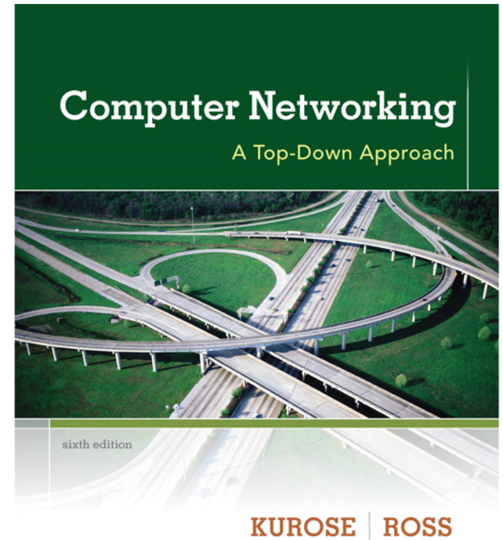
2. Application Layer



Computer Networking: A Top Down Approach
6th edition
Jim Kurose, Keith Ross
Addison-Wesley
March 2012

2. Application layer: Outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 FTP

2.4 electronic mail
- SMTP, POP3, IMAP

2.5 DNS

2.6 P2P applications

2.7 socket programming with UDP and TCP

2. Application layer: Goals

our goals:

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

Some network apps

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

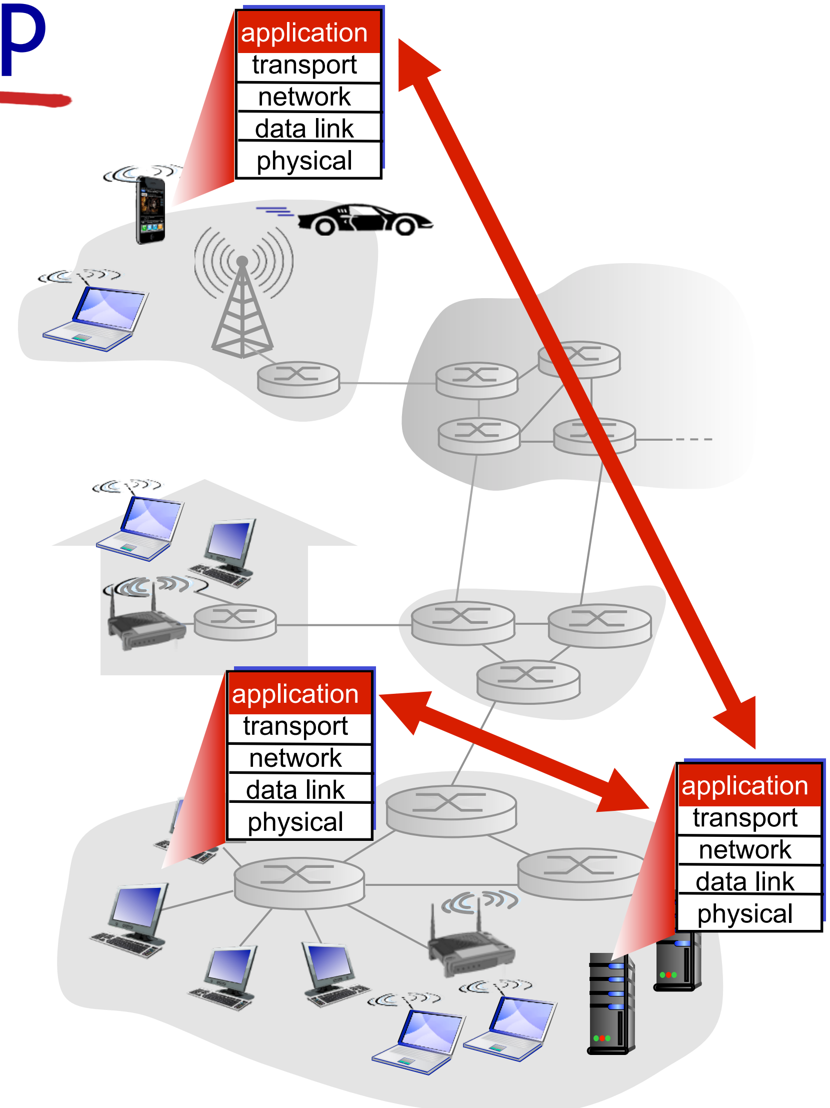
Creating a network app

write programs that:

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

no need to write software for network-core devices

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

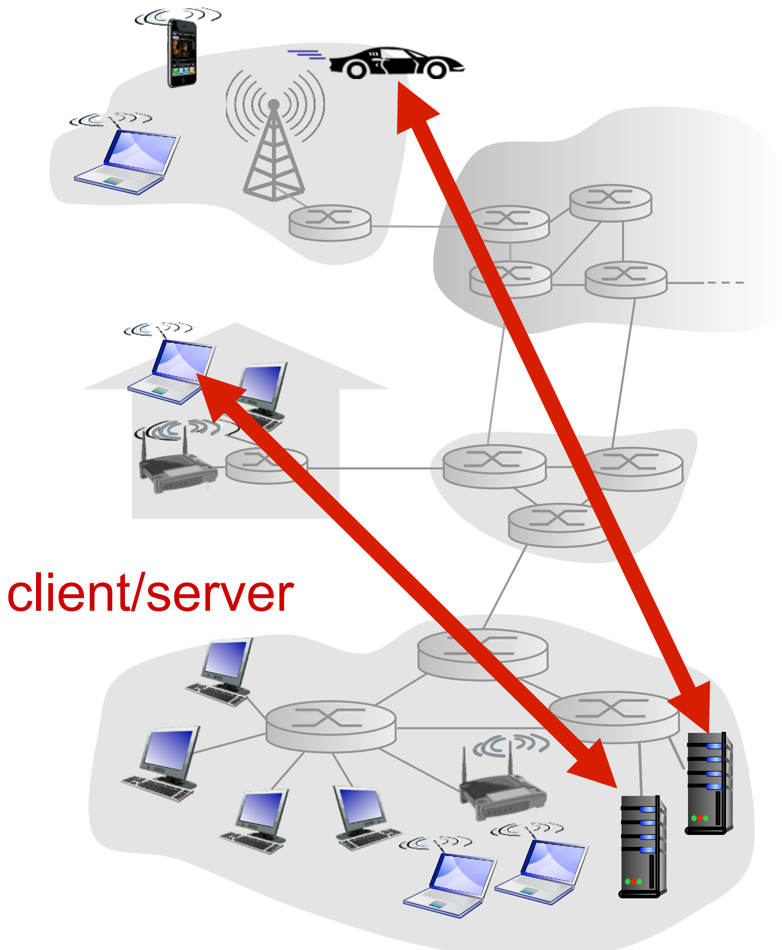


Application architectures

possible structure of applications:

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

Client-server architecture



server:

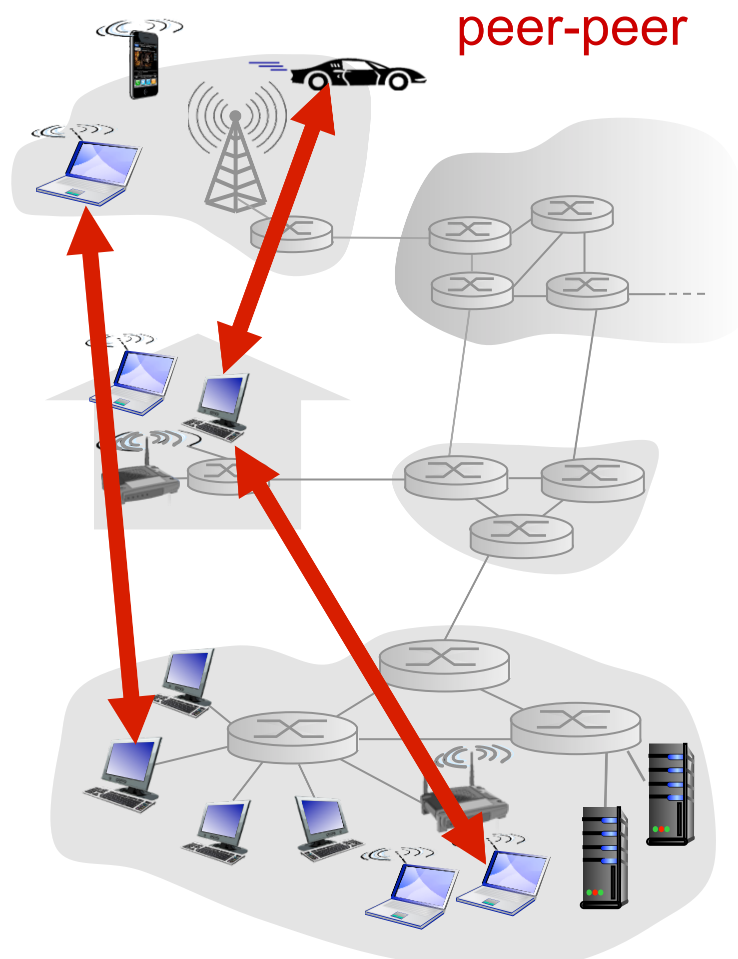
- always-on host
- permanent IP address
- data centers for scaling

clients:

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

P2P architecture

- *no* always-on server
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, as well as new service demands
- peers are intermittently connected and change IP addresses
  - complex management



Processes communicating

process: program running within a host

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

clients, servers

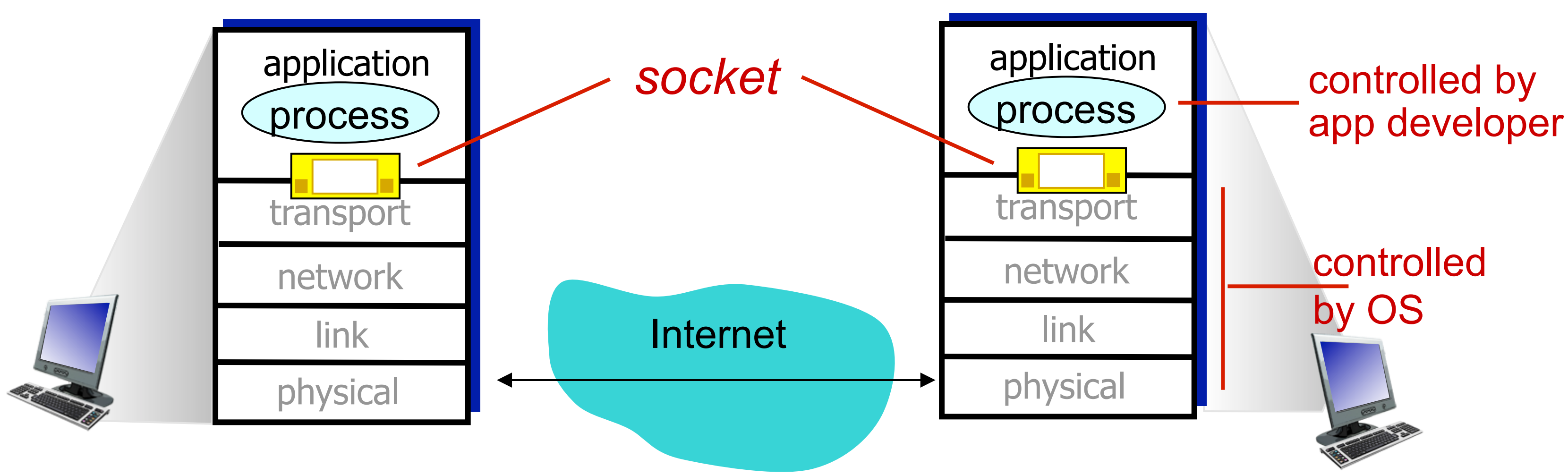
client process: process that initiates communication

server process: process that waits to be contacted

- aside: even P2P applications have client processes & server processes

Sockets

- process sends/receives messages to/from its socket
- socket analogous to a dropbox at door
  - sending process shoves message into dropbox
  - sending process relies on transport to deliver message to dropbox at receiving process



Addressing processes

- to receive messages, process must have *identifier*
- host device has unique 32-bit IP address
- *Q:* does IP address of host on which process runs suffice for identifying the process?
  - *A:* no, *many* processes can be running on same host

- *identifier* includes both IP address and port numbers associated with process on host.
- example port numbers:
  - HTTP server: 80
  - mail server: 25
- to send HTTP message to www.cs.umass.edu web server:
  - IP address: 128.119.240.84
  - port number: 80
- more shortly…

App-layer protocol defines

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

open protocols:

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

proprietary protocols:

- e.g., Skype

What transport service does an app need?

data integrity

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

timing

- some apps (e.g., Internet telephony, interactive games) require low delay to be "effective"

throughput

- some apps (e.g., multimedia) require minimum amount of throughput to be "effective"
- other apps ("elastic apps") make use of whatever throughput they get

security

- encryption, data integrity, …

Transport service requirements: common apps

application	data loss	throughput	time sensitive
file transfer	no loss	elastic	no
e-mail	no loss	elastic	no
Web documents	no loss	elastic	no
real-time audio/video	loss-tolerant	audio: 5kbps-1Mbps video:10kbps-5Mbps	yes, 100's msec
stored audio/video	loss-tolerant	same as above	
interactive games	loss-tolerant	few kbps up	yes, few secs
text messaging	no loss	elastic	yes and no, 100s msec

Common Internet transport services

TCP service:

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

UDP service:

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

Q: why bother? Why is there a UDP?

Internet apps: application, transport protocols

application	application layer protocol	underlying transport protocol
e-mail	SMTP [RFC 2821]	TCP
remote terminal access	Telnet [RFC 854]	TCP
Web	HTTP [RFC 2616]	TCP
file transfer	FTP [RFC 959]	TCP
streaming multimedia	HTTP (e.g., YouTube), RTP [RFC 1889]	TCP or UDP
Internet telephony	SIP, RTP, proprietary (e.g., Skype)	TCP or UDP

Q: Why might skype use TCP?

Securing TCP

TCP & UDP

- no encryption
- cleartext passwds sent into socket traverse Internet in cleartext

SSL

- provides encrypted TCP connection
- data integrity
- end-point authentication

SSL is at app layer

- Apps use SSL libraries, which "talk" to TCP

SSL socket API

- cleartext passwds sent into socket encrypted before transmission
- See Chapter 7

Q1: TCP vs. UDP

- Which of the following is true?
  A. FTP uses UDP
  B. HTTP uses UDP
  C. UDP ensures in-order delivery but not reliability
  D. HTTP uses TCP

Q2 Endpoint process identifier

- A network application process is identified uniquely by which of the following?

A. IP address
B. IP address, port
C. IP address, port, MAC address
D. domain name

Q3 Transport

- Pick the true statement

A. TCP provides reliability and guarantees a minimum bandwidth.
B. TCP provides reliability while UDP provides bandwidth guarantees.
C. TCP provides reliability while UDP does not.
D. Neither TCP nor UDP provide reliability.

Q4 HTTP

- Persistent HTTP fetches multiple web objects over a single TCP connection while non-persistent HTTP uses a separate TCP connection for each object. True/false?

A. True

B. False

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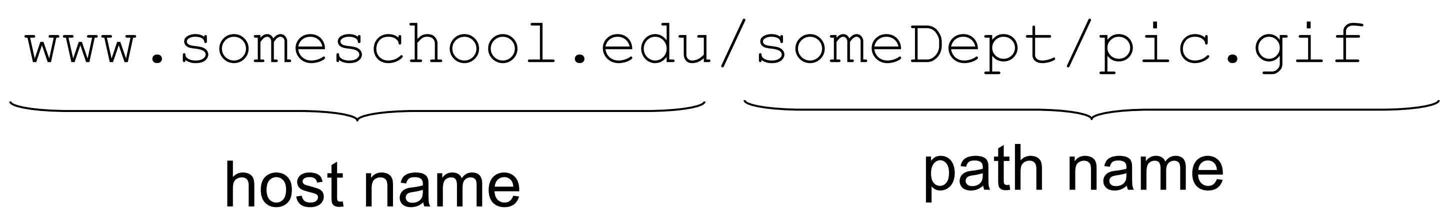
Web and HTTP

First, a review…

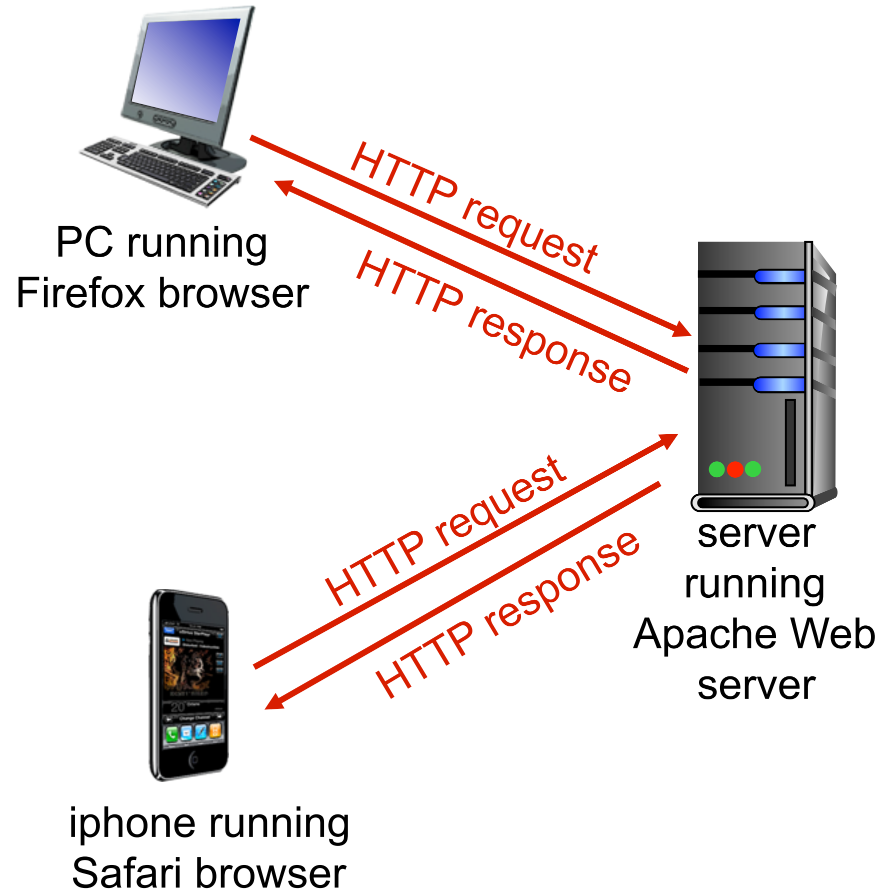
- *web page* consists of *objects*
- object can be HTML file, JPEG image, Java applet, audio file,…
- web page consists of *base HTML-file* which includes *several referenced objects*
- each object is addressable by a *URL,* e.g.,



HTTP overview

HTTP: hypertext transfer protocol

- Web's application layer protocol
- client/server model
  - *client:* browser that requests, receives, (using HTTP protocol) and "displays" Web objects
  - *server:* Web server sends (using HTTP protocol) objects in response to requests



HTTP overview (continued)

uses TCP:

- client initiates TCP connection (creates socket) to server, port 80
- server accepts TCP connection from client
- HTTP messages (application-layer protocol messages) exchanged between browser (HTTP client) and Web server (HTTP server)
- TCP connection closed

HTTP is "stateless"

- server maintains no information about past client requests
  - cookies an exception

aside

protocols that maintain "state" are complex!

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

HTTP connections

non-persistent HTTP

- at most one object sent over TCP connection
  - connection then closed
- downloading multiple objects required multiple connections

persistent HTTP

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

Non-persistent HTTP

suppose user enters URL:

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

(contains text, references to 10 jpeg images)

1a. HTTP client initiates TCP connection to HTTP server (process) at www.someSchool.edu on port 80

1b. HTTP server at host www.someSchool.edu waiting for TCP connection at port 80. "accepts" connection, notifying client

2. HTTP client sends HTTP *request message* (containing URL) into TCP connection socket. Message indicates that client wants object someDepartment/home.index

3. HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time

Non-persistent HTTP (cont.)

4. HTTP server closes TCP connection.

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

time

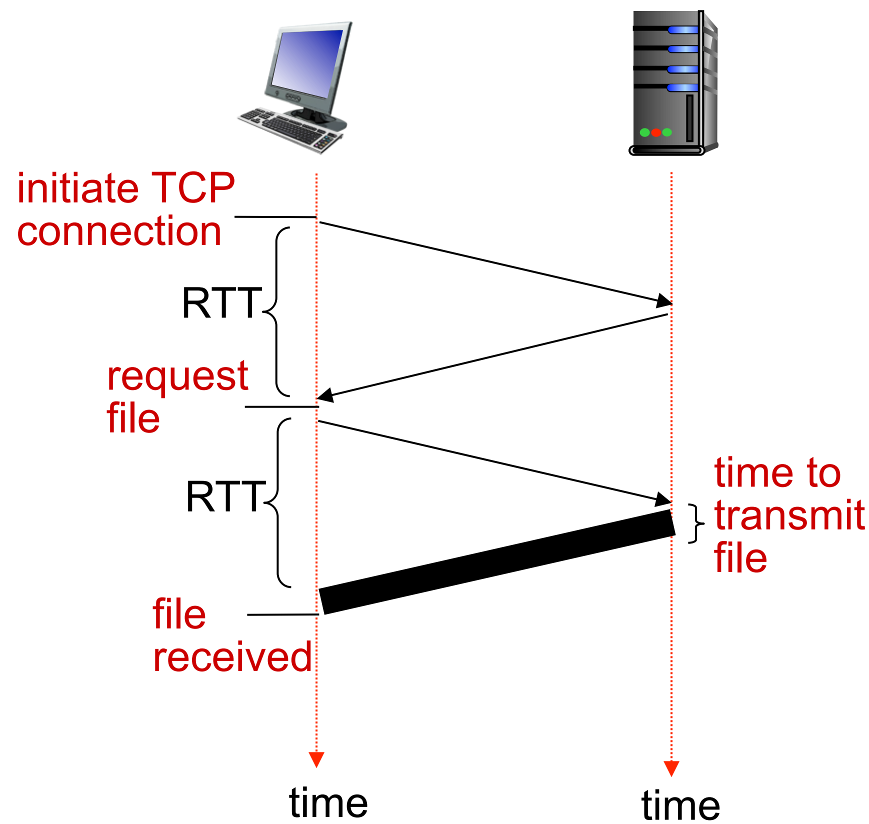
6. Steps 1-5 repeated for each of 10 jpeg objects

Non-persistent HTTP: response time

RTT (definition): time for a small packet to travel from client to server and back

HTTP response time:

- one RTT to initiate TCP connection
- one RTT for HTTP request and first few bytes of HTTP response to return
- file transmission time
- non-persistent HTTP response time =
  2RTT+ file transmission time



Persistent HTTP

non-persistent HTTP issues:

- requires 2 RTTs per object
- OS overhead for *each* TCP connection
- browsers often open parallel TCP connections to fetch referenced objects

persistent HTTP:

- server leaves connection open after sending response
- subsequent HTTP messages between same client/server sent over open connection
- client sends requests as soon as it encounters a referenced object
- as little as one RTT for all the referenced objects

HTTP request message

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

carriage return character

line-feed character

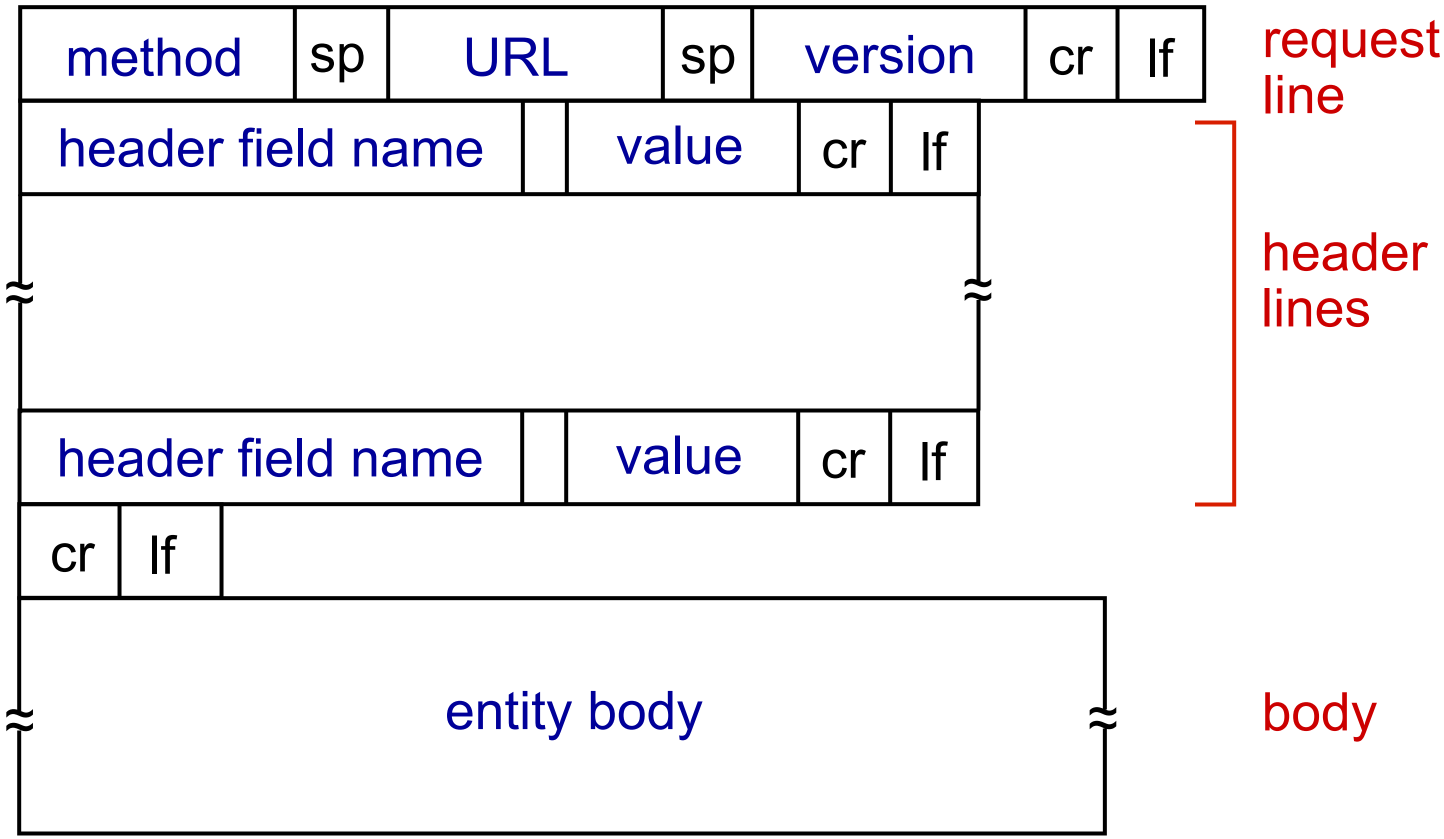
request line (GET, POST, HEAD commands)

```
GET /index.html HTTP/1.1\r\n
Host: www-net.cs.umass.edu\r\n
User-Agent: Firefox/3.6.10\r\n
Accept: text/html,application/xhtml+xml\r\n
Accept-Language: en-us,en;q=0.5\r\n
Accept-Encoding: gzip,deflate\r\n
Accept-Charset: ISO-8859-1,utf-8;q=0.7\r\n
Keep-Alive: 115\r\n
Connection: keep-alive\r\n
\r\n
```

header lines

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

HTTP request message: general format



Uploading form input

POST method:

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

URL method:

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

```
www.somesite.com/animalsearch?monkeys&banana
```

Method types

HTTP/1.0:

- GET
- POST
- HEAD
  - asks server to leave requested object out of response

HTTP/1.1:

- GET, POST, HEAD
- PUT
  - uploads file in entity body to path specified in URL field
- DELETE
  - deletes file specified in the URL field

HTTP response message

status line (protocol status code status phrase)

```
HTTP/1.1 200 OK\r\n
Date: Sun, 26 Sep 2010 20:09:20 GMT\r\n
Server: Apache/2.0.52 (CentOS)\r\n
Last-Modified: Tue, 30 Oct 2007 17:00:02 GMT
   \r\n
ETag: "17dc6-a5c-bf716880"\r\n
Accept-Ranges: bytes\r\n
Content-Length: 2652\r\n
Keep-Alive: timeout=10, max=100\r\n
Connection: Keep-Alive\r\n
Content-Type: text/html;
   charset=ISO-8859-1\r\n
\r\n
data data data data data ...
```

header lines

data, e.g., requested HTML file

HTTP response status codes

- status code appears in 1st line in server-to-client response message.
- some sample codes:

`200 OK`

- request succeeded, requested object later in this msg

`301 Moved Permanently`

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

`400 Bad Request`

- request msg not understood by server

`404 Not Found`

- requested document not found on this server

`505 HTTP Version Not Supported`

Trying out HTTP (client side) for yourself

1. Telnet to your favorite Web server:

```
telnet 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!

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

User-server state: cookies

many Web sites use cookies

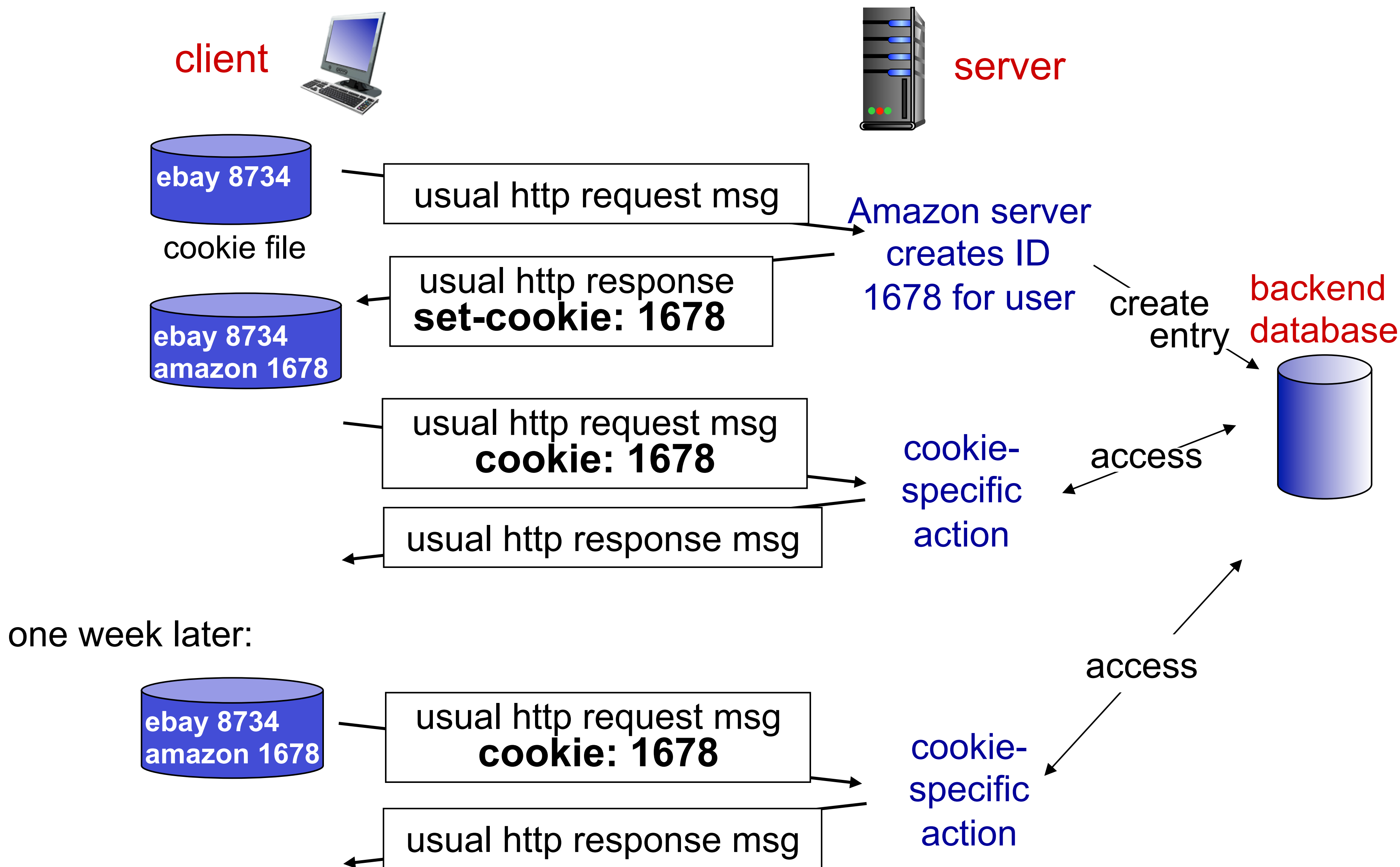
four components:

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

example:

- Susan always access Internet from her 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
- subsequent HTTP requests carry cookie

Cookies: keeping "state" (cont.)



Cookies (continued)

cookies uses:

- 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

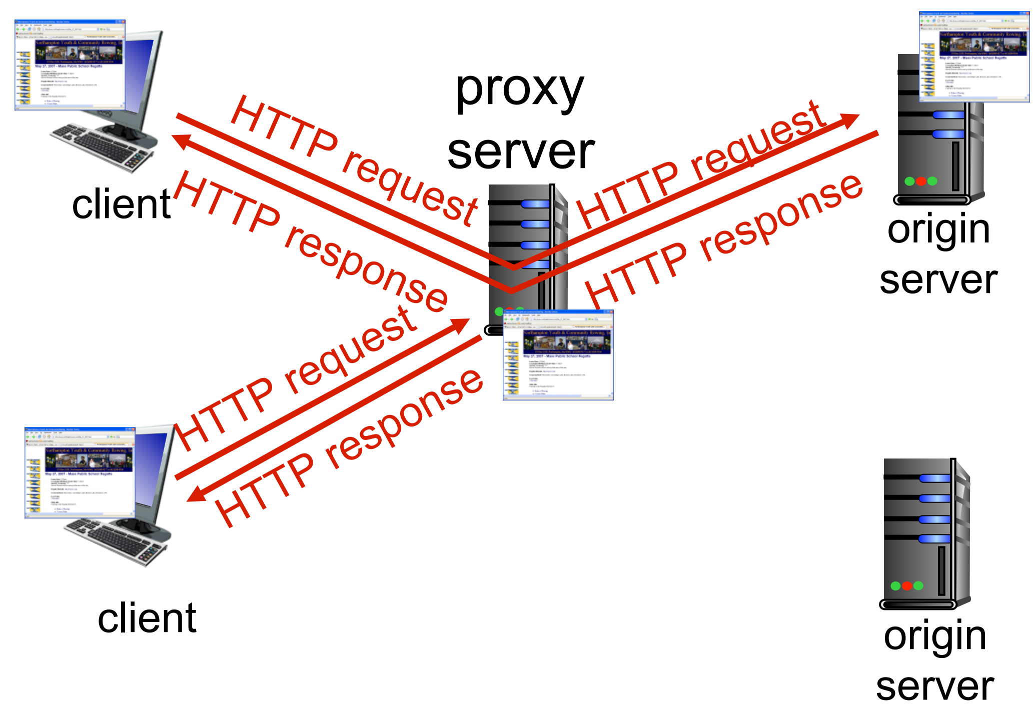
"stateful" protocols:

- protocol endpoints maintain state at sender/receiver over multiple transactions
  - cookies in 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
  - if object in cache: cache returns object
  - else cache requests object from origin server, then returns object to client



More about Web caching

- cache acts as both client and server
  - server for original requesting client
  - client to origin server
- typically cache is installed by ISP (university, company, residential ISP)

why Web caching?

1. reduce response time for client request
2. reduce traffic on an institution's access link
3. reduce server load (as does P2P file sharing)

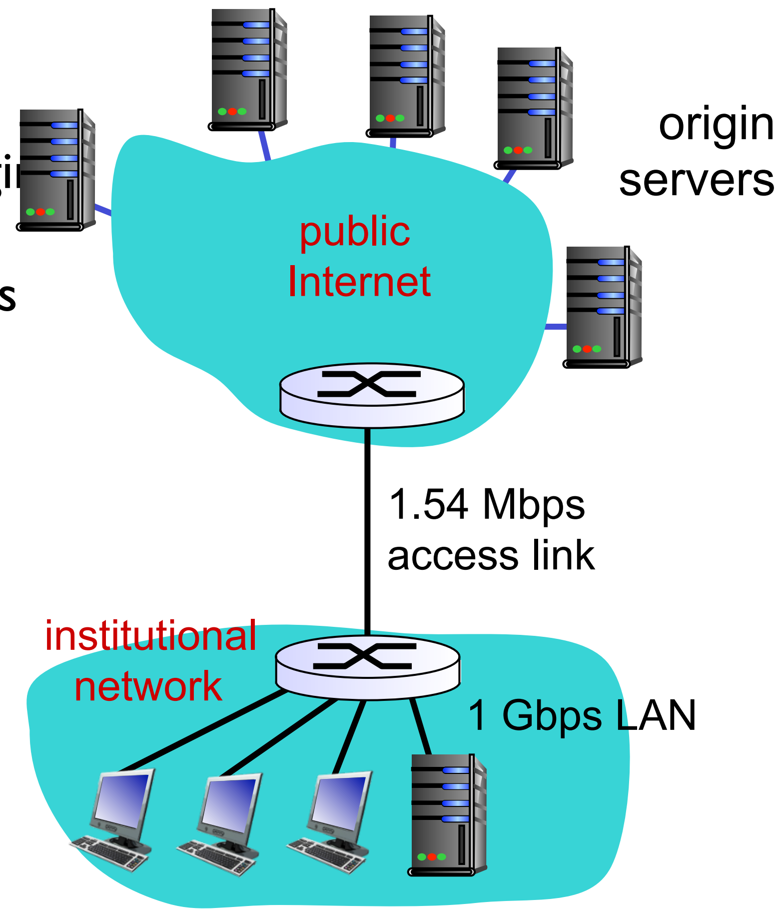
Caching example:

assumptions:

- avg object size: S=100K bits
- avg request rate from browsers to origin servers: A=15/sec
- avg data rate to browsers: R=1.50 Mbps
- access link rate: C=1.54 Mbps
- RTT from institutional router to any origin server: T=200 ms

consequences:

- LAN utilization: 0.15%
- access link utilization ≈ 99% *problem!*
- total delay = Internet delay + access delay + LAN delay
  = 200 ms + ≈minutes + µsecs



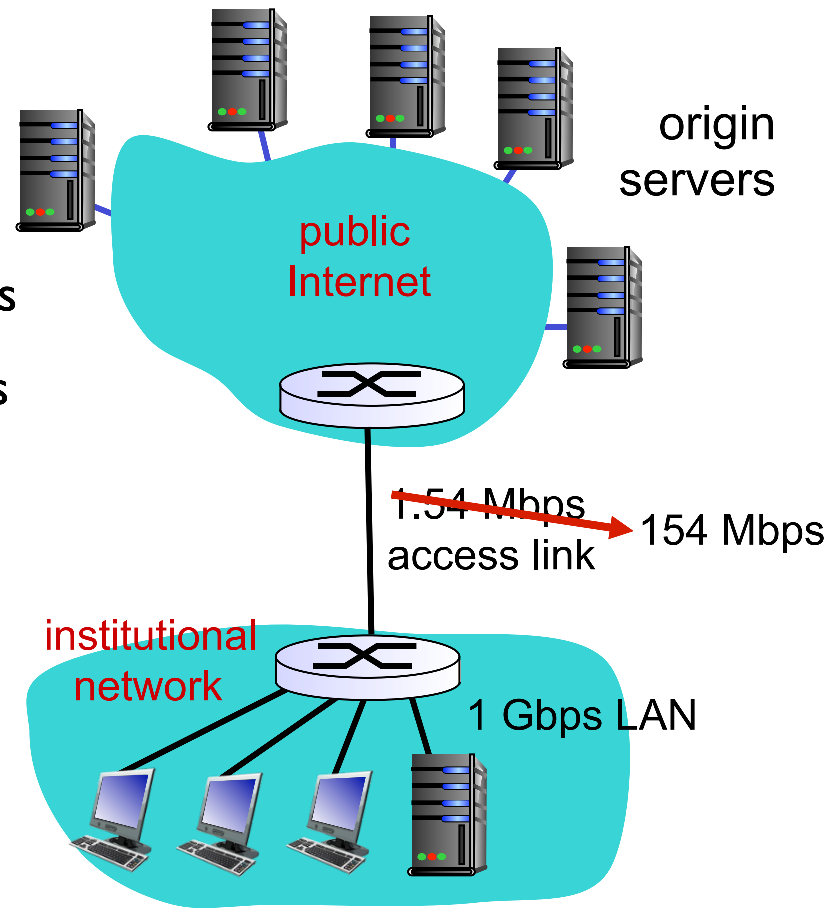
Caching example: fatter access link

assumptions:

- avg object size: S=100K bits
- avg request rate from browsers to origin servers: A=15/sec
- avg data rate to browsers: R=1.50 Mbps
- access link rate: C=~~1.54 Mbps~~ 154 Mbps
- RTT from institutional router to any origin server: T=200 ms

consequences:

- LAN utilization: 0.15% (as before)
- access link utilization = ~~99%~~ 9.9%
- total delay = Internet delay + access delay + LAN delay
  = 200 ms + ~~minutes~~ + usecs
  ≈ms



Cost: increased access link speed (not cheap!)

Caching example: install local cache

assumptions:

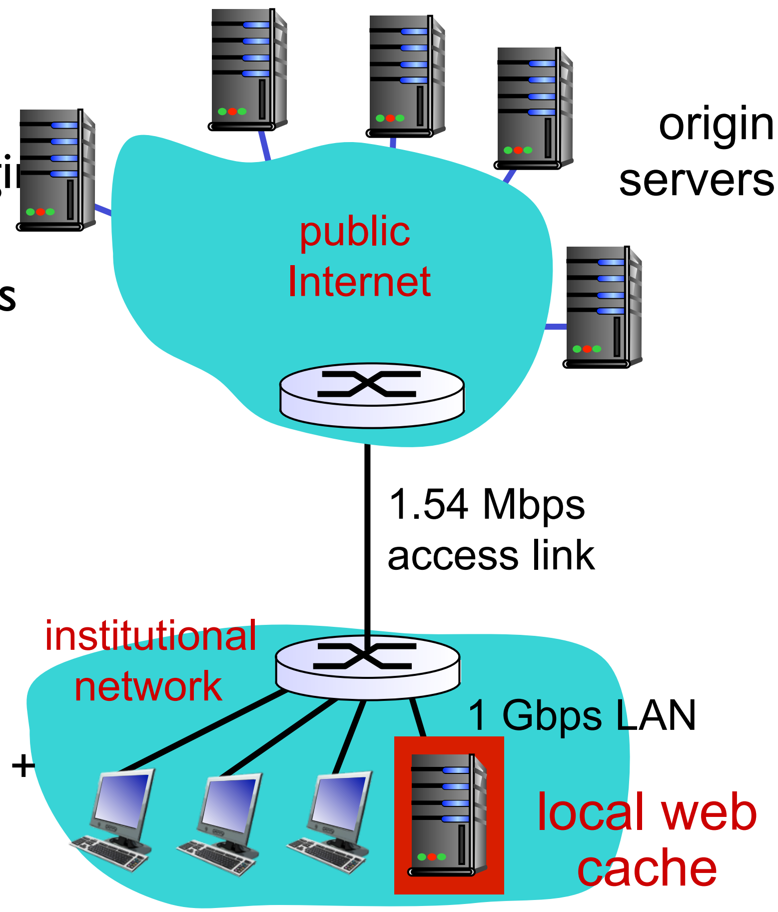
- avg object size: S=100K bits
- avg request rate from browsers to origin servers: A=15/sec
- avg data rate to browsers: R=1.50 Mbps
- access link rate: C=1.54 Mbps
- RTT from institutional router to any origin server: T=200 ms

consequences:

- LAN utilization: 0.15% (as before)
- access link utilization = ?
- total delay = ?

How to compute link utilization, delay?

Cost: web cache (cheap!)



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install local cache

assumptions:

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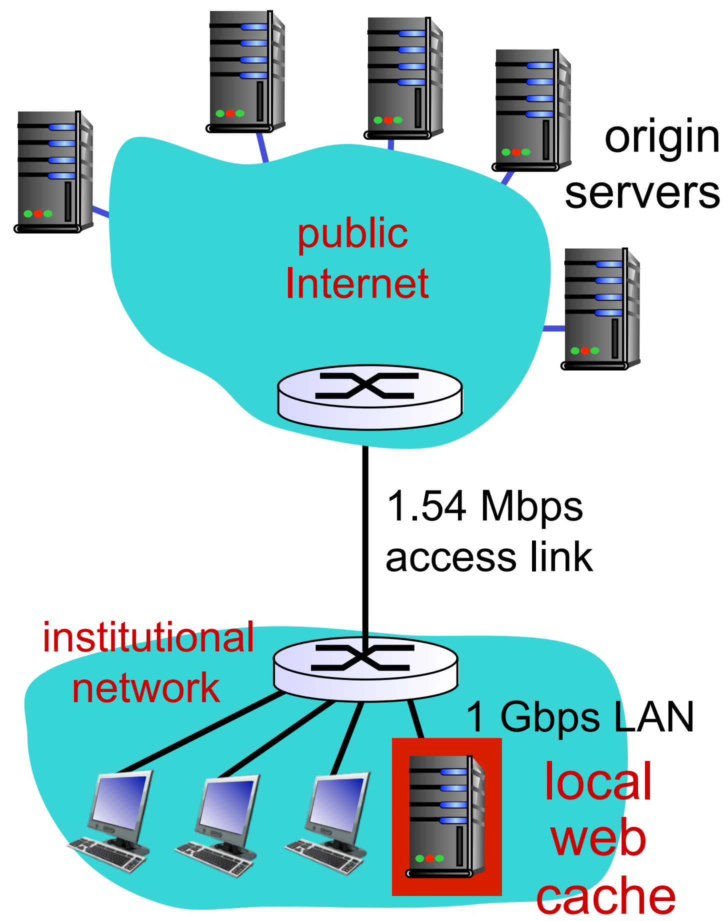
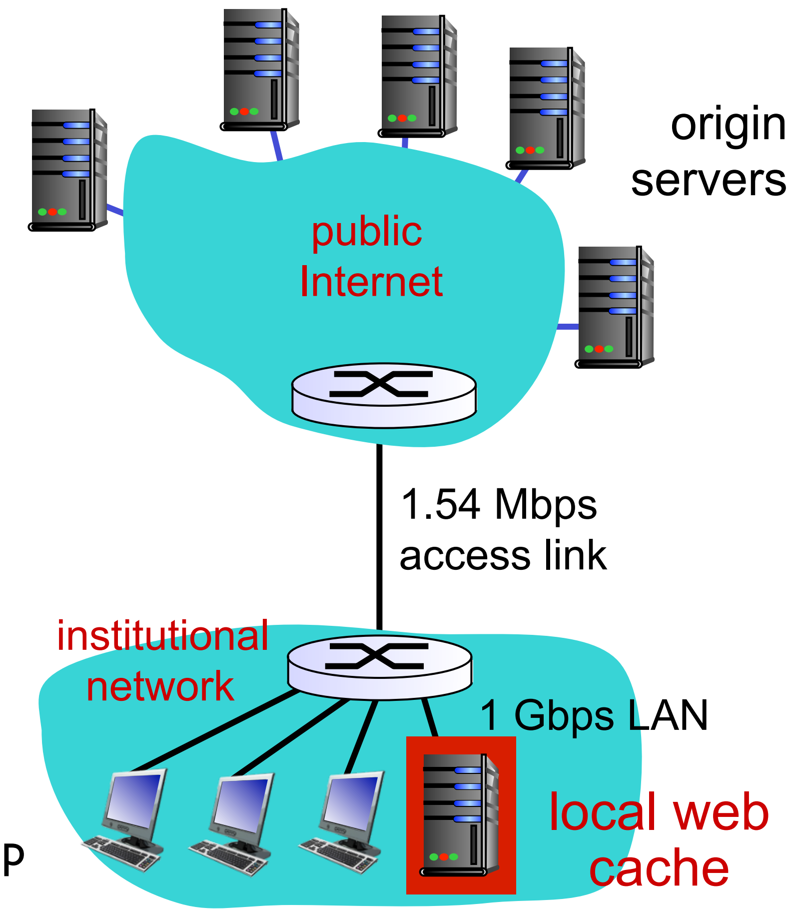


Caching example: install local cache

Calculating access link utilization, delay with cache:

- suppose cache hit rate is 0.4
  - p=40% requests satisfied at cache, 60% (=1-p) satisfied at origin
- access link utilization:
  - 60% of request data rate
- data rate to browsers over access link = pR = 0.6*1.50 Mbps = .9 Mbps
  - utilization u = pR/C = 0.9/1.54 = 0.58
  - transmission delay d = S/C = 0.067s
  - queuing delay q = (S/C)/(1-u) = 0.16s
- total delay
  - (1-p)*miss_delay + p*hit_delay
  - = (1-p) * (delay from origin servers) + p * (delay when satisfied at cache)
  - = (1-p)*(T+d+q) + p*(?)
  - =
  - = ≈250ms



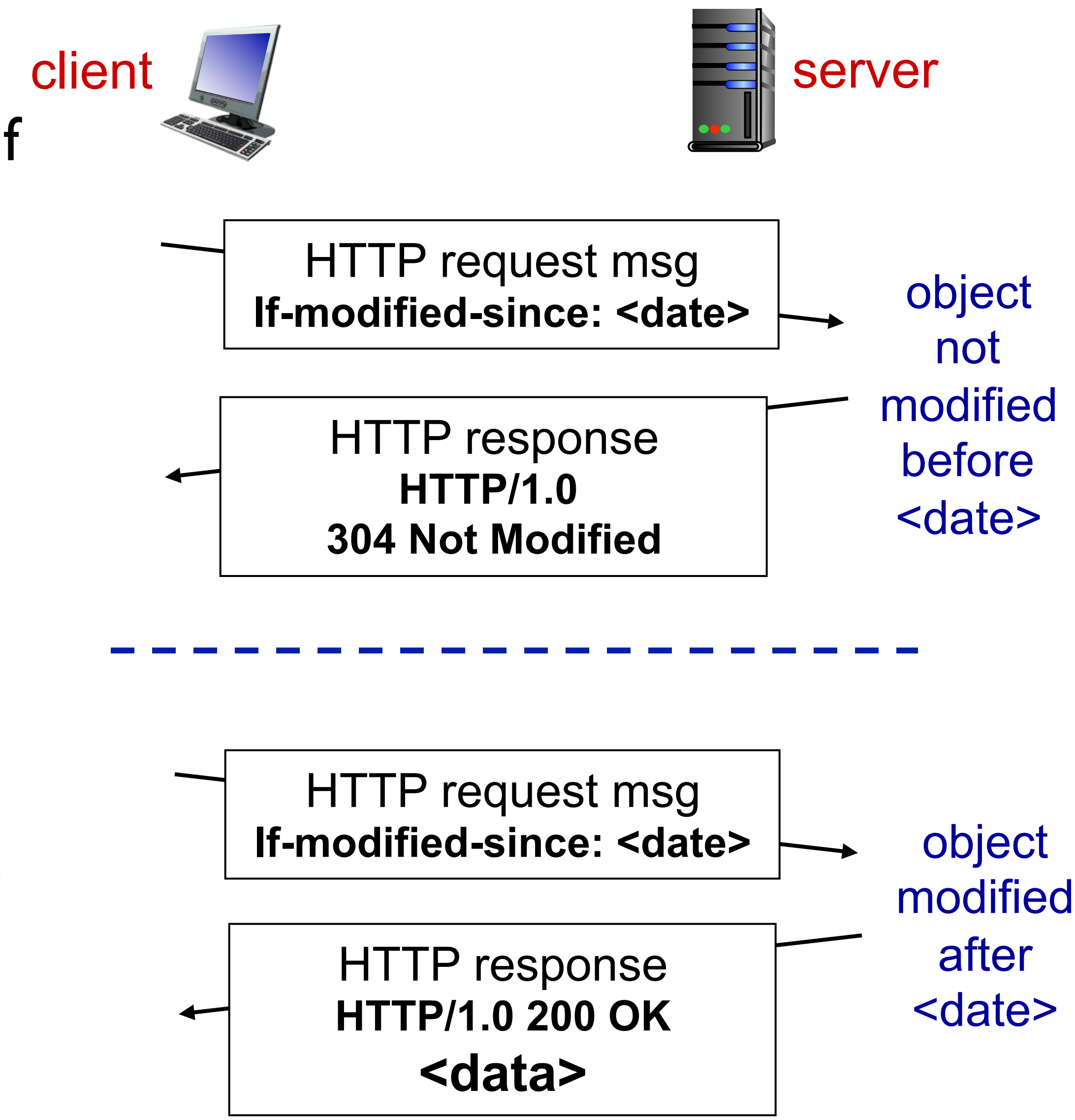
Benefit: Lower latency without costly upgrade!

Conditional GET

- *Goal:* don't send object if cache has up-to-date cached version
  - no object transmission delay
  - lower link utilization
- *cache:* specify date of cached copy in HTTP request

  `If-modified-since: <date>`
- *server:* response contains no object if cached copy is up-to-date:

  `HTTP/1.0 304 Not Modified`



Q1: HTTP conn. persistence

- Which of the following is true about persistent HTTP compared to non-persistent HTTP
  A. Persistent HTTP improves throughput using more connections.
  B. Persistent HTTP improves download time by reducing the number of connection setup round trips
  C. Persistent HTTP improves throughput by sending fewer HTTP requests.
  D. Persistent HTTP improves download time by sending fewer HTTP requests.

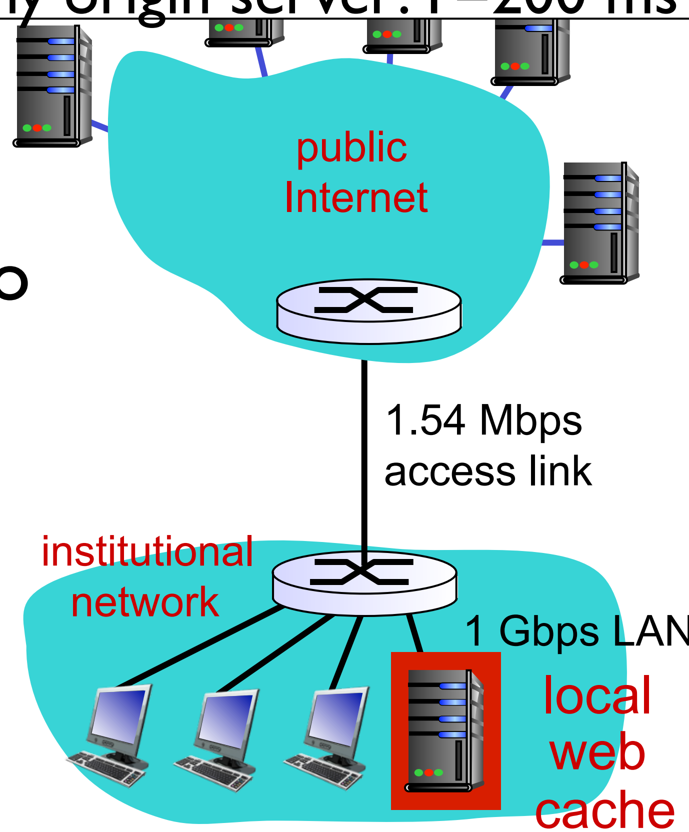
Q2: HTTP conn. persistence

- Among the following, in which case would you get the greatest improvement in performance with persistent HTTP compared to non-persistent?
  - A. Low capacity (bits/sec) network paths
  - B. High capacity network paths
  - C. Long-distance network paths
  - D. High capacity, short-distance network paths
  - E. High capacity, long-distance network paths

Q3: Web caching

assumptions:

- avg object size: S=100K bits
- avg request rate from browsers to origin servers: A=15/sec
- access link rate: C=1.54 Mbps
- RTT from institutional router to any origin server: T=200 ms



- If the cache captured a fraction p=0.3 of requests, what is the average delay contributed by transmission delays alone (i.e., no queuing) for each object? Ignore LAN transmission delays.
  A. S/C
  B. pS/C
  C. (1-p)S/C
  D. (p + AS/C)(S/C)
  E. (1-p)(AS/C)(S/C)

Q4 HTTP download time

- Consider a web page with a base file of size S_0 bits and N inline objects each of size S bits being downloaded by a client over a link of capacity C bits/sec and RTT T. How much time is saved by using persistent HTTP compared to non-persistent assuming requests for all inline objects are sent in a pipelined manner?

A. T
B. T(2N-1)
C. NT + S/C
D. T + NS/C
E. T(N-1)

Q5 HTTP download time

- Consider a web page with a base file of size S_0 bits and N inline objects each of size S bits being downloaded by a client over a link of capacity C bits/sec and RTT T. How much time is saved by using persistent HTTP compared to non-persistent assuming requests for all inline objects are sent in a sequential manner, i.e., a request for the next object is sent after the previous object has been completely received?

A. T
B. NT
C. (2N-1)T
D. 2NT

Q6 HTTP download time

- Consider a web page with a base file of size S_0 bits and N inline objects each of size S bits being downloaded by a client over a link of capacity C bits/sec and RTT T bits/sec and RTT T. How much time will persistent HTTP (with pipelined requests) take if it used two parallel connections? Assume both connections are set up in parallel at the start, they share the available capacity equally, and inline objects are equally split across them.

A. (2T+S0) + T + NS/C
B. (2T+S0) + NT + NS/C
C. (2T+S0) + NS/C

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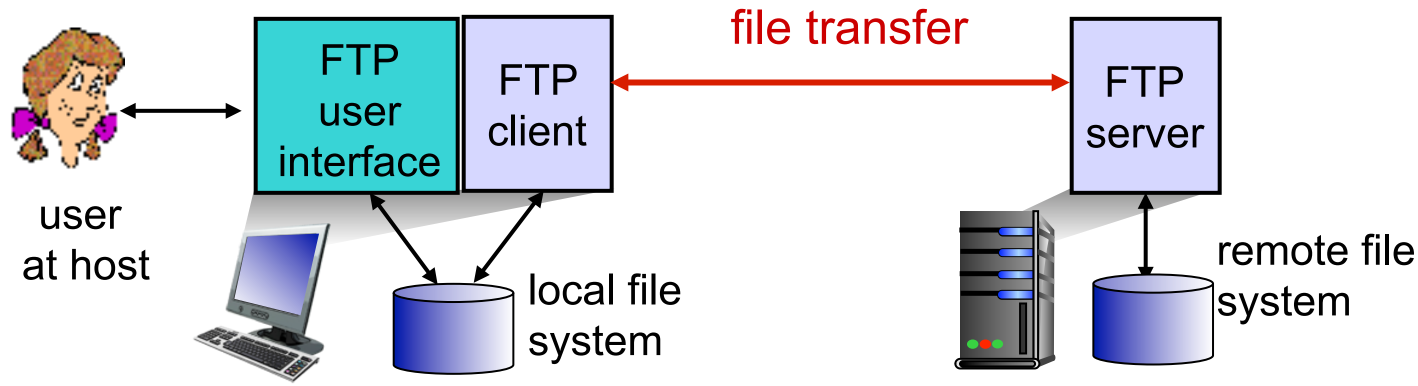
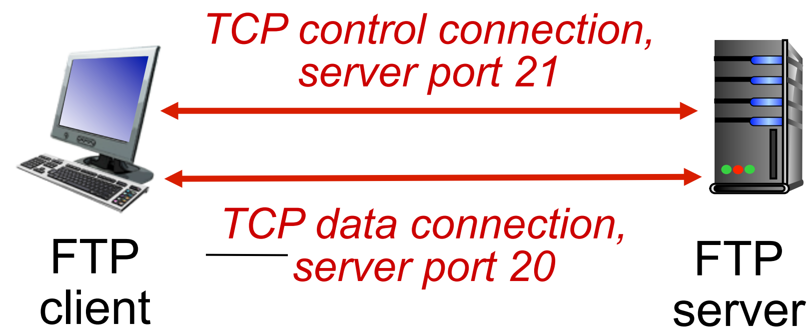
FTP: the file transfer protocol



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

FTP: separate control, data connections

- FTP client contacts FTP server at port 21, using TCP
- client authorized over control connection
- client browses remote directory, sends commands over control connection
- when server receives file transfer command, *server* opens 2nd TCP data connection (for file) *to* client
- after transferring one file, server closes data connection



- server opens another TCP data connection to transfer another file
- control connection: *"out of band"*
- FTP server maintains "state": current directory, earlier authentication

FTP commands, responses

sample commands:

- sent as ASCII text over control channel
- **`USER`** ***`username`***
- **`PASS`** ***`password`***
- **`LIST`** return list of file in current directory
- **`RETR filename`** retrieves (gets) file
- **`STOR filename`** stores (puts) file onto remote host

sample return codes

- status code and phrase (as in HTTP)
- **`331 Username OK, password required`**
- **`125 data connection already open; transfer starting`**
- **`425 Can't open data connection`**
- **`452 Error writing file`**

2. Application layer: Outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 FTP

2.4 electronic mail

- SMTP, POP3, IMAP

2.5 DNS

2.6 P2P applications

2.7 socket programming with UDP and TCP

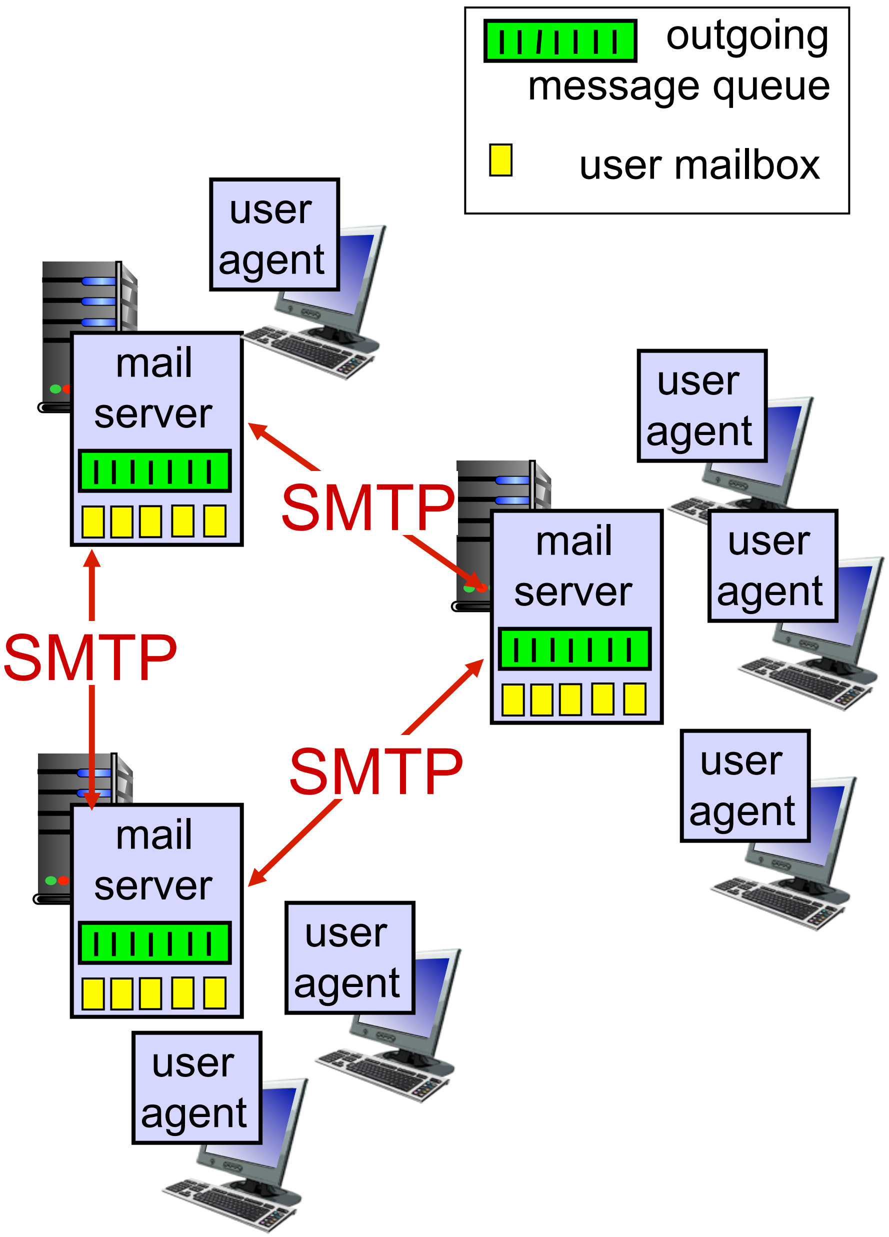
Electronic mail

Three major components:

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

User Agent

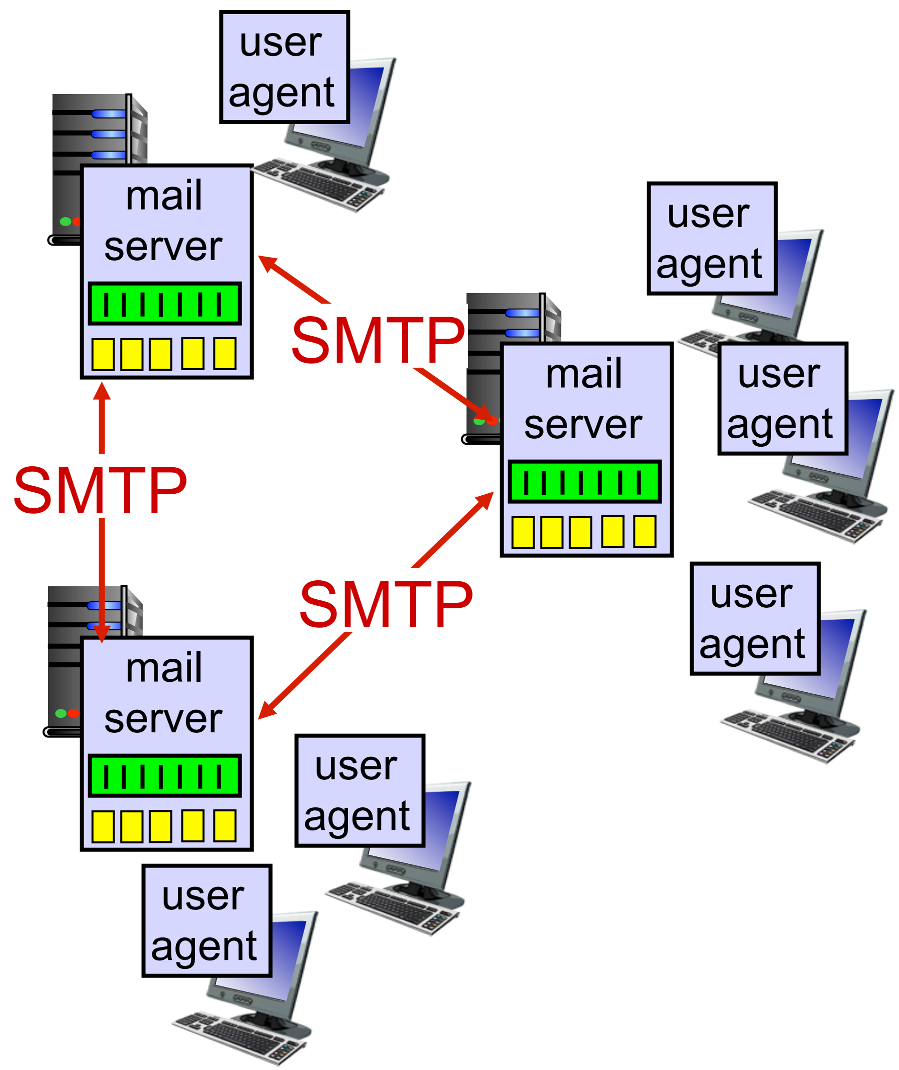
- a.k.a. "mail reader"
- composing, editing, reading mail messages
- e.g., Outlook, Thunderbird, iPhone mail client
- outgoing, incoming messages stored on server



Electronic mail: mail servers

mail servers:

- *mailbox* contains incoming messages for user
- *message queue* of outgoing (to be sent) mail messages
- *SMTP protocol* between mail servers to send email messages
  - client: sending mail server
  - "server": receiving mail server

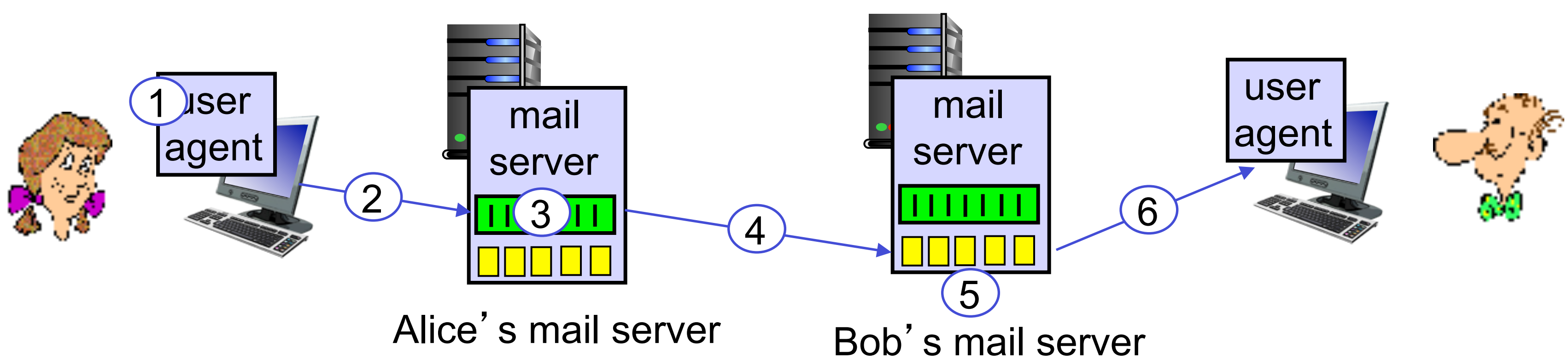


Electronic Mail: SMTP [RFC 2821]

- uses TCP to reliably transfer email message from client to server, port 25
- three phases of transfer
  - handshaking (greeting)
  - transfer of messages
  - closure
- command/response interaction (like HTTP, FTP)
  - commands: ASCII text
  - response: status code and phrase
- messages must be in 7-bit ASCI

Scenario: Alice sends message to Bob

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



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 vs HTTP

SMTP

- persistent connections
- 7-bit ASCII request/ response + status codes
- `CRLF.CRLF` for end of message
- Push
- Multiple objects sent in multipart message

HTTP

- persistent or non-persistent
- ASCII request/response + status codes
- `CRLF` or `CRLFCRLF` for end of message
- Pull
- Single object encapsulated in its own response message

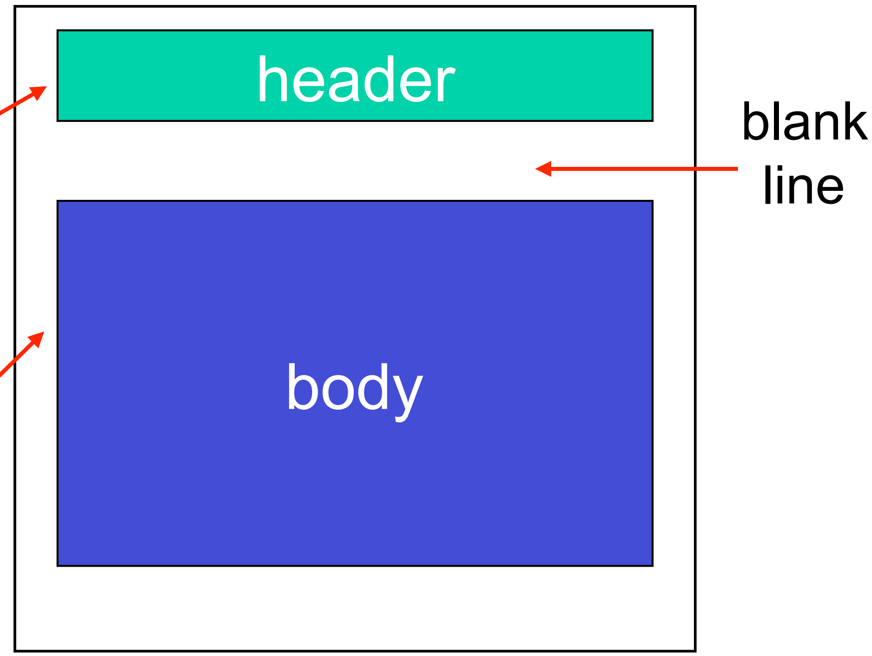
Mail message format

SMTP: protocol for exchanging email msgs

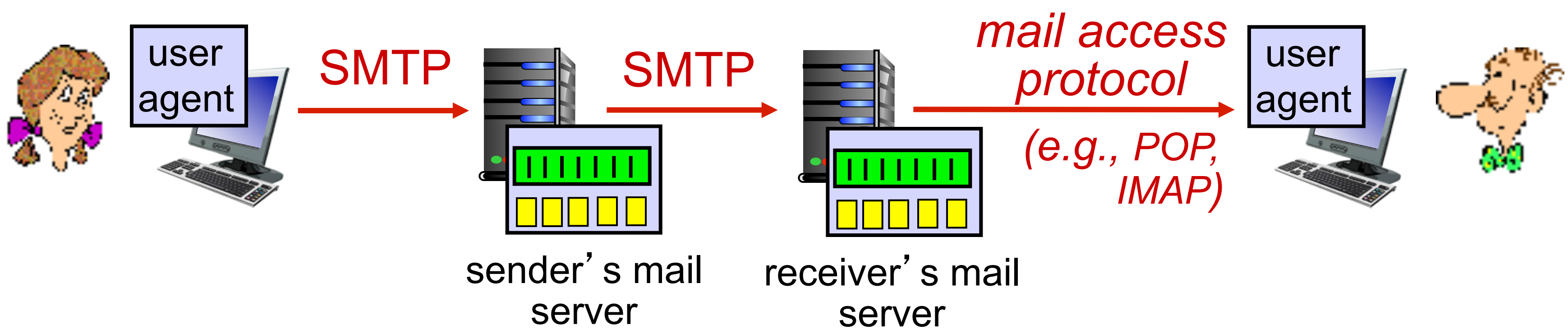
RFC 822: standard for text message format:

- header lines, e.g.,
  - To:
  - From:
  - Subject:

  different from SMTP MAIL FROM, RCPT TO: commands!
- Body: the "message"
  - ASCII characters only



Mail access protocols



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

POP3 protocol

authorization phase

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

transaction phase, client:

- **`list`**: list message numbers
- **`retr`**: retrieve message by number
- **`dele`**: delete
- **`quit`**

```
S: +OK POP3 server ready
C: user bob
S: +OK
C: pass hungry
S: +OK user successfully logged on
```

```
C: list
S: 1 498
S: 2 912
S: .
C: retr 1
S: <message 1 contents>
S: .
C: dele 1
C: retr 2
S: <message 1 contents>
S: .
C: dele 2
C: quit
S: +OK POP3 server signing off
```

POP3 (more) and IMAP

more about POP3

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

IMAP

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

2. Application layer: Outline

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2.2 Web and HTTP

2.3 FTP

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DNS: domain name system

people: many identifiers:

- SSN, name, passport #

Internet hosts, routers:

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

Q: how to map between IP address and name, and vice versa ?

Domain Name System:

- *distributed database* implemented in hierarchy of many *name servers*
- *application-layer protocol:* hosts, name servers communicate to *resolve* names → addresses
  - note: core Internet function, implemented as application-layer protocol
  - complexity at network's "edge"

DNS: services, structure

DNS services

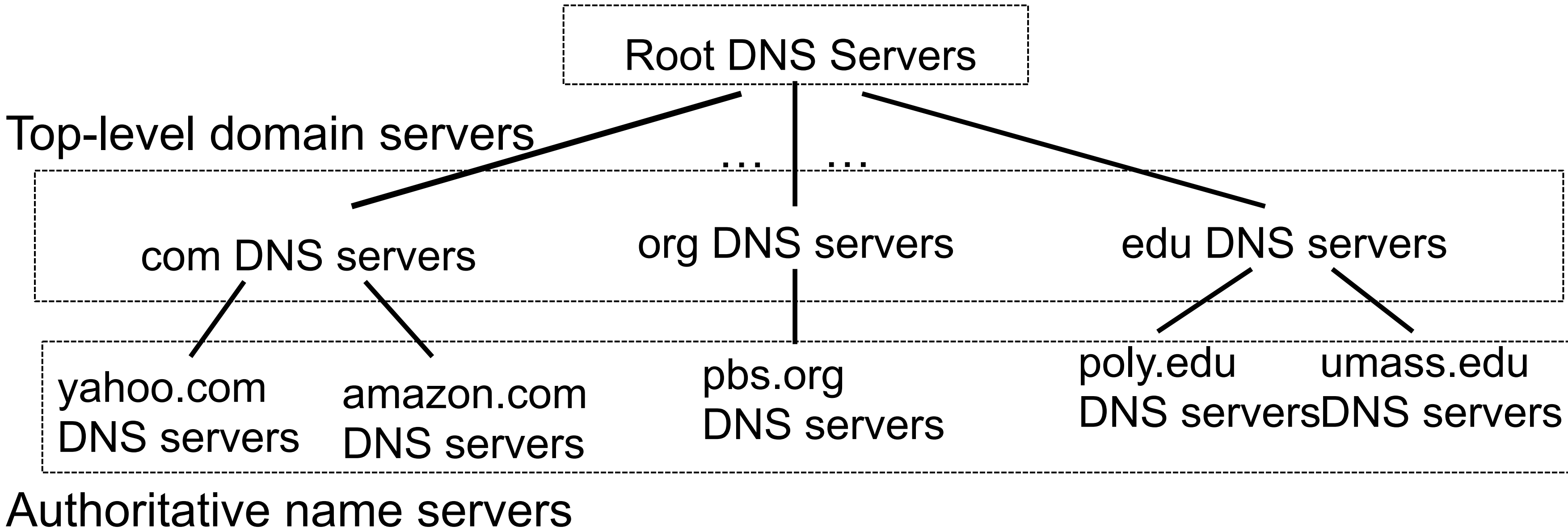
- Resolution
  - hostname → IP address
- Aliasing
  - canonical, alias names
  - mail server aliasing
- Load balancing with replicated web servers:
  - many IP addresses correspond to one name

why not centralize DNS?

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

A: doesn't scale!

DNS: a distributed, hierarchical database

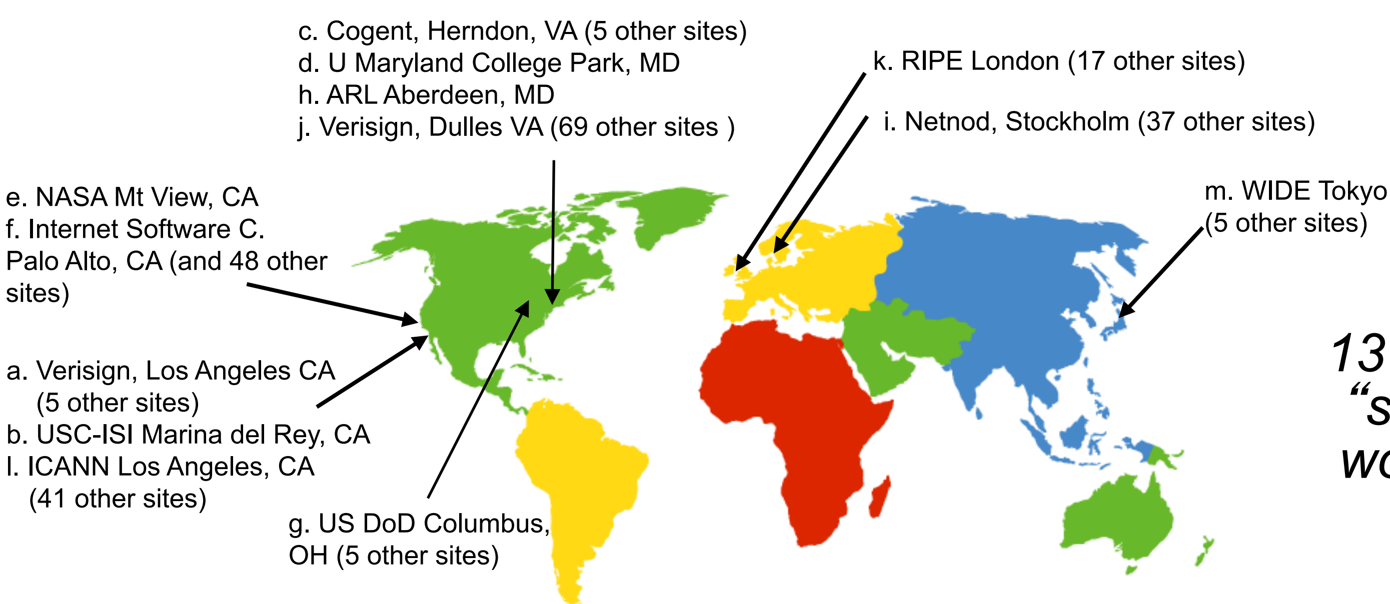


client wants IP for www.amazon.com; 1st approx:

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

DNS: root name servers

- contacted when no info about top-level or auth server
- root name server can:
  - return top-level or auth name server address
  - or contact auth server and return final resolved address



13 root name "servers" worldwide

TLD, authoritative servers

top-level domain (TLD) servers:

- responsible for com, org, net, edu, aero, jobs, museums, and all top-level country domains, e.g.: uk, fr, ca, jp
- Network Solutions maintains servers for .com TLD
- Educause for .edu TLD

authoritative DNS servers:

- organization's own DNS server(s), providing authoritative hostname to IP mappings for organization's named hosts
- can be maintained by organization or service provider

Local DNS name server

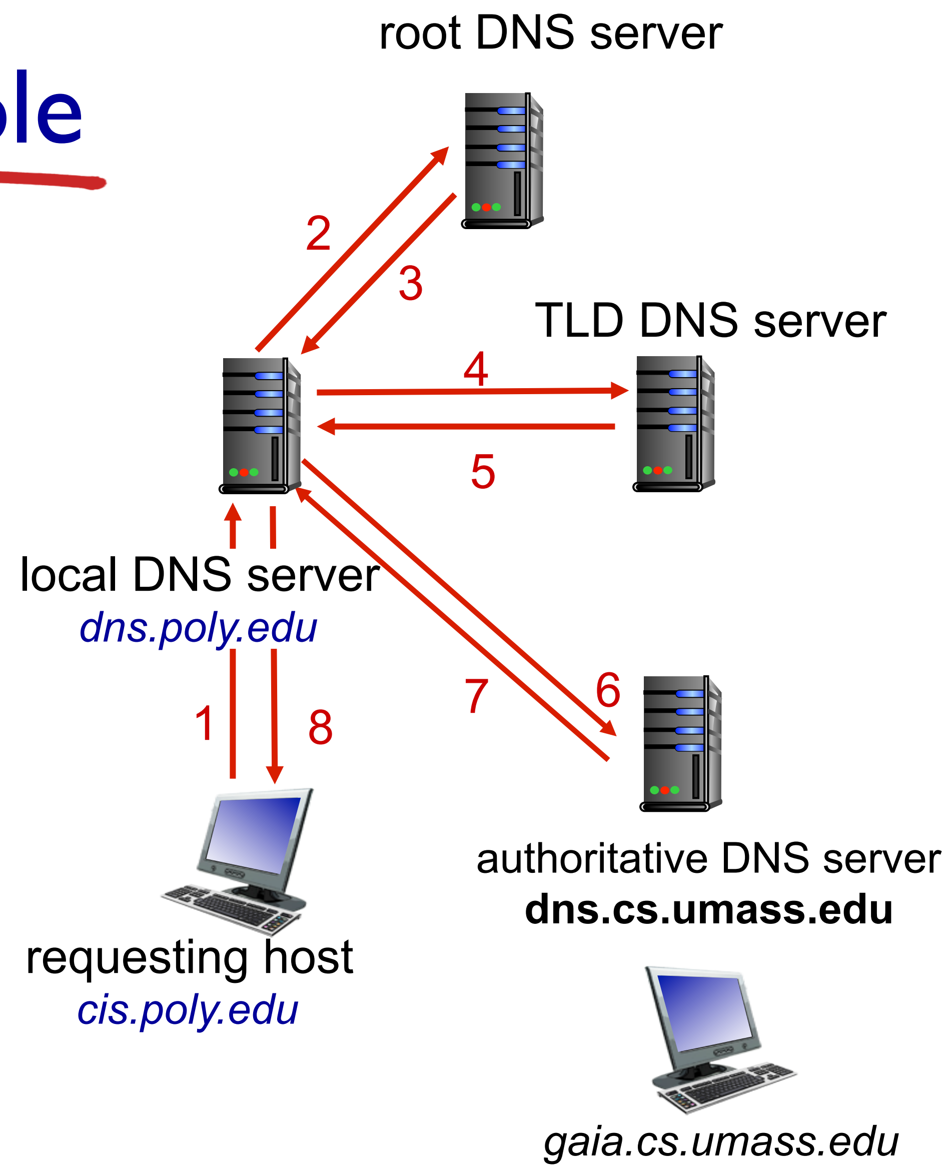
- does not strictly belong to hierarchy
- deployed by ISP (residential, company, university)
  - also called "default name server"
- acts as proxy between host and DNS hierarchy
  - has local cache of recent name-to-address translation pairs (but may be out of date!)

DNS name resolution example

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

iterated query:

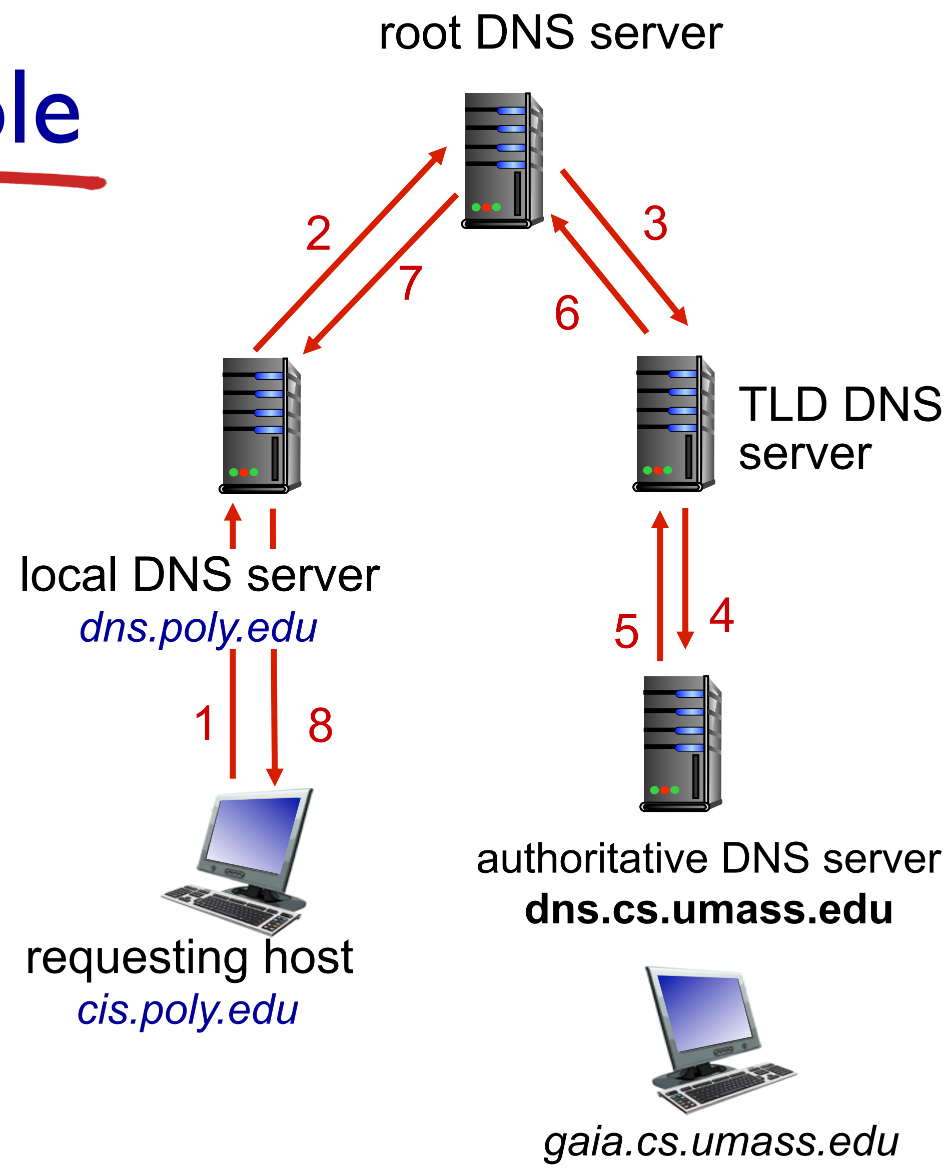
- contacted server replies with name of server to contact
- "I don't know this name, but ask this server"



DNS name resolution example

recursive query:

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



DNS: caching, updating records

- any name server can *cache* learned mappings
  - cache entries timeout (disappear) after some time (TTL)
  - TLD servers typically cached in local name servers, so root name servers not often visited
- cached entries may be *out-of-date* (best effort name-to-address translation!)
  - if name host changes IP address, may not be known Internet-wide until all TTLs expire
- update/notify mechanisms proposed IETF standard
  - RFC 2136

DNS records

DNS: distributed db storing resource records (RR)

RR format: `(name, value, type, ttl)`

type=A
- **`name`** is hostname
- **`value`** is IP address

type=NS
- **`name`** is domain (e.g., foo.com)
- **`value`** is hostname of authoritative name server for this domain

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

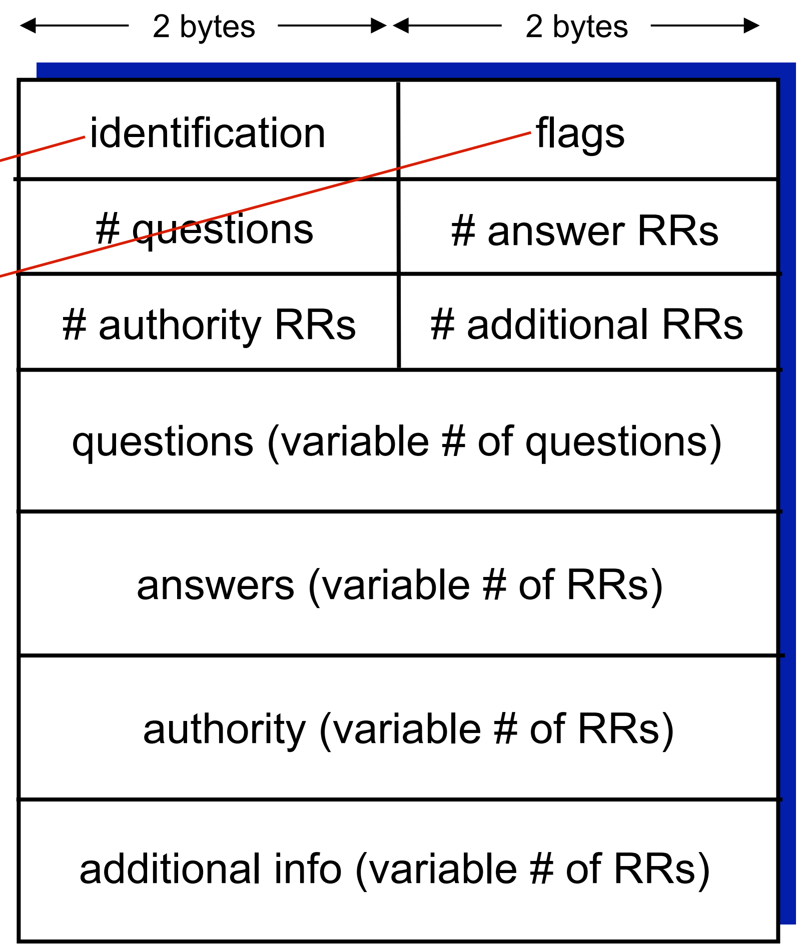
type=MX
- **`value`** is name of mailserver associated with **`name`**

DNS protocol, messages

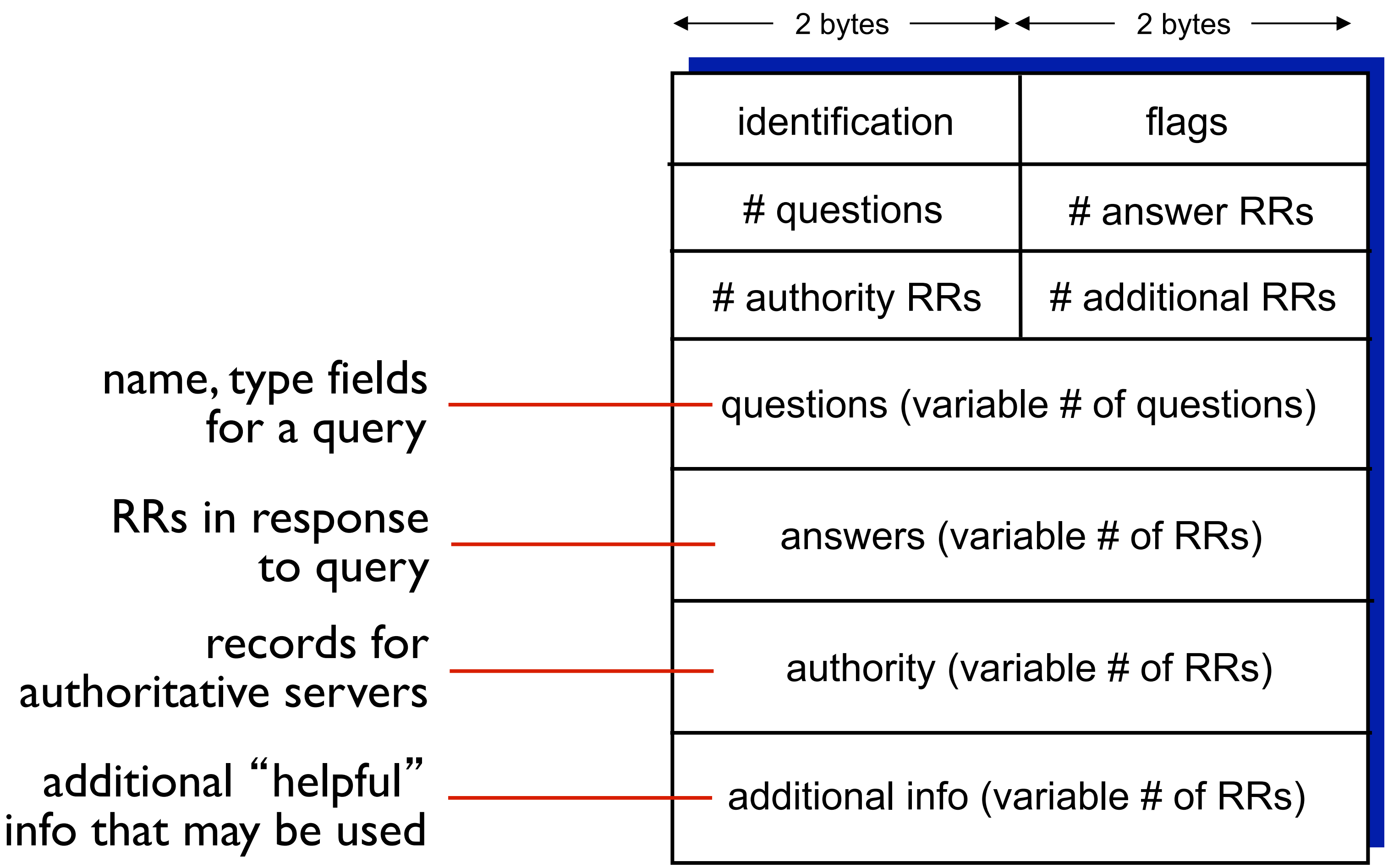
- *query* and *reply* messages, both with same *message format*

msg header

- identification: 16 bit # for query, reply to query uses same #
- flags:
  - query or reply
  - recursion desired
  - recursion available
  - reply is authoritative



DNS protocol, messages



Inserting records into DNS

- example: new startup "Network Utopia"
- register name networkuptopia.com at *DNS registrar* (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts two RRs into .com TLD server:

    `(networkutopia.com, dns1.networkutopia.com, NS)`

    `(dns1.networkutopia.com, 212.212.212.1, A)`
- create authoritative server type A record for www.networkuptopia.com; type MX record for networkutopia.com

Attacking DNS

DDoS attacks

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

Redirect attacks

- Man-in-middle
  - Intercept queries
- DNS poisoning
  - Send bogus replies to DNS server that caches

Exploit DNS for DDoS

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

Q1: HTTP vs. FTP

- Which of the following is not true?

A. HTTP and FTP are client-server protocols
B. HTTP separates control and data across two connections while FTP does not
C. FTP separates control and data across two connections while HTTP does not
D. Both HTTP and FTP use multiple connections to complete typical user operations
E. Both HTTP and FTP allow clients to upload (send) as well as download (receive) data

Q2: HTTP vs SMTP

- Which of the following is not true?

A. HTTP is pull-based, SMTP is push-based

B. HTTP uses a separate header for each object, SMTP uses a multipart message format

C. SMTP uses persistent connections

D. HTTP uses client-server communication but SMTP does not

Q3: Mail agent protocols

- Which of the following is not a difference between POP3 and IMAP?

A. Session state maintenance
B. Folders
C. Use of TCP

Q4: DNS

- Which one of the following pairs are <u>*respectively*</u> maintained by the client-side ISP and the domain name owner?
  A. Local, Authoritative
  B. Root, Top-level domain
  C. Root, Local
  D. Top-level domain, authoritative
  E. Authoritative, Top-level domain

2. Application layer: Outline

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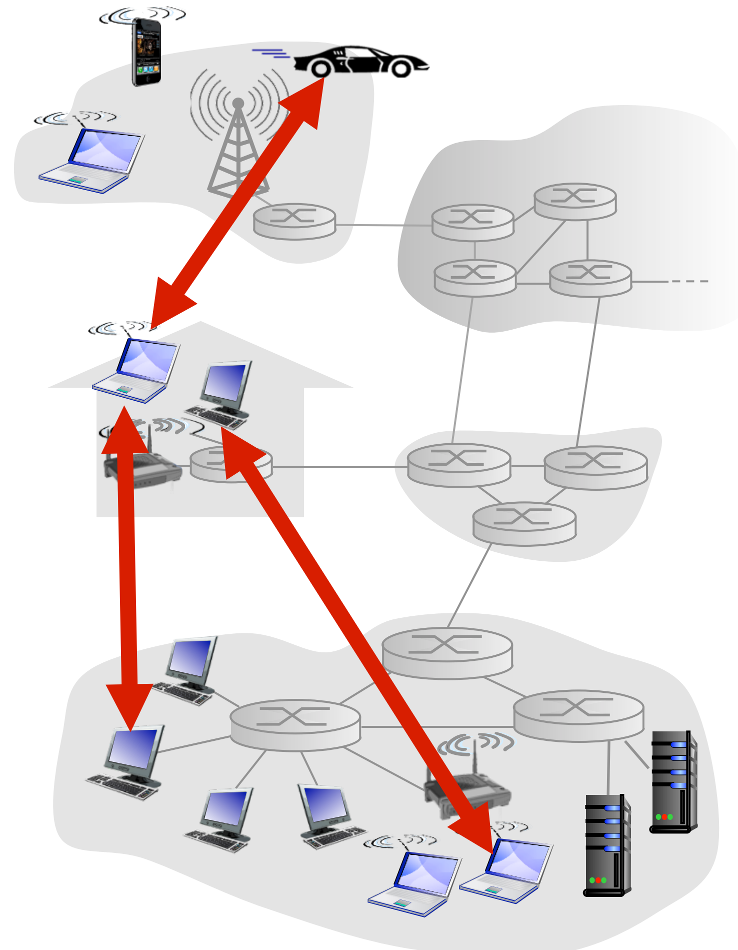
P2P architecture

- *no* always-on server
- arbitrary host-host communication
- intermittent connectivity with changing IP addresses

examples:

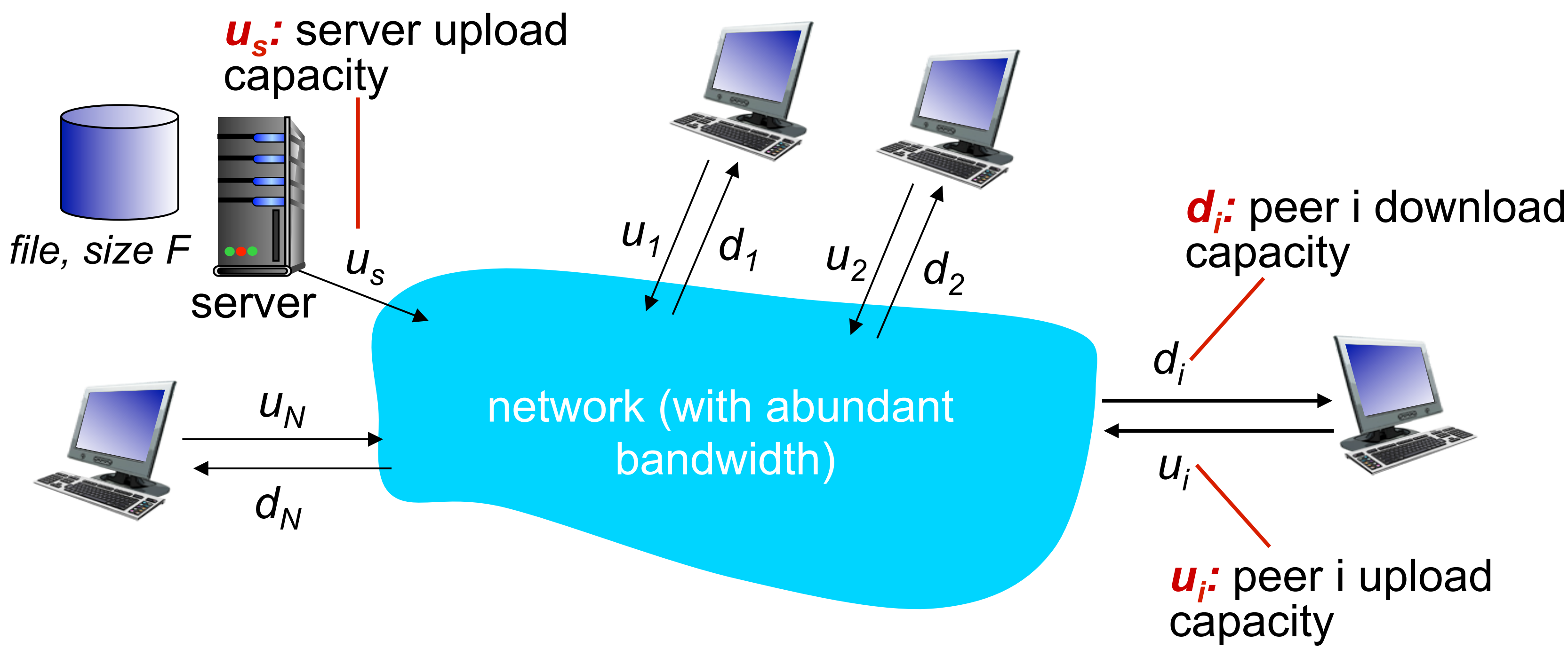
- file distribution (BitTorrent)
- Streaming (KanKan)
- VoIP (Skype)



File distribution: client-server vs P2P

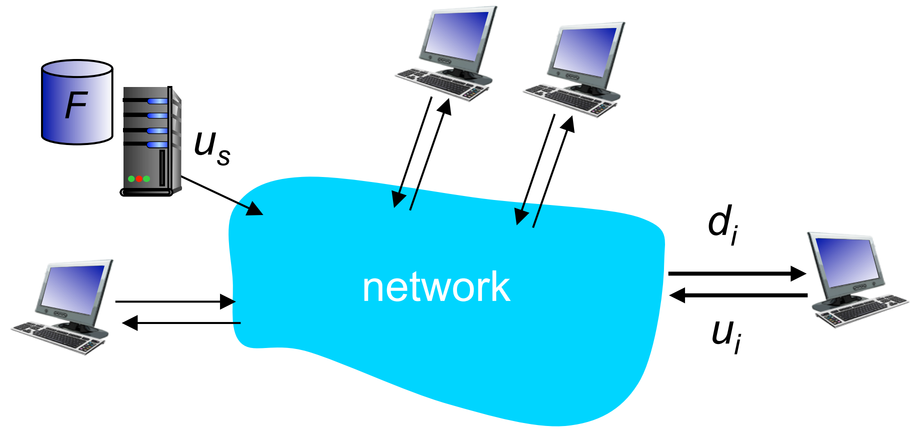
Question: how much time to distribute file (size F) from one server to N *peers*?

- peer upload/download capacity is limited resource



File distribution time: client-server

- *server transmission:* must sequentially send (upload) *N* file copies:
  - time to send one copy: F/u_s
  - time to send N copies: NF/u_s
- *client:* each client must download file copy
  - d_{min} = min client download rate
  - min client download time: F/d_{min}



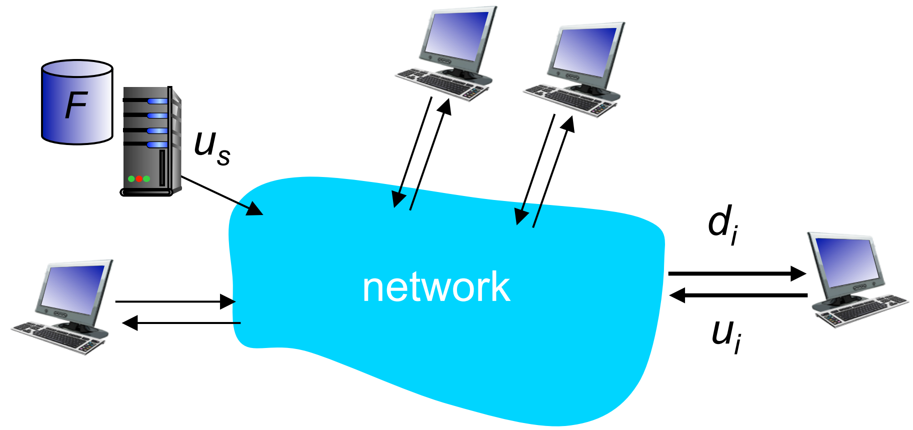
time to distribute F to N clients using client-server approach

$$D_{cs} \geq max\{NF/u_{s,},F/d_{min}\}$$

increases linearly in N

File distribution time: P2P

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



time to distribute F to N clients using P2P approach

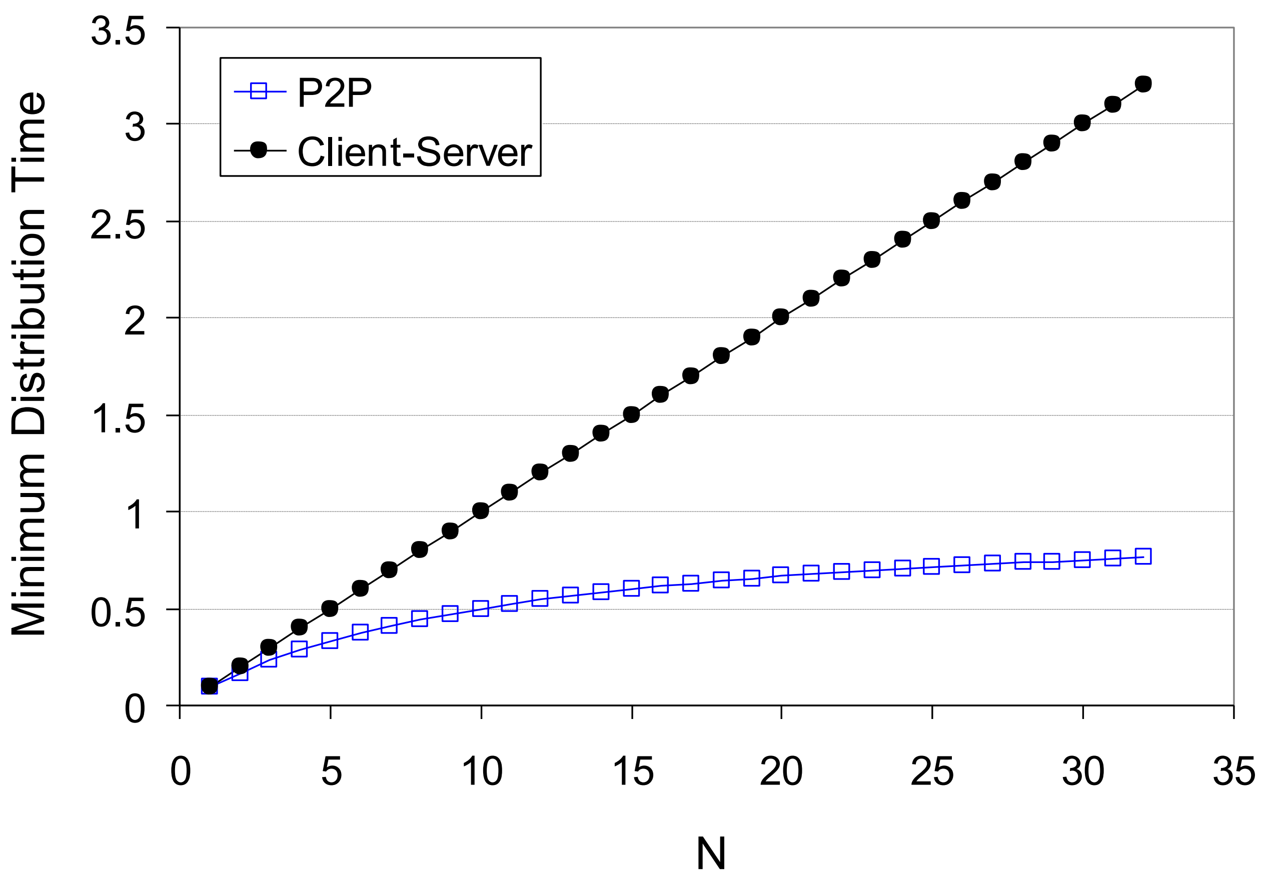
$$D_{P2P} \geq max\{F/u_s, F/d_{min}, NF/(u_s + \Sigma u_i)\}$$

increases linearly in *N* …

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

Client-server vs. P2P: example

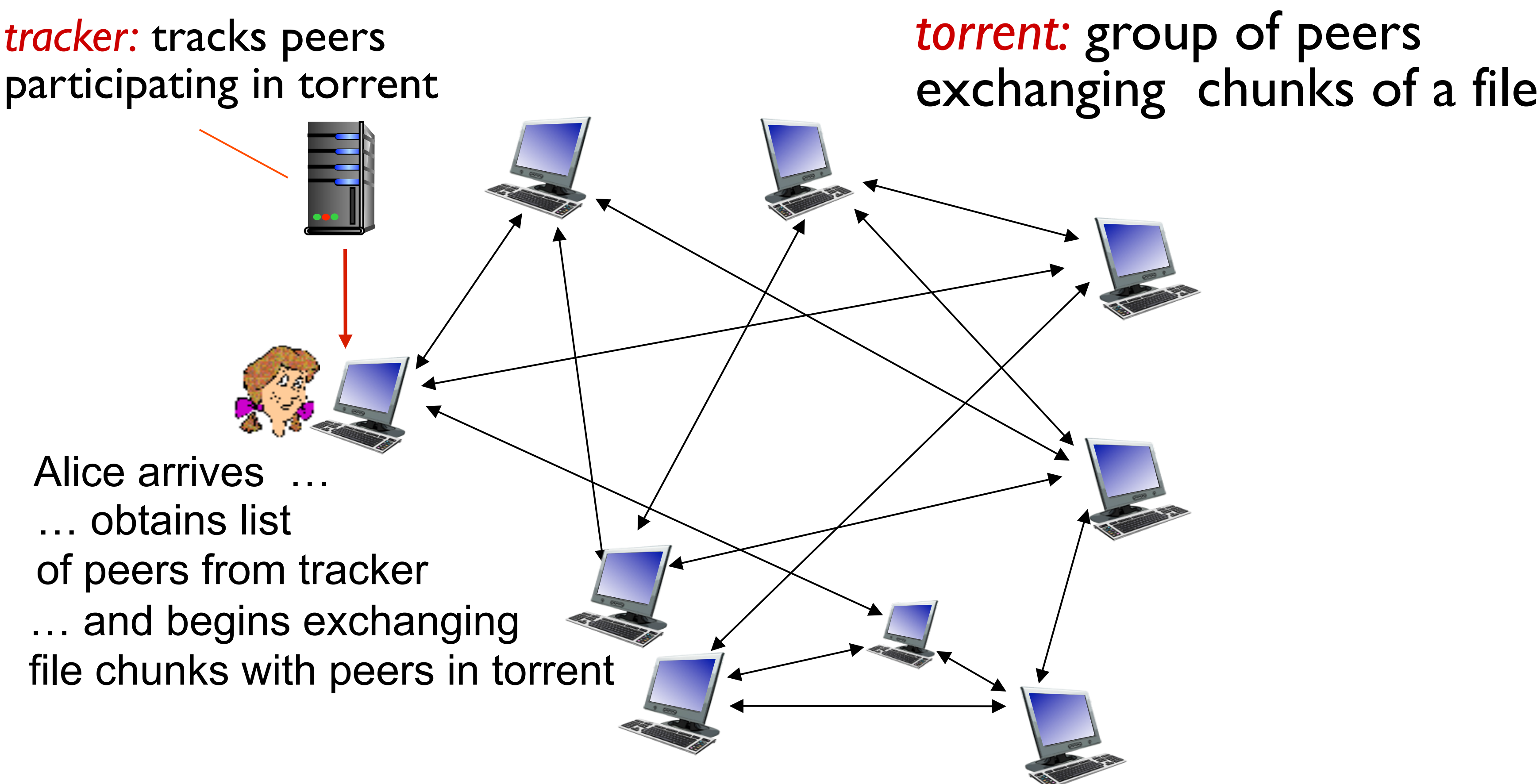
client upload rate = u, F/u = 1 hour, $u_s = 10u$, $d_{min} \geq u_s$



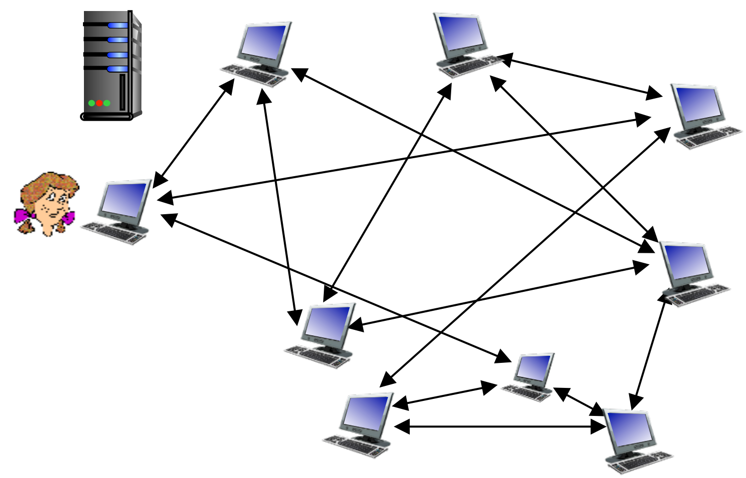
P2P: BitTorrent and precursors

P2P file distribution: BitTorrent

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



P2P file distribution: BitTorrent



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

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

BitTorrent: requesting, sending file chunks

requesting chunks:

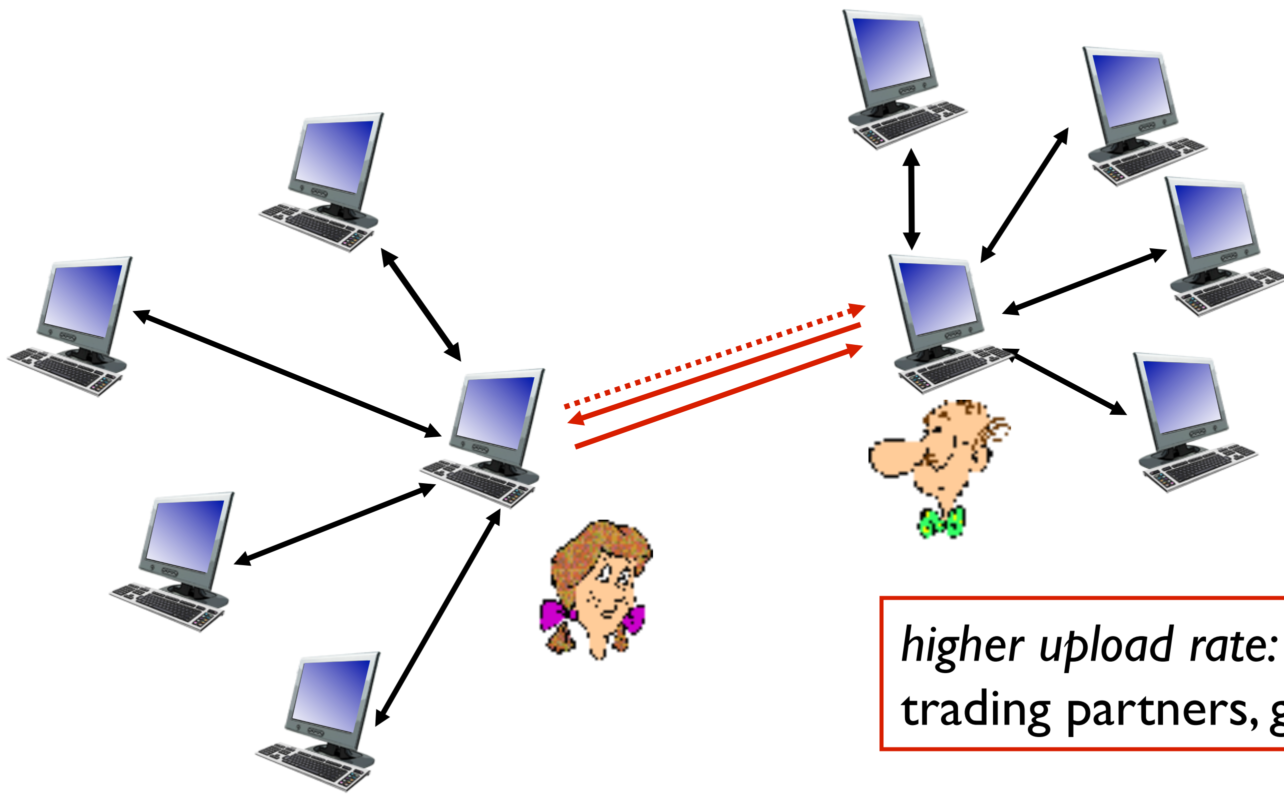
- at any given time, different peers have different chunks
- periodically, Alice asks each peer for their list of chunks
- Alice seeks missing chunks from peers, rarest first

sending chunks: tit-for-tat

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

BitTorrent: tit-for-tat

(1) Alice "optimistically unchokes" Bob
(2) Alice becomes one of Bob's top-four providers; Bob reciprocates
(3) Bob becomes one of Alice's top-four providers



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

Distributed Hash Table (DHT)

Distributed Hash Table (DHT)

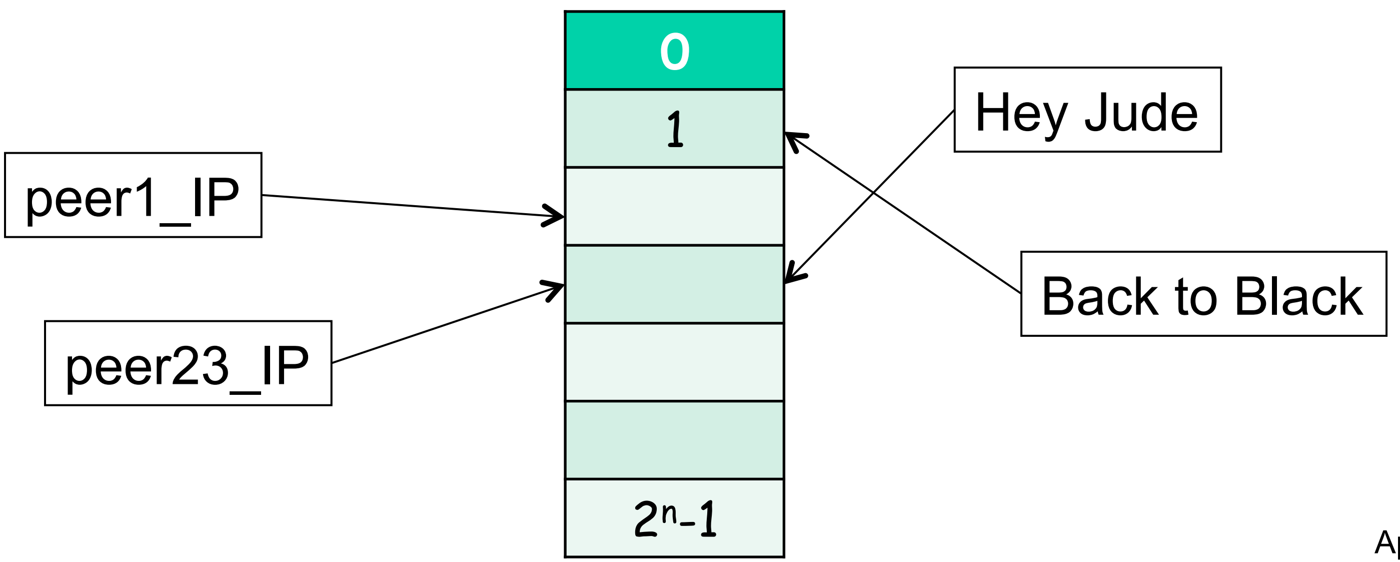
- DHT: a *distributed P2P database*
- database has (key, value) pairs; examples:
  - key: ss number; value: human name
  - key: movie title; value: peer IP address
- Distribute the (key, value) pairs over the (millions of peers)
- a peer queries DHT with key
  - DHT returns values that match the key
- peers can also insert (key, value) pairs

Q: how to assign keys to peers?

- central issue:
  - assigning (key, value) pairs to peers.
- basic idea:
  - convert each key to an integer
  - assign integer to each peer
  - put (key,value) pair in the peer that is closest to the key

DHT identifiers

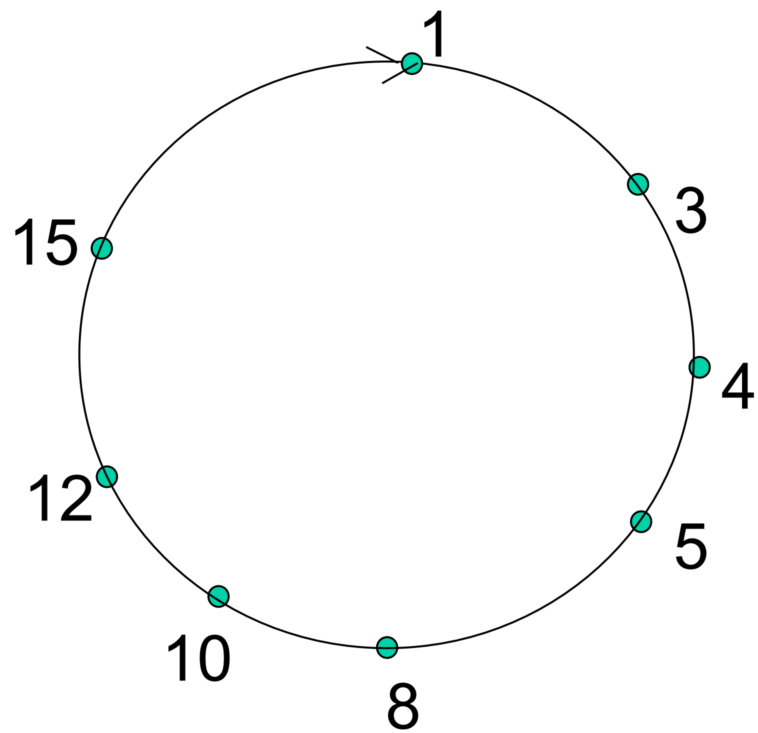
- assign n-bit integer identifier to each peer in range $[0,2^n-1]$ for some *n*.
- require each key to be an integer in same range
- to get integer key, hash original key, e.g., key = hash("Led Zeppelin IV")



Assign keys to peers

- rule: assign key to the peer that has the *closest* ID.
- convention: closest is the *immediate successor* of the key if no peer exists
- e.g., n=4; peers: 1,3,4,5,8,10,12,14;
  - key = 13, then successor peer = 14
  - key = 15, then successor peer = 1

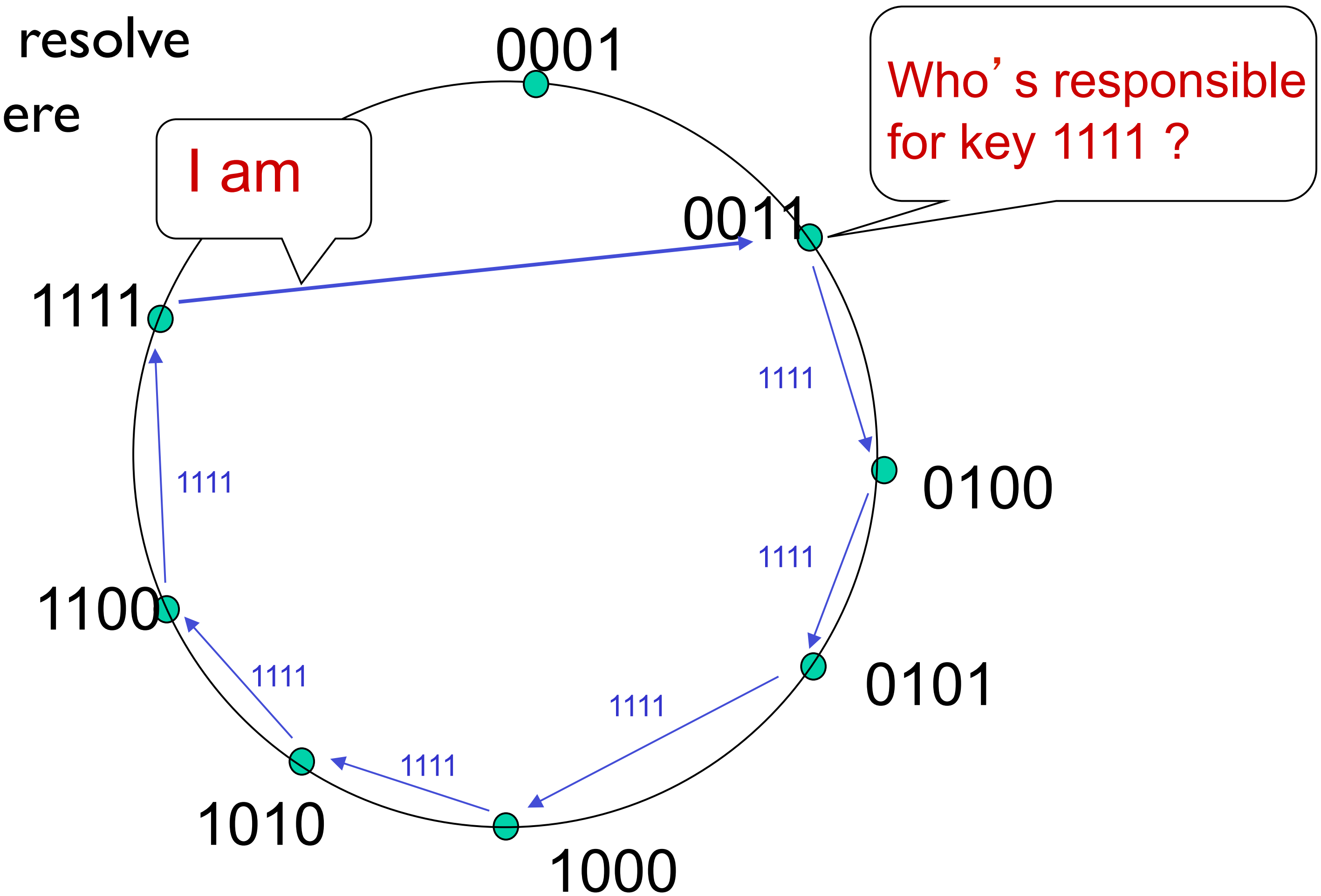
Simplistic circular DHT



- "Overlay" network where each peer *only* aware of immediate successor and predecessor.

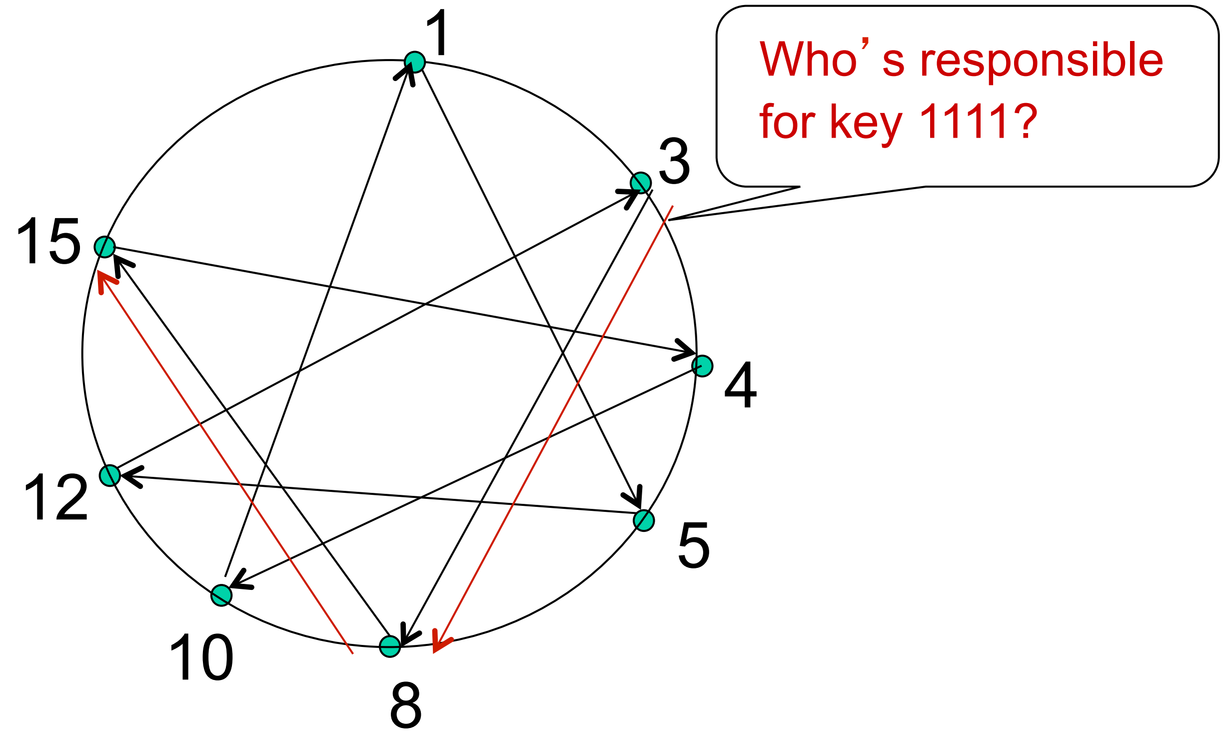
Simplistic circular DHT

O(N) messages on avgerage to resolve query, when there are *N* peers



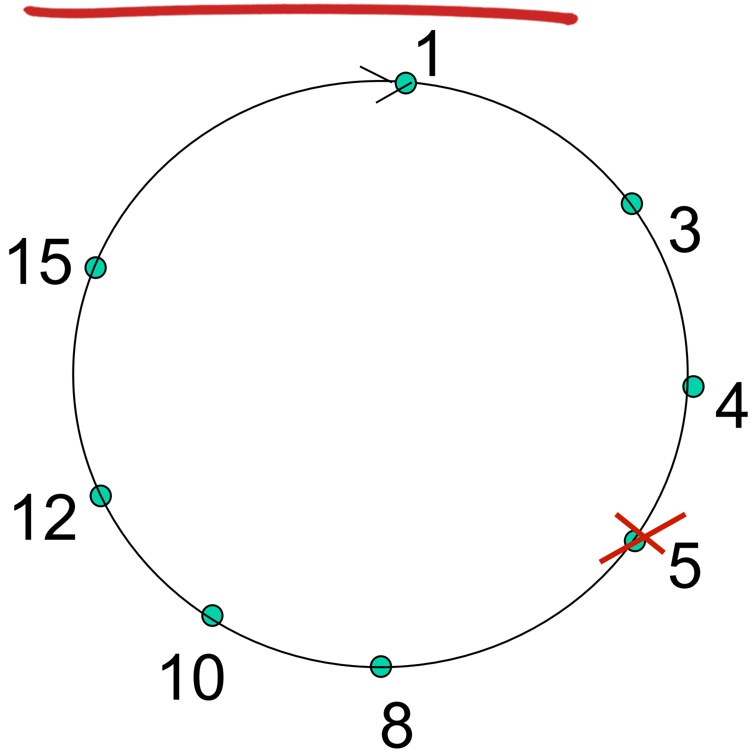
Define closest as closest successor

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



handling peer churn:

- each peer knows address of its two successors
- each peer periodically pings its two successors to check aliveness
- if immediate successor leaves, choose next successor as new immediate successor

example: peer 5 abruptly leaves

- peer 4 detects peer 5 departure; 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?

Q1: What protocol?

- When your mail client contacts a mail server like “mail.cs.umass.edu”, what does it use to infer the address of this server?
  A. IMAP
  B. SMTP
  C. POP3
  D. DNS
  E. HTTP

Q2: What protocol?

- What transport protocol does DNS use for requests and responses?
  A. TCP
  B. UDP
  C. HTTP

Q3: P2P

- BitTorrent is typically used as a hybrid P2P + client-server system.
  A. True
  B. False

Q4: P2P

- BitTorrent uses tit-for-tat in each round to
  A. Determine which chunks to download
  B. Determine from which peers to download chunks
  C. Determine to which peers to upload chunks
  D. Determine which peers to report to the tracker as uncooperative
  E. Determine whether or how long it should stay after completing download

Q5: Ideal P2P

- With a server of upload capacity **C** and **K** clients with uniform upload capacity **U** and uniform download capacity **D**, how much time does it take for an ideal P2P system to transmit a file of size **S** to all K clients?
  A. max(S/D, S/C, KS/(C+KD))
  B. KS/C
  C. min(S/C, S/U, S/D)
  D. max(S/C, S/D, S/(C/K+U))
  E. KS/(C+KD+KU)

Q6: DHT

- Which of the following is not true?
  A. DHTs distribute portions of a hash table across peers.
  B. The key corresponding to an object (e.g., movie) depends on the current number of peers.
  C. Which peer is responsible for an object depends on the current number of peers.

Q7: DHT

- In a circular DHT with N peers and M objects where each peer maintains a pointer only to its immediate neighbors, the arrival or departure of a single peer
  A. Causes a constant number of peers to update a constant amount of routing information
  B. Causes O(N) peers to update a constant amount of routing information
  C. Causes O(N) peers to update O(M) routing information
  D. Causes a constant number of peers to update O(M) routing information

2. Application layer: Outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 FTP

2.4 electronic mail

- SMTP, POP3, IMAP

2.5 DNS

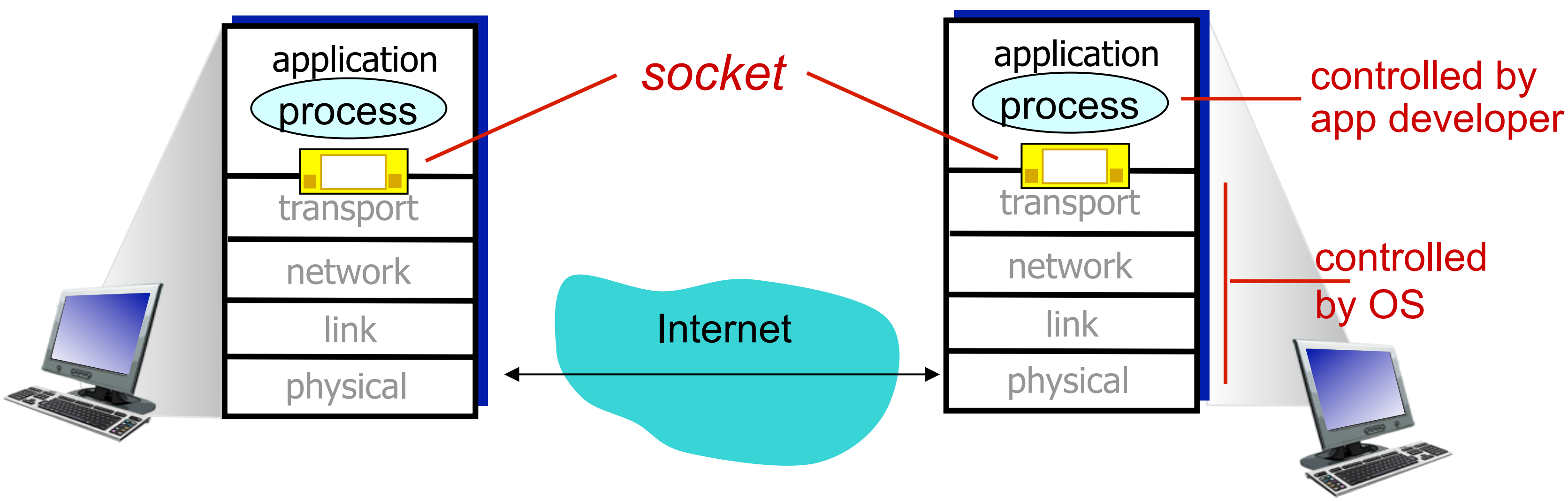
2.6 P2P applications

2.7 socket programming with UDP and TCP

Socket programming

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

socket: dropbox between application process and end-end-transport protocol



Socket programming

Two socket types for two transport services:

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

Application Example:

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

Socket programming *with UDP*

UDP: no "connection" between client & server

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

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

Application viewpoint:

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

Client/server socket interaction: UDP

server (running on serverIP)

create socket, port= x:
serverSocket =
DatagramSocket(x)

read datagram from
serverSocket

write reply to
serverSocket
specifying
client address,
port number

client

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)

create input stream →

create client socket →

translate hostname to IP addr 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)

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
    {

      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)

```
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);
  }
 }
}
```

get IP addr port #, of sender → (InetAddress IPAddress, int port)

create datagram to send to client → (DatagramPacket sendPacket)

write out datagram to socket → (serverSocket.send)

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

Example app: UDP client

Python UDPClient

include Python's socket library → `import socket`

```
serverName = 'hostname'
serverPort = 12000
```

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

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

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

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

print out received string and close socket →

```
print modifiedMessage
clientSocket.close()
```

Example app: UDP server

Python UDPServer

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

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

loop forever → while 1:

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

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

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET, SOCK_DGRAM)
serverSocket.bind(('', serverPort))
print "The server is ready to receive"
while 1:
    message, clientAddress = serverSocket.recvfrom(2048)
    modifiedMessage = message.upper()
    serverSocket.sendto(modifiedMessage, clientAddress)
```

Socket programming *with TCP*

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

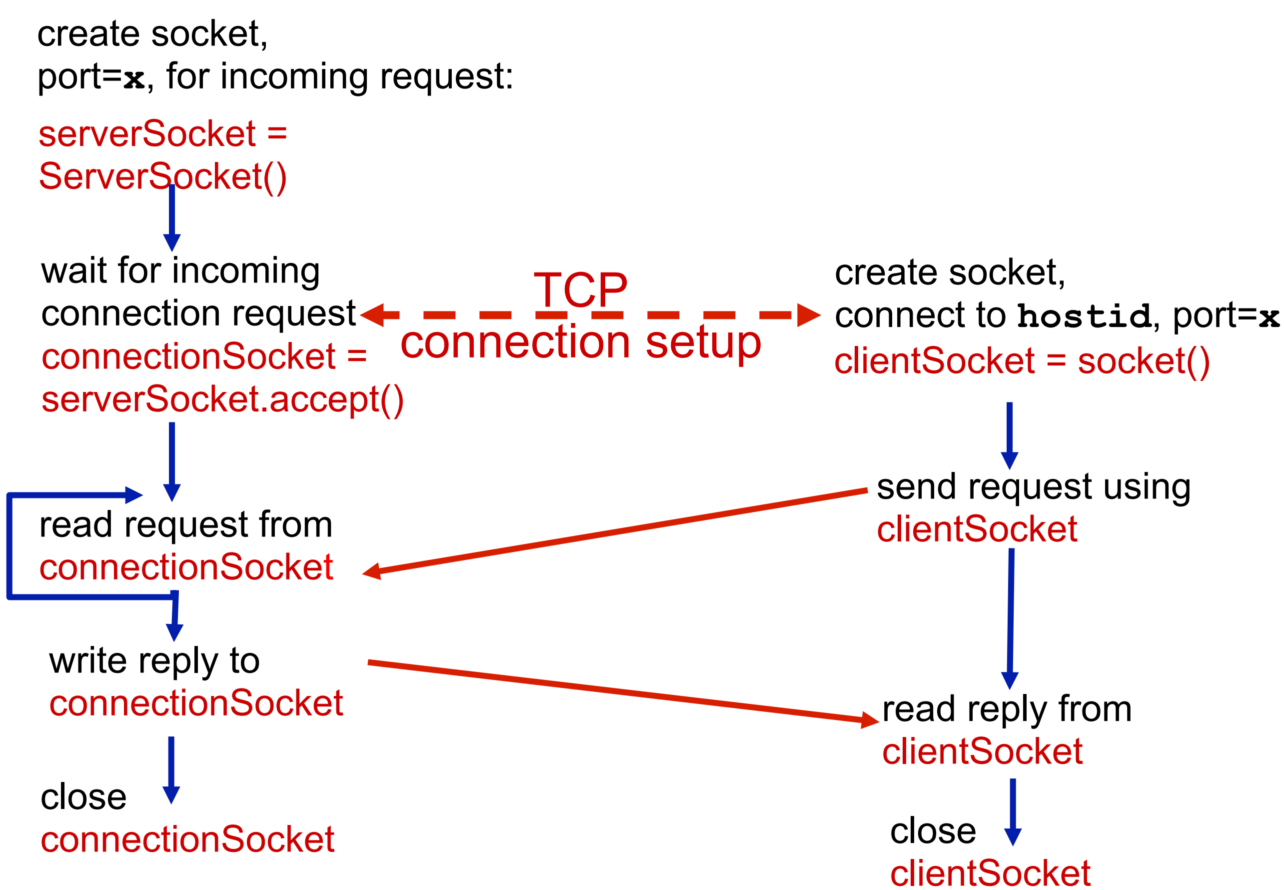
client connects to server by:
- creating TCP socket, specifying IP address, port number of server process
- client socket is now bound to that specific server

- server accepts connect by:
  - *creating new connection-specific socket*
  - allows server to talk with multiple clients

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

Client/server socket interaction: TCP

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



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());
```

this package defines Socket() and ServerSocket() classes

server name, e.g., www.umass.edu

server port #

create input stream

create clientSocket object of type Socket, connect to server

create output stream attached to socket

Example: Java client (TCP)

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);
```

close socket (clean up behind yourself!) →

```
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 accept() method for client contact create, *new* socket on return → Socket connectionSocket = welcomeSocket.accept();

create input stream, attached to socket → BufferedReader inFromClient = new BufferedReader(new InputStreamReader(connectionSocket.getInputStream()));

Example: Java server (TCP)

create output stream, attached to socket →

read in line from socket →

write out line to socket →

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

clientSentence = inFromClient.readLine();

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

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

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

Example app: TCP client

Python TCPClient

create TCP socket for server, remote port 12000

No need to attach server name, port

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

Example app: TCP server

Python TCPServer

create TCP welcoming socket → `serverSocket = socket(AF_INET,SOCK_STREAM)`

server begins listening for incoming TCP requests → `serverSocket.listen(1)`

loop forever → `while 1:`

server waits on accept() for incoming requests, new socket created on return → `connectionSocket, addr = serverSocket.accept()`

read bytes from socket (but not address as in UDP) → `sentence = connectionSocket.recv(1024)`

close connection to this client (but *not* welcoming socket) → `connectionSocket.close()`

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

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

2. Application layer: Summary

our study of network apps now complete!

- application architectures
  - client-server
  - P2P
- application service requirements:
  - reliability, bandwidth, delay
- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP
- specific protocols:
  - HTTP
  - FTP
  - SMTP, POP, IMAP
  - DNS
  - P2P: BitTorrent, DHT
- socket programming: TCP, UDP sockets

2. Application layer: 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"