

Computer Networks and Applications

COMP 3331/COMP 9331

Week 2

Application Layer (Principles, Web,
Email)

Chapter 2, Sections 2.1-2.3

2. Application Layer: outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP

2.4 DNS

2.5 P2P applications

2.6 video streaming and content distribution networks (CDNs)

2.7 socket programming with UDP and TCP

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
 - SMTP / POP3 / IMAP
 - DNS
- ❖ creating network applications
 - socket API

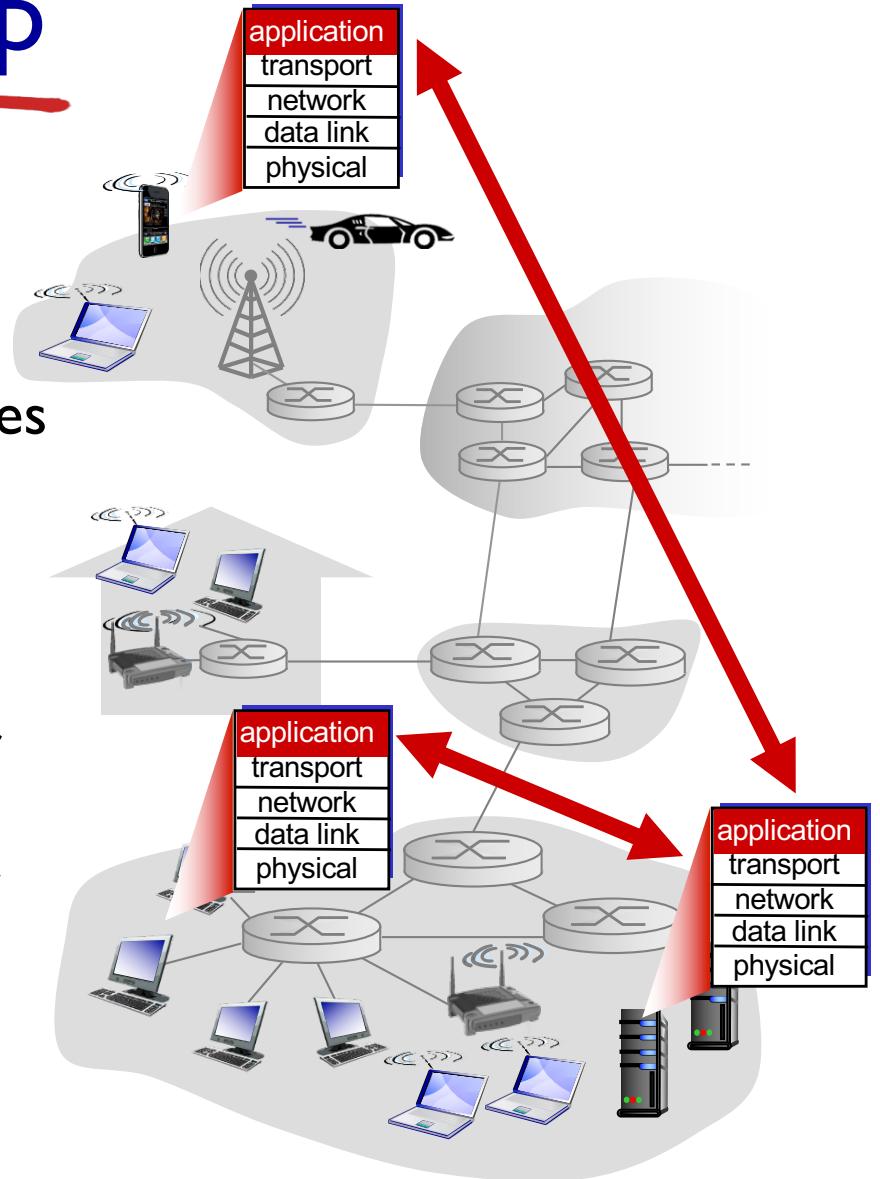
Creating a network app

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

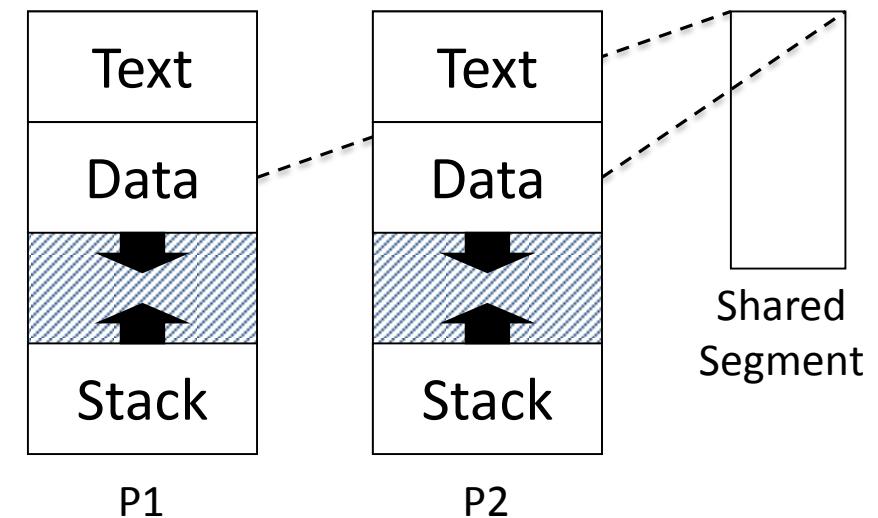
- ❖ network-core devices do not run user applications
- ❖ applications on end systems allows for rapid app development



Interprocess Communication (IPC)

- ❖ Processes talk to each other through Inter-process communication (IPC)

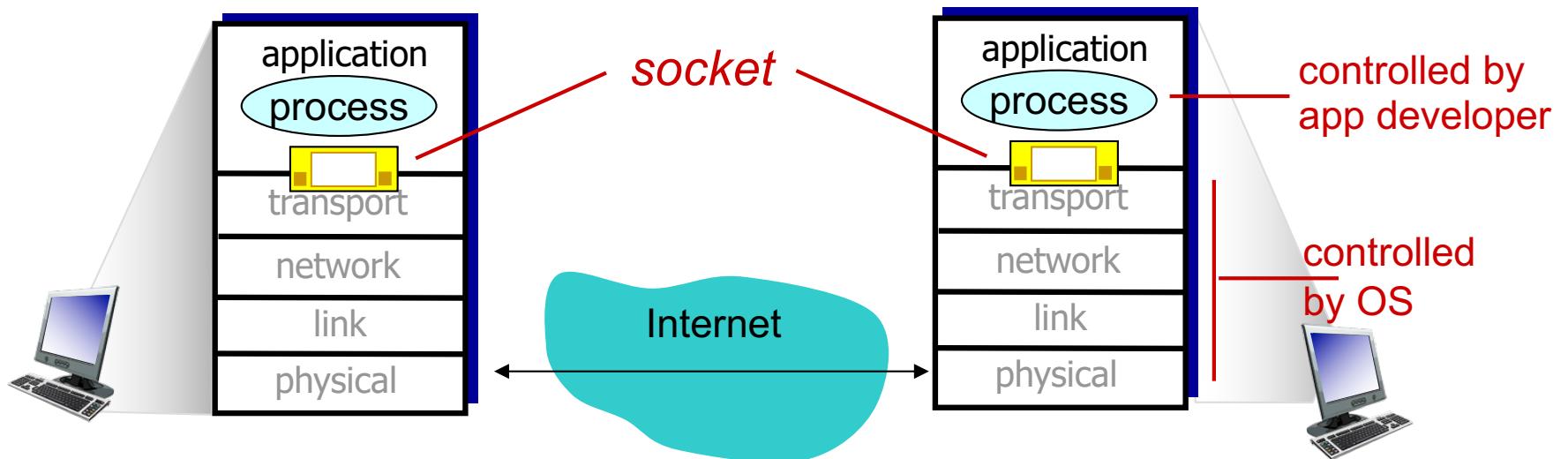
- ❖ On a single machine:
 - Shared memory



- ❖ Across machines:
 - We need other abstractions (message passing)

Sockets

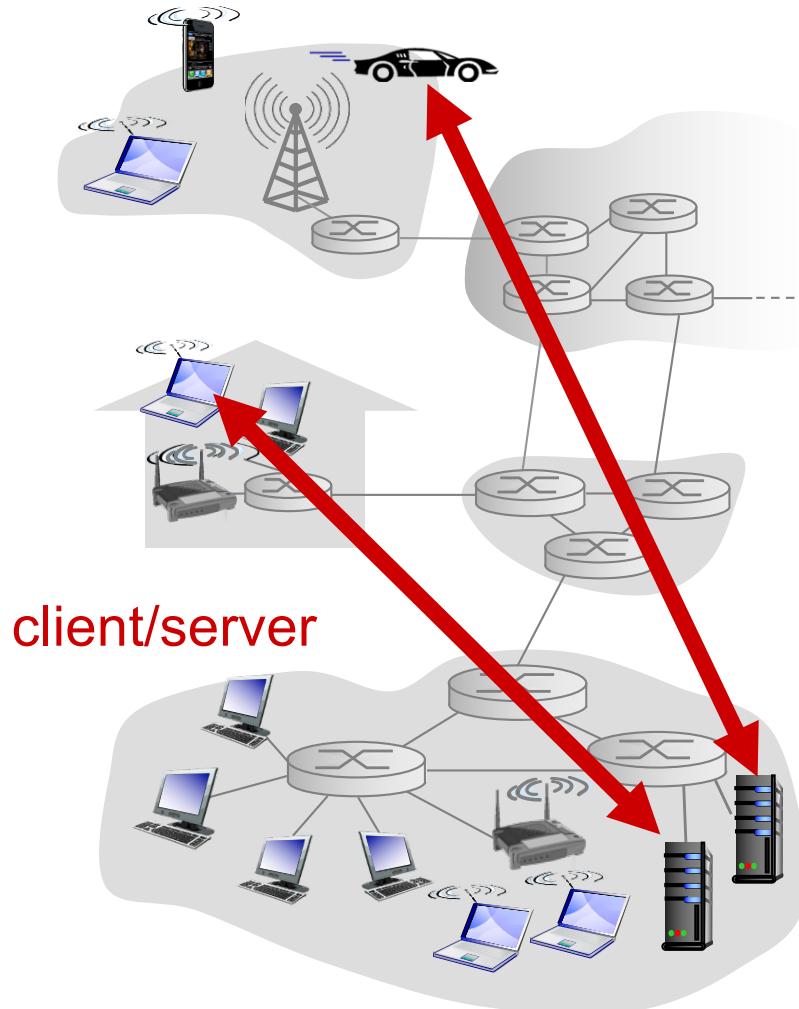
- ❖ process sends/receives messages to/from its **socket**
- ❖ socket analogous to door
 - sending process shoves message out through the door
 - sending process relies on transport infrastructure on other side of door to deliver message to socket at receiving process
- ❖ Application has a few options, OS handles the details



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 cse.unsw.edu.au web server:
 - IP address: 129.94.242.51
 - port number: 80

Client-server architecture



server:

- ❖ Exports well-defined request/response interface
- ❖ long-lived process that waits for requests
- ❖ Upon receiving request, carries it out

clients:

- ❖ Short-lived process that makes requests
- ❖ “User-side” of application
- ❖ Initiates the communication

Client versus Server

❖ Server

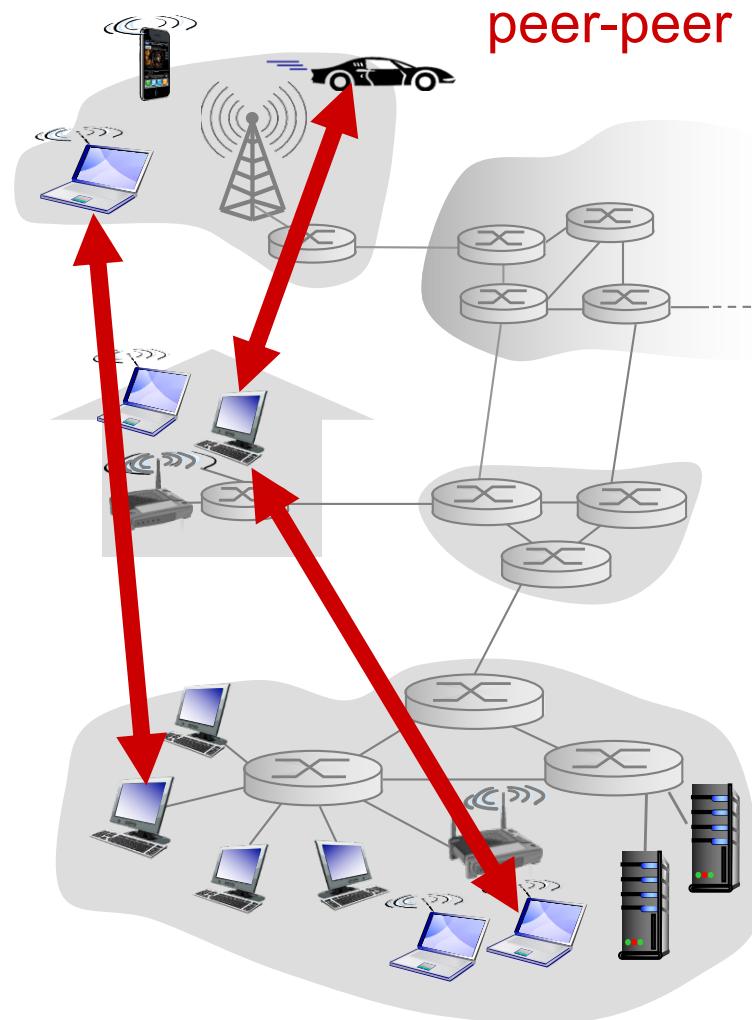
- Always-on host
- Permanent IP address (rendezvous location)
- Static port conventions (http: 80, email: 25, ssh:22)
- Data centres for scaling
- May communicate with other servers to respond

❖ Client

- May be intermittently connected
- May have dynamic IP addresses
- Do not communicate directly with each other

P2P architecture

- ❖ no always-on server
 - No permanent rendezvous involved
- ❖ arbitrary end systems (peers) directly communicate
- ❖ Symmetric responsibility (unlike client/server)
- ❖ Often used for:
 - File sharing (BitTorrent)
 - Games
 - Blockchain and cryptocurrencies
 - Video distribution, video chat
 - In general: “distributed systems”



P2P architecture: Pros and Cons

+ 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

+ Speed: parallelism, less contention

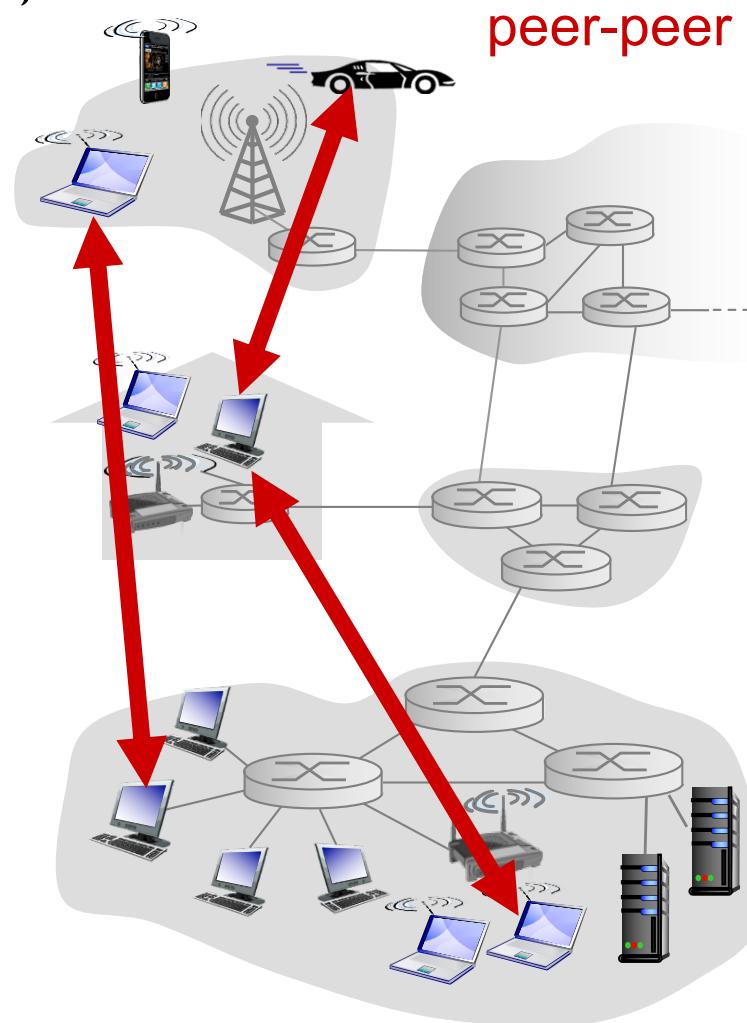
+ Reliability: redundancy, fault tolerance

+ Geographic distribution

-Fundamental problems of decentralized control

- State uncertainty: no shared memory or clock
- Action uncertainty: mutually conflicting decisions

-Distributed algorithms are complex



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, WebRTC

proprietary protocols:

- ❖ e.g., Skype, Teams, Zoom

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: 50kbps-1Mbps video:100kbps-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
Chat/messaging	no loss	elastic	yes and no

Internet transport protocols services

TCP service:

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

UDP service:

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

Q: why bother? Why is there a UDP?

NOTE: More on transport later on

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



Quiz: 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 provides reliability

Answer: C

Open a browser and type: **www.zeetings.com/salil**

2. Application Layer: outline

2.1 principles of network applications

- app architectures
- app requirements

2.2 Web and HTTP

2.3 electronic mail

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2.5 P2P applications

2.6 video streaming and content distribution networks (CDNs)

2.7 socket programming with UDP and TCP

The Web – Precursor



Ted Nelson

- ❖ **1967, Ted Nelson, Xanadu:**
 - A world-wide publishing network that would allow information to be stored not as separate files but as connected literature
 - Owners of documents would be automatically paid via electronic means for the virtual copying of their documents
- ❖ **Coined the term “Hypertext”**

The Web – History



Tim Berners-Lee

- ❖ World Wide Web (WWW): a distributed database of “pages” linked through **Hypertext Transport Protocol (HTTP)**
 - First HTTP implementation - 1990
 - Tim Berners-Lee at CERN
 - HTTP/0.9 – 1991
 - Simple GET command for the Web
 - HTTP/1.0 – 1992
 - Client/Server information, simple caching
 - HTTP/1.1 – 1996
 - HTTP2.0 - 2015

<http://info.cern.ch/hypertext/WWW/TheProject.html>

2020 This Is What Happens In An Internet Minute



Web and HTTP

First, a review...

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

www.someschool.edu/someDept/pic.gif

host name

path name

Web and HTTP

```
<!DOCTYPE html>
<html>
    <head>
        <title>Hyperlink Example</title>
    </head>
    <body>
        <p>Click the following link</p>
        <a href = "http://www.cnn.com" target ="_self">CNN</a>
    </body>
</html>
```

Uniform Resource Locator (URL)

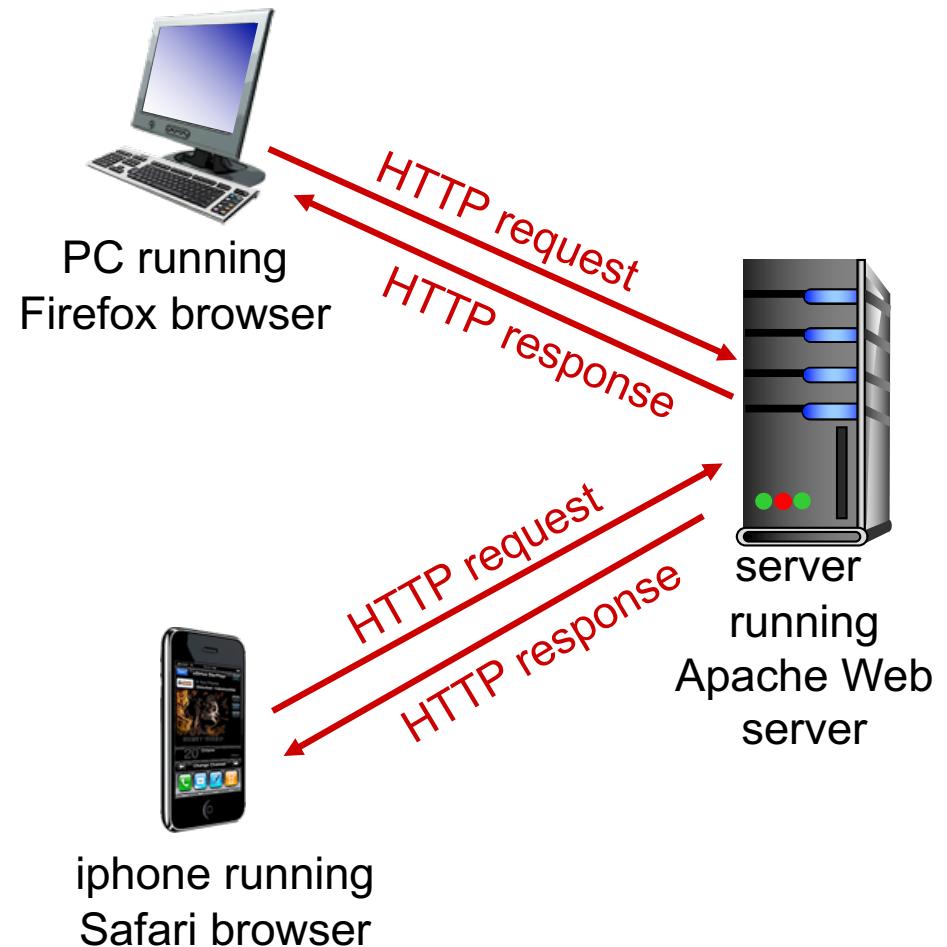
protocol://host-name[:port]/directory-path/resource

- ❖ *protocol*: http, ftp, https, smtp etc.
- ❖ *hostname*: DNS name, IP address
- ❖ *port*: defaults to protocol's standard port; e.g. http: 80 https: 443
- ❖ *directory path*: hierarchical, reflecting file system
- ❖ *resource*: Identifies the desired resource

HTTP overview

HTTP: hypertext transfer protocol

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



HTTP overview (continued)

uses TCP:

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

HTTP is “stateless”

- ❖ server maintains no information about past client requests

aside
protocols that maintain “state” are complex!

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

HTTP request message

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

request line
(GET, POST,
HEAD commands)

header
lines

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

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

carriage return character

line-feed character

HTTP response message

status line
(protocol
status code
status phrase)

header
lines

data, e.g.,
requested
HTML file

```
HTTP/1.1 200 OK\r\nDate: Sun, 26 Sep 2010 20:09:20 GMT\r\nServer: Apache/2.0.52 (CentOS) \r\nLast-Modified: Tue, 30 Oct 2007 17:00:02  
GMT\r\nETag: "17dc6-a5c-bf716880"\r\nAccept-Ranges: bytes\r\nContent-Length: 2652\r\nKeep-Alive: timeout=10, max=100\r\nConnection: Keep-Alive\r\nContent-Type: text/html; charset=ISO-8859-  
1\r\n\r\ndata data data data data ...
```

HTTP response status codes

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

200 OK

- request succeeded, requested object later in this msg

301 Moved Permanently

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

400 Bad Request

- request msg not understood by server

404 Not Found

- requested document not found on this server

505 HTTP Version Not Supported

451 Unavailable for Legal Reasons

429 Too Many Requests

418 I'm a Teapot

HTTP is all text

- ❖ Makes the protocol simple
 - Easy to delineate messages (\r\n)
 - (relatively) human-readable
 - No issues about encoding or formatting data
 - Variable length data
- ❖ Not the most efficient
 - Many protocols use binary fields
 - Sending "12345678" as a string is 8 bytes
 - As an integer, 12345678 needs only 4 bytes
 - Headers may come in any order
 - Requires string parsing/processing
- ❖ Non-text content needs to be encoded

Request Method types (“verbs”)

HTTP/1.0:

- ❖ GET
 - Request page
- ❖ POST
 - Uploads user response to a form
- ❖ 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
- ❖ TRACE, OPTIONS, CONNECT, PATCH
 - For persistent connections

Uploading form input

POST method:

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

Get (in-URL) method:

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

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

User-server state: cookies

many Web sites use cookies

four components:

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

example:

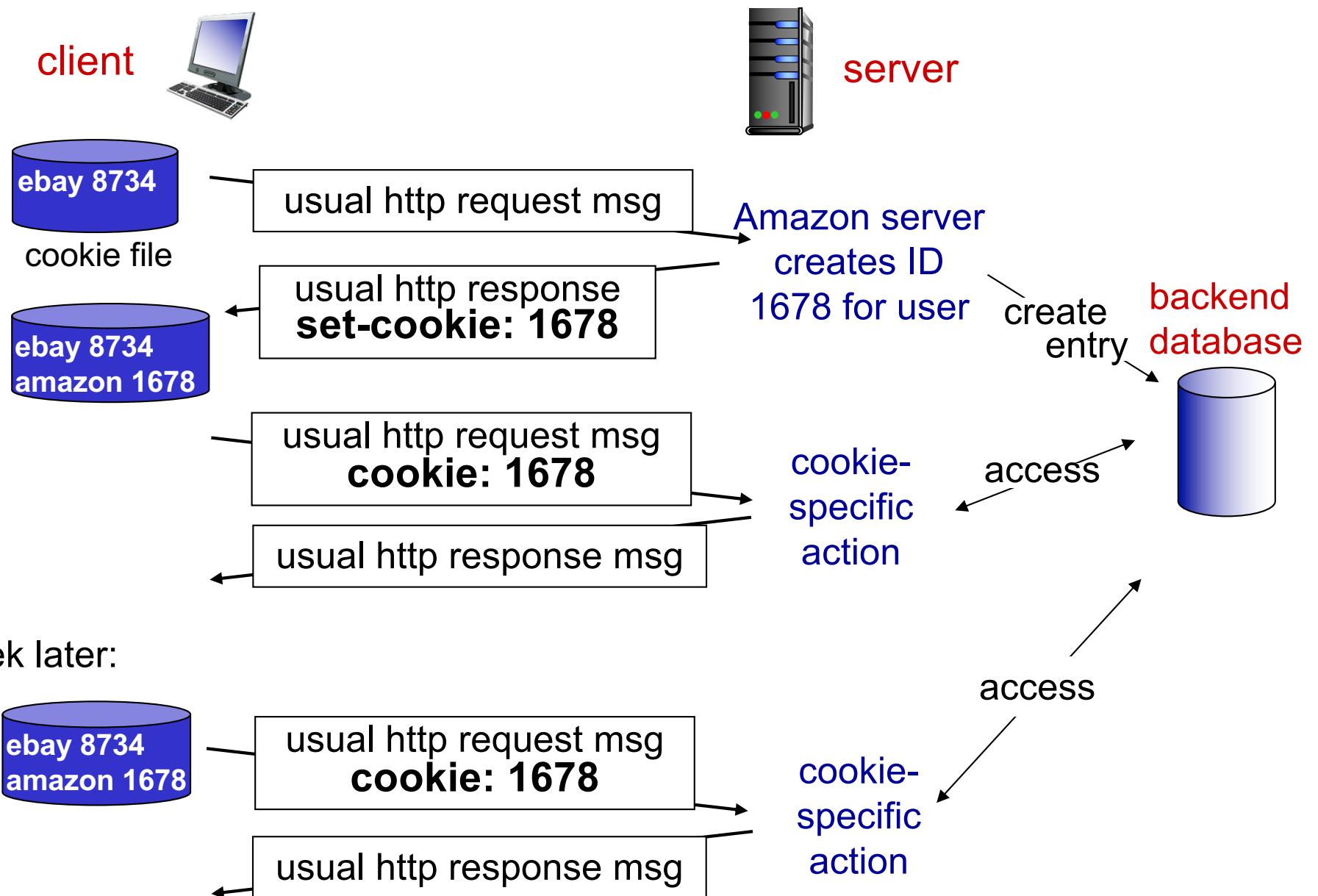
- ❖ Susan always access Internet from PC
- ❖ visits specific e-commerce site for first time
- ❖ when initial HTTP requests arrives at site, site creates:
 - unique ID
 - entry in backend database for ID

HTTP is stateless

It does not save the clients request



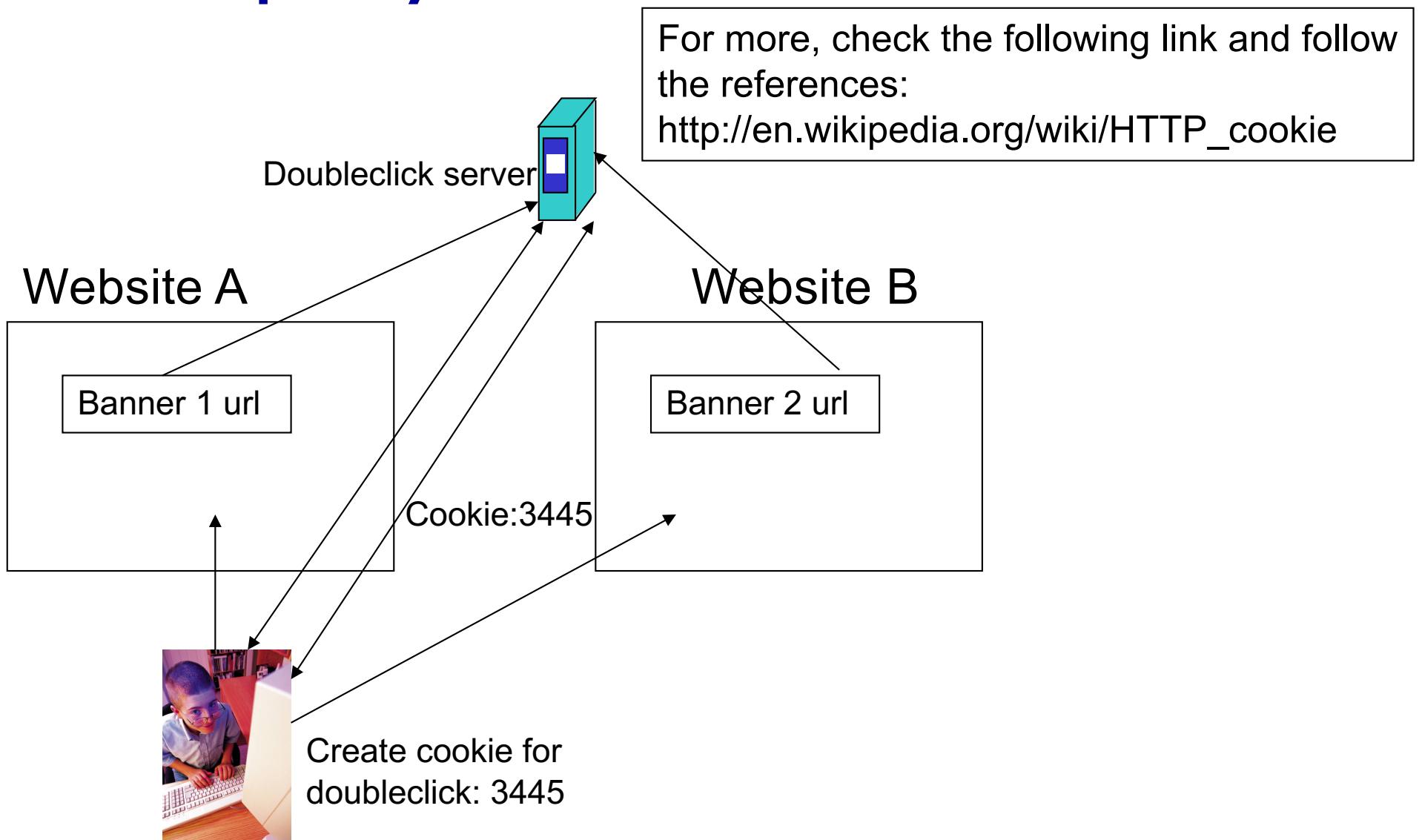
Cookies: keeping “state” (cont.)



The Dark Side of Cookies

- ❖ Cookies permit sites to learn a lot about you
- ❖ You may supply name and e-mail to sites (and more)
- ❖ 3rd party cookies (from ad networks, etc.) can follow you across multiple sites
 - Ever visit a website, and the next day ALL your ads are from them ?
 - Check your browser's cookie file (cookies.txt, cookies.plist)
 - Do you see a website that you have never visited
- ❖ You COULD turn them off
 - But good luck doing anything on the Internet !!

Third party cookies



In practice the banner can be a single pixel (invisible to the user)

Performance of HTTP

- Page Load Time (PLT) as the metric
 - From click until user sees page
 - Key measure of web performance
- Depends on many factors such as
 - page content/structure,
 - protocols involved and
 - Network bandwidth and RTT

Performance Goals

- ❖ User
 - fast downloads
 - high availability
- ❖ Content provider
 - happy users (hence, above)
 - cost-effective infrastructure
- ❖ Network (secondary)
 - avoid overload

Solutions?

- ❖ User
 - fast downloads
 - high availability
- ❖ Content provider
 - happy users (hence, above)
 - cost-effective infrastructure
- ❖ Network (secondary)
 - avoid overload

Improve HTTP to
achieve faster
downloads



Solutions?

- ❖ User

- fast downloads
- high availability

Improve HTTP to
achieve faster
downloads

- ❖ Content provider

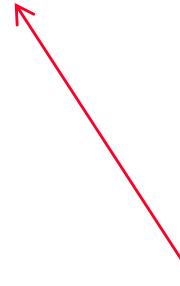
- happy users (hence, above)
- cost-effective delivery infrastructure

Caching and Replication

- ❖ Network (secondary)

- avoid overload

Solutions?

- ❖ User
 - fast downloads
 - high availability
 - ❖ Content provider
 - happy users (hence, above)
 - cost-effective delivery infrastructure
 - ❖ Network (secondary)
 - avoid overload
- Improve HTTP to
achieve faster
downloads
- Caching and Replication
- Exploit economies of scale
(Webhosting, CDNs, datacenters)
- 

How to improve PLT

- Reduce content size for transfer
 - Smaller images, compression
- Change HTTP to make better use of available bandwidth
 - Persistent connections and pipelining
- Change HTTP to avoid repeated transfers of the same content
 - Caching and web-proxies
- Move content closer to the client
 - CDNs

HTTP Performance

- ❖ Most Web pages have multiple objects
 - e.g., HTML file and a bunch of embedded images
- ❖ How do you retrieve those objects (naively)?
 - *One item at a time*
- ❖ New TCP connection per (small) object!

non-persistent HTTP

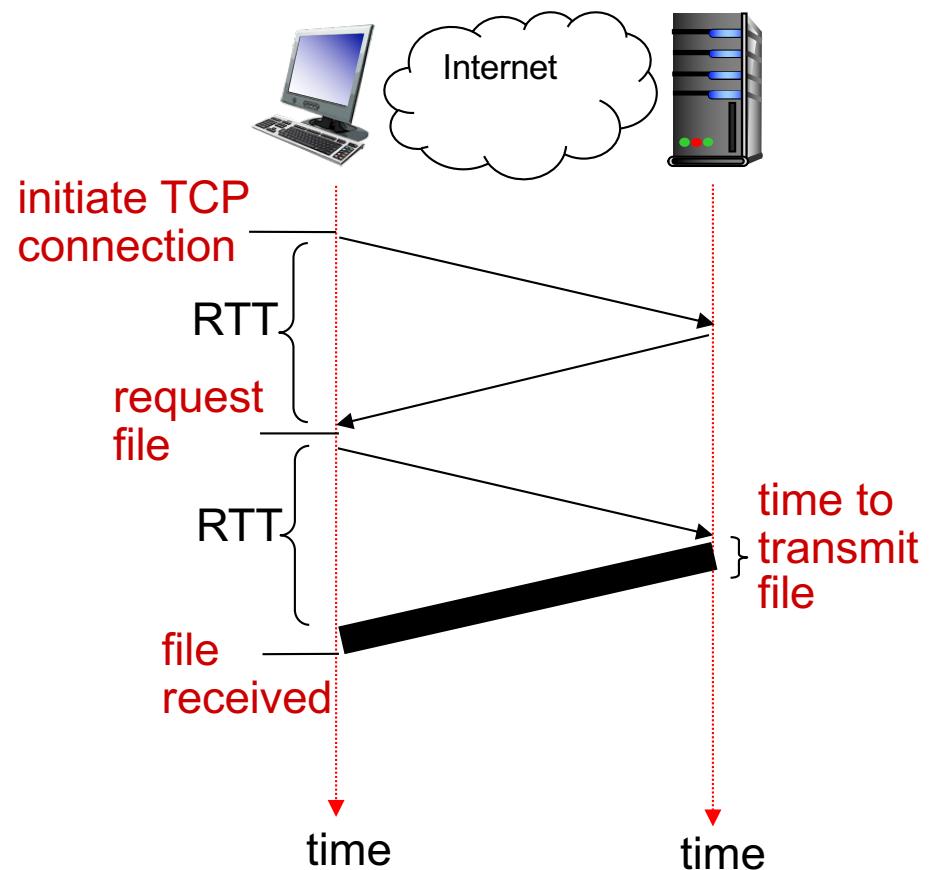
- ❖ at most one object sent over TCP connection
 - connection then closed
- ❖ downloading multiple objects required multiple connections

Non-persistent HTTP: response time

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

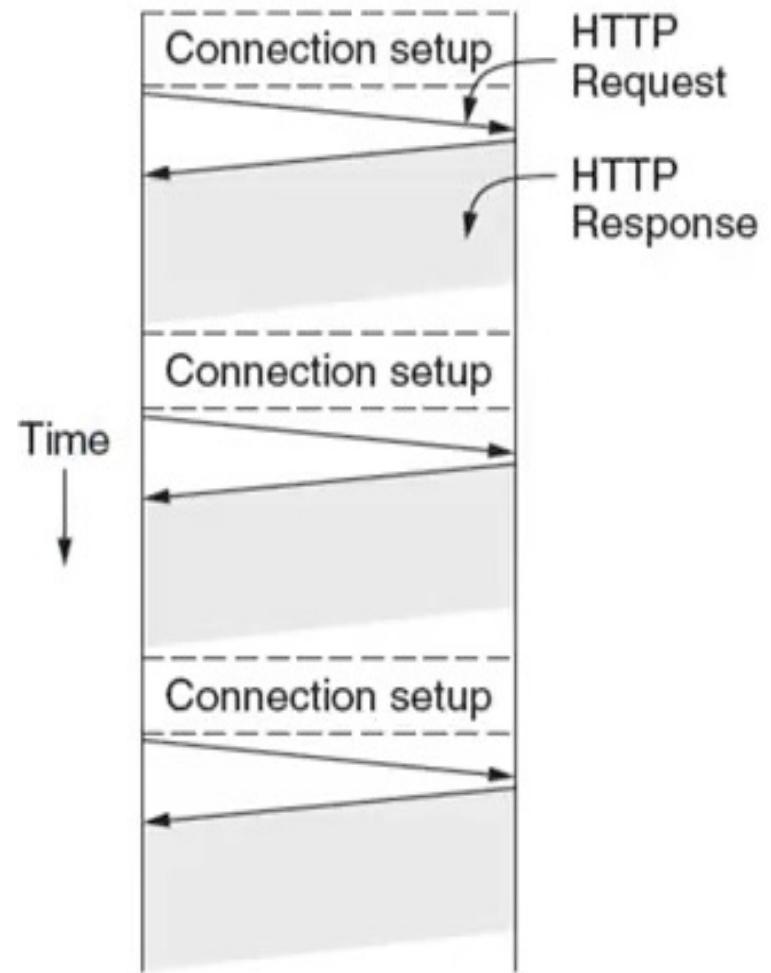
HTTP response time:

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



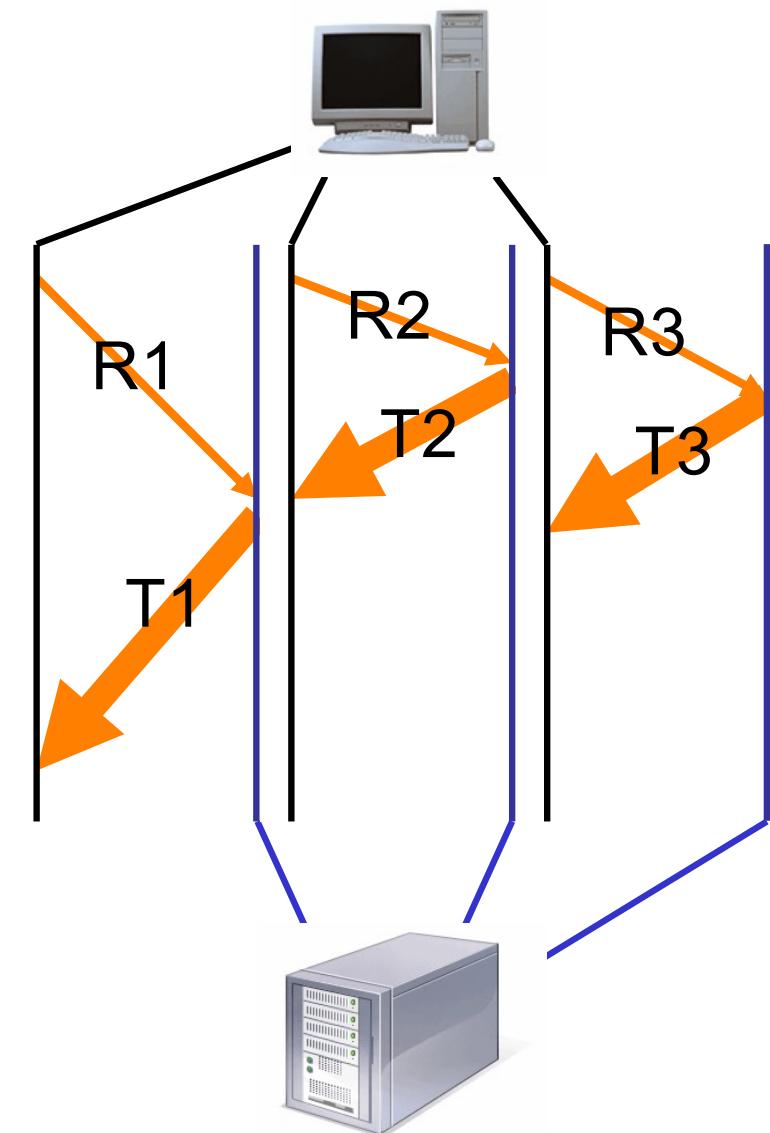
HTTP/1.0

- Non-Persistent: One TCP connection to fetch one web resource
- Fairly poor PLT
- 2 Scenarios
 - Multiple TCP connections setups to the **same server**
 - Sequential request/responses even when resources are located on **different servers**
- Multiple TCP slow-start phases (more in lecture on TCP)



Improving HTTP Performance: Concurrent Requests & Responses

- ❖ Use multiple connections *in parallel*
- ❖ Does not necessarily maintain order of responses



Quiz: Parallel HTTP Connections



- ❖ What are potential downsides of parallel HTTP connections, i.e., can opening too many parallel connections be harmful and if so in what way?

- ❖ Answer: Extra load on the server for managing parallel connections

Open a browser and type: **www.zeetings.com/salil**

Persistent HTTP

Persistent HTTP

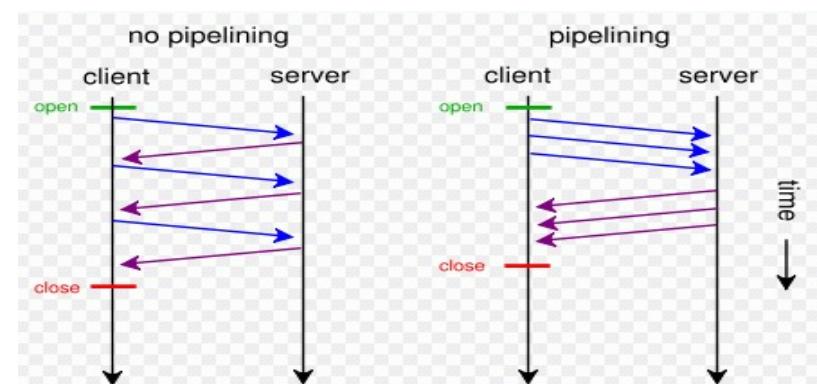
- ❖ server leaves TCP connection open after sending response
- ❖ subsequent HTTP messages between same client/server are sent over the same TCP connection
- ❖ Allow TCP to learn more accurate RTT estimate (APPARENT LATER IN THE COURSE)
- ❖ Allow TCP congestion window to increase (APPARENT LATER)
- ❖ i.e., leverage previously discovered bandwidth (APPARENT LATER)

Persistent without pipelining:

- ❖ client issues new request only when previous response has been received
- ❖ one RTT for each referenced object

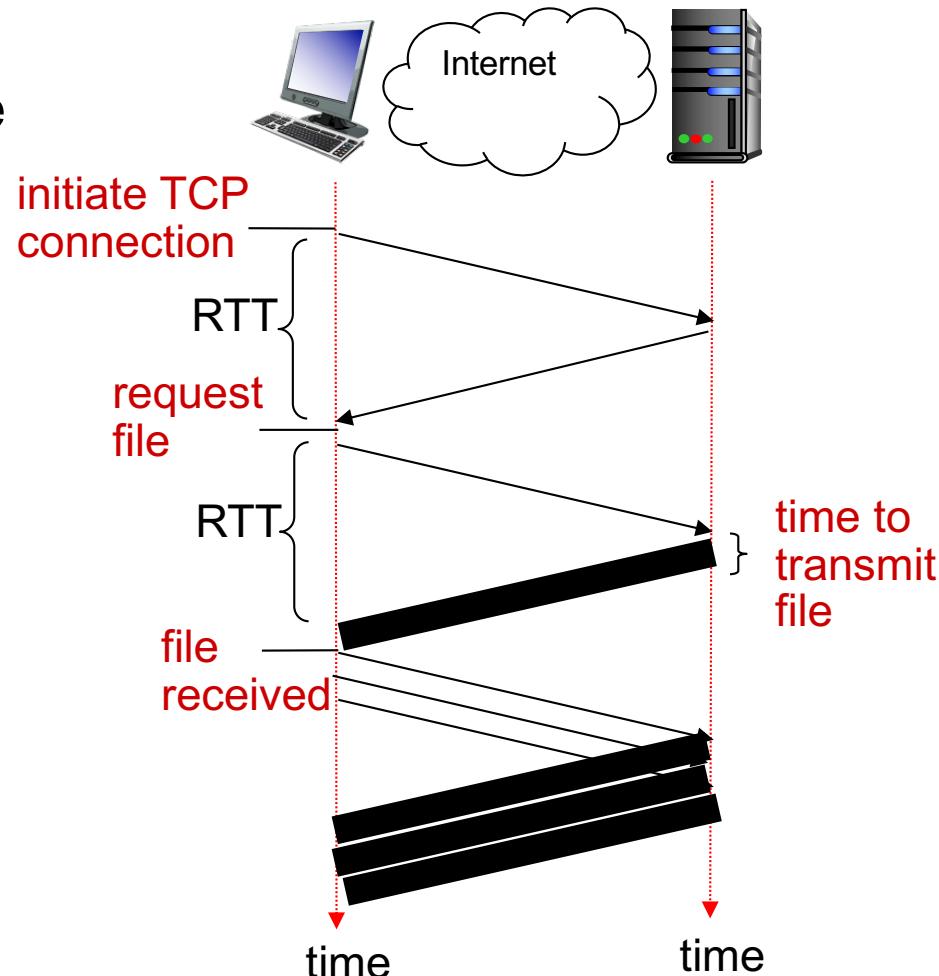
Persistent with pipelining:

- ❖ introduced in HTTP/1.1
- ❖ client sends requests as soon as it encounters a referenced object
- ❖ as little as one RTT for all the referenced objects



HTTP 1.1: response time with pipelining

Website with one index page and three embedded objects



How to improve PLT

- Reduce content size for transfer
 - Smaller images, compression
- Change HTTP to make better use of available bandwidth
 - Persistent connections and pipelining
- Change HTTP to avoid repeated transfers of the same content
 - Caching and web-proxies
- Move content closer to the client
 - CDNs

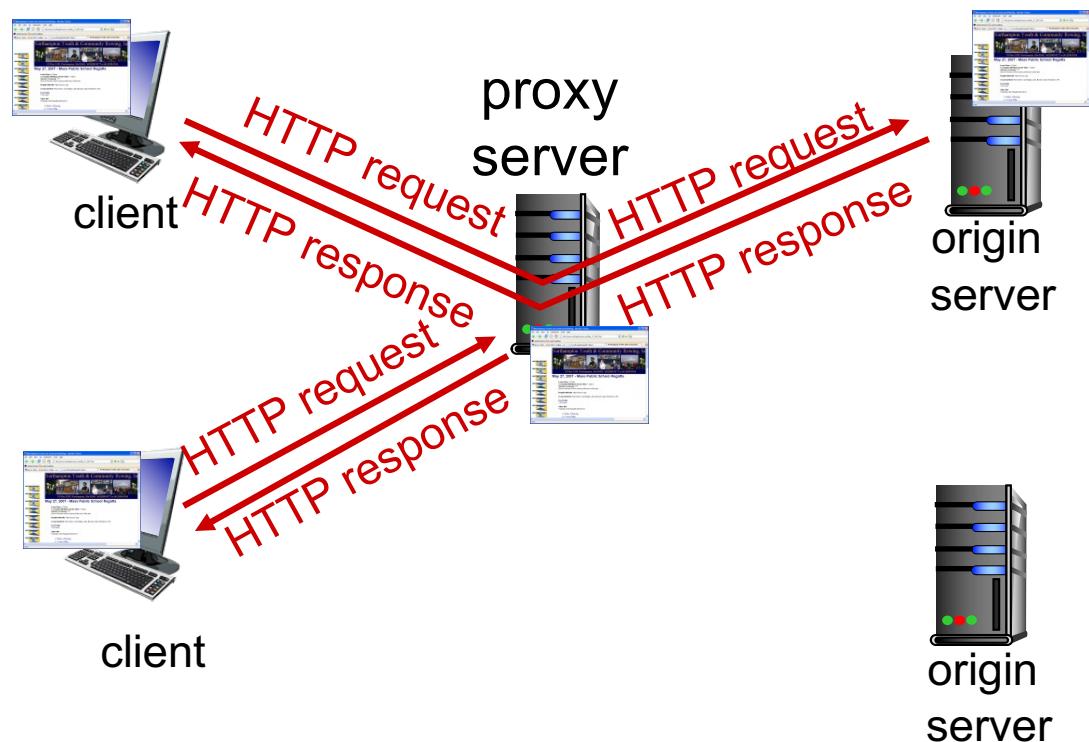
Improving HTTP Performance: Caching

- Why does caching work?
 - Exploit *locality of reference*
- How well does caching work?
 - Very well, up to a limit
 - Large overlap in content
 - But many unique requests
- Trend: increase in dynamic content
 - For example, customization of web pages
 - Reduces benefits of caching
 - Some exceptions, for example, video content

Web caches (proxy server)

goal: satisfy client request without involving origin server

- ❖ user sets browser: Web accesses via cache
- ❖ browser sends all HTTP requests to cache
 - object in cache: cache returns object
 - else cache requests object from origin server, then returns object to client



More about Web caching

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

why Web caching?

- ❖ reduce response time for client request
- ❖ reduce traffic on an institution's access link
- ❖ Internet dense with caches: enables “poor” content providers to effectively deliver content

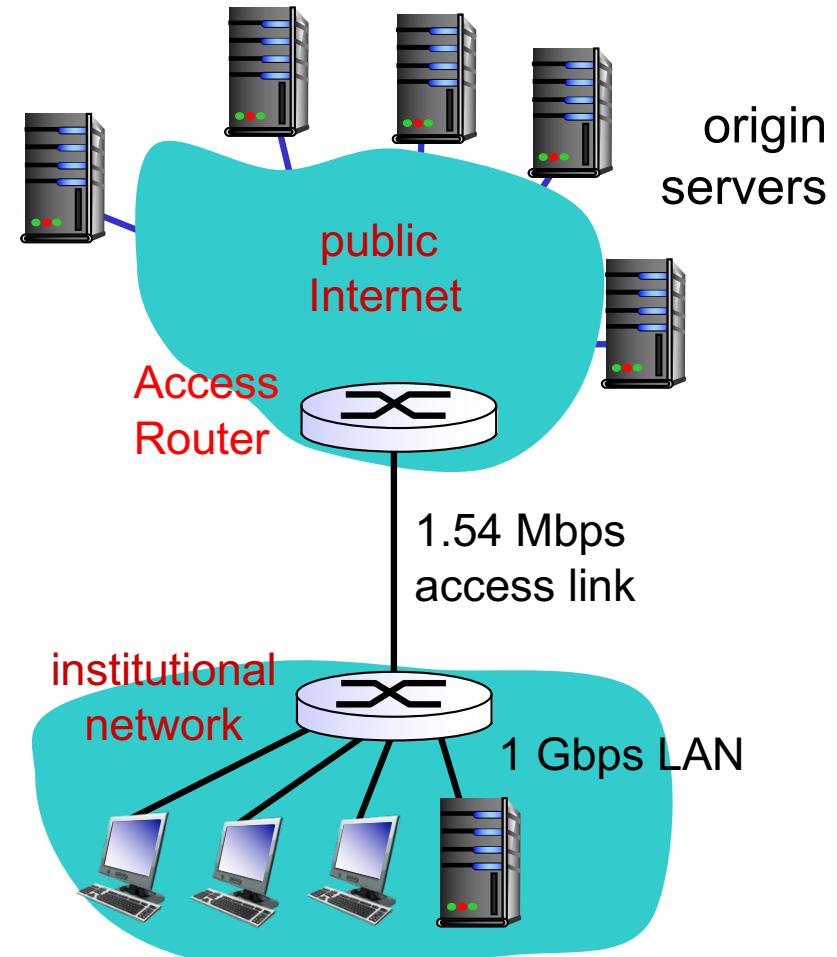
Caching example:

assumptions:

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

consequences:

- ❖ LAN utilization: 0.15%
- ❖ access link utilization = **99%**
- ❖ total delay = Internet delay +
access delay + LAN delay
= 2 sec + minutes + usecs



problem!

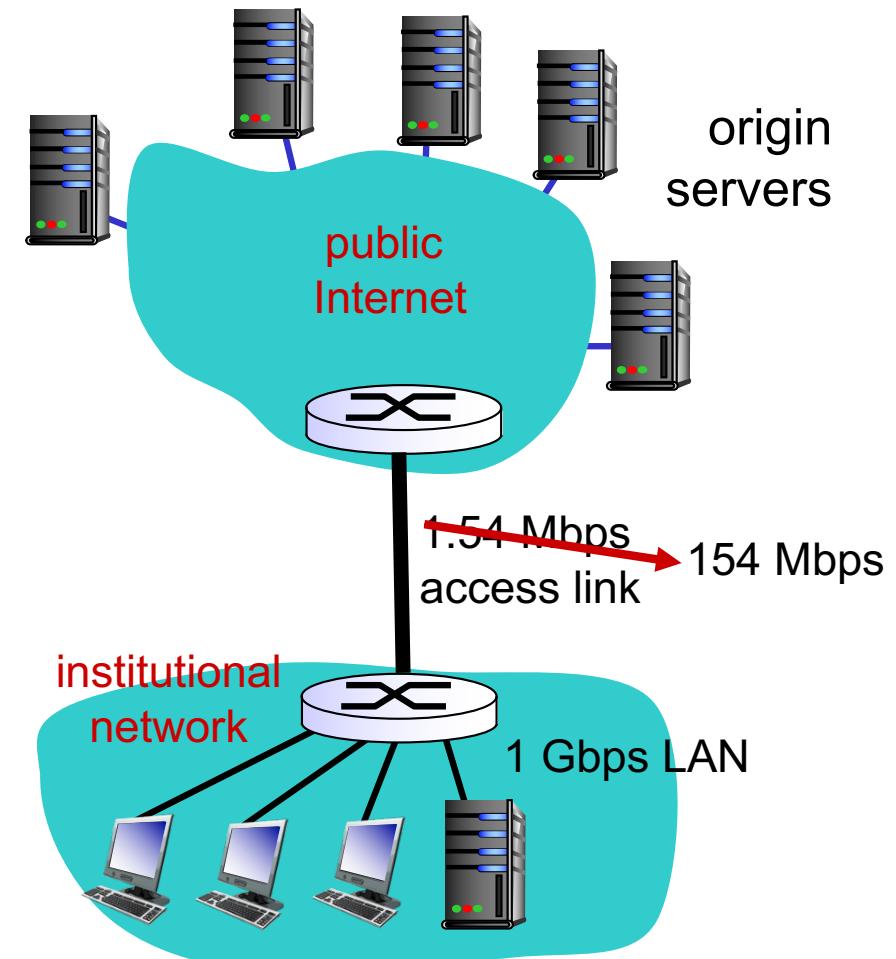
Caching example: fatter access link

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- ❖ avg request rate from browsers to origin servers: 15/sec
- ❖ avg data rate to browsers: 1.50 Mbps
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consequences:

- ❖ LAN utilization: 0.15%
- ❖ access link utilization = ~~99%~~ 0.99%
- ❖ total delay = Internet delay + access delay + LAN delay
= 2 sec + minutes + usecs
msecs



Cost: increased access link speed (not cheap!)

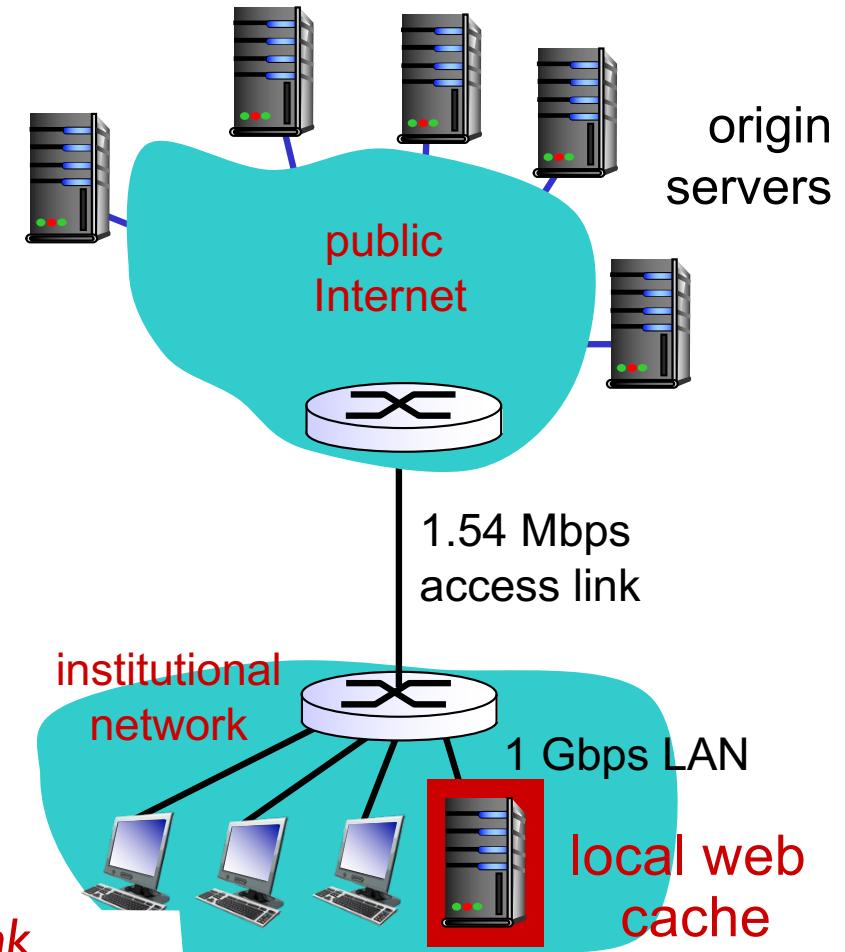
Caching example: install local cache

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consequences:

- ❖ LAN utilization: ?
- ❖ access link utilization = ?
- ❖ total delay = ? *How to compute link utilization, delay?*

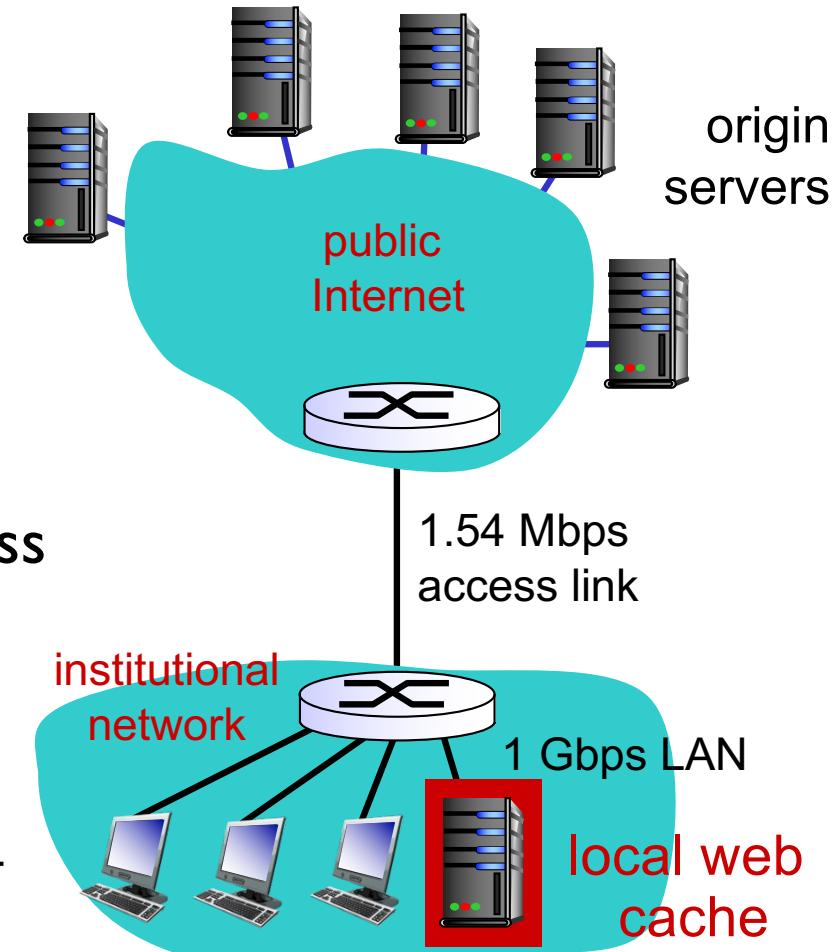


Cost: web cache (cheap!)

Caching example: install local cache

Calculating access link utilization, delay with cache:

- ❖ suppose cache hit rate is 0.4
 - 40% requests satisfied at cache;
 - 60% requests satisfied at origin
- ❖ access link utilization:
 - 60% of requests use access link
- ❖ data rate to browsers over access link = $0.6 * 1.50 \text{ Mbps} = .9 \text{ Mbps}$
 - utilization = $0.9 / 1.54 = .58$
- ❖ total delay
 - $= 0.6 * (\text{delay from origin servers}) + 0.4 * (\text{delay when satisfied at cache})$
 - $= 0.6 (2.01) + 0.4 (\sim \text{msecs})$
 - $= \sim 1.2 \text{ secs}$
 - less than with 154 Mbps link (and cheaper too!)



Conditional GET

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

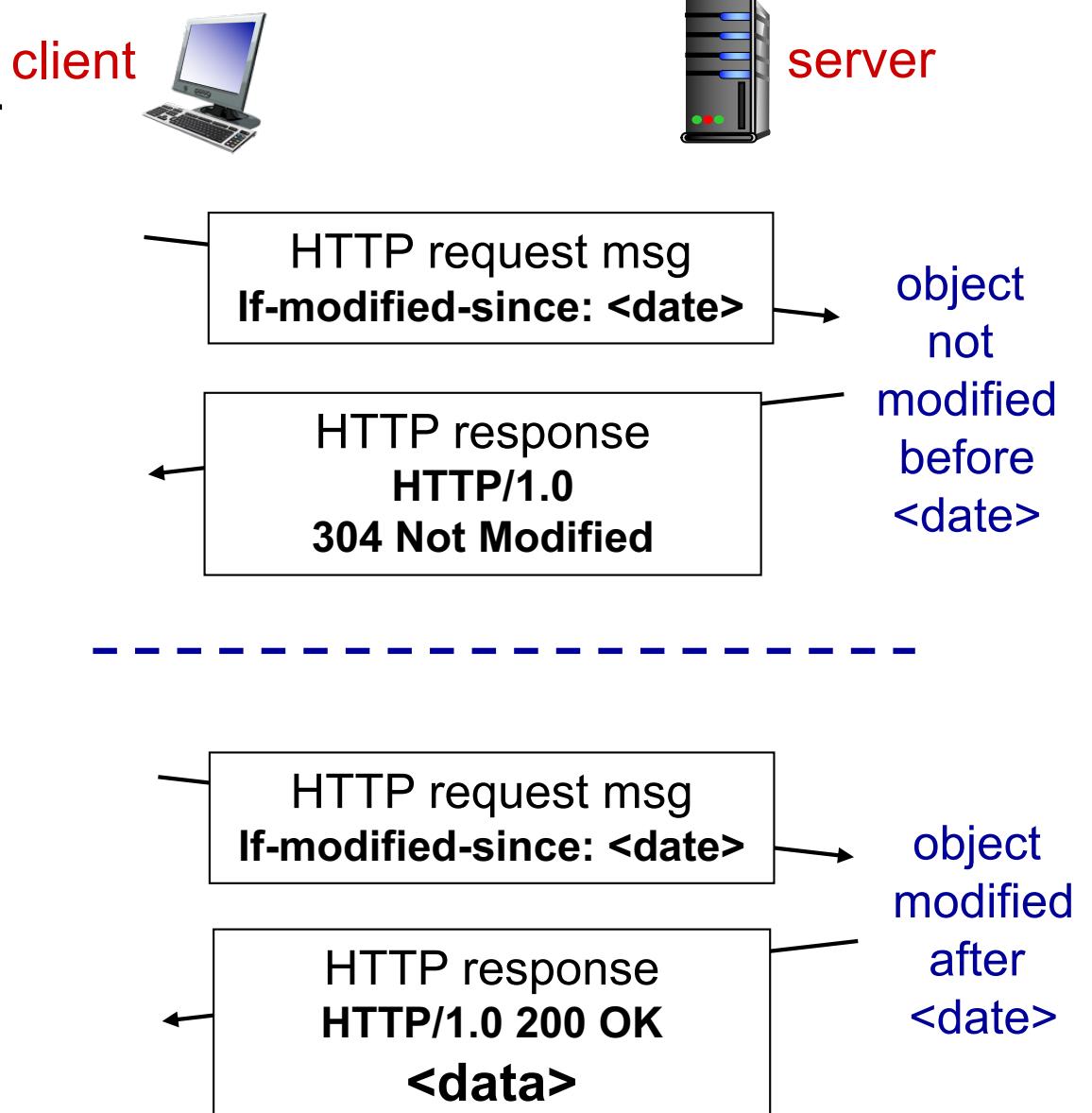
- no object transmission delay
- lower link utilization

- ❖ **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



Example Cache Check Request

GET / HTTP/1.1

Accept: */*

Accept-Language: en-us

Accept-Encoding: gzip, deflate

If-Modified-Since: Mon, 29 Jan 2001 17:54:18 GMT

If-None-Match: "7a11f-10ed-3a75ae4a"

User-Agent: Mozilla/4.0 (compatible; MSIE 5.5; Windows NT
5.0)

Host: www.intel-iris.net

Connection: Keep-Alive

Example Cache Check Response

HTTP/1.1 304 Not Modified

Date: Tue, 27 Mar 2001 03:50:51 GMT

Server: Apache/1.3.14 (Unix) (Red-Hat/Linux) mod_ssl/2.7.1
OpenSSL/0.9.5a DAV/1.0.2 PHP/4.0.1pl2 mod_perl/1.24

Connection: Keep-Alive

Keep-Alive: timeout=15, max=100

ETag: "7a11f-10ed-3a75ae4a"

Etag: Usually used for dynamic content. The value is often a cryptographic hash of the content.

Improving HTTP Performance: Replication

- Replicate popular Web site across many machines
 - Spreads load on servers
 - Places content closer to clients
 - Helps when content isn't cacheable
- Problem:
 - Want to direct client to a particular replica
 - Balance load across server replicas
 - Pair clients with nearby servers
 - Expensive
- Common solution:
 - DNS returns different addresses based on client's geo-location, server load, etc.

Improving HTTP Performance: CDN

- Caching and replication as a service
- Large-scale distributed storage infrastructure (usually) administered by one entity
 - e.g., Akamai has servers in 20,000+ locations
- Combination of (pull) caching and (push) replication
 - **Pull:** Direct result of clients' requests
 - **Push:** Expectation of high access rate
- Also do some processing
 - Handle dynamic web pages
 - Transcoding

What about HTTPS?

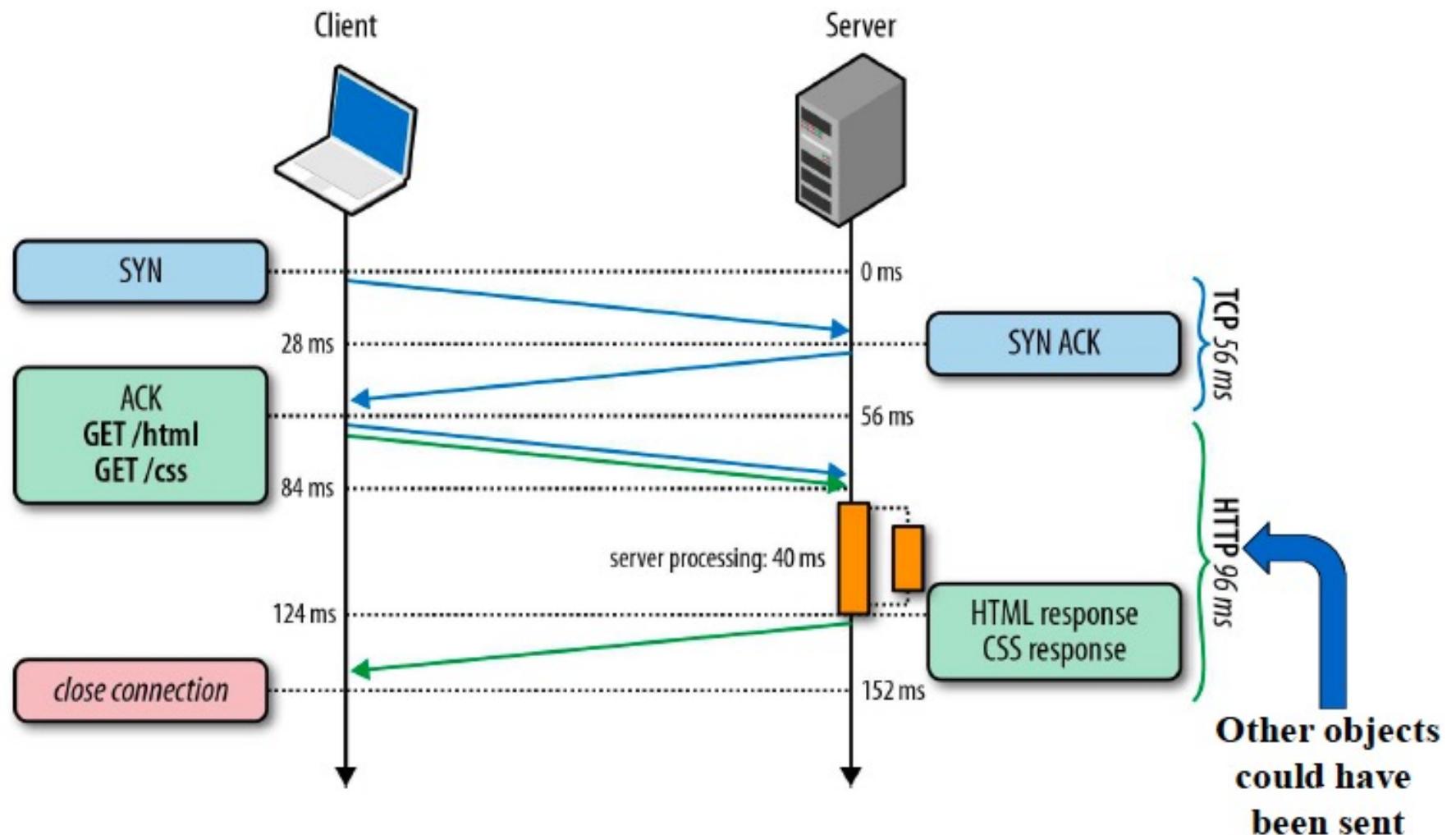
- HTTP is insecure
- HTTP basic authentication: password sent using base64 encoding (can be readily converted to plaintext)
- HTTPS: HTTP over a connection encrypted by Transport Layer Security (TLS)
- Provides:
 - Authentication
 - Bidirectional encryption
- Widely used in place of plain vanilla HTTP



Issues with HTTP

- Head of line blocking: “slow” objects delay later requests
 - Example objects from remote storage vs from local memory
- Browsers often open multiple TCP connections for parallel transfers
 - Increases throughput and reduces impact of HOL blocking
 - Increases load on servers and network
- HTTP headers are big
 - Overheads higher for small objects
- Objects have dependencies, different priorities
 - Javascript vs images
 - Extra RTTs for “dependent” objects

Head of Line Blocking Example



What's on the horizon: HTTP/2

- Google SPDY (speedy) -> HTTP/2: (RFC 7540 May 2015)
- Binary instead of text
 - Efficient to parse, more compact and much less error-prone
- Responses are multiplexed over a single TCP connection
 - Server can send response data whenever it is ready
 - “Fast” objects can bypass “slow” objects – avoid HOL blocking
 - Fewer handshakes, more traffic (helps congestion control)
- Multiplexing uses prioritized flow-controlled schemes
 - Urgent responses can bypass non-critical responses
- Single TCP connection
- HTTP headers are compressed
- Push feature allows server to push embedded objects to the client without waiting for request
 - Saves RTT

More details: <https://http2.github.io/faq/>
Demo: <http://www.http2demo.io>



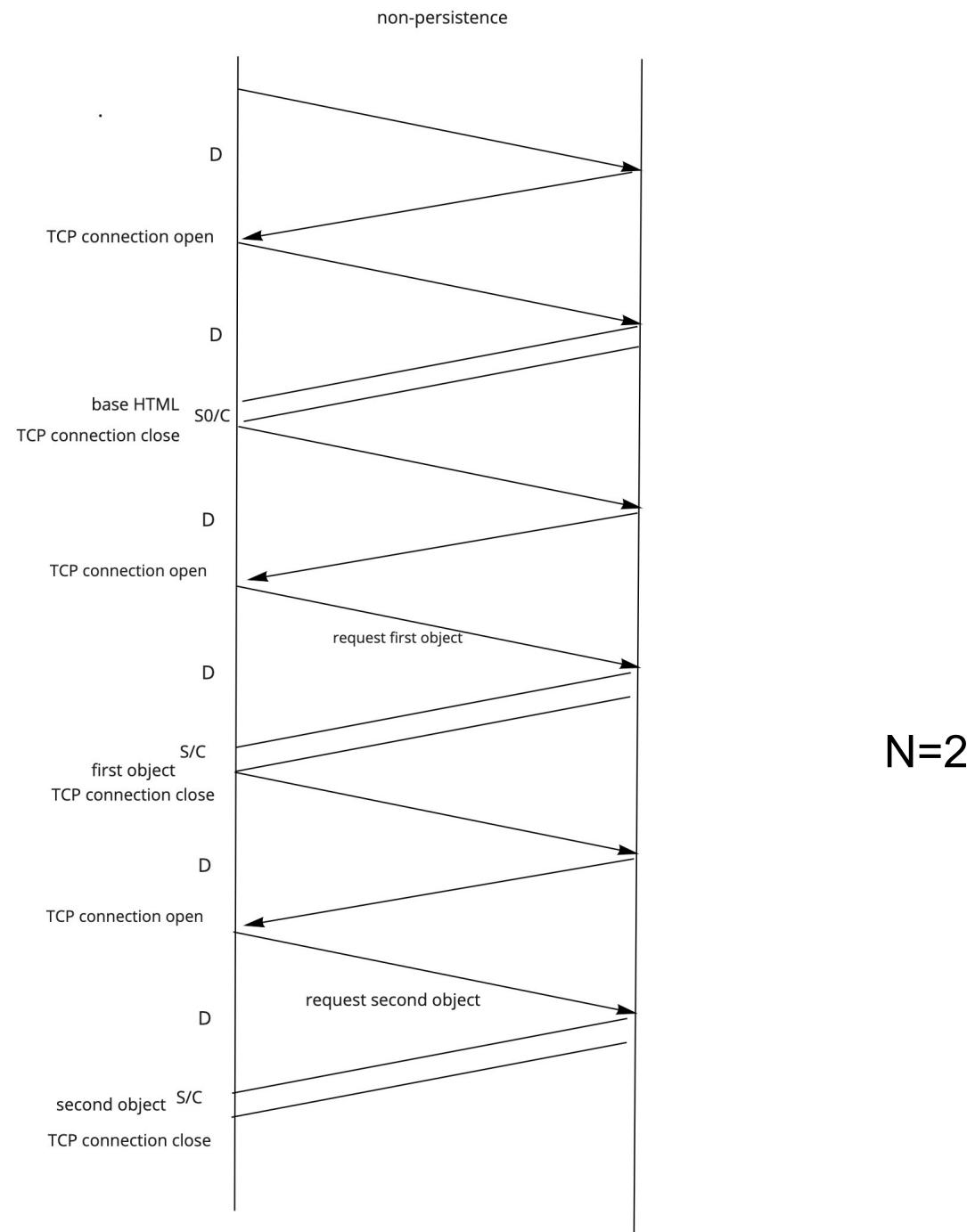
Quiz: HTTP (1)

Consider an HTML page with a base file of size S_0 bits and N inline objects each of size S bits. Assume a client fetching the page across a link of capacity C bits/s and RTT of D . How long does it take to download the page using **non-persistent HTTP (without parallelism)**?

- A. $D + (S_0 + NS)/C$
- B. $2D + (S_0 + NS)/C$
- C. $N(D + S/C)$
- D. $2D + S_0/C + N(2D + S/C)$
- E. $2D + S_0/C + N(D + S/C)$

Answer: D
(see picture on next slide)

Open a browser and type: www.zeetings.com/salil



N=2



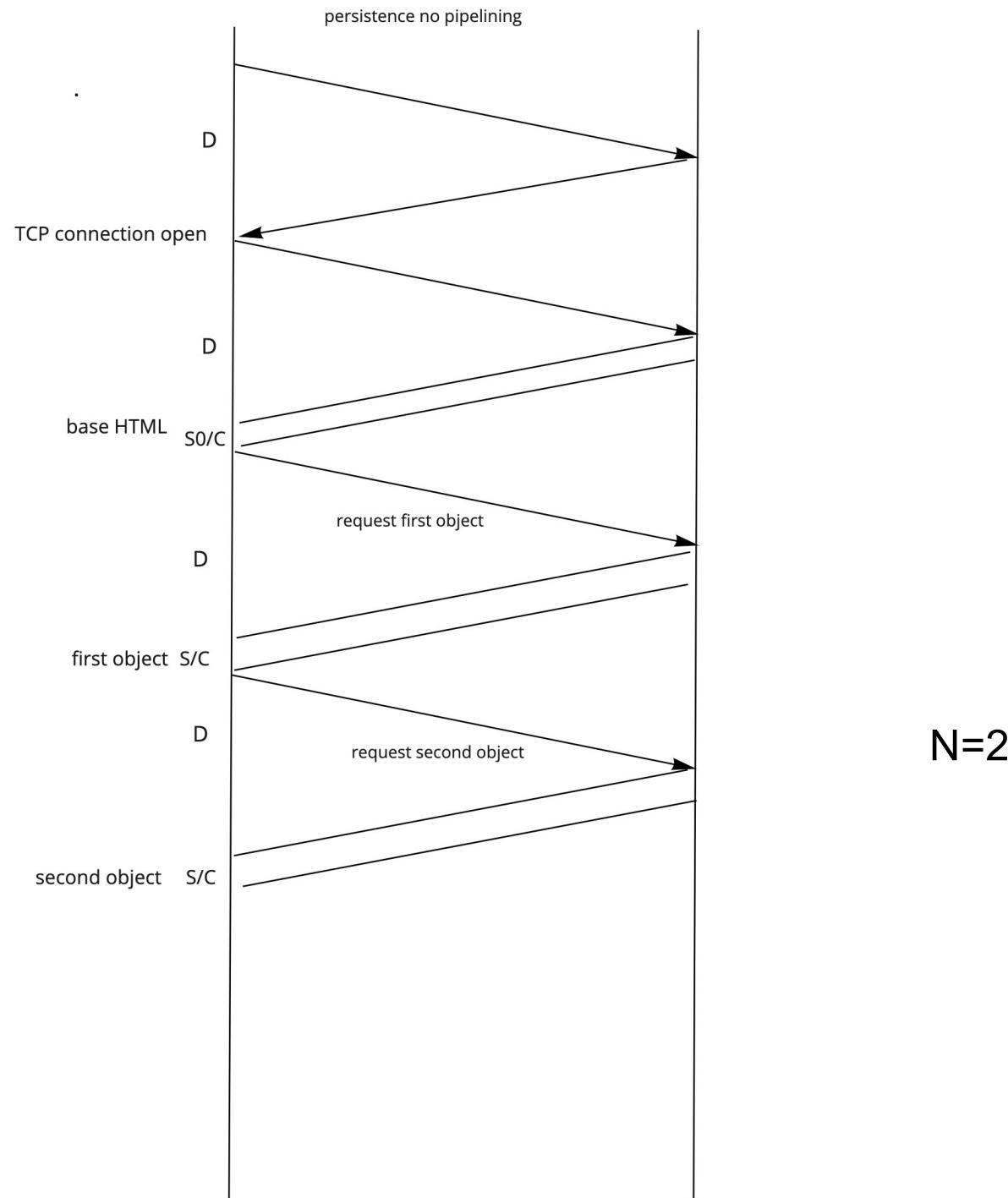
Quiz: HTTP (2)

Consider an HTML page with a base file of size S_0 bits and N inline objects each of size S bits. Assume a client fetching the page across a link of capacity C bits/s and RTT of D . How long does it take to download the page using **persistent HTTP (without parallelism or pipelining)**?

- A. $2D + (S_0 + NS)/C$
- B. $3D + (S_0 + NS)/C$
- C. $N(D + S/C)$
- D. $2D + S_0/C + N(2D + S/C)$
- E. $2D + S_0/C + N(D + S/C)$

Answer: E
(see picture on next slide)

Open a browser and type: www.zeetings.com/salil





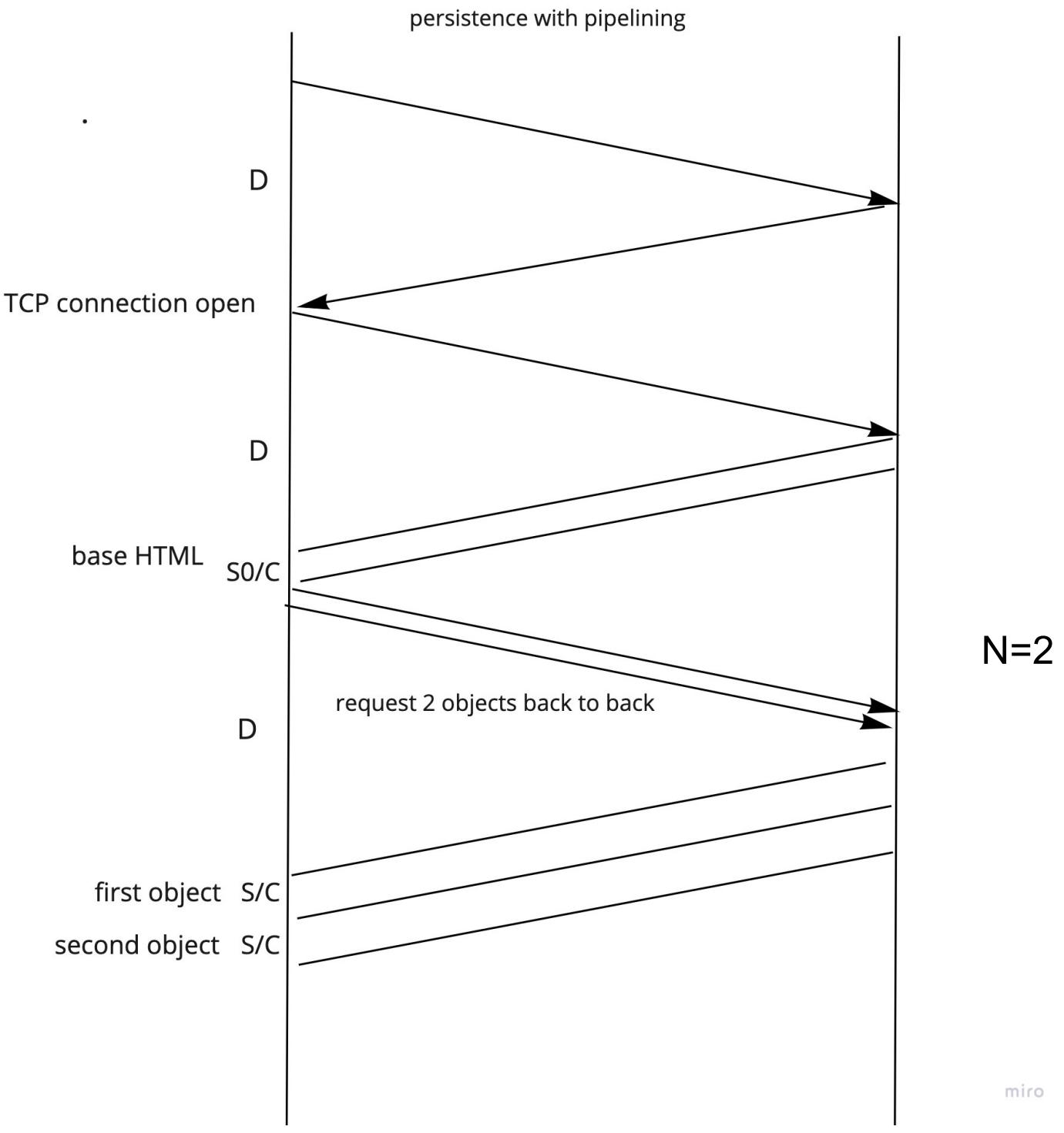
Quiz: HTTP (3)

Consider an HTML page with a base file of size S_0 bits and N inline objects each of size S bits. Assume a client fetching the page across a link of capacity C bits/s and RTT of D . How long does it take to download the page using **persistent HTTP with pipelining?**

- A. $2D + (S_0 + NS)/C$
- B. $4D + (S_0 + NS)/C$
- C. $N(D + S/C)$
- D. $3D + S_0/C + NS/C$
- E. $2D + S_0/C + N(D + S/C)$

Answer: D
(see picture on next slide)

Open a browser and type: www.zeetings.com/salil



Application Layer: outline

2.1 principles of network applications

- app architectures
- app requirements

2.2 Web and HTTP

2.3 electronic mail

- SMTP

2.4 DNS

2.5 P2P applications

2.6 video streaming and content distribution networks (CDNs)

2.7 socket programming with UDP and TCP

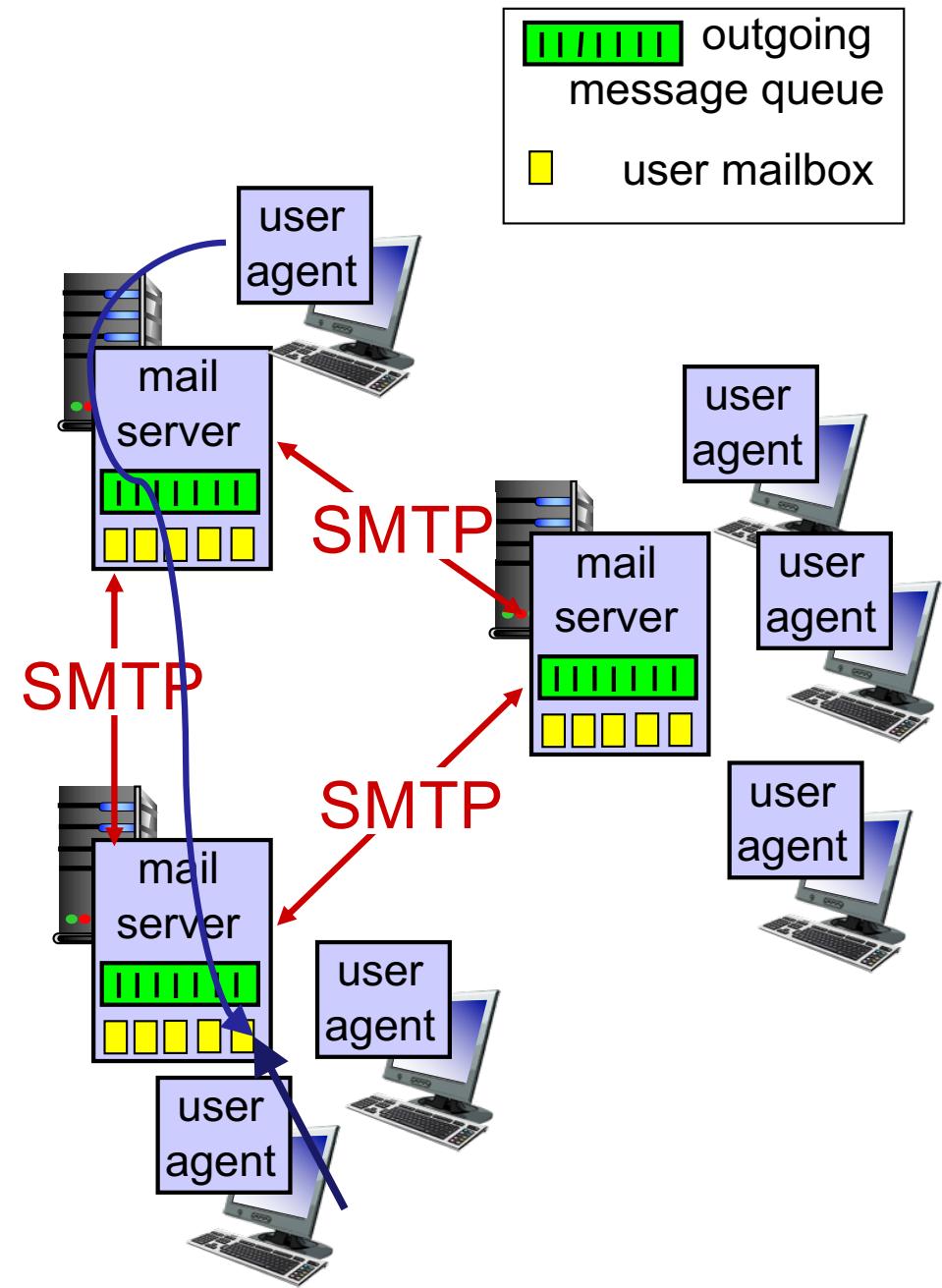
Electronic mail

Three major components:

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

User Agent

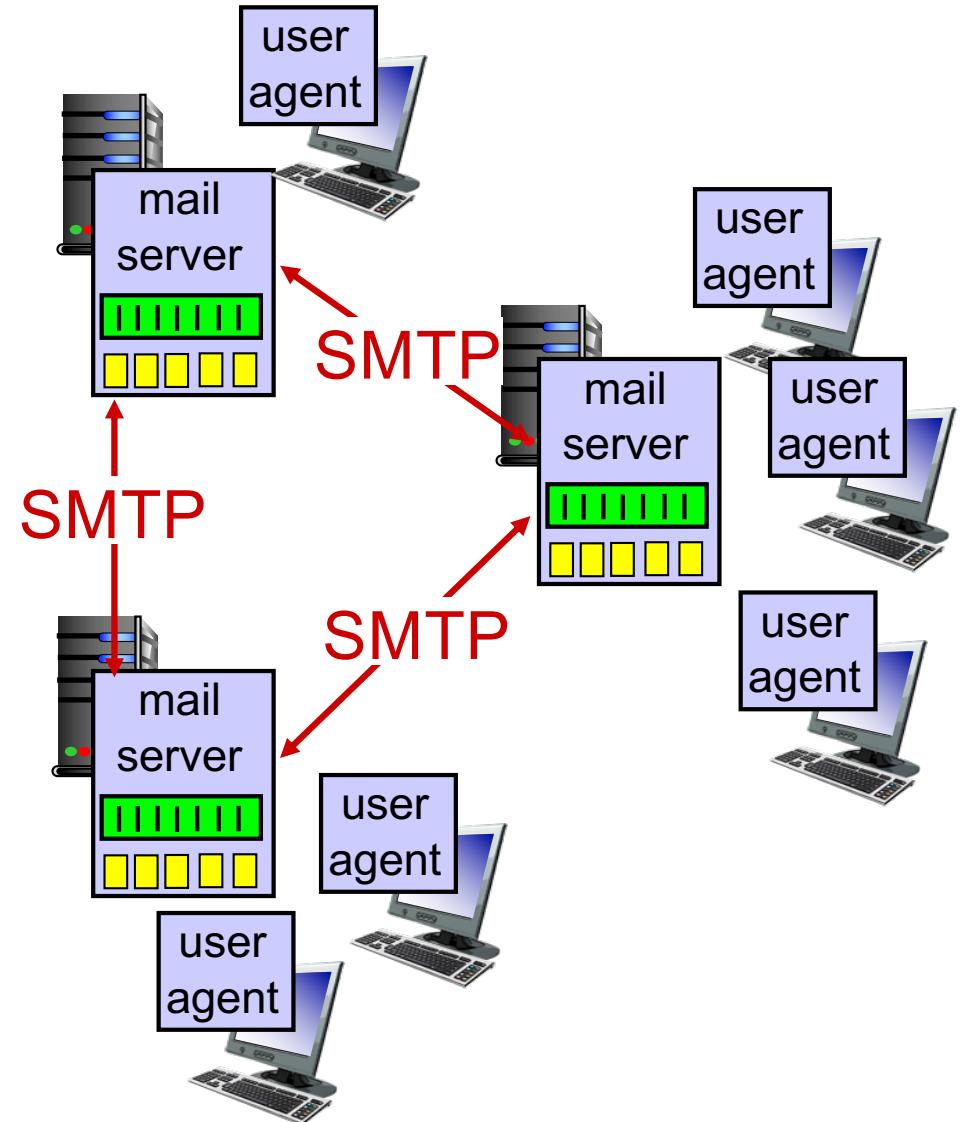
- ❖ a.k.a. “mail reader”
- ❖ composing, editing, reading mail messages
- ❖ e.g., Outlook, Thunderbird, iPhone mail client
- ❖ outgoing, incoming messages stored on server



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

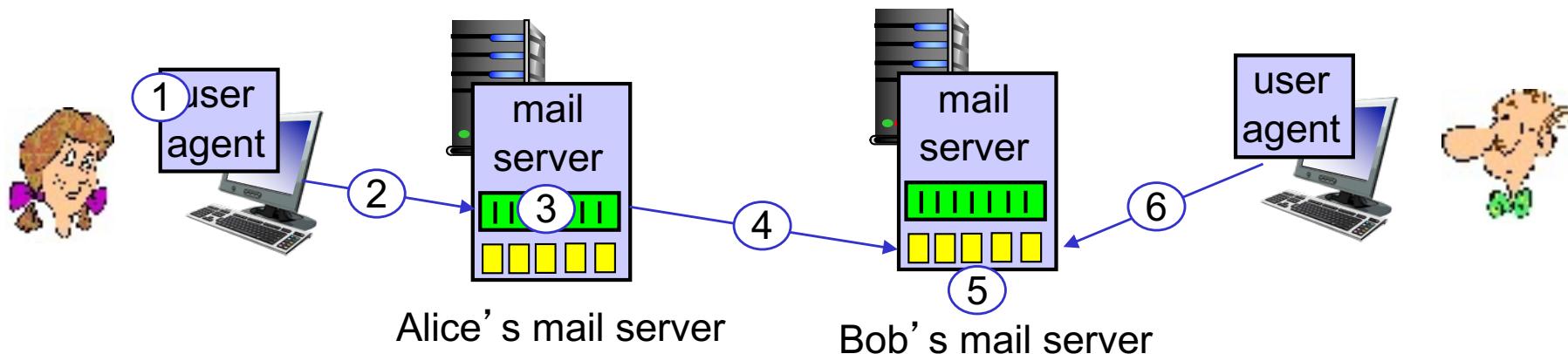


Electronic Mail: SMTP [RFC 2821]

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

Scenario: Alice sends message to Bob

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



Sample SMTP interaction

```
S: 220 hamburger.edu
C: HELO crepes.fr
S: 250 Hello crepes.fr, pleased to meet you
C: MAIL FROM: <alice@crepes.fr>
S: 250 alice@crepes.fr... Sender ok
C: RCPT TO: <bob@hamburger.edu>
S: 250 bob@hamburger.edu ... Recipient ok
C: DATA
S: 354 Enter mail, end with "." on a line by itself
C: Do you like ketchup?
C: How about pickles?
C: .
S: 250 Message accepted for delivery
C: QUIT
S: 221 hamburger.edu closing connection
```

SMTP: final words

- ❖ SMTP uses persistent connections
- ❖ SMTP requires message (header & body) to be in 7-bit ASCII
- ❖ SMTP server uses CRLF .CRLF to determine end of message

comparison with HTTP:

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

Mail message format

SMTP: protocol for
exchanging email msgs

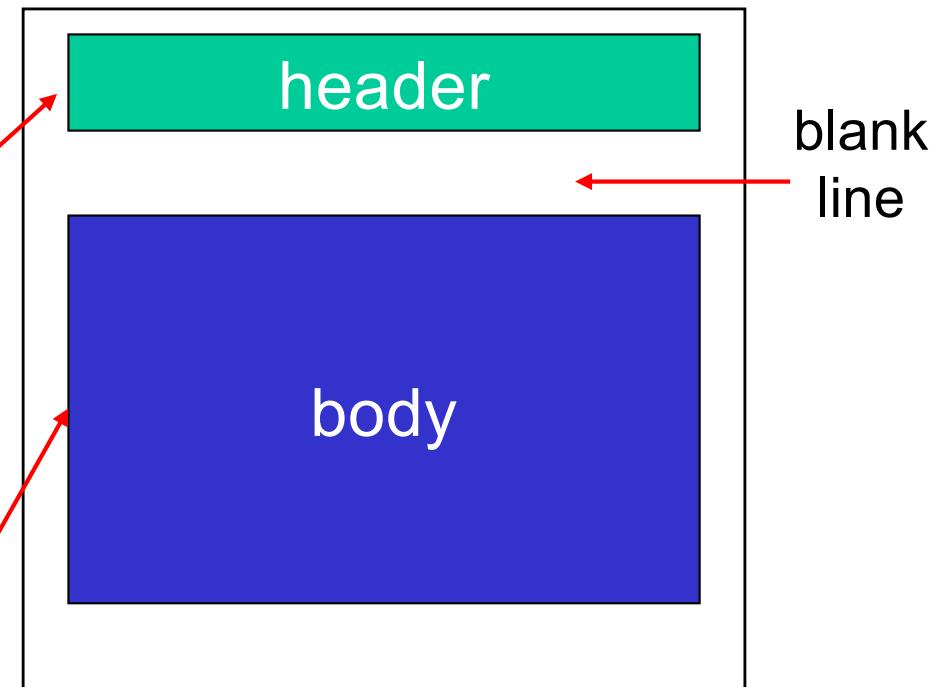
RFC 5322 (822,2822):
standard for text message
format (Internet Message
Format, IMF):

- ❖ header lines, e.g.

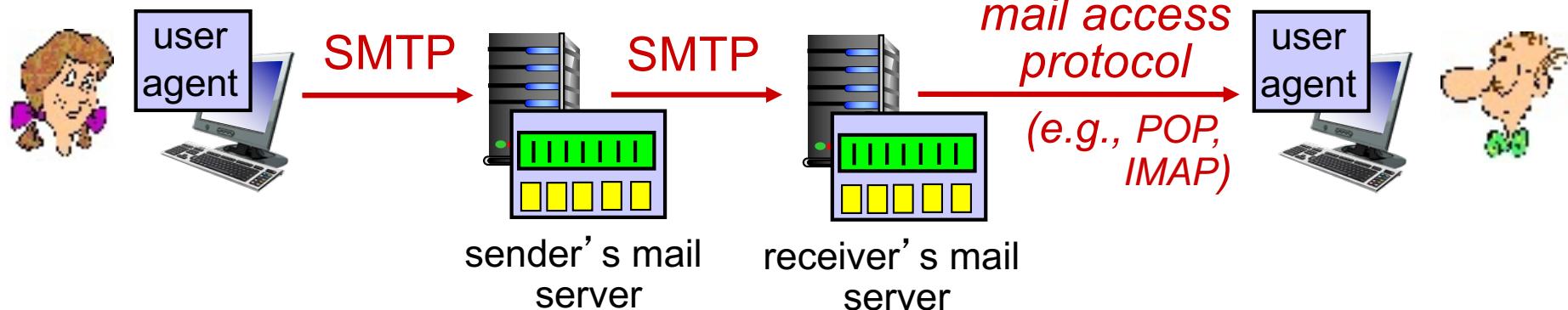
- To:
 - From:
 - Subject:

*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(S):** Gmail, Yahoo! Mail, etc.

Read about POP and IMAP from the text in your own time

Quiz: SMTP

Why do we have Sender's mail server?

- User agent can directly connect with recipient mail server without the need of sender's mail server? What's the catch?

ANSWER: TO ENSURE THAT THE MAIL CAN BE DELIVERED IF THE RECEIVER'S MAIL SERVER IS DOWN MOMENTARILY

Open a browser and type: www.zeetings.com/salil

Quiz: SMTP

Why do we have a separate Receiver's mail server?

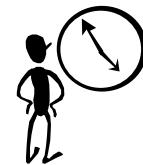
- Can't the recipient run the mail server on own end system?

ANSWER: THE RECIPIENT MAY NOT BE ALWAYS CONNECTED

Open a browser and type: www.zeetings.com/salil

Summary

- ❖ Application Layer (Chapter 2)
 - Principles of Network Applications
 - HTTP
 - E-mail
- ❖ Next:
 - DNS
 - P2P



**Reading Exercise for next week
Chapter 2: 2.4 – 2.7**

