

Chapter 2

Application Layer

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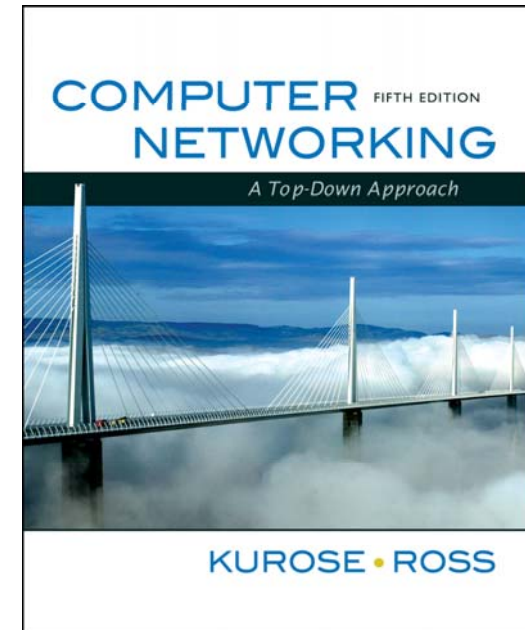
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*Computer Networking:
A Top Down Approach,
5th edition.*

*Jim Kurose, Keith Ross
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2009.*

Chapter 2: Application layer

- ❑ 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 TCP
- ❑ 2.8 Socket programming with UDP

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
- ❑ programming network applications
 - ❖ socket API

Some network apps

- ☐ e-mail
- ☐ web
- ☐ instant messaging
- ☐ remote login
- ☐ P2P file sharing
- ☐ multi-user network games
- ☐ streaming stored video clips
- ☐ voice over IP
- ☐ real-time video conferencing
- ☐ grid computing
- ☐
- ☐
- ☐

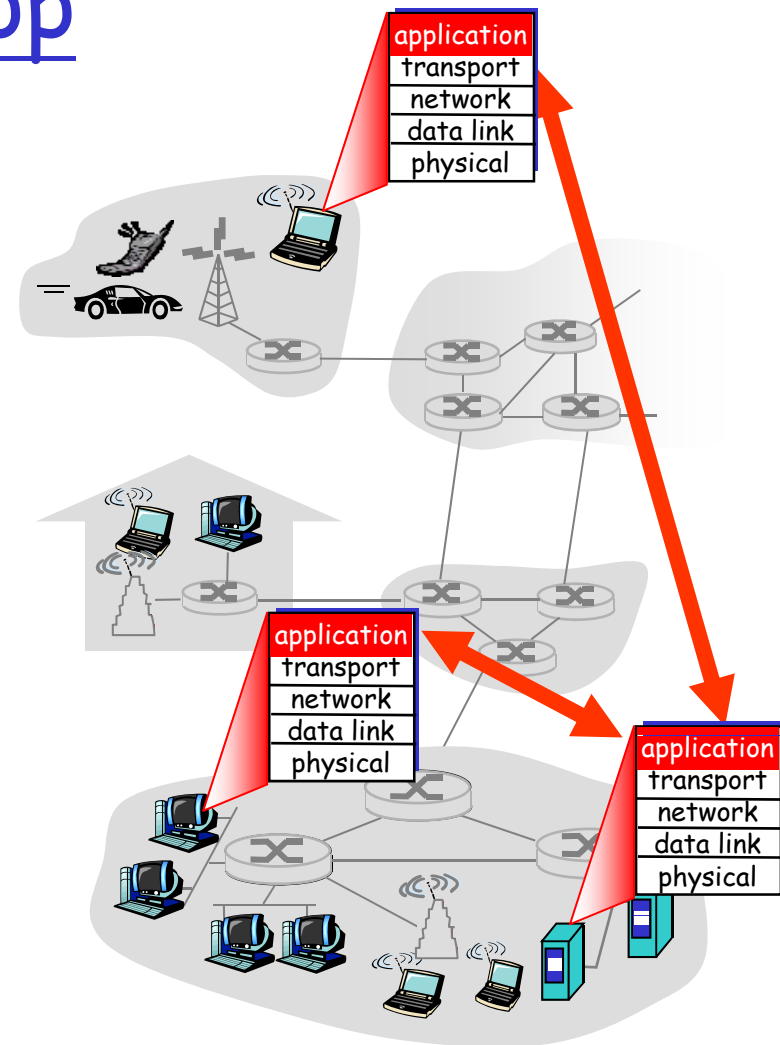
Creating a network app

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



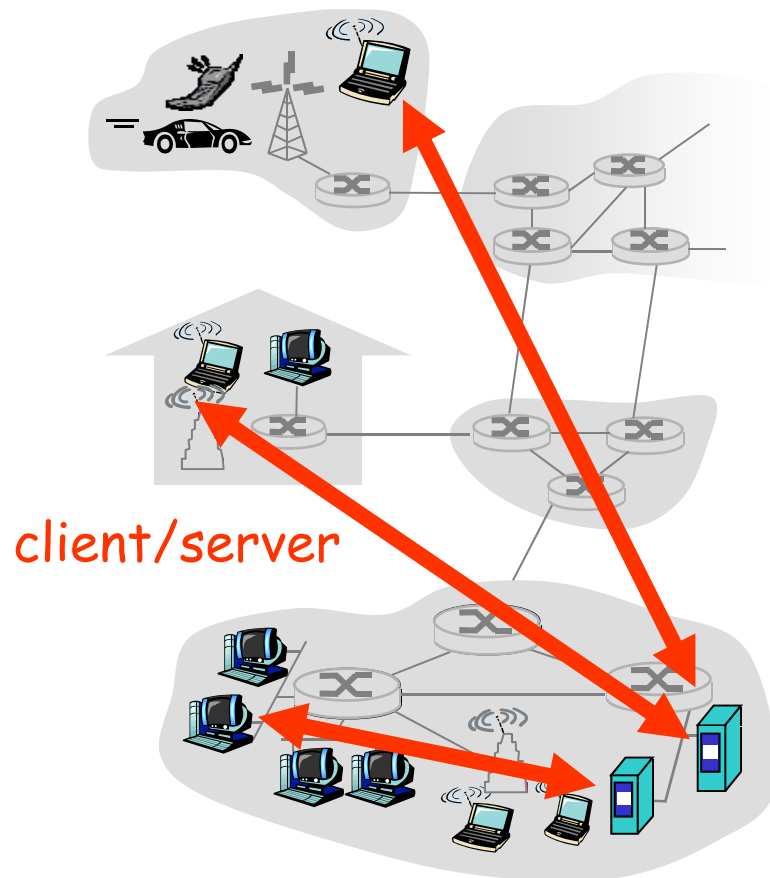
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- ❑ 2.9 Building a Web server

Application architectures

- ❑ Client-server
- ❑ Peer-to-peer (P2P)
- ❑ Hybrid of client-server and P2P

Client-server architecture



server:

- ❖ always-on host
- ❖ permanent IP address
- ❖ server farms for scaling

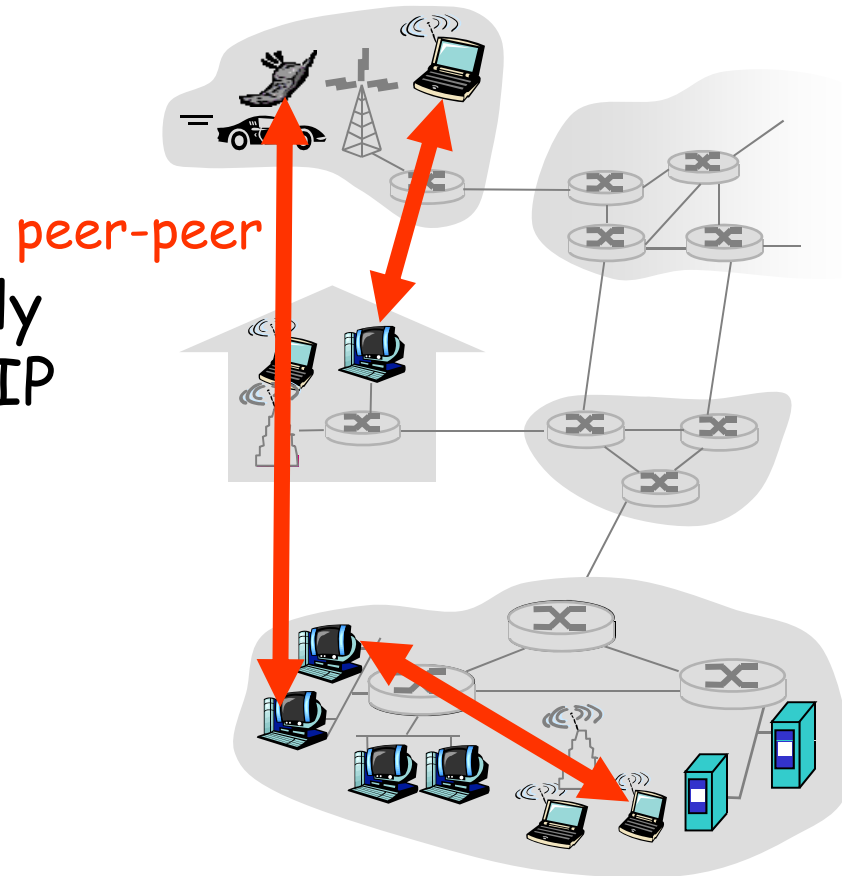
clients:

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

Pure P2P architecture

- ❑ *no* always-on server
- ❑ arbitrary end systems directly communicate
- ❑ peers are intermittently connected and change IP addresses

Highly scalable but
difficult to manage



Hybrid of client-server and P2P

Skype

- ❖ voice-over-IP P2P application
- ❖ centralized server: finding address of remote party:
- ❖ client-client connection: direct (not through server)

Instant messaging

- ❖ chatting between two users is P2P
- ❖ centralized service: client presence detection/location
 - user registers its IP address with central server when it comes online
 - user contacts central server to find IP addresses of buddies

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**

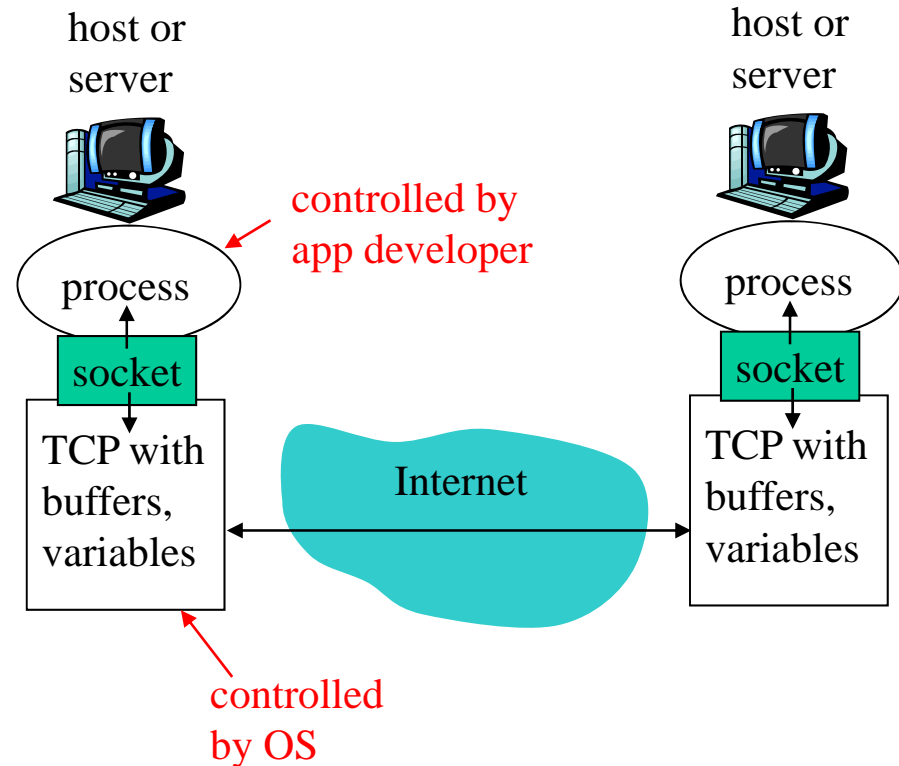
Client process: process that initiates communication

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 which brings message to socket at receiving process



- ❑ API: (1) choice of transport protocol; (2) ability to fix a few parameters (lots more on this later)

Addressing processes

- ❑ to receive messages, process must have *identifier*
- ❑ host device has unique 32-bit IP address
- ❑ Q: does IP address of host suffice for identifying the 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

Public-domain protocols:

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

Proprietary protocols:

- ❑ e.g., Skype

What transport service does an app need?

Data loss

- ❑ some apps (e.g., audio) can tolerate some loss
- ❑ other apps (e.g., file transfer, telnet) require 100% reliable data transfer

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 of 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 |
| instant messaging | no loss | elastic | yes and no |

Internet transport protocols services

TCP service:

- ❑ *connection-oriented*: setup required between client and server processes
- ❑ *reliable transport* between sending and receiving process
- ❑ *flow control*: sender won't overwhelm receiver
- ❑ *congestion control*: throttle sender when network overloaded
- ❑ *does not provide*: timing, minimum throughput guarantees, security

UDP service:

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

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

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 - ❖ app architectures
 - ❖ app requirements
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Web and HTTP

First some jargon

- ❑ 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
- ❑ Example URL:

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

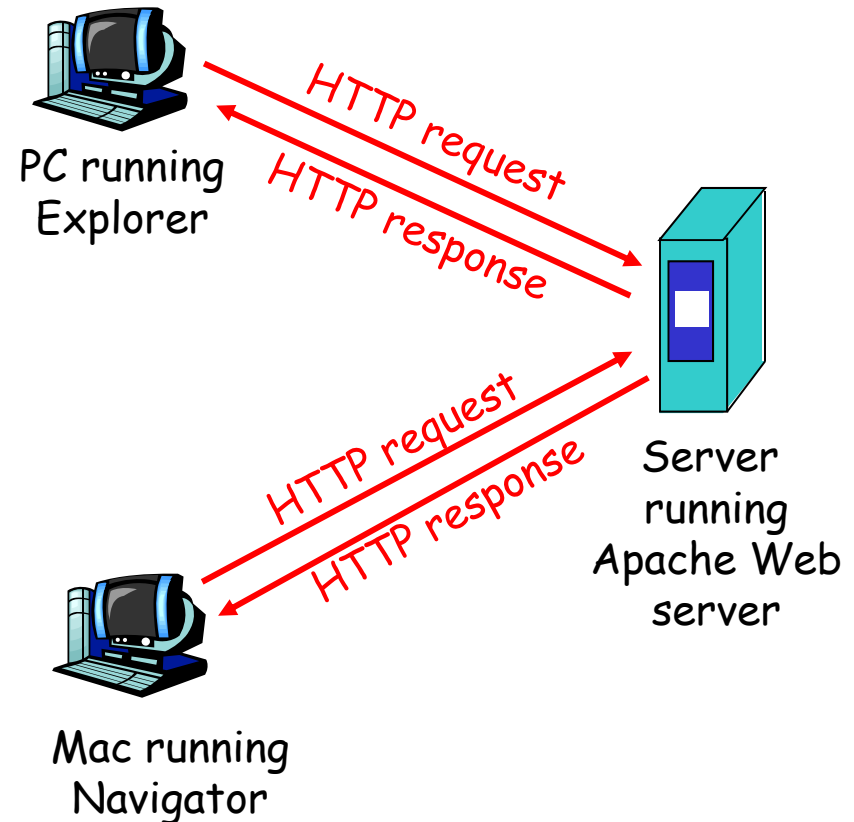
host name

path name

HTTP overview

HTTP: hypertext transfer protocol

- ❑ Web's application layer protocol
- ❑ client/server model
 - ❖ *client*: browser that requests, receives, "displays" Web objects
 - ❖ *server*: Web server sends 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

Protocols that maintain "state" are complex! aside

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

HTTP connections

Nonpersistent HTTP

- ❑ At most one object is sent over a TCP connection.

Persistent HTTP

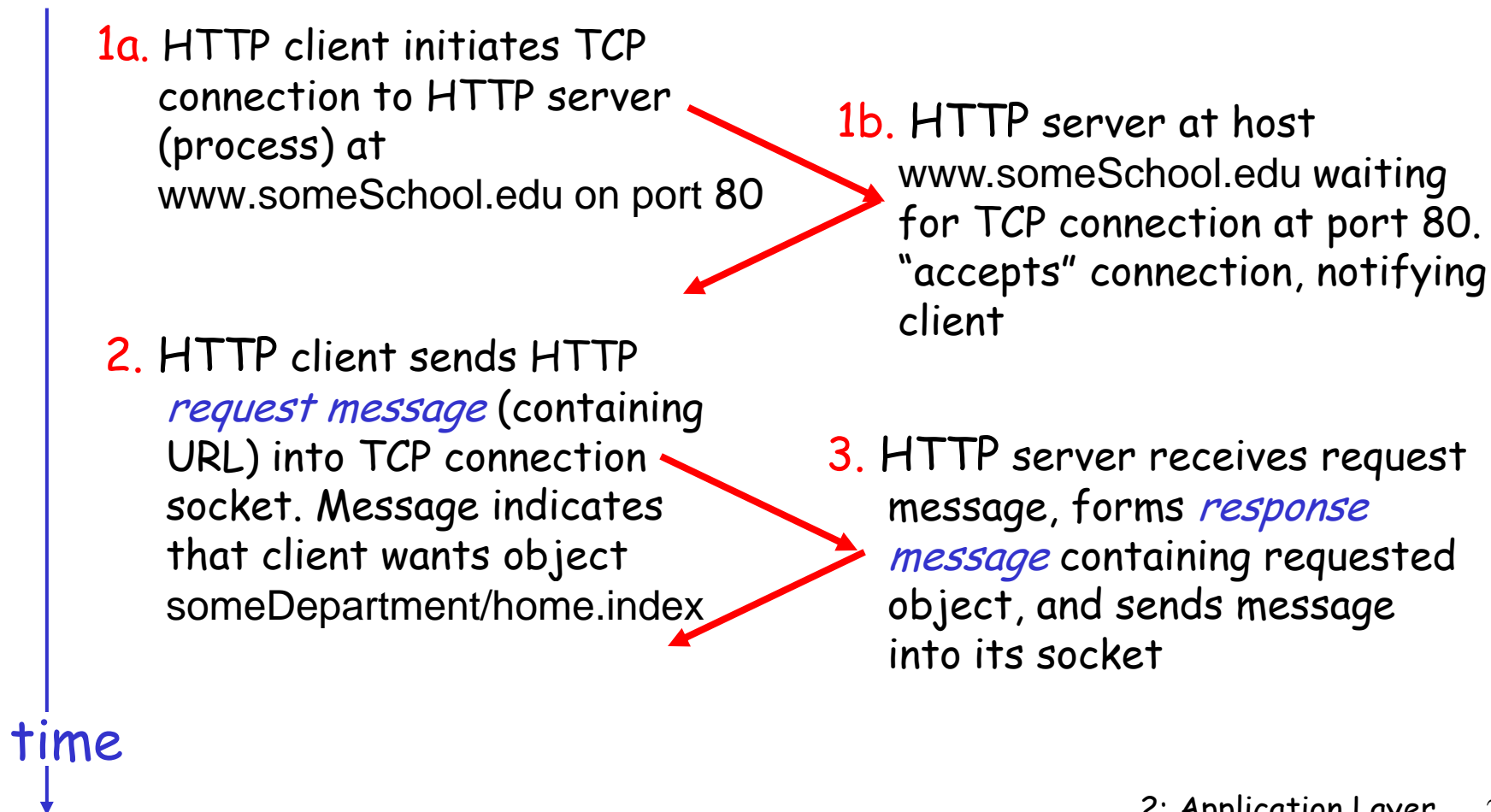
- ❑ Multiple objects can be sent over single TCP connection between client and server.

Nonpersistent HTTP

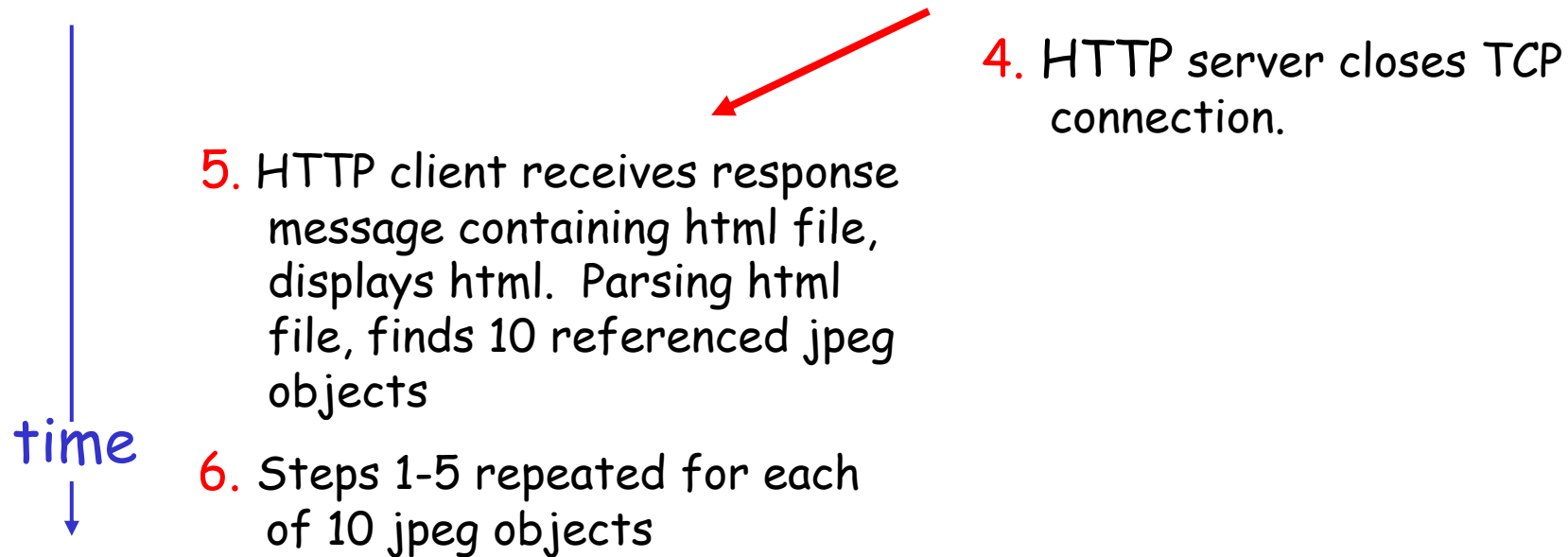
Suppose user enters URL

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

(contains text,
references to 10
jpeg images)



Nonpersistent HTTP (cont.)



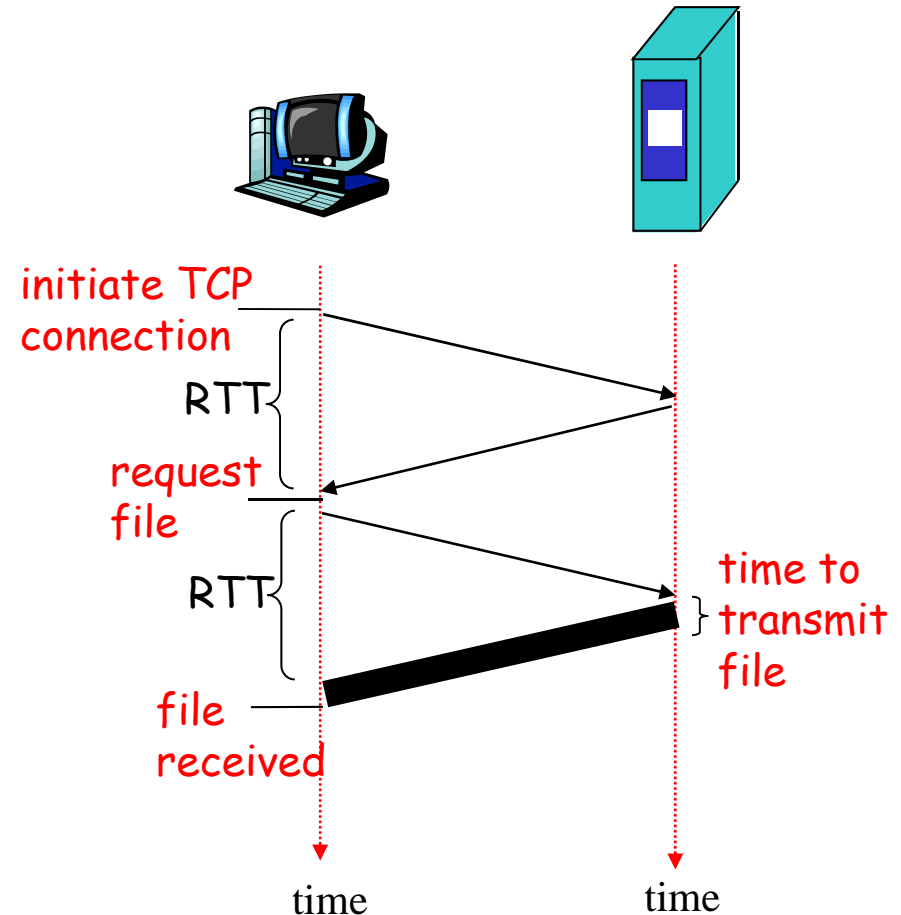
Non-Persistent HTTP: Response time

Definition of RTT: time for a small packet to travel from client to server and back.

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

total = $2RTT + \text{transmit time}$



Persistent HTTP

Nonpersistent 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)

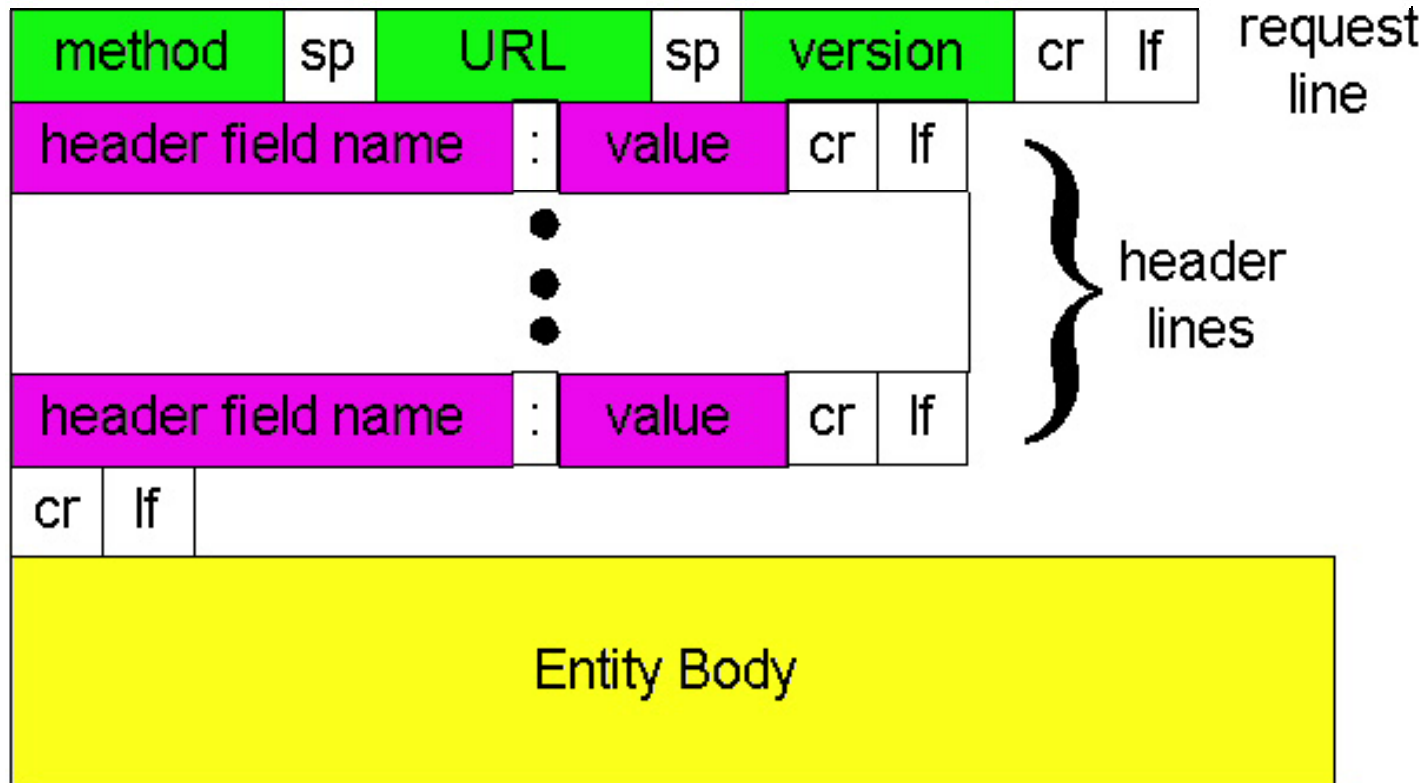
header
lines

```
GET /somedir/page.html HTTP/1.1
Host: www.someschool.edu
User-agent: Mozilla/4.0
Connection: close
Accept-language: fr
```

Carriage return,
line feed
indicates end
of message

(extra carriage return, line feed)

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

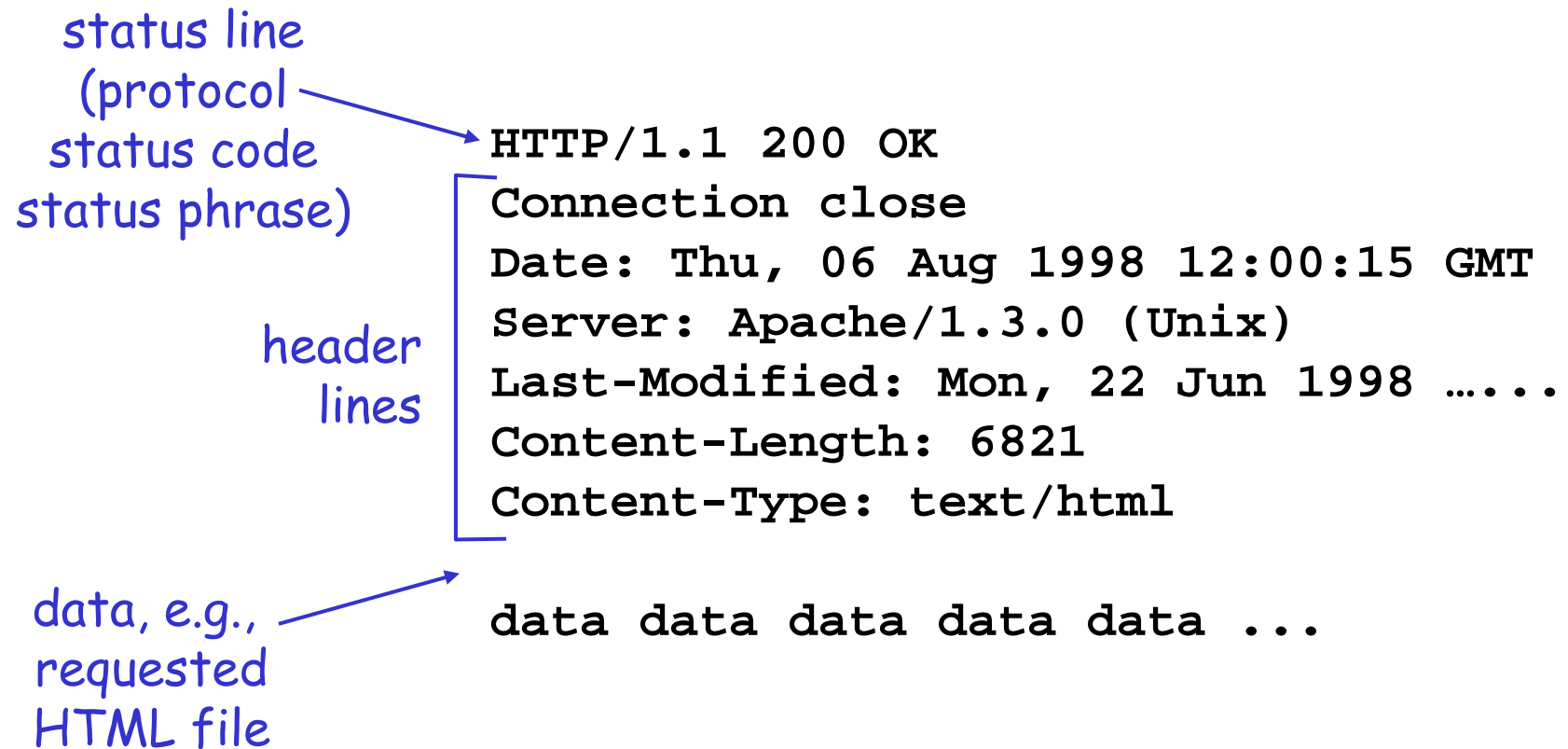
HTTP/1.0

- ❑ 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



HTTP response status codes

In first line in server->client response message.

A few sample codes:

200 OK

- ❖ request succeeded, requested object later in this message

301 Moved Permanently

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

400 Bad Request

- ❖ request message 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 cis.poly.edu 80
```

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

2. Type in a GET HTTP request:

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

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

3. Look at response message sent by HTTP server!

User-server state: cookies

Many major Web sites
use cookies

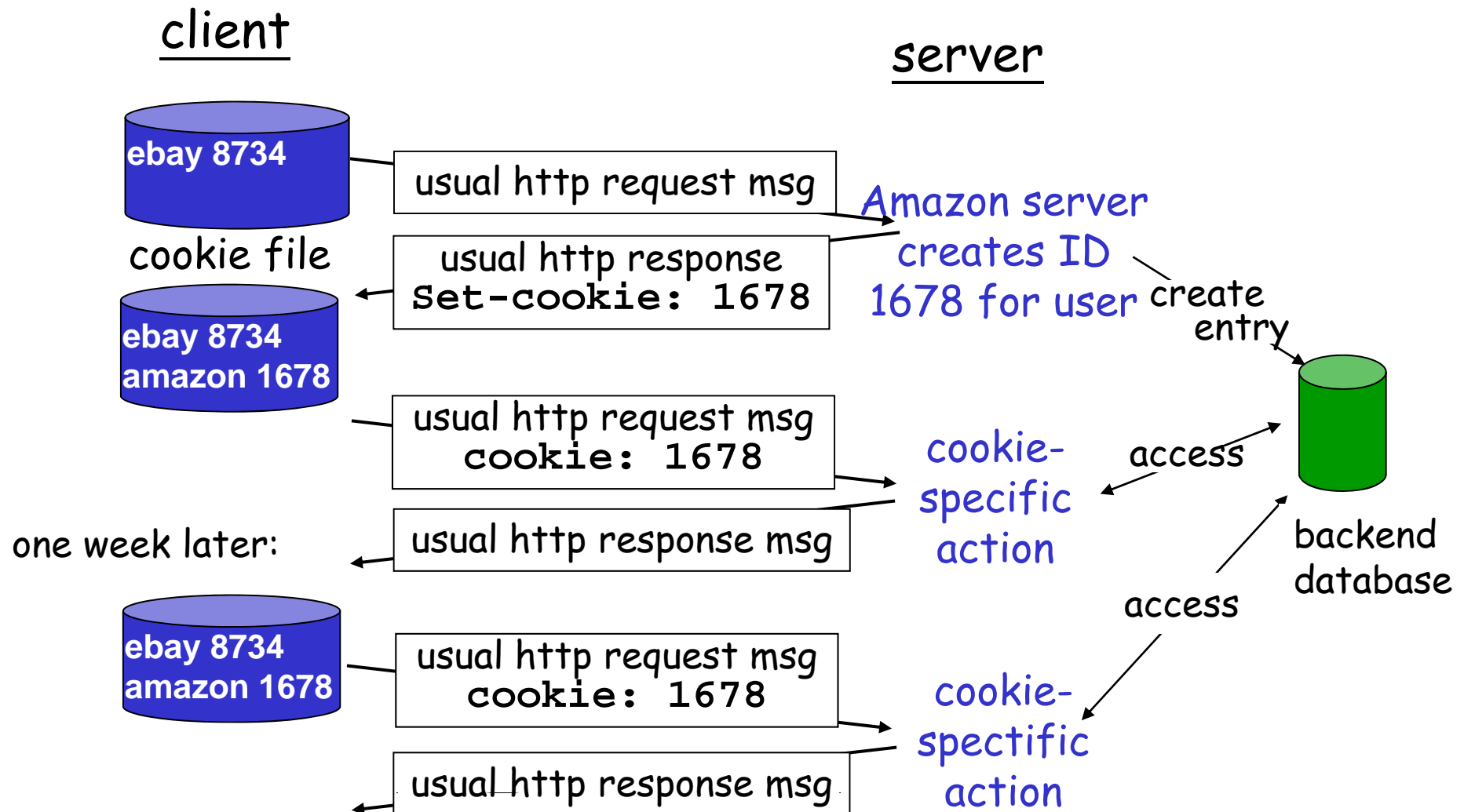
Four components:

- 1) cookie header line of HTTP *response* message
- 2) cookie header line in 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 always from PC
- visits specific e-commerce site for first time
- when initial HTTP requests arrives at site, site creates:
 - ❖ unique ID
 - ❖ entry in backend database for ID

Cookies: keeping "state" (cont.)



Cookies (continued)

What cookies can bring:

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

How to keep "state":

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

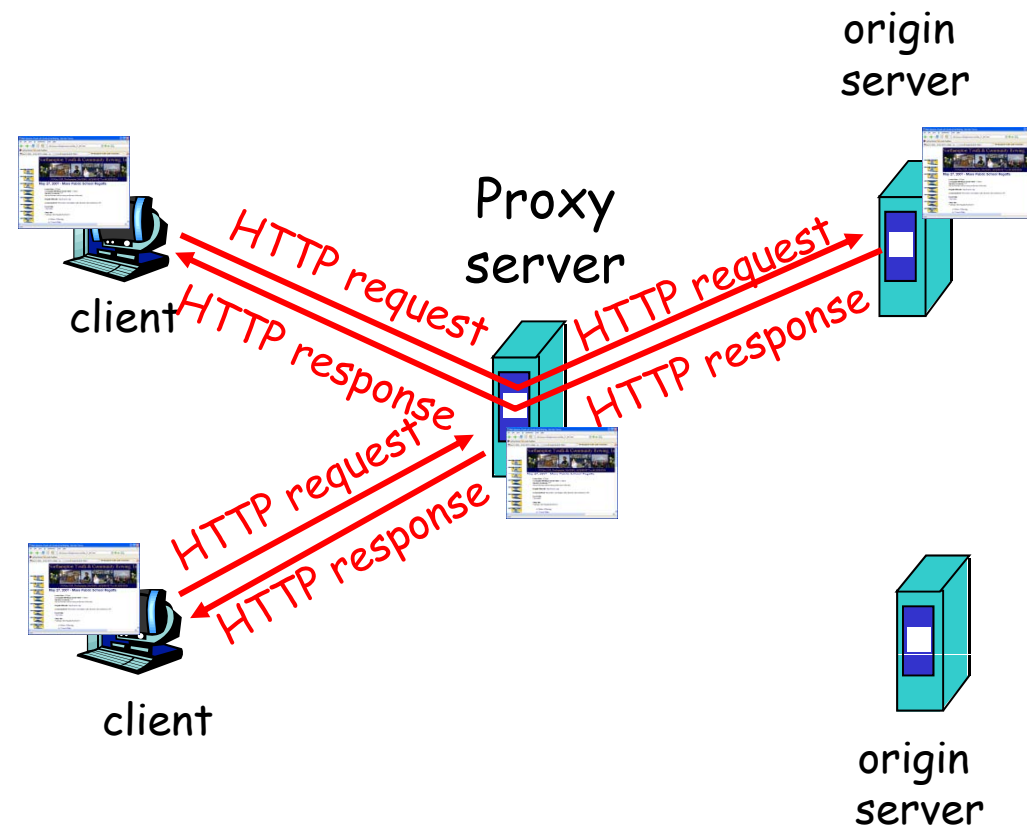
Cookies and privacy: aside

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

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
- ❑ 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 (but so does P2P file sharing)

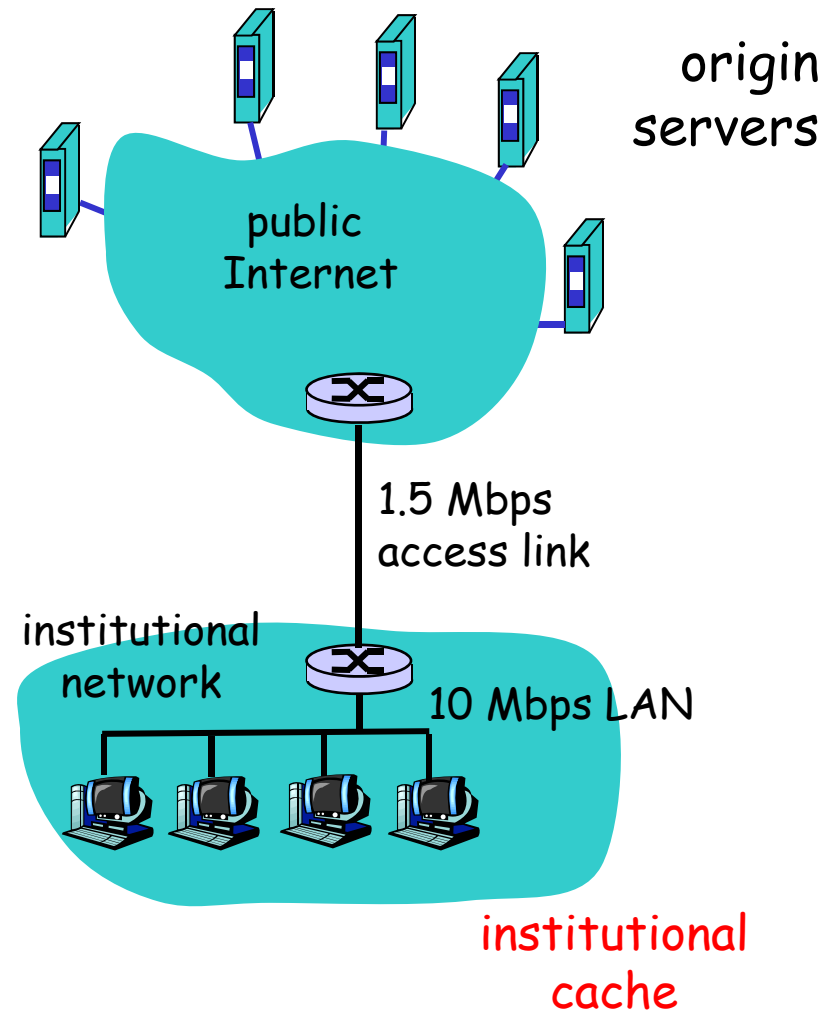
Caching example

Assumptions

- ❑ average object size = 100,000 bits
- ❑ avg. request rate from institution's browsers to origin servers = 15/sec
- ❑ delay from institutional router to any origin server and back to router = 2 sec

Consequences

- ❑ utilization on LAN = 15%
- ❑ utilization on access link = 100%
- ❑ total delay = Internet delay + access delay + LAN delay
= 2 sec + minutes + milliseconds



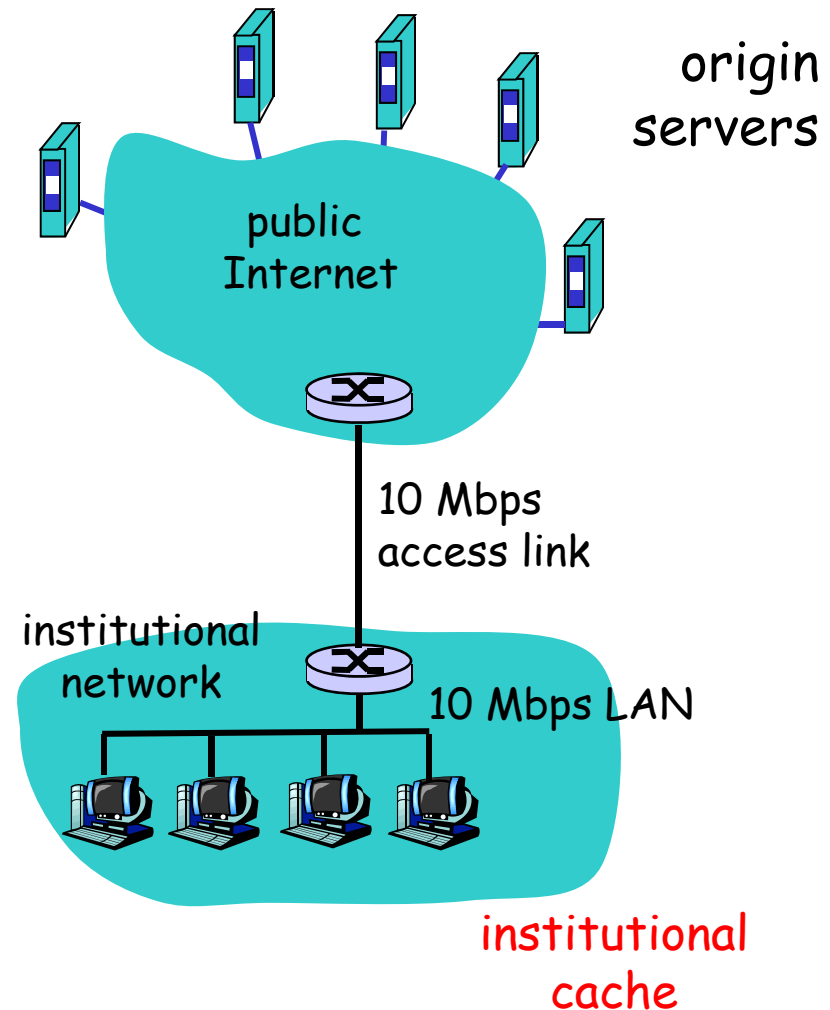
Caching example (cont)

possible solution

- ❑ increase bandwidth of access link to, say, 10 Mbps

consequence

- ❑ utilization on LAN = 15%
- ❑ utilization on access link = 15%
- ❑ Total delay = Internet delay + access delay + LAN delay
= 2 sec + msec + msec
- ❑ often a costly upgrade



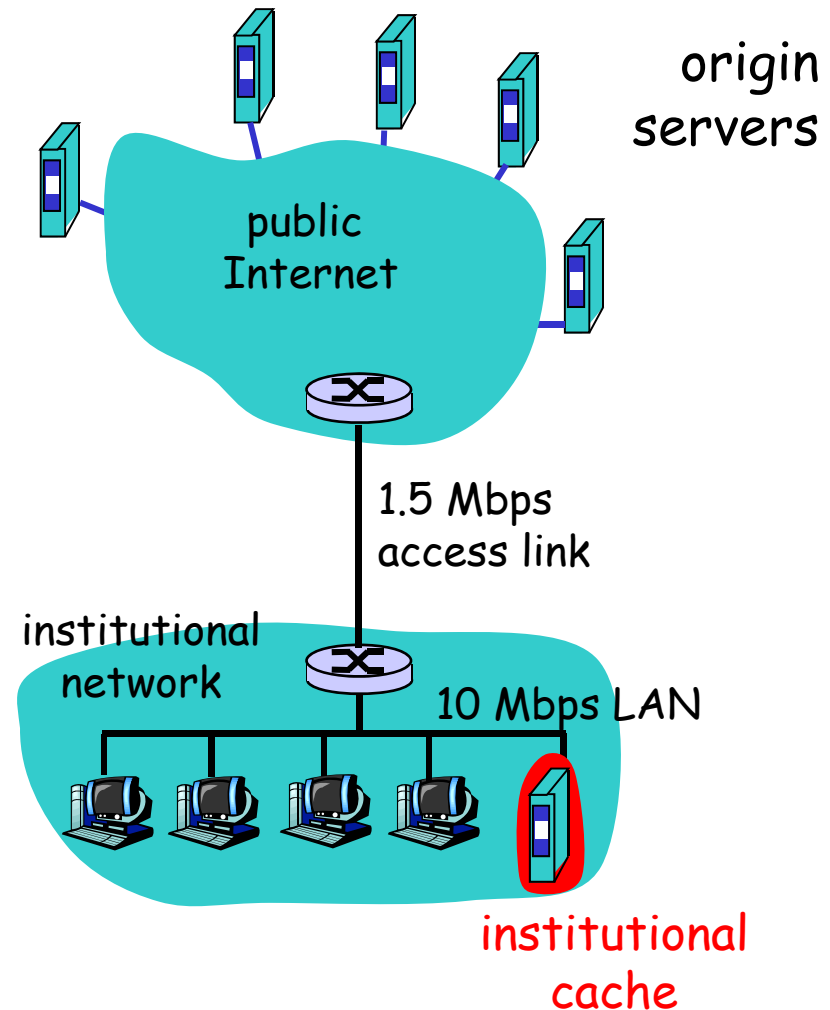
Caching example (cont)

possible solution: install cache

- suppose hit rate is 0.4

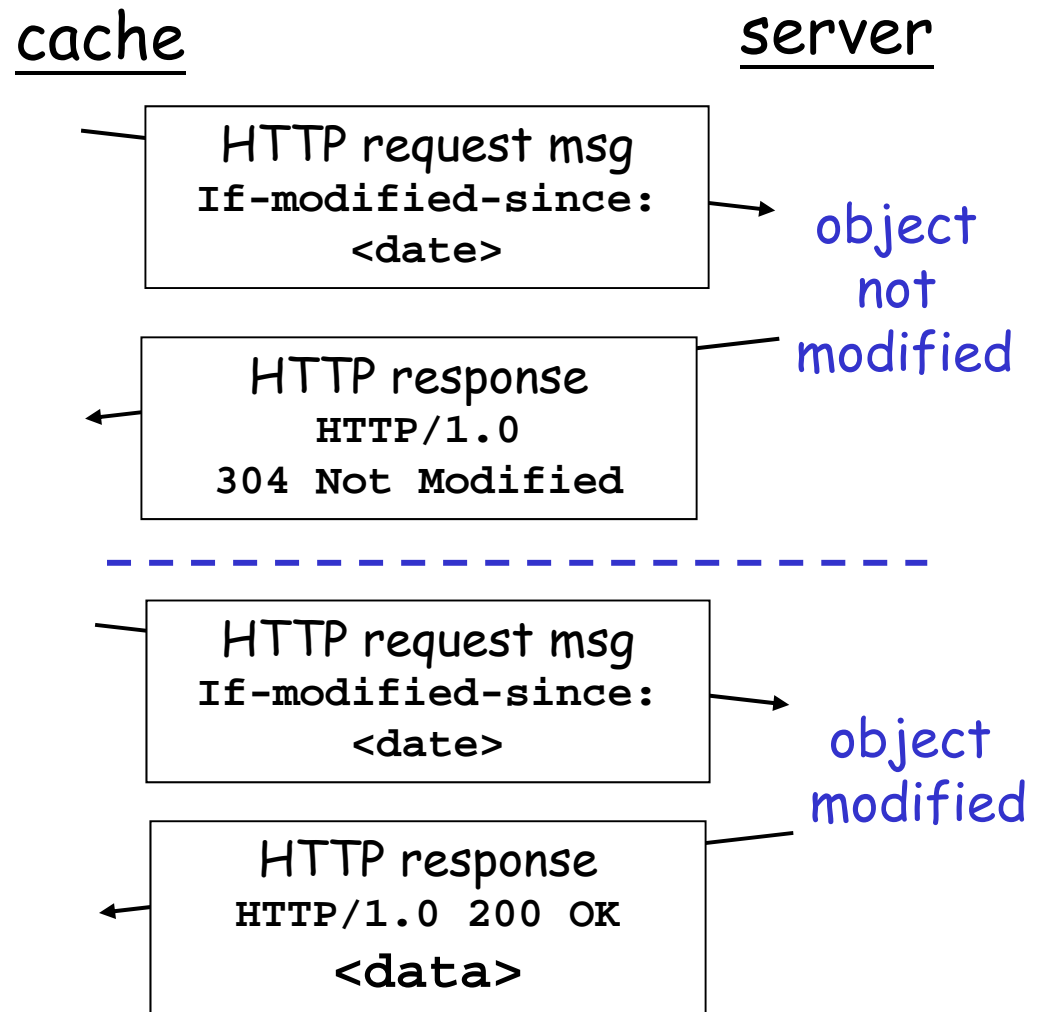
consequence

- 40% requests will be satisfied almost immediately
- 60% requests satisfied by origin server
- utilization of access link reduced to 60%, resulting in negligible delays (say 10 msec)
- total avg delay = Internet delay + access delay + LAN delay
$$= .6 \cdot (2.01) \text{ secs} + .4 \cdot \text{milliseconds} < 1.4 \text{ secs}$$



Conditional GET

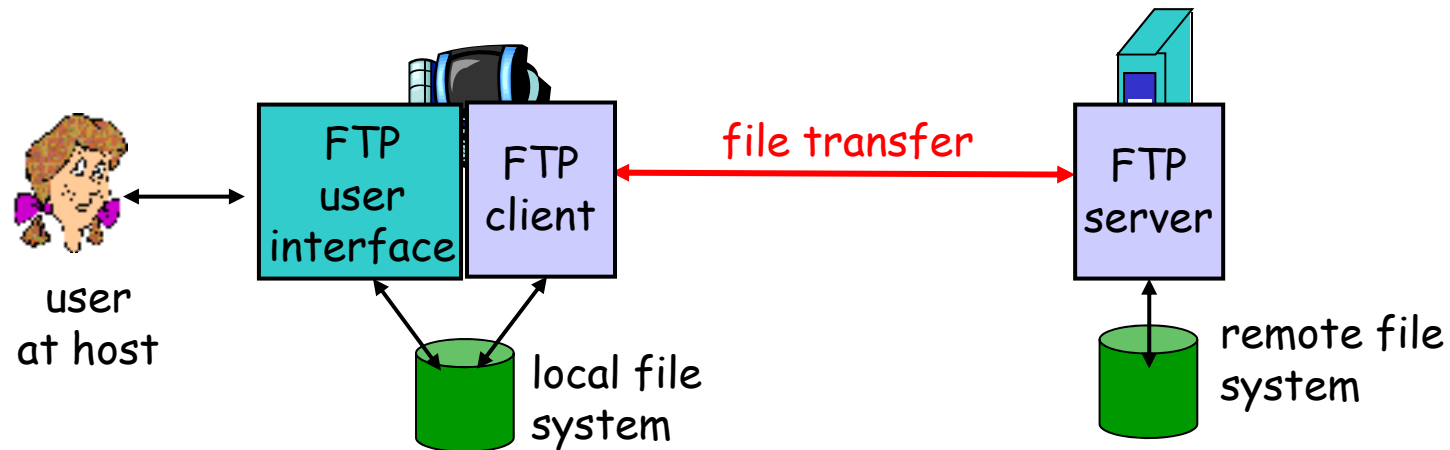
- ❑ **Goal:** don't send object if cache has up-to-date cached version
- ❑ cache: specify date of cached copy in HTTP request
If-modified-since:
<date>
- ❑ server: response contains no object if cached copy is up-to-date:
HTTP/1.0 304 Not Modified



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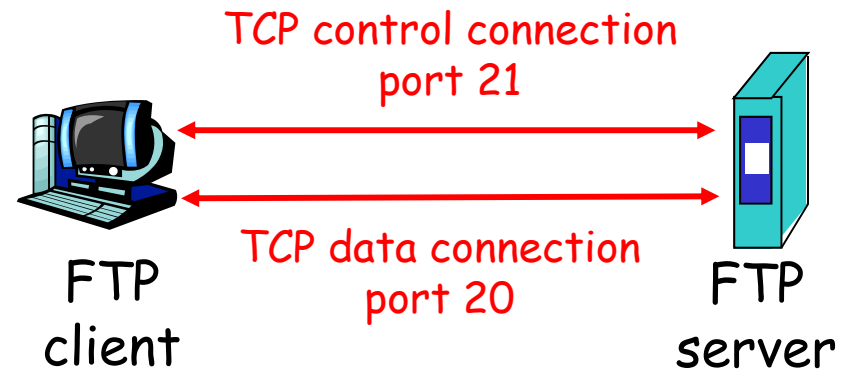
FTP: the file transfer protocol



- ❑ 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, TCP is transport protocol
- ❑ client authorized over control connection
- ❑ client browses remote directory by sending commands over control connection.
- ❑ when server receives file transfer command, server opens 2nd TCP 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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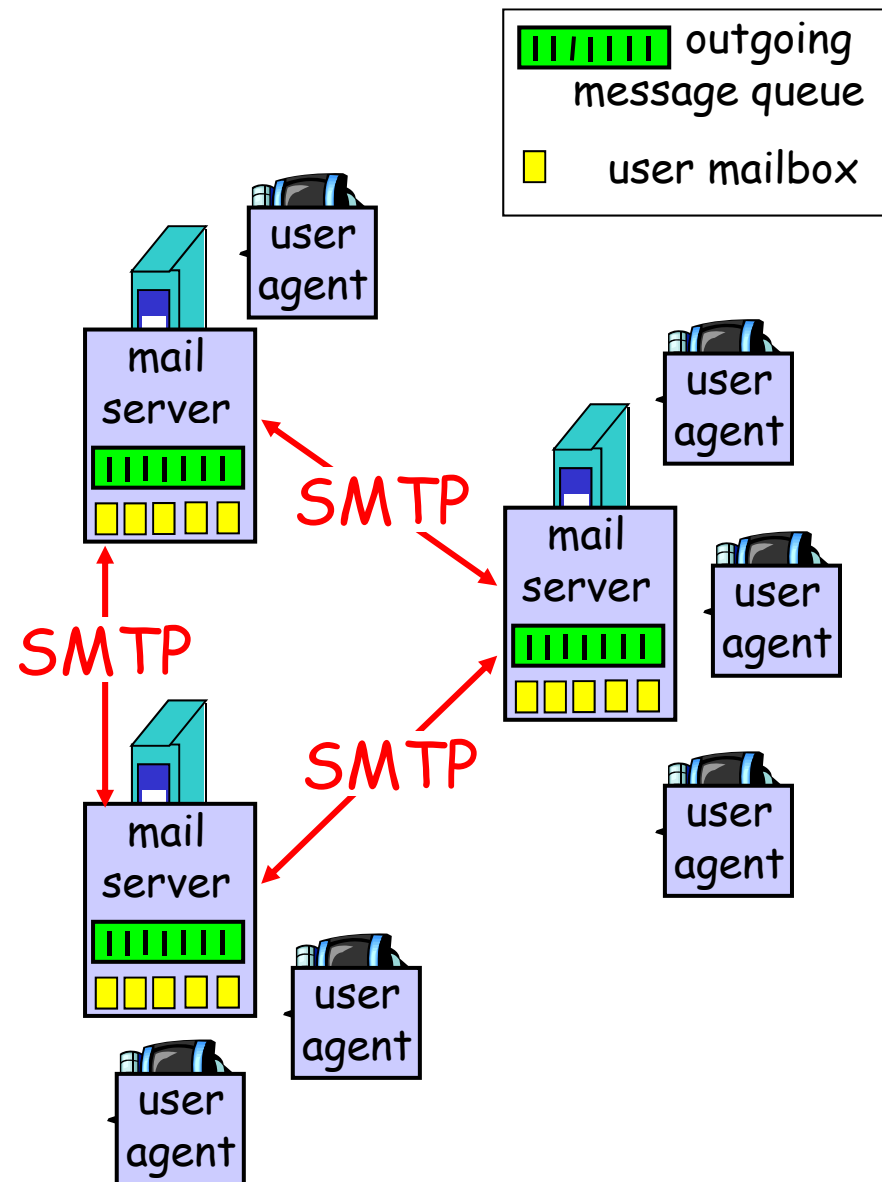
Electronic Mail

Three major components:

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

User Agent

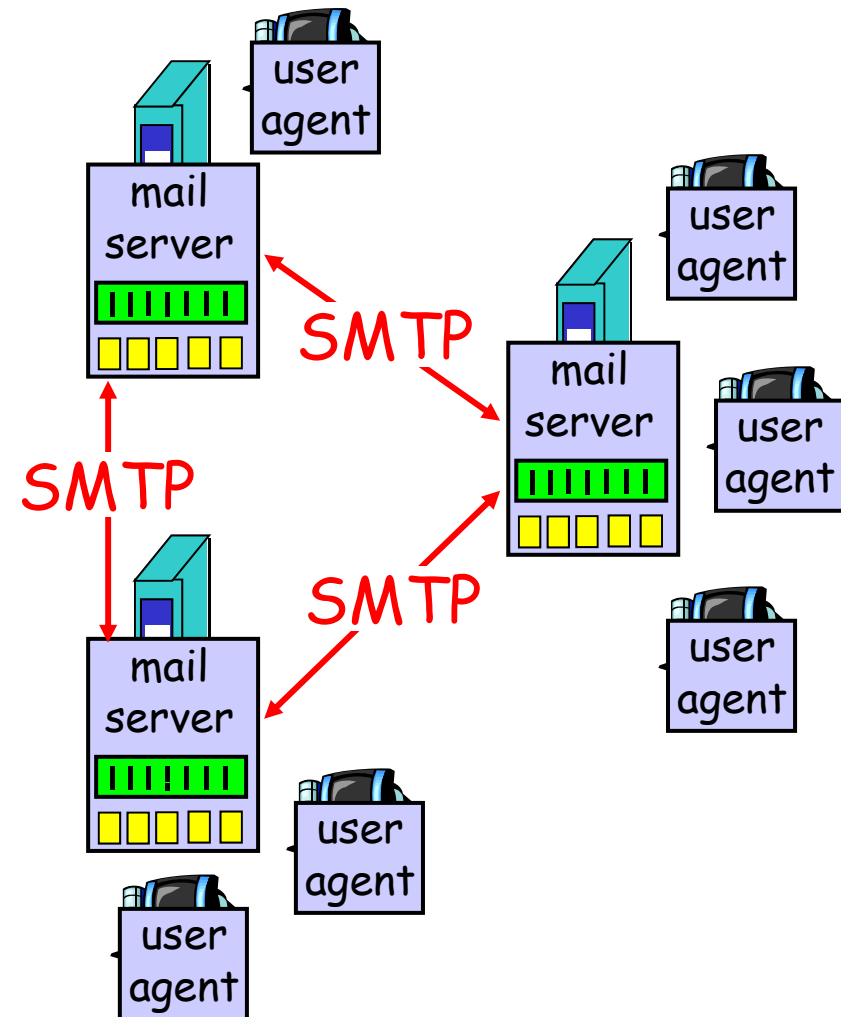
- ❑ a.k.a. "mail reader"
- ❑ composing, editing, reading mail messages
- ❑ e.g., Eudora, Outlook, elm, Mozilla Thunderbird
- ❑ outgoing, incoming messages stored on server



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

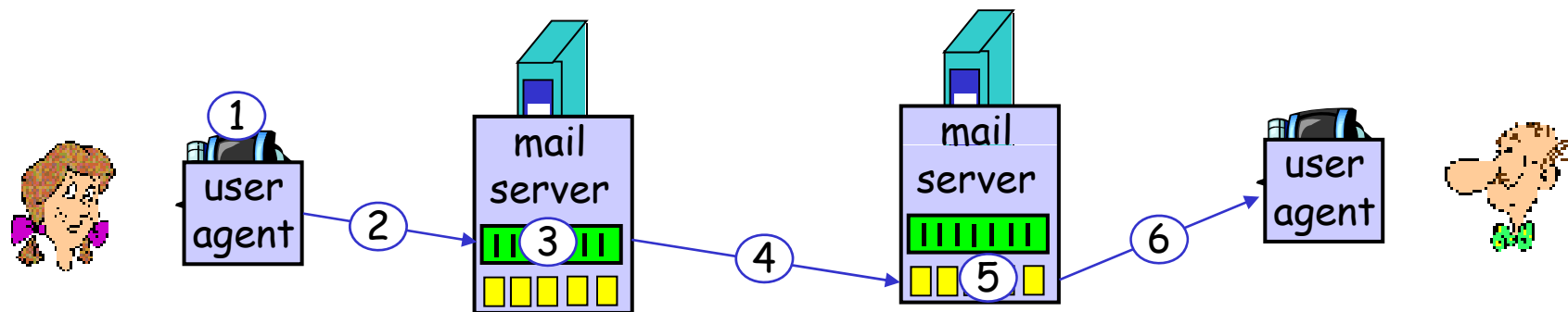


Electronic Mail: SMTP [RFC 2821]

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



Sample SMTP interaction

```
S: 220 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:

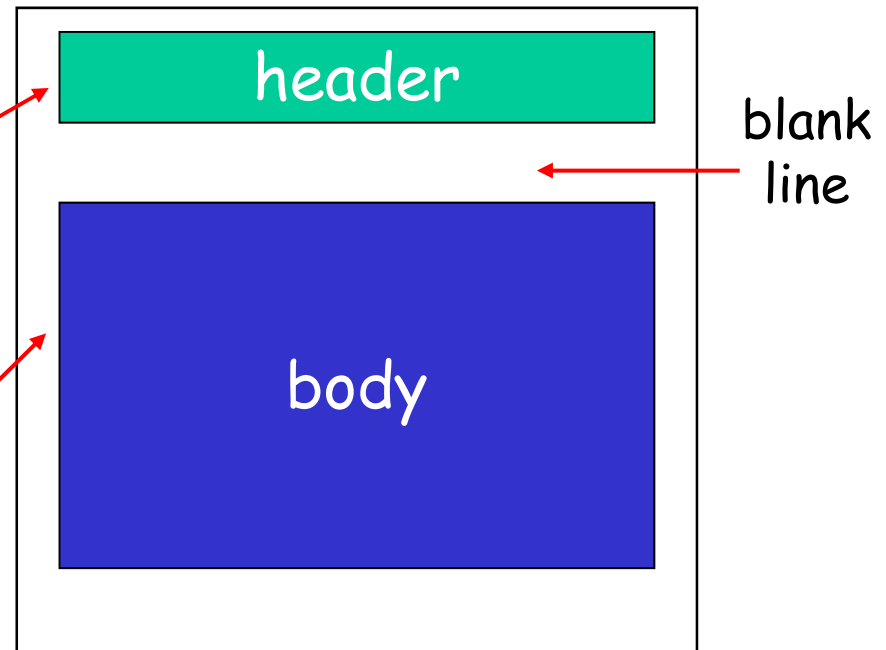
- ❑ HTTP: pull
- ❑ SMTP: push
- ❑ both have ASCII command/response interaction, status codes
- ❑ HTTP: each object encapsulated in its own response msg
- ❑ SMTP: multiple objects sent in multipart msg

Mail message format

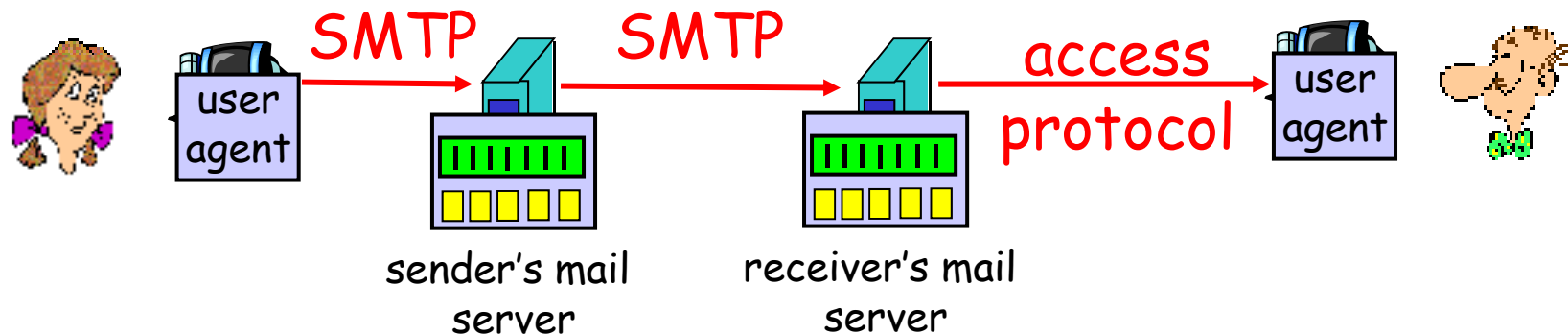
SMTP: protocol for exchanging email msgs

RFC 822: standard for text message format:

- ❑ header lines, e.g.,
 - ❖ To:
 - ❖ From:
 - ❖ Subject:*different from SMTP 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 (agent <-->server) and download
 - ❖ IMAP: Internet Mail Access Protocol [RFC 1730]
 - more features (more complex)
 - 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 “download and delete” mode.
- ❑ Bob cannot re-read e-mail if he changes client
- ❑ “Download-and-keep”: copies of messages on different clients
- ❑ POP3 is stateless across sessions

IMAP

- ❑ Keep all messages in one place: the server
- ❑ Allows user to organize messages in folders
- ❑ IMAP keeps user state across sessions:
 - ❖ names of folders and mappings between message IDs and folder name

Chapter 2: Application layer

- ❑ 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 TCP
- ❑ 2.8 Socket programming with UDP
- ❑ 2.9 Building a Web server

DNS: Domain Name System

People: many identifiers:

- ❖ SSN, name, passport #

Internet hosts, routers:

- ❖ IP address (32 bit) - used for addressing datagrams
- ❖ "name", e.g.,
ww.yahoo.com - used by humans

Q: map between IP addresses and name ?

Domain Name System:

- *distributed database*
implemented in hierarchy of many *name servers*
- *application-layer protocol*
host, routers, name servers to communicate to *resolve* names (address/name translation)
 - ❖ note: core Internet function, implemented as application-layer protocol
 - ❖ complexity at network's "edge"

DNS

DNS services

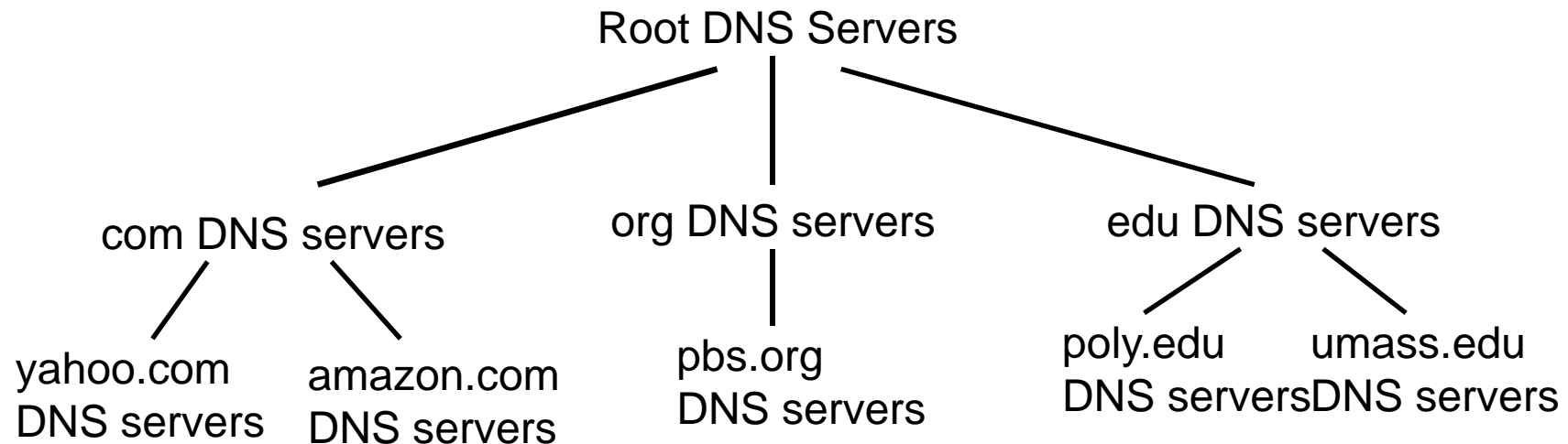
- ❑ hostname to IP address translation
- ❑ host aliasing
 - ❖ Canonical, alias names
- ❑ mail server aliasing
- ❑ load distribution
 - ❖ replicated Web servers: set of IP addresses for one canonical name

Why not centralize DNS?

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

doesn't *scale*!

Distributed, Hierarchical Database

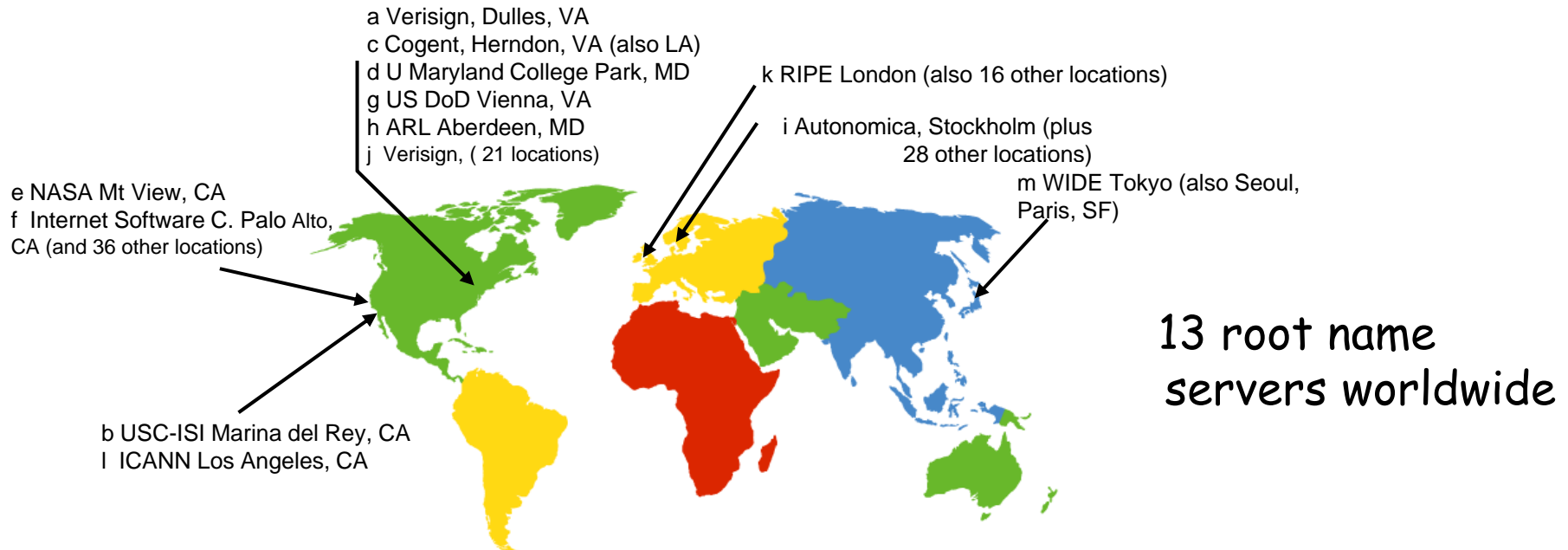


Client wants IP for www.amazon.com; 1st approx:

- ❑ client queries a 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



TLD and Authoritative Servers

❑ Top-level domain (TLD) servers:

- ❖ responsible for com, org, net, edu, etc, and all top-level country domains uk, fr, ca, jp.
- ❖ Network Solutions maintains servers for com TLD
- ❖ Educause for edu TLD

❑ Authoritative DNS servers:

- ❖ organization's DNS servers, providing authoritative hostname to IP mappings for organization's servers (e.g., Web, mail).
- ❖ can be maintained by organization or service provider

Local Name Server

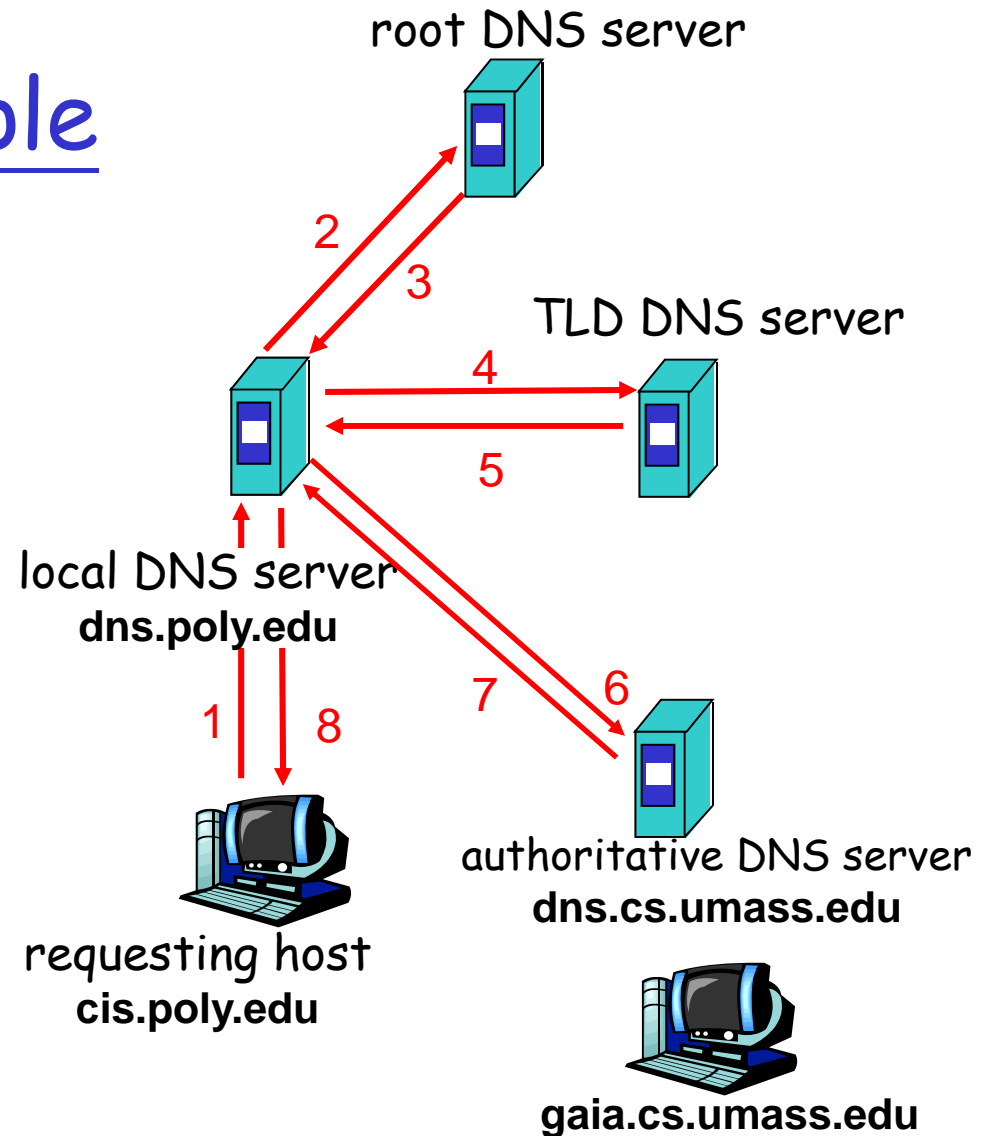
- ❑ does not strictly belong to hierarchy
- ❑ each ISP (residential ISP, company, university) has one.
 - ❖ also called "default name server"
- ❑ when host makes DNS query, query is sent to its local DNS server
 - ❖ acts as proxy, forwards query into hierarchy

DNS name resolution example

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

iterated query:

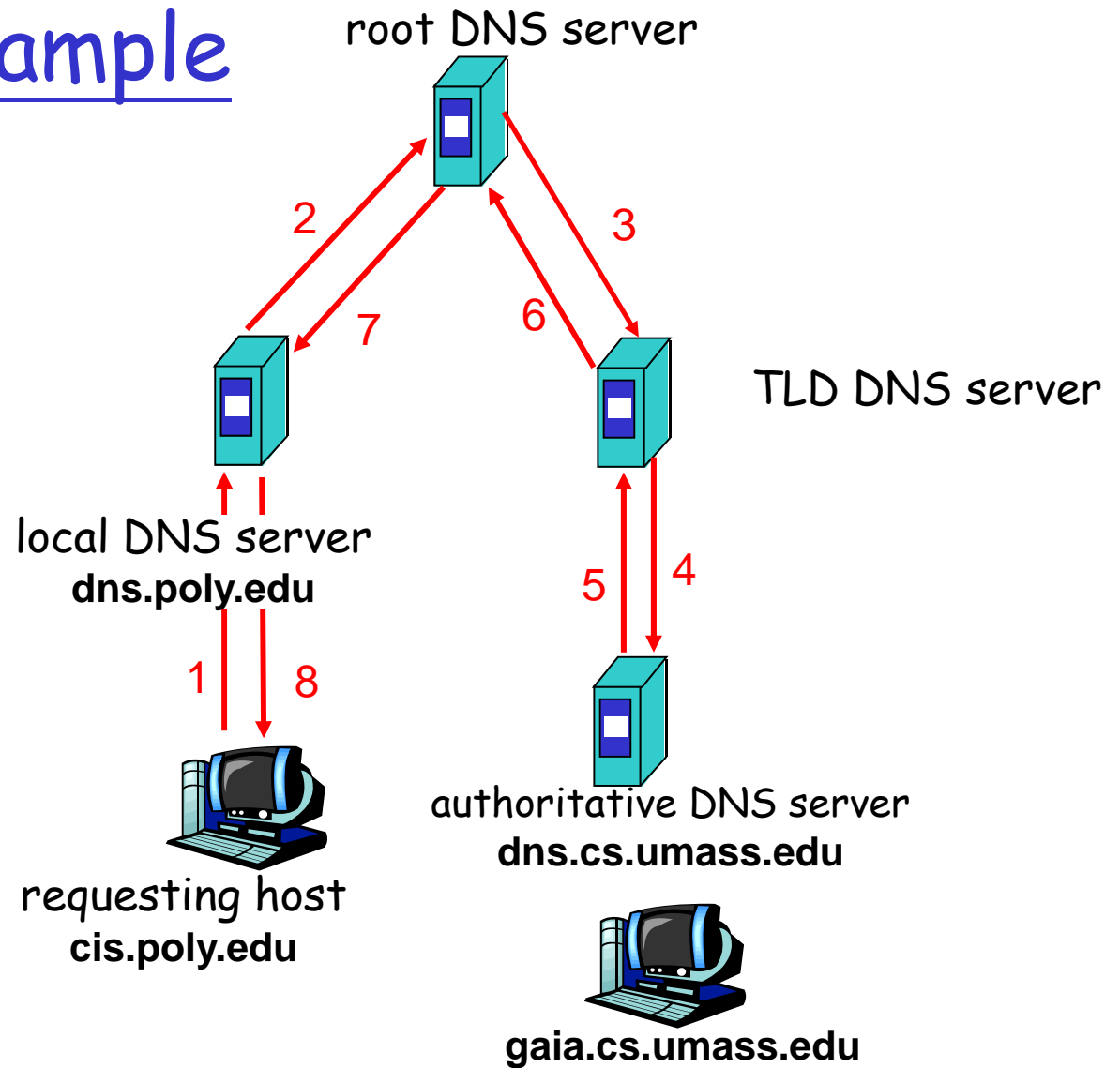
- contacted server replies with name of server to contact
- "I don't know this name, but ask this server"



DNS name resolution example

recursive query:

- ❑ puts burden of name resolution on contacted name server
- ❑ heavy load?



DNS: caching and updating records

- once (any) name server learns mapping, it *caches* mapping
 - ❖ cache entries timeout (disappear) after some time
 - ❖ TLD servers typically cached in local name servers
 - Thus root name servers not often visited
- update/notify mechanisms under design by IETF
 - ❖ RFC 2136
 - ❖ <http://www.ietf.org/html.charters/dnsind-charter.html>

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

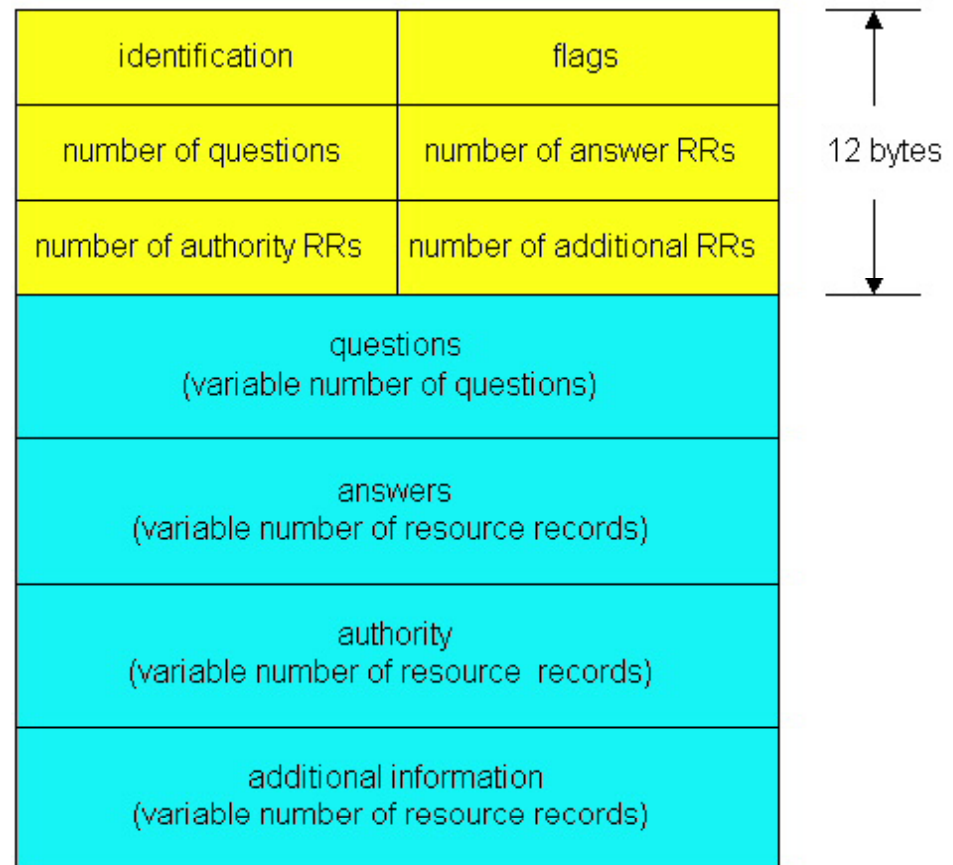
- ❖ value is name of mailserver associated with name

DNS protocol, messages

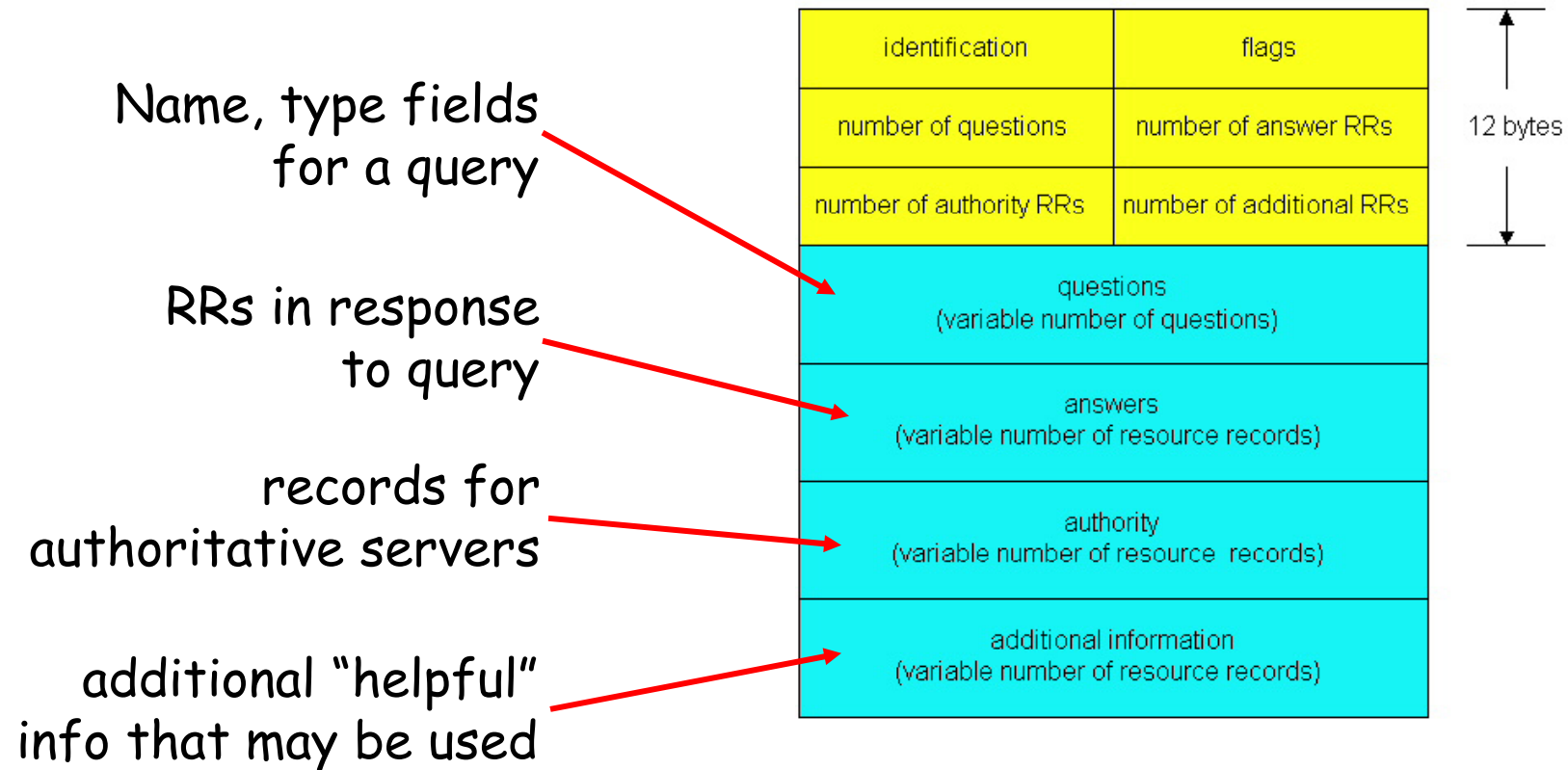
DNS protocol : *query* and *reply* messages, both with same *message format*

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)
```

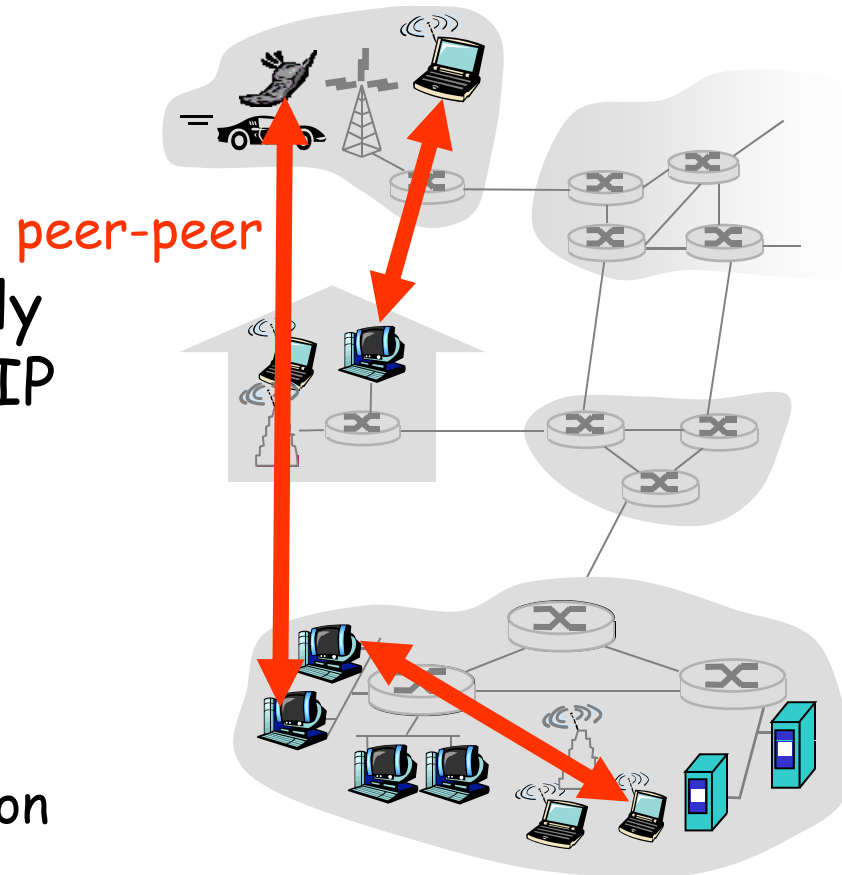
- ❑ create authoritative server Type A record for `www.networkutopia.com`; Type MX record for `networkutopia.com`
- ❑ *How do people get IP address of your Web site?*

Chapter 2: Application layer

- ❑ 2.1 Principles of network applications
 - ❖ app architectures
 - ❖ app requirements
- ❑ 2.2 Web and HTTP
- ❑ 2.4 Electronic Mail
 - ❖ SMTP, POP3, IMAP
- ❑ 2.5 DNS
- ❑ 2.6 P2P applications
- ❑ 2.7 Socket programming with TCP
- ❑ 2.8 Socket programming with UDP

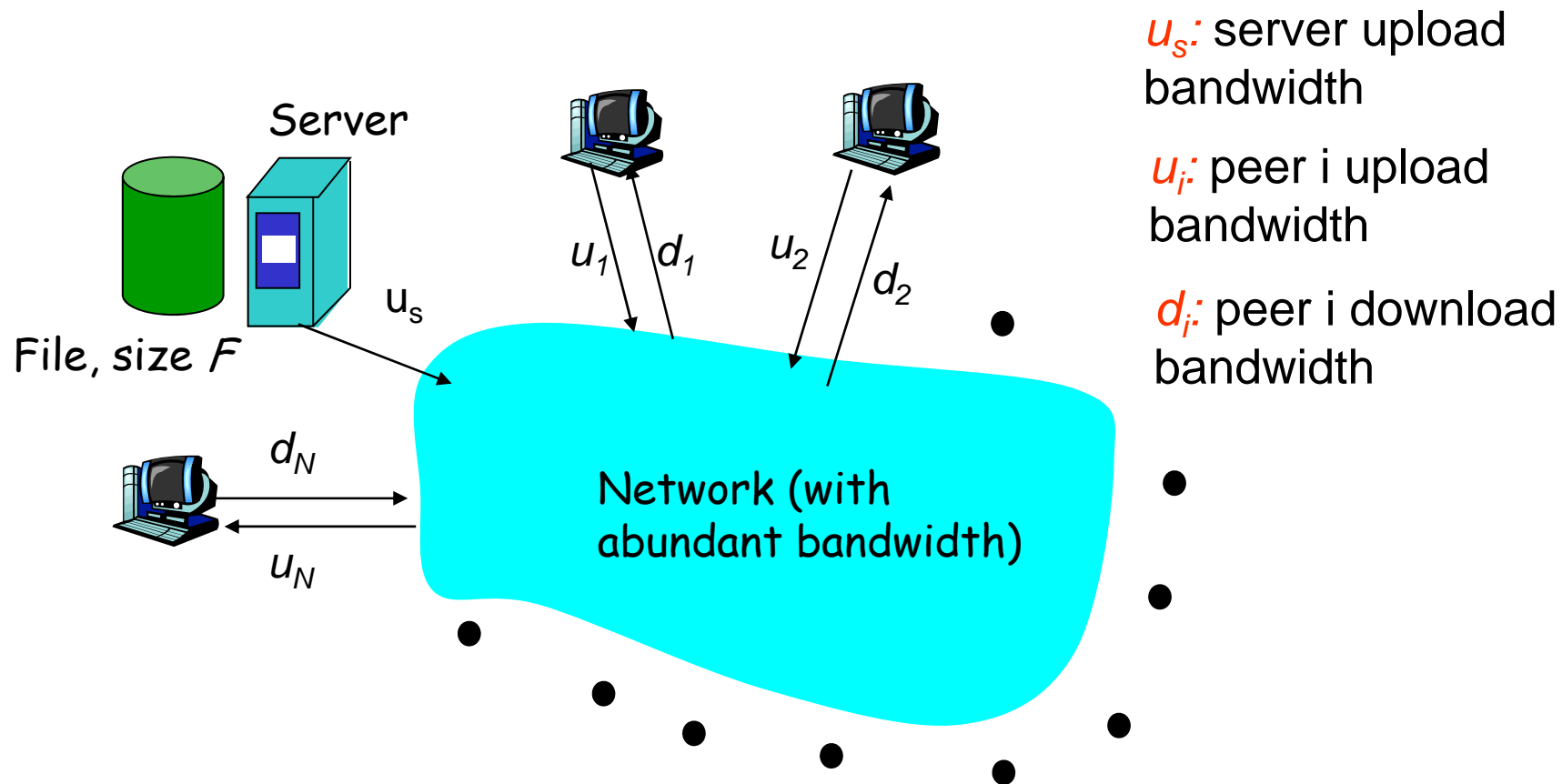
Pure P2P architecture

- ❑ *no* always-on server
- ❑ arbitrary end systems directly communicate
- ❑ peers are intermittently connected and change IP addresses
- ❑ Three topics:
 - ❖ File distribution
 - ❖ Searching for information
 - ❖ Case Study: Skype



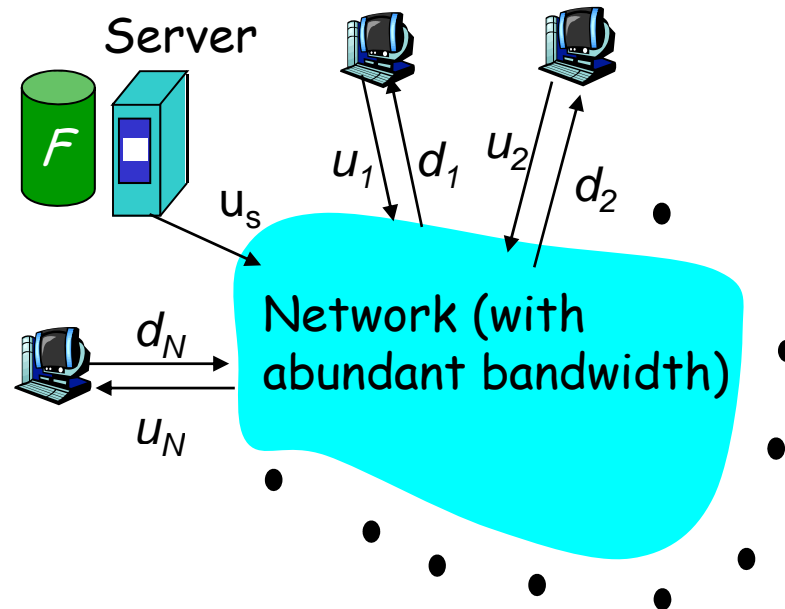
File Distribution: Server-Client vs P2P

Question: How much time to distribute file from one server to N peers?



File distribution time: server-client

- server sequentially sends N copies:
 - ❖ NF/u_s time
- client i takes F/d_i time to download

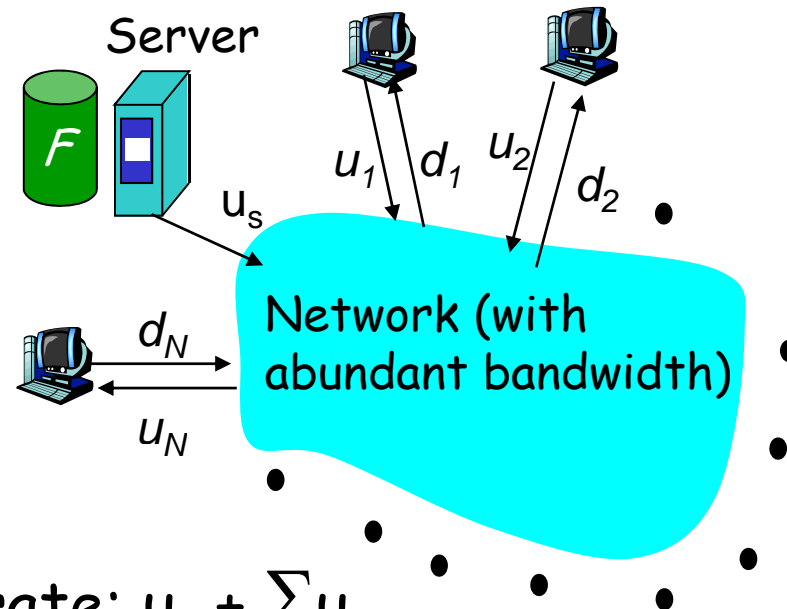


Time to distribute F
to N clients using client/server approach $= d_{cs} = \max \{ NF/u_s, F/\min_i(d_i) \}$

increases linearly in N
(for large N)

File distribution time: P2P

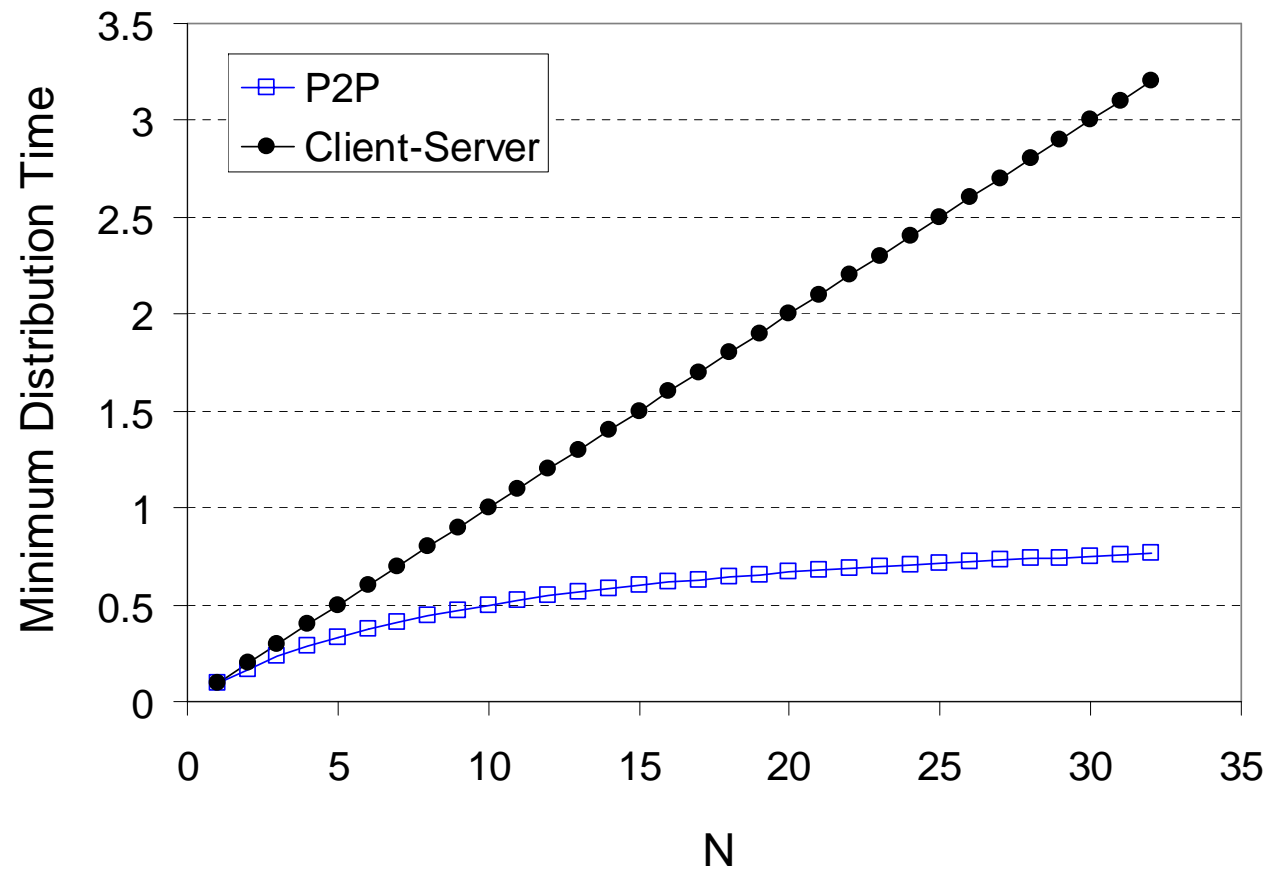
- ❑ server must send one copy: F/u_s time
- ❑ client i takes F/d_i time to download
- ❑ NF bits must be downloaded (aggregate)
 - ❑ fastest possible upload rate: $u_s + \sum u_i$



$$d_{\text{P2P}} = \max \left\{ F/u_s, F/\min(d_i)_i, NF/(u_s + \sum u_i) \right\}$$

Server-client vs. P2P: example

Client upload rate = u , $F/u = 1$ hour, $u_s = 10u$, $d_{\min} \geq u_s$

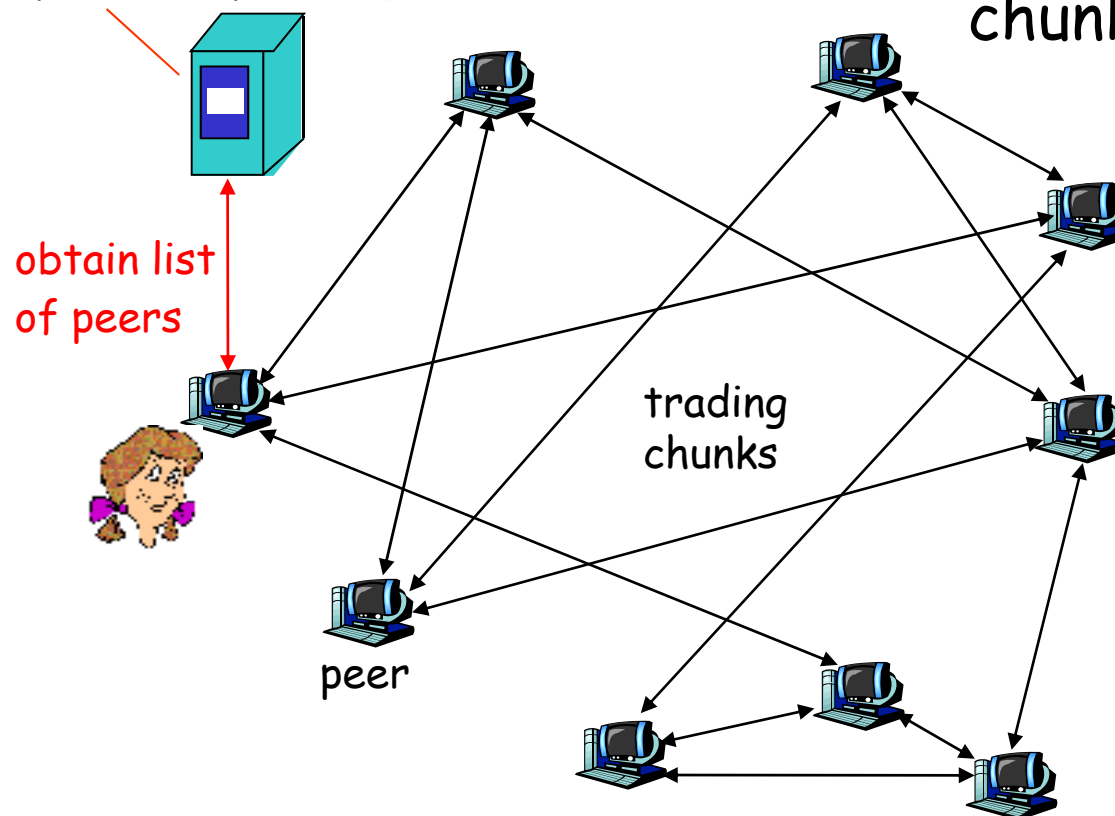


File distribution: BitTorrent

□ P2P file distribution

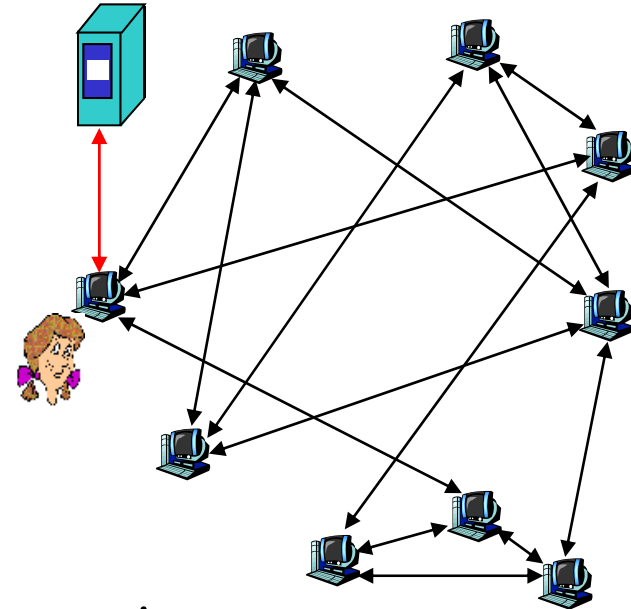
tracker: tracks peers participating in torrent

torrent: group of peers exchanging chunks of a file



BitTorrent (1)

- ❑ file divided into 256KB *chunks*.
- ❑ peer joining torrent:
 - ❖ has no chunks, but will accumulate them over time
 - ❖ registers with tracker to get list of peers, connects to subset of peers ("neighbors")
- ❑ while downloading, peer uploads chunks to other peers.
- ❑ peers may come and go
- ❑ once peer has entire file, it may (selfishly) leave or (altruistically) remain



BitTorrent (2)

Pulling Chunks

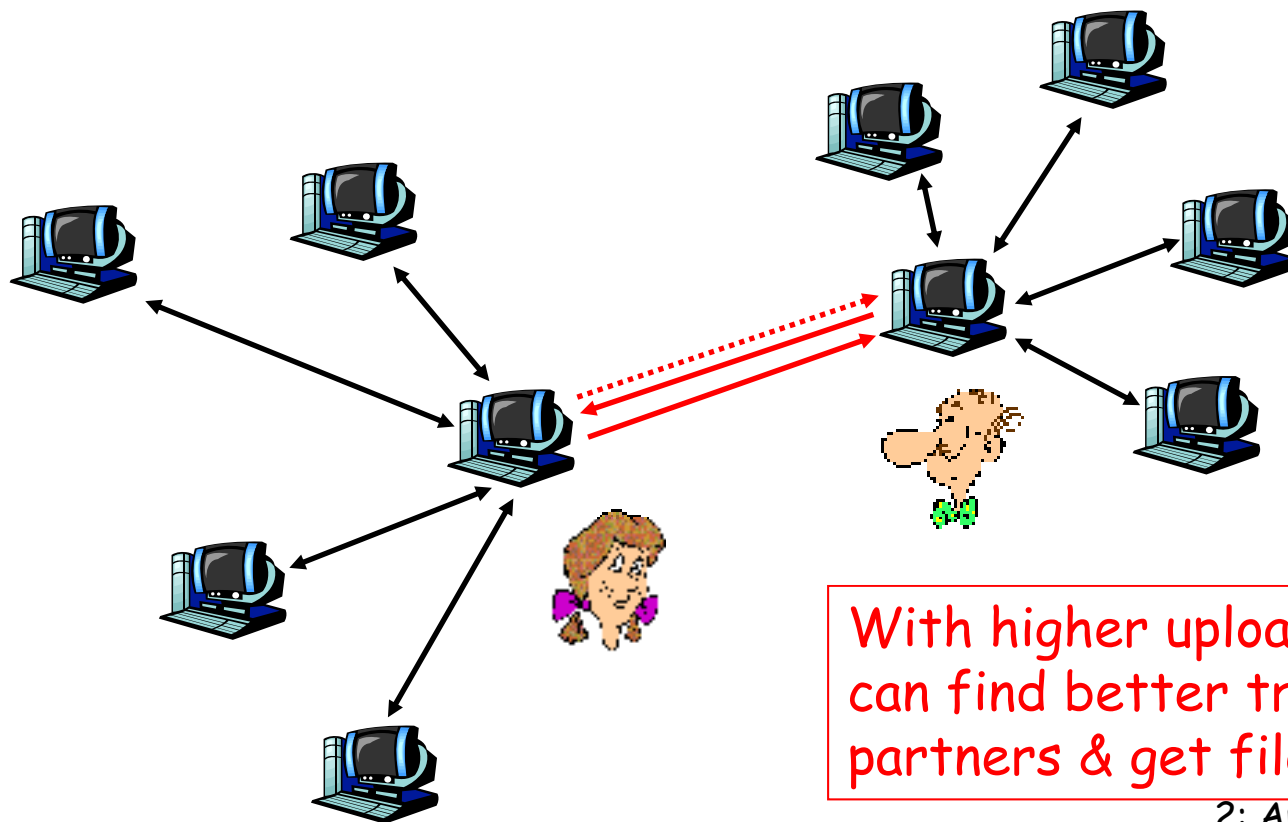
- at any given time, different peers have different subsets of file chunks
- periodically, a peer (Alice) asks each neighbor for list of chunks that they have.
- Alice sends requests for her missing chunks
 - ❖ rarest first

Sending Chunks: tit-for-tat

- Alice sends chunks to four neighbors currently sending her chunks *at the highest rate*
 - ❖ re-evaluate top 4 every 10 secs
- every 30 secs: randomly select another peer, starts sending chunks
 - ❖ newly chosen peer may join top 4
 - ❖ "optimistically unchoke"

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



With higher upload rate,
can find better trading
partners & get file faster!

Distributed Hash Table (DHT)

- ❑ DHT = distributed P2P database
- ❑ Database has (key, value) pairs;
 - ❖ key: ss number; value: human name
 - ❖ key: content type; value: IP address
- ❑ Peers query DB with key
 - ❖ DB returns values that match the key
- ❑ Peers can also insert (key, value) peers

DHT Identifiers

- ❑ Assign integer identifier to each peer in range $[0, 2^n - 1]$.
 - ❖ Each identifier can be represented by n bits.
- ❑ Require each key to be an integer in **same range**.
- ❑ To get integer keys, hash original key.
 - ❖ eg, key = $h(\text{"Led Zeppelin IV"})$
 - ❖ This is why they call it a distributed "hash" table

How to assign keys to peers?

- Central issue:

- ❖ Assigning (key, value) pairs to peers.

- Rule: assign key to the peer that has the **closest** ID.

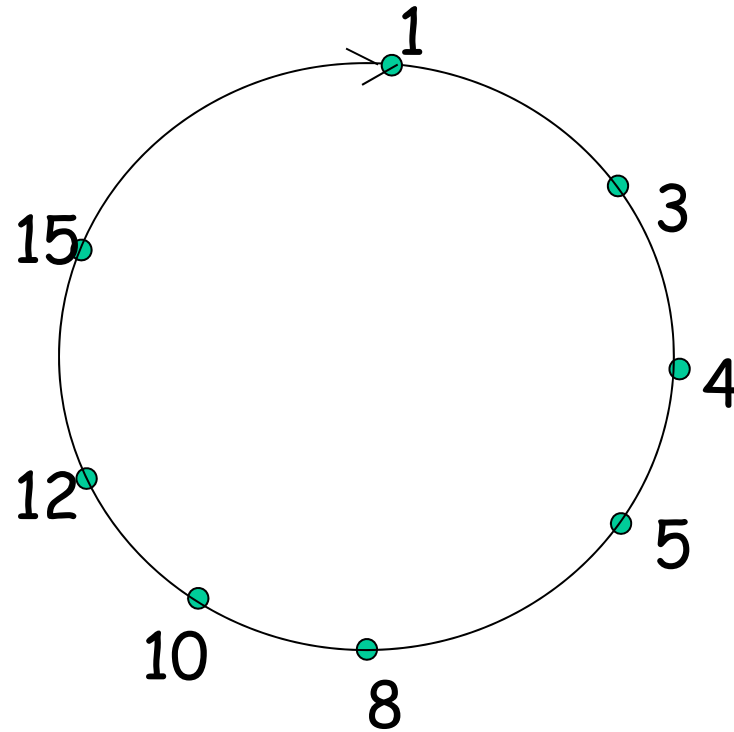
- Convention in lecture: closest is the **immediate successor** of the key.

- Ex: $n=4$; peers: 1,3,4,5,8,10,12,14;

- ❖ key = 13, then successor peer = 14

- ❖ key = 15, then successor peer = 1

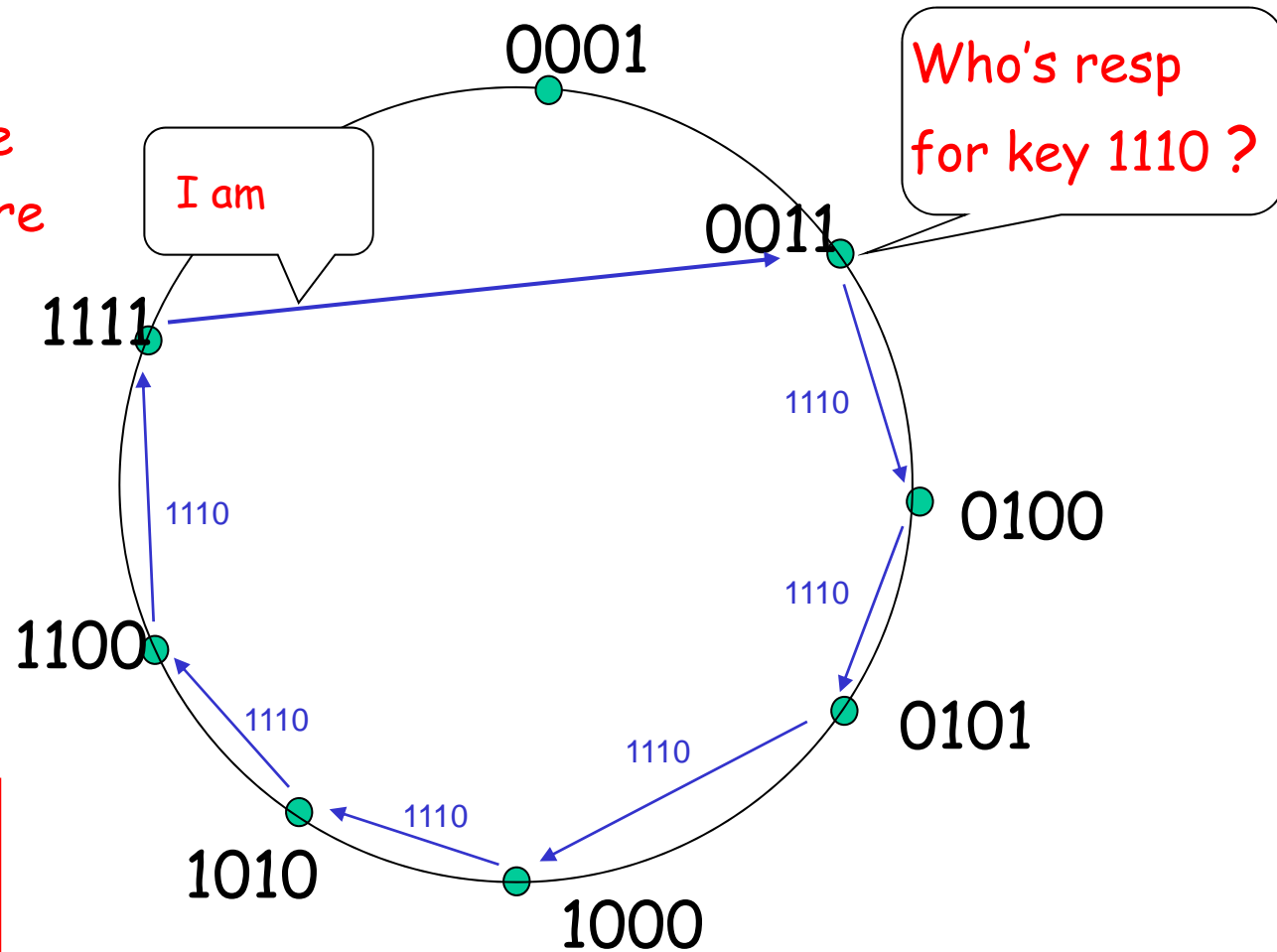
Circular DHT (1)



- ❑ Each peer *only* aware of immediate successor and predecessor.
- ❑ "Overlay network"

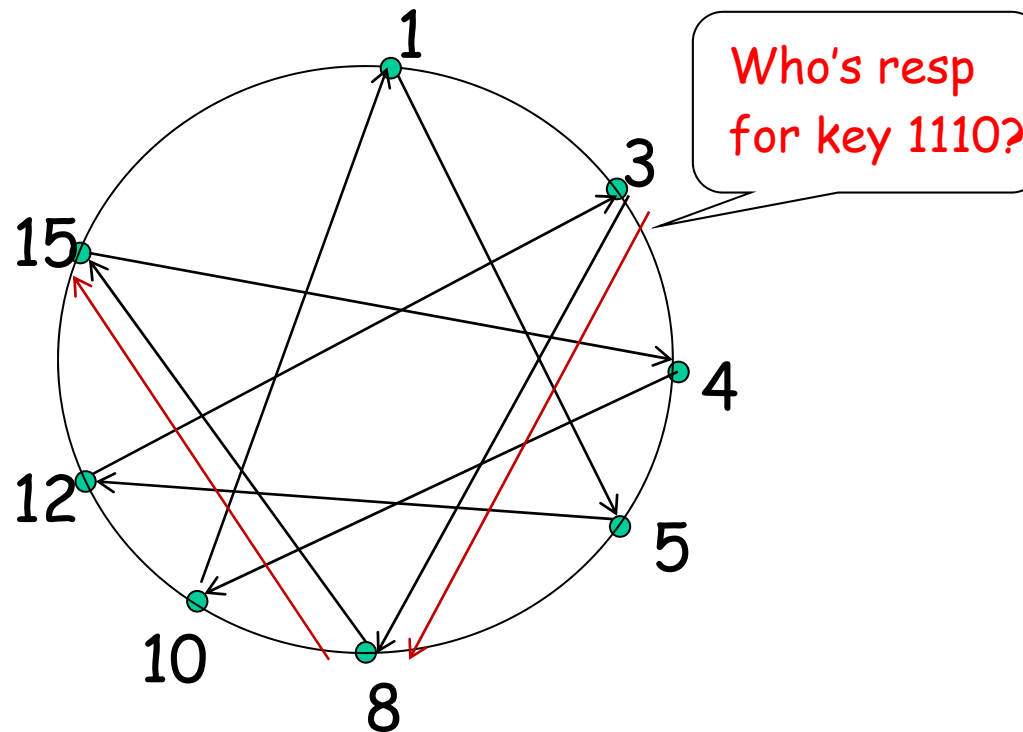
Circle DHT (2)

$O(N)$ messages
on avg to resolve
query, when there
are N peers



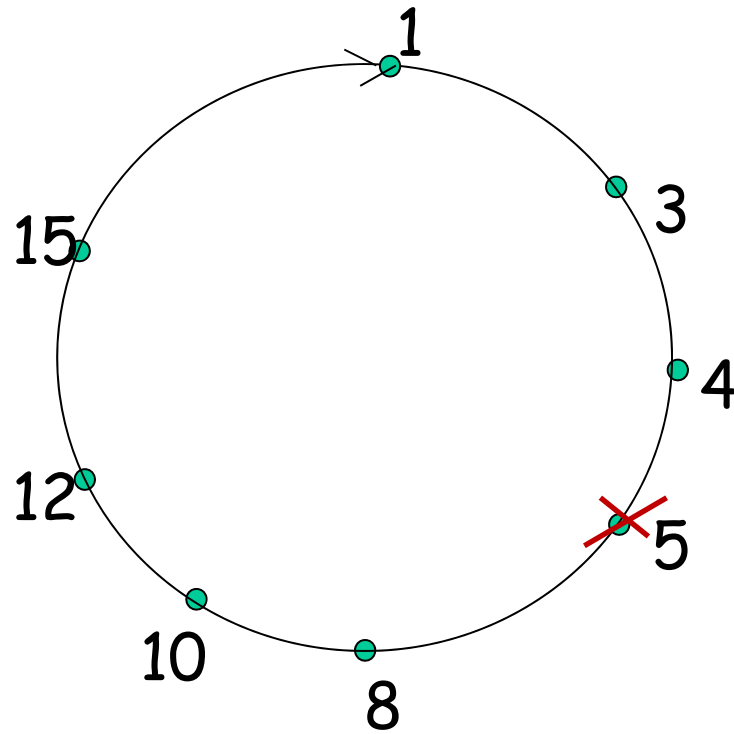
Define closest
as closest
successor

Circular DHT with Shortcuts



- ❑ Each peer keeps track of IP addresses of predecessor, successor, short cuts.
- ❑ Reduced from 6 to 2 messages.
- ❑ Possible to design shortcuts so $O(\log N)$ neighbors, $O(\log N)$ messages in query

Peer Churn

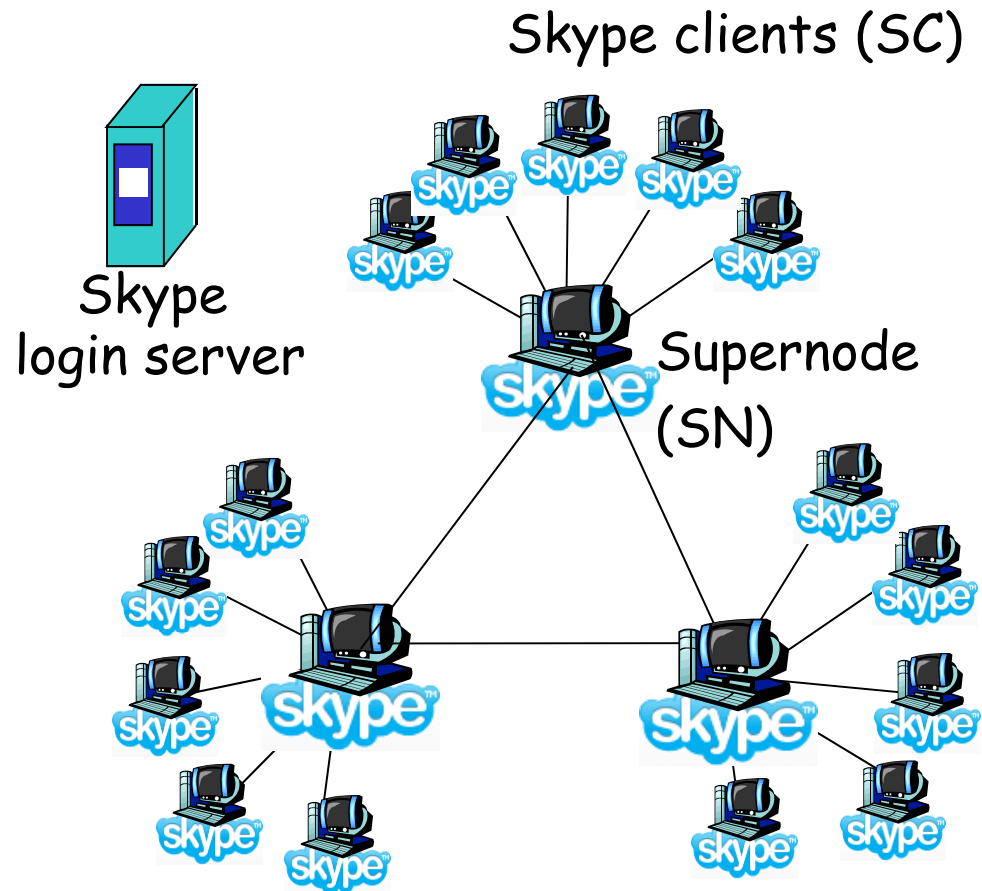


- To handle peer churn, require each peer to know the IP address of its two successors.
- Each peer periodically pings its two successors to see if they are still alive.

- ❑ Peer 5 abruptly leaves
- ❑ Peer 4 detects; makes 8 its immediate successor; asks 8 who its immediate successor is; makes 8's immediate successor its second successor.
- ❑ What if peer 13 wants to join?

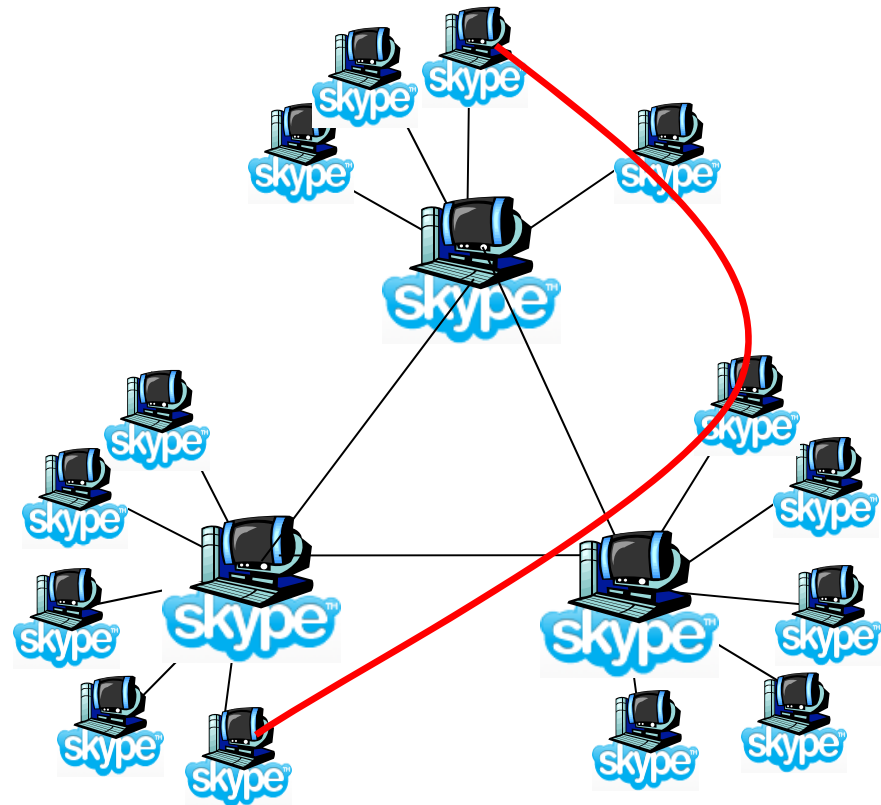
P2P Case study: Skype

- ❑ inherently P2P: pairs of users communicate.
- ❑ proprietary application-layer protocol (inferred via reverse engineering)
- ❑ hierarchical overlay with SNs
- ❑ Index maps usernames to IP addresses; distributed over SNs



Peers as relays

- ❑ Problem when both Alice and Bob are behind "NATs".
 - ❖ NAT prevents an outside peer from initiating a call to insider peer
- ❑ Solution:
 - ❖ Using Alice's and Bob's SNs, Relay is chosen
 - ❖ Each peer initiates session with relay.
 - ❖ Peers can now communicate through NATs via relay



Chapter 2: Application layer

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- ❑ 2.2 Web and HTTP
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- ❑ 2.8 Socket programming with UDP

Socket programming

Goal: learn how to build client/server application that communicate using sockets

Socket API

- ❑ introduced in BSD4.1 UNIX, 1981
- ❑ explicitly created, used, released by apps
- ❑ client/server paradigm
- ❑ two types of transport service via socket API:
 - ❖ unreliable datagram
 - ❖ reliable, byte stream-oriented

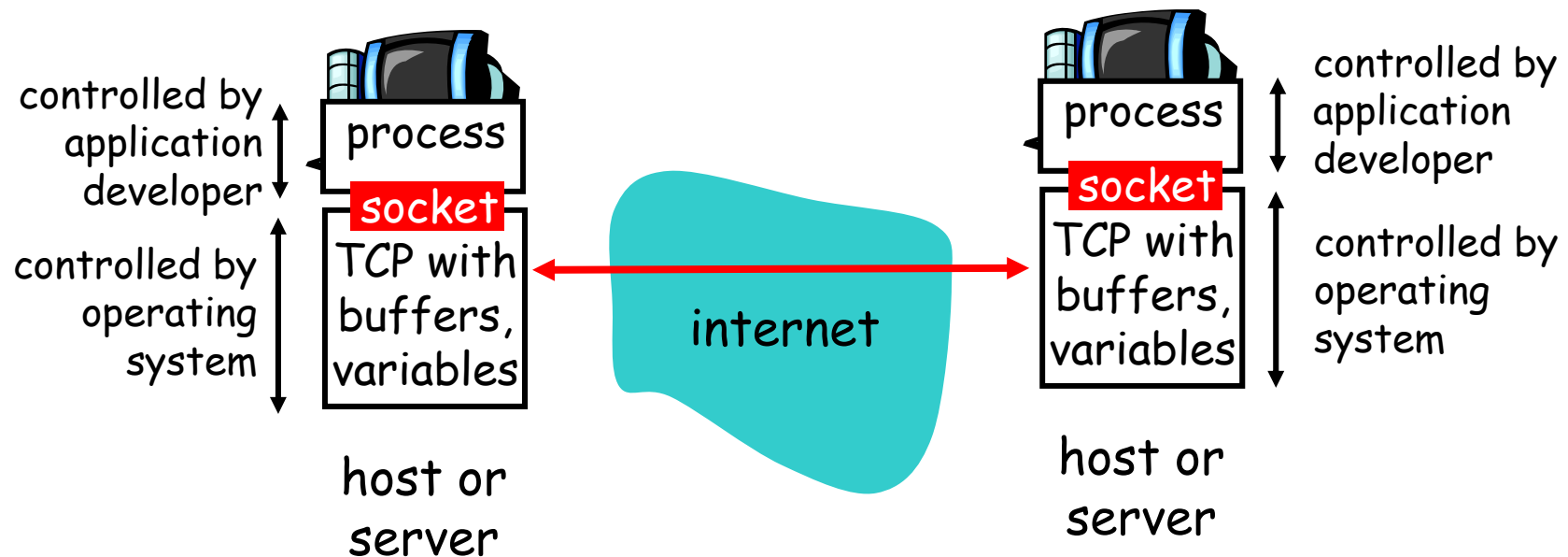
socket

a *host-local, application-created, OS-controlled* interface (a "door") into which application process can *both send and receive* messages to/from another application process

Socket-programming using TCP

Socket: a door between application process and end-end-transport protocol (UCP or TCP)

TCP service: reliable transfer of **bytes** from one process to another



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 client-local 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 client
 - ❖ allows server to talk with multiple clients
 - ❖ source port numbers used to distinguish clients (*more in Chap 3*)

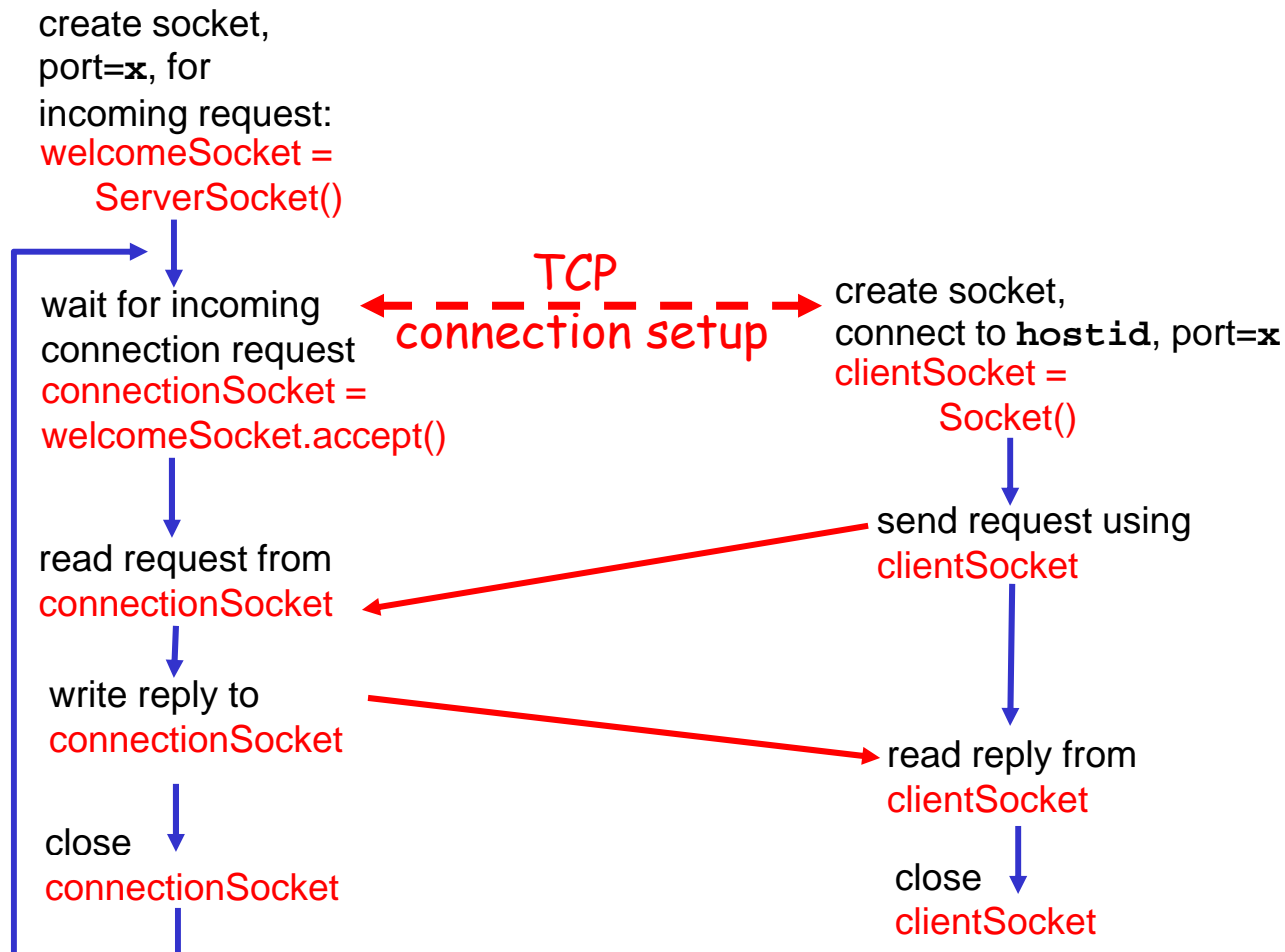
application viewpoint

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

Client/server socket interaction: TCP

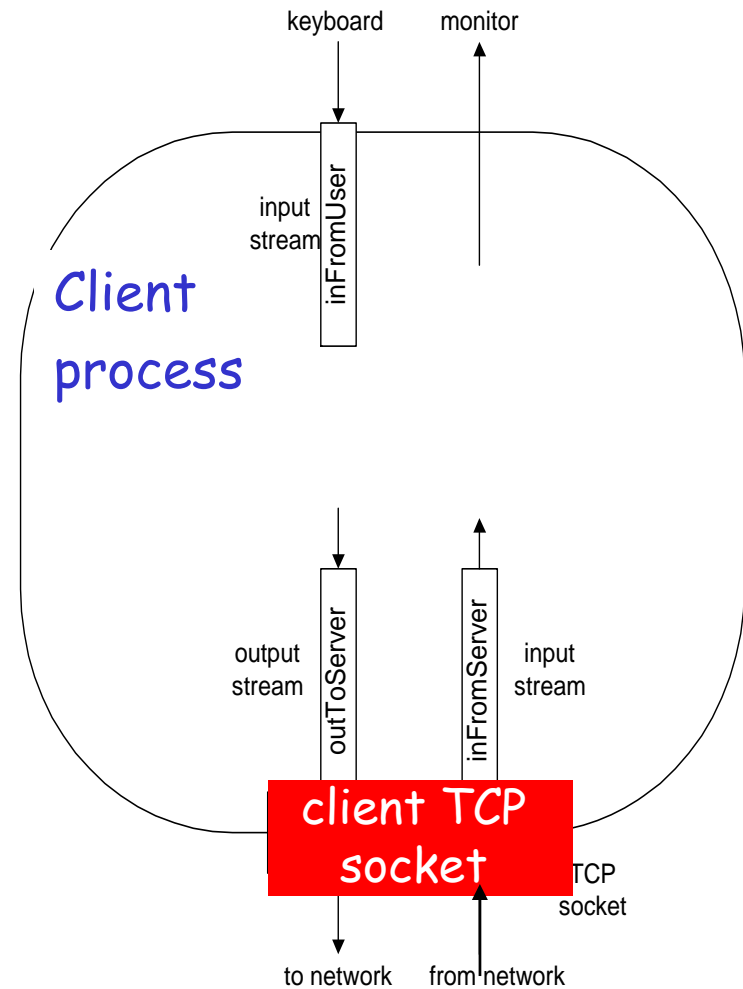
Server (running on `hostid`)

Client



Stream jargon

- A **stream** is a sequence of characters that flow into or out of a process.
- An **input stream** is attached to some input source for the process, e.g., keyboard or socket.
- An **output stream** is attached to an output source, e.g., monitor or socket.



Socket programming with TCP

Example client-server app:

- 1) client reads line from standard input (`inFromUser` stream) , sends to server via socket (`outToServer` stream)
- 2) server reads line from socket
- 3) server converts line to uppercase, sends back to client
- 4) client reads, prints modified line from socket (`inFromServer` stream)

Example: Java client (TCP)

```
import java.io.*;
import java.net.*;
class TCPCClient {
```

```
    public static void main(String argv[]) throws Exception
    {
```

```
        String sentence;
        String modifiedSentence;
```

Create
input stream



```
        BufferedReader inFromUser =
            new BufferedReader(new InputStreamReader(System.in));
```

Create
client socket,
connect to server



```
        Socket clientSocket = new Socket("hostname", 6789);
```

Create
output stream
attached to socket



```
        DataOutputStream outToServer =
            new DataOutputStream(clientSocket.getOutputStream());
```

Example: Java client (TCP), cont.

Create
input stream
attached to socket

→

```
BufferedReader inFromServer =  
    new BufferedReader(new  
        InputStreamReader(clientSocket.getInputStream()));  
  
sentence = inFromUser.readLine();  
  
Send line  
to server

→



```
outToServer.writeBytes(sentence + '\n');

Read line
from server

→


```
modifiedSentence = inFromServer.readLine();  
  
System.out.println("FROM SERVER: " + modifiedSentence);  
  
clientSocket.close();  
  
}  
}
```


```


```

Example: Java server (TCP)

```
import java.io.*;  
import java.net.*;
```

```
class TCPServer {
```

```
    public static void main(String argv[]) throws Exception  
    {
```

```
        String clientSentence;  
        String capitalizedSentence;
```

Create
welcoming socket
at port 6789

```
        ServerSocket welcomeSocket = new ServerSocket(6789);
```

Wait, on welcoming
socket for contact
by client

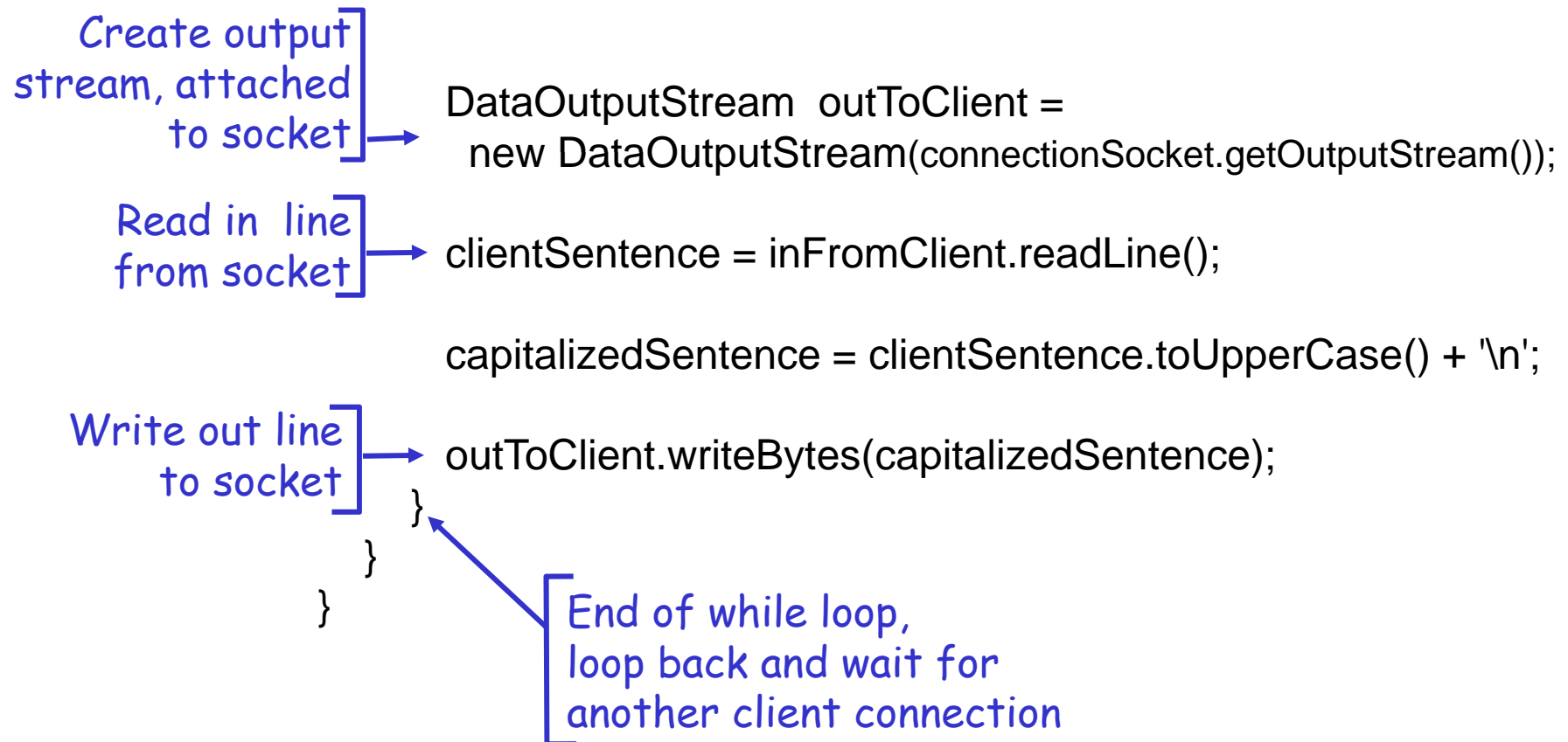
```
        while(true) {
```

```
            Socket connectionSocket = welcomeSocket.accept();
```

Create input
stream, attached
to socket

```
            BufferedReader inFromClient =  
                new BufferedReader(new  
                    InputStreamReader(connectionSocket.getInputStream()));
```

Example: Java server (TCP), cont



Chapter 2: Application layer

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Socket programming *with UDP*

UDP: no "connection" between client and server

- ❑ no handshaking
- ❑ sender explicitly attaches IP address and port of destination to each packet
- ❑ server must extract IP address, port of sender from received packet

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

application viewpoint

UDP provides unreliable transfer of groups of bytes ("datagrams") between client and server

Client/server socket interaction: UDP

Server (running on `hostid`)

Client

create socket,
port= x.
`serverSocket =`
`DatagramSocket()`

read datagram from
`serverSocket`

write reply to
`serverSocket`
specifying
client address,
port number

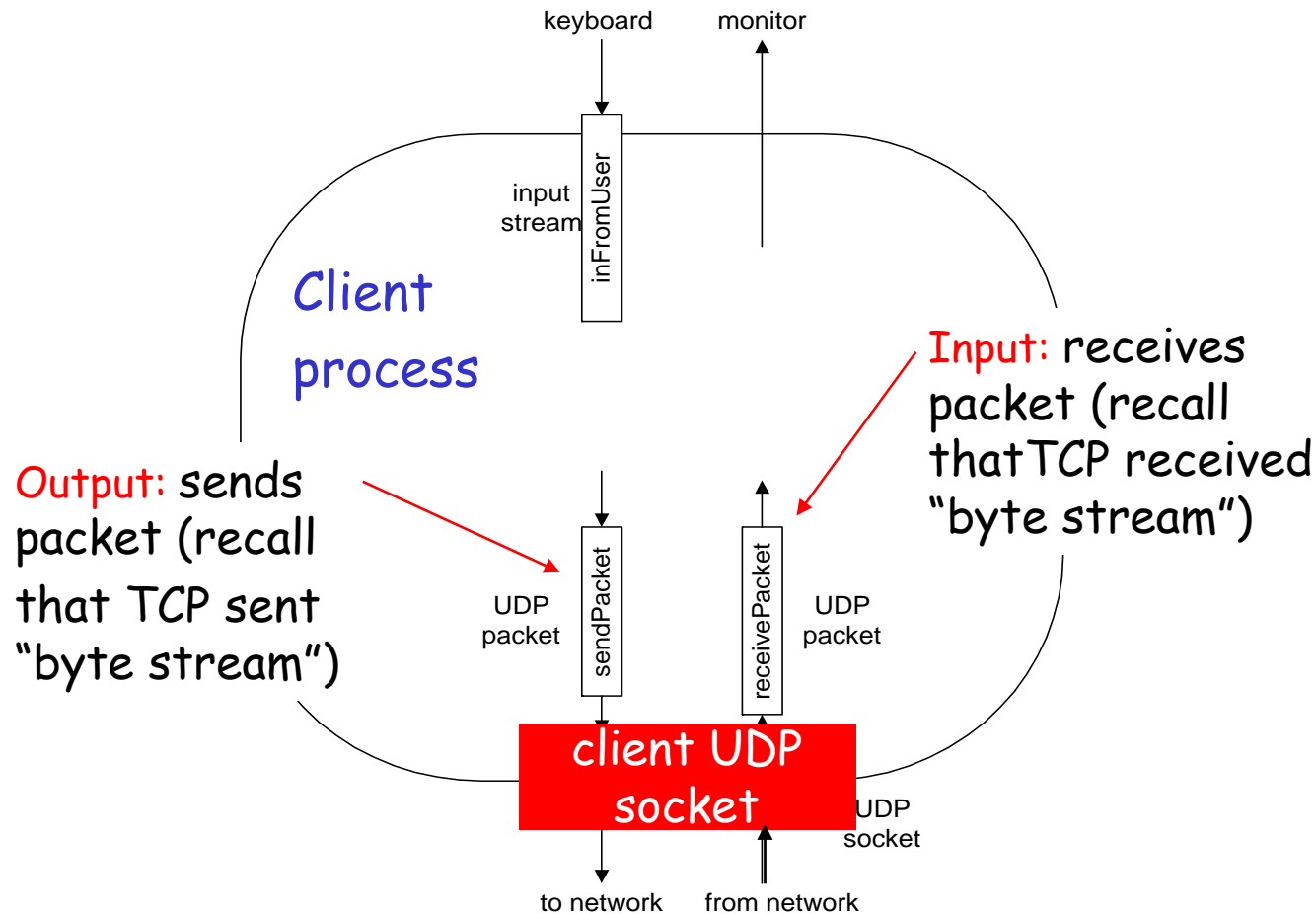
create socket,
`clientSocket =`
`DatagramSocket()`

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

read datagram from
`clientSocket`

close
`clientSocket`

Example: Java client (UDP)



Example: Java client (UDP)

```
import java.io.*;
import java.net.*;
```

```
class UDPClient {
    public static void main(String args[]) throws Exception
    {
```

Create
input stream

```
        BufferedReader inFromUser =
            new BufferedReader(new InputStreamReader(System.in));
```

Create
client socket

```
        DatagramSocket clientSocket = new DatagramSocket();
```

Translate
hostname to IP
address using DNS

```
        InetAddress IPAddress = InetAddress.getByName("hostname");
```

```
        byte[] sendData = new byte[1024];
        byte[] receiveData = new byte[1024];
```

```
        String sentence = inFromUser.readLine();
        sendData = sentence.getBytes();
```

Example: Java client (UDP), cont.

Create datagram
with data-to-send,
length, IP addr, port

Send datagram
to server

Read datagram
from server

```
DatagramPacket sendPacket =  
    new DatagramPacket(sendData, sendData.length, IPAddress, 9876);  
  
clientSocket.send(sendPacket);  
  
DatagramPacket receivePacket =  
    new DatagramPacket(receiveData, receiveData.length);  
  
clientSocket.receive(receivePacket);  
  
String modifiedSentence =  
    new String(receivePacket.getData());  
  
System.out.println("FROM SERVER:" + modifiedSentence);  
clientSocket.close();  
}  
}
```

Example: Java server (UDP)

```
import java.io.*;  
import java.net.*;
```

```
class UDPServer {  
    public static void main(String args[]) throws Exception  
    {
```

Create
datagram socket
at port 9876

```
        DatagramSocket serverSocket = new DatagramSocket(9876);
```

```
        byte[] receiveData = new byte[1024];  
        byte[] sendData = new byte[1024];
```

```
        while(true)  
        {
```

Create space for
received datagram

```
            DatagramPacket receivePacket =  
                new DatagramPacket(receiveData, receiveData.length);
```

Receive
datagram

```
            serverSocket.receive(receivePacket);
```

Example: Java server (UDP), cont

```
String sentence = new String(receivePacket.getData());
```

Get IP addr
port #, of
sender

```
→ InetAddress IPAddress = receivePacket.getAddress();
```

```
→ int port = receivePacket.getPort();
```

```
String capitalizedSentence = sentence.toUpperCase();
```

```
sendData = capitalizedSentence.getBytes();
```

Create datagram
to send to client

```
→ DatagramPacket sendPacket =  
  new DatagramPacket(sendData, sendData.length, IPAddress,  
    port);
```

Write out
datagram
to socket

```
→ serverSocket.send(sendPacket);
```

```
}  
}  
}
```

End of while loop,
loop back and wait for
another datagram

Chapter 2: Summary

our study of network apps now complete!

- application architectures

- ❖ client-server
- ❖ P2P
- ❖ hybrid

- 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, Skype

- socket programming

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"