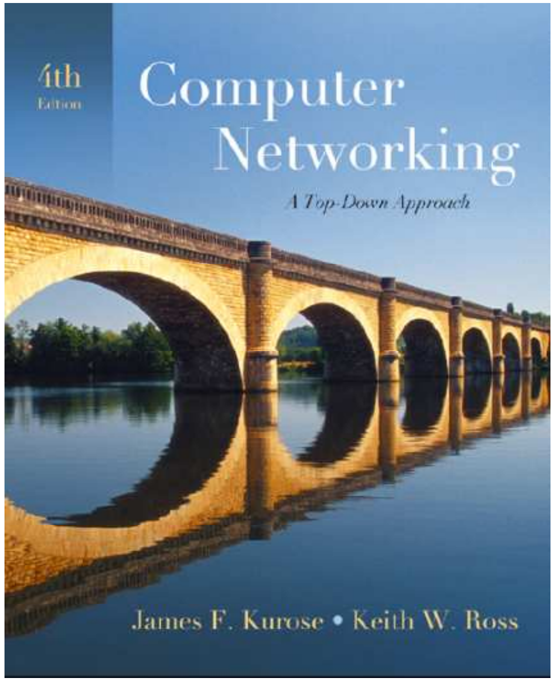
# Chapter 2
# Application Layer




*Computer Networking: A Top Down Approach,*
4th edition.
Jim Kurose, Keith Ross
Addison-Wesley, July 2007.

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# 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

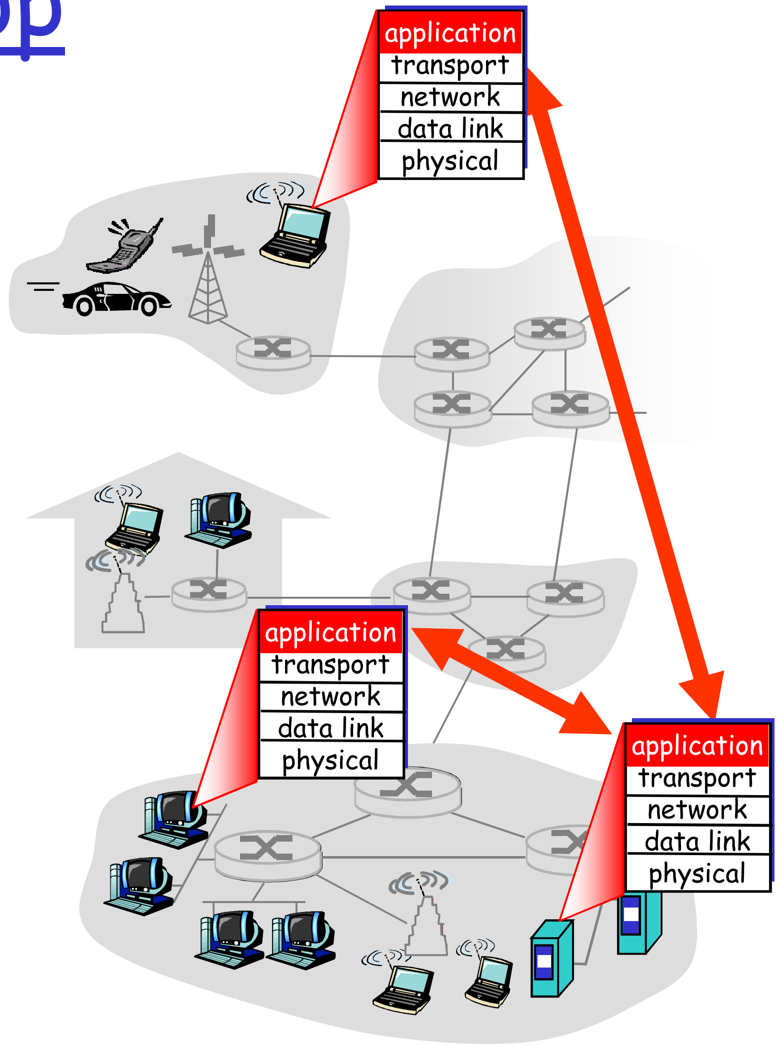
# Creating a network app

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

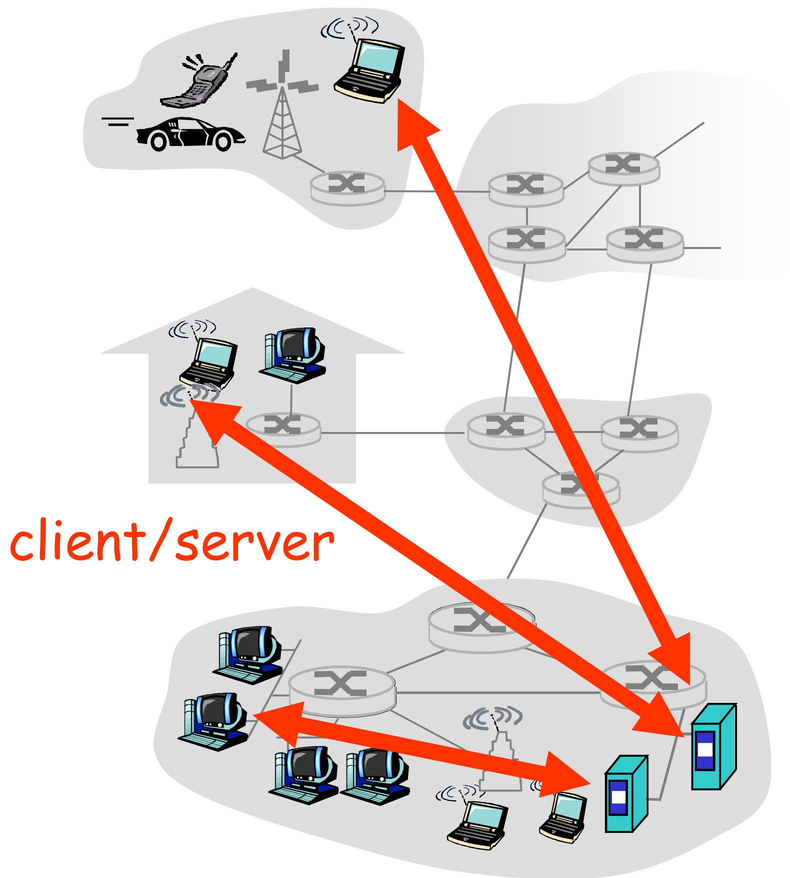
# Application architectures

Client-server

Peer-to-peer (P2P)

Hybrid of client-server and P2P

# Client-server architecture




server:

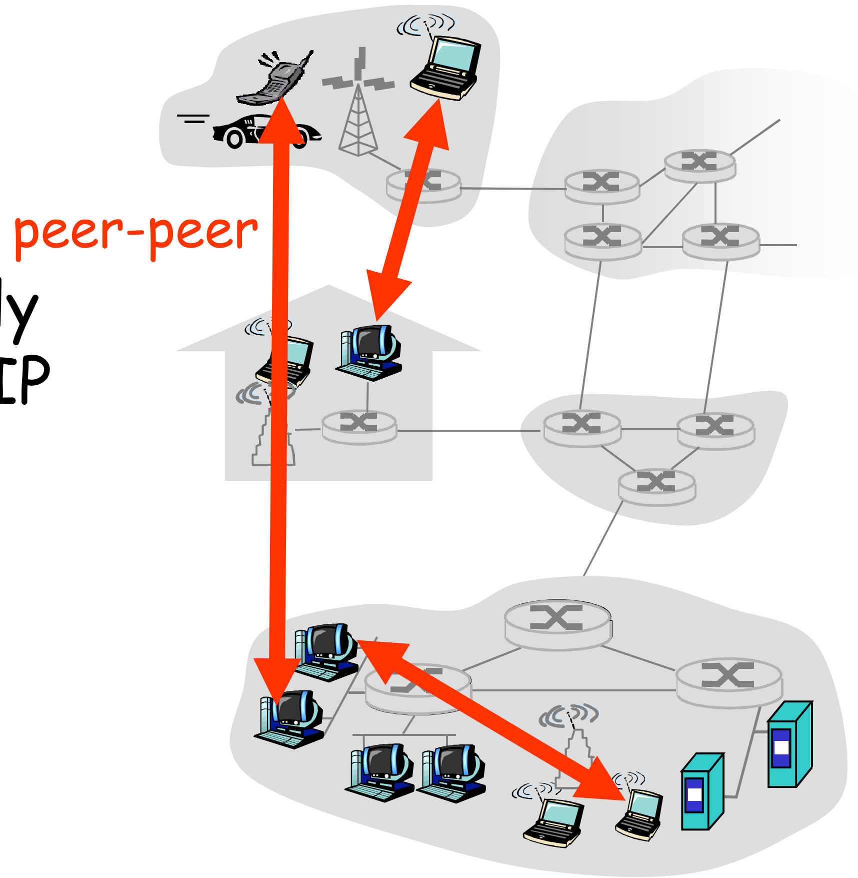
- always-on host
- permanent IP address
- server farms for scaling

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

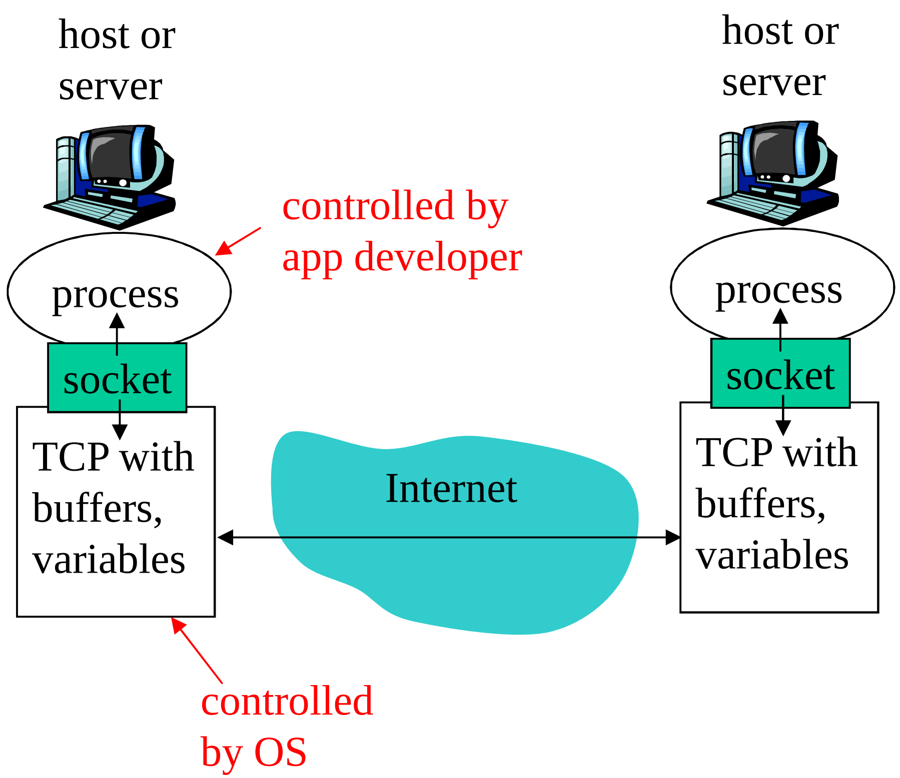
Note: applications with P2P architectures have client processes & server processes

# 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<br>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 |

# Chapter 2: Application layer

# 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:

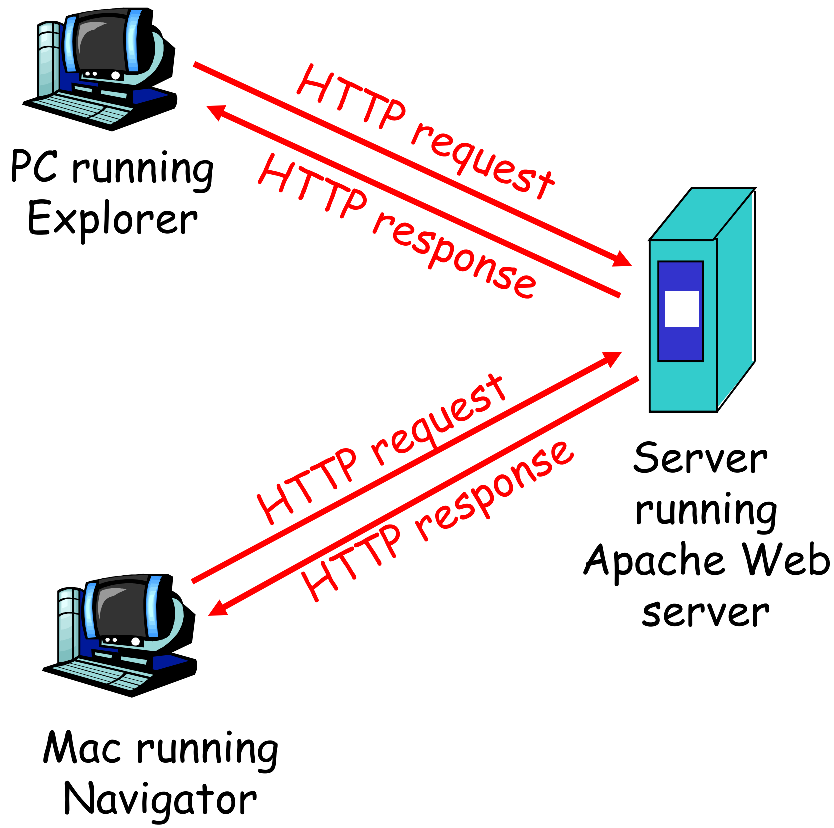
```
www.someschool.edu/someDept/pic.gif
```

host name (www.someschool.edu) — path name (/someDept/pic.gif)

# 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

*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

**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)

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

# Nonpersistent HTTP (cont.)

4. HTTP server closes TCP connection.

5. HTTP client receives response message containing html file, displays html. Parsing html file, finds 10 referenced jpeg objects

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

time

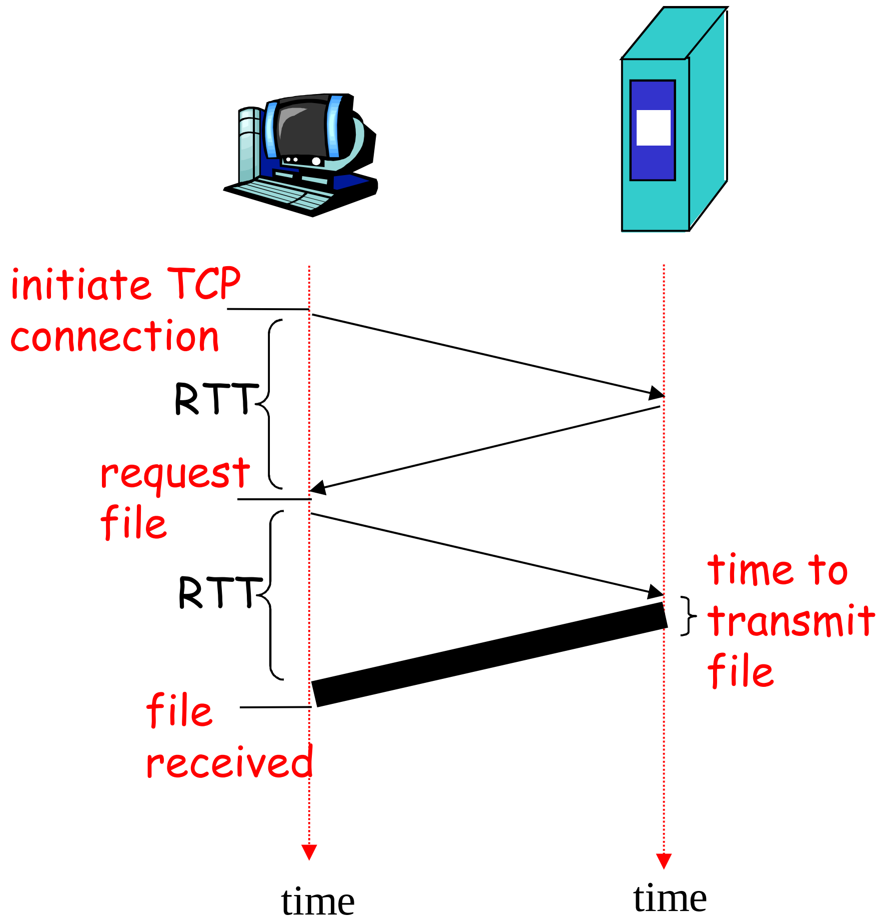
# Non-Persistent HTTP: Response time

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+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)

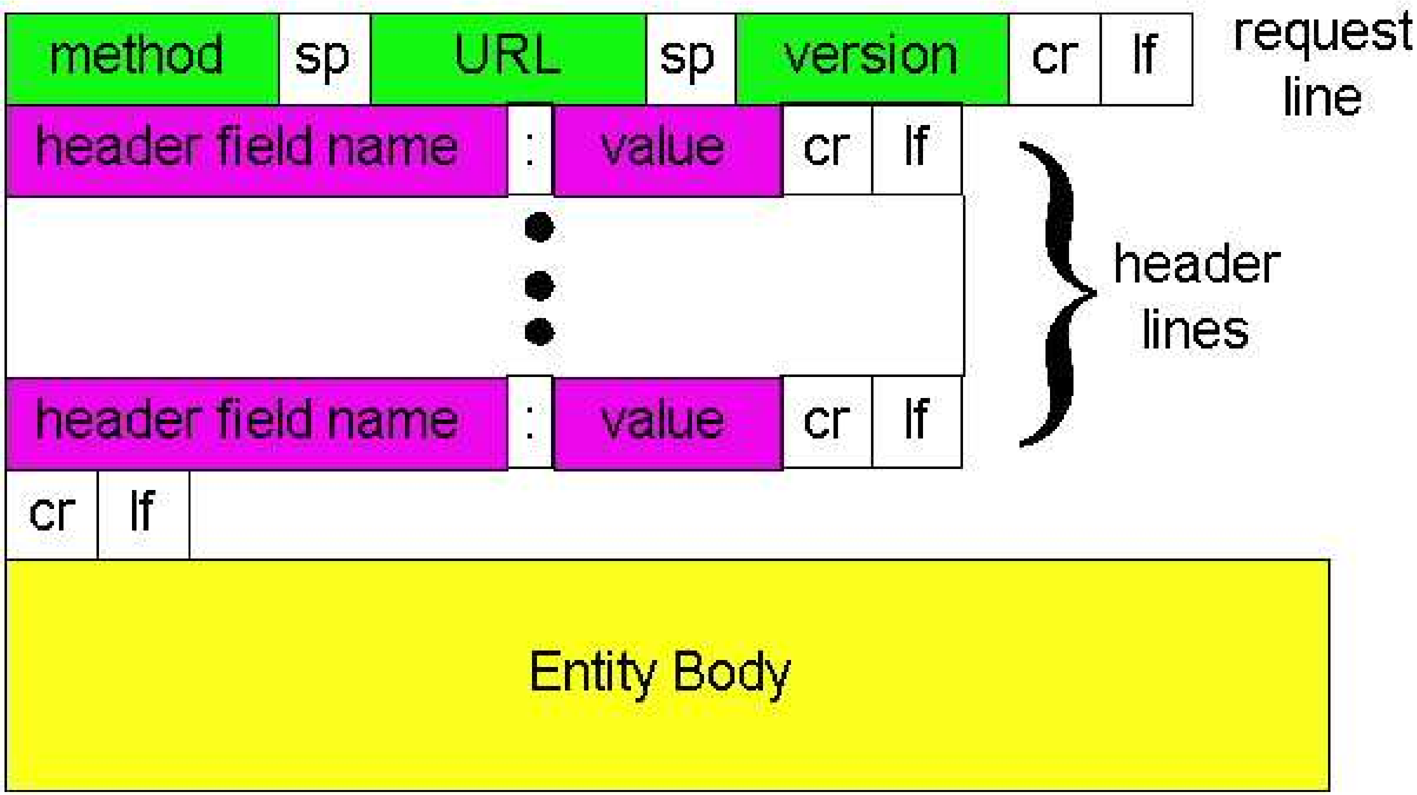
header lines

Carriage return, line feed indicates end of message

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

(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

status line (protocol status code status phrase)

header lines

data, e.g., requested HTML file

```
HTTP/1.1 200 OK
Connection close
Date: Thu, 06 Aug 1998 12:00:15 GMT
Server: Apache/1.3.0 (Unix)
Last-Modified: Mon, 22 Jun 1998 …...
Content-Length: 6821
Content-Type: text/html

data data data data data ...
```

# 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:

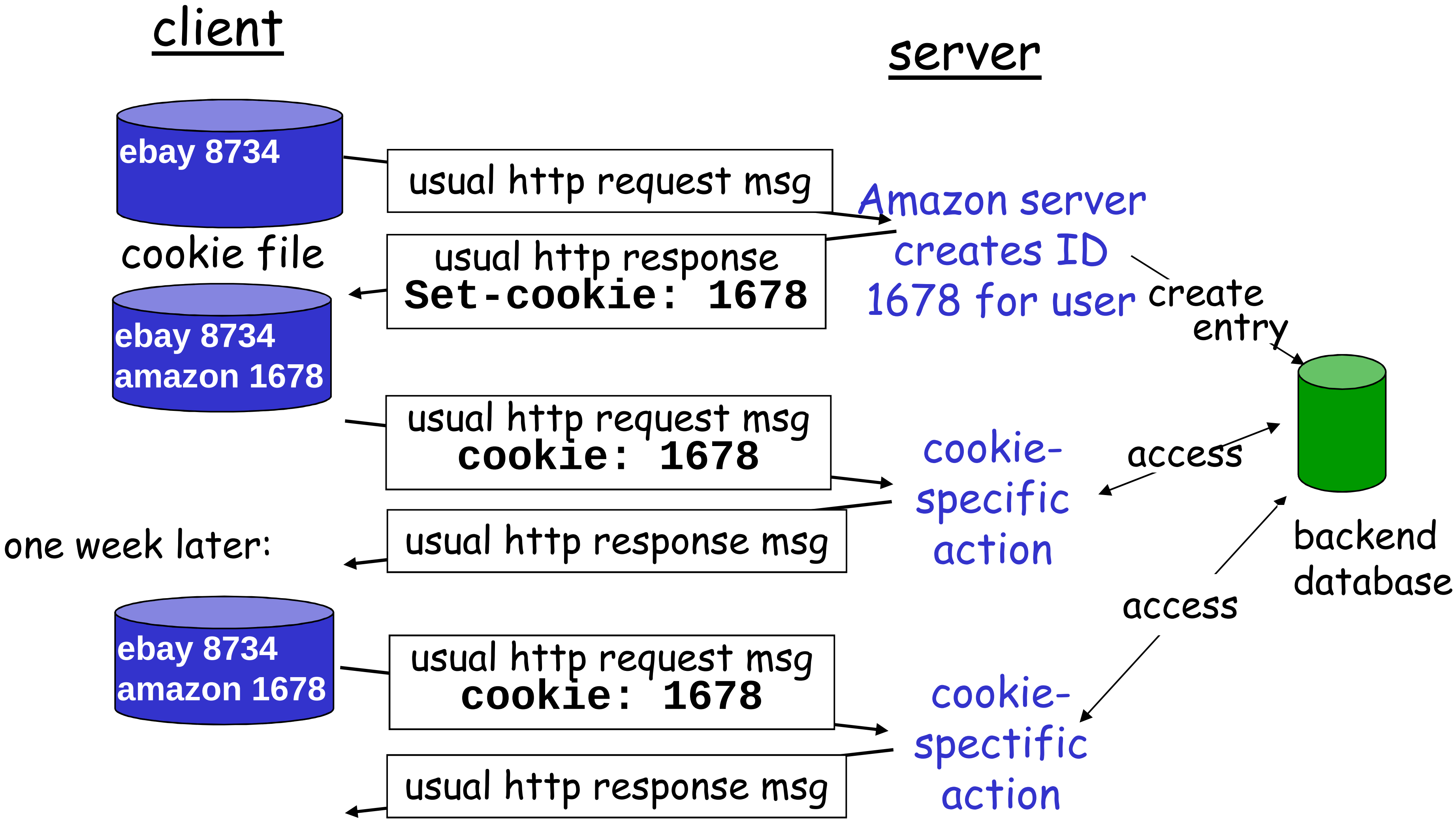
Susan always access Internet always from PC

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)

**aside**

**Cookies and privacy:**

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

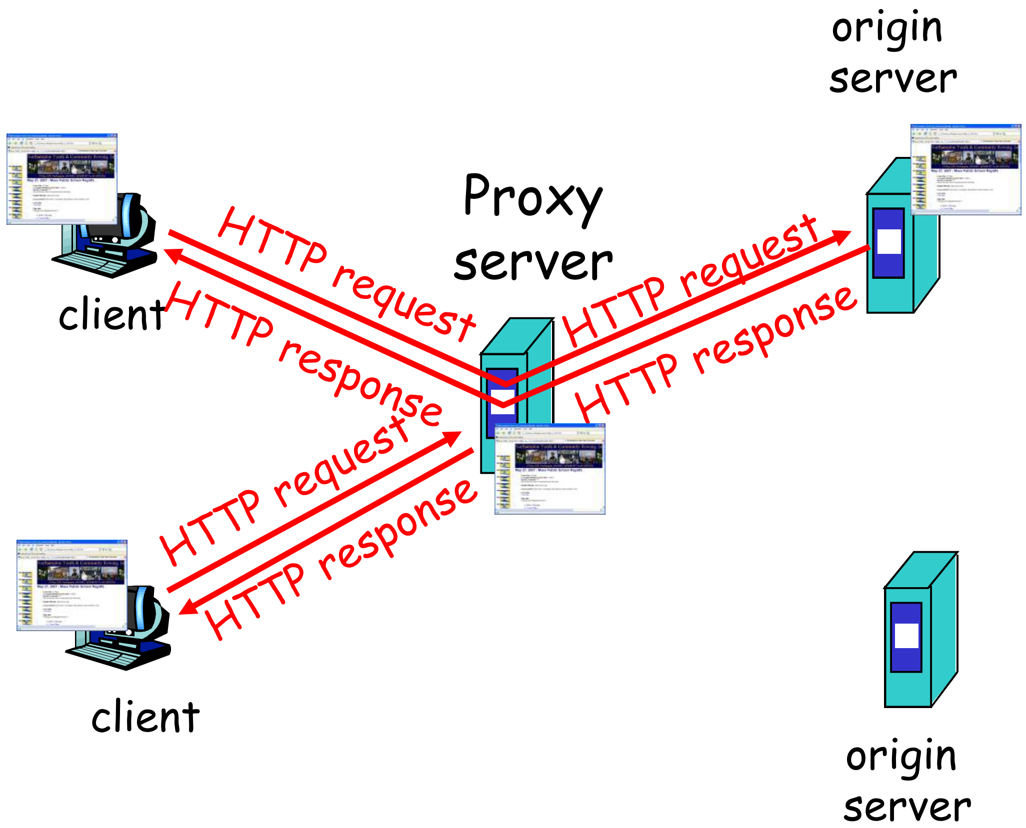
**How to keep "state":**

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

# 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)

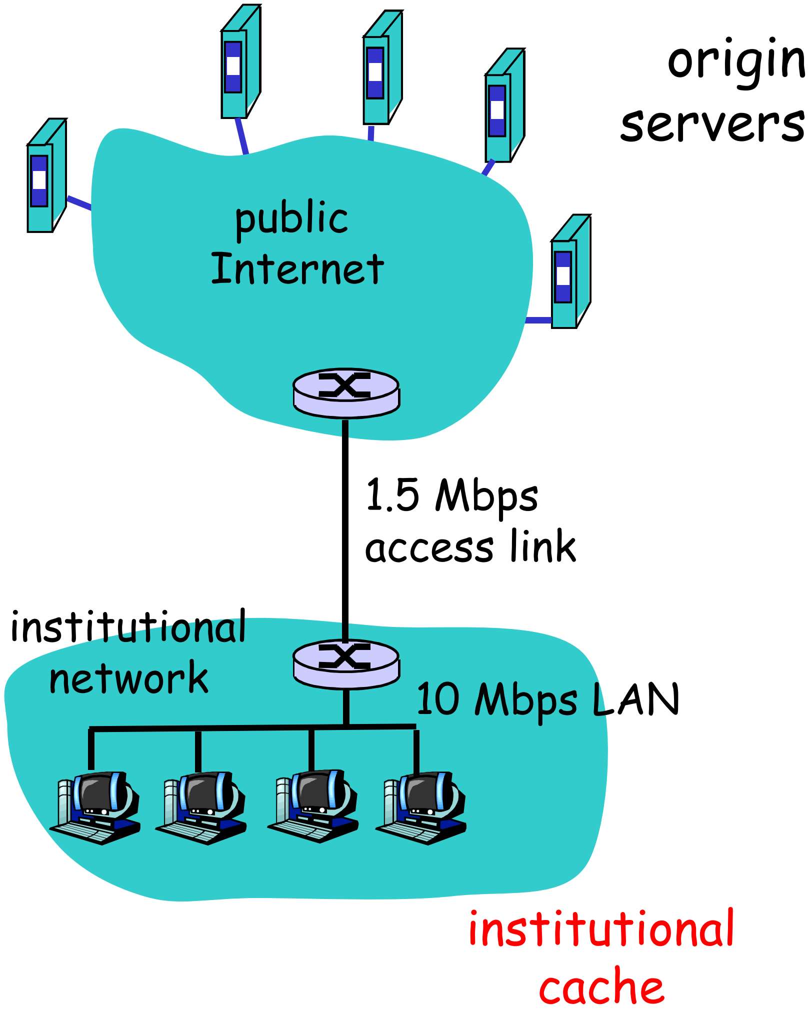
# Caching example

## 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



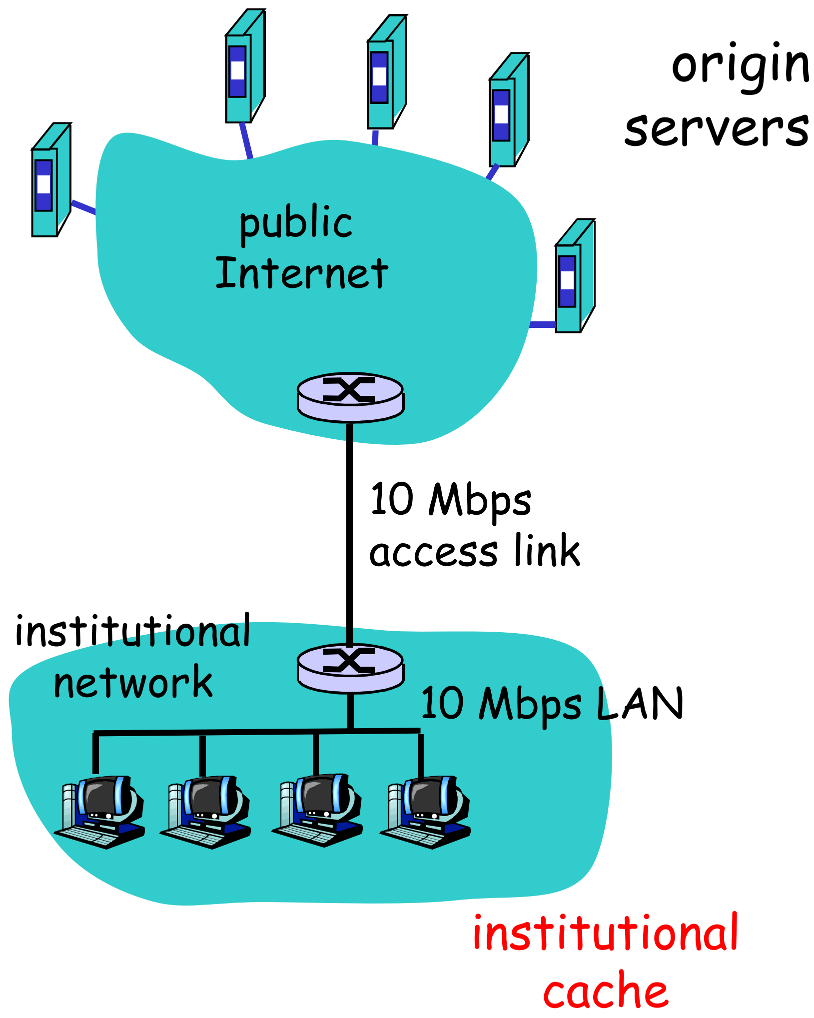
# Caching example (cont)

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 + msecs + msecs
- often a costly upgrade



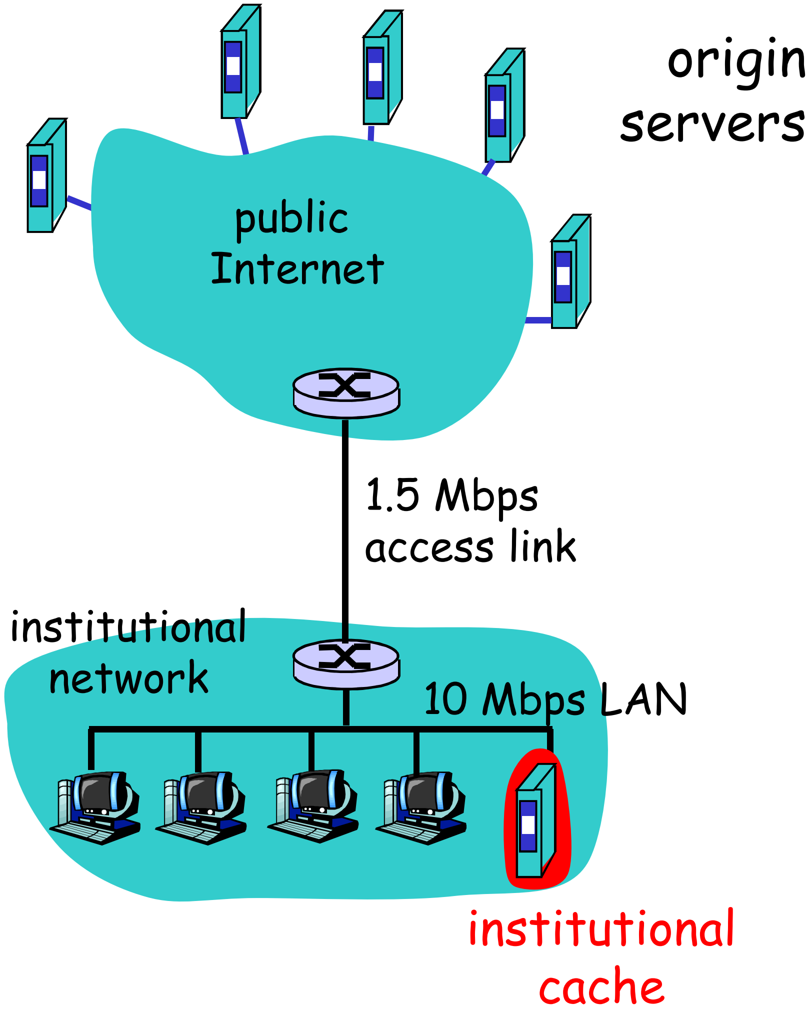
# Caching example (cont)

**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*(2.01) secs + .4*milliseconds < 1.4 secs



# Conditional GET

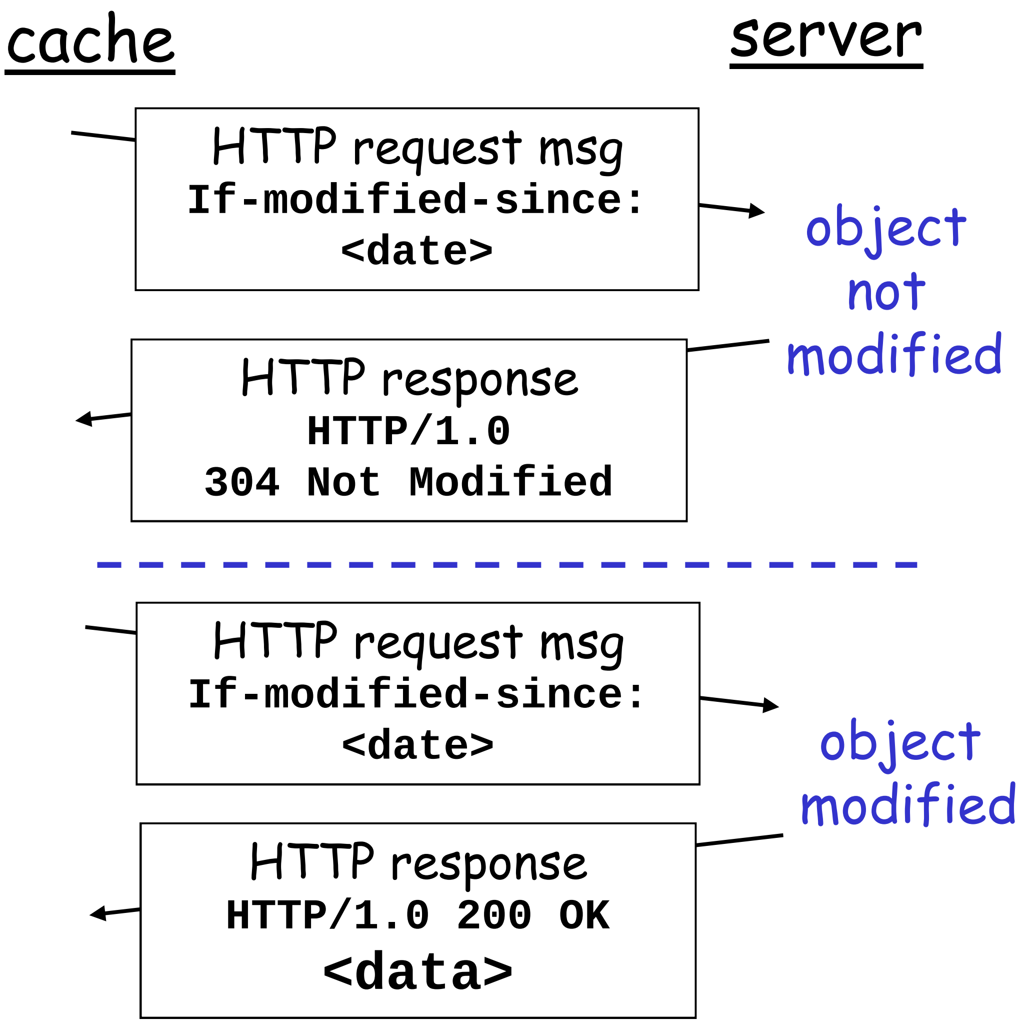
Goal: don't send object if cache has up-to-date cached version

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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2.3 FTP

2.4 Electronic Mail
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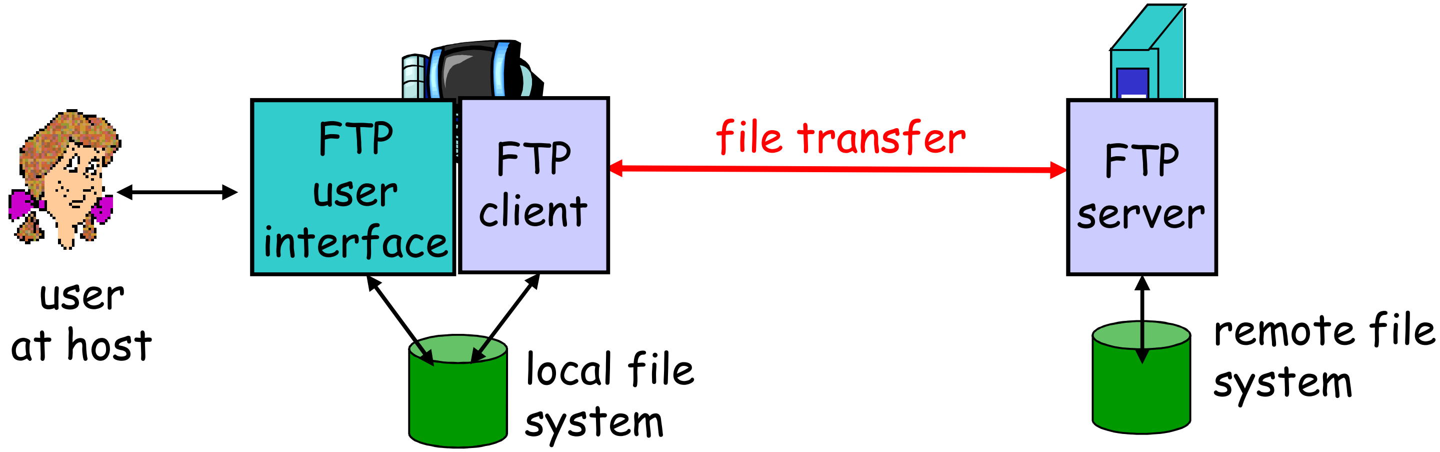
# FTP: the file transfer protocol




transfer file to/from remote host

client/server model

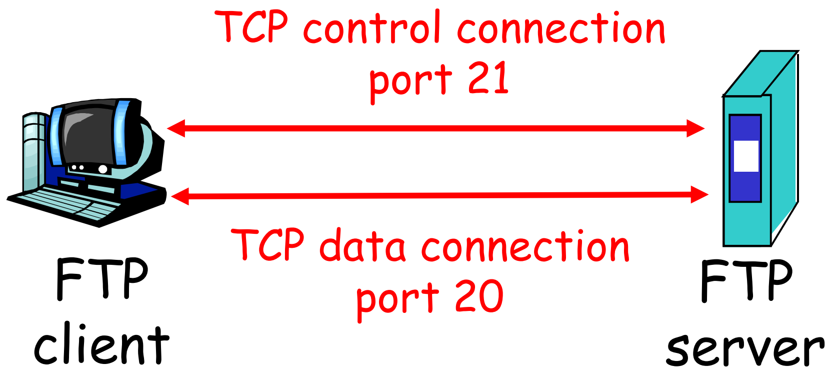
- *client:* side that initiates transfer (either to/from remote)
- *server:* remote host

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**

# Chapter 2: Application layer

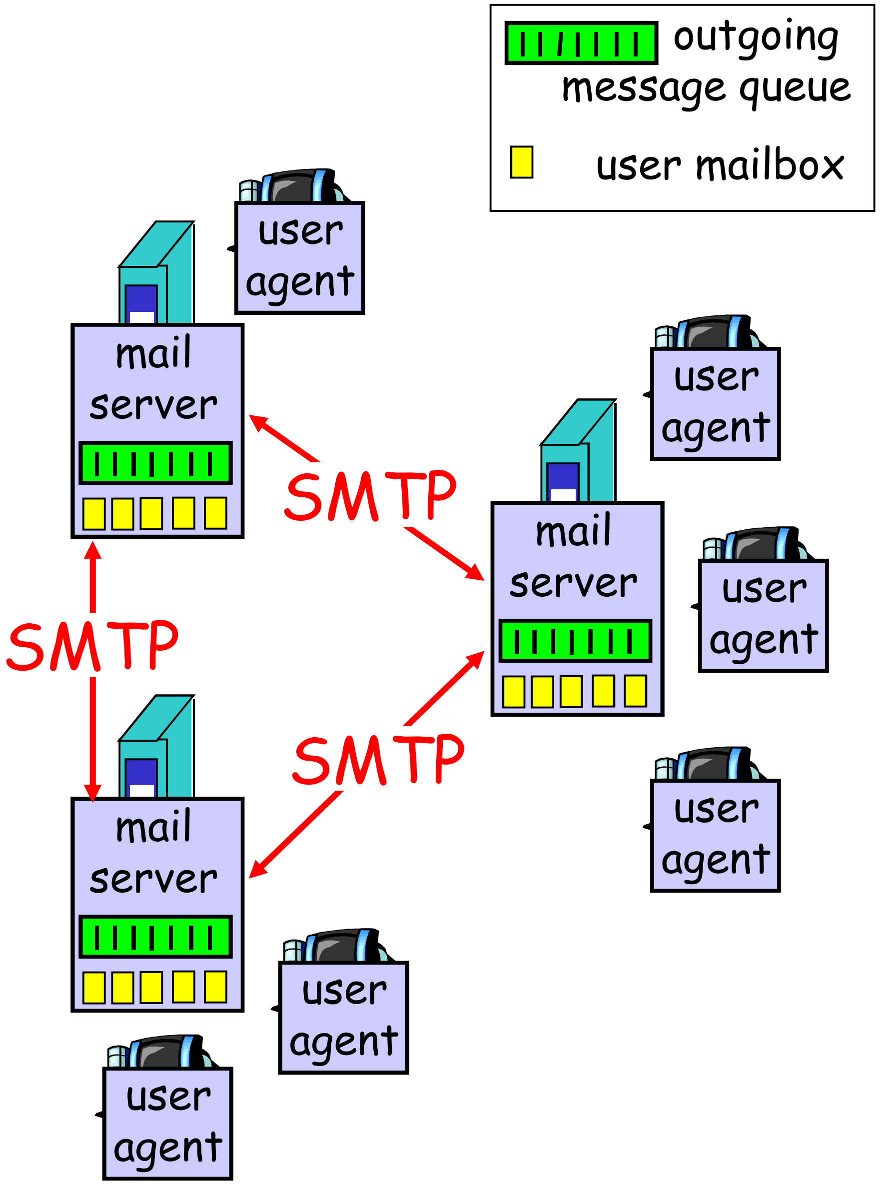
# Electronic Mail

Three major components:

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

## User Agent

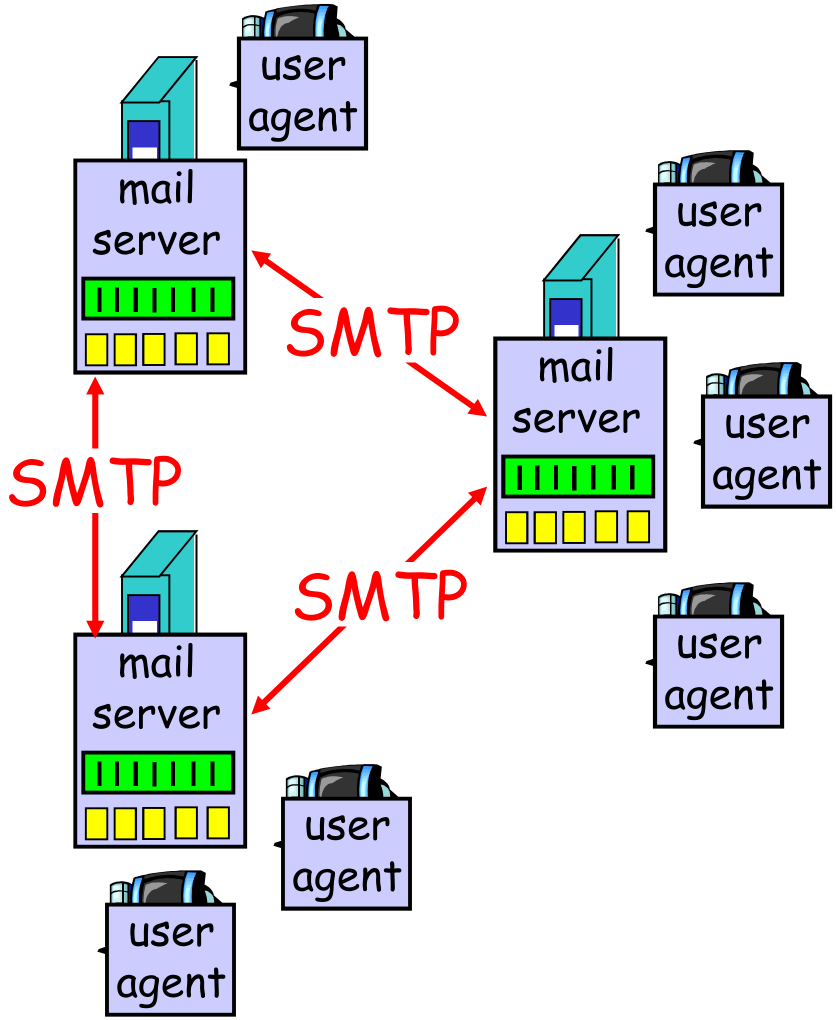
- a.k.a. "mail reader"
- composing, editing, reading mail messages
- e.g., Eudora, Outlook, elm, Mozilla Thunderbird
- outgoing, incoming messages stored on server



# 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

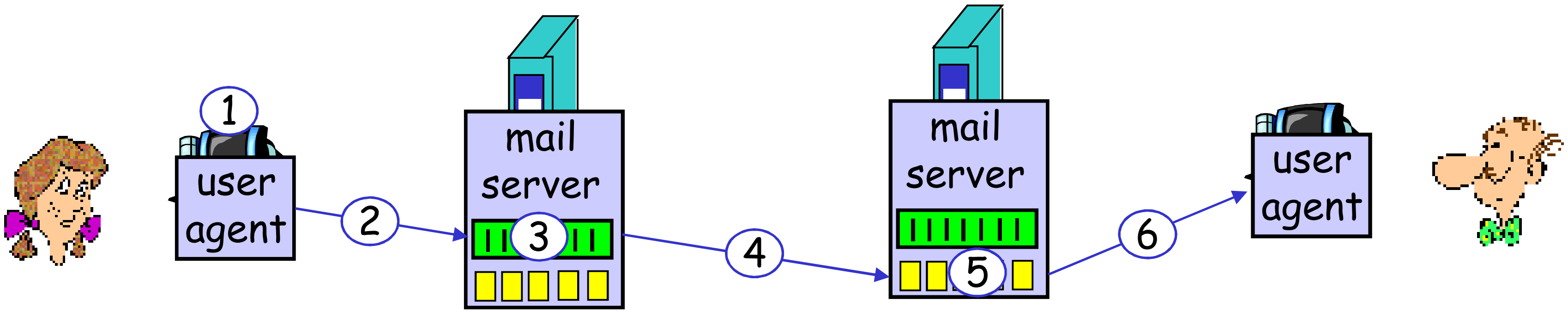


# Electronic Mail: SMTP [RFC 2821]

- 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

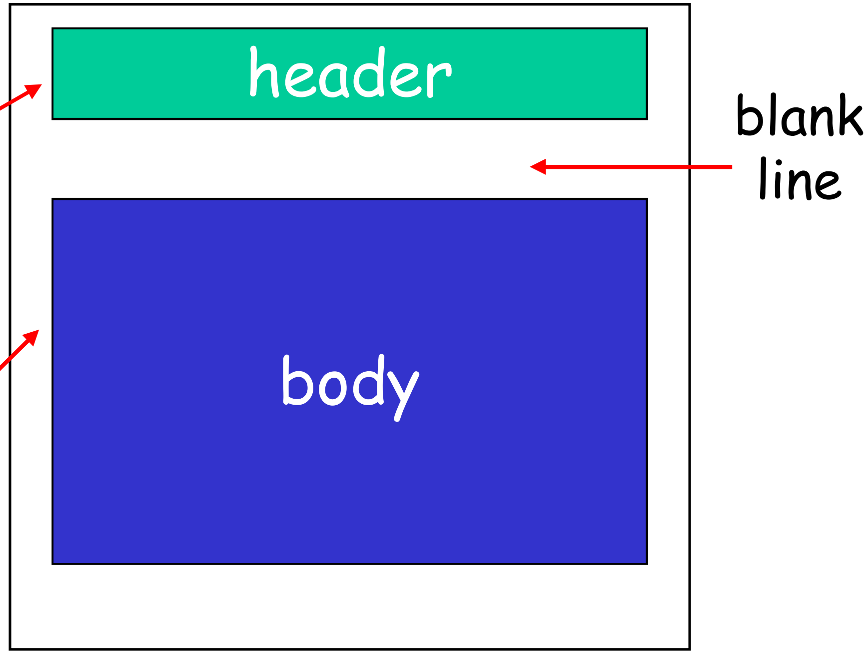
# Mail message format

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



# Message format: multimedia extensions

MIME: multimedia mail extension, RFC 2045, 2056

additional lines in msg header declare MIME content type

MIME version

method used to encode data

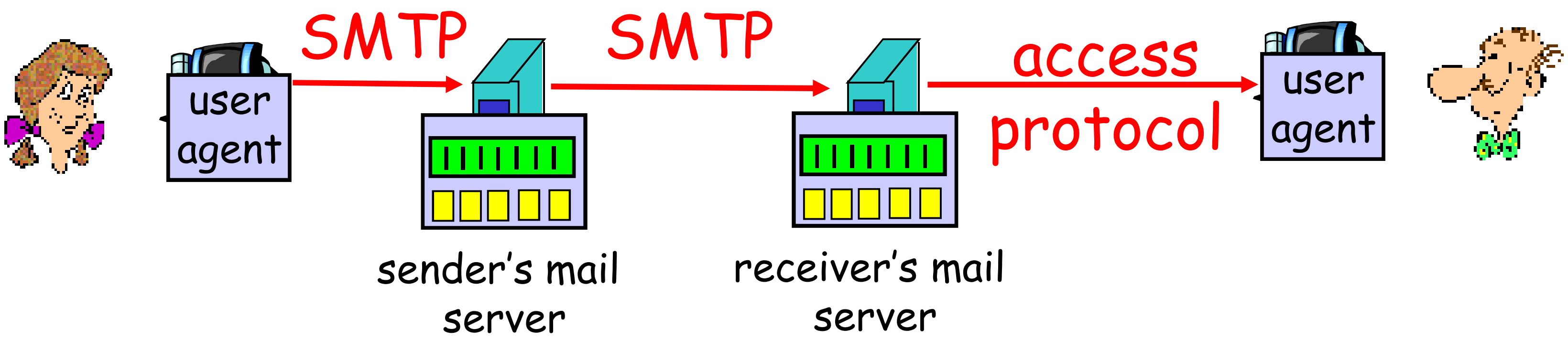
multimedia data type, subtype, parameter declaration

encoded data

```
From: alice@crepes.fr
To: bob@hamburger.edu
Subject: Picture of yummy crepe.
MIME-Version: 1.0
Content-Transfer-Encoding: base64
Content-Type: image/jpeg

base64 encoded data .....
.........................
......base64 encoded data
```

# 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

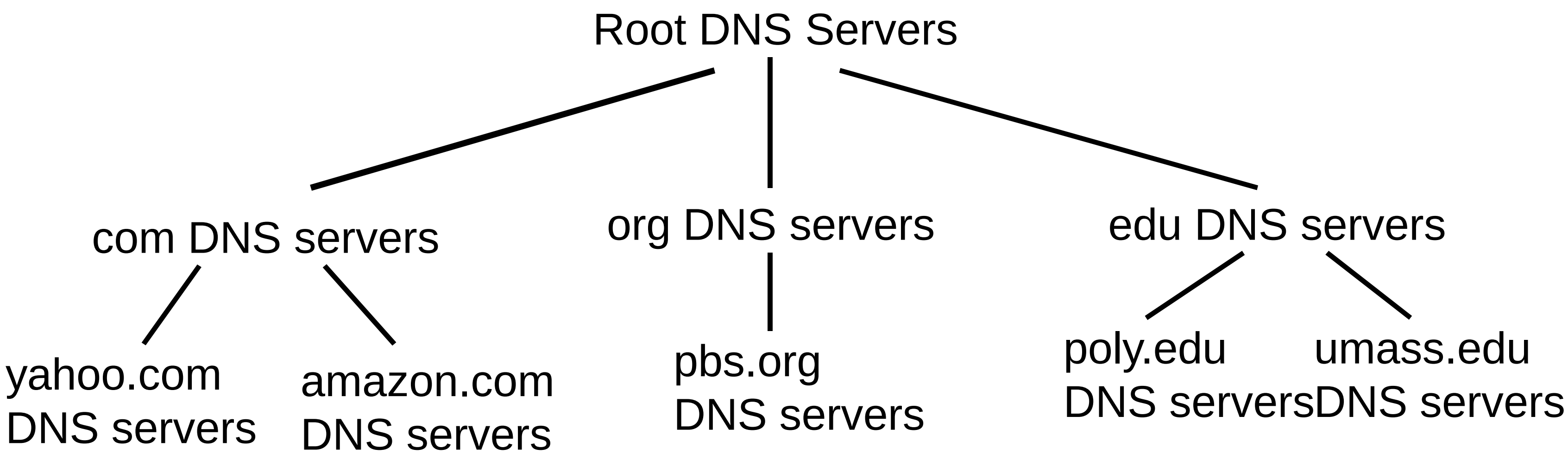
- hostname to IP address translation
- host aliasing
  - Canonical, alias names
- mail server aliasing
- load distribution
  - replicated Web servers: set of IP addresses for one canonical name

## 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:

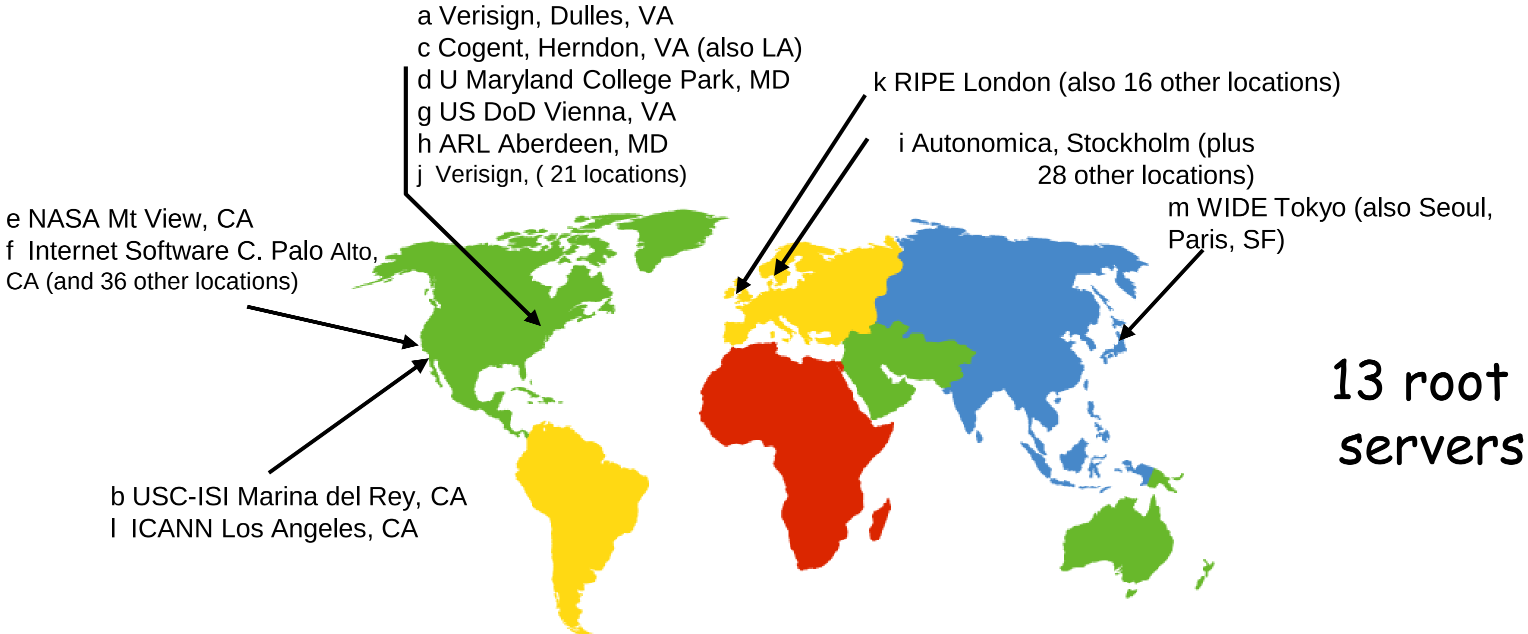
- client queries a root server to find com DNS server
- client queries com DNS server to get amazon.com DNS server
- client queries amazon.com DNS server to get IP address for www.amazon.com

# 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




13 root name servers worldwide

# 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

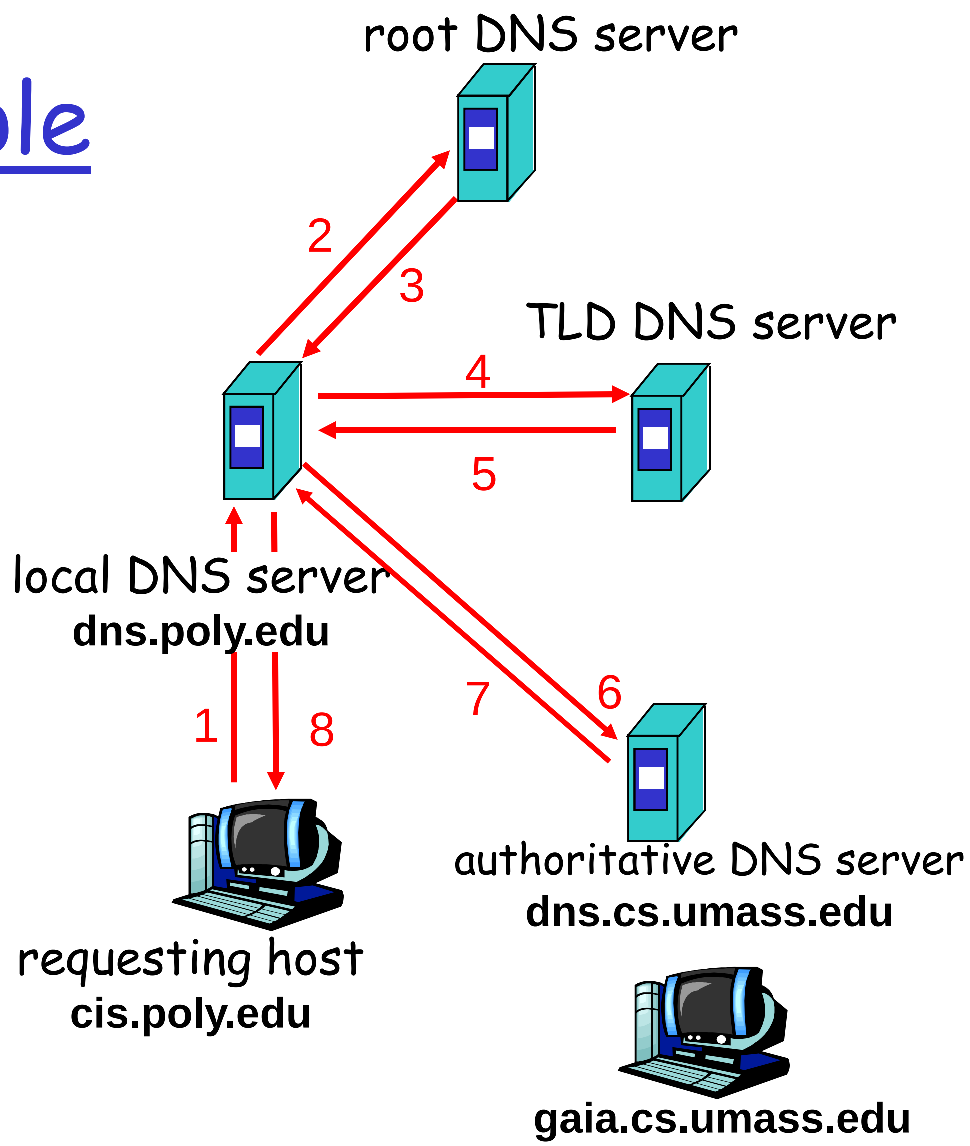
- does not strictly belong to hierarchy
- each ISP (residential ISP, company, university) has one.
  - also called “default name server”
- when host makes DNS query, query is sent to its local DNS server
  - acts as proxy, forwards query into hierarchy

# DNS name resolution example

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

iterated query:

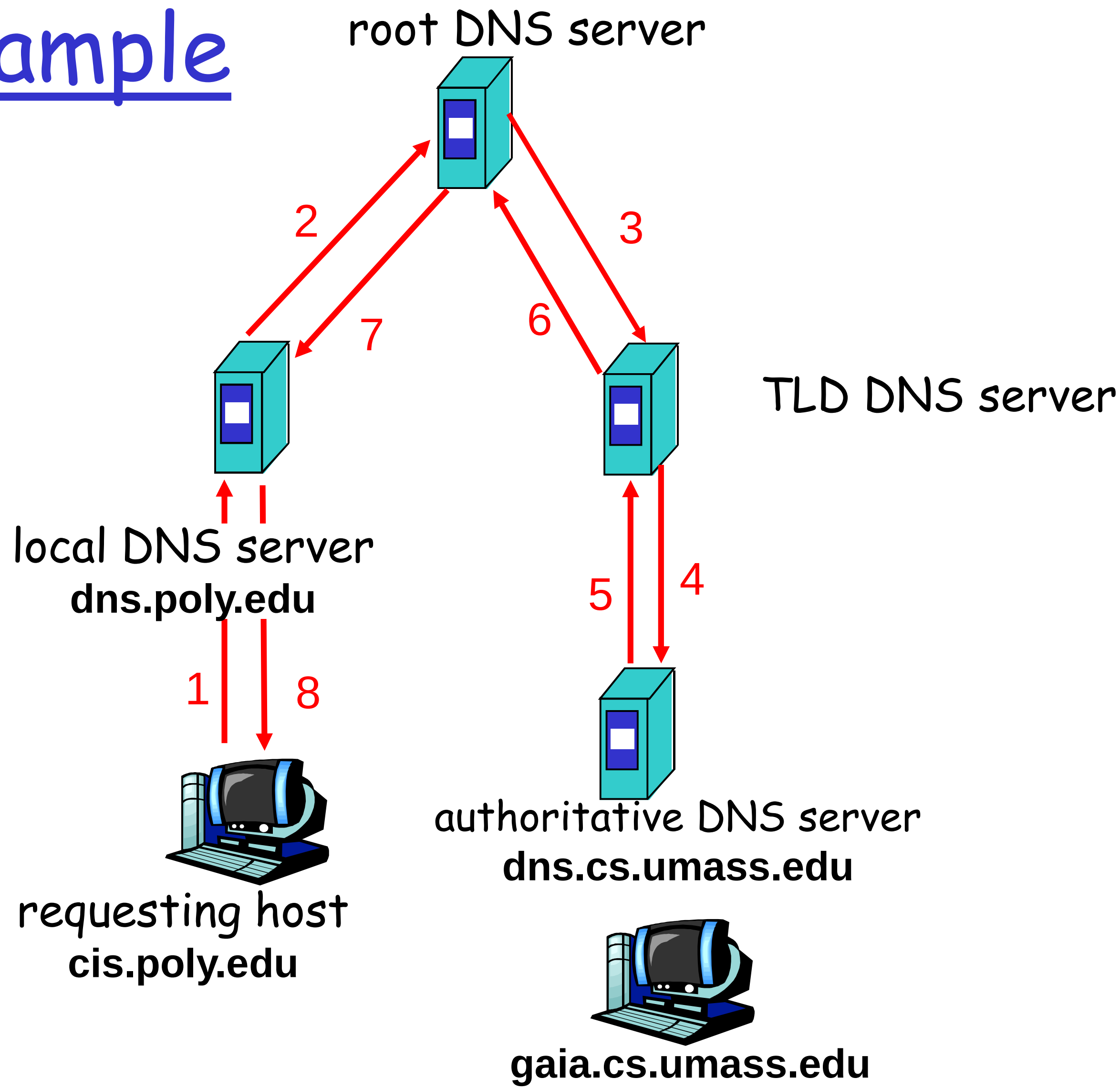
- contacted server replies with name of server to contact
- "I don't know this name, but ask this server"



# 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

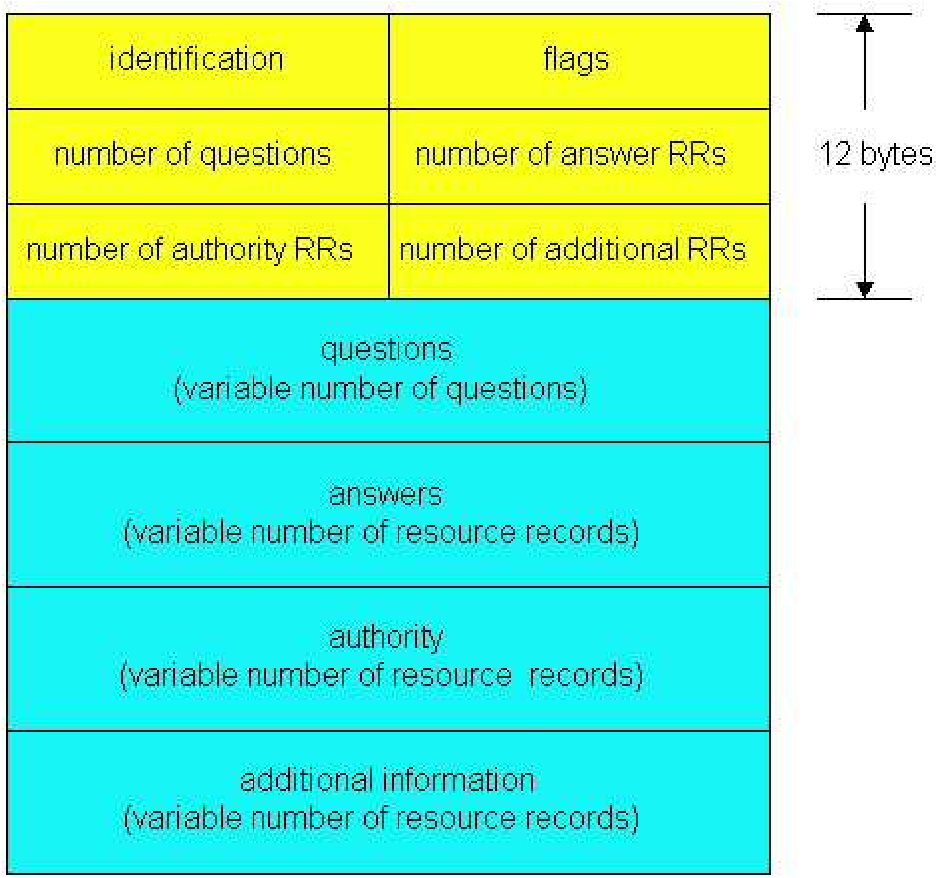
- **name** is alias name for some "canonical" (the real) name
  `www.ibm.com` is really
  `servereast.backup2.ibm.com`
- **value** is canonical name

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

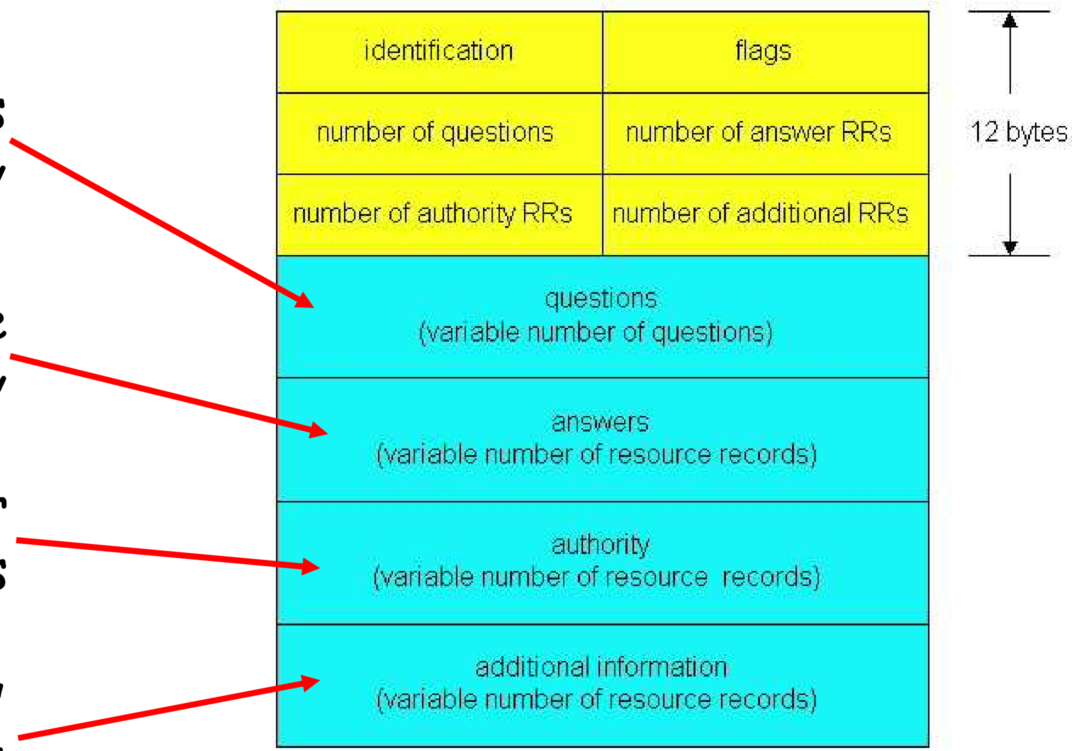
# DNS protocol, messages

Name, type fields for a query

RRs in response to query

records for authoritative servers

additional "helpful" info that may be used



# 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

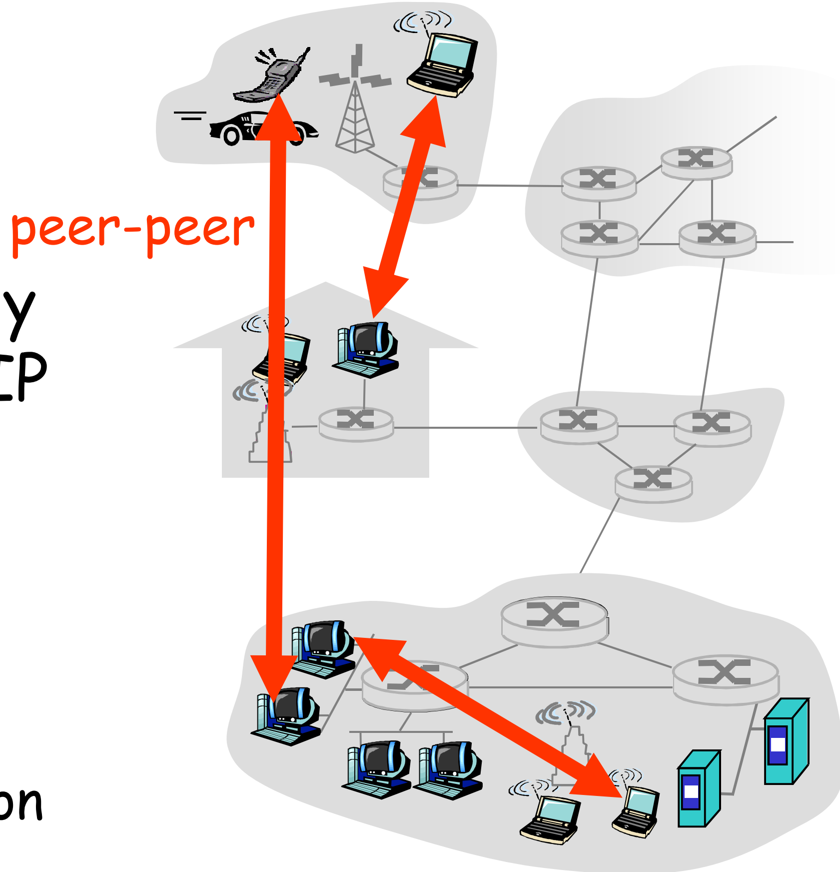
How do people get IP address of your Web site?

# 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

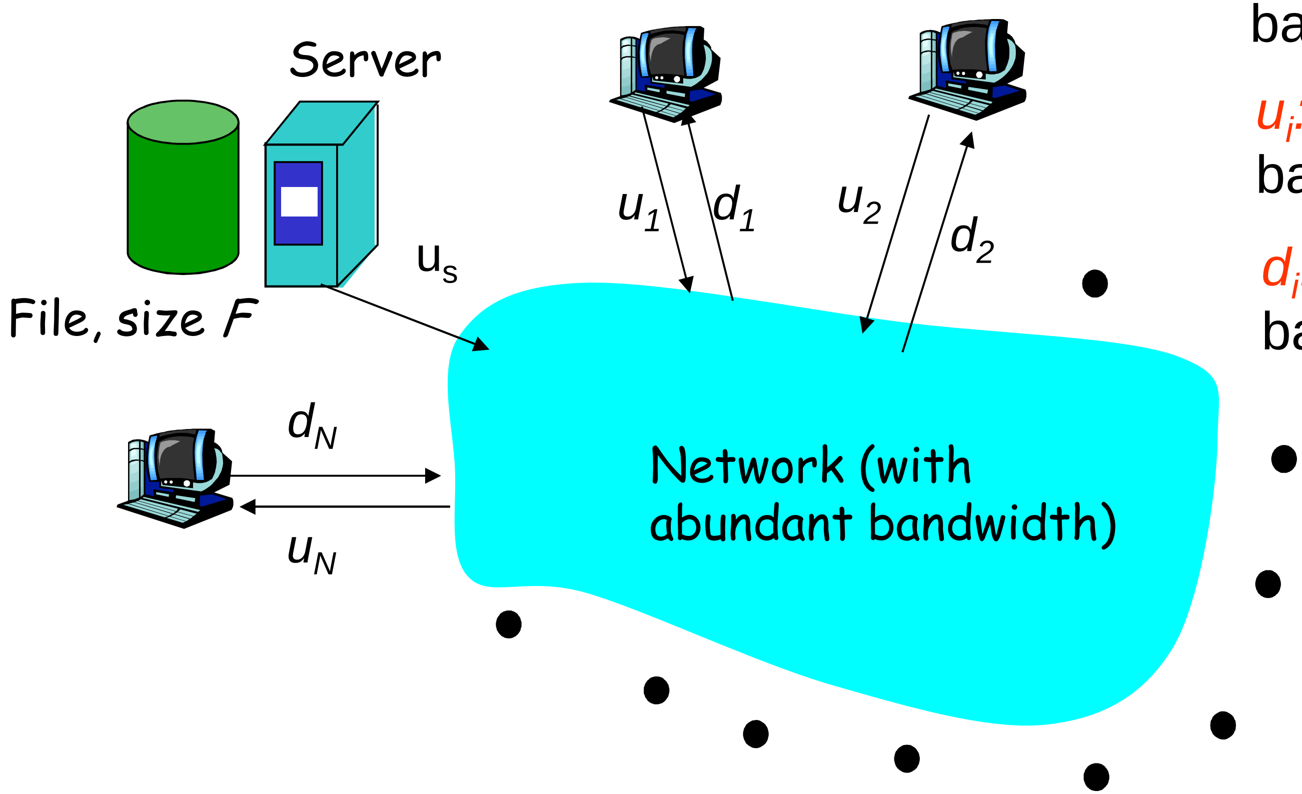



## Three topics:

- 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*?

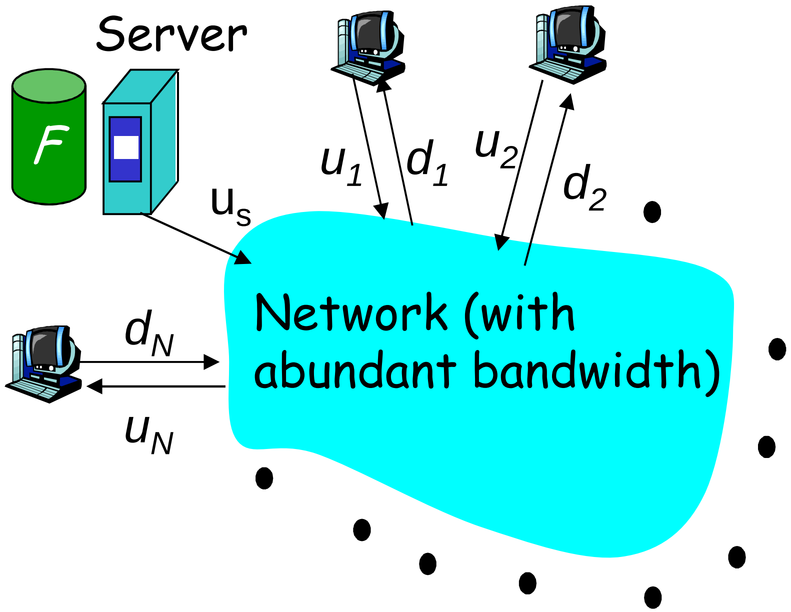



$u_s$: server upload bandwidth

$u_i$: peer i upload bandwidth

$d_i$: peer i download bandwidth

# File distribution time: server-client

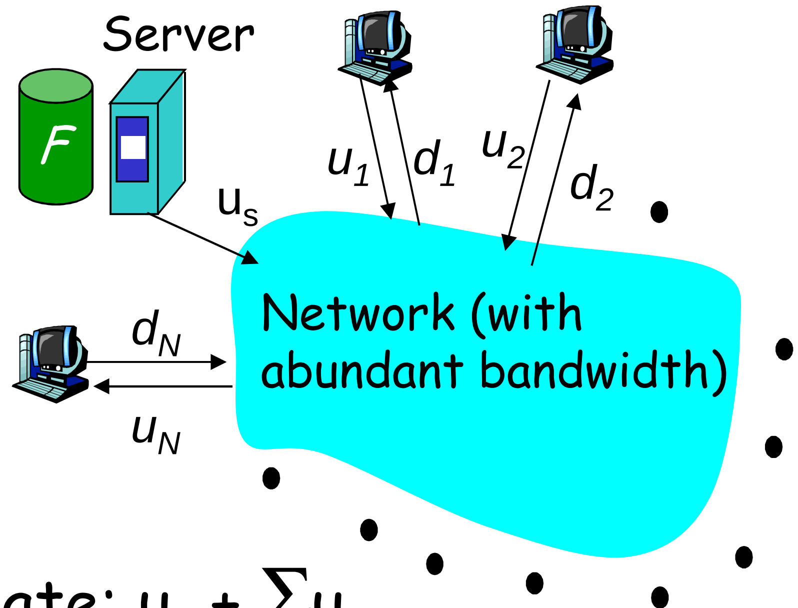



- server sequentially sends N copies:
  - $NF/u_s$ time
- client i takes $F/d_i$ time to download

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

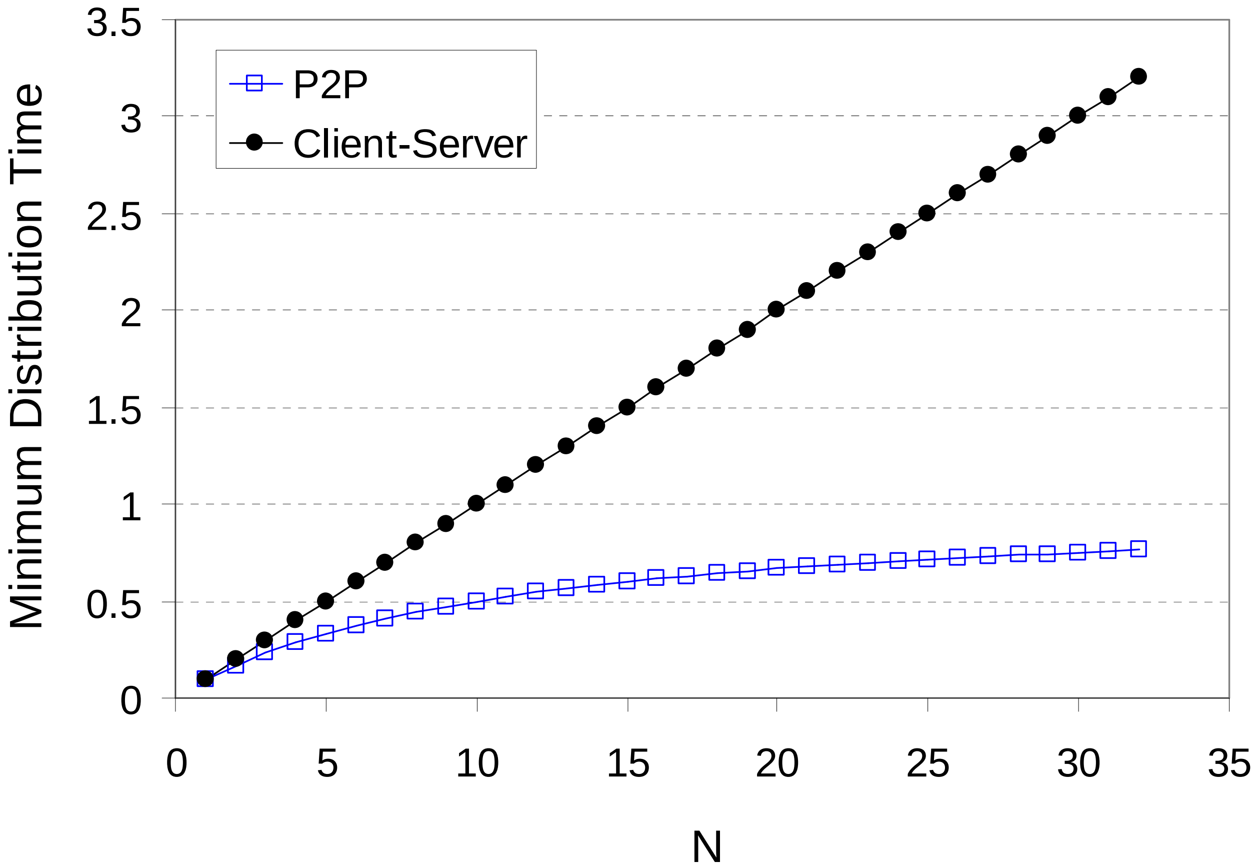



- server must send one copy: $F/u_s$ time
- client i takes $F/d_i$ time to download
- NF bits must be downloaded (aggregate)
  - fastest possible upload rate: $u_s + \Sigma u_i$

$$d_{P2P} = \max \{ F/u_s, F/\min_i(d_i), NF/(u_s + \Sigma u_i) \}$$

# Server-client vs. P2P: example

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

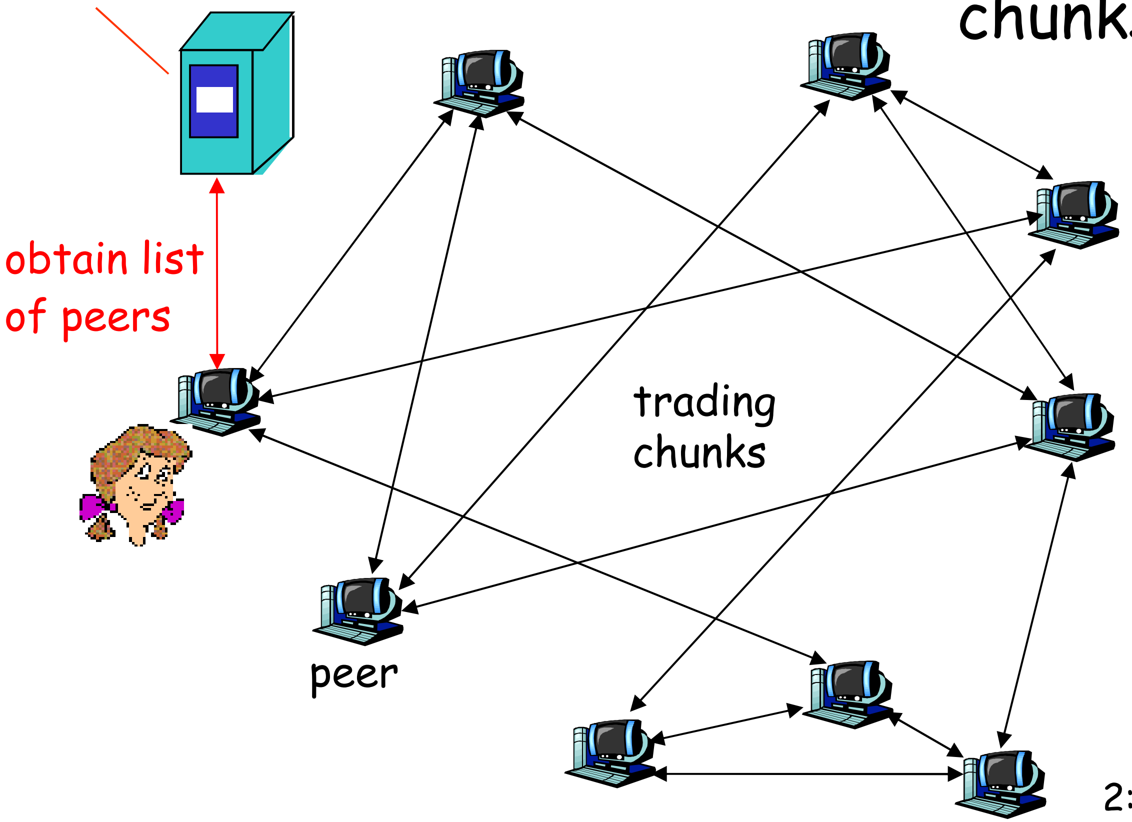


# File distribution: BitTorrent

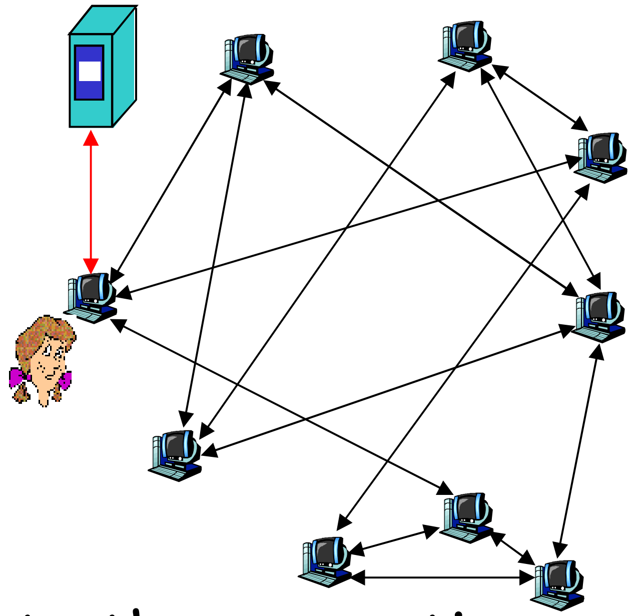
P2P file distribution

*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

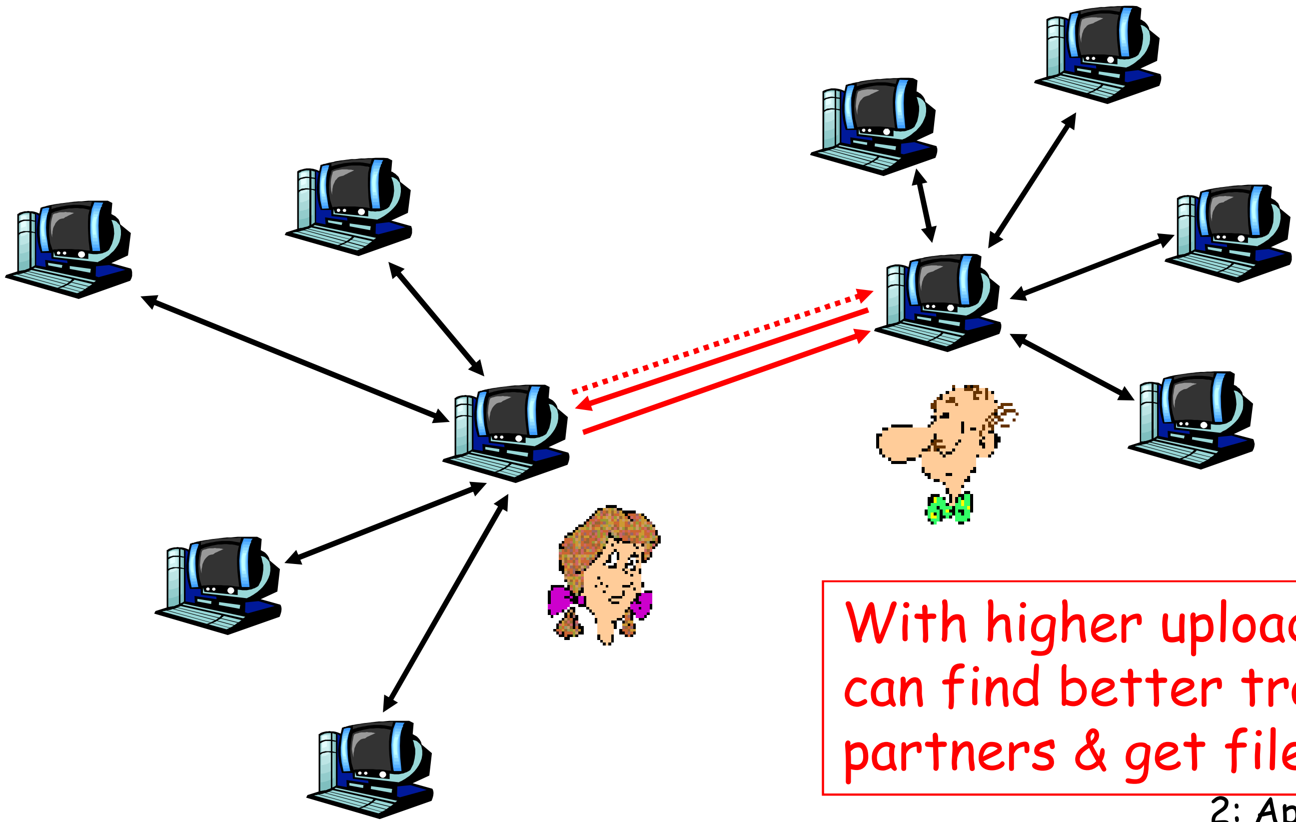
- at any given time, different peers have different subsets of file chunks
- periodically, a peer (Alice) asks each neighbor for list of chunks that they have.
- Alice sends requests for her missing chunks
  - rarest first

## 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!

# P2P: searching for information

Index in P2P system: maps information to peer location (location = IP address & port number)

**File sharing (eg e-mule)**

- Index dynamically tracks the locations of files that peers share.
- Peers need to tell index what they have.
- Peers search index to determine where files can be found

**Instant messaging**

- Index maps user names to locations.
- When user starts IM application, it needs to inform index of its location
- Peers search index to determine IP address of user.

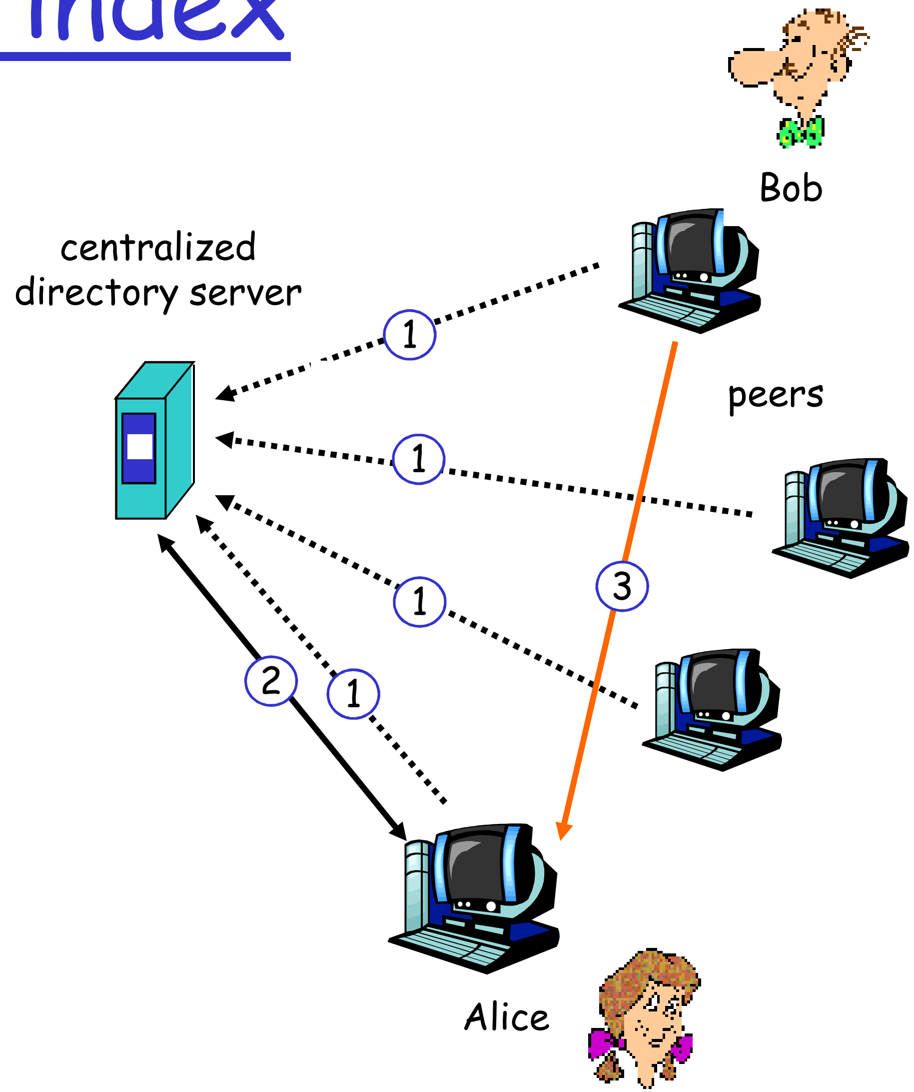
# P2P: centralized index

original "Napster" design

1) when peer connects, it informs central server:
   - IP address
   - content

2) Alice queries for "Hey Jude"

3) Alice requests file from Bob



# P2P: problems with centralized directory

- single point of failure
- performance bottleneck
- copyright infringement: "target" of lawsuit is obvious

file transfer is decentralized, but locating content is highly centralized

# Query flooding

- fully distributed
  - no central server
- used by Gnutella
- Each peer indexes the files it makes available for sharing (and no other files)

overlay network: graph

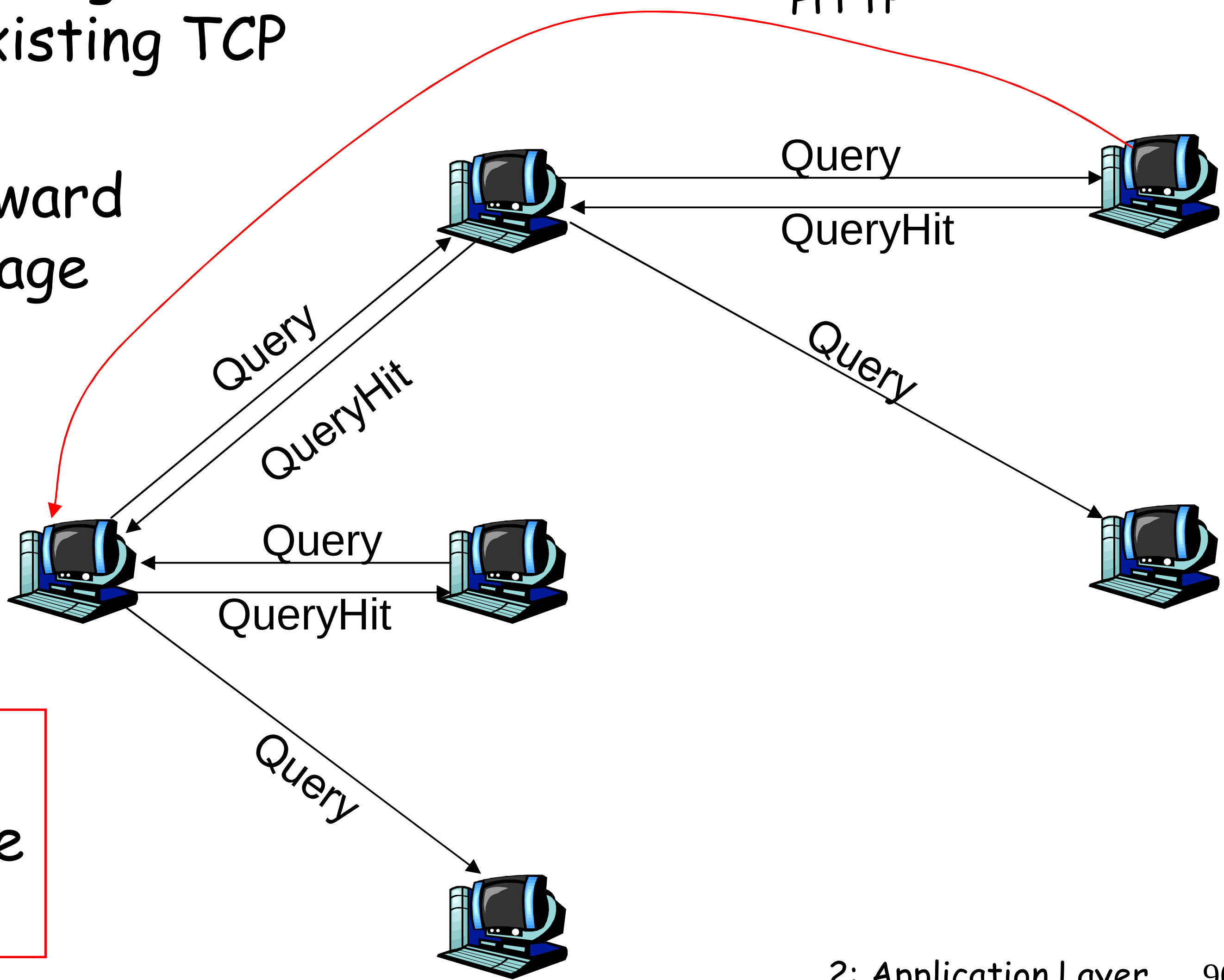
- edge between peer X and Y if there's a TCP connection
- all active peers and edges form overlay net
- edge: virtual (*not* physical) link
- given peer typically connected with < 10 overlay neighbors

# Query flooding

Query message sent over existing TCP connections

peers forward Query message

QueryHit sent over reverse path




Scalability:

limited scope flooding

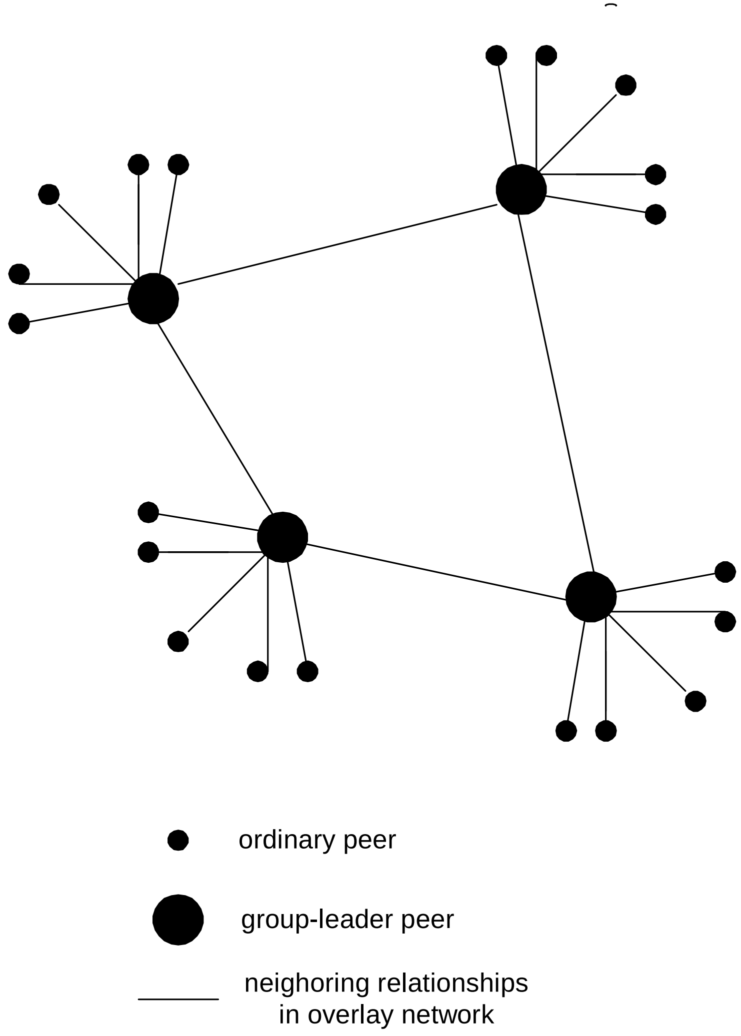
# Gnutella: Peer joining

1. joining peer Alice must find another peer in Gnutella network: use list of candidate peers
2. Alice sequentially attempts TCP connections with candidate peers until connection setup with Bob
3. *Flooding:* Alice sends Ping message to Bob; Bob forwards Ping message to his overlay neighbors (who then forward to their neighbors….)
   - peers receiving Ping message respond to Alice with Pong message
4. Alice receives many Pong messages, and can then setup additional TCP connections

Peer leaving: see homework problem!

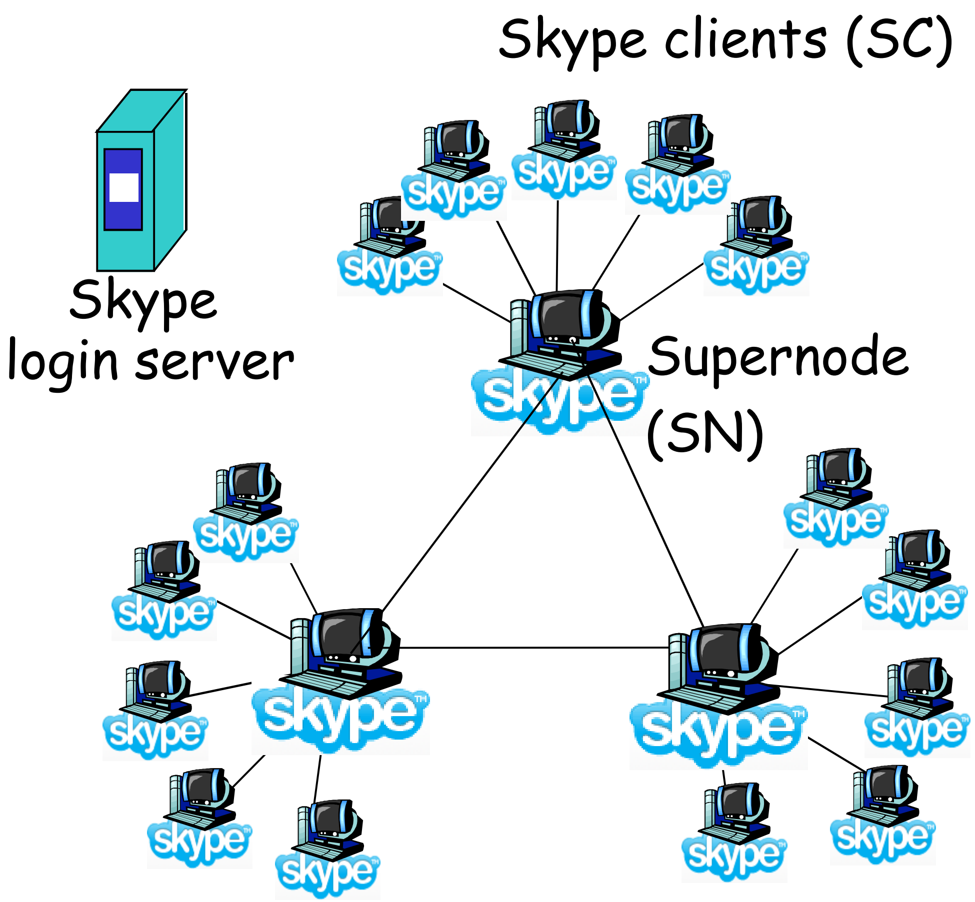
# Hierarchical Overlay

- between centralized index, query flooding approaches
- each peer is either a *super node* or assigned to a super node
  - TCP connection between peer and its super node.
  - TCP connections between some pairs of super nodes.
- Super node tracks content in its children



# 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



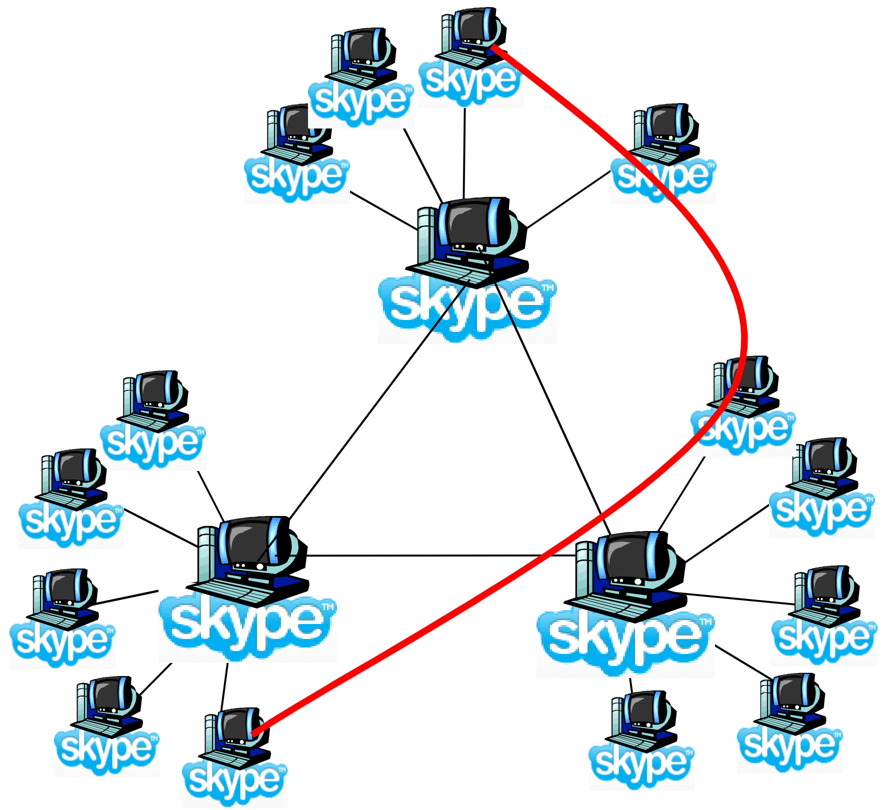
# Peers as relays

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

# 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

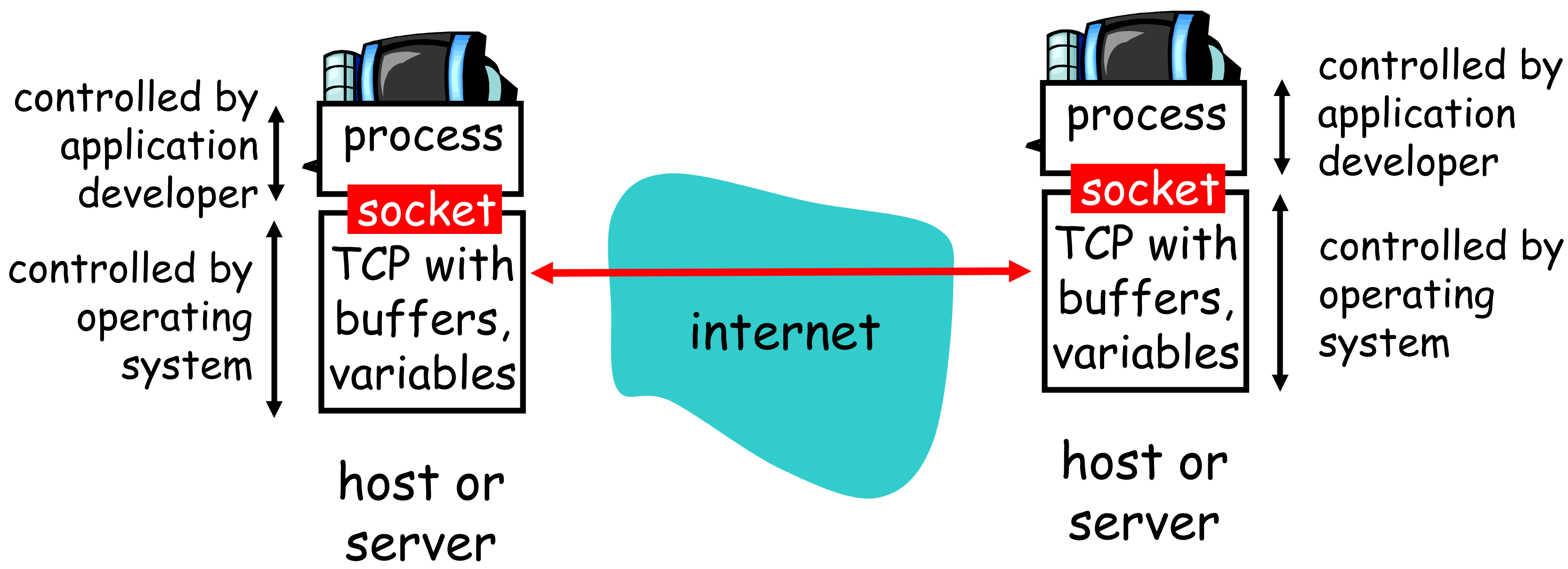
**socket**

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

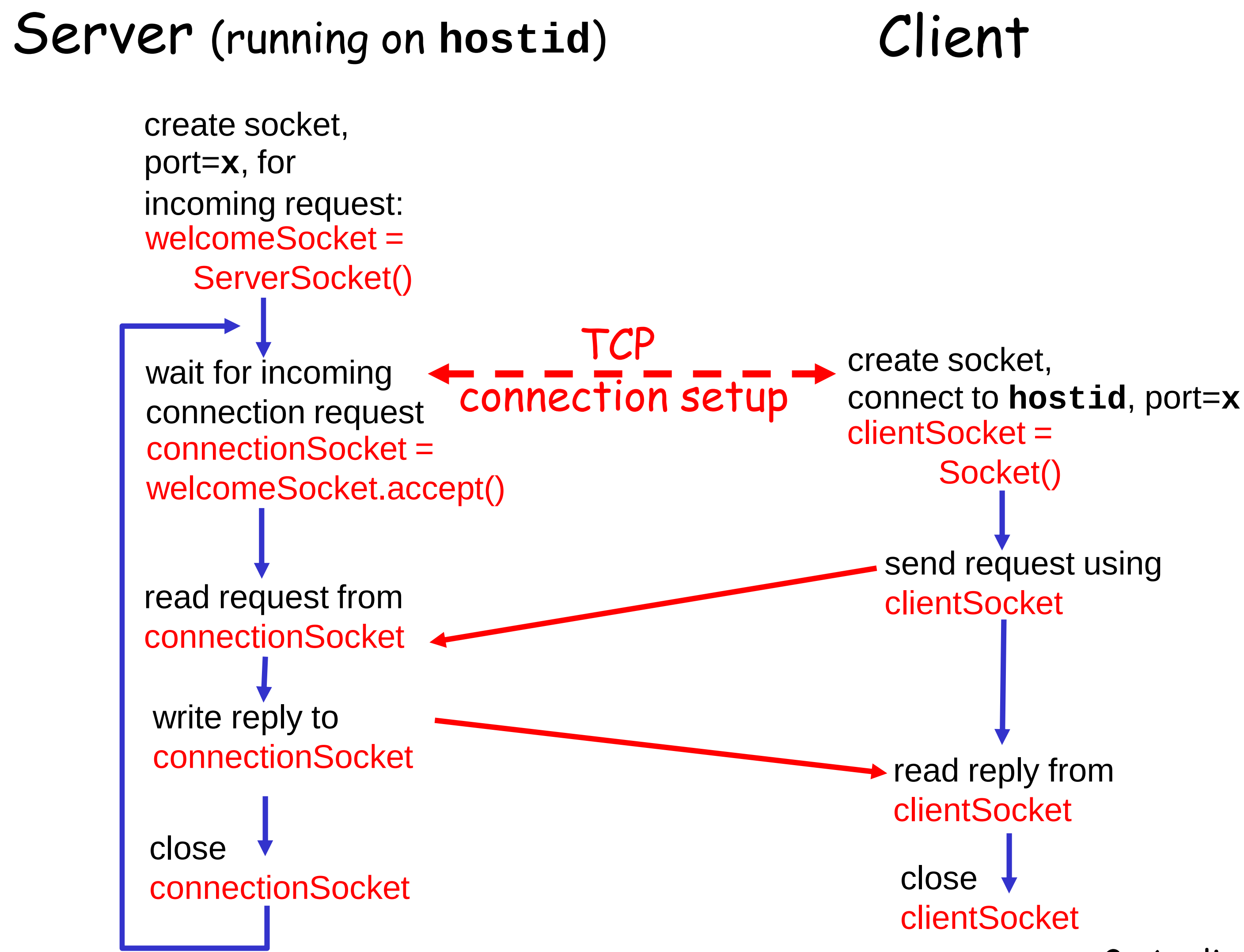
When contacted by client, server TCP creates new socket for server process to communicate with client

- 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

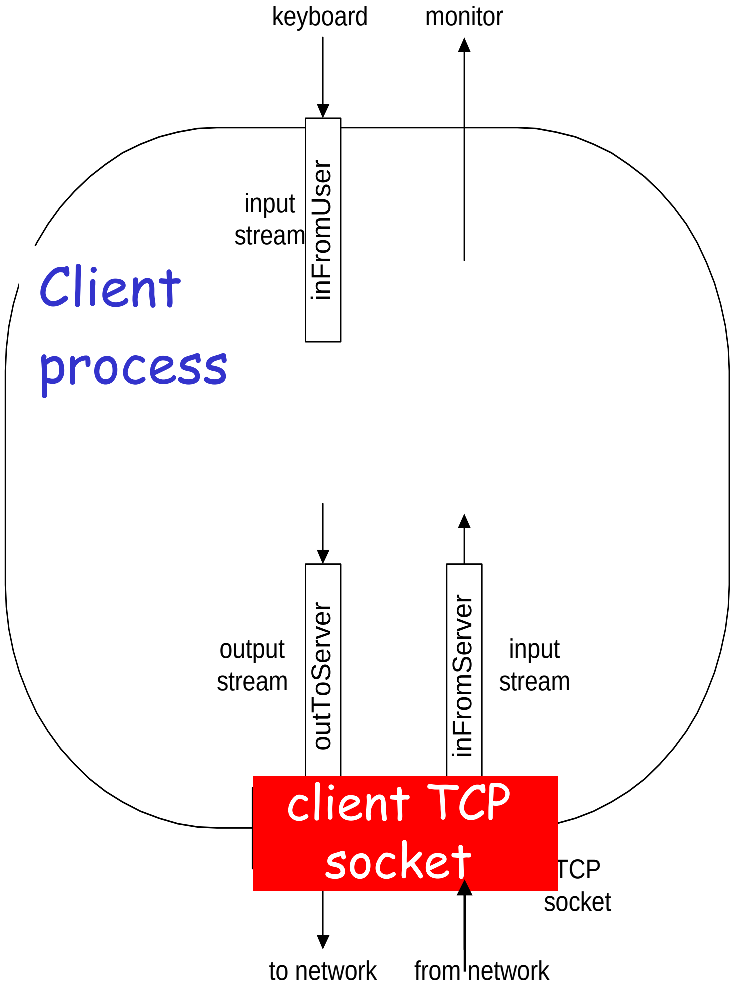


# Stream jargon

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 TCPClient {

    public static void main(String argv[]) throws Exception
    {
        String sentence;
        String modifiedSentence;

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

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

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

Create input stream → BufferedReader inFromUser

Create client socket, connect to server → Socket clientSocket

Create output stream attached to socket → DataOutputStream outToServer

# 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;

     ServerSocket welcomeSocket = new ServerSocket(6789);

     while(true) {

        Socket connectionSocket = welcomeSocket.accept();

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

Create welcoming socket at port 6789 → `ServerSocket welcomeSocket = new ServerSocket(6789);`

Wait, on welcoming socket for contact by client → `Socket connectionSocket = welcomeSocket.accept();`

Create input stream, attached to socket → `BufferedReader inFromClient = ...`

# Example: Java server (TCP), cont

Create output stream, attached to socket →

```
DataOutputStream  outToClient =
  new DataOutputStream(connectionSocket.getOutputStream());
```

Read in line from socket →

```
clientSentence = inFromClient.readLine();

capitalizedSentence = clientSentence.toUpperCase() + '\n';
```

Write out line to socket →

```
outToClient.writeBytes(capitalizedSentence);
}
      }
  }
```

End of while loop, loop back and wait for another client connection

# Chapter 2: Application layer

# 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

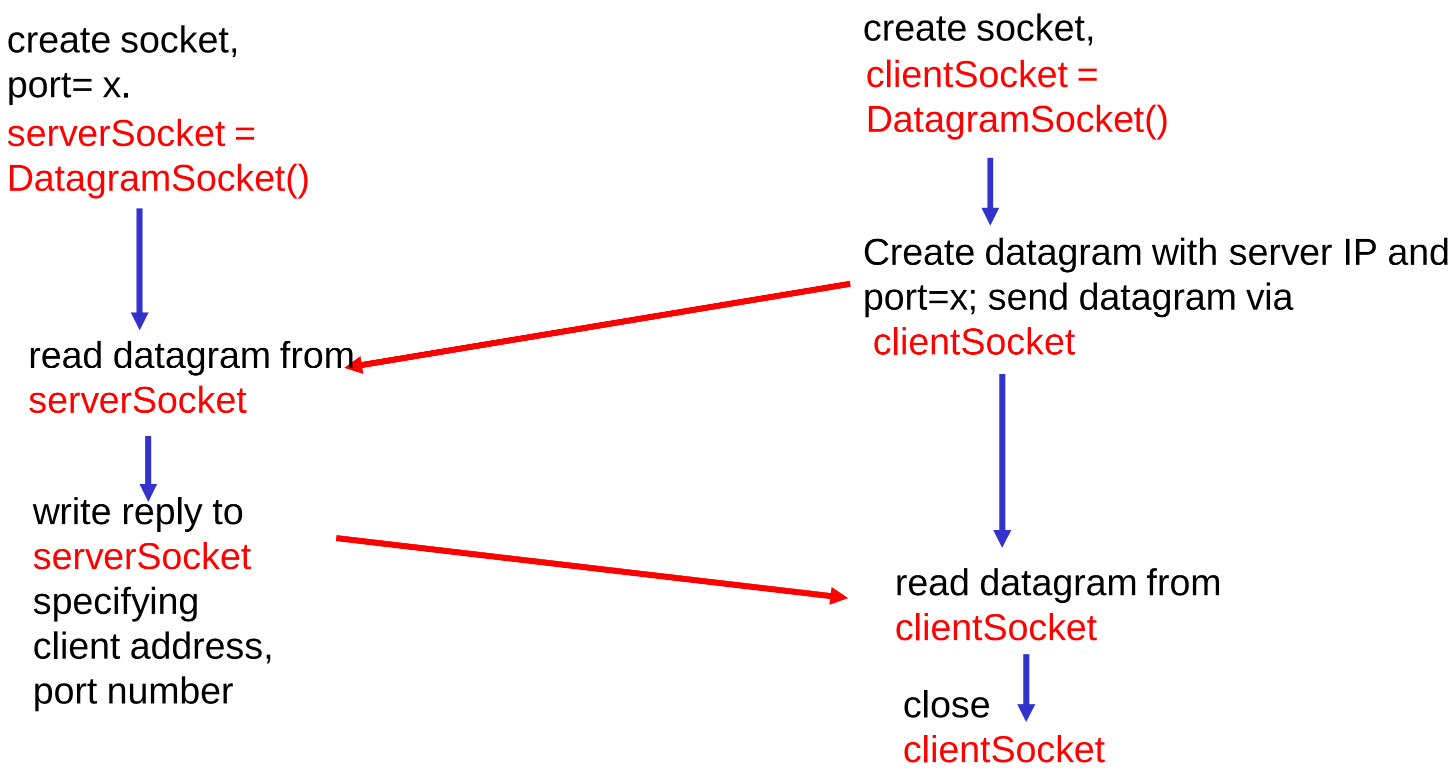
UDP: transmitted data may be received out of order, or lost

**application viewpoint**

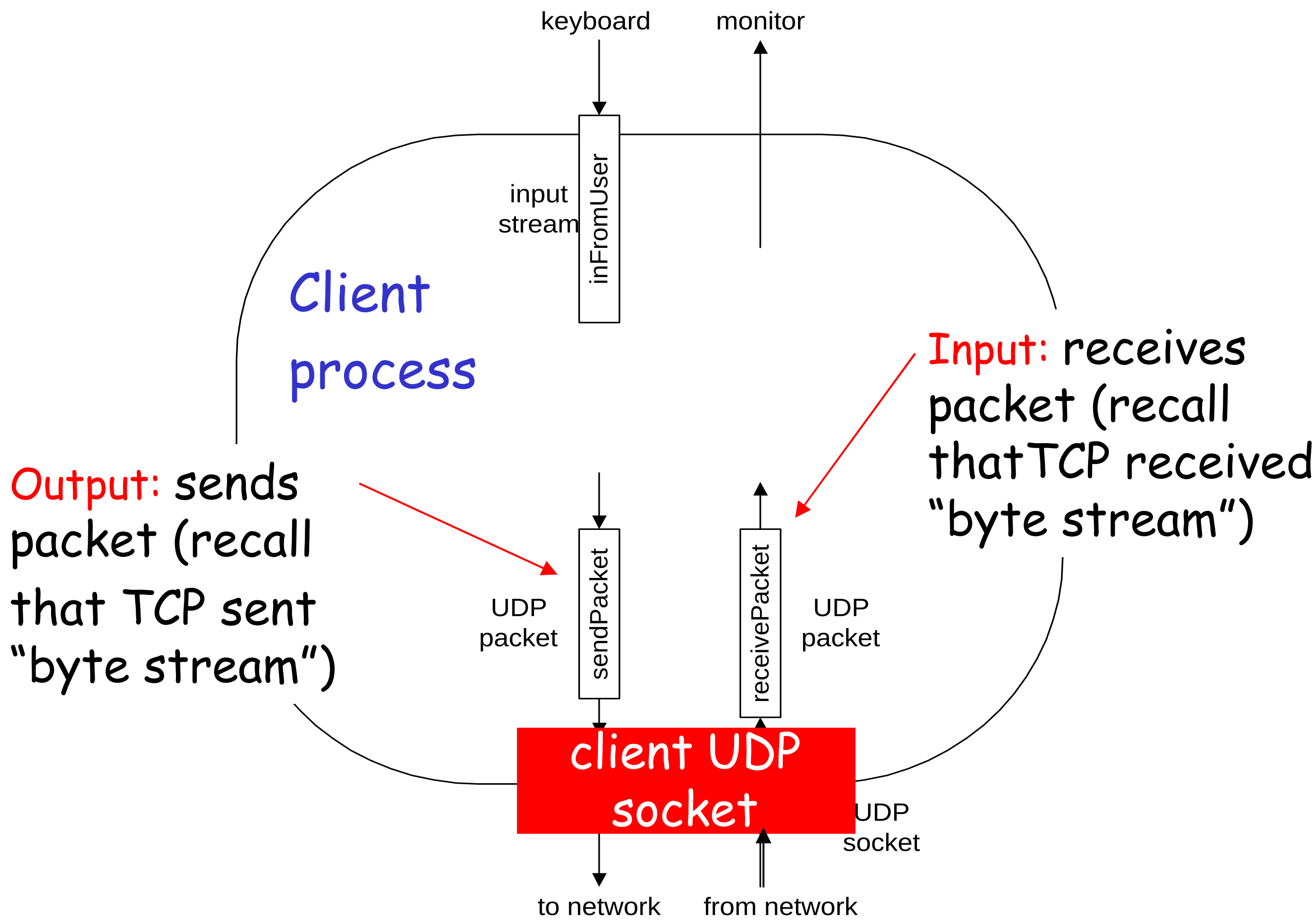
*UDP provides unreliable transfer of groups of bytes ("datagrams") between client and server*

# Client/server socket interaction: UDP

**Server** (running on `hostid`) **Client**



# Example: Java client (UDP)



# Example: Java client (UDP)

Create input stream

Create client socket

Translate hostname to IP address using DNS

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

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

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

      DatagramSocket clientSocket = new DatagramSocket();

      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

```
DatagramPacket sendPacket =
  new DatagramPacket(sendData, sendData.length, IPAddress, 9876);
```

Send datagram to server

```
clientSocket.send(sendPacket);

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

Read datagram from server

```
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
    {

      DatagramSocket serverSocket = new DatagramSocket(9876);

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

      while(true)
        {

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

Create datagram socket at port 9876 → `DatagramSocket serverSocket = new DatagramSocket(9876);`

Create space for received datagram → `DatagramPacket receivePacket = new DatagramPacket(receiveData, receiveData.length);`

Receive datagram → `serverSocket.receive(receivePacket);`

# Example: Java server (UDP), cont

Get IP addr port #, of sender

Create datagram to send to client

Write out datagram to socket

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

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

InetAddress IPAddress = receivePacket.getAddress();

int port = receivePacket.getPort();

        String capitalizedSentence = sentence.toUpperCase();

sendData = capitalizedSentence.getBytes();

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

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

# 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"