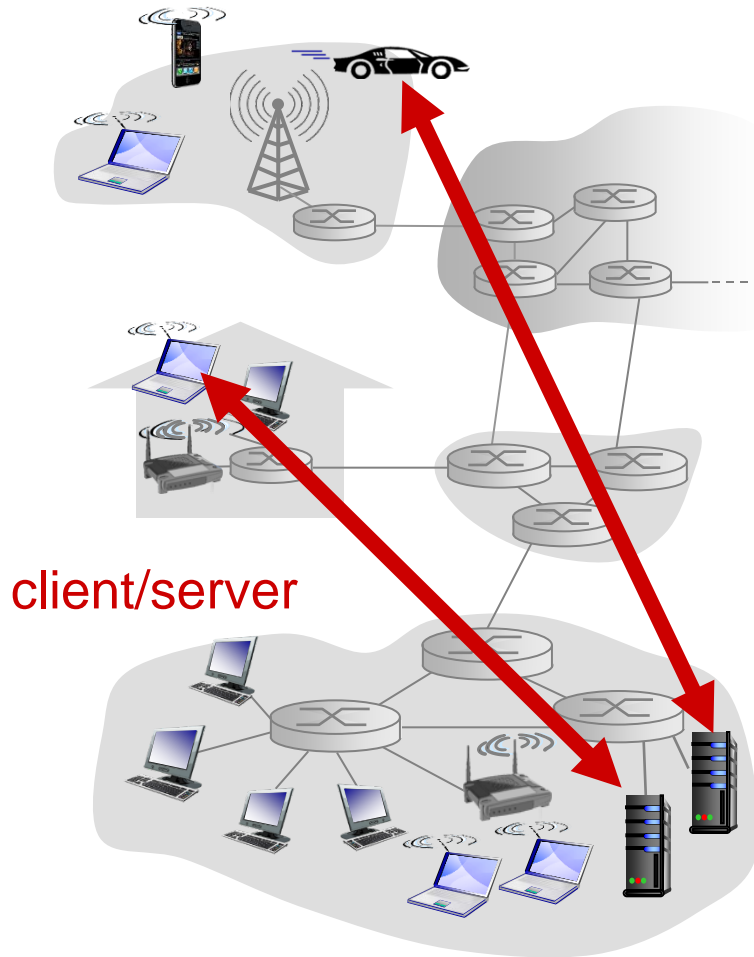- ❖ applications on end systems allows for rapid app development, propagation
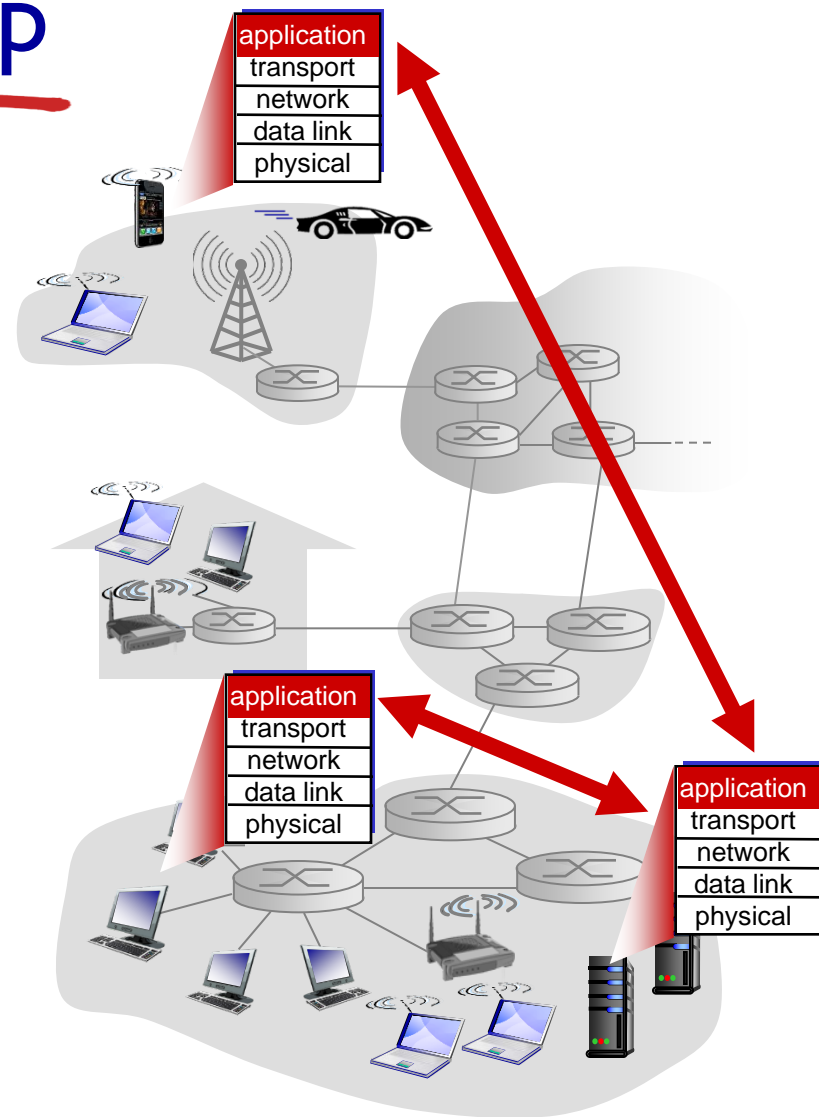
Application architectures

possible structure of applications:

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

Client-server architecture

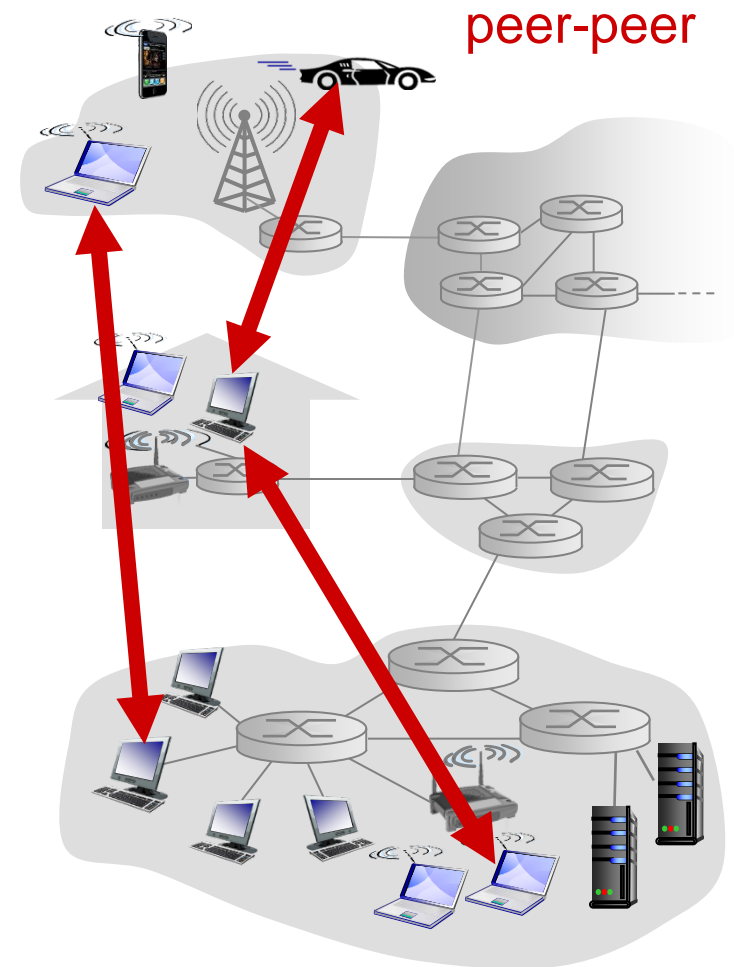

client/server

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

peer-peer

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

❖ 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
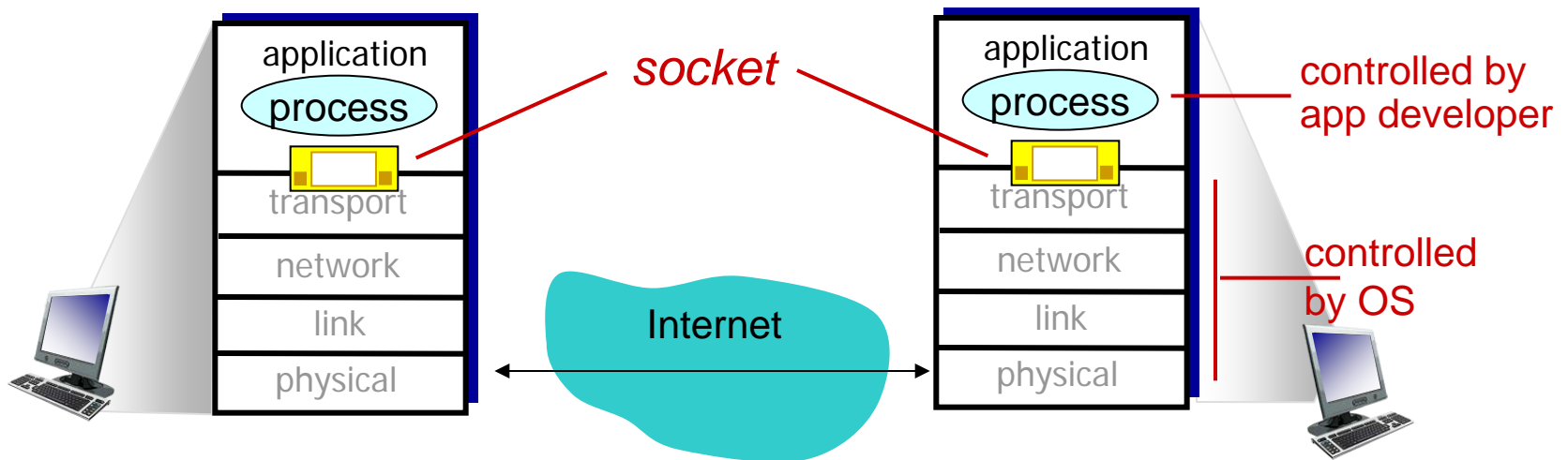
Addressing processes

❖ 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 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

- ❖ 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	yes, few secs
interactive games	loss-tolerant	few kbps up	yes, 100'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 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

Securing TCP

TCP & UDP

❖ no encryption

❖ clear-text passwds sent into socket traverse Internet in clear text

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

❖ clear-text passwds sent into socket traverse Internet encrypted

❖ See Chapter 8

Chapter 2: outline

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

PC running
Firefox browser

HTTP request

HTTP response

server running Apache Web server

HTTP request

HTTP response

iphone running Safari browser
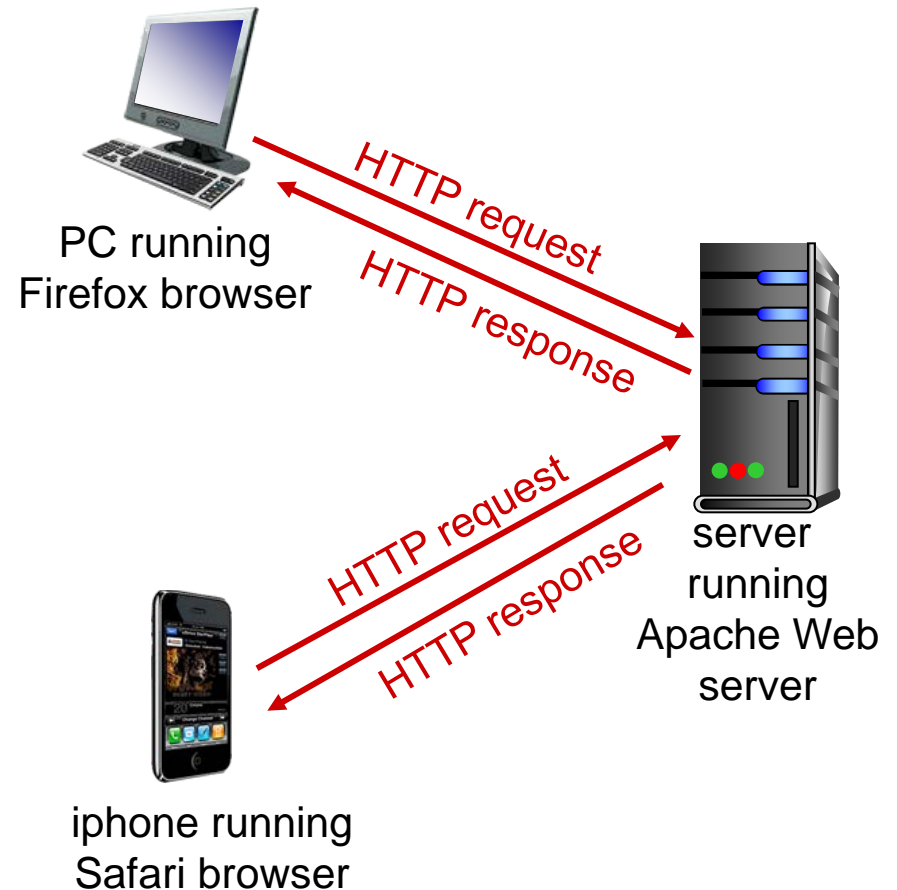
HTTP overview (continued)

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

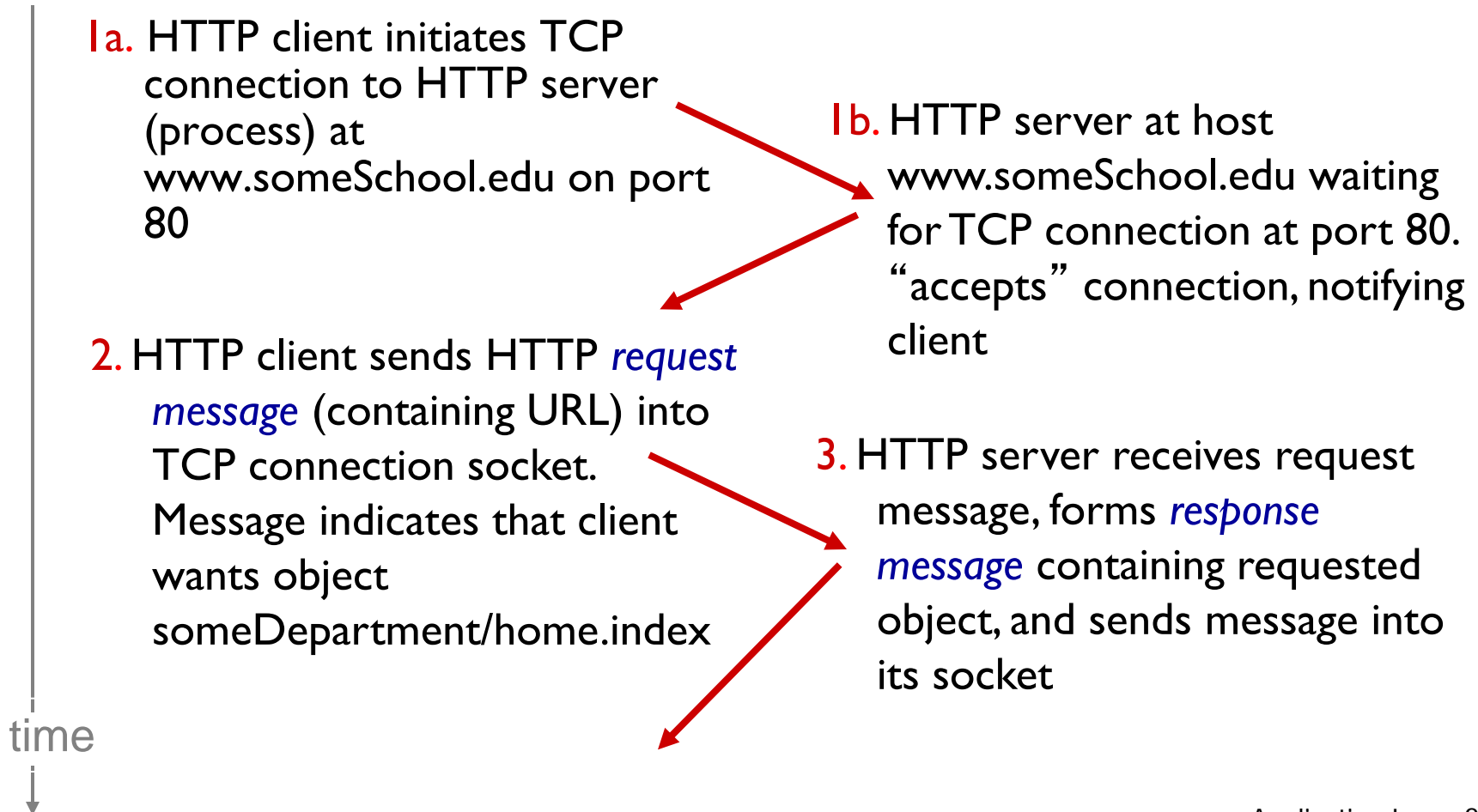❖ downloading multiple objects required multiple connections

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)

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.)

time

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

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

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

initiate TCP connection

RTT

request file

RTT

time to transmit file

file received

time

time
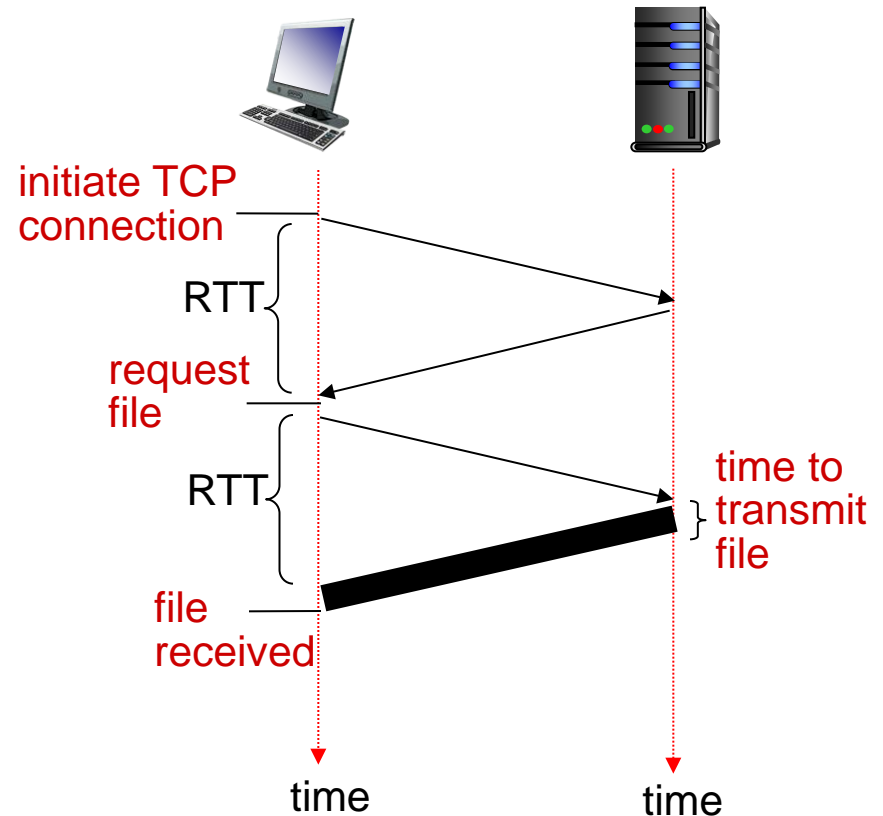
Persistent HTTP

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)

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

method	sp	URL	sp	version	cr	lf	request line

header field name		value	cr	lf	header lines

header field name		value	cr	lf

cr	lf
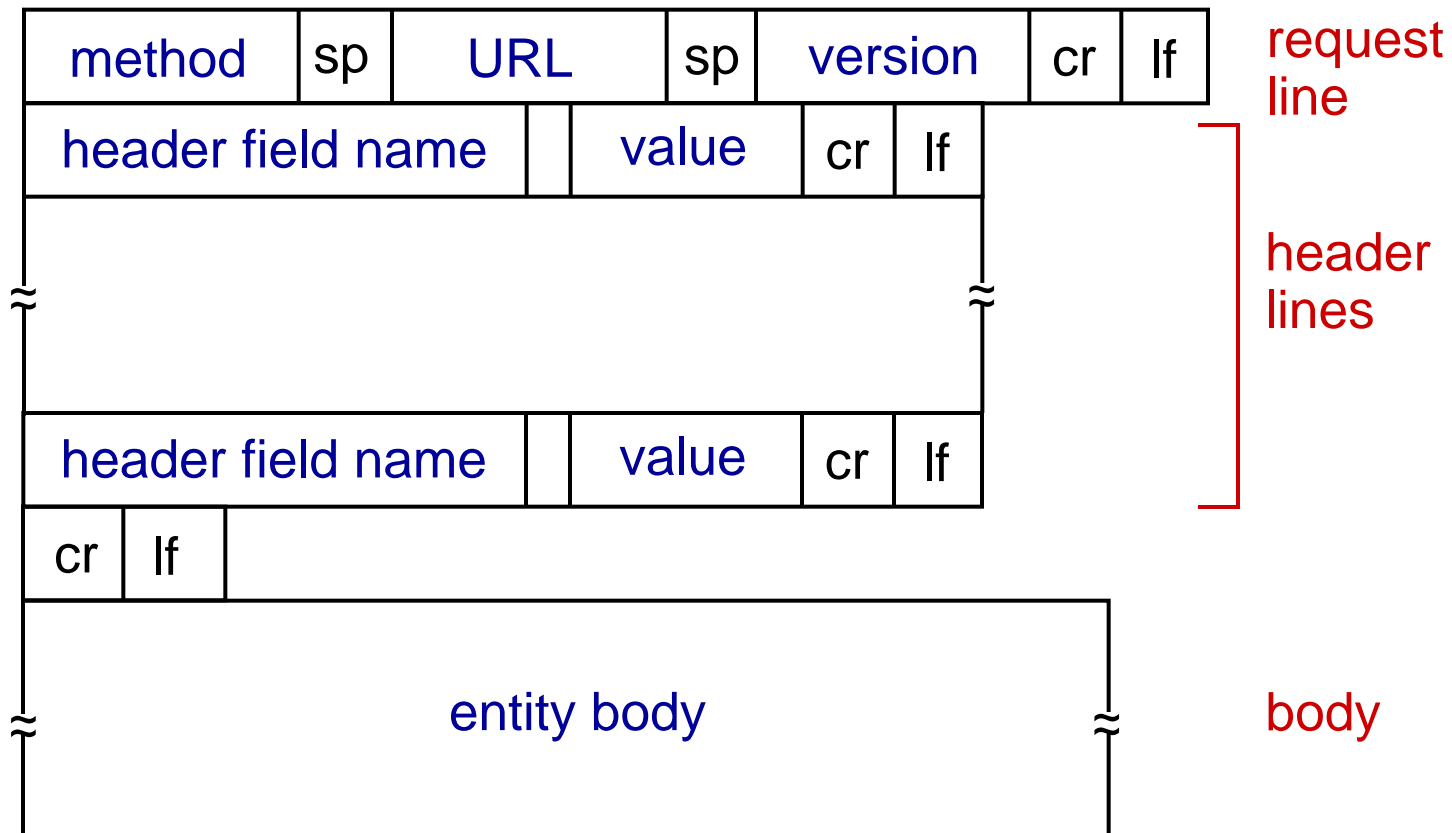
entity body	body

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)

```
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 ...
```

header
lines

data, e.g.,
requested
HTML file

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

Trying out HTTP (client side) for yourself

1. Telnet to your favorite Web server:

telnet H   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!

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

User-server state: cookies
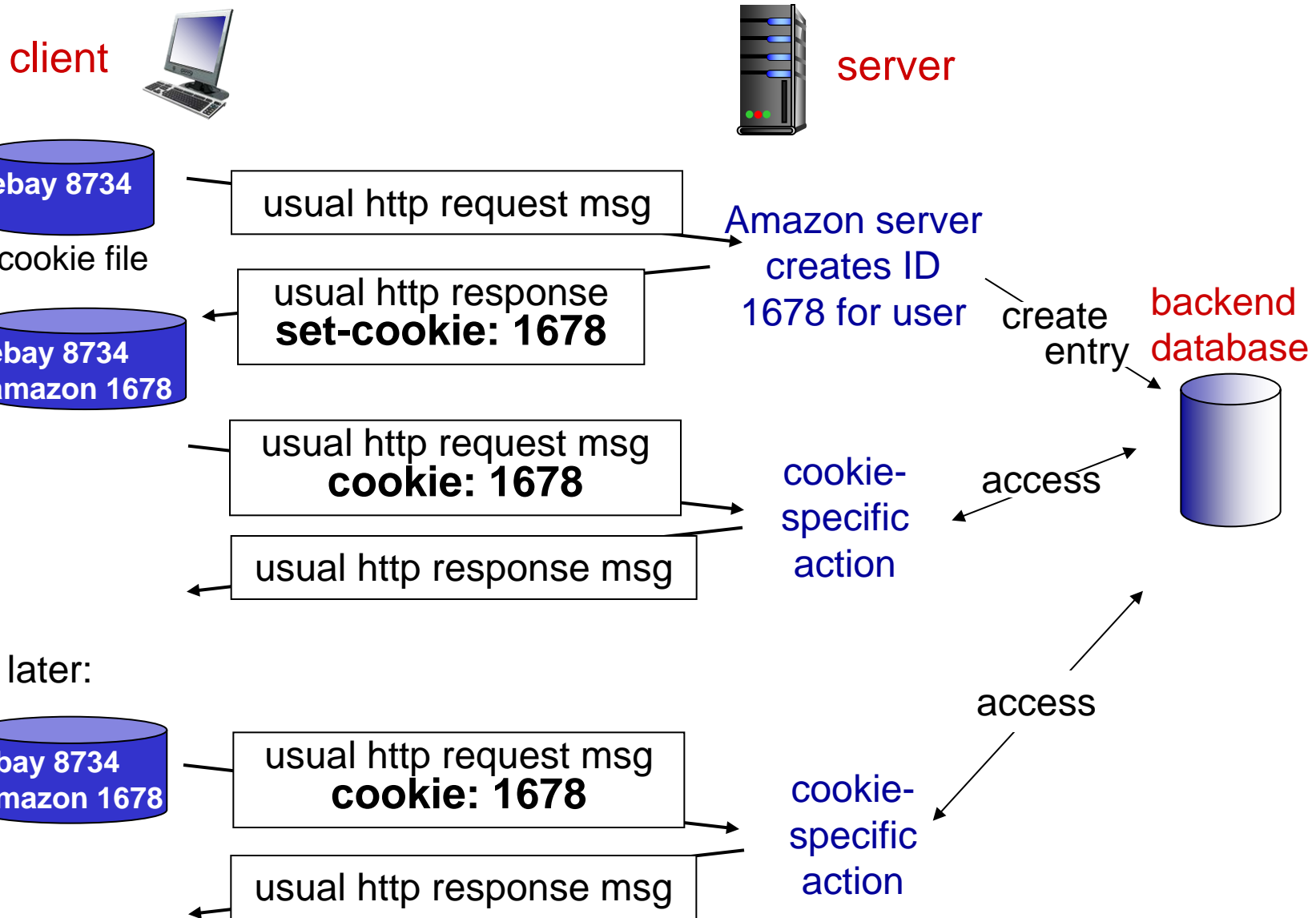
many Web sites use cookies

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

ebay 8734

cookie file

usual http request msg

Amazon server creates ID 1678 for user

create entry

backend database

usual http response
set-cookie: 1678

ebay 8734
amazon 1678

usual http request msg
cookie: 1678

cookie-specific action

access

usual http response msg

one week later:

ebay 8734
amazon 1678

usual http request msg
cookie: 1678

usual http response msg

cookie-specific action

access

Cookies (continued)

what cookies can be used for:

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

cookies and privacy:

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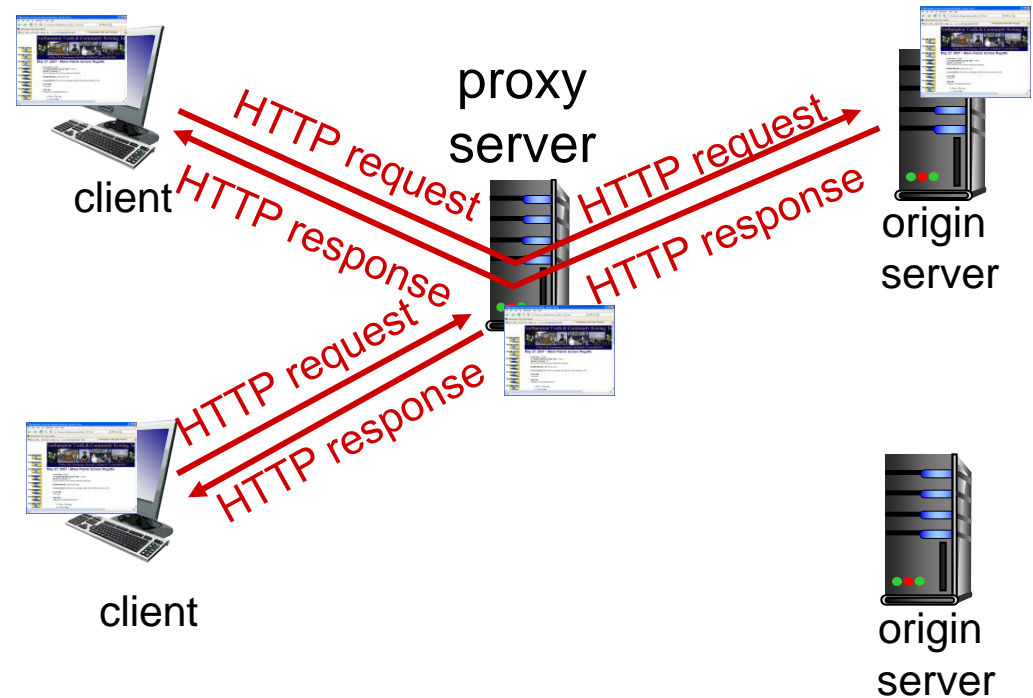- ❖ you may supply name and e-mail to sites

how to keep "state":

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

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

proxy server

client

HTTP request

HTTP response

HTTP request

HTTP response

HTTP request

HTTP response

origin server

client

origin server

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)
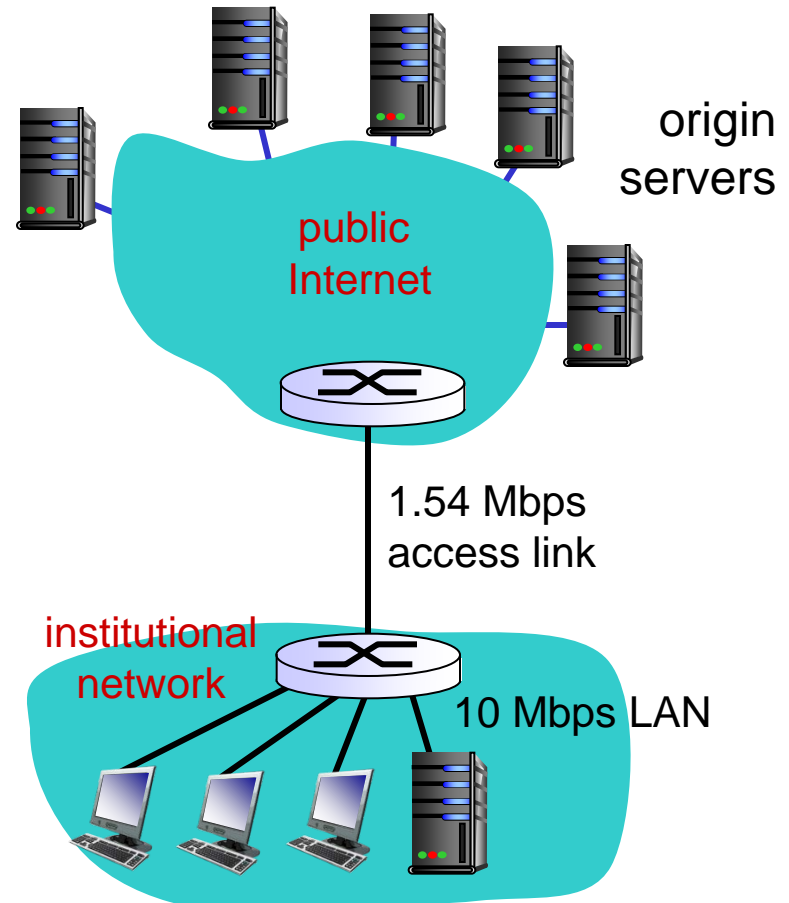
Caching example:

assumptions:

* avg object size: 100K bits
* avg request rate from browsers to origin servers:15/sec
* avg data rate to browsers: 1.50 Mbps
* RTT from institutional router to any origin server: 2 sec
* access link rate: 1.54 Mbps

consequences:

* LAN utilization: 15%   *problem!*
* access link utilization = 99%
* total delay = Internet delay + access delay + LAN delay

  = 2 sec + minutes + usecs

origin servers

public Internet

1.54 Mbps access link

institutional network
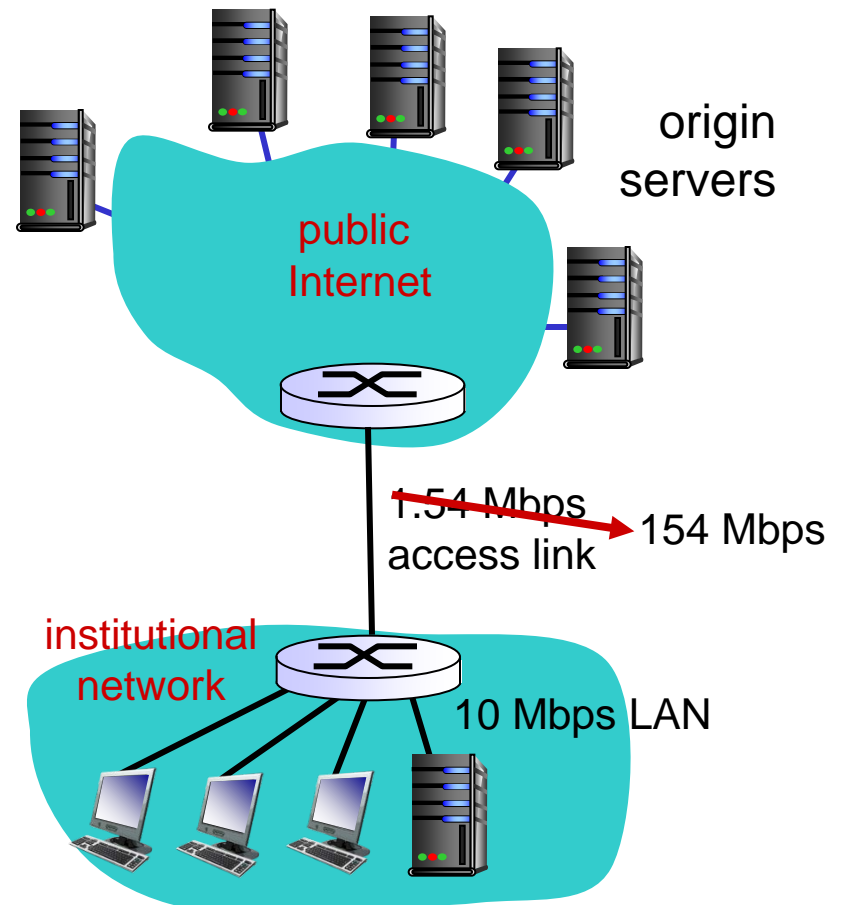
10 Mbps LAN

Caching example: fatter access link

assumptions:

❖ avg object size: 100K bits

❖ avg request rate from browsers to origin servers: 15/sec

❖ avg data rate to browsers: 1.50 Mbps

❖ RTT from institutional router to any origin server: 2 sec

❖ access link rate: 1.54 Mbps → 154 Mbps

consequences:

❖ LAN utilization: 15%

❖ access link utilization = 99% → 0.99%

❖ total delay = Internet delay + access delay + LAN delay

= 2 sec + minutes + usecs → msecs

origin servers

public Internet

1.54 Mbps → 154 Mbps access link

institutional network

10 Mbps LAN

Cost: increased access link speed (not cheap!)
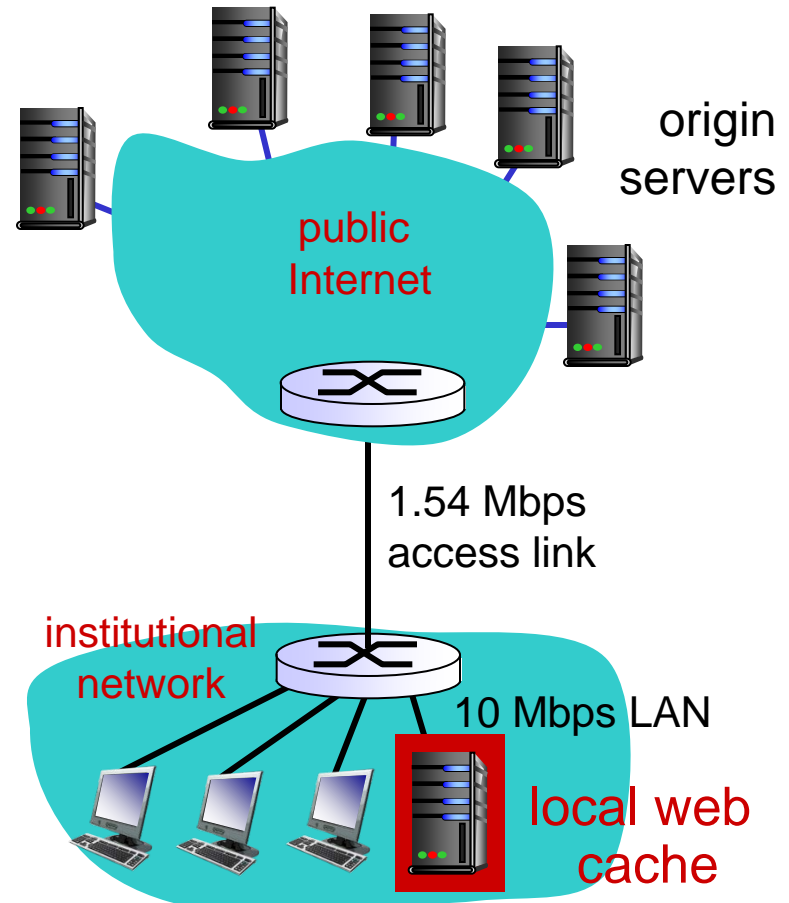
Caching example: install local cache

assumptions:

- avg object size: 100K bits
- avg request rate from browsers to origin servers:15/sec
- avg data rate to browsers: 1.50 Mbps
- RTT from institutional router to any origin server: 2 sec
- access link rate: 1.54 Mbps

consequences:

- LAN utilization: 15%
- access link utilization = ?
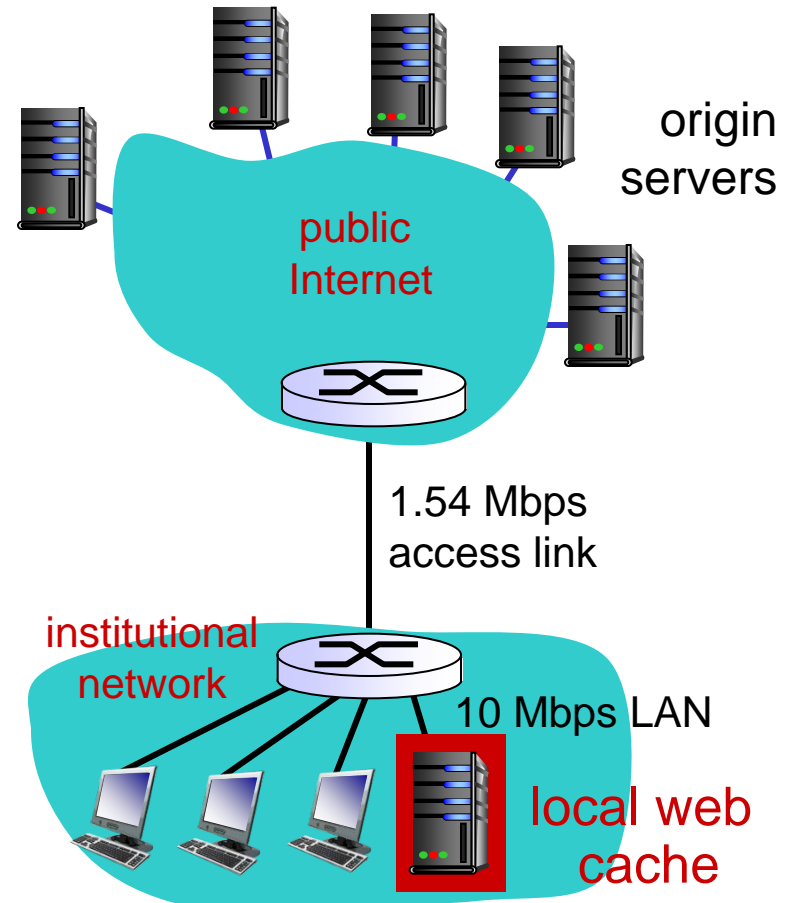- total delay = ?

How to compute link utilization, delay?

Cost: web cache (cheap!)

origin servers

public Internet

1.54 Mbps access link

institutional network

10 Mbps LAN

local web cache

Caching example: install local cache

Calculating access link utilization, delay with cache:

❖ suppose cache hit rate is 0.4
  ▪ 40% requests satisfied at cache, 60% requests satisfied at origin

❖ access link utilization:
  ▪ 60% of requests use access link

❖ data rate to browsers over access link = 0.6*1.50 Mbps = .9 Mbps
  ▪ utilization = 0.9/1.54 = .58

❖ total delay
  ▪ = 0.6 * (delay from origin servers) +0.4 * (delay when satisfied at cache)
  ▪ = 0.6 (2.01) + 0.4 (0.01)
  ▪ = ~ 1.2 secs
  ▪ less than with 1.54 Mbps link (and cheaper too!)

origin servers

public Internet

1.54 Mbps access link

institutional network

10 Mbps LAN

local web cache

Conditional GET

client   server

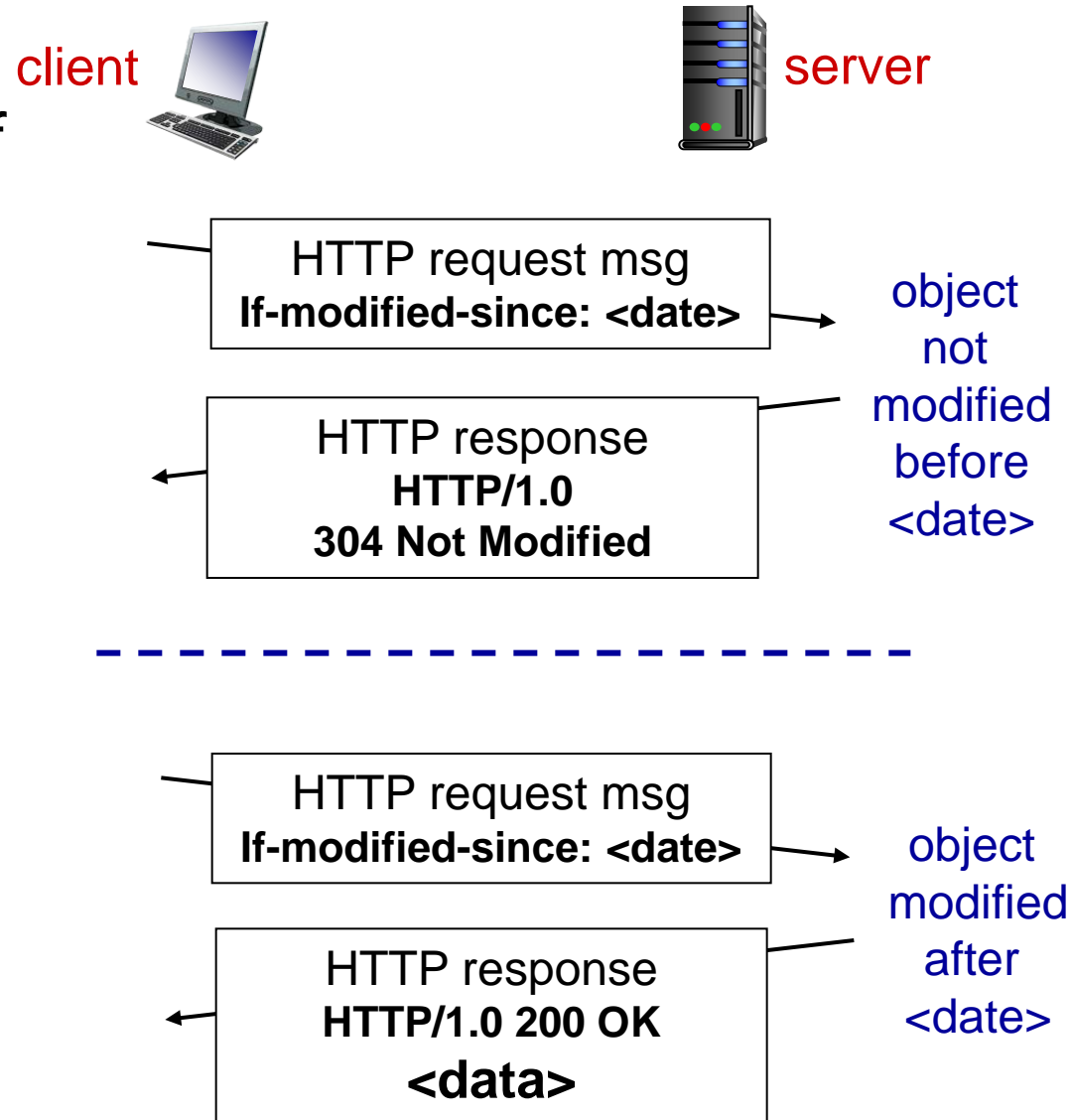❖ *Goal:* don't send object if cache has up-to-date cached version
- no object transmission delay
- lower link utilization

❖ *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 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>**

Chapter 2: outline

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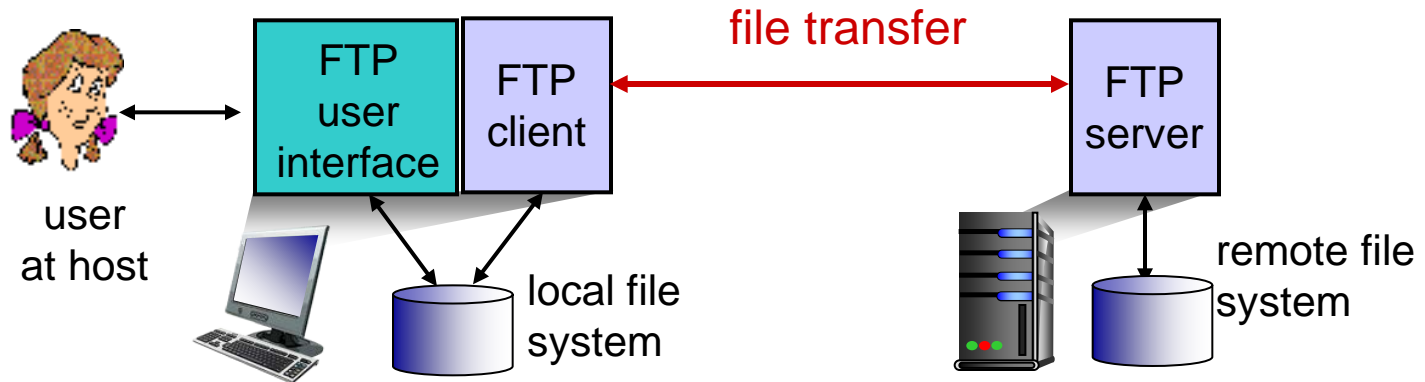
- ❖ transfer file to/from remote host
- ❖ client/server model
  - ■ *client:* side that initiates transfer (either to/from remote)
  - ■ *server:* remote host
- ❖ ftp: RFC 959
- ❖ ftp server: port 21

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

TCP control connection, server port 21

TCP data connection, server port 20

FTP client
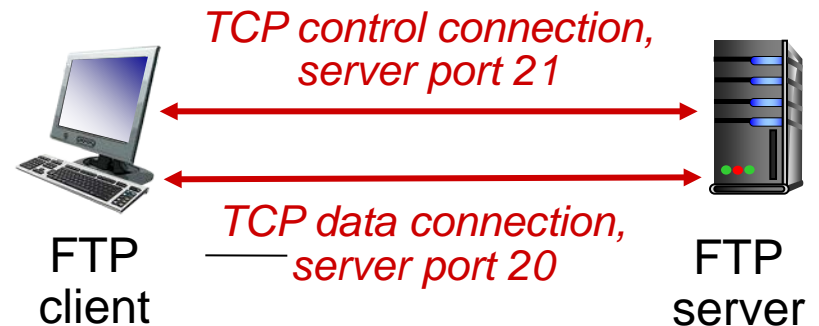
FTP server

- ❖ 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`
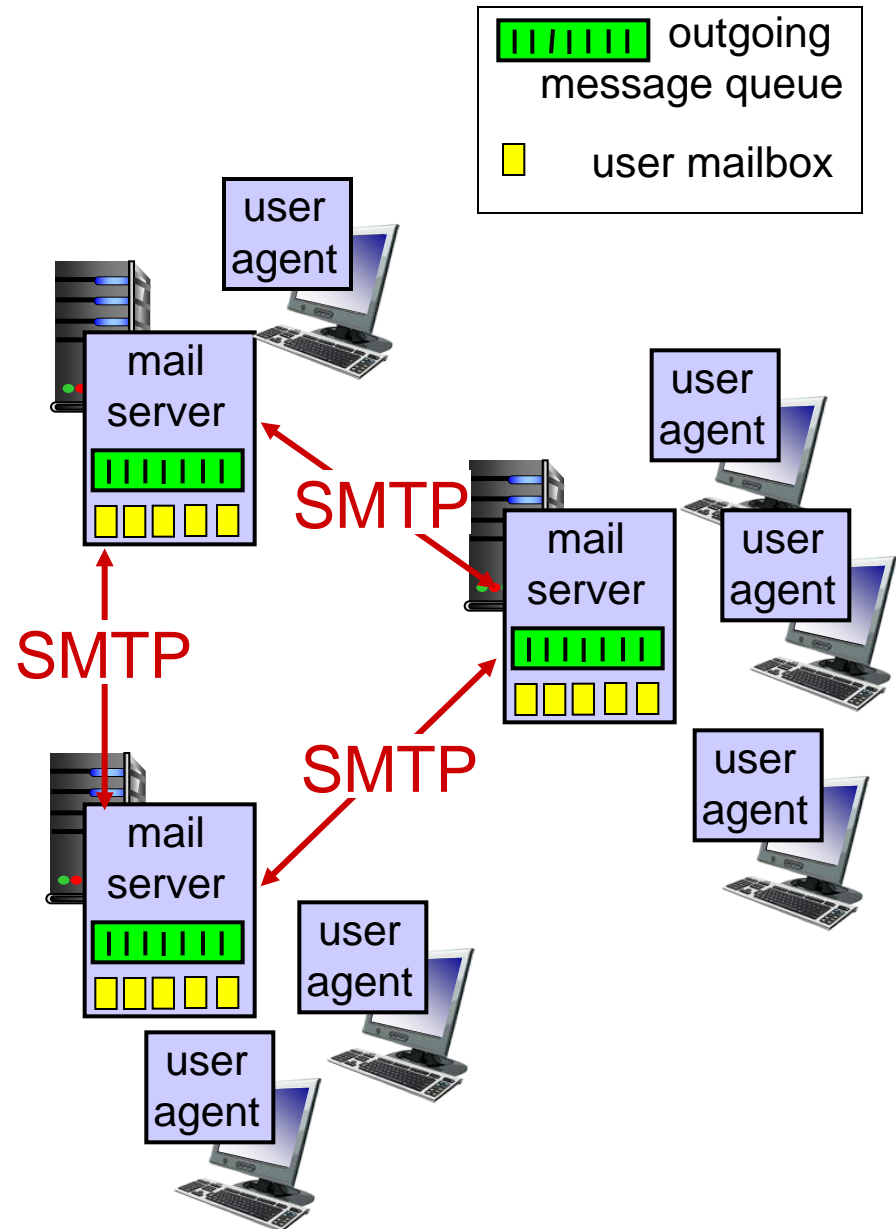- ❖ `452 Error writing file`

Chapter 2: outline

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

outgoing message queue

user mailbox

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
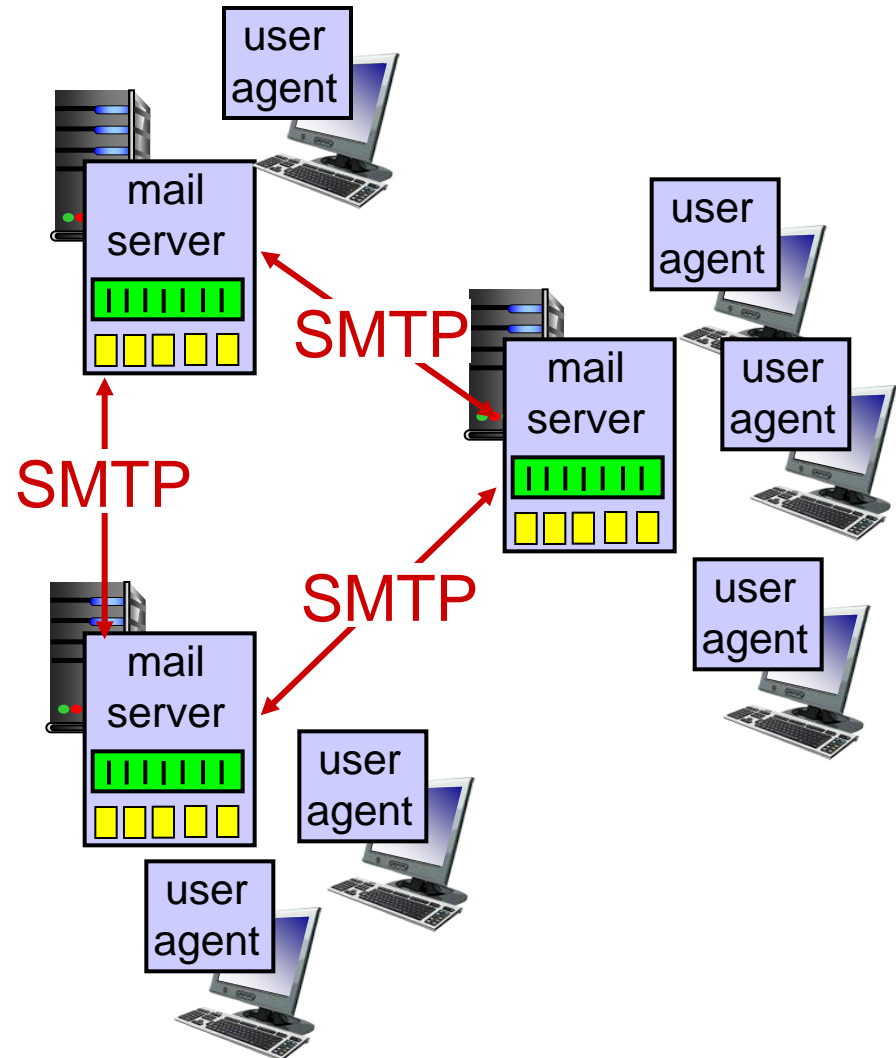
Electronic Mail: SMTP [RFC 2821]

- ❖ 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, 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

Alice's mail server

Bob's mail server
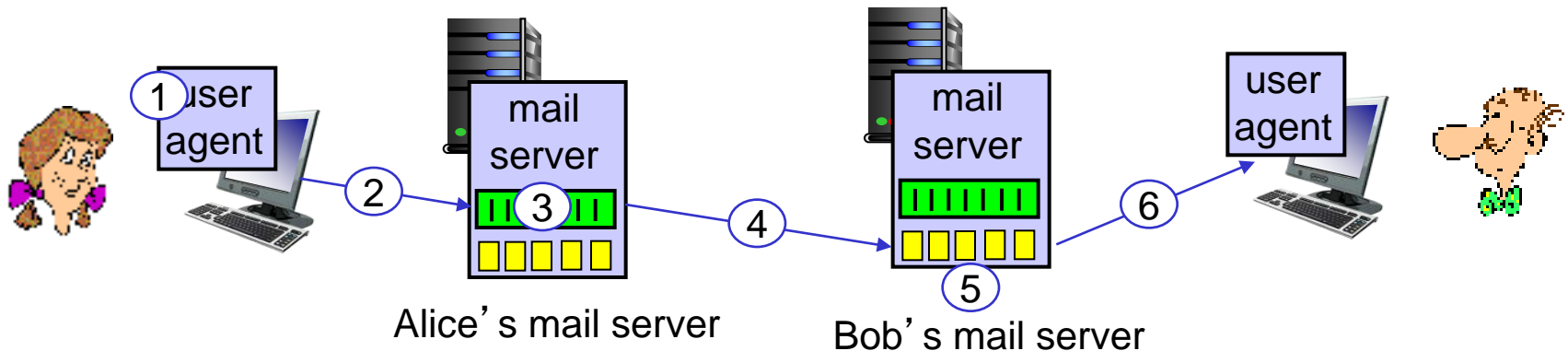
Sample SMTP interaction

```
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 email client (reader)

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

header

body

blank line

Mail access protocols

sender's mail server   receiver's mail server
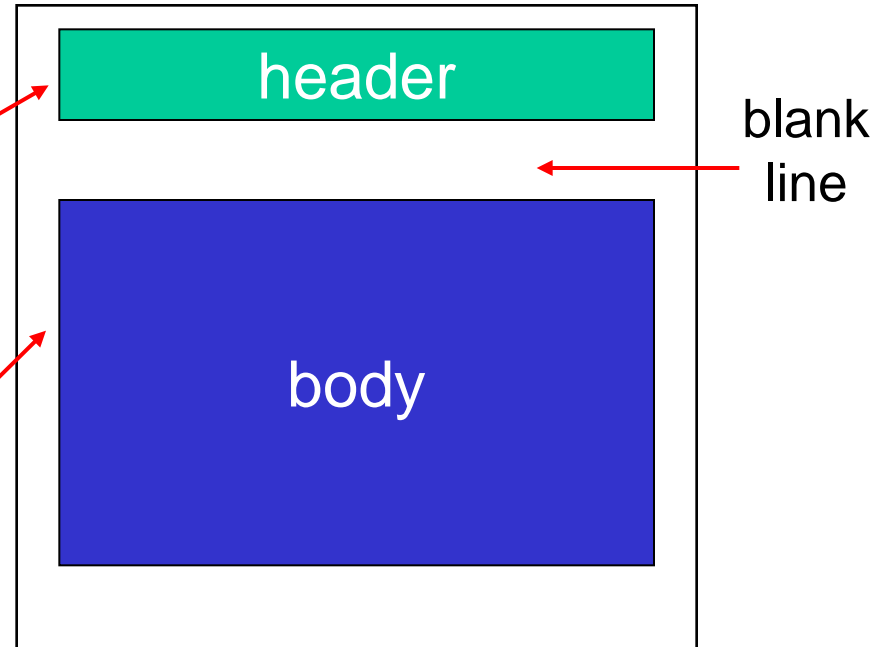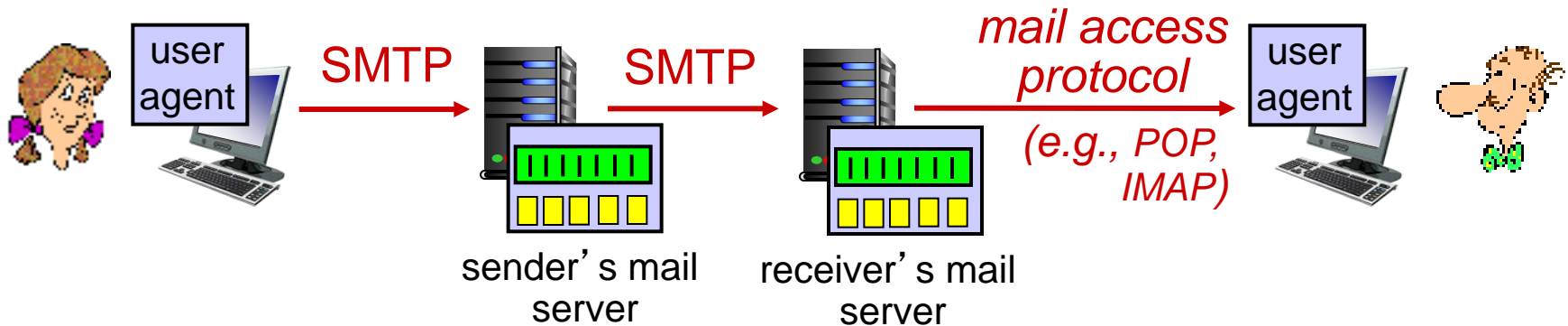
- ❖ **SMTP:** delivery/storage to receiver's server
- ❖ mail access protocol: retrieval from server
    - **POP:** Post Office Protocol [RFC 1939]: authorization, download
    - **IMAP:** Internet Mail Access Protocol [RFC 1730]: more features, including manipulation of stored msgs on server
    - **HTTP:** 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

Chapter 2: outline

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

Root DNS Servers

… | …

com DNS servers

org DNS servers

edu DNS servers

yahoo.com
DNS servers

amazon.com
DNS servers

pbs.org
DNS servers

poly.edu
DNS servers

umass.edu
DNS servers
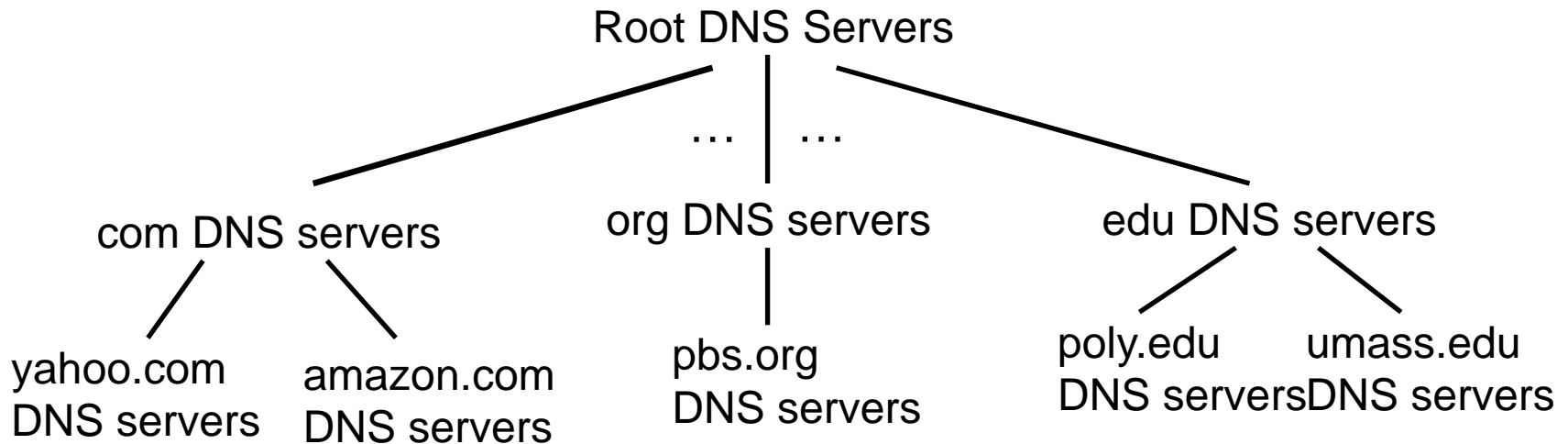
client wants IP for www.amazon.com; 1st approx:

❖ 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

c. Cogent, Herndon, VA (5 other sites)
d. U Maryland College Park, MD
h. ARL Aberdeen, MD
j. Verisign, Dulles VA (69 other sites)

k. RIPE London (17 other sites)

i. Netnod, Stockholm (37 other sites)

e. NASA Mt View, CA
f. Internet Software C.
Palo Alto, CA (and 48 other
sites)

m. WIDE Tokyo
(5 other sites)

a. Verisign, Los Angeles CA
   (5 other sites)
b. USC-ISI Marina del Rey, CA
l. ICANN Los Angeles, CA
   (41 other sites)

g. US DoD Columbus,
OH (5 other sites)

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"

root DNS server

2
3

TLD DNS server

4
5

local DNS server
dns.poly.edu

1   8

7   6

requesting host
cis.poly.edu

authoritative DNS server
dns.cs.umass.edu

gaia.cs.umass.edu
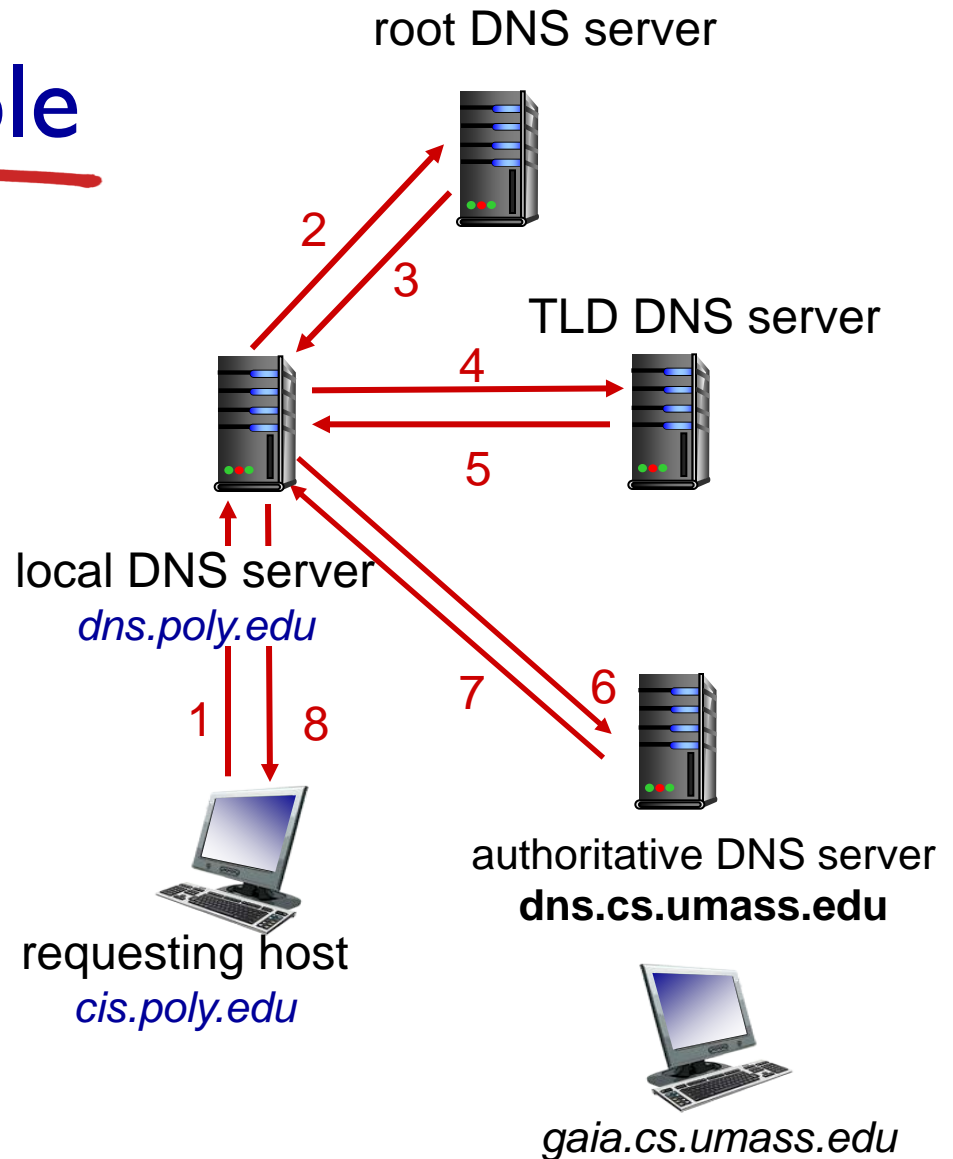
DNS name resolution example

recursive query:

❖ puts burden of name resolution on contacted name server

❖ heavy load at upper levels of hierarchy?

root DNS server

2

7

3

6

local DNS server
dns.poly.edu

TLD DNS server

5

4

1

8

authoritative DNS server
dns.cs.umass.edu

requesting host
cis.poly.edu

gaia.cs.umass.edu
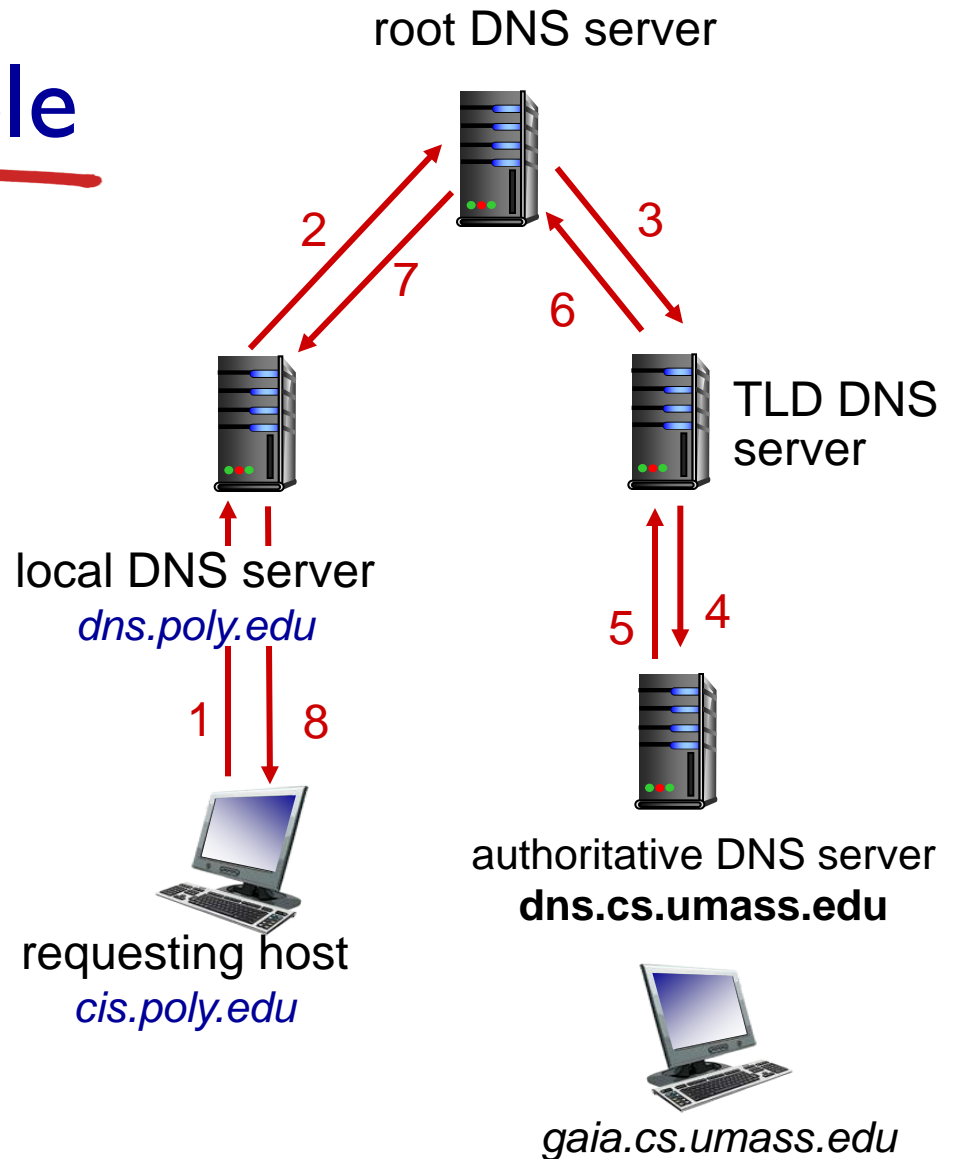
DNS: caching, updating records

❖ 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

2 bytes ———————→ 2 bytes ———————→

identification	flags
# questions	# answer RRs
# authority RRs	# additional RRs
questions (variable # of questions)	
answers (variable # of RRs)	
authority (variable # of RRs)	
additional info (variable # of RRs)	

DNS protocol, messages

← 2 bytes →	← 2 bytes →
identification	flags
# questions	# answer RRs
# authority RRs	# additional RRs
questions (variable # of questions)	
answers (variable # of RRs)	
authority (variable # of RRs)	
additional info (variable # of RRs)	

name, type fields for a query — questions (variable # of questions)

RRs in response to query — answers (variable # of RRs)

records for authoritative servers — authority (variable # of RRs)

additional "helpful" info that may be used — additional info (variable # of RRs)

```
$ dig redhat.com

; <<>> DiG 9.7.3-RedHat-9.7.3-2.e16 <<>> redhat.com
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 62863
;; flags: qr rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 4, ADDITIONAL: 3

;; QUESTION SECTION:
;redhat.com.                     IN      A

;; ANSWER SECTION:
redhat.com.             37      IN      A       209.132.183.81

;; AUTHORITY SECTION:
redhat.com.             73      IN      NS      ns4.redhat.com.
redhat.com.             73      IN      NS      ns3.redhat.com.
redhat.com.             73      IN      NS      ns2.redhat.com.
redhat.com.             73      IN      NS      ns1.redhat.com.

;; ADDITIONAL SECTION:
ns1.redhat.com.         73      IN      A       209.132.186.218
ns2.redhat.com.         73      IN      A       209.132.183.2
ns3.redhat.com.         73      IN      A       209.132.176.100

;; Query time: 13 msec
;; SERVER: 209.144.50.138#53(209.144.50.138)
;; WHEN: Thu Jan 12 10:09:49 2012
;; MSG SIZE  rcvd: 164
```

Picture from http://www.thegeekstuff.com/2012/02/dig-command-examples/   Application Layer 2-73

Inserting records into DNS

❖ example: new startup "Network Utopia"

❖ register name networkuptopia.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)`

❖ create authoritative server type A record for www.networkuptopia.com; type MX record for networkutopia.com

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 bypassed

❖ **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**

Chapter 2: outline

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 (KanKan)
- VoIP (Skype)

File distribution: client-server vs P2P

Question: how much time to distribute file (size *F*) from one server to N peers?

- peer upload/download capacity is limited resource

u_s: server upload capacity

file, size F

server

u_s

u_1 d_1 u_2 d_2

d_i: peer i download capacity

d_i

network (with abundant bandwidth)

u_N

d_N

u_i

u_i: peer i upload capacity
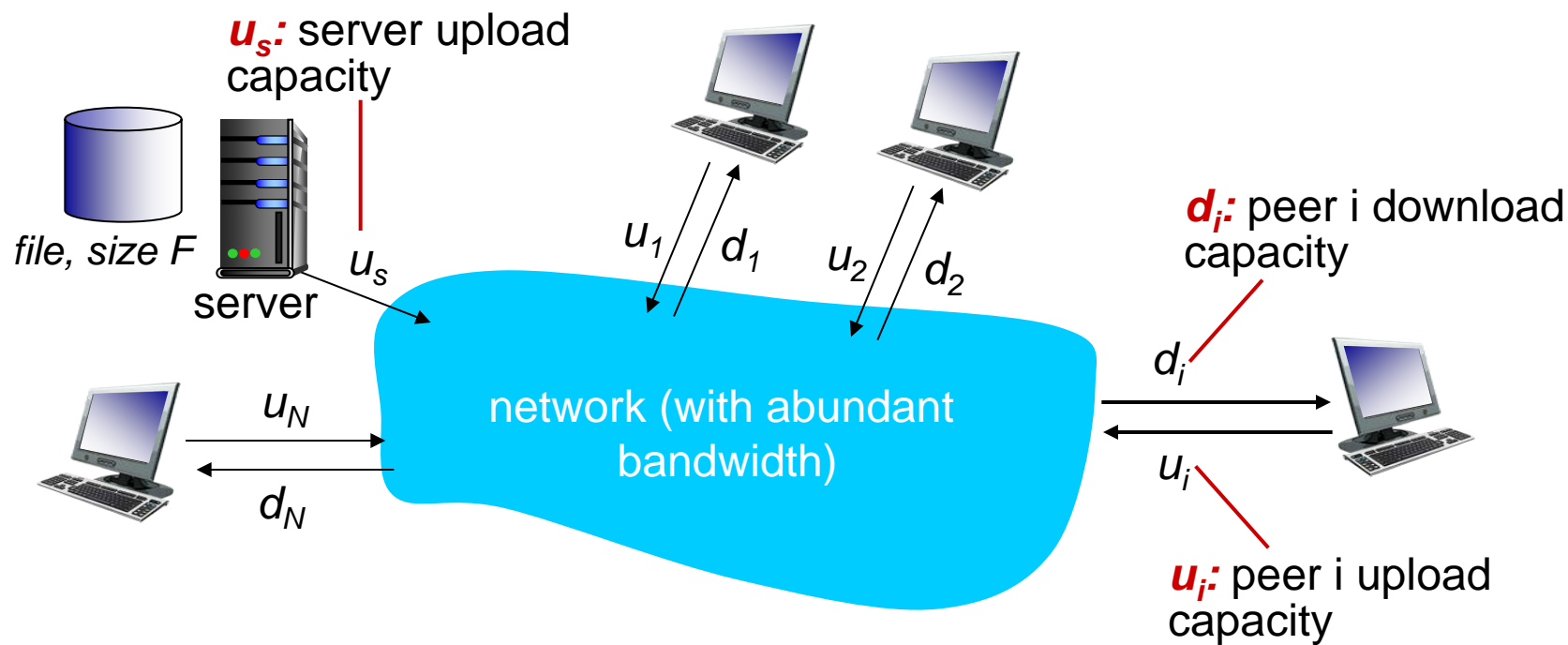
File distribution time: client-server

❖ *server transmission:* must sequentially send (upload) N file copies:
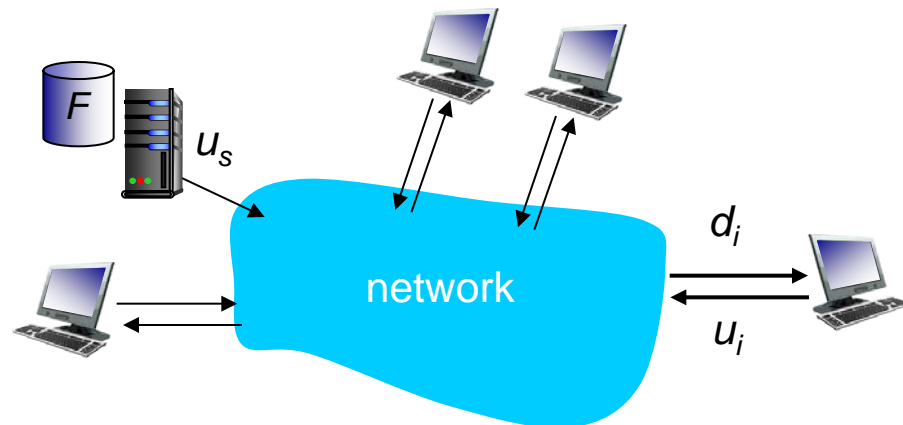
- time to send one copy: F/u_s
- time to send N copies: NF/u_s

❖ *client:* each client must download file copy

- d_{min} = min client download rate
- max client download time: F/d_{min}

$$
\begin{array}{l}
\text{time to distribute F} \\
\text{to N clients using} \\
\text{client-server approach}
\end{array}
\quad D_{c\text{-}s} \geq max\{NF/u_s,\ F/d_{min}\}
$$

increases linearly in N

File distribution time: P2P

- **server transmission:** must upload at least one copy
  - time to send one copy: F/u_s
- **client:** each client must download file copy
  - max client download time: F/d_{min}
- **clients:** as aggregate must download NF bits
  - max upload rate (limting max download rate) is $u_s + \Sigma u_i$
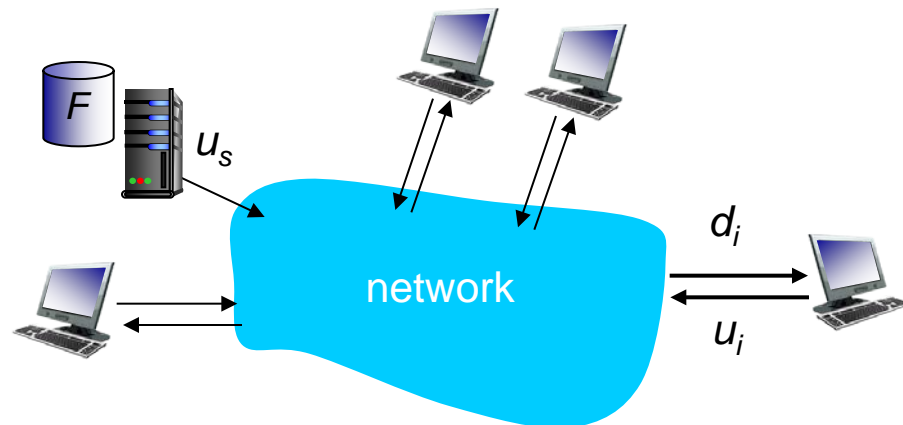
time to distribute F to N clients using P2P approach

$$D_{P2P} \geq max\{F/u_s, F/d_{min}, NF/(u_s + \Sigma u_i)\}$$

increases linearly in N …

… but so does this, as each peer brings service capacity

Client-server vs. P2P: example

client upload rate = u, F/u = 1 hour, $u_s = 10u$, $d_{min} \geq u_s$
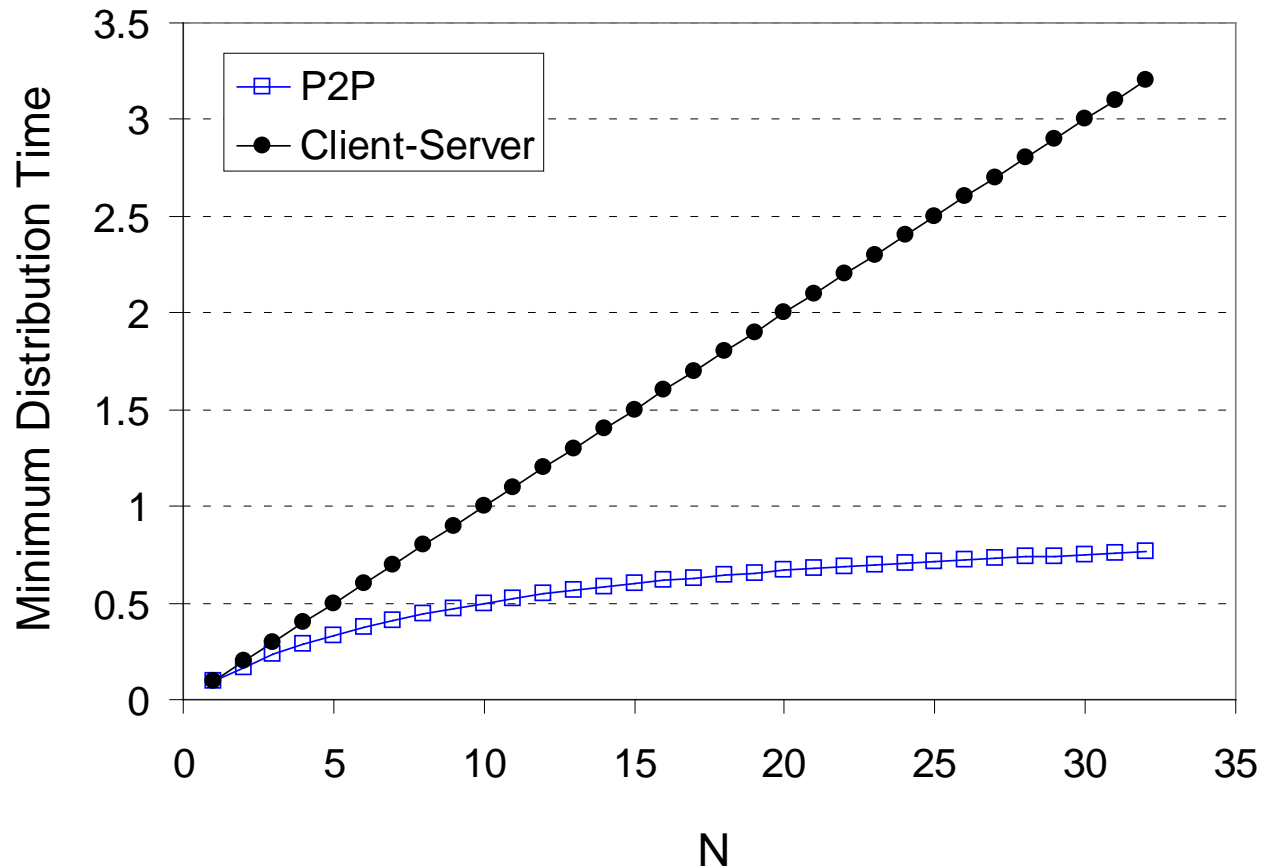
P2P file distribution: BitTorrent

❖ 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
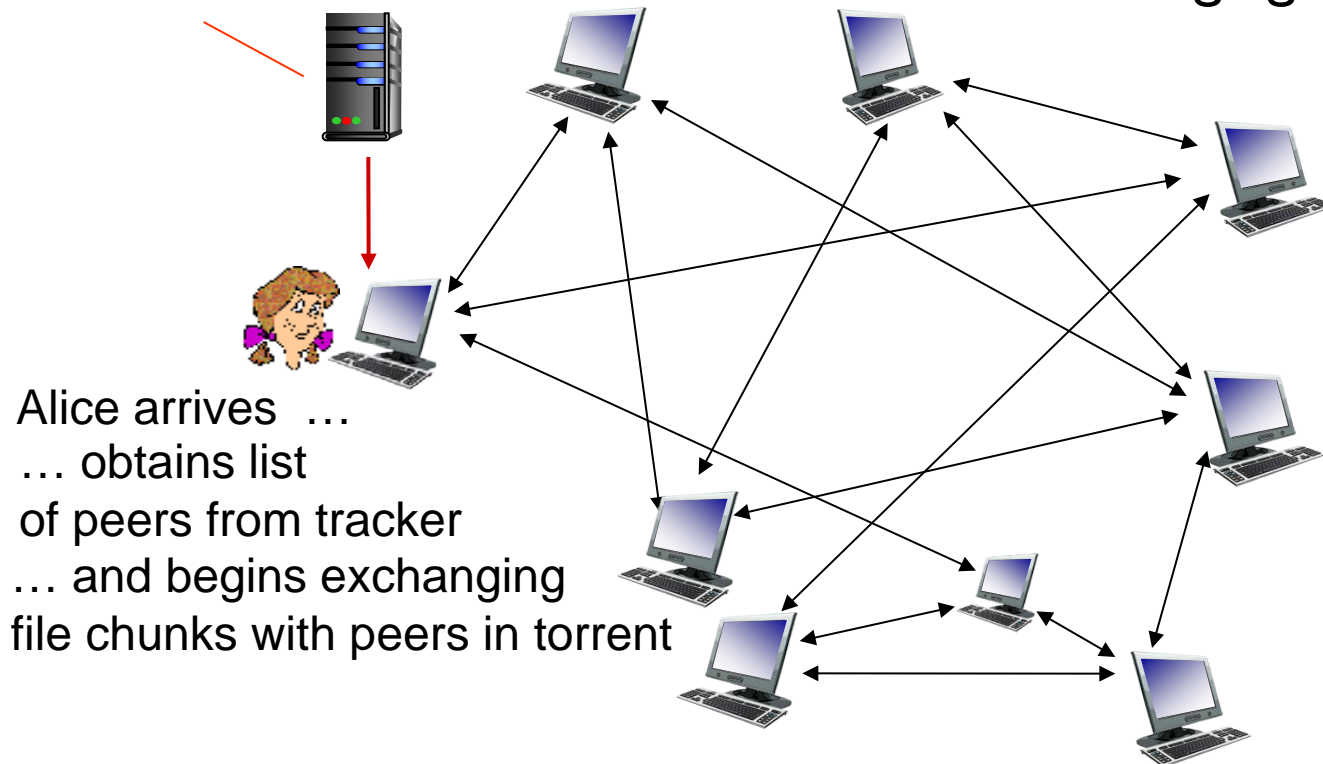
P2P file distribution: BitTorrent

❖ 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
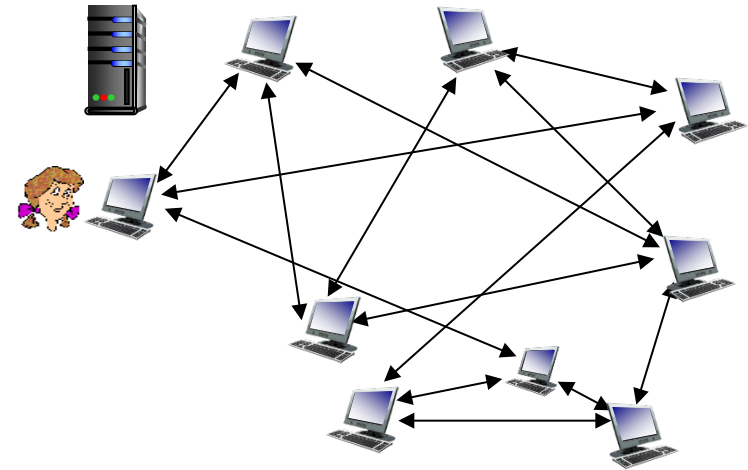
BitTorrent: requesting, sending file chunks

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**

sending chunks: tit-for-tat

❖ 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

BitTorrent: tit-for-tat

(1) Alice "optimistically unchokes" Bob

(2) Alice becomes one of Bob's top-four providers; Bob reciprocates

(3) Bob becomes one of Alice's top-four providers

higher upload rate: find better trading partners, get file faster !
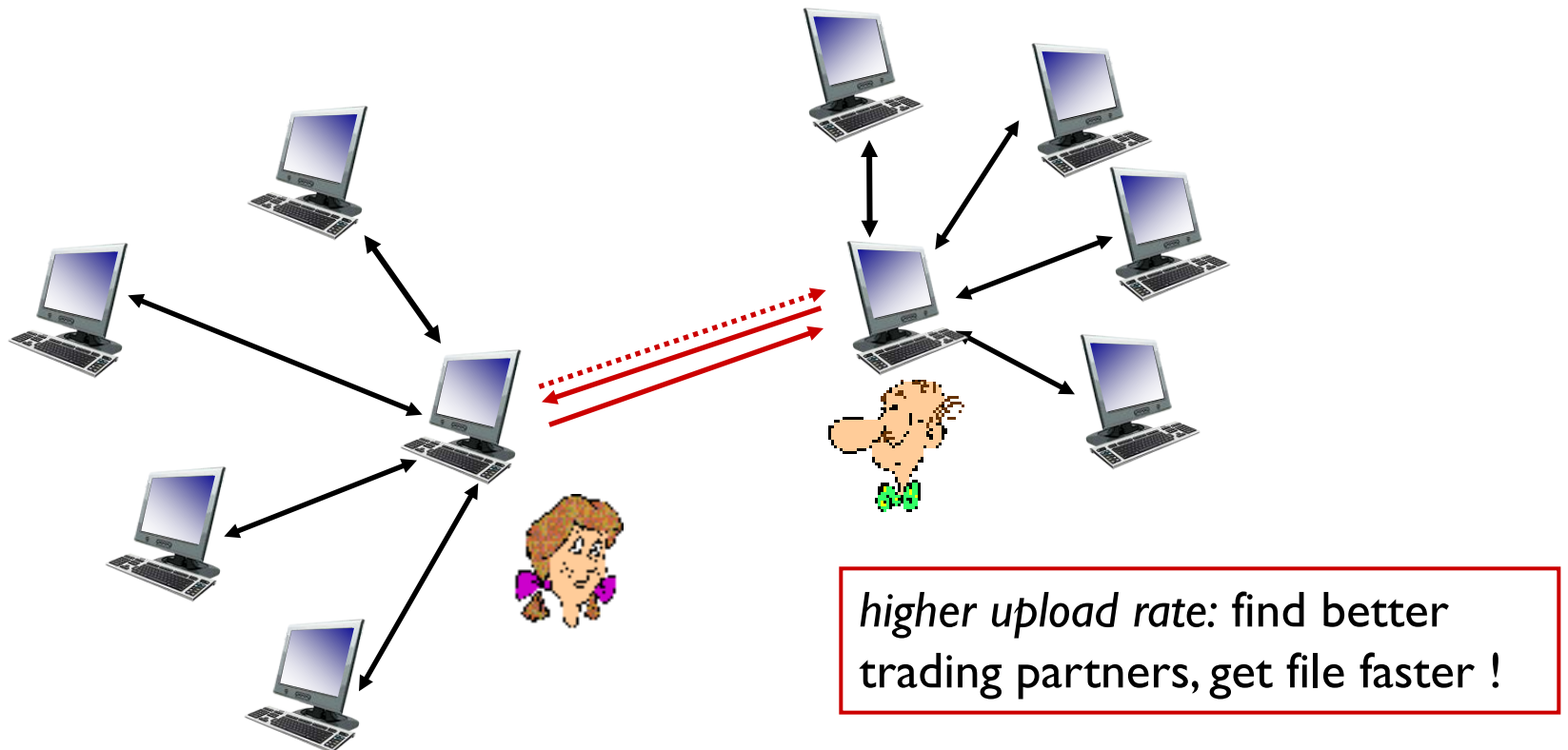
Chapter 2: outline

2.1 principles of network applications
- app architectures
- app requirements

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

Socket programming

goal: learn how to build client/server applications that communicate using sockets

socket: door between application process and end-end-transport protocol
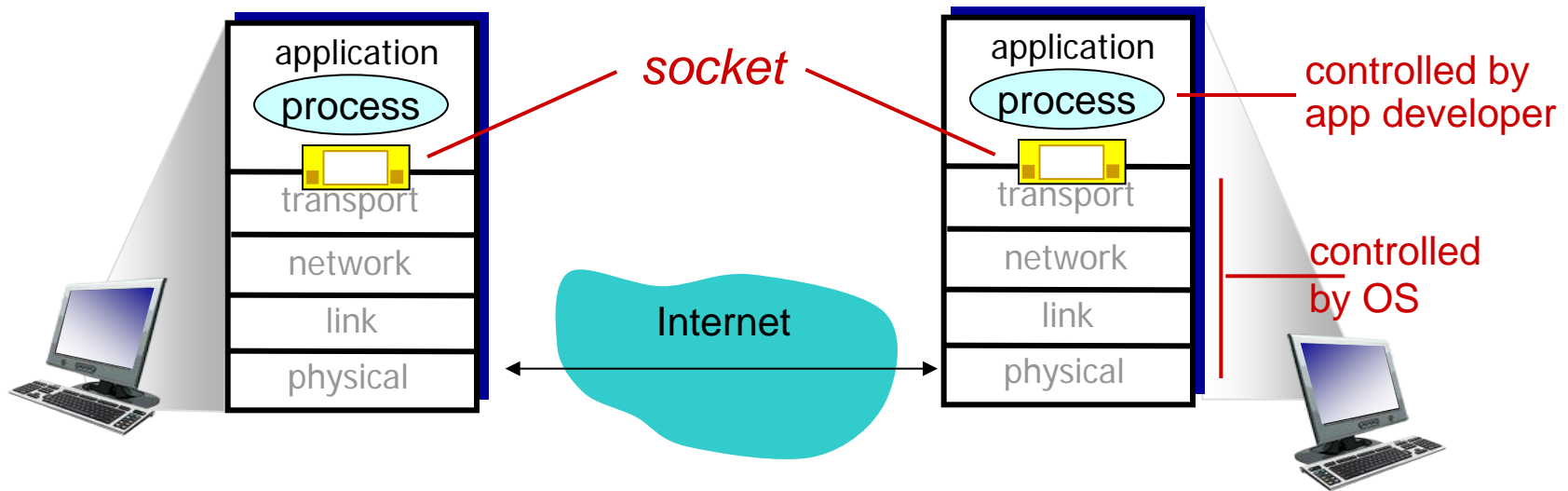
Socket programming

Two socket types for two transport services:

- *UDP:* unreliable datagram
- *TCP:* reliable, byte stream-oriented

Application Example:

1. Client reads a line of characters (data) from its keyboard and sends the data to the server.
2. The server receives the data and converts characters to uppercase.
3. The server sends the modified data to the client.
4. The client receives the modified data and displays the line on its screen.

Socket programming *with UDP*

UDP: no "connection" between client & server

- no handshaking before sending data
- sender explicitly attaches IP destination address and port # to each packet
- rcvr extracts sender IP address and port# from received packet

UDP: transmitted data may be lost or received out-of-order

Application viewpoint:
- UDP provides *unreliable* transfer of groups of bytes ("datagrams") between client and server

Client/server socket interaction: UDP

server (running on serverIP)   **client**

create socket, port= x:
serverSocket =
socket(AF_INET,SOCK_DGRAM)

read datagram from
serverSocket

write reply to
serverSocket
specifying
client address,
port number

create socket:
clientSocket =
socket(AF_INET,SOCK_DGRAM)

Create datagram with server IP and
port=x; send datagram via
clientSocket

read datagram from
clientSocket

close
clientSocket

Example app: UDP client

Python UDPClient

include Python's socket library →
```
from socket import *
serverName = 'hostname'          //here, 127.0.0.1
serverPort = 12000
```

create UDP socket for server →
```
clientSocket = socket(AF_INET,
                               SOCK_DGRAM)
```

get user keyboard input →
```
message = raw_input('Input lowercase sentence:')
```

Attach server name, port to message; send into socket →
```
clientSocket.sendto(message,(serverName, serverPort))
```

read reply characters from socket into string →
```
modifiedMessage, serverAddress =
                        clientSocket.recvfrom(2048)
```

print out received string and close socket →
```
print modifiedMessage
clientSocket.close()
```

Example app: UDP server

Python UDPServer

from socket import *

serverPort = 12000

create UDP socket ⟶ serverSocket = socket(AF_INET, SOCK_DGRAM)

bind socket to local port number 12000 ⟶ serverSocket.bind(('', serverPort))

print '*The server is ready to receive*'

loop forever ⟶ while 1:

Read from UDP socket into message, getting client's address (client IP and port) ⟶ message, clientAddress = serverSocket.recvfrom(2048)

modifiedMessage = message.upper()

send upper case string back to this client ⟶ serverSocket.sendto(modifiedMessage, clientAddress)

Socket programming *with TCP*

client must contact server

- server process must first be running
- server must have created socket (door) that **welcomes** client's contact

client contacts server by:

- Creating TCP socket, specifying IP address, port number of server process
- *when client creates socket:* client TCP establishes connection to server TCP

- when contacted by client, *server TCP creates new socket* for server process to communicate with that particular client
  - allows server to talk with multiple clients
  - source port numbers used to distinguish clients (more in Chap 3)

application viewpoint:

TCP provides reliable, in-order byte-stream transfer ("pipe") between client and server

Client/server socket interaction: TCP

server (running on `hostid`)   **client**

create socket,
port=**x**, for incoming
request:
serverSocket = socket()

↓

wait for incoming
connection request   **TCP**   create socket,
connectionSocket =   **connection setup**   connect to **hostid**, port=**x**
serverSocket.accept()   clientSocket = socket()

↓   ↓

read request from   send request using
connectionSocket   clientSocket

↓

write reply to   read reply from
connectionSocket   clientSocket

↓   ↓

close   close
connectionSocket   clientSocket
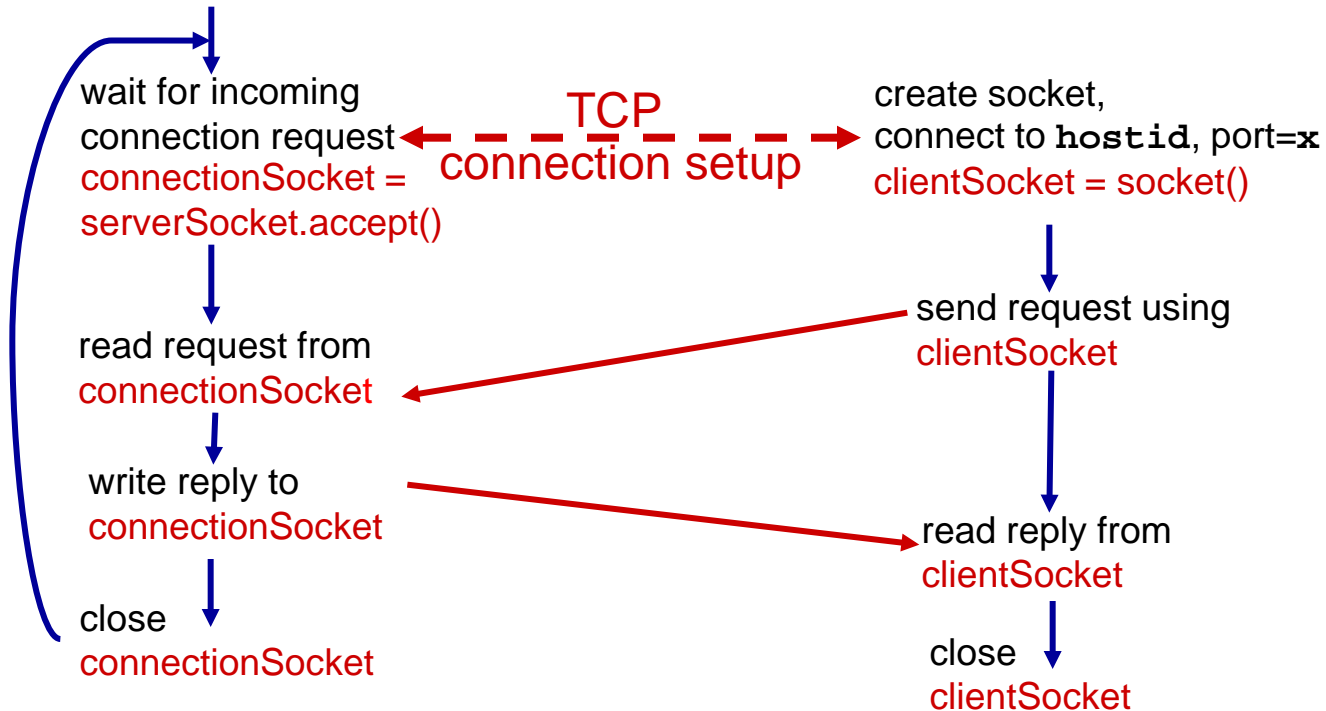
Example app: TCP client

Python TCPClient

```
from socket import *
serverName = 'servername'        //here, 127.0.0.1
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName,serverPort))
sentence = raw_input('Input lowercase sentence:')
clientSocket.send(sentence)
modifiedSentence = clientSocket.recv(1024)
print 'From Server:', modifiedSentence
clientSocket.close()
```

create TCP socket for server, remote port 12000

No need to attach server name, port

Example app: TCP server

Python TCPServer

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind(('',serverPort))
serverSocket.listen(1)
print 'The server is ready to receive'
while 1:
    connectionSocket, addr = serverSocket.accept()

    sentence = connectionSocket.recv(1024)
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence)
    connectionSocket.close()
```

create TCP welcoming socket

server begins listening for incoming TCP requests

loop forever

server waits on accept() for incoming requests, new socket created on return

read bytes from socket (but not address as in UDP)

close connection to this client (but *not* welcoming socket)

Socket API in C Programming Language

❖ What is a socket?
  ▪ The **point** where a **local application process** attaches to the **network**
  ▪ An **interface** between an **application** and the **network**
  ▪ An application creates the socket
❖ The interface defines operations for
  ▪ Creating a socket
  ▪ Attaching a socket to the network
  ▪ Sending and receiving messages through the socket
  ▪ Closing the socket

Socket

❖ **Socket** Family
  ▪ PF_INET denotes the Internet family
  ▪ PF_UNIX denotes the Unix pipe facility
  ▪ PF_PACKET denotes direct access to the network interface (i.e., it bypasses the TCP/IP protocol stack)

❖ **Socket** Type
  ▪ SOCK_STREAM is used to denote a byte stream
  ▪ SOCK_DGRAM is an alternative that denotes a message oriented service, such as that provided by UDP

Creating a Socket

```
int sockfd = socket(address_family, type,
   protocol);
```

- ❖ **The socket number returned is the socket descriptor for the newly created socket**

- ❖ `int sockfd = socket (PF_INET, SOCK_STREAM, 0);`
- ❖ `int sockfd = socket (PF_INET, SOCK_DGRAM, 0);`

   The combination of PF_INET and SOCK_STREAM implies TCP

Client-Serve Model with TCP

Server

- Passive open
- Prepares to accept connection, does not actually establish a connection

Server invokes

```
int bind (int socket, struct sockaddr *address,
                                int addr_len)
int listen (int socket, int backlog)
int accept (int socket, struct sockaddr
*address,
                        int *addr_len)
```

Client-Serve Model with TCP

Bind

- Binds the newly created socket to the specified address i.e. the network address of the local participant (the server)
- Address is a data structure which combines IP and port

Listen

- Defines how many connections can be pending on the specified socket

Client-Serve Model with TCP

Accept

- Carries out the passive open
- Blocking operation
  - **Does not return** until a remote participant has established a connection
  - When it does, it returns a new socket that corresponds to the new established connection and the address argument contains the remote participant's address

Client-Serve Model with TCP

Client

- Application performs active open
- It says who it wants to communicate with

Client invokes

```
int connect (int socket, struct sockaddr
*address,
                            int addr_len)
```

Connect

- **Does not return** until TCP has successfully established a connection at which application is free to begin sending data
- Address contains remote machine's address

Client-Serve Model with TCP

In practice

- The client usually specifies only remote participant's address and let's the system fill in the local information

- Whereas a server usually listens for messages on a well-known port

- A client does not care which port it uses for itself, the OS simply selects an unused one

Client-Serve Model with TCP

Once **a connection is established**, the application process invokes two operation

```
int send (int socket, char *msg, int msg_len,
                                   int flags)

int recv (int socket, char *buff, int buff_len,
                                    int
flags)
```

Example Application: Client

```c
#include <stdio.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
#include <netdb.h>

#define SERVER_PORT 5432
#define MAX_LINE 256

int main(int argc, char * argv[])
{
    FILE *fp;
    struct hostent *hp;
    struct sockaddr_in sin;
    char *host;
    char buf[MAX_LINE];
    int s;
    int len;
    if (argc==2) {
            host = argv[1];
    }
    else {
            fprintf(stderr, "usage: simplex-talk host\n");
    exit(1);
    }
```

Example Application: Client

```
/* translate host name into peer's IP address */
hp = gethostbyname(host);
if (!hp) {
        fprintf(stderr, "simplex-talk: unknown host: %s\n", host);
        exit(1);
}
/* build address data structure */
bzero((char *)&sin, sizeof(sin));
sin.sin_family = AF_INET;  /* Internet Address*/
bcopy(hp->h_addr, (char *)&sin.sin_addr, hp->h_length);
sin.sin_port = htons(SERVER_PORT);
/* active open  PF_INET is protocol family*/
if ((s = socket(PF_INET, SOCK_STREAM, 0)) < 0) {
        perror("simplex-talk: socket");
        exit(1);
}
if (connect(s, (struct sockaddr *)&sin, sizeof(sin)) < 0) {
        perror("simplex-talk: connect");
        close(s);
        exit(1);
}
/* main loop: get and send lines of text */
while (fgets(buf, sizeof(buf), stdin)) {
        buf[MAX_LINE-1] = '\0';
        len = strlen(buf) + 1;
        send(s, buf, len, 0);
}
```

Example Application: Server

```c
#include <stdio.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
#include <netdb.h>
#define SERVER_PORT 5432
#define MAX_PENDING 5
#define MAX_LINE 256

int main()
{
    struct sockaddr_in sin;
    char buf[MAX_LINE];
    int len;
    int s, new_s;
    /* build address data structure */
    bzero((char *)&sin, sizeof(sin));
    sin.sin_family = AF_INET;
    sin.sin_addr.s_addr = INADDR_ANY;
    sin.sin_port = htons(SERVER_PORT);

    /* setup passive open */
    if ((s = socket(PF_INET, SOCK_STREAM, 0)) < 0) {
            perror("simplex-talk: socket");
            exit(1);
    }
```

Example Application: Server

```
if ((bind(s, (struct sockaddr *)&sin, sizeof(sin))) < 0) {
        perror("simplex-talk: bind");
        exit(1);
}
listen(s, MAX_PENDING);
/* wait for connection, then receive and print text */
while(1) {
        if ((new_s = accept(s, (struct sockaddr *)&sin, &len)) < 0) {
                perror("simplex-talk: accept");
                exit(1);
        }
        while (len = recv(new_s, buf, sizeof(buf), 0))
                fputs(buf, stdout);
        close(new_s);
    }
}
```

Chapter 2: summary

our study of network apps now complete!

- ❖ application architectures
    - ▪ client-server
    - ▪ P2P
- ❖ application service requirements:
    - ▪ reliability, bandwidth, delay
- ❖ Internet transport service model
    - ▪ connection-oriented, reliable: TCP
    - ▪ unreliable, datagrams: UDP

- ❖ specific protocols:
    - ▪ HTTP
    - ▪ FTP
    - ▪ SMTP, POP, IMAP
    - ▪ DNS
    - ▪ P2P: BitTorrent, DHT
- ❖ socket programming: TCP, UDP sockets

Chapter 2: summary

most importantly: learned about protocols!

- ❖ typical request/reply message exchange:
  - client requests info or service
  - server responds with data, status code
- ❖ message formats:
  - headers: fields giving info about data
  - data: info being communicated

important themes:

- ❖ control vs. data msgs
  - in-band, out-of-band
- ❖ centralized vs. decentralized
- ❖ stateless vs. stateful
- ❖ reliable vs. unreliable msg transfer
- ❖ "complexity at network edge"

Chapter 2
Additional Slides

WIRESHARK

packet
analyzer

packet
capture
(pcap)

copy of all
Ethernet frames
sent/received

application
(www browser,
email client)

application

OS

Transport (TCP/UDP)

Network (IP)

Link (Ethernet)

Physical