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Computer Networks

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Material with thanks to James F. Kurose, Mosharaf Chowdhury, and other colleagues.

Internet Applications

- Internet Applications Overview
- Domain Name Service (DNS)
- WWW and HTTP

- Electronic Mail
- File Transfer Protocol (FTP)

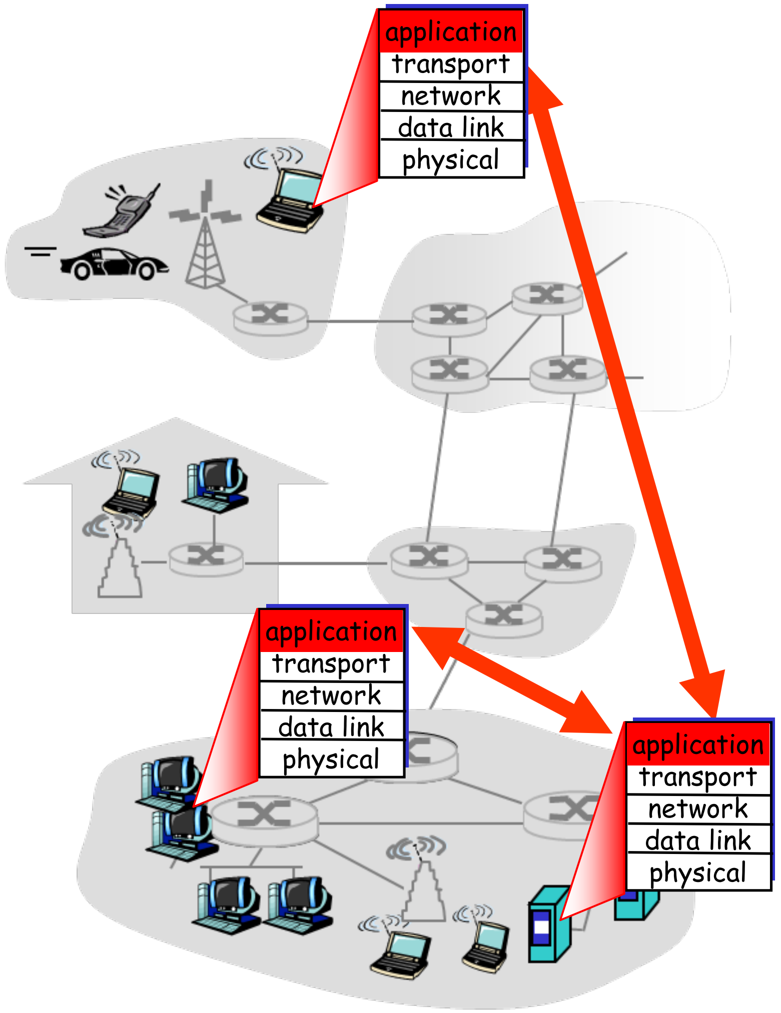
Internet Applications Overview

Application: communicating, distributed processes

- e.g., Email, Web, P2P file sharing, instant messaging
- Running in end systems (hosts)
- Exchange messages to implement application

Application-layer protocols

- One "piece" (agent) of an app
- Define messages exchanged by apps and actions taken
- Use communication services provided by lower layer protocols (TCP, UDP, RTP)



Typical Internet Applications

Application	App-Layer Protocol	Underlying Transport Protocol
Email	SMTP [RFC 2821]	TCP
Remote terminal access	Telnet [RFC 854]	TCP
Web	HTTP [RFC 2616]	TCP
File transfer	FTP [RFC 959]	TCP
Streaming multimedia	Proprietary e.g. RealNetworks	RTP, RTSP TCP or UDP
Internet telephony	Proprietary e.g. Dialpad	SIP on UDP

Jargons of Internet Applications

- Process: program running within a host
  - Within same host, 2 processes communicate using inter-process communication (defined by *OS*)
  - Processes running in different hosts communicate with an app-layer protocol

- User agent: interfaces with app "above" and network "below"
  - Implements user interface & app-layer protocol, e.g.
  - Web: browser, web server
  - Email: mail reader, mail server
  - Streaming audio/video: media player, media server

App-Layer Protocols

- Types of messages exchanged
  - e.g. request & response messages
- Syntax of message types
  - What fields in messages & how fields are delineated
- Semantics of the fields
  - Meaning of information in fields
- Rules for when and how processes send & respond to messages

Application Architectures

possible structure of applications:

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

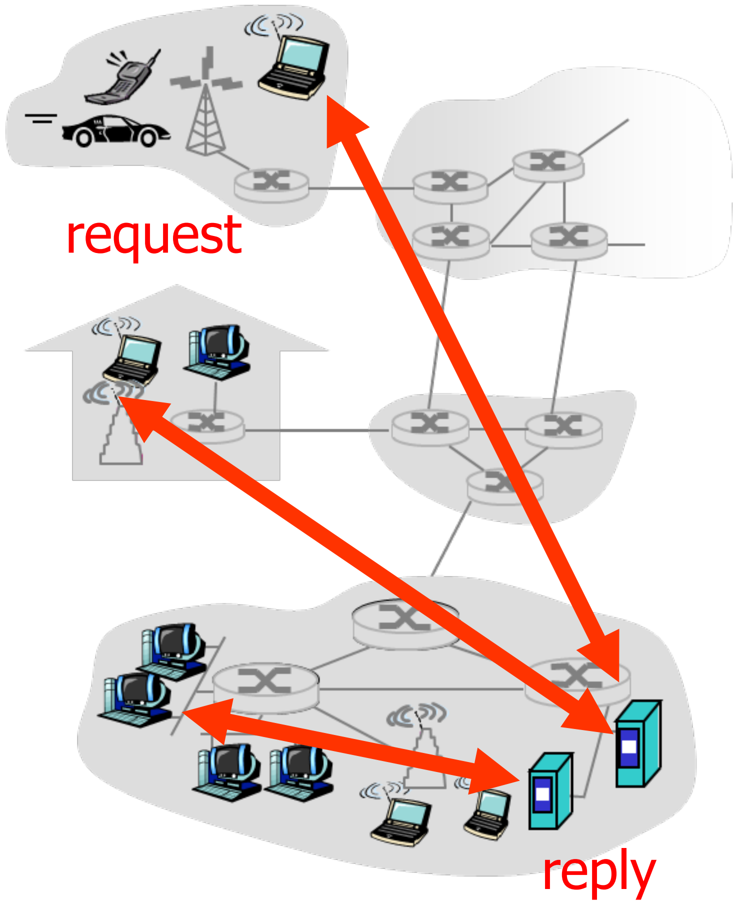
Client-Server Paradigm

Client:

- Start as required
- Initiates contact with server, "speaks first"
- Host may have dynamic IP addresses
- e.g. Web: client implemented in browser; Email: in mail reader

Server:

- Run as daemon (always-on)
- Provides requested service to Client
- Host has permanent IP address
- e.g. Web server sends requested Web page, mail server delivers Email

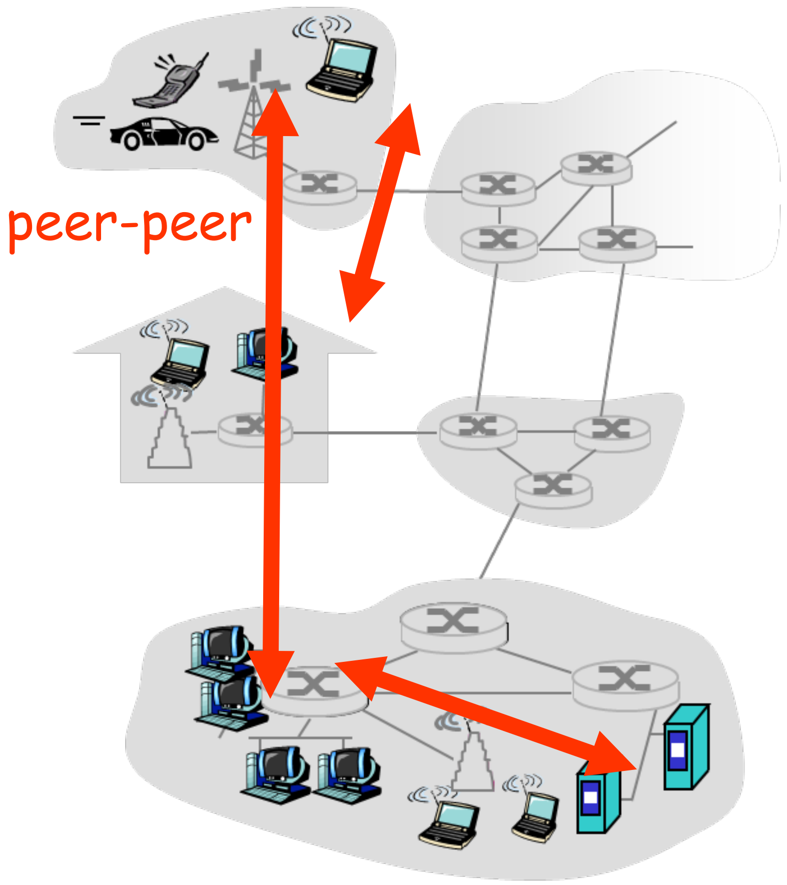


Peer-to-Peer Paradigm

- 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
  - Highly scalable but difficult to manage
- Examples: Gnutella, BitTorrent, Skype



Client-Server and P2P

Skype

- Voice-over-IP P2P application
- Centralized server: finding address of remote party
- Direct client-client connection

Instant messaging

- Chatting between two users is P2P
- Centralized service: user presence detection/location
- User registers its IP address with central server when it comes online
- User contacts central server to find IP addresses of parties

Typical Applications

- DNS
- Email
- FTP
- Web and HTTP
- CDN
- P2P Applications

Domain Name Service (DNS)

Domain Name Service (DNS)

- Function
  - Map "domain names" into IP addresses
  - e.g. www.baidu.com → 119.75.217.109
- Domain Name System
  - Distributed database implemented in hierarchy of many name servers
  - App-layer protocol host and name servers to communicate to resolve "domain names"
  - Load balancing: set of IP addresses for one server name

Q: why not centralize DNS?

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

A: doesn't scale!

Goals

- Uniqueness: no naming conflicts
- Scalable
  - Many names and frequent updates (secondary)
- Distributed, autonomous administration
  - Ability to update my own (machines') names
  - Don't have to track everybody's updates
- Highly available
- Lookups are fast
- Perfect consistency is a non-goal

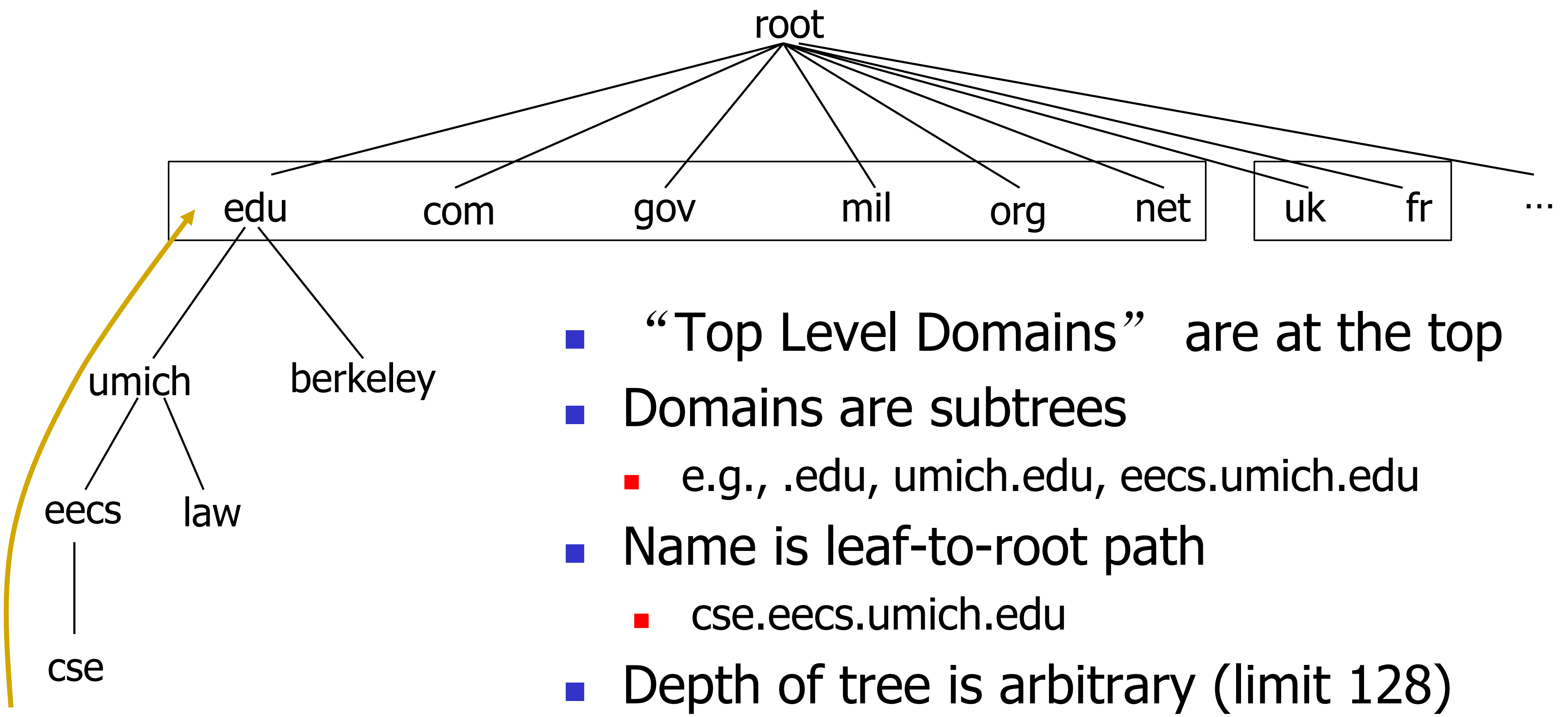
How?

- Partition the namespace
- Distribute administration of each partition
  - Autonomy to update my own (machines') names
  - Don't have to track everybody's updates
- Distribute name resolution for each partition
- How should we partition things?

Key idea: Hierarchy

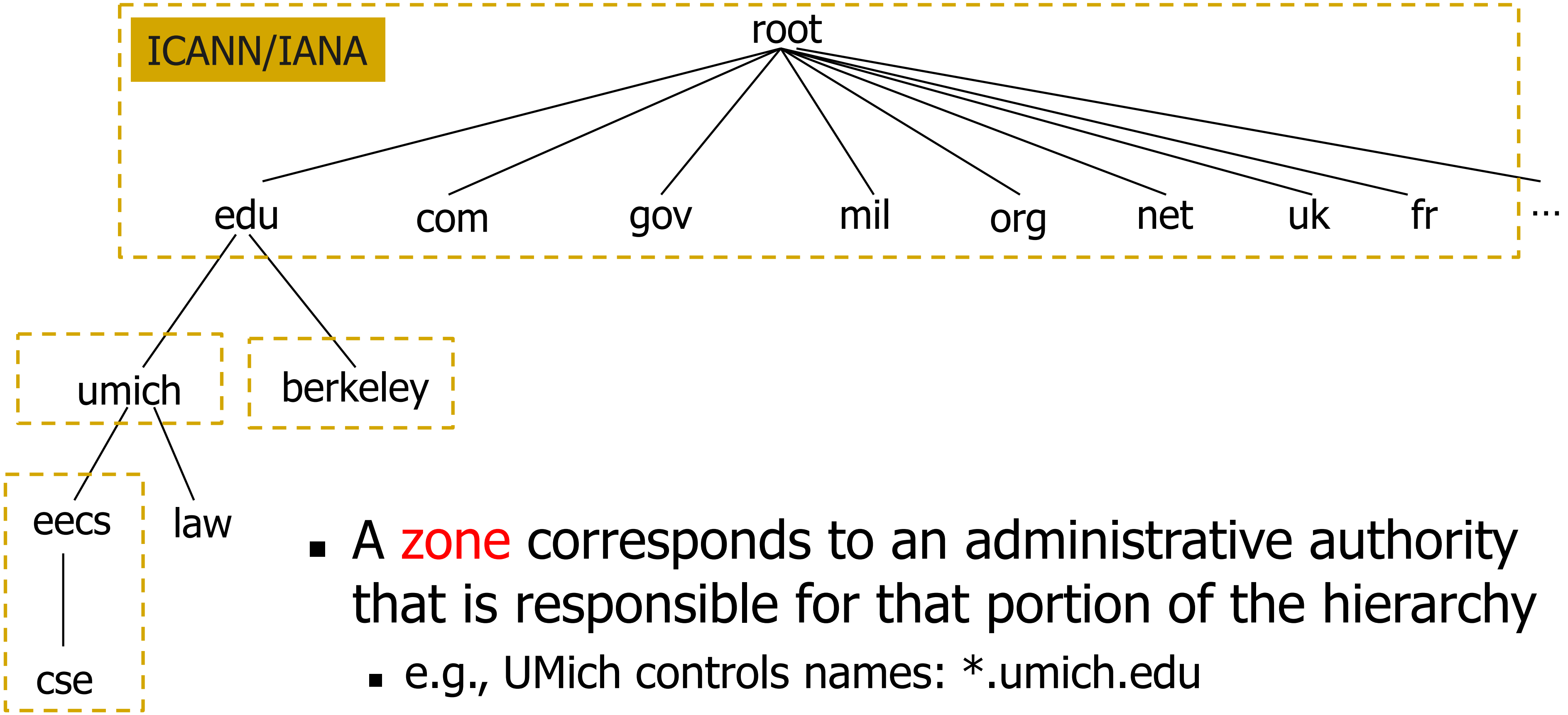
- Three intertwined hierarchies
  - Hierarchical namespace
    - As opposed to original flat namespace
  - Hierarchically administered
    - As opposed to centralized
  - (Distributed) hierarchy of servers
    - As opposed to centralized storage

Hierarchical namespace



- “Top Level Domains” are at the top
- Domains are subtrees
  - e.g., .edu, umich.edu, eecs.umich.edu
- Name is leaf-to-root path
  - cse.eecs.umich.edu
- Depth of tree is arbitrary (limit 128)
- Name collisions trivially avoided
  - Each domain is responsible

Hierarchical administration



- A zone corresponds to an administrative authority that is responsible for that portion of the hierarchy
  - e.g., UMich controls names: *.umich.edu
  - e.g., EECS controls names: *.eecs.umich.edu

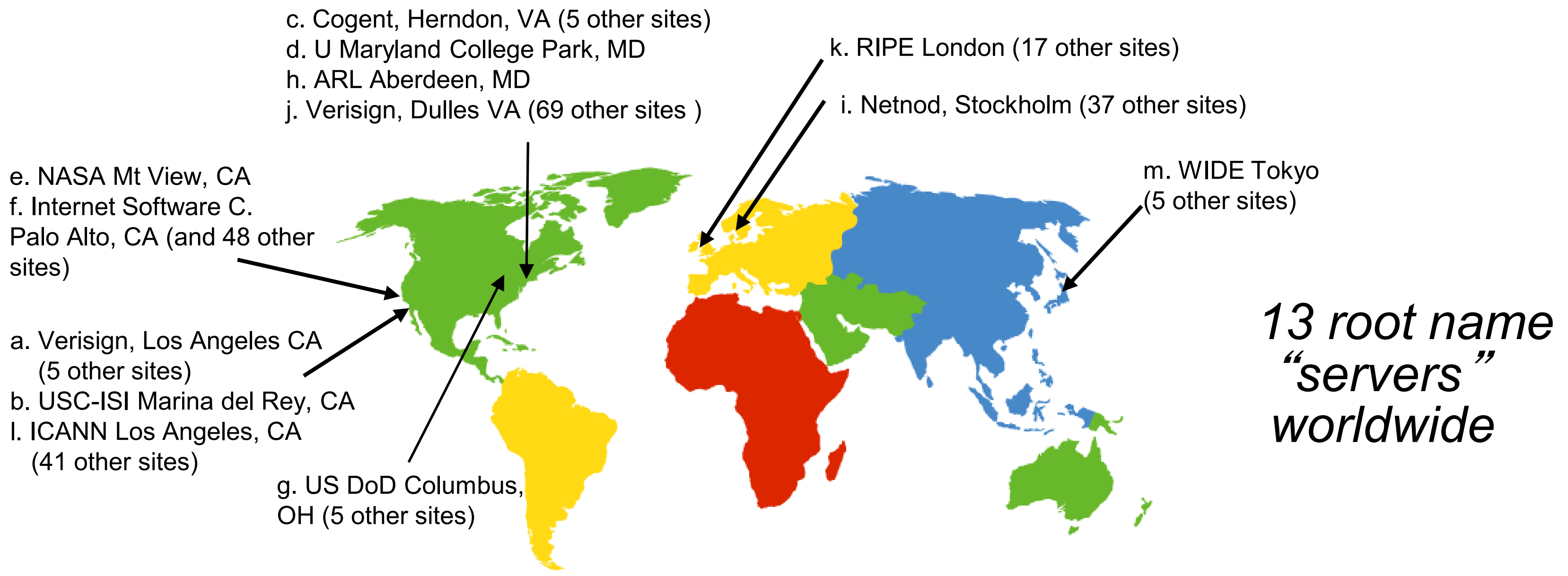
Hierarchy of DNS Servers

- Root name servers
  - Contacted by local name server that can not resolve name
- Top-level domain servers
  - Responsible for com, org, net, edu, etc, and all top-level country domains, e.g. cn, uk, fr
- Authoritative DNS servers
  - Organization's DNS servers, providing authoritative hostname to IP mappings
- Local Name Servers
  - Maintained by each residential ISP, company, university
  - When host makes DNS query, query is sent to its local DNS server

- Each server stores a (small!) subset of the total DNS database
- An authoritative DNS server stores "resource records" for all DNS names in the domain that it has authority for
- Each server needs to know other servers that are responsible for the other portions of the hierarchy
  - Every server knows the root
  - Root server knows about all top-level domains

DNS: root name servers

- root name server:
  - contacts authoritative name server if name mapping not known
  - gets mapping
  - returns mapping to local name server


c. Cogent, Herndon, VA (5 other sites)
d. U Maryland College Park, MD
h. ARL Aberdeen, MD
j. Verisign, Dulles VA (69 other sites)
k. RIPE London (17 other sites)
i. Netnod, Stockholm (37 other sites)
e. NASA Mt View, CA
f. Internet Software C. Palo Alto, CA (and 48 other sites)
m. WIDE Tokyo (5 other sites)
a. Verisign, Los Angeles CA (5 other sites)
b. USC-ISI Marina del Rey, CA
l. ICANN Los Angeles, CA (41 other sites)
g. US DoD Columbus, OH (5 other sites)
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

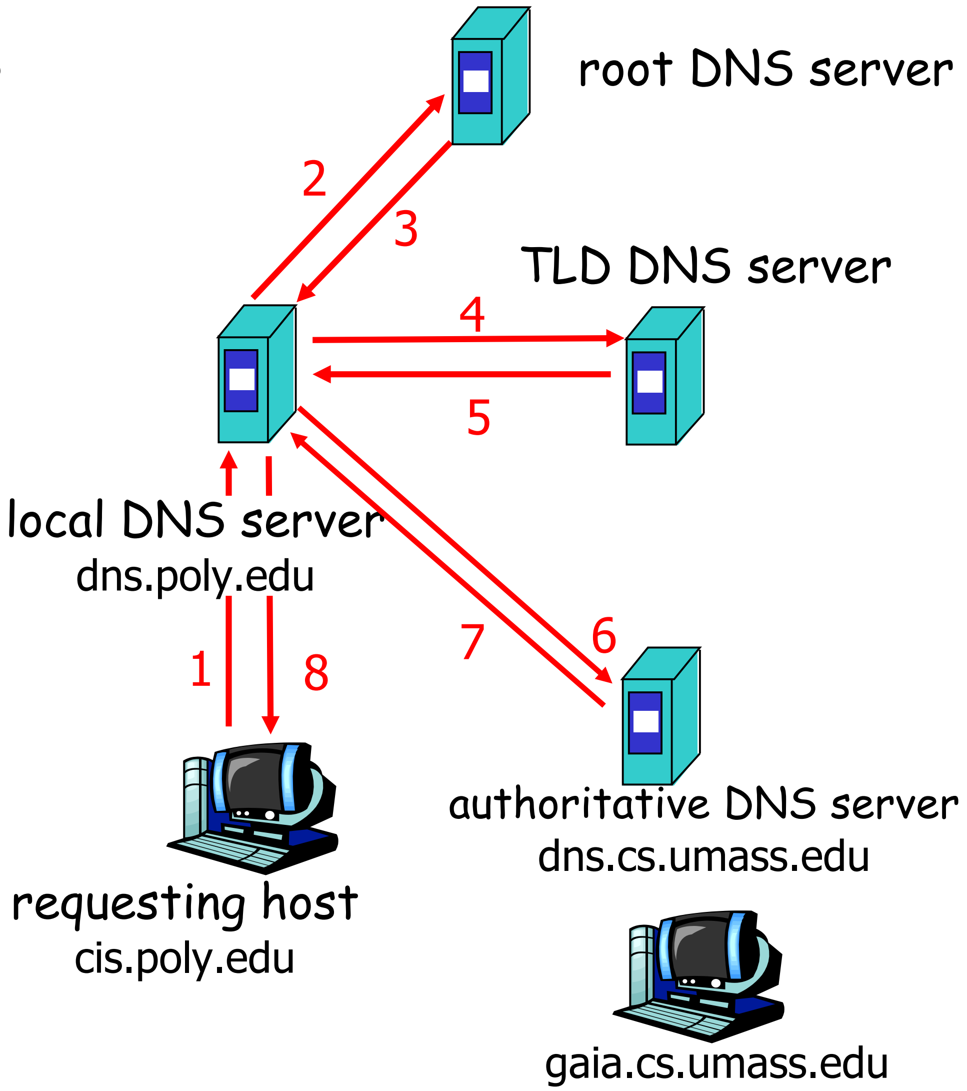
- Does not strictly belong to hierarchy
- Each ISP (residential ISP, company, university) has one
  - also called "default name server"
- When host makes DNS query, query is sent to its local DNS server
  - has local cache of recent name-to-address translation pairs (but may be out of date!)
  - acts as proxy, forwards query into hierarchy

DNS Name Resolution Example

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

- Iterated query:
- Contacted server replies with name of next server to contact

- Host-Server: iterative query
- Server-Server: one-step query



DNS Records

- A DNS resource record (RR)

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

- "Name" is the domain name, "type" denotes how "value" is explained
  - e.g. Name Server records (NS), Mail Exchangers (MX), Host IP Address (A), Canonical name (CNAME)
- Examples
  - (networkutopia.com, dns1.networkutopia.com, NS, 32768)
  - (dns1.networkutopia.com, 212.212.212.1, A, 5600)

DNS protocol

- Query and Reply messages; both with the same message format
  - Header: identifier, flags, etc.
  - Plus resource records
  - See text/section for details
- Client–server interaction on UDP Port 53
  - Spec supports TCP too, but not always implemented

Goals: Are we there yet?

- Uniqueness: No naming conflicts
- Scalable
- Distributed, autonomous administration
- Highly available?

Reliability

- Replicated DNS servers (primary/secondary)
  - Name service available if at least one replica is up
  - Queries can be load-balanced between replicas
- Usually, UDP used for queries
  - Reliability, if needed, must be implemented on UDP
- Try alternate servers on timeout
  - Exponential backoff when retrying same server
- Same identifier for all queries
  - Don’t care which server responds

Goals: Are we there yet?

- Uniqueness: No naming conflicts
- Scalable
- Distributed, autonomous administration
- Highly available
- Fast lookups?

DNS caching

- Performing all these queries takes time
  - Up to 1-second latency before starting download
- Caching can greatly reduce overhead
  - The top-level servers very rarely change
  - Popular sites (e.g., www.cnn.com) visited often
  - Local DNS server often has the information cached
- How DNS caching works
  - DNS servers cache responses to queries
  - Responses include a "time to live" (TTL) field
  - Server deletes cached entry after TTL expires

Attacking DNS

DDoS attacks

- 2002年10月，攻击者利用僵尸网络向13个root服务器发送大量ICMP报文
  - 攻击并未奏效
  - 大部分DNS根服务器执行分组过滤，阻止ICMP报文
  - 很多域名被本地缓存，可以绕过根服务器得到解析
- 更有效的攻击应该向顶级域名服务器发送大量DNS请求（近年来较常见）

Redirect attacks

- Man-in-middle
  - Intercept queries
- DNS poisoning
  - Send bogus relies to DNS server, which caches
  - DNS污染（解决办法：修改host文件）

Exploit DNS for DDoS

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

WWW and HTTP

The Web: History

- 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

蒂姆·伯纳斯-李爵士
Sir Tim Berners-Lee

出生	1955年6月8日（61歲）[1] 英格兰伦敦
机构	万维网联盟 南安普敦大学 Plessey 麻省理工学院
知名于	发明万维网 麻省理工学院计算机科学及人工智能实验室创办主席

2016 Turing Award

The Web: History (cont’d)

- World Wide Web (WWW): a distributed database of “pages” linked through Hypertext Transport Protocol (HTTP)
  - HTTP/1.1 – 1996
    - Performance and security optimizations
  - HTTP/2 – 2015
    - Latency optimizations via request multiplexing over single TCP connection
    - Binary protocol instead of text
    - Server push

Web components

- Infrastructure:
  - Clients
  - Servers (DNS, CDN, Datacenters)
- Content:
  - URL: naming content
  - HTML: formatting content
- Protocol for exchanging information: HTTP

URL – Uniform Resource Locator

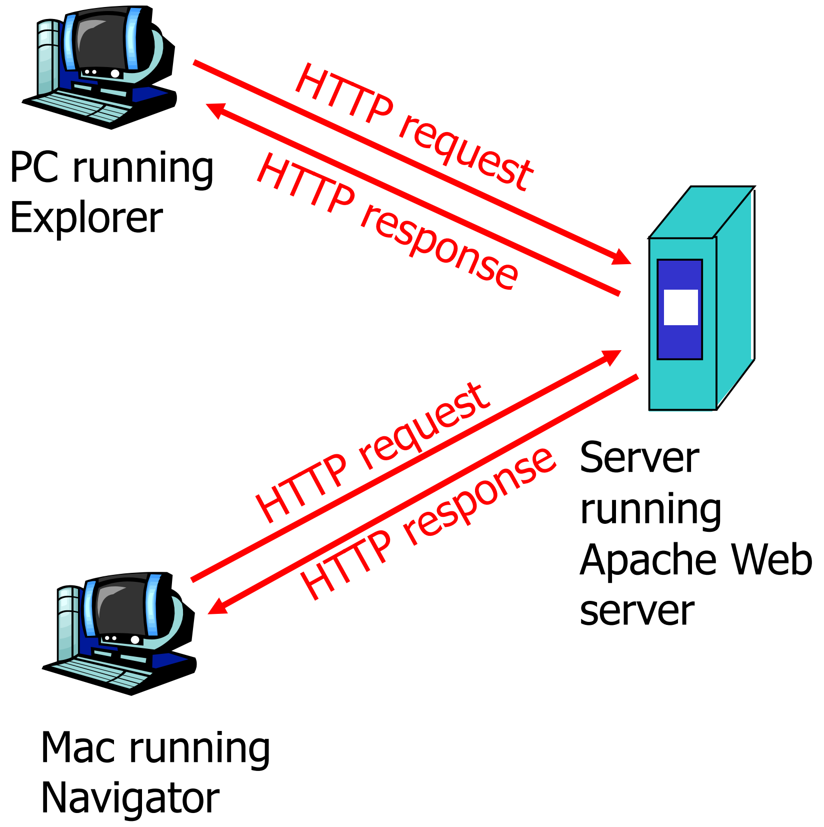
- A unique identifier for an object on WWW
- URL format

  <protocol>://<host>:<port>/<path>?query_string
  - Protocol: method for transmission or interpretation of the object, e.g. http, ftp, Gopher
  - Host: DNS name or IP address of the host where object resides
  - Path: pathname of the file that contains the object
  - Query_string: name/value pairs sent to app on the server
- An example

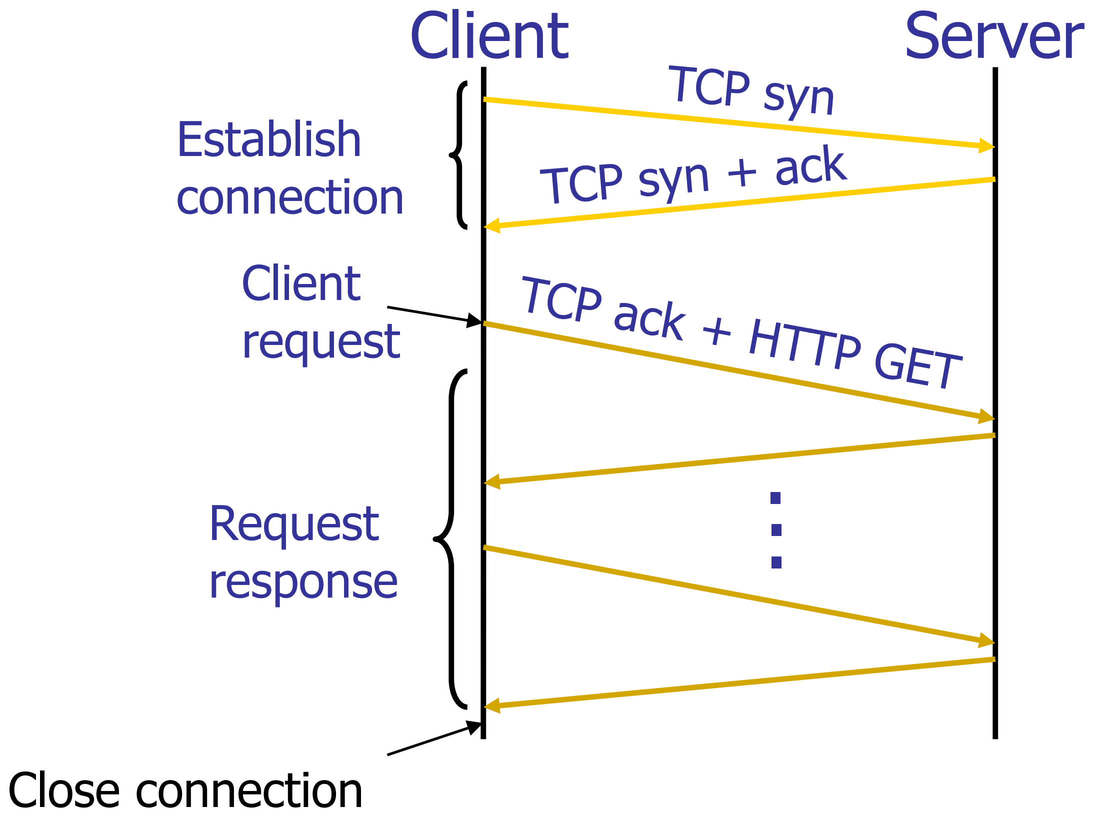
  http://www.nju.edu.cn:8080/somedir/page.htm

Hyper Text Transfer Protocol (HTTP)

- Client-server architecture
  - Server is "always on" and "well known"
  - Clients initiate contact to server
- Synchronous request/reply protocol
  - Runs over TCP, Port 80
- Stateless
- ASCII format
  - Before HTTP/2



Steps in HTTP request/response

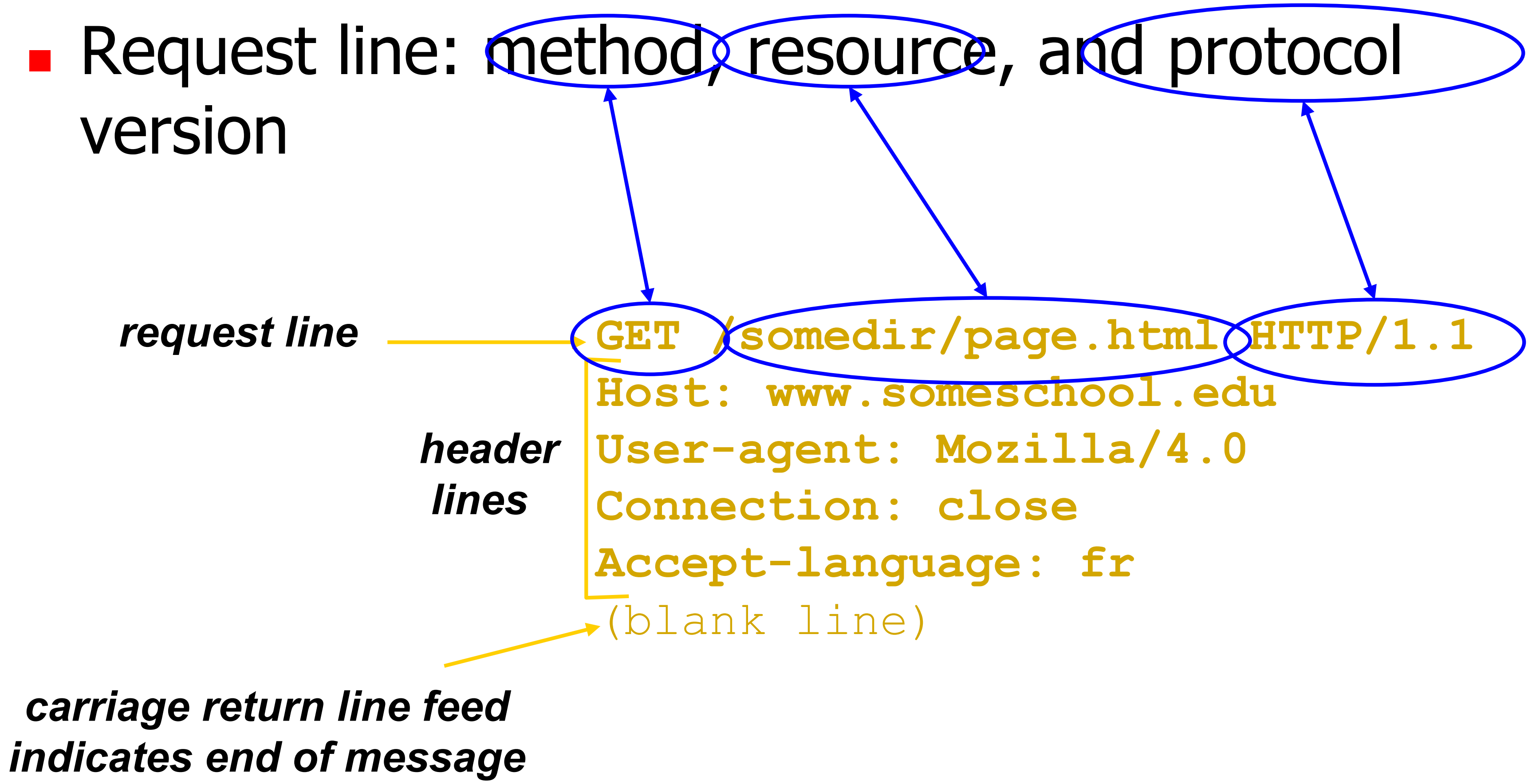


Method types (HTTP 1.1)

- GET, HEAD
- POST
  - Send information (e.g., web forms)
- PUT
  - Uploads file in entity body to path specified in URL field
- DELETE
  - Deletes file specified in the URL field

Client-to-server communication

- HTTP Request Message
  - Request line: method, resource, and protocol version



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

Server-to-client communication

- HTTP Response Message
  - Status line: protocol version, status code, status phrase
  - Response headers: provide information
  - Body: optional data

status line
(protocol, status code, status phrase)

header lines

data
e.g., requested HTML file

```
HTTP/1.1 200 OK
Connection close
Date: Thu, 06 Jan 2017 12:00:15 GMT
Server: Apache/1.3.0 (Unix)
Last-Modified: Mon, 22 Jun 2006 ...
Content-Length: 6821
Content-Type: text/html
(blank line)
data data data data data ...
```

HTTP is stateless

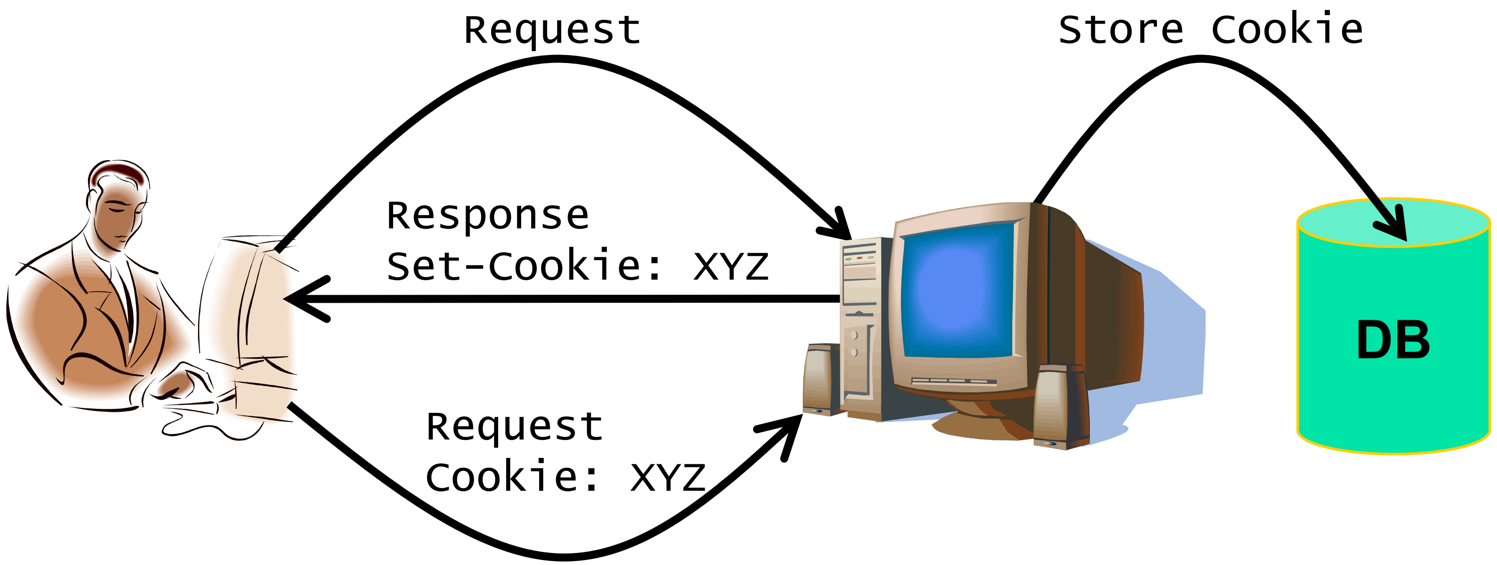
- Each request-response treated independently
  - Servers not required to retain state
- Good: Improves scalability on the server-side
  - Failure handling is easier
  - Can handle higher rate of requests
  - Order of requests doesn’t matter
- Bad: Some applications need persistent state
  - Need to uniquely identify user or store temporary info
  - e.g., Shopping cart, user profiles, usage tracking, …

Question

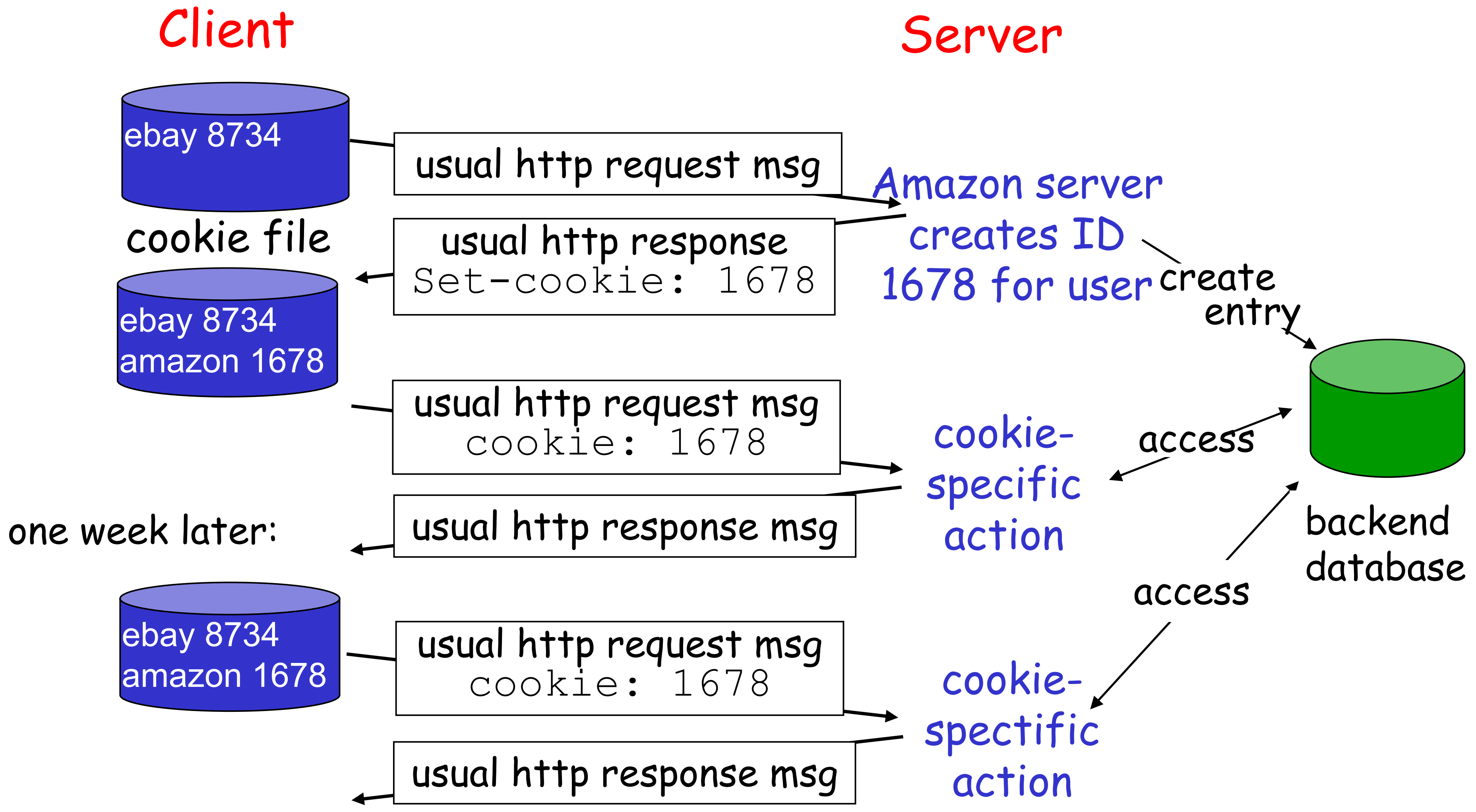
- How does a stateless protocol keep state?

State in a stateless protocol: Cookies

- Client-side state maintenance
  - Client stores small state on behalf of server
  - Client sends state in future requests to the server
- Can provide authentication



A Cookies Example



Application of Cookies

What cookies can bring

- Authorization
- Shopping carts
- Recommendations
- User session state (Web Email)

aside

Cookies and privacy

- Cookies permit servers to learn a lot about user
- User may supply name and Email to servers
- Search engines may use cookies to obtain info across sites
- Hacked browser may do bad things with cookies

Performance goals

- User
  - Fast downloads (not identical to low-latency communication!)
  - High availability
- Content provider
  - Happy users (hence, above)
  - Cost-effective infrastructure
- Network (secondary)
  - Avoid overload

Solutions?

- User
  - Fast downloads (not ~~...~~atency communication!)
  - High availability
- Content provider
  - Happy users (hence, above)
  - Cost-effective infrastructure
- Network (secondary)
  - Avoid overload

Improve networking protocols including HTTP, TCP, etc.

Solutions?

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Improve networking protocols including HTTP, TCP, etc.

Caching and replication

Solutions?

- User
  - Fast downloads (not atency communication!)
  - High availability
- Content provider
  - Happy users (hence, above)
  - Cost-effective infrastructure
- Network (secondary)
  - Avoid overload

Improve networking protocols including HTTP, TCP, etc.

Caching and replication

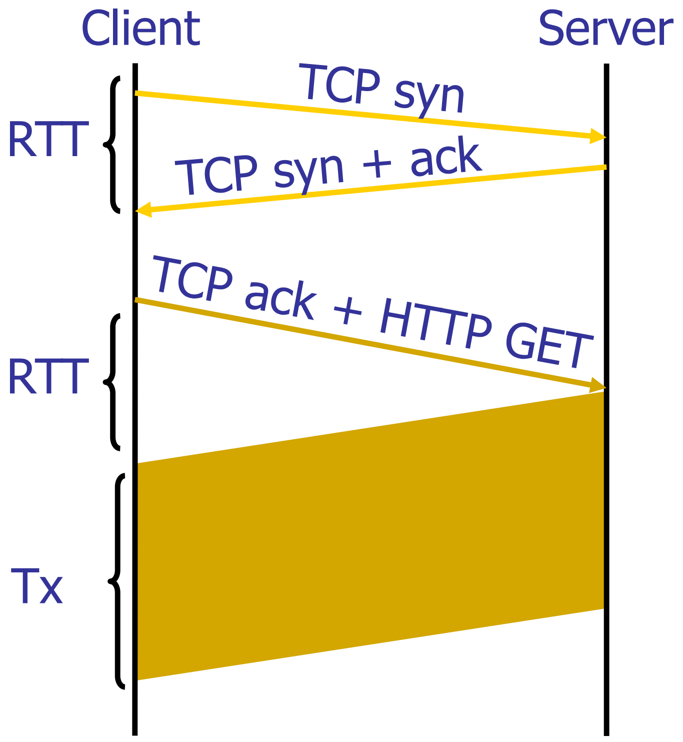
Exploit economies of scale; e.g., webhosting, CDNs, datacenters

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!

Object request response time

- RTT (round-trip time)
  - Time for a small packet to travel from client to server and back
- Response time
  - 1 RTT for TCP setup
  - 1 RTT for HTTP request and first few bytes
  - Transmission time
  - Total = 2RTT + Transmission Time

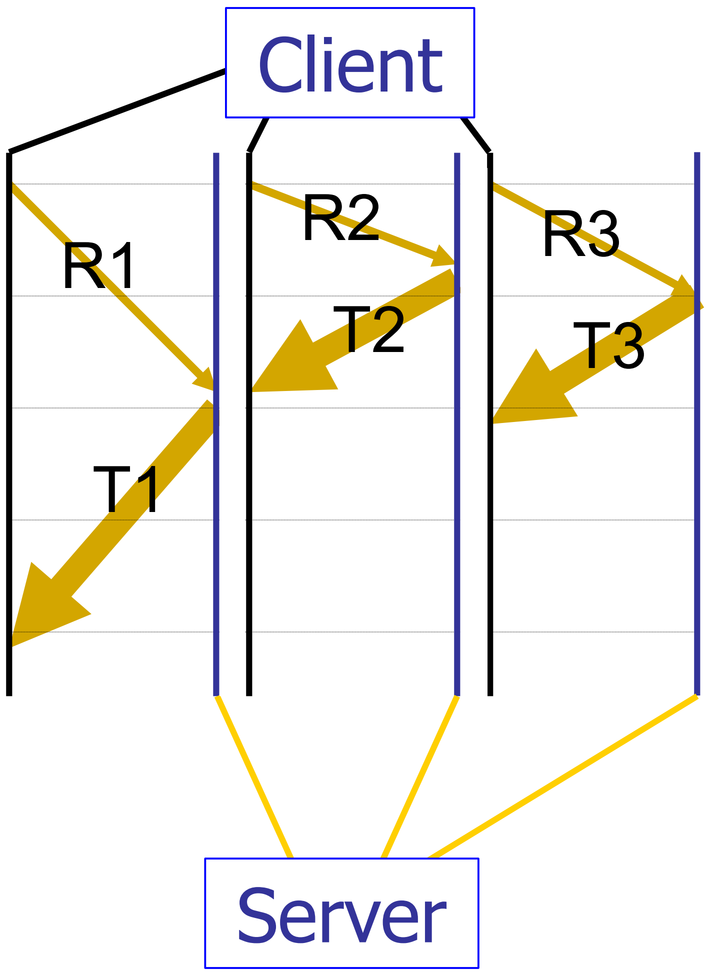


Non-persistent connections

- Default in HTTP/1.0
- 2RTT+△ for each object in the HTML file!
    - One more 2RTT+△ for the HTML file itself
- Doing the same thing over and over again
    - Inefficient

Concurrent requests and responses

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



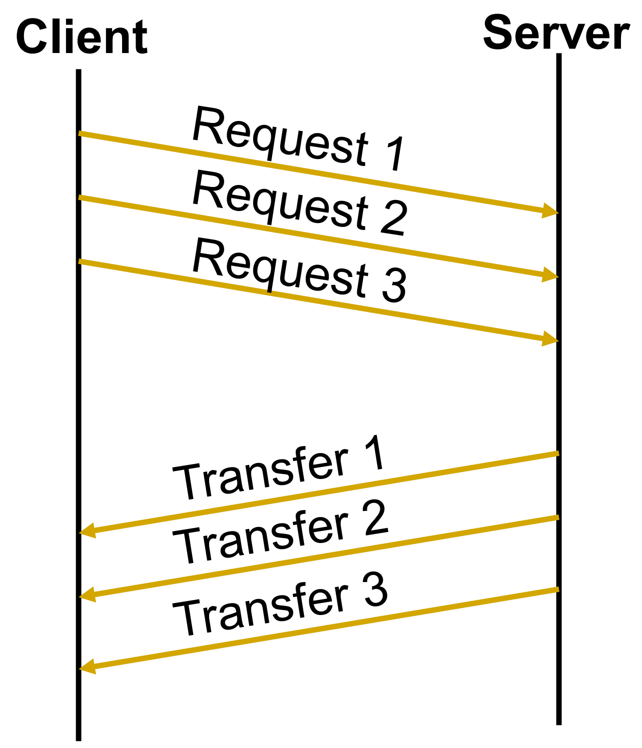
- Client = ☺
- Content provider = ☺
- Network = ☹ Why?

Persistent connections

- Maintain TCP connection across multiple requests
  - Including transfers subsequent to current page
  - Client or server can tear down connection
- Advantages
  - Avoid overhead of connection set-up and tear-down
  - Allow underlying layers (e.g., TCP) to learn about RTT and bandwidth characteristics
- Default in HTTP/1.1

Pipelined requests & responses

- Batch requests and responses to reduce the number of packets
- Multiple requests can be contained in one TCP segment



Scorecard: Getting n small objects

- Time dominated by latency

- One-at-a-time: ~2n RTT
- m concurrent: ~2[n/m] RTT
- Persistent: ~ (n+1)RTT
- Pipelined: ~2 RTT
- Pipelined/Persistent: ~2 RTT first time, RTT later

Scorecard: Getting n large objects each of size F

- Time dominated by bandwidth

- One-at-a-time: ~ nF/B
- m concurrent: ~ [n/m] F/B
  - Assuming shared with large population of users and each TCP connection gets the same bandwidth
- Pipelined and/or persistent: ~ nF/B
  - The only thing that helps is getting more bandwidth

Caching

- Why does caching work?
  - Exploits locality of reference
- How well does caching work?
  - Very well, up to a limit
  - Large overlap in content
  - But many unique requests
    - A universal story!
    - Effectiveness of caching grows logarithmically with size

Caching: How

- Modifier to GET requests:
  - `If-modified-since` – returns "not modified" if resource not modified since specified time

```
GET /somedir/page.html HTTP/1.1
Host: www.someschool.edu
User-agent: Mozilla/4.0
If-modified-since: Wed, 18 Jan 2017 10:25:50 GMT
(blank line)
```

Caching: How

- Modifier to GET requests:
  - `If-modified-since` – returns "not modified" if resource not modified since specified time
- Client specifies "`if-modified-since`" time in request
- Server compares this against "last modified" time of resource
- Server returns "Not Modified" if resource has not changed
- …. or a "OK" with the latest version otherwise

Caching: How

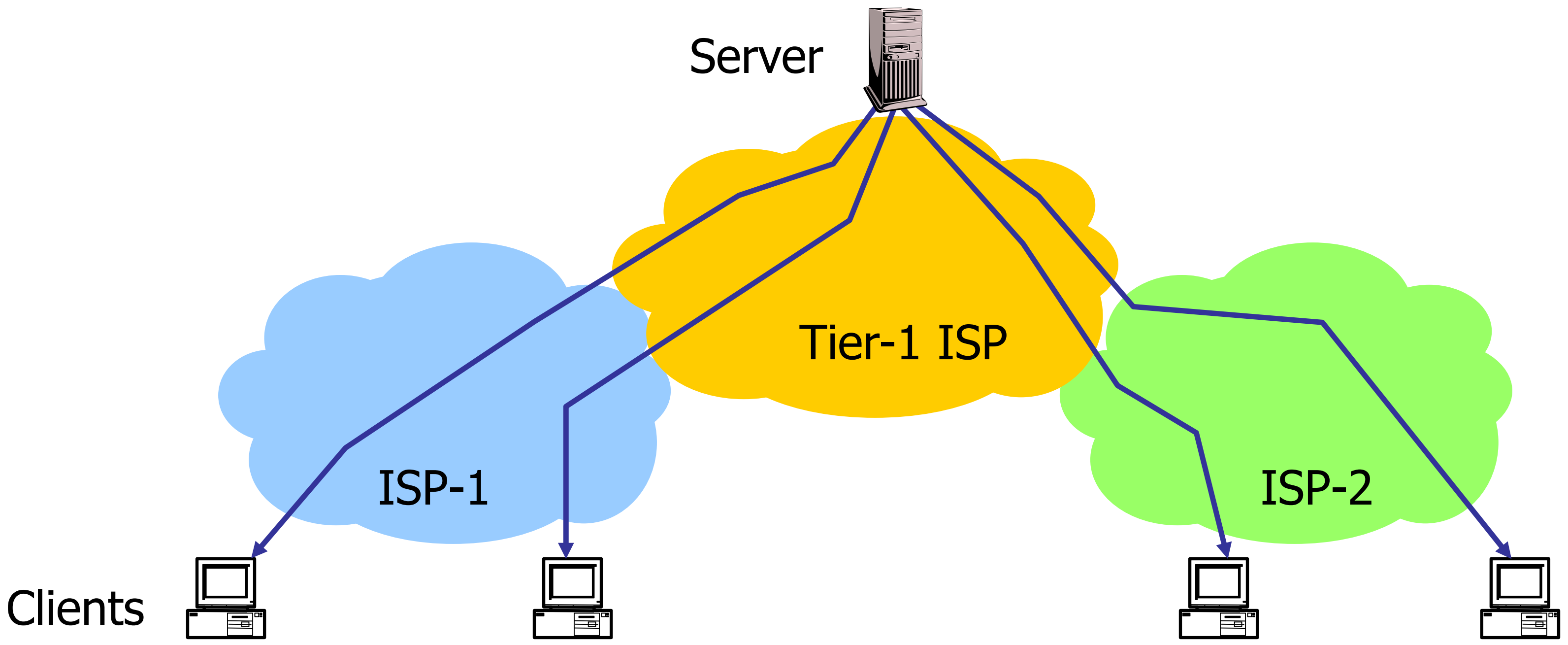
- Modifier to GET requests:
  - `If-modified-since` – returns "not modified" if resource not modified since specified time
- Response header:
  - `Expires` – how long it's safe to cache the resource
  - `No-cache` – ignore all caches; always get resource directly from server

Caching: Where?

- Options
  - Client (browser)
  - Forward proxies
  - Reverse proxies
  - Content Distribution Network

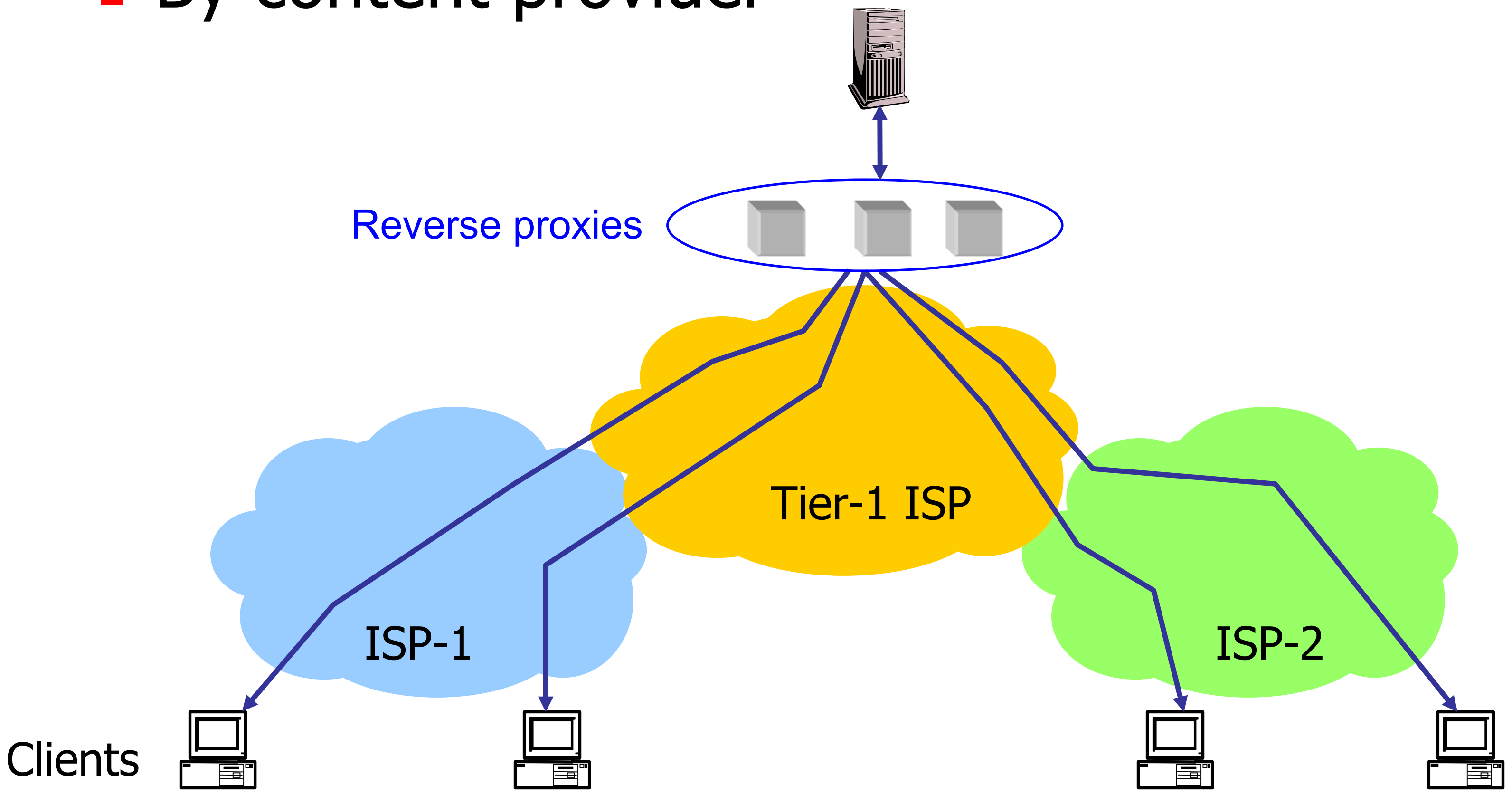
Caching: Where?

- Many clients transfer same information
  - Generate unnecessary server and network load
  - Clients experience unnecessary latency



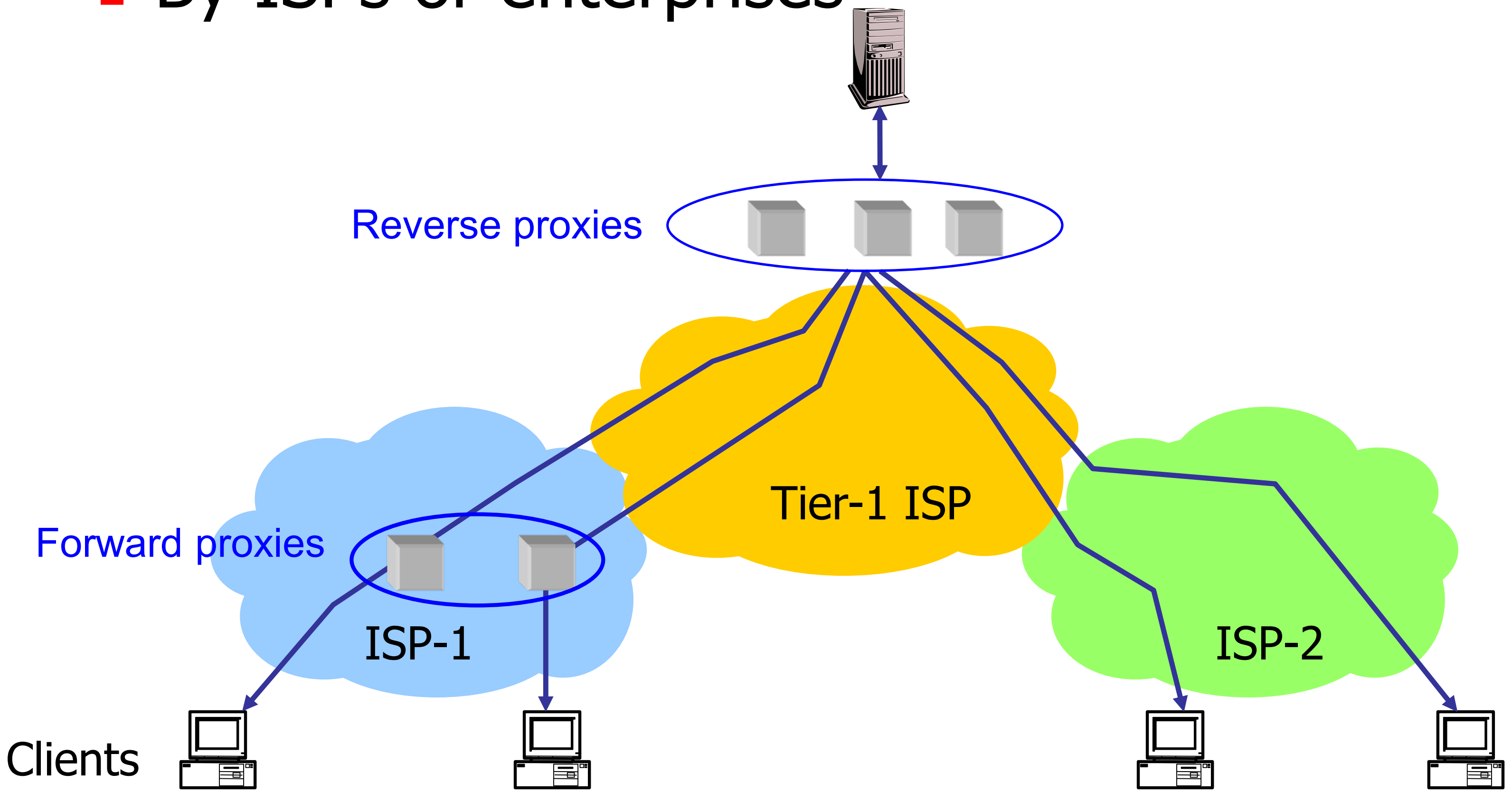
Caching with Reverse Proxies

- Cache documents close to server
  - Decrease server load
  - By content provider



Caching with Forward Proxies

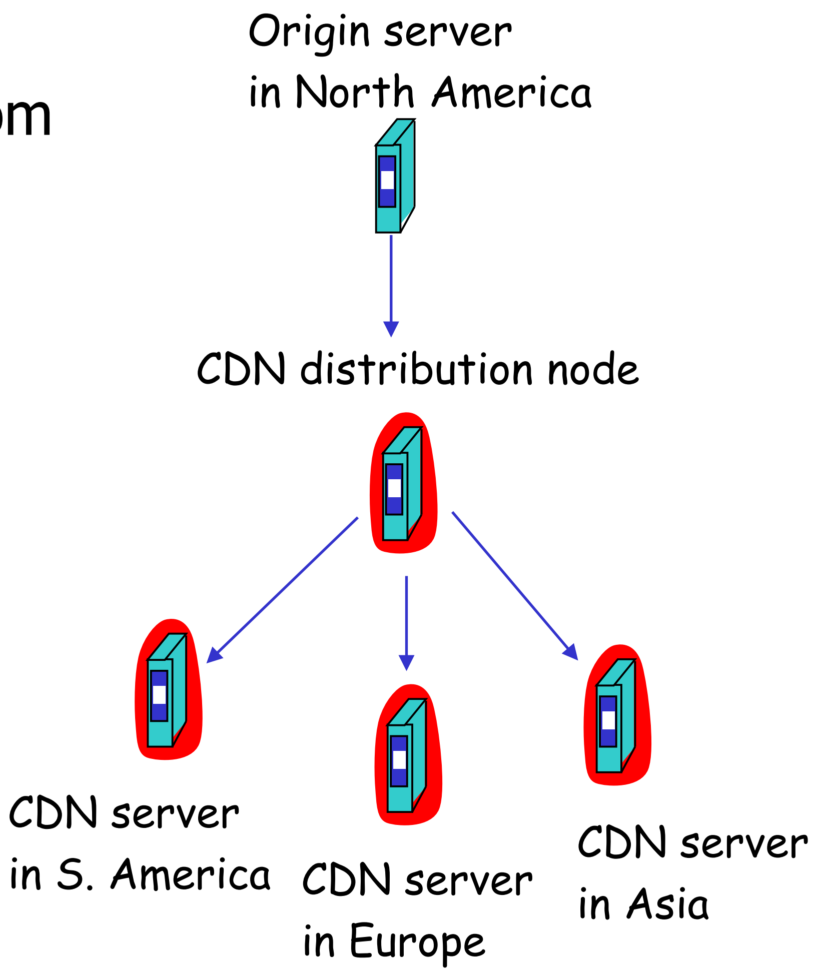
- Cache documents close to clients
  - Reduce network traffic and decrease latency
  - By ISPs or enterprises



- HTTP/1.1
  - Text-based protocol
  - Being replaced by binary HTTP/2 protocol
- Many ways to improve performance
  - Pipelining and batching
  - Caching in proxies and CDNs
  - Datacenters

Content Distribution Networks (CDNs)

- Challenge
  - Stream large files (e.g. video) from single origin server in real time
  - Protect origin server from DDOS attacks
- Solution
  - Replicate content at hundreds of servers throughout Internet
  - CDN distribution node coordinate the content distribution
  - Placing content close to user



Content Replication

- Content provider (origin server) is CDN customer

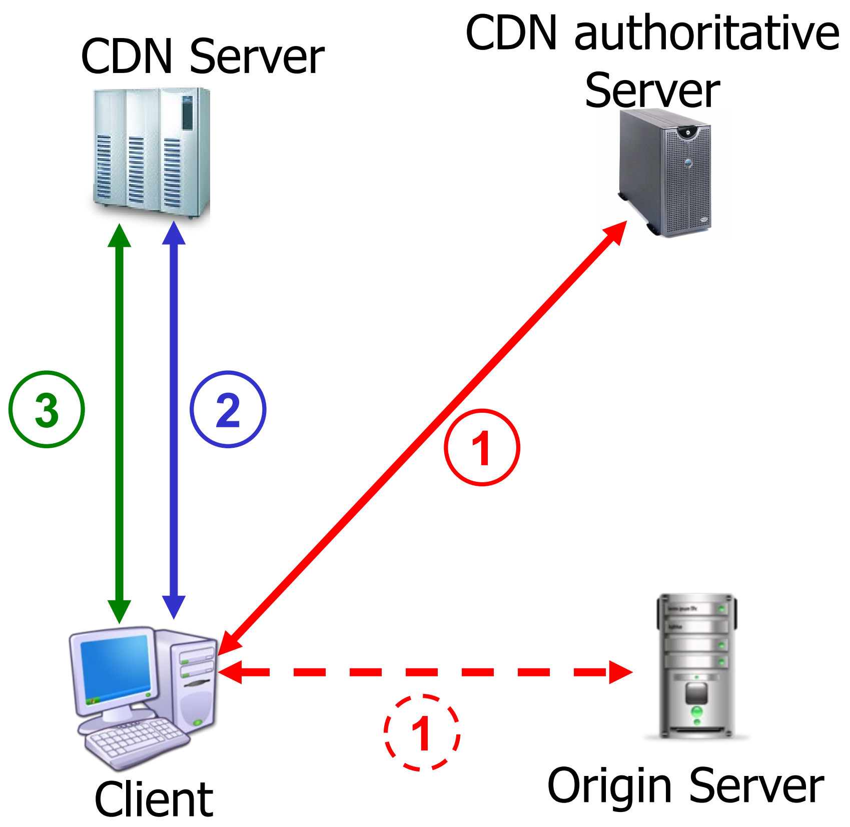
- CDN replicates customers' content in CDN servers
- When provider updates content, CDN updates its servers

- Use authoritative DNS server to redirect requests

Supporting Techniques

- DNS
  - One name maps onto many addresses
- Routing
  - Content-based routing (to nearest CDN server)
- URL Rewriting
  - Replaces "http://www.sina.com/sports/tennis.mov" with "http://www.cdn.com/www.sina.com/sports/tennis.mov"
- Redirection strategy
  - Load balancing, network delay, cache/content locality

CDN Operation



1′ URL rewriting – get authoritative server

1. Get near CDN server IP address

2. Warm up CDN cache

3. Retrieve pages/media from CDN Server

Redirection

- CDN creates a "map", indicating distances from leaf ISPs and CDN servers
- When query arrives at authoritative DNS server
  - Server determines ISP from which query originates
  - Uses "map" to determine best CDN server
- CDN servers create an application-layer overlay network

- Conceptual, implementation aspects of network application protocols
  - Client-Server vs. Peer-to-Peer
  - Data presentation formatting

- Examining popular application-level protocols
  - DNS, SNMP / MIB
  - HTTP, FTP, SMTP / POP3 / MIME
  - Content distribution networks (CDNs)

Electronic Mail

Electronic Mail

- One of most heavily used apps on Internet
- SMTP: Simple Mail Transfer Protocol
  - Delivery of simple text messages
- MIME: Multi-purpose Internet Mail Extension
  - Delivery of other types of data, e.g. voice, images, video clips
- POP: Post Office Protocol
  - Msg retrieval from server, including authorization and download
- IMAP: Internet Mail Access Protocol
  - Manipulation of stored msgs on server

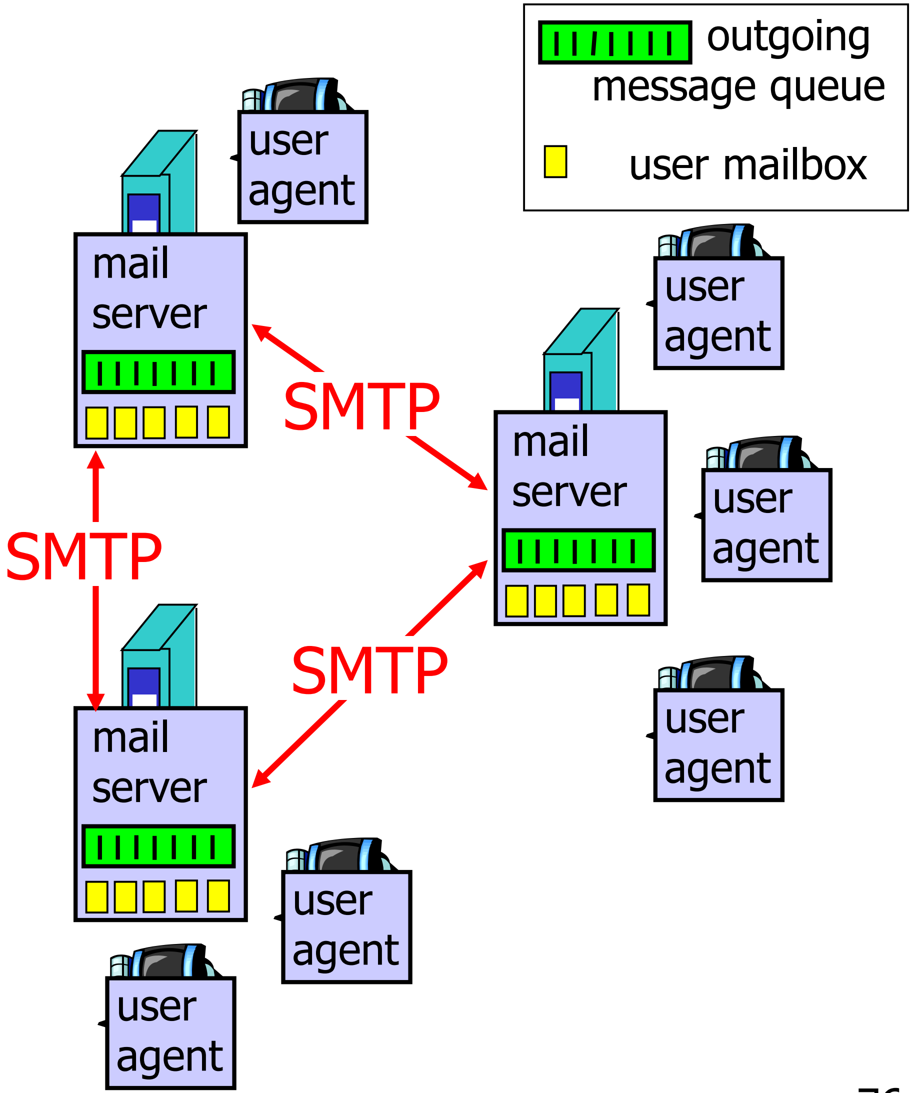
Components of Email System

User Agent

- Composing, editing, reading mail messages
- e.g. Eudora, Outlook, Foxmail, Netscape Messenger
- Outgoing, incoming mail messages stored on server

Mail Servers (Host)

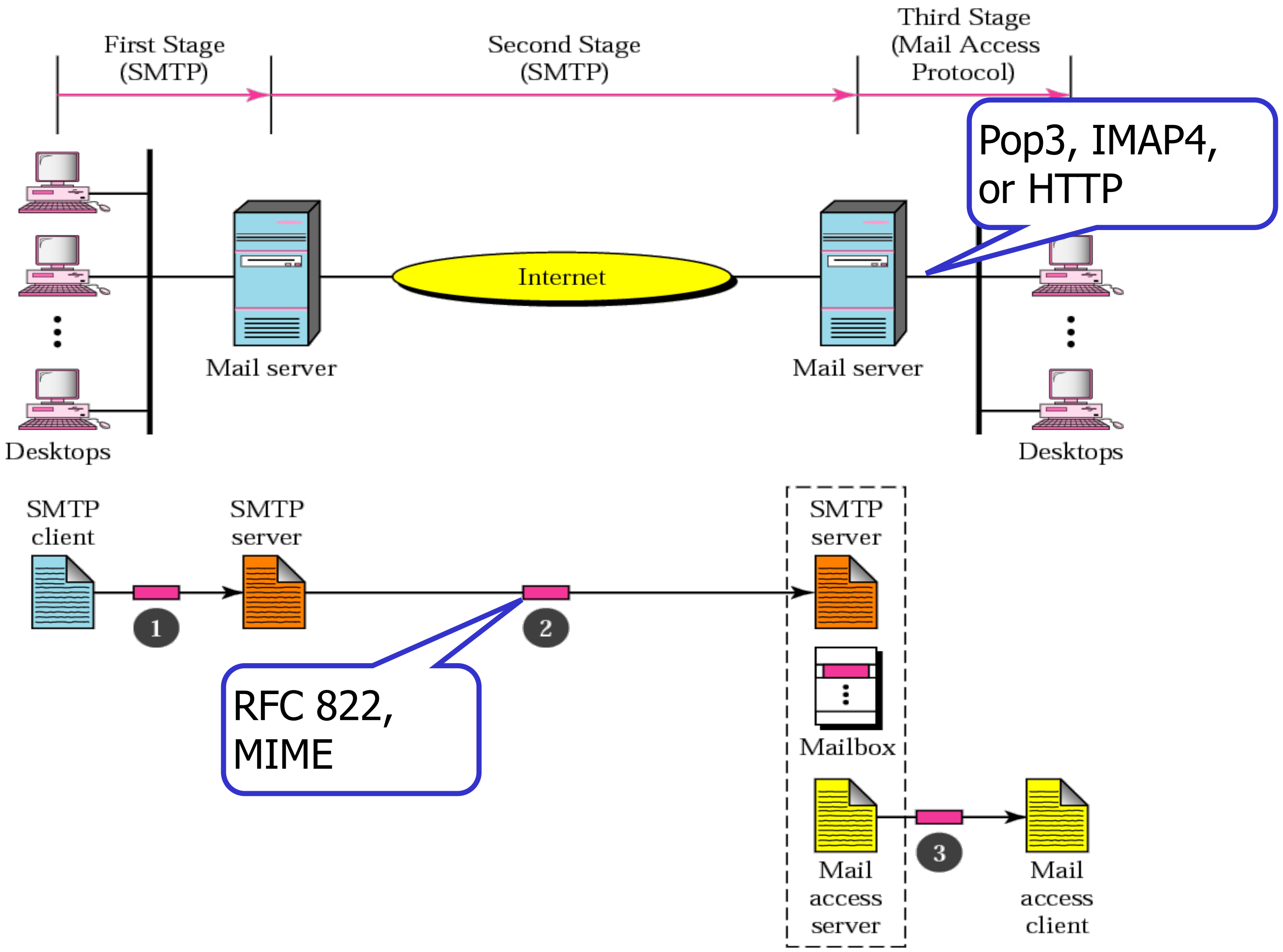
- Mailbox contains incoming mail messages for user
- Message queue of outgoing mail messages
- SMTP protocol between mail servers to send mail messages



3 Stages of Mail Delivery

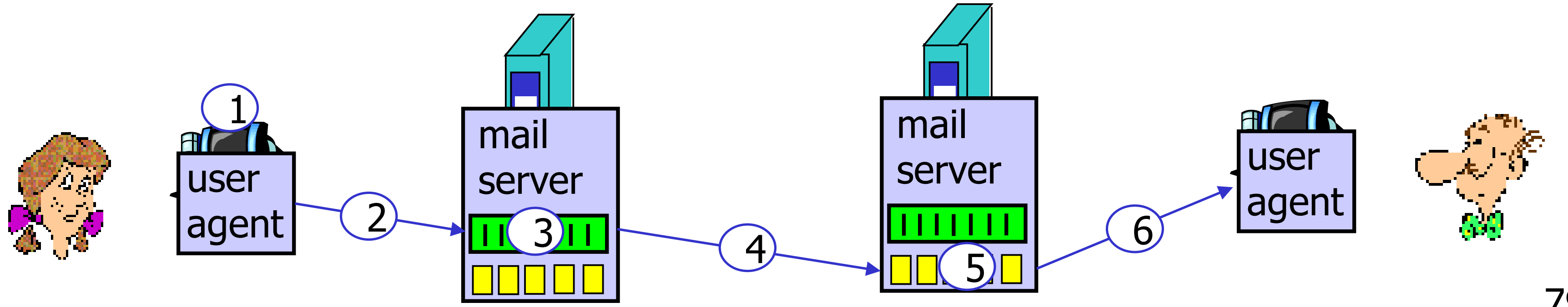
- 1st Stage
  - Email goes from local user agent to the local SMTP server
  - User agent acts as SMTP client
  - Local server acts as SMTP server
- 2nd Stage
  - Email is relayed by the local server to the remote SMTP server
  - Local server acts as SMTP client now
- 3rd Stage
  - The remote user agent uses a mail access protocol to access the mailbox on remote server
  - POP3 or IMAP4

Illustration of Mail Delivery



A Mail Delivery Scenario

- 1) Alice uses UA to compose a mail message and to bob@someschool.edu
- 2) Alice's UA sends mail to her mail server using SMTP, mail placed in message queue
- 3) Client side of SMTP opens TCP connection with Bob's mail server
- 4) SMTP client sends Alice's mail over the TCP connection
- 5) Bob's mail server places the mail in Bob's mailbox
- 6) Bob invokes his UA to read the mail, e.g. by Pop3



SMTP

- RFC 821:
  - Uses TCP, port 25
  - Direct transfer: transfer Email message from client to server

  - Needs info written on envelope of a mail (i.e. *message header*)
  - May add log info to *message header* to show the path taken

- Does not cover format of mail messages or data
  - Defined in RFC 822 or *MIME*
  - Messages must be in 7-bit *ASCII*

SMTP Transaction

3 phases of transfer

- Handshaking (greeting)
- Transfer of one or more mails data
- Close connection

```
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: RCPT TO: <Johm@hamburger.edu>
S: 550 No such user here
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
```

Command/response interaction

- Commands: ASCII text
- Response: status code and phrase

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)

Reliability of SMTP

- Transfer mails from sender to receiver over *TCP* connection
  - Rely on TCP to provide reliable service

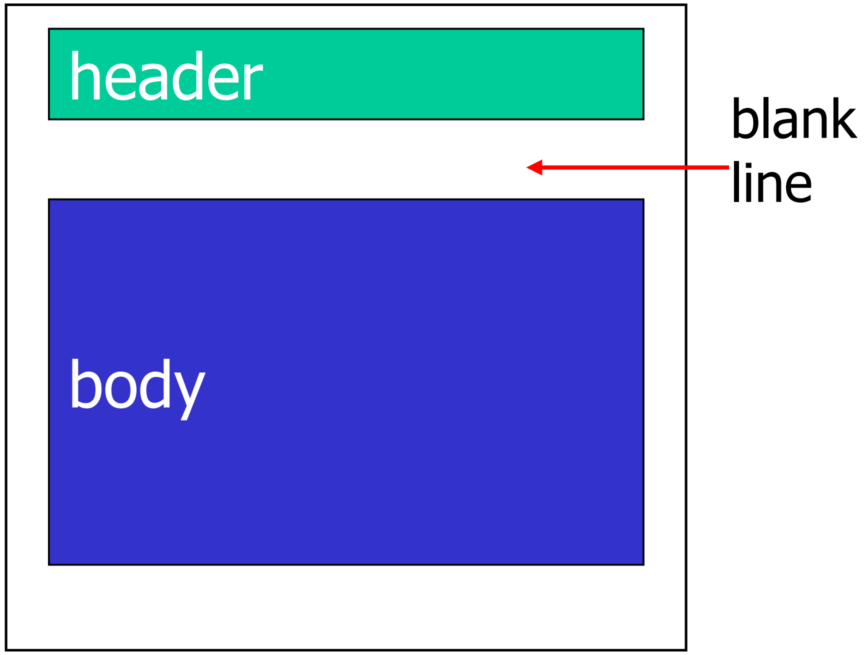
- No guarantee to recover lost mails
- No end to end acknowledgement to originator (user)

- Error indication delivery not guaranteed
  - Indicates mail has arrived at host, but not user

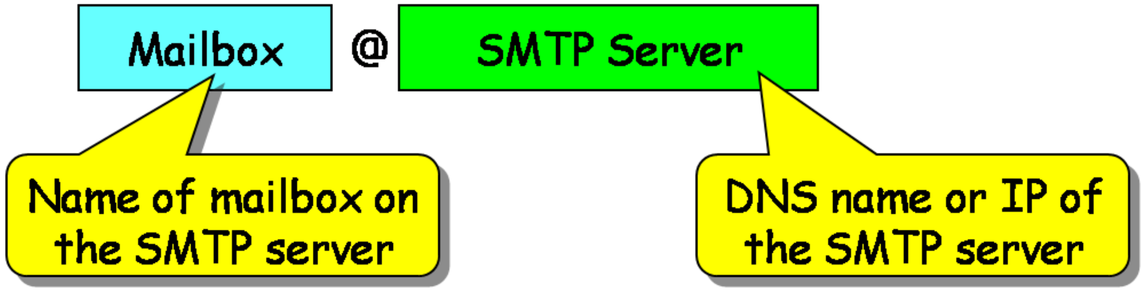
- Generally considered reliable

An Email Message

- Header lines, e.g.
  - To: Alice@sina.com
  - From: Bob@gmail.com
  - Subject: Dinner tonight
- Body
  - Mail contents, ASCII characters only



- Mail destinations


Mailbox
@
SMTP Server
Name of mailbox on the SMTP server
DNS name or IP of the SMTP server

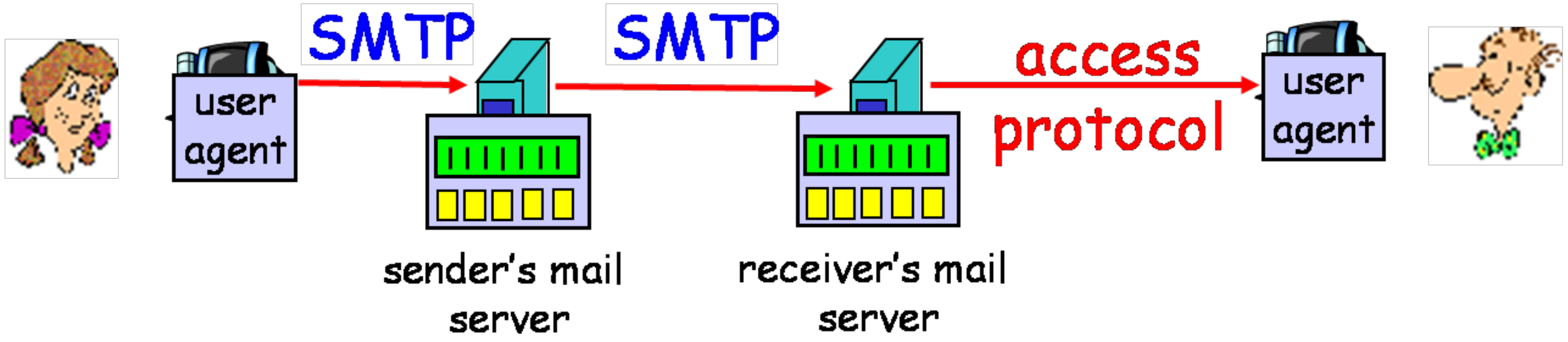
Mail Access Protocols

- SMTP: delivery/storage to receiver's server

- Mail access protocol: mail retrieval from server
- POP: Post Office Protocol [RFC 1939]
  - Authorization (agent <-->server) and download

- IMAP: Internet Mail Access Protocol [RFC 1730]
  - more features, including manipulation of stored mails on server

- HTTP: gmail, Hotmail, Yahoo!, etc.



POP3 Protocol

Authorization phase

- Client commands
  - user: declare username
  - pass: password
- Server responses
  - +OK
  - -ERR

Transaction phase, by client

- list: list mail numbers
- retr: retrieve mail 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

- Internet Mail Access Protocol, RFC 1730
- keeps all messages in one place: at server
  - A complicated use case
    - Bob reads emails at his office while his wife is simultaneously reading from same mailbox at home
- allows user to organize messages in folders
- keeps user state across sessions:
  - names of folders and mappings between message IDs and folder name
  - Keeps track of mail states (read, replied, deleted)

RFC 822 – Format for Text Mails

- Simple 2-part format
  - Header (envelope) includes transmit and delivery info
  - Lines of text in format keyword: information value
  - Body (contents) carries text of message
  - Header and body separated by a blank line
- Mail is a sequence of lines of text
  - Ends with two <CRLF>

```
From: John@hamburger.edu
To: Alice@crepes.fr
Cc: bob@hamburger.edu
Date: Wed, 4 Sep 2003 10:21:22 EST
Subject: Lunch with me

Alice,
   Can we get together for lunch
when you visit next week? I'm free
on Tuesday or Wednesday. Let me
know which day you would prefer.

John
```

MIME

- Multipurpose Internet Mail Extension
  - Extends and automates encoding mechanisms
  - Allows inclusion of separate components in a single mail
    - e.g. programs, pictures, audio clips, videos

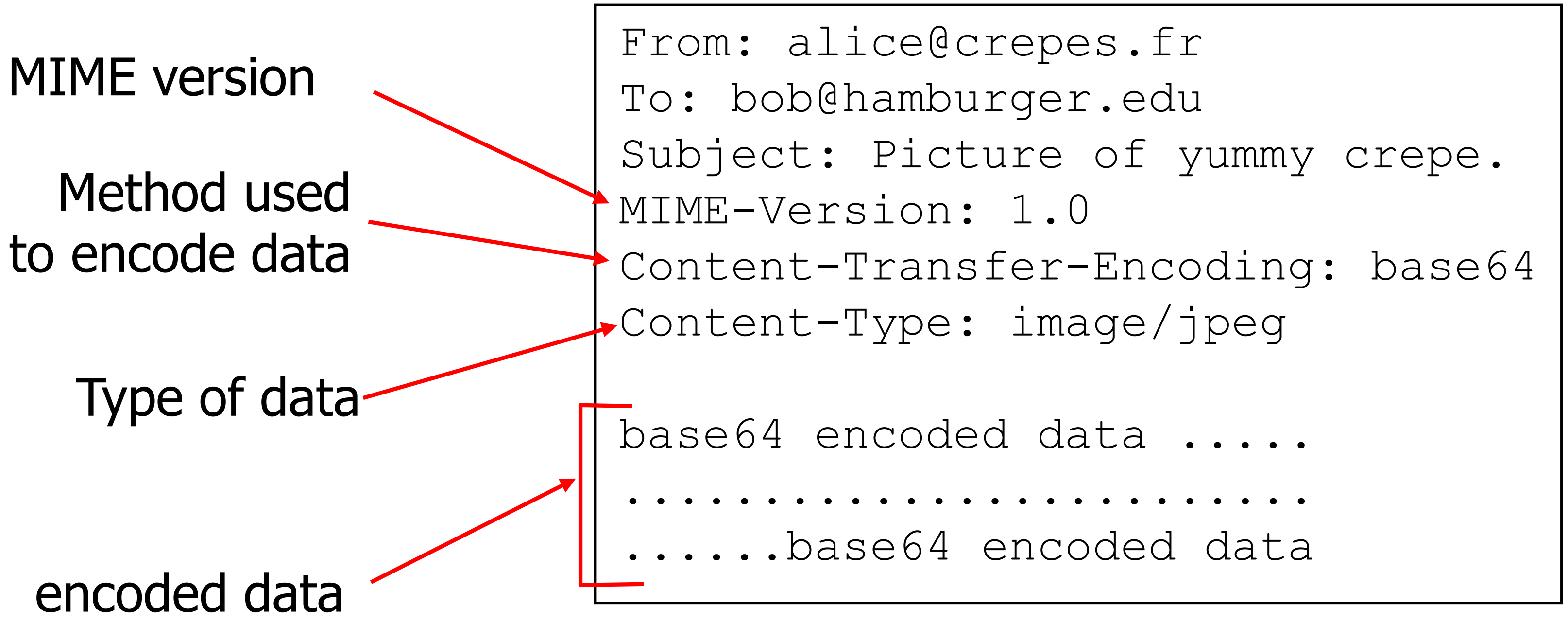
- Features
  - Compatible with existing mail systems
    - Everything encoded as 7-bit *ASCII*
    - Headers and separators ignored by *non-MIME* mail systems
  - *MIME* is extensible
    - As long as sender and receiver agree on encoding scheme

Overview of MIME

- 5 new mail header fields
  - MIME version
  - Content type
  - Content transfer encoding
  - Content Id
  - Content Description

- Number of content formats defined
- Transfer encoding defined

A MIME Mail Example



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

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

A Multi-Part Example

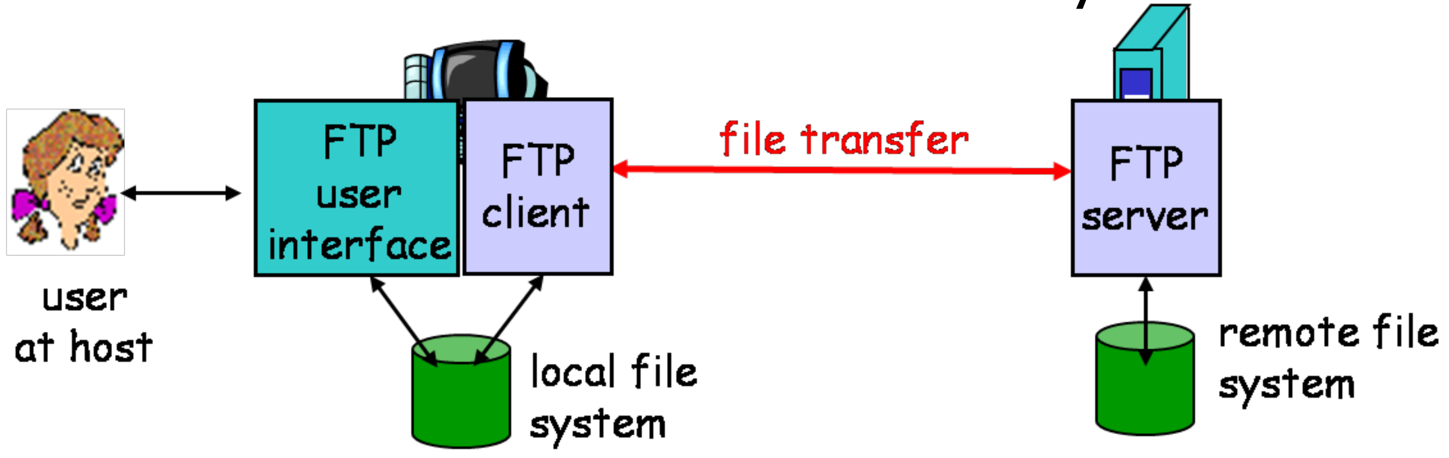
```
From: alice@crepes.fr
To: bob@hamburger.edu
Subject: Picture of yummy crepe.
MIME-Version: 1.0
Content-Type: multipart/mixed; boundary="StartOfNextPart"

--StartOfNextPart
Dear Bob, Please find a picture of a crepe.
--StartOfNextPart
Content-Transfer-Encoding: base64
Content-Type: image/jpeg
base64 encoded data .....
.........................
......base64 encoded data
--StartOfNextPart
Do you want the recipe?
--StartOfNextPart--
```

File Transfer Protocol (FTP)

File Transfer Protocol (FTP)

- RFC 959, use TCP, port 21/20
- Transfer file to/from remote host
- Client/Server model, client side initiates file transfer (either to/from remote)
- Deals with heterogeneous OS and file systems
- Needs access control on remote file system



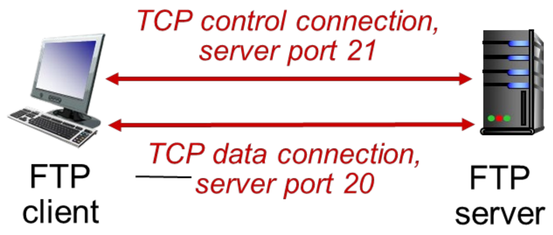
Control and Data Connections

- FTP client contacts FTP server at port 21, opens a control connection

- Client authorized over control connection
- Client browses remote directory by sending commands over control connection

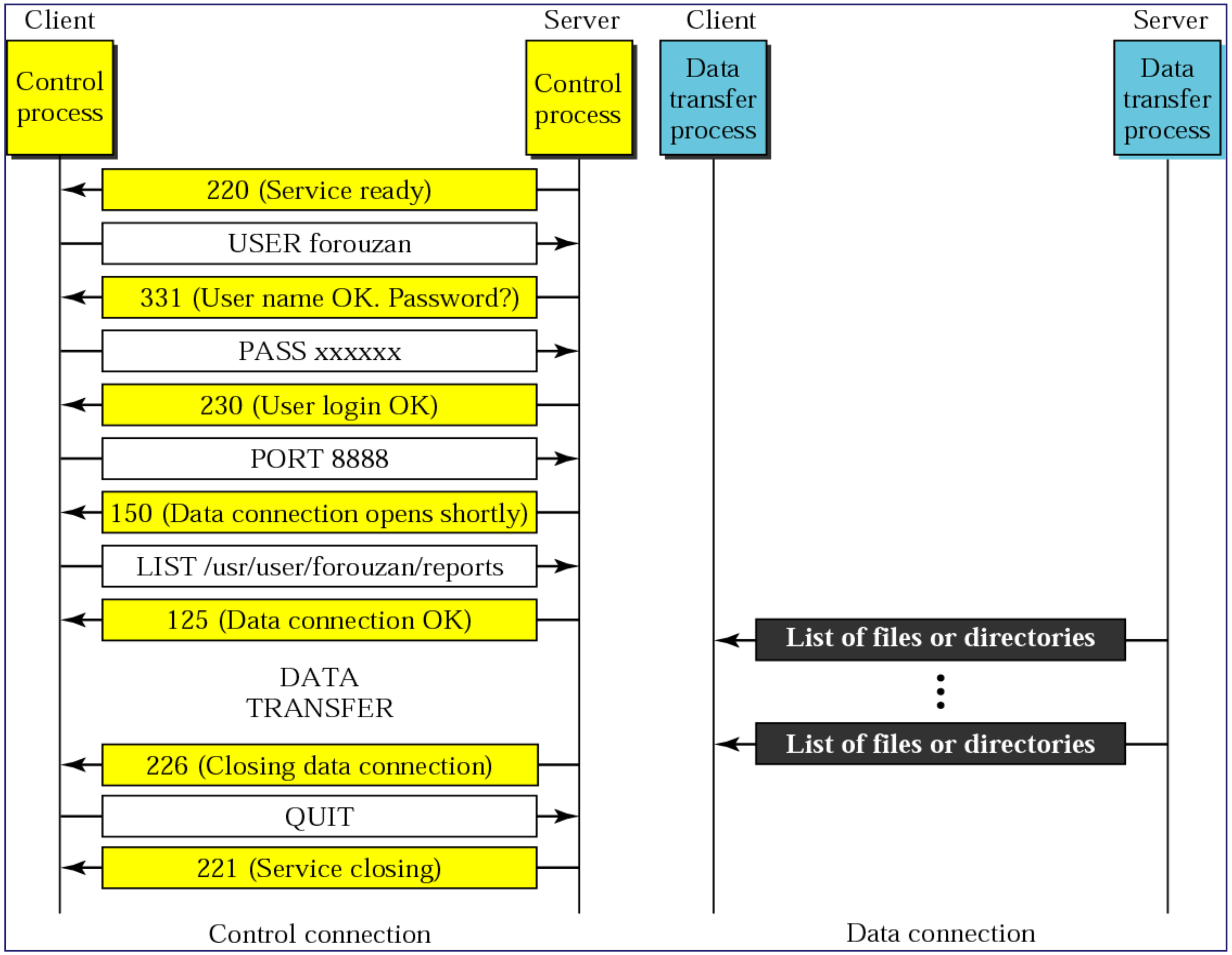
- When server receives file transfer command, *server* opens 2nd TCP data connection (for file) *to* client
  - One connection for each file transferred
- After transferring one file, server closes data connection

- Control connection stays "out of band"
- FTP server maintains "user state": current directory, earlier authentication



TCP control connection, server port 21
TCP data connection, server port 20
FTP client
FTP server

Illustration of FTP Session



FTP Commands and 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 server

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

Summary

- Internet Applications
  - C/S & P2P
  - Domain Name Service (DNS)
  - HTTP and the Web
  - Electronic Mail
  - File Transfer Protocol (FTP)