CS2105

An *Awesome* Introduction to Computer Networks

Lectures 2&3: The Application Layer

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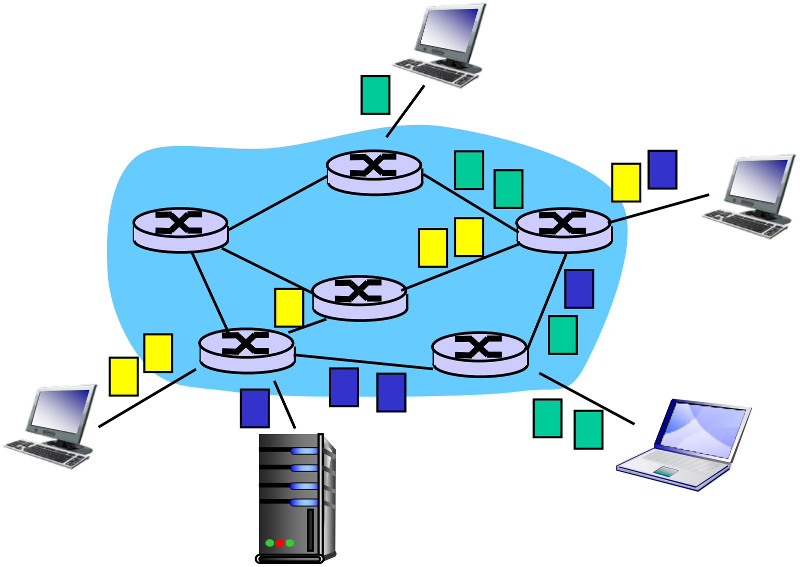
PREVIOUS LECTURE

Packet Switching

- The Internet is a packet switching network
  - Hosts share and contend network resources.
  - Application message is broken into a bunch of packets and sent onto the link one by one.
  - A router stores and forwards packets.
  - Receiver assembles all the packets to restore the application message.

Anyone can use the network at any time

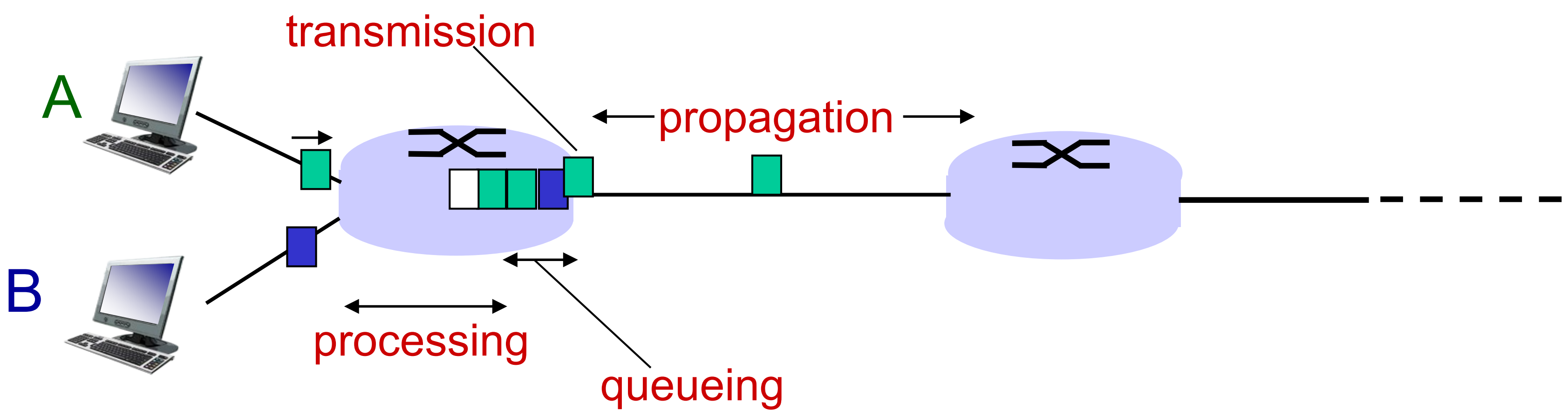
~~Bandwidth division into "pieces"~~
~~Dedicated allocation~~
~~Resource reservation~~



PREVIOUS LECTURE

Packet Delay

- End-to-end delay is the time taken for a packet to travel from source to destination. It consists of:
  - processing delay
  - queueing delay
  - transmission delay
  - propagation delay

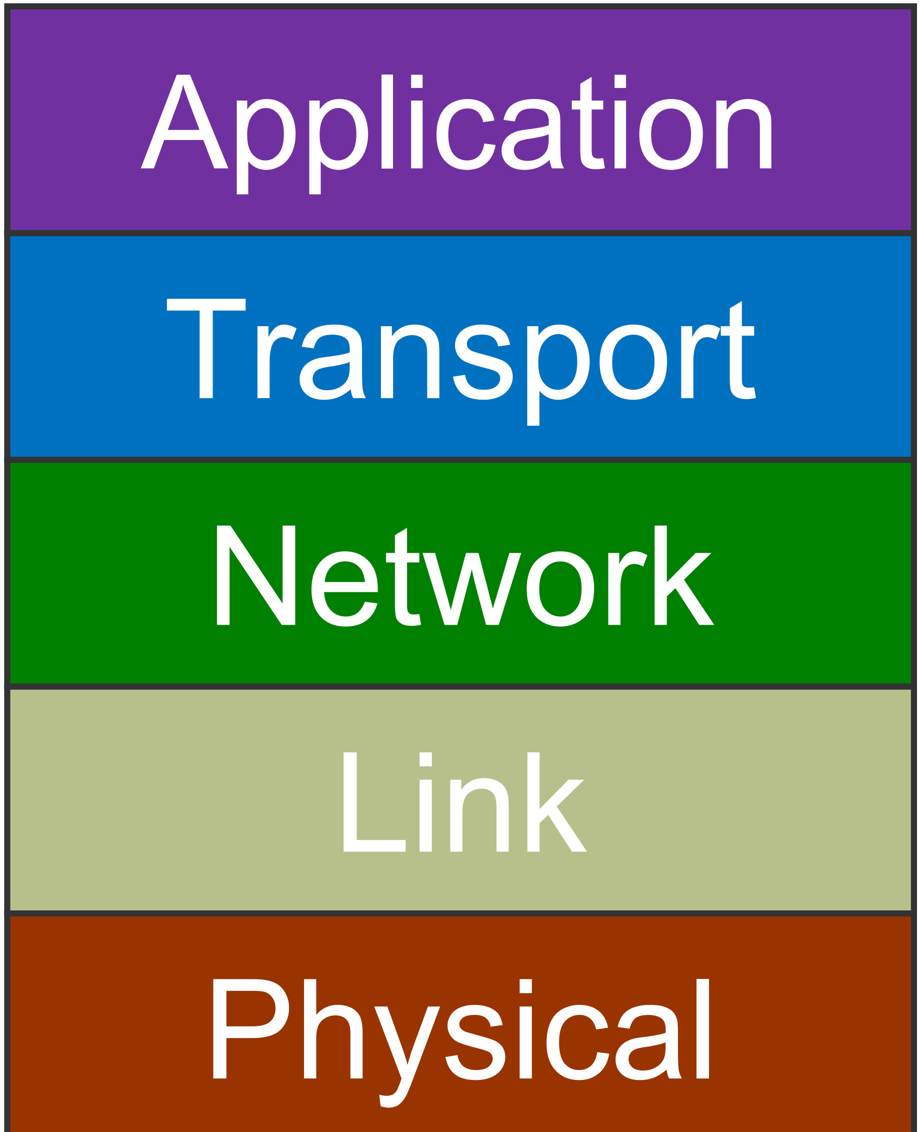


PREVIOUS LECTURE

Network Protocols

- Networks are complex. There are many issues to consider, to support different applications running on large number of hosts through different access technology and physical media.

- Protocols regulate communication activities in a network.
  - Define the *format* and *order* of messages exchanged between hosts for a specific purpose.



Upper layer protocols will use the service provided by lower layers

Lectures 2&3: Application Layer

After this class, you are expected to:

- understand the basic HTTP interactions between the client and the server, the concepts of persistent and non-persistent connections.
- understand the services provided by DNS and how a DNS query is resolved.
- understand the concept of socket.
- be able to write simple client/server programs through socket programming.

Lectures 2&3: Roadmap

2.1 Principles of Network Applications

2.2 Web and HTTP

2.4 DNS

2.7 Socket programming

To discuss next week

Kurose Textbook, Chapter 2
(Some slides are taken from the book)

Evolution of Network Applications

- Early days of Internet
  - Remote access (e.g. telnet, now ssh)
- 70s – 80s
  - Email, FTP
- 90s
  - Web
- 2000s – now
  - P2P file sharing
  - Online games
  - Instant Messaging, Skype
  - YouTube, Facebook

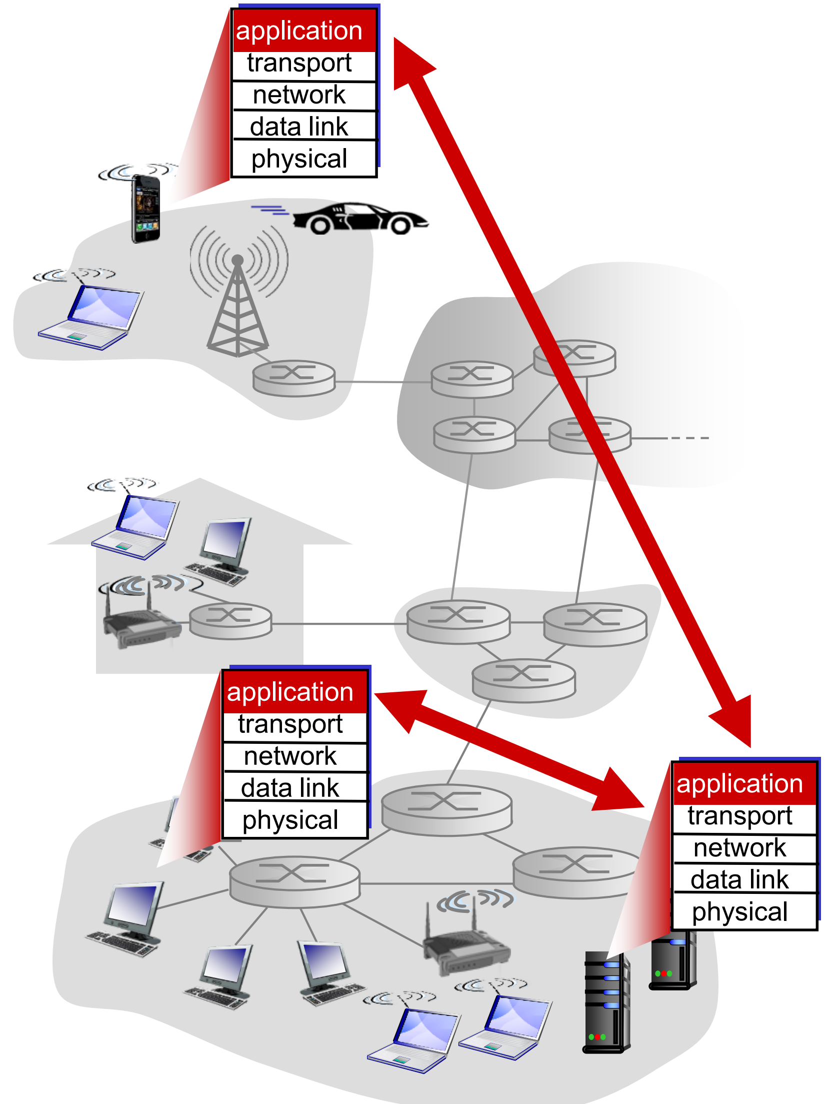
Creating Network Applications

write programs that:

- run on (different) *hosts*
- communicate over network
- e.g., web server software ⇔ browser software

classic structure of network applications:

- Client-server
- Peer-to-peer (P2P)



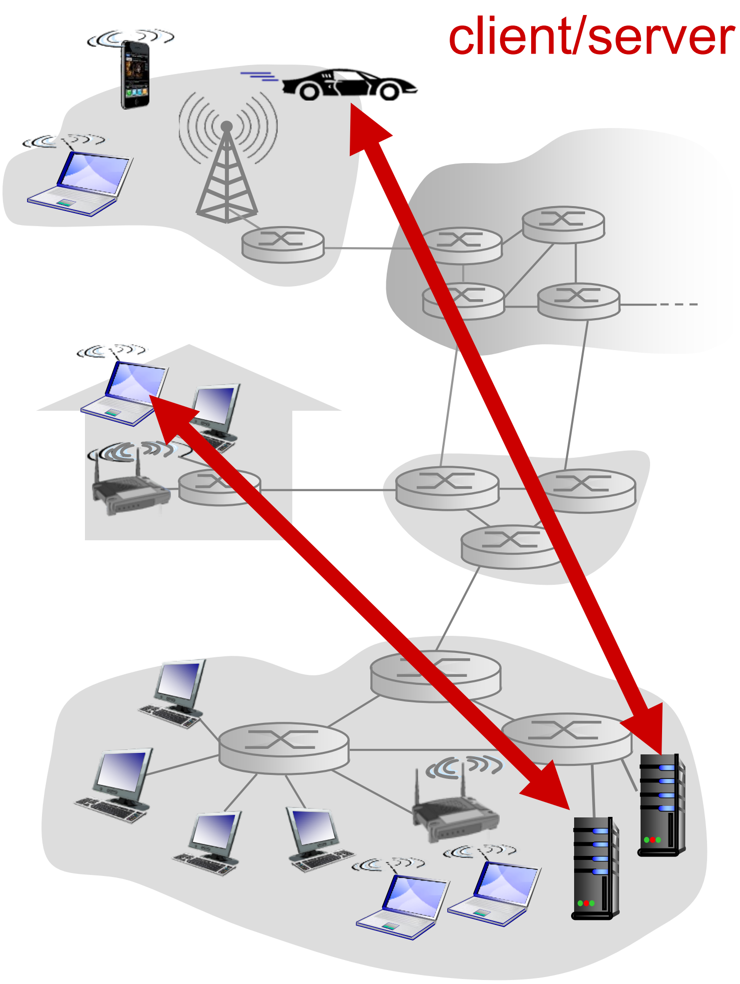
Client-Server Architecture

Server:

- Waits for incoming requests
- Provides requested service to client
- data centers for scaling

Client:

- Initiates contact with server ("speaks first")
- Typically requests service from server
- For Web, client is usually implemented in browser

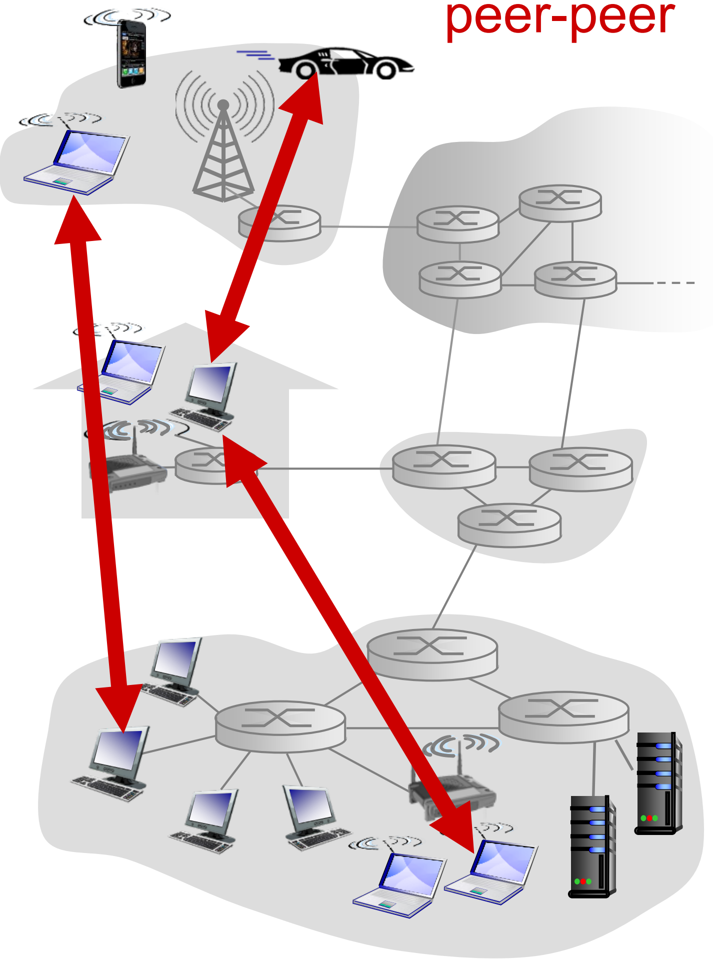


Eg: Bit torrent

P2P Architecture

download and upload simultaneously

- *No* always-on server
- Arbitrary end systems directly communicate.
- Peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, as well as new service demands
- Peers are intermittently connected and change IP addresses
  - complex management



What transport service does an app need?

retransmission is not useful since the old/corrupted data might not be useful anymore

Data integrity

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

Timing

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

Throughput

- some apps (e.g., multimedia) require minimum amount of bandwidth to be "effective"
- other apps (e.g., file transfer) make use of whatever throughput available

Security

- encryption, data integrity, authentication …

Requirements of Example Apps

Application	Data loss	Throughput	Time-sensitive
File transfer	No loss	Elastic	No
Electronic mail	No loss	Elastic	No
Web documents	No loss	Elastic	No
Real-time audio/video	Loss-tolerant	Audio: 5kbps-1Mbps Video:10kbps-5Mbps	Yes: 100s of msec
Stored audio/video	Loss-tolerant	Same as above	Yes: few seconds
Interactive games	Loss-tolerant	Few kbps – 10 kbps	Yes: 100s of msec
Text messaging	No loss	Elastic	Yes and no

App-layer Protocols Define…

- 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 applications send & respond to messages

- open protocols:
  - defined in RFCs
  - allows for interoperability
  - e.g., HTTP, SMTP
- proprietary protocols:
  - e.g., Skype

Transport Layer Protocols: TCP/UDP

- App-layer protocols ride on transport layer protocols:

TCP service:

- *reliable data transfer*
- *flow control:* sender won't overwhelm receiver
- *congestion control:* throttle sender when network is overloaded
- *does not provide:* timing, minimum throughput guarantee, security

UDP service:

- *unreliable data transfer*
- *no flow control*
- *no congestion control*
- *does not provide:* timing, throughput guarantee or security

cannot guarantee any performance/throughput because the packet switching network does not allow for any reservation of the resource - inherent problem of internet architecture

Example App/Transport Protocols

Application	Application Layer Protocol	Underlying Transport Protocol
Electronic mail	SMTP [RFC 5321]	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)	Typically TCP
Internet telephony	SIP [RFC 3261], RTP [RFC 3550], or proprietary (e.g., Skype)	TCP or UDP

Lectures 2&3: Roadmap

2.1 Principles of Network Applications

2.2 Web and HTTP

2.4 DNS

2.7 Socket programming

The Web: Some Jargon

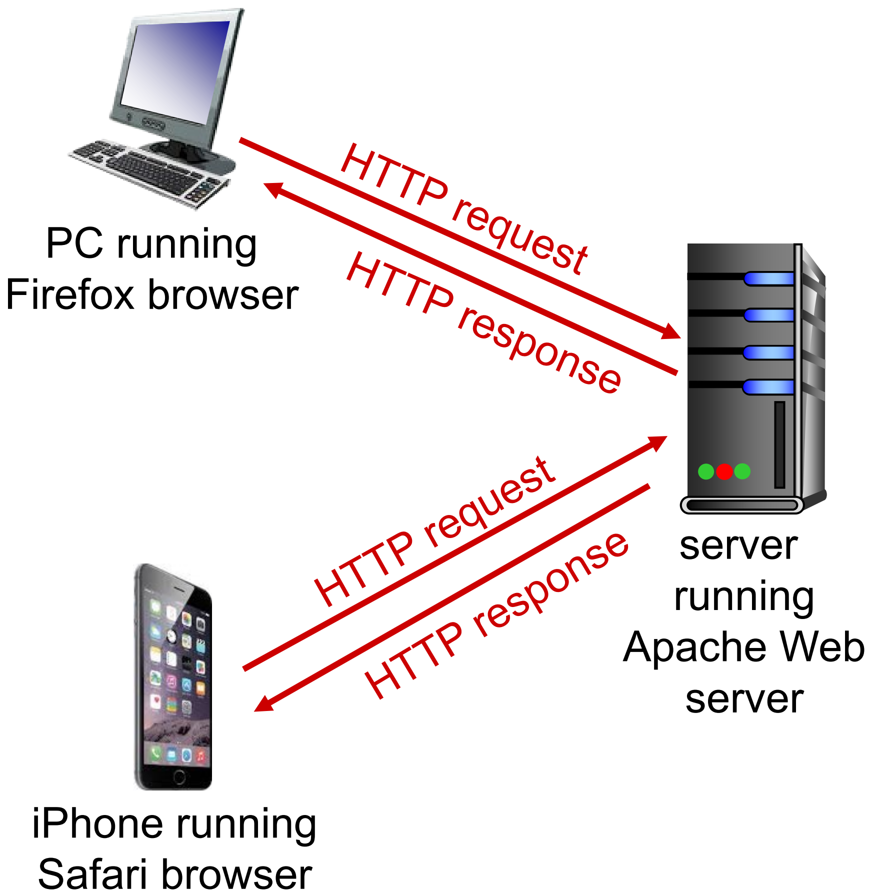
- A Web page typically consists of:
  - *base HTML file*, and
  - *several referenced objects*.
- An object can be HTML file, JPEG image, Java applet, audio file, …
- Each object is addressable by a *URL*, e.g.,

$$\underbrace{\texttt{www.comp.nus.edu.sg}}_{\text{host name}}\underbrace{\texttt{/\textasciitilde cs2105/img/doge.jpg}}_{\text{path name}}$$

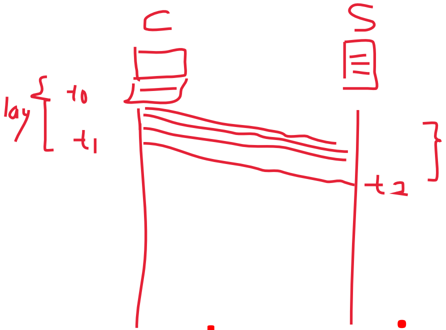
HTTP Overview

HTTP: Hypertext transfer protocol

- Web's application layer protocol
- Client/server model
  - *client:* usually is browser that requests, receives and displays Web objects
  - *server:* Web server sends objects in response to requests
- http 1.0: RFC 1945
- http 1.1: RFC 2616



$t_1 - t_0 =$ transmission delay



$t_2 - t_1 =$ propagation delay

HTTP Over TCP

HTTP uses TCP as transport service

- Client initiates TCP connection to server.
- Server accepts TCP connection request from client.
- HTTP messages are exchanged between browser (HTTP client) and Web server (HTTP server) over TCP connection.
- TCP connection closed.

workflow

Two Versions of HTTP

Non-persistent HTTP

- at most one object sent over a 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 Example

suppose user enters URL:

`www.comp.nus.edu.sg/~cs2105/demo.html`

(contains text, reference to a jpeg image)

time

1a. HTTP client initiates TCP connection to HTTP server at www.comp.nus.edu.sg on port 80

1b. HTTP server at host www.comp.nus.edu.sg is waiting for TCP connection at port 80. It "accepts" connection and reply client

2. HTTP client sends HTTP *request message* (containing URL) into TCP connection socket. Message indicates that client wants object ~cs2105/demo.html

3. HTTP server receives request message, forms ***response message*** containing requested object, and sends message to the client

Non-persistent HTTP Example

time

4. HTTP server closes TCP connection.

5. HTTP client receives response message containing html file, displays html. Parsing html file, client notices the referenced jpeg object

6. Steps 1-5 repeated for the jpeg object

- This is an example of *non-persistent connection* (http 1.0).
  - One object per connection
- HTTP 1.1 allows *persistent connection* (to discuss).
  - Multiple objects per connection

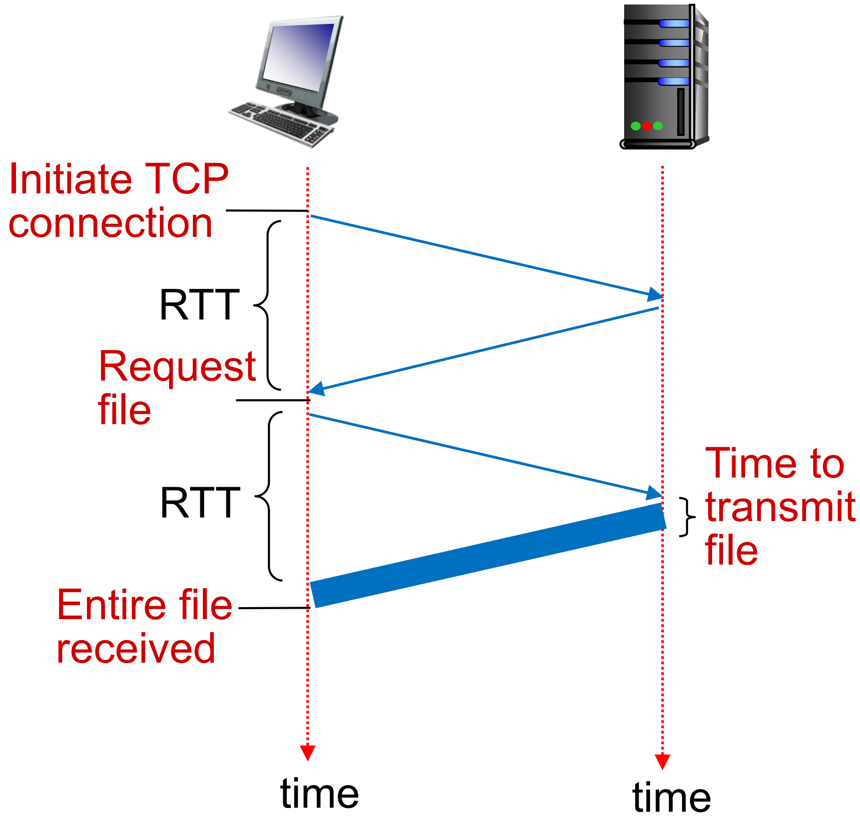
Non-persistent HTTP: Response Time

RTT: time for a packet to travel from client to server and go back

HTTP response time:

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

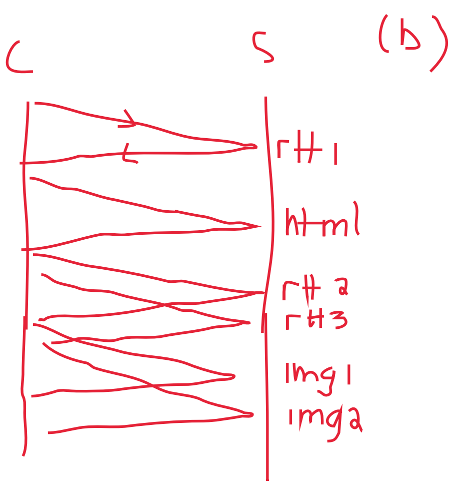
  2 * RTT+ file transmission time



Persistent HTTP

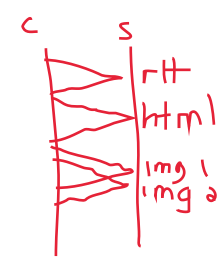
non-persistent HTTP issues:

- 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 the same TCP connection
- moreover, client may send requests as soon as it encounters a referenced object (persistent with pipelining)
  - as little as one RTT for all the referenced objects



Example HTTP Request Message

- Two types of HTTP messages: *request, response*
- HTTP request message:

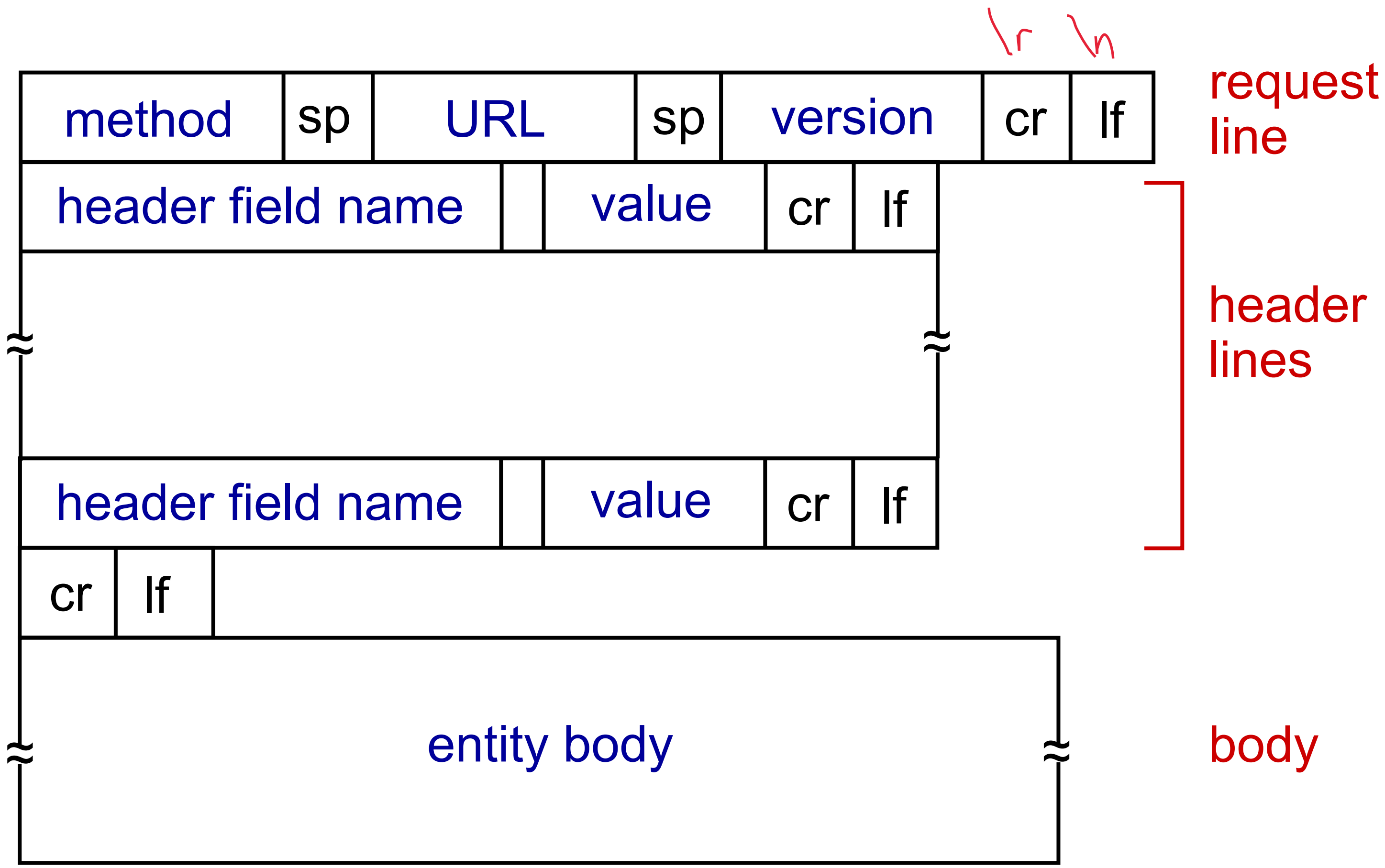
request line
(GET method)

```
GET /index.html HTTP/1.1\r\n
Host: www.example.org\r\n
Connection: keep-alive\r\n
...
\r\n
```

header lines

Extra "blank" line indicates the end of header lines

HTTP Request Message: General Format



HTTP Request Method Types

HTTP/1.0:

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

Example HTTP Response Message

status line
(protocol status code)

client request is successful - shows the response to the request here

```
HTTP/1.1 200 OK\r\n
Date: Wed, 23 Jan 2019 13:11:15 GMT\r\n
Content-Length: 606\r\n
Content-Type: text/html\r\n
...
\r\n
data data data data data ...
```

header lines

data, e.g. requested HTML file

For a full list of request/response header fields, check
http://www.w3.org/Protocols/rfc2616/rfc2616-sec14.html

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:)

403 Forbidden
- server declines to show the requested webpage

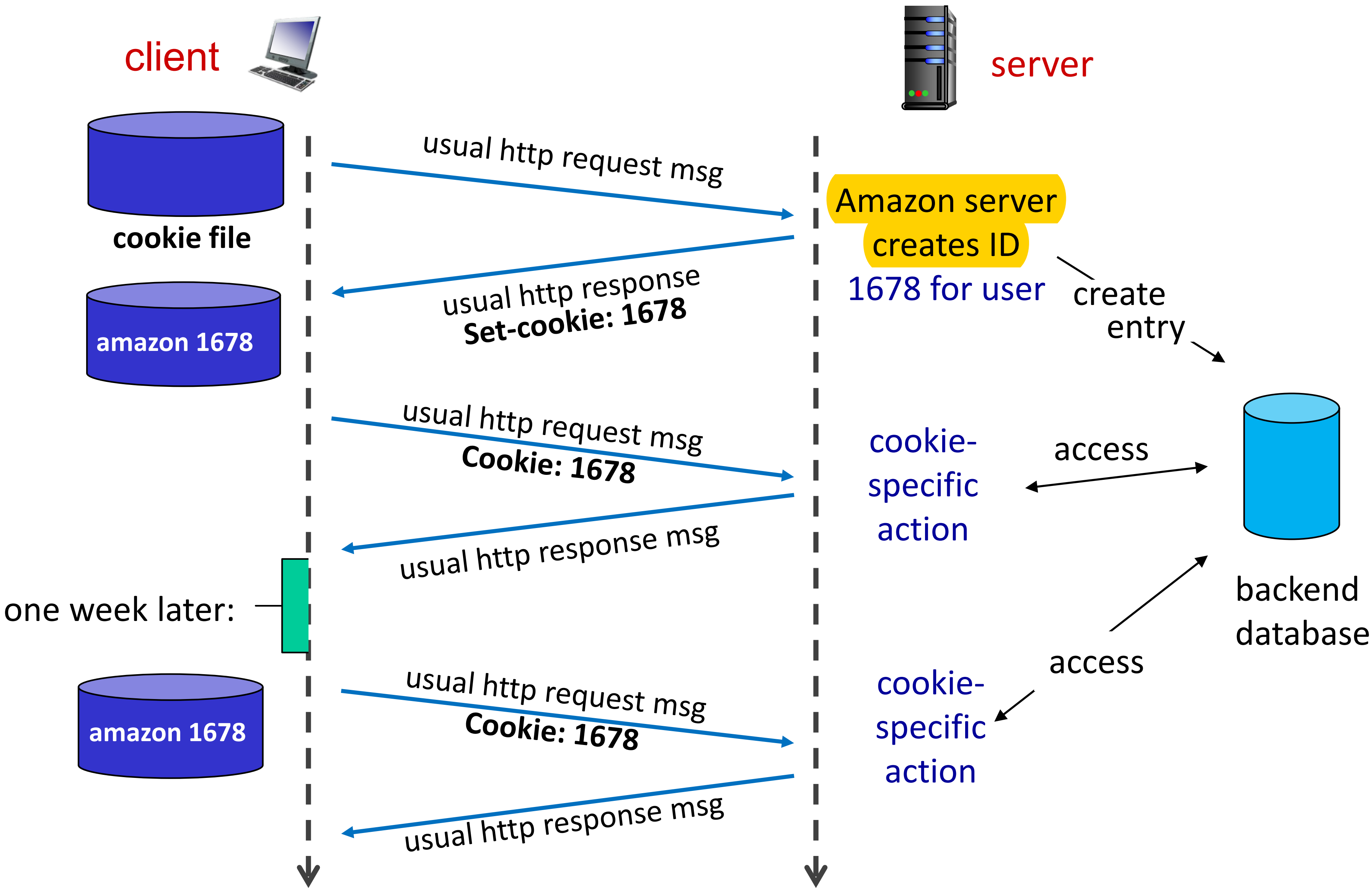
404 Not Found
- requested document not found on this server

For a full list of status codes, check http://www.w3.org/Protocols/rfc2616/rfc2616-sec10.html

Cookies

- HTTP is designed to be "stateless".
  - Server maintains no information about past client requests.
- Sometimes it's good to maintain states (history) at server/client over multiple transactions.
  - E.g. shopping carts
- Cookie: http messages carry "state"
  1) cookie header field of HTTP *request* / *response* messages can be used as a token to prove identity
  2) cookie file kept on user's host, managed by user's browser
  3) back-end database at Web site

Keep User States with Cookie



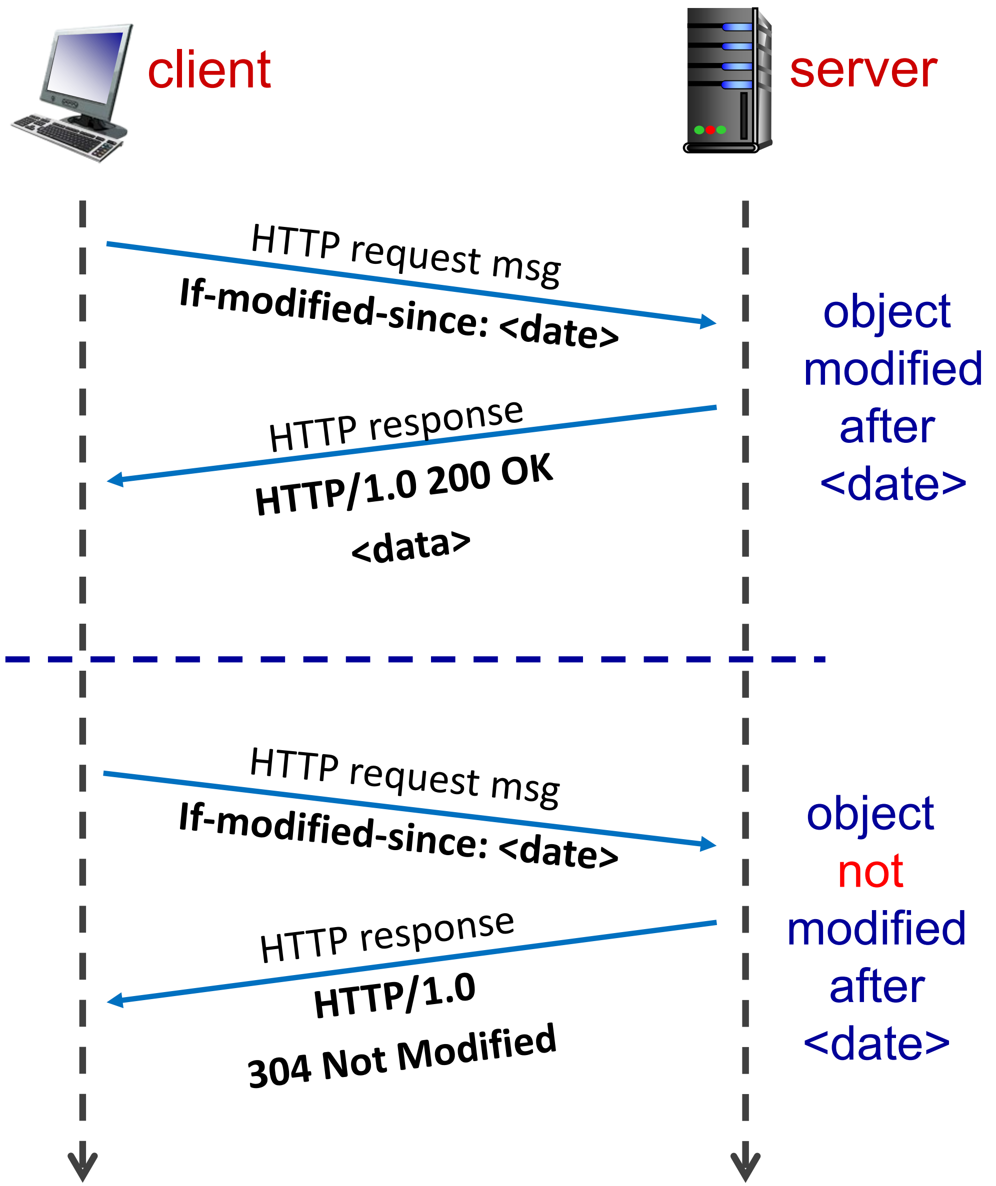
Conditional GET

- *Goal:* don't send object if (client) cache has up-to-date cached version
- *cache:* specify date of cached copy in HTTP request

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

  `HTTP/1.0 304 Not Modified`

saves bandwidth



Lectures 2&3: Roadmap

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Domain Name System [RFC 1034, 1035]

- Two ways to identify a host:
  - **Hostname**, e.g., www.example.org
  - **IP address**, e.g., 93.184.216.34

- DNS (Domain Name System) translates between the two.
  - A client must carry out a DNS query to determine the IP address corresponding to the server name (e.g., www.example.org) prior to the connection.

canonical name = actual / true name

DNS: Resource Records (RR)

- Mapping between host names and IP addresses (and others) are stored as **r**esource **r**ecords (RR).

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

type = A

- **`name`** is hostname
- **`value`** is IP address

type = NS

name server

- **`name`** is domain (e.g., **`nus.edu.sg`**)
- **`value`** is hostname of authoritative name server for this domain

type = CNAME

- **`name`** is alias name (e.g. **`www.nus.edu.sg`**) for some "canonical" (the real) name
- **`value`** is canonical name (e.g. **`mgnzsqc.x.incapdns.net`**)

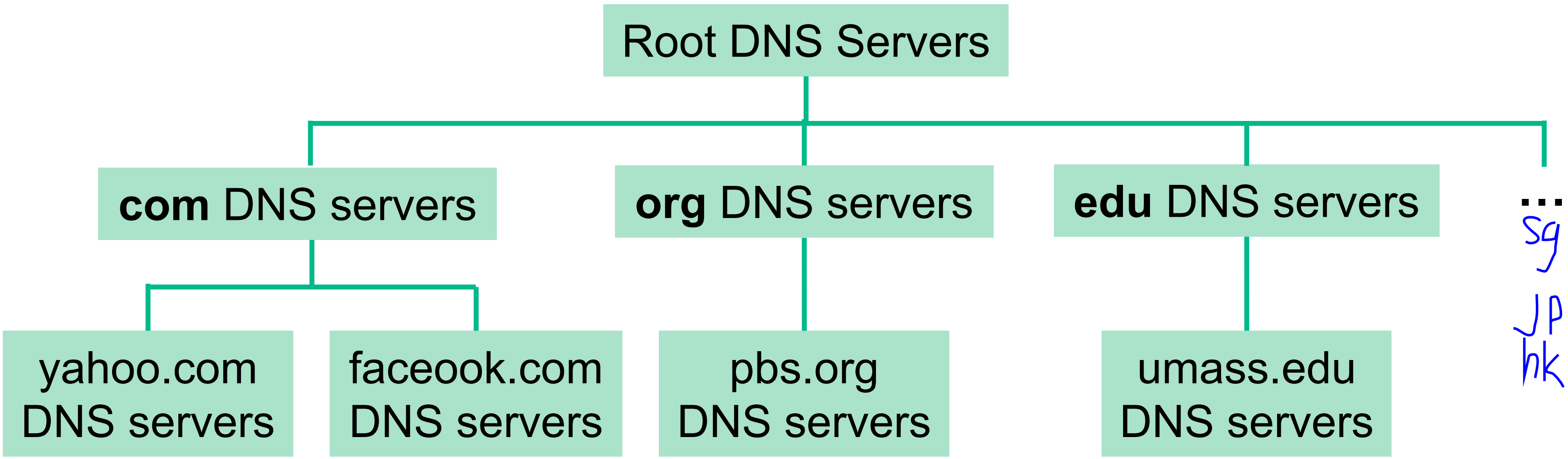
type = MX

mail exchanger = email server

- **`value`** is name of mail server associated with **`name`**

Distributed, Hierarchical Database

- DNS stored RR in distributed databases implemented in hierarchy of many name servers.

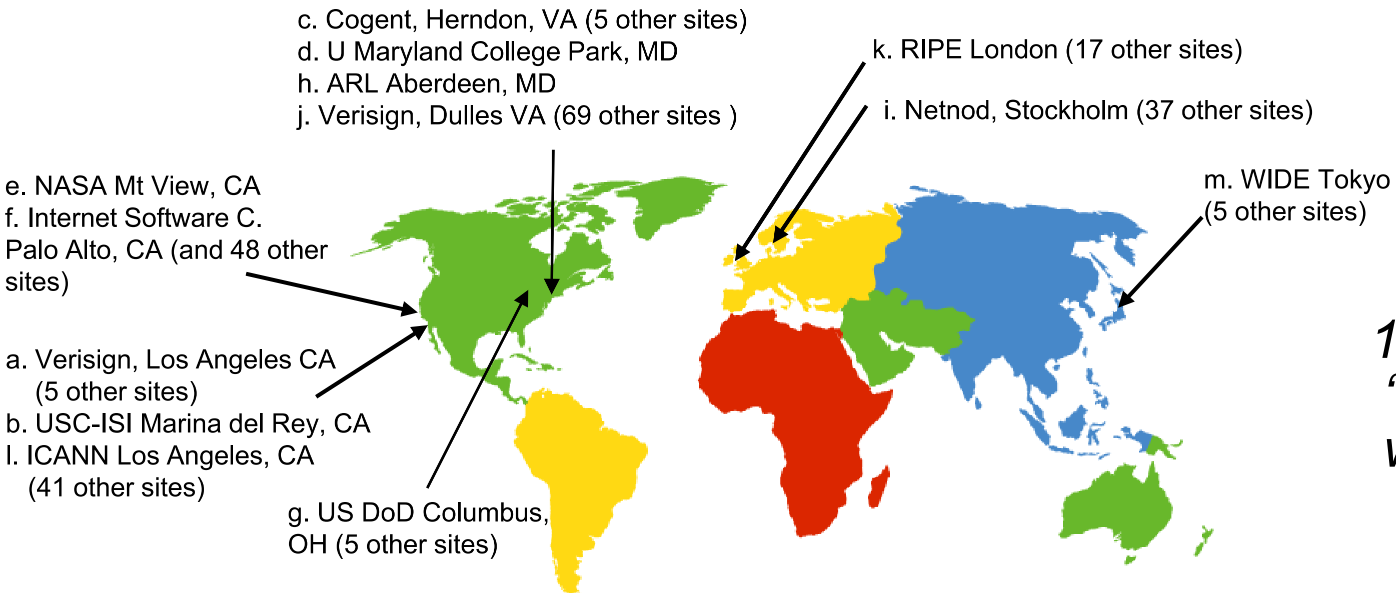


A client wants IP address for www.facebook.com:

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

Root Servers

- Answers requests for records in the root zone by returning a list of the authoritative name servers for the appropriate top-level domain (TLD).



13 root name "servers" worldwide

TLD and Authoritative Servers

Top-level domain (TLD) servers:

- responsible for com, org, net, edu, … and all top-level country domains, e.g., uk, sg, jp

Authoritative servers:

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

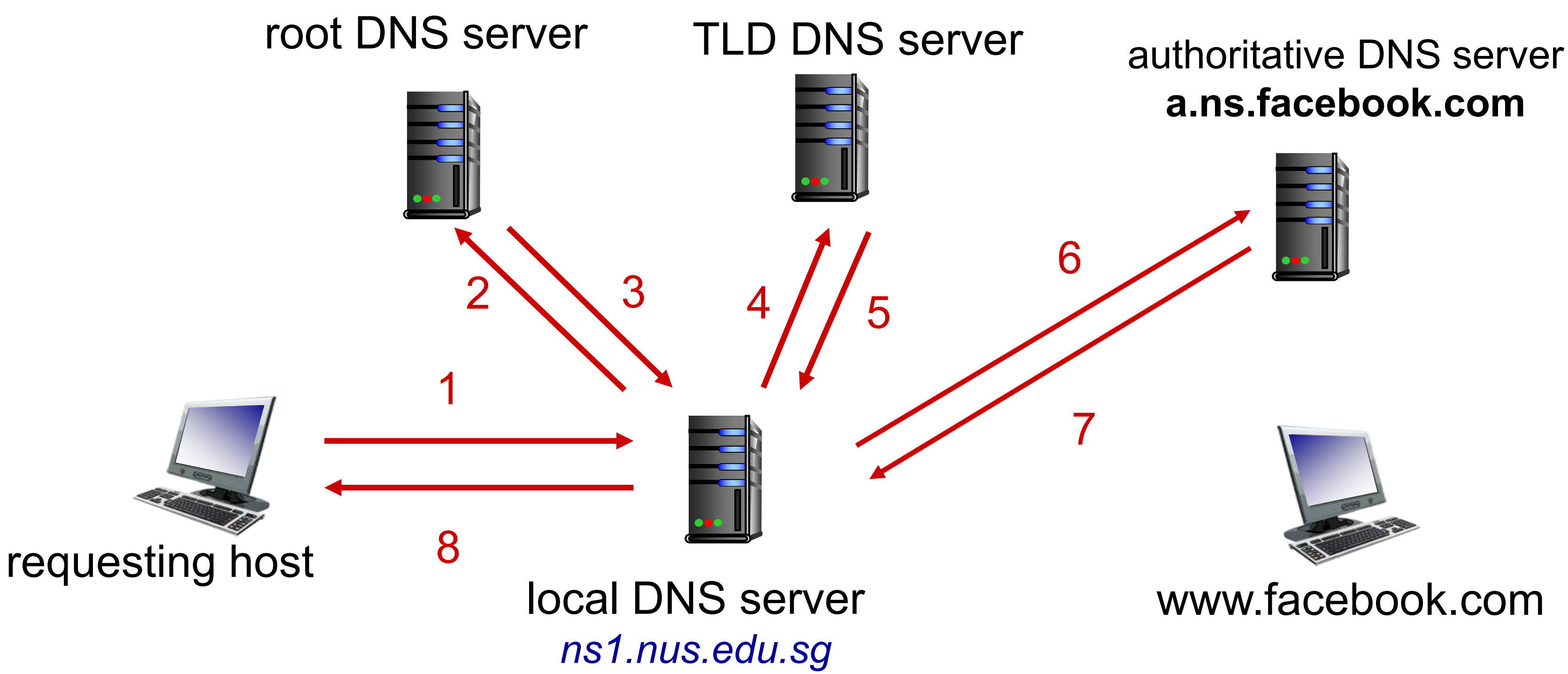
Local DNS Server

- Does not strictly belong to hierarchy
- Each ISP (residential ISP, company, university) has one local DNS server.
  - also called “default name server”
- When host makes a DNS query, query is sent to its local DNS server
  - Retrieve name-to-address translation from local cache
  - Local DNS server acts as proxy and forwards query into hierarchy if answer is not found locally

DNS Caching

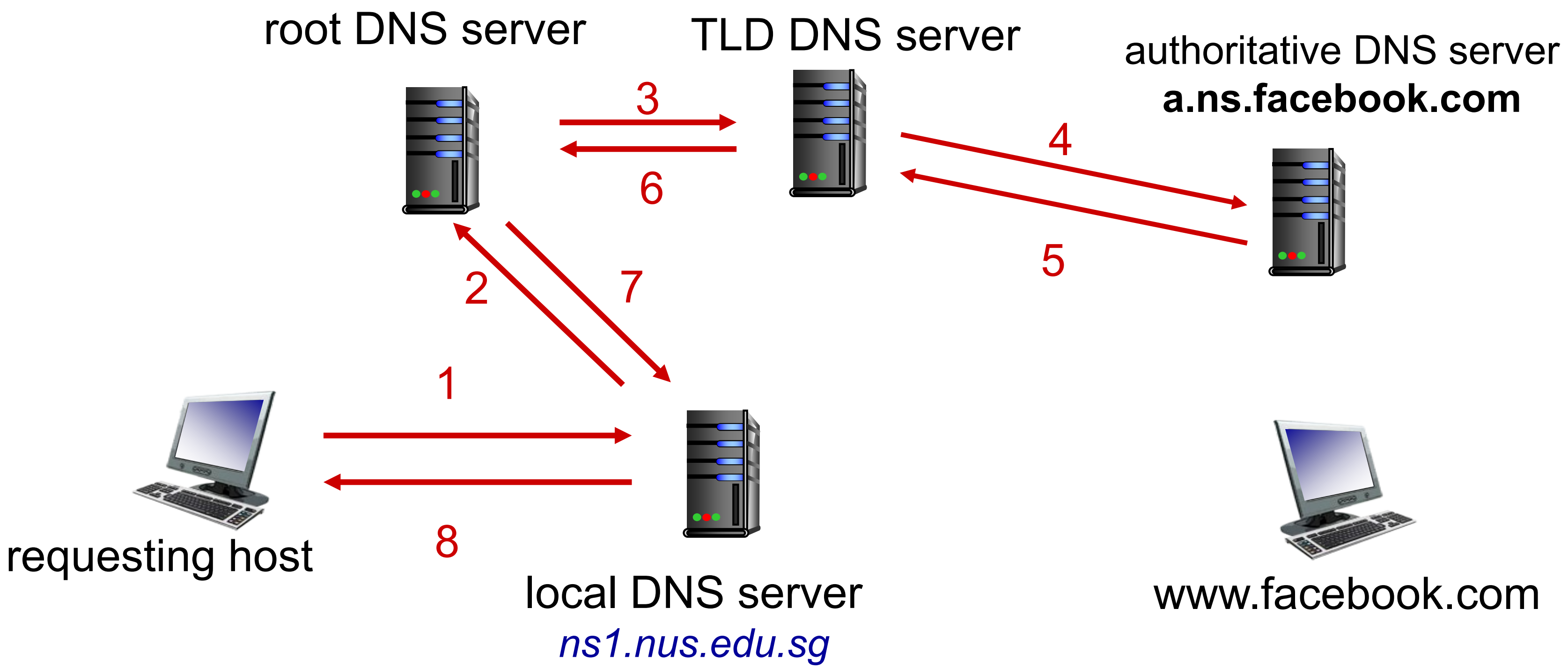
- Once a name server learns mapping, it *caches* mapping.
  - cached entries may be out-of-date (best effort name-to-address translation!)
  - cached entries expire after some time (TTL).
  - if name host changes IP address, may not be known Internet-wide until all TTLs expire.
- Update/notify mechanisms proposed IETF standard
  - RFC 2136
- DNS runs over **UDP**.

DNS Name Resolution



- This is known as *iterative query*.

DNS Name Resolution



- This is known as ***recursive query***.
  - rarely used in practice

Lectures 2&3: Roadmap

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2.7 Socket programming: Creating Network Applications

Processes

- Process: program running within a host.
  - Within the same host, two processes communicate using inter-process communication (defined by OS).
  - Processes in different hosts communicate by exchanging messages (according to protocols).

In C/S model

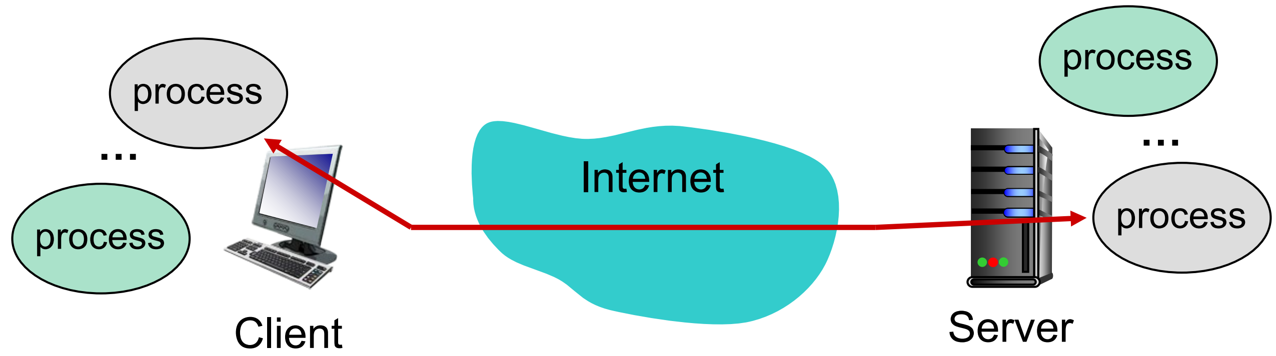
server process waits to be contacted

client process initiates the communication

Addressing Processes

- IP address is used to identify a host
  - A 32-bit integer (e.g. 137.132.21.27)
- Question: is IP address of a host suffice to identify a process running inside that host?

A: no, many processes may run concurrently in a host.



Addressing Processes

- A process is identified by (IP address, port number).
  - Port number is 16-bit integer (1-1023 are reserved for standard use).
- Example port numbers
  - HTTP server: 80
  - SMTP server: 25
- IANA coordinates the assignment of port number:
  - http://www.iana.org/assignments/service-names-port-numbers/service-names-port-numbers.xhtml

Analogy

Postal service:

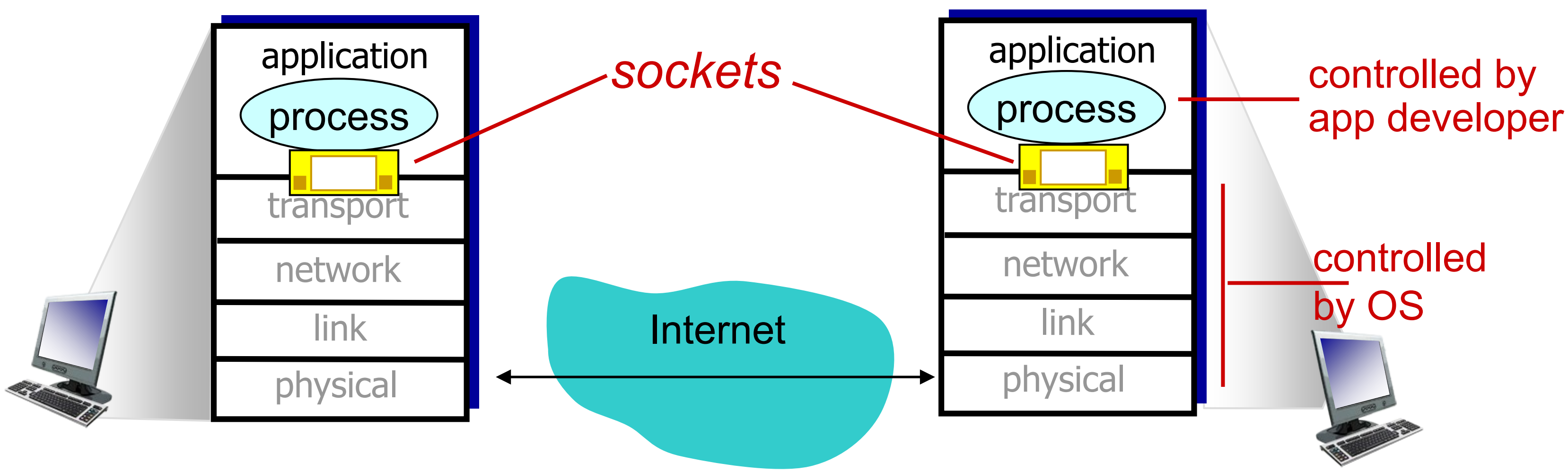
- *deliver letter to the doorstep:* home address
- *dispatch letter to the right person in the house:* name of the receiver as stated on the letter

Protocol service:

- *deliver packet to the right host:* IP address of the host
- *dispatch packet to the right process in the host:* port number of the process

Sockets

- Socket is the software interface between app processes and transport layer protocols.
  - Process sends/receives messages to/from its socket.
  - Programming-wise: a set of APIs



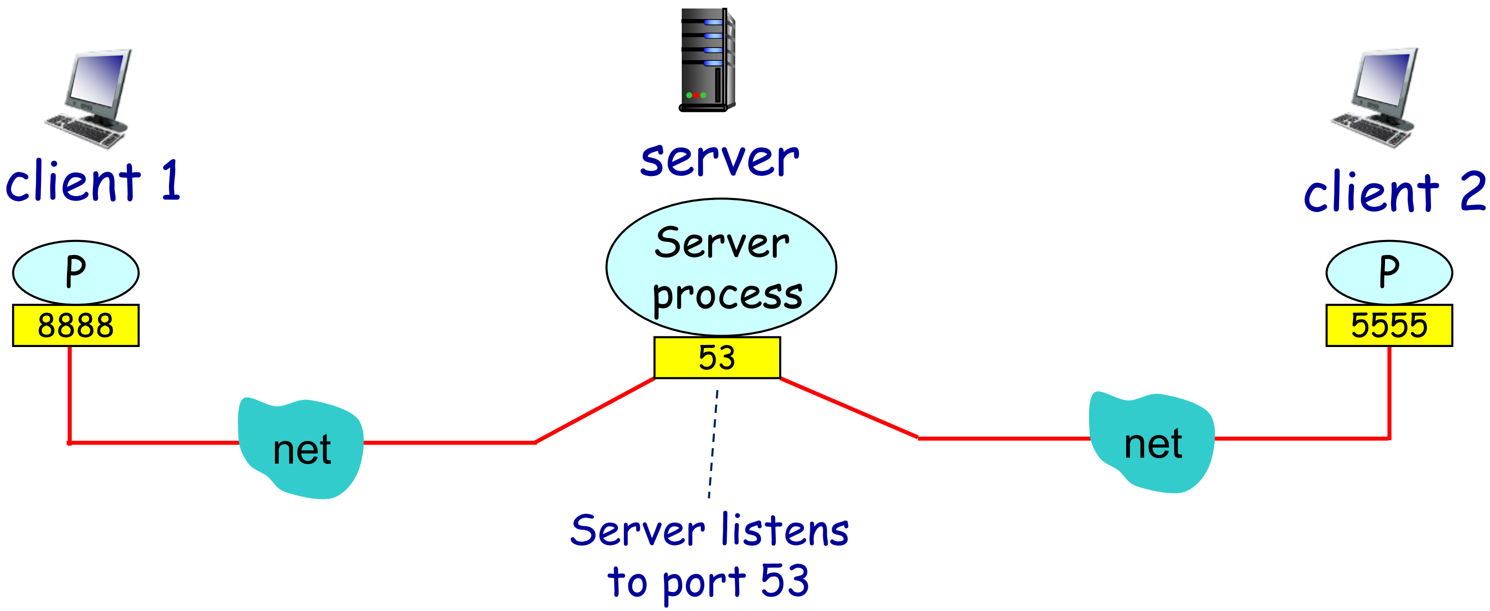
Socket Programming

- Applications (or processes) treat the Internet as a black box, sending and receiving messages through sockets.
- Two types of sockets
  - TCP: reliable, byte stream-oriented socket
  - UDP: unreliable datagram socket
- Now let's write a simple client/server application that client sends a line of text to server, and server echoes it.
  - We will demo both TCP socket version and UDP socket version.

Socket Programming with *UDP*

UDP: no "connection" between client and server

- Sender (client) explicitly attaches destination IP address and port number to each packet.
- Receiver (server) extracts sender IP address and port number from the received packet.



UDP: Client/server Socket Interaction

work flow

Server (running on **`serverIP`**)

create **`serverSocket`**, port = **`x`**:

read datagram from **`serverSocket`**

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

Client

create **`clientSocket`**

create packet with **`serverIP`** and port = **`x`**; send packet via **`clientSocket`**

read datagram from **`clientSocket`**

close **`clientSocket`**

Example: UDP Echo Server

code for udp echo

```
from socket import *        ← include Python's socket library

serverPort = 2105
                                     IPv4              UDP socket
# create a socket
serverSocket = socket(AF_INET, SOCK_DGRAM)

# bind socket to local port number 2105
serverSocket.bind(('', serverPort))
print('Server is ready to receive message')      receive datagram
                                                  buffer size: 2048B
# extract client address from received packet
message, clientAddress = serverSocket.recvfrom(2048)

serverSocket.sendto(message, clientAddress)

serverSocket.close()
```

Example: UDP Echo Client

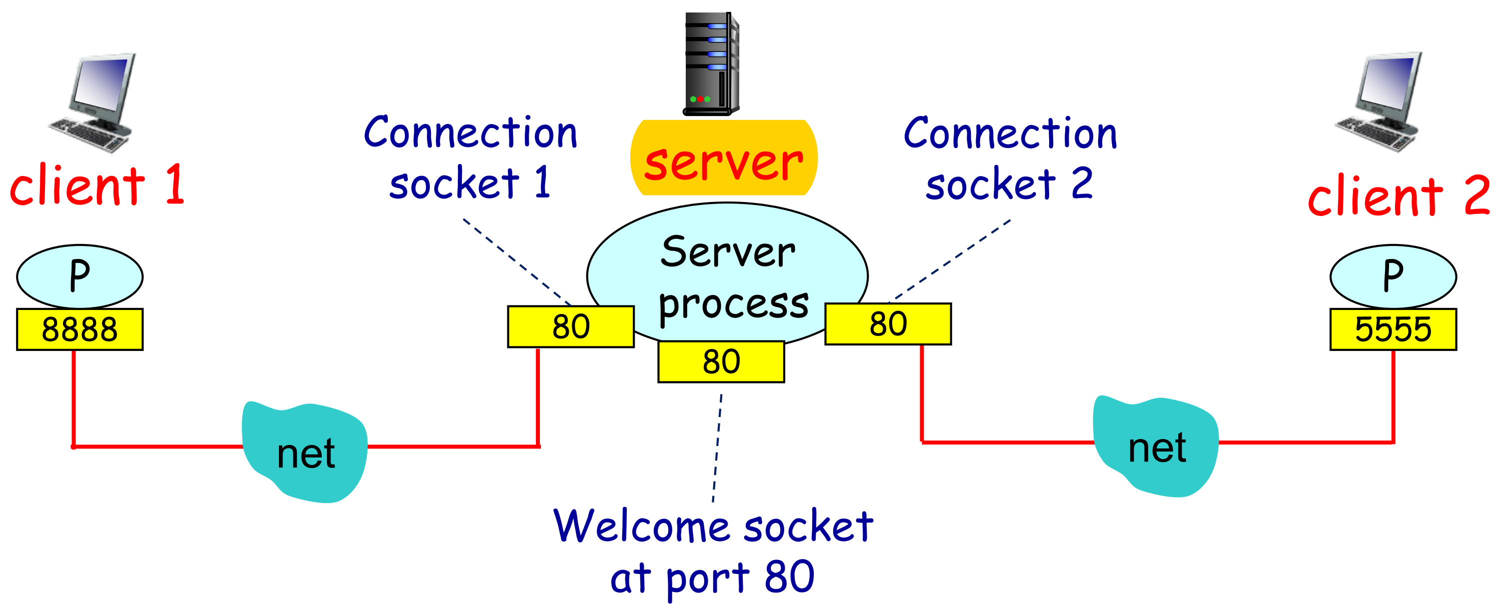
```
from socket import *

serverName = 'localhost' # client, server on the same host
serverPort = 2105

clientSocket = socket(AF_INET, SOCK_DGRAM)

message = input('Enter a message: ')

# send msg to server address
clientSocket.sendto(message.encode(), (serverName, serverPort))

receivedMsg, serverAddress = clientSocket.recvfrom(2048)

print('from server:', receivedMsg.decode())

clientSocket.close()
```

convert message from string to bytes and send it

convert from bytes to string

Socket Programming with *TCP*

- When client creates socket, client TCP establishes a connection to server TCP.
- When contacted by client, server TCP creates a new socket for server process to communicate with that client.
  - allows server to talk with multiple clients individually.



TCP: Client/server Socket Interaction

Server (running on **serverIP**)

create **serverSocket**, port = **x**

wait for incoming connection request **connectionSocket**

read request from **connectionSocket**

write reply to **connectionSocket**

close **connectionSocket**

TCP connection setup

Client

create **clientSocket**, connect to **serverIP**, port = **x**

send request using **clientSocket**

read reply from **clientSocket**

close **clientSocket**

Example: TCP Echo Server

```
from socket import *

serverPort = 2105

serverSocket = socket(AF_INET, SOCK_STREAM)

serverSocket.bind(('', serverPort))

serverSocket.listen()
print('Server is ready to receive message')

connectionSocket, clientAddr = serverSocket.accept()
message = connectionSocket.recv(2048)

connectionSocket.send(message)

connectionSocket.close()
```

TCP socket

listens for incoming TCP request (not available in UDP socket)

returns a *new* socket to communicate with client socket

no need to specify the receiver here, since the connectionSocket is specific for this client

Example: TCP Echo Client

```
from socket import *

serverName = 'localhost'
serverPort = 2105

clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName, serverPort))

message = input('Enter a message: ')

clientSocket.send(message.encode())

receivedMsg = clientSocket.recv(2048)

print('from server:', receivedMsg.decode())

clientSocket.close()
```

establish a connection

no need to attach server name, port

TCP Socket vs. UDP Socket

- In TCP, two processes communicate as if there is a pipe between them. The pipe remains in place until one of the two processes closes it.
  - When one of the processes wants to send more bytes to the other process, it simply writes data to that pipe.
  - The sending process doesn't need to attach a destination IP address and port number to the bytes in each sending attempt as the logical pipe has been established (which is also reliable).
- In UDP, programmers need to form UDP datagram packets explicitly and attach destination IP address / port number to every packet.

Lectures 2&3: Summary

- Application architectures
  - Client-server
  - P2P
- Application service requirements:
  - reliability, throughput, delay, security
- Specific protocols:
  - HTTP
  - DNS
- Internet transport service model
  - connection-oriented, reliable: TCP
  - Connection-less, unreliable: UDP

Lectures 2&3: Summary

- Socket programming
  - TCP socket
    - When contacted by client, server TCP creates new socket.
    - Server uses (client IP + port #) to distinguish clients.
    - When client creates its socket, client TCP establishes connection to server TCP.
  - UDP socket
    - Server uses one socket to serve all clients.
    - No connection is established before sending data.
    - Sender explicitly attaches destination IP address and port # to each packet.
    - Transmitted data may be lost or received out-of-order.