Data Communications & Networks

Session 2 – Main Theme
Application Layer

Dr. Jean-Claude Franchitti

New York University
Computer Science Department
Courant Institute of Mathematical Sciences

Adapted from course textbook resources
Computer Networking: A Top-Down Approach, 5/E
Copyright 1996-2009
J.F. Kurose and K.W. Ross, All Rights Reserved

Agenda

1 Session Overview
2 Application Layer
3 Summary and Conclusion
What is the class about?

- **Course description and syllabus:**
  
  - [http://www.nyu.edu/classes/jcf/g22.2262-001/](http://www.nyu.edu/classes/jcf/g22.2262-001/)
  

- **Textbooks:**
  
    
    James F. Kurose, Keith W. Ross
    
    Addison Wesley
    

---

Course Overview

- Computer Networks and the Internet
- Application Layer
- Fundamental Data Structures: queues, ring buffers, finite state machines
- Data Encoding and Transmission
- Local Area Networks and Data Link Control
- Wireless Communications
- Packet Switching
- OSI and Internet Protocol Architecture
- Congestion Control and Flow Control Methods
- Internet Protocols (IP, ARP, UDP, TCP)
- Network (packet) Routing Algorithms (OSPF, Distance Vector)
- IP Multicast
- Sockets
Application Layer Session in Brief

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

Creating a network app

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

No need to write software for network-core devices
- Network-core devices do not run user applications
- applications on end systems allows for rapid app development, propagation
Some network apps

- e-mail
- web
- instant messaging
- remote login
- P2P file sharing
- multi-user network games
- streaming stored video clips

- social networks
- voice over IP
- real-time video conferencing
- grid computing
Application layer Session Agenda and Related Textbook Sub-sections

- 2.1 Principles of network applications
- 2.2 Web and HTTP
- 2.3 FTP
- 2.4 Electronic Mail
  » SMTP, POP3, IMAP
- 2.5 DNS
- 2.6 P2P applications
- 2.7 Socket programming with UDP
- 2.8 Socket programming with TCP

Icons / Metaphors

- Information
- Common Realization
- Knowledge/Competency Pattern
- Governance
- Alignment
- Solution Approach
Agenda

1 Session Overview
2 Application Layer
3 Summary and Conclusion

Application Layer - Roadmap

2 Application Layer
- Principles of Network Applications
- Web and HTTP
- FTP
- Electronic Mail (SMTP, POP3, IMAP)
- DNS
- P2P Applications
- Socket Programming with UDP
- Socket Programming and TCP
Application architectures

- Client-server
  » Including data centers / cloud computing
- Peer-to-peer (P2P)
- Hybrid of client-server and P2P

Client-server architecture

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

clients:
» communicate with server
» may be intermittently connected
» may have dynamic IP addresses
» do not communicate directly with each other
Google Data Centers

- Estimated cost of data center: $600M
- Google spent $2.4B in 2007 on new data centers
- Each data center uses 50-100 megawatts of power

Pure P2P architecture

- *no* always-on server
- arbitrary end systems directly communicate
- peers are intermittently connected and change IP addresses

Highly scalable but difficult to manage
Hybrid of client-server and P2P

**Skype**
- voice-over-IP P2P application
- centralized server: finding address of remote party:
  - client-client connection: direct (not through server)

**Instant messaging**
- chatting between two users is P2P
- centralized service: client presence detection/location
  - user registers its IP address with central server when it comes online
  - user contacts central server to find IP addresses of buddies

Processes communicating

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

**Client process**: process that initiates communication

**Server process**: process that waits to be contacted

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

- process sends/receives messages to/from its socket
- socket analogous to door
  - sending process shoves message out door
  - sending process relies on transport infrastructure on other side of door which brings message to socket at receiving process

- API: (1) choice of transport protocol; (2) ability to fix a few parameters (lots more on this later)

Addressing processes

- to receive messages, process must have identifier
- host device has unique 32-bit IP address
- Exercise: use ipconfig from command prompt to get your IP address (Windows)
- Q: does IP address of host on which process runs suffice for identifying the process?
  - A: No, many processes can be running on same
- Identifier includes both IP address and port numbers associated with process on host.
- Example port numbers:
  - HTTP server: 80
  - Mail server: 25
### App-layer protocol defines

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

### Public-domain protocols:
- defined in RFCs
- allows for interoperability
  - e.g., HTTP, SMTP, BitTorrent

### Proprietary protocols:
- e.g., Skype, ppstream

### What transport service does an app need?

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

#### Timing
- some apps (e.g., Internet telephony, interactive games) require low delay to be “effective”

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

#### Security
- Encryption, data integrity, …
### Transport service requirements of common apps

<table>
<thead>
<tr>
<th>Application</th>
<th>Data loss</th>
<th>Throughput</th>
<th>Time Sensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>file transfer</td>
<td>no loss</td>
<td>elastic</td>
<td>no</td>
</tr>
<tr>
<td>e-mail</td>
<td>no loss</td>
<td>elastic</td>
<td>no</td>
</tr>
<tr>
<td>Web documents</td>
<td>no loss</td>
<td>elastic</td>
<td>no</td>
</tr>
<tr>
<td>real-time audio/video</td>
<td>loss-tolerant</td>
<td>audio: 5kbps-1Mbps, video: 10kbps-5Mbps</td>
<td>yes, 100's msec</td>
</tr>
<tr>
<td>stored audio/video</td>
<td>loss-tolerant</td>
<td>same as above</td>
<td>yes, few secs</td>
</tr>
<tr>
<td>interactive games</td>
<td>loss-tolerant</td>
<td>few kbps up</td>
<td>yes, 100's msec</td>
</tr>
<tr>
<td>instant messaging</td>
<td>no loss</td>
<td>elastic</td>
<td>yes and no</td>
</tr>
</tbody>
</table>

### Internet transport protocols services

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

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

**Q:** why bother? Why is there a UDP?
### Internet apps: application, transport protocols

<table>
<thead>
<tr>
<th>Application</th>
<th>Application layer protocol</th>
<th>Underlying transport protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-mail</td>
<td>SMTP [RFC 2821]</td>
<td>TCP</td>
</tr>
<tr>
<td>remote terminal access</td>
<td>Telnet [RFC 854]</td>
<td>TCP</td>
</tr>
<tr>
<td>Web</td>
<td>HTTP [RFC 2616]</td>
<td>TCP</td>
</tr>
<tr>
<td>file transfer</td>
<td>FTP [RFC 959]</td>
<td>TCP</td>
</tr>
<tr>
<td>streaming multimedia</td>
<td>HTTP (eg Youtube), RTP [RFC 1889]</td>
<td>TCP or UDP</td>
</tr>
<tr>
<td>Internet telephony</td>
<td>SIP, RTP, proprietary (e.g., Skype)</td>
<td>typically UDP</td>
</tr>
</tbody>
</table>

### Application Layer - Roadmap

2 Application Layer

- Principles of Network Applications
- Web and HTTP
- FTP
- Electronic Mail (SMTP, POP3, IMAP)
- DNS
- P2P Applications
- Socket Programming with UDP
- Socket Programming and TCP
Web and HTTP

**First some jargon**
- Web page consists of objects
- Object can be HTML file, JPEG image, Java applet, audio file,…
- Web page consists of base HTML-file which includes several referenced objects
- Each object is addressable by a URL
- Example URL:
  ```
  www.someschool.edu/someDept/pic.gif
  ```
  ```
  host name          path name
  ```

HTTP overview (1/2)

HTTP: hypertext transfer protocol
- Web’s application layer protocol
- client/server model
  - **client**: browser that requests, receives, “displays” Web objects
  - **server**: Web server sends objects in response to requests
HTTP overview (2/2)

<table>
<thead>
<tr>
<th>Uses TCP:</th>
<th>HTTP is “stateless”</th>
</tr>
</thead>
<tbody>
<tr>
<td>- client initiates TCP connection (creates socket) to server, port 80</td>
<td>- server maintains no information about past client requests</td>
</tr>
<tr>
<td>- server accepts TCP connection from client</td>
<td></td>
</tr>
<tr>
<td>- HTTP messages (application-layer protocol messages) exchanged</td>
<td></td>
</tr>
<tr>
<td>between browser (HTTP client) and Web server (HTTP server)</td>
<td></td>
</tr>
<tr>
<td>- TCP connection closed</td>
<td></td>
</tr>
</tbody>
</table>

Aside

Protocols that maintain “state” are complex!
- past history (state) must be maintained
- if server/client crashes, their views of “state” may be inconsistent, must be reconciled

HTTP connections

<table>
<thead>
<tr>
<th>Nonpersistent HTTP</th>
<th>Persistent HTTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>- At most one object is sent over a TCP connection.</td>
<td>- Multiple objects can be sent over single TCP connection between client and server.</td>
</tr>
</tbody>
</table>
Suppose user enters URL

www.someSchool.edu/someDepartment/home.index
time (contains text, references to 10 jpeg images)

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

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

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

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

4. HTTP server closes TCP connection.

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

6. Steps 1-5 repeated for each of 10 jpeg objects
Non-Persistent HTTP: Response time

Definition of RTT: time for a small packet to travel from client to server and back.

Response time:
- one RTT to initiate TCP connection
- one RTT for HTTP request and first few bytes of HTTP response to return
- file transmission time

total = 2RTT+transmit time

Persistent HTTP

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

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

HTTP request message:
» ASCII (human-readable format)

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

(Entity Body)
Uploading form input

Post method:
- Web page often includes form input
- Input is uploaded to server in entity body

URL method:
- Uses GET method
- Input is uploaded in URL field of request line:

www.somesite.com/animalsearch?monkeys&banana

Method types

HTTP/1.0
- GET
- POST
- HEAD
  » asks server to leave requested object out of response

HTTP/1.1
- GET, POST, HEAD
- PUT
  » uploads file in entity body to path specified in URL field
- DELETE
  » deletes file specified in the URL field
HTTP response message

status line (protocol, status code, status phrase)

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

data, e.g., requested HTML file

HTTP response status codes

In first line in server->client response message.  
A few sample codes:

200 OK  
  » request succeeded, requested object later in this message
301 Moved Permanently  
  » requested object moved, new location specified later in this message  
    (Location:)
400 Bad Request  
  » request message not understood by server
404 Not Found  
  » requested document not found on this server
505 HTTP Version Not Supported
Trying out HTTP (client side) for yourself

1. Telnet to your favorite Web server:
   ```
   telnet cis.poly.edu 80
   ```
   Opens TCP connection to port 80 (default HTTP server port) at cis.poly.edu.
   Anything typed in sent to port 80 at cis.poly.edu

2. Type in a GET HTTP request:
   ```
   GET /~ross/ HTTP/1.1
   Host: cis.poly.edu
   ```
   By typing this in (hit carriage return twice), you send this minimal (but complete)
   GET request to HTTP server

3. Look at response message sent by HTTP server!

User-server state: cookies

Many major Web sites use cookies

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

**Example:**
- Susan always access Internet always from PC
- visits specific e-commerce site for first time
- when initial HTTP requests arrives at site, site creates:
  - unique ID
  - entry in backend database for ID
Cookies: keeping “state” (1/2)

client

usual http request msg

usual http response msg

cookie file

one week later:

usual http request msg

cookie: 1678

usual http response msg

server

Amazon server creates ID 1678 for user

create entry

access

backend database

cookie-specific action

cookie-specific action

Cookies: keeping state (2/2)

What cookies can bring:

- authorization
- shopping carts
- recommendations
- user session state (Web e-mail)

Cookies and privacy:

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

How to keep “state”:

- protocol endpoints: maintain state at sender/receiver over multiple transactions
- cookies: http messages carry state
Web caches (proxy server)

**Goal:** satisfy client request without involving origin server

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

---

More about Web caching

- cache acts as both client and server
- typically cache is installed by ISP (university, company, residential ISP)

**Why Web caching?**

- reduce response time for client request
- reduce traffic on an institution’s access link.
- Internet dense with caches: enables “poor” content providers to effectively deliver content (but so does P2P file sharing)
Caching example (1/3)

**Assumptions**
- average object size = 1,000,000 bits
- avg. request rate from institution’s browsers to origin servers = 15/sec
- delay from institutional router to any origin server and back to router = 2 sec

**Consequences**
- utilization on LAN = 15%
- utilization on access link = 100%
- total delay = Internet delay + access delay + LAN delay = 2 sec + minutes + milliseconds

Caching example (2/3)

**possible solution**
- increase bandwidth of access link to, say, 100 Mbps

**consequence**
- utilization on LAN = 15%
- utilization on access link = 15%
- Total delay = Internet delay + access delay + LAN delay = 2 sec + msecs + msecs
- often a costly upgrade
Caching example (3/3)

**possible solution:** install cache
- suppose hit rate is 0.4

**consequence**
- 40% requests will be satisfied almost immediately
- 60% requests satisfied by origin server
- utilization of access link reduced to 60%, resulting in negligible delays (say 10 msec)
- total avg delay = Internet delay + access delay + LAN delay = .6*(2.01) secs + .4*milliseconds < 1.4 secs

---

Conditional GET

- **Goal:** don’t send object if cache has up-to-date cached version
- cache: specify date of cached copy in HTTP request
  - If-modified-since: <date>
- server: response contains no object if cached copy is up-to-date:
  - HTTP/1.0 304 Not Modified
- object not modified

- 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
- object not modified

- 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/1.0 200 OK <data>
- object modified
FTP: the file transfer protocol

- transfer file to/from remote host
- client/server model
  - client: side that initiates transfer (either to/from remote)
  - server: remote host
- ftp: RFC 959
- ftp server: port 21
FTP: separate control, data connections

- FTP client contacts FTP server at port 21, TCP is transport protocol
- client authorized over control connection
- client browses remote directory by sending commands over control connection.
- when server receives file transfer command, server opens 2nd TCP connection (for file) to client
- after transferring one file, server closes data connection.

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

FTP commands, responses

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

**Sample return codes**
- status code and phrase (as in HTTP)
- 331 Username OK, password required
- 125 data connection already open; transfer starting
- 425 Can’t open data connection
- 452 Error writing file
Application Layer - Roadmap

2 Application Layer

- Principles of Network Applications
- Web and HTTP
- FTP
- Electronic Mail (SMTP, POP3, IMAP)
- DNS
- P2P Applications
- Socket Programming with UDP
- Socket Programming 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., Eudora, Outlook, elm, Mozilla Thunderbird
- outgoing, incoming messages stored on server
**Electronic Mail: mail servers**

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

**Electronic Mail: SMTP [RFC 2821]**
- uses TCP to reliably transfer email message from client to server, port 25
- direct transfer: sending server to receiving server
- three phases of transfer
  - handshaking (greeting)
  - transfer of messages
  - closure
- command/response interaction
  - commands: ASCII text
  - response: status code and phrase
- messages must be in 7-bit ASCII
**Scenario: Alice sends message to Bob**

1) Alice uses UA to compose message and “to” `bob@someschool.edu`

2) Alice’s UA sends message to her mail server; message placed in message queue

3) Client side of SMTP opens TCP connection with Bob’s mail server

4) SMTP client sends Alice’s message over the TCP connection

5) Bob’s mail server places the message in Bob’s mailbox

6) Bob invokes his user agent to read message

**Sample SMTP interaction**

<table>
<thead>
<tr>
<th>S: 220 hamburger.edu</th>
</tr>
</thead>
<tbody>
<tr>
<td>C: HELO crepes.fr</td>
</tr>
<tr>
<td>S: 250 Hello crepes.fr, pleased to meet you</td>
</tr>
<tr>
<td>C: MAIL FROM: <a href="mailto:alice@crepes.fr">alice@crepes.fr</a></td>
</tr>
<tr>
<td>S: 250 <a href="mailto:alice@crepes.fr">alice@crepes.fr</a>... Sender ok</td>
</tr>
<tr>
<td>C: RCPT TO: <a href="mailto:bob@hamburger.edu">bob@hamburger.edu</a></td>
</tr>
<tr>
<td>S: 250 <a href="mailto:bob@hamburger.edu">bob@hamburger.edu</a> ... Recipient ok</td>
</tr>
<tr>
<td>C: DATA</td>
</tr>
<tr>
<td>S: 354 Enter mail, end with &quot;.&quot; on a line by itself</td>
</tr>
<tr>
<td>C: Do you like ketchup?</td>
</tr>
<tr>
<td>C: How about pickles?</td>
</tr>
<tr>
<td>C: .</td>
</tr>
<tr>
<td>S: 250 Message accepted for delivery</td>
</tr>
<tr>
<td>C: QUIT</td>
</tr>
<tr>
<td>S: 221 hamburger.edu closing connection</td>
</tr>
</tbody>
</table>
Try SMTP interaction for yourself

- telnet servername 25
- see 220 reply from server
- enter HELO, MAIL FROM, RCPT TO, DATA, QUIT commands

Above lets you send email without using email client (reader)

SMTP: final words

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

Comparison with HTTP:

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

SMTP: protocol for exchanging email msgs
RFC 822: standard for text message format:
  - header lines, e.g.,
    » To:
    » From:
    » Subject: different from SMTP commands!
  - body
    » the “message”, ASCII characters only

Mail access protocols

- SMTP: delivery/storage to receiver’s server
- Mail access protocol: retrieval from server
  - POP: Post Office Protocol [RFC 1939]
    • authorization (agent <->server) and download
  - IMAP: Internet Mail Access Protocol [RFC 1730]
    • more features (more complex)
    • manipulation of stored msgs on server
  - HTTP: gmail, Hotmail, Yahoo! Mail, etc.
**POP3 protocol**

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

**transaction phase, client:**
- list: list message numbers
- retr: retrieve message by number
- dele: delete
- quit

```
S: +OK POP3 server ready
C: user bob
S: +OK
C: pass hungry
S: +OK user successfully logged on
C: list
S: 1 498
S: 2 912
S: .
C: retr 1
S: <message 1 contents>
S: .
C: dele 1
C: retr 2
S: <message 1 contents>
S: .
C: dele 2
C: quit
S: +OK POP3 server signing off
```

**POP3 (more) and IMAP**

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

**IMAP**
- Keep all messages in one place: the server
- Allows user to organize messages in folders
- IMAP keeps user state across sessions:
  - names of folders and mappings between message IDs and folder name
Application Layer - Roadmap

2 Application Layer

- Web and HTTP
- FTP
- Electronic Mail (SMTP, POP3, IMAP)
- DNS
- P2P Applications
- Socket Programming with UDP
- Socket Programming and TCP

DNS: Domain Name System

People: many identifiers:
  » SSN, name, passport #

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

Q: map between IP addresses and name?

Domain Name System:
  - distributed database
    implemented in hierarchy of many name servers
  - application-layer protocol
    host, routers, name servers to communicate to resolve names
    (address/name translation)
  » note: core Internet function,
    implemented as application-layer protocol
  » complexity at network’s “edge”
### DNS

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

**Why not centralize DNS?**
- single point of failure
- traffic volume
- distant centralized database
- maintenance
doesn’t *scale*!

### Distributed, Hierarchical Database

Client wants IP for www.amazon.com; *1st approx*:
- client queries a root server to find com DNS server
- client queries com DNS server to get amazon.com DNS server
- client queries amazon.com DNS server to get IP address for www.amazon.com
DNS: Root name servers

- contacted by local name server that can not resolve name
- root name server:
  - contacts authoritative name server if name mapping not known
  - gets mapping
  - returns mapping to local name server

TLD and Authoritative Servers

- Top-level domain (TLD) servers:
  - responsible for com, org, net, edu, etc, and all top-level country domains uk, fr, ca, jp.
  - Network Solutions maintains servers for com TLD
  - Educause for edu TLD
- Authoritative DNS servers:
  - organization’s DNS servers, providing authoritative hostname to IP mappings for organization’s servers (e.g., Web, mail).
  - can be maintained by organization or service provider
Local Name Server

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

DNS name resolution example

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

iterated query:
- contacted server replies with name of server to contact
- “I don’t know this name, but ask this server”
DNS name resolution example

recursive query:
- puts burden of name resolution on contacted name server
- heavy load?

DNS: caching and updating records

- once (any) name server learns mapping, it caches mapping
  » cache entries timeout (disappear) after some time
  » TLD servers typically cached in local name servers
    • Thus root name servers not often visited
- update/notify mechanisms under design by IETF
  » RFC 2136
  » http://www.ietf.org/html.charters/dnsind-charter.html
DNS records

**DNS:** distributed db storing resource records (RR)

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

- **Type=A**
  - name is hostname
  - value is IP address
- **Type=NS**
  - name is domain (e.g. foo.com)
  - value is hostname of authoritative name server for this domain
- **Type=CNAME**
  - name is alias name for some "canonical" (the real) name
  - value is canonical name
- **Type=MX**
  - value is name of mailserver associated with name

DNS protocol, messages

**DNS protocol:** query and reply messages, both with same message format

<table>
<thead>
<tr>
<th>msg header</th>
</tr>
</thead>
<tbody>
<tr>
<td>identification: 16 bit # for query, reply to query uses same #</td>
</tr>
<tr>
<td>flags:</td>
</tr>
<tr>
<td>query or reply</td>
</tr>
<tr>
<td>recursion desired</td>
</tr>
<tr>
<td>recursion available</td>
</tr>
<tr>
<td>reply is authoritative</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>msg header</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of questions</td>
</tr>
<tr>
<td>number of answer RRs</td>
</tr>
<tr>
<td>number of authority RRs</td>
</tr>
<tr>
<td>number of additional RRs</td>
</tr>
</tbody>
</table>

| questions (variable number of questions) |
| answers (variable number of resource records) |
| authority (variable number of resource records) |
| additional information (variable number of resource records) |

12 bytes
Inserting records into DNS

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

  (networkutopia.com, dns1.networkutopia.com, NS)
  (dns1.networkutopia.com, 212.212.212.1, A)

- create authoritative server Type A record for www.networkutopia.com; Type MX record for networkutopia.com
- How do people get IP address of your Web site?
**Application Layer - Roadmap**

2 Application Layer
- Principles of Network Applications
- Web and HTTP
- FTP
- Electronic Mail (SMTP, POP3, IMAP)
- DNS
- P2P Applications
- Socket Programming with UDP
- Socket Programming and TCP

**Pure P2P architecture**

- *no always-on server*
- *arbitrary end systems directly communicate*
- *peers are intermittently connected and change IP addresses*

**Three topics:**
- File distribution
- Searching for information
- Case Study: Skype
**Question**: How much time to distribute file from one server to $N$ peers?

- $u_s$: server upload bandwidth
- $u_i$: peer $i$ upload bandwidth
- $d_i$: peer $i$ download bandwidth

**File distribution time: server-client**

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

Time to distribute $F$ to $N$ clients using client/server approach:

$$d_{cs} = \max \{ NF/u_s, F/min(d_i) \}$$

increases linearly in $N$ (for large $N$)
**File distribution time: P2P**

- server must send one copy: \( \frac{F}{u_s} \) time
- client i takes \( \frac{F}{d_i} \) time to download
- NF bits must be downloaded (aggregate)

- fastest possible upload rate: \( u_s + \sum u_i \)

\[
d_{P2P} = \max \{ \frac{F}{u_s}, \frac{F}{\min(d_i)}, \frac{NF}{(u_s + \sum u_i)} \}
\]

**Server-client vs. P2P: example**

*Client upload rate = u, \( \frac{F}{u} = 1 \) hour, \( u_s = 10u \), \( d_{min} \geq u_s \)*

![Graph showing minimum distribution time for P2P and Client-Server models with N on the x-axis and minimum distribution time on the y-axis.](image)
File distribution: BitTorrent

- P2P file distribution

  tracker: tracks peers participating in torrent
torrent: group of peers exchanging chunks of a file

BitTorrent (1/2)

- file divided into 256KB chunks.
- peer joining torrent:
  » has no chunks, but will accumulate them over time
  » registers with tracker to get list of peers, connects to subset of peers ("neighbors")
- while downloading, peer uploads chunks to other peers.
- peers may come and go
- once peer has entire file, it may (selfishly) leave or (altruistically) remain
**Pulling Chunks**
- at any given time, different peers have different subsets of file chunks
- periodically, a peer (Alice) asks each neighbor for list of chunks that they have.
- Alice sends requests for her missing chunks ➔ rarest first

**Sending Chunks: tit-for-tat**
- Alice sends chunks to four neighbors currently sending her chunks at the highest rate
  - re-evaluate top 4 every 10 secs
- every 30 secs: randomly select another peer, starts sending chunks
  - newly chosen peer may join top 4
  - “optimistically unchoke”

**BitTorrent: Tit-for-tat**
1. Alice "optimistically unchokes" Bob
2. Alice becomes one of Bob's top-four providers; Bob reciprocates
3. Bob becomes one of Alice's top-four providers

With higher upload rate, can find better trading partners & get file faster!
Distributed Hash Table (DHT)

- DHT = distributed P2P database
- Database has (key, value) pairs;
  - key: ss number; value: human name
  - key: content type; value: IP address
- Peers query DB with key
  - DB returns values that match the key
- Peers can also insert (key, value) peers

DHT Identifiers

- Assign integer identifier to each peer in range [0, \(2^n-1\)].
  - Each identifier can be represented by n bits.
- Require each key to be an integer in same range.
- To get integer keys, hash original key.
  - eg, key = h(“Led Zeppelin IV”)
  - This is why they call it a distributed “hash” table
How to assign keys to peers?

- Central issue:
  - Assigning (key, value) pairs to peers.
- Rule: assign key to the peer that has the closest ID.
- Convention in lecture: closest is the immediate successor of the key.
- Ex: n=4; peers: 1,3,4,5,8,10,12,14;
  - key = 13, then successor peer = 14
  - key = 15, then successor peer = 1

Circular DHT (1)

- Each peer only aware of immediate successor and predecessor.
- “Overlay network”
Circle DHT (2)

- \(O(N)\) messages on avg to resolve query, when there are \(N\) peers

Define closest as closest successor

Circular DHT with Shortcuts

- Each peer keeps track of IP addresses of predecessor, successor, short cuts.
- Reduced from 6 to 2 messages.
- Possible to design shortcuts so \(O(\log N)\) neighbors, \(O(\log N)\) messages in query
**Peer Churn**

- Peer 5 abruptly leaves
- Peer 4 detects; makes 8 its immediate successor; asks 8 who its immediate successor is; makes 8’s immediate successor its second successor.
- What if peer 13 wants to join?

- To handle peer churn, require each peer to know the IP address of its two successors.
- Each peer periodically pings its two successors to see if they are still alive.

**P2P Case study: Skype**

- inherently P2P: pairs of users communicate.
- proprietary application-layer protocol (inferred via reverse engineering)
- hierarchical overlay with SNs
- Index maps usernames to IP addresses; distributed over SNs

[Diagram of Skype architecture showing Skype clients (SC), Skype login server, and Supernode (SN).]
Peers as relays

- Problem when both Alice and Bob are behind “NATs”.
  - NAT prevents an outside peer from initiating a call to insider peer
- Solution:
  - Using Alice’s and Bob’s SNs, Relay is chosen
  - Each peer initiates session with relay.
  - Peers can now communicate through NATs via relay

Application Layer - Roadmap

<table>
<thead>
<tr>
<th>2 Application Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principles of Network Applications</td>
</tr>
<tr>
<td>Web and HTTP</td>
</tr>
<tr>
<td>FTP</td>
</tr>
<tr>
<td>Electronic Mail (SMTP, POP3, IMAP)</td>
</tr>
<tr>
<td>DNS</td>
</tr>
<tr>
<td>P2P Applications</td>
</tr>
<tr>
<td>Socket Programming with UDP</td>
</tr>
<tr>
<td>Socket Programming and TCP</td>
</tr>
</tbody>
</table>
### Socket programming

**Goal:** learn how to build client/server application that communicate using sockets

**Socket API**
- introduced in BSD4.1 UNIX, 1981
- explicitly created, used, released by apps
- client/server paradigm
- two types of transport service via socket API:
  - UDP
  - TCP

---

### Socket programming basics

- Server must be **running** before client can send anything to it.
- Server must have a **socket** (door) through which it receives and sends segments
- Similarly client needs a socket
- **Socket** is locally identified with a **port number**
  - Analogous to the apt # in a building
- Client **needs to know** server IP address and socket port number.
UDP programming with UDP

UDP: no “connection” between client and server
- no handshaking
- sender explicitly attaches IP address and port of destination to each segment
- OS attaches IP address and port of sending socket to each segment
- Server can extract IP address, port of sender from received segment

Note: the official terminology for a UDP packet is “datagram”. In this class, we instead use “UDP segment”.

Running example

- **Client:**
  - User types line of text
  - Client program sends line to server

- **Server:**
  - Server receives line of text
  - Capitalizes all the letters
  - Sends modified line to client

- **Client:**
  - Receives line of text
  - Displays
Client/server socket interaction: UDP

Server (running on hostid)

create socket, port=x
serverSocket = DatagramSocket()

read datagram from serverSocket

write reply to serverSocket specifying client address, port number

Client

create socket, clientSocket = DatagramSocket()

Create datagram with server IP and port=x; send datagram via clientSocket

read datagram from clientSocket

close clientSocket

Example: Java client (UDP) – (1/5)

Client process

Input: receives packet (recall that TCP received "byte stream")

Output: sends packet (recall that TCP sent "byte stream")

Client UDP socket

keyboard

monitor

input stream

monitor

input stream

UTC packet

UTC packet

to network

from network

UTC packet

UTC packet

UTC packet

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

class UDPClient {
    public static void main(String args[]) throws Exception {
        BufferedReader inFromUser =
            new BufferedReader(new InputStreamReader(System.in));
        DatagramSocket clientSocket = new DatagramSocket();
        InetAddress IPAddress = InetAddress.getByName("hostname");
        byte[] sendData = new byte[1024];
        byte[] receiveData = new byte[1024];
        String sentence = inFromUser.readLine();
        sendData = sentence.getBytes();
        DatagramPacket sendPacket =
            new DatagramPacket(sendData, sendData.length, IPAddress, 9876);
        clientSocket.send(sendPacket);
        DatagramPacket receivePacket =
            new DatagramPacket(receiveData, receiveData.length);
        clientSocket.receive(receivePacket);
        String modifiedSentence =
            new String(receivePacket.getData());
        System.out.println("FROM SERVER:" + modifiedSentence);
        clientSocket.close();
    }
}
```
import java.io.*;
import java.net.*;

class UDPServer {
    public static void main(String args[]) throws Exception {
        DatagramSocket serverSocket = new DatagramSocket(9876);
        byte[] receiveData = new byte[1024];
        byte[] sendData = new byte[1024];

        while(true) {
            DatagramPacket receivePacket = new DatagramPacket(receiveData, receiveData.length);
            serverSocket.receive(receivePacket);

            String sentence = new String(receivePacket.getData());
            InetAddress IPAddress = receivePacket.getAddress();
            int port = receivePacket.getPort();

            String capitalizedSentence = sentence.toUpperCase();
            sendData = capitalizedSentence.getBytes();

            DatagramPacket sendPacket = new DatagramPacket(sendData, sendData.length, IPAddress, port);
            serverSocket.send(sendPacket);
        }
    }
}
**UDP observations & questions**

- Both client server use DatagramSocket
- Dest IP and port are **explicitly attached** to segment.
- What would happen if change both clientSocket and serverSocket to “mySocket”?
- Can the client send a segment to server **without knowing** the server’s IP address and/or port number?
- Can multiple clients use the server?

---

**Application Layer - Roadmap**

2 Application Layer

- Principles of Network Applications
- Web and HTTP
- FTP
- Electronic Mail (SMTP, POP3, IMAP)
- DNS
- P2P Applications
- Socket Programming with UDP
- Socket Programming and TCP
**Socket-programming using TCP**

**TCP service:** reliable transfer of **bytes** from one process to another

- **controlled by application developer**
- **controlled by operating system**

---

**Socket programming with TCP**

- **Client must contact server**
  - server process must first be running
  - server must have created socket (door) that welcomes client’s contact

- **Client contacts server by:**
  - creating client-local TCP socket
  - specifying IP address, port number of server process
  - When client creates socket, client TCP establishes connection to server TCP

- **When contacted by client, server TCP creates new socket** for server process to communicate with client
  - allows server to talk with multiple clients
  - source port numbers used to distinguish clients (*more in Chap 3*)

**application viewpoint**

- **TCP provides reliable, in-order transfer of bytes (“pipe”) between client and server**
Client/server socket interaction: TCP

Server (running on hostid)
- create socket, port=x, for incoming request:
  - welcomeSocket = ServerSocket()
- wait for incoming connection request
  - connectionSocket = welcomeSocket.accept()
- read request from connectionSocket
- write reply to connectionSocket
- close connectionSocket

Client
- create socket, connect to hostid, port=x
- clientSocket = Socket()
- send request using clientSocket
- read reply from clientSocket
- close clientSocket

TCP connection setup

Stream jargon
- A **stream** is a sequence of characters that flow into or out of a process.
- An **input stream** is attached to some input source for the process, e.g., keyboard or socket.
- An **output stream** is attached to an output source, e.g., monitor or socket.
Example client-server app:

1) client reads line from standard input (inFromUser stream), sends to server via socket (outToServer stream)
2) server reads line from socket
3) server converts line to uppercase, sends back to client
4) client reads, prints modified line from socket (inFromServer stream)

Example: Java client (TCP) – (1/4)

```java
import java.io.*;
import java.net.*;
class TCPClient {
    public static void main(String argv[]) throws Exception {
        String sentence;
        String modifiedSentence;
        BufferedReader inFromUser =
            new BufferedReader(new InputStreamReader(System.in));
        Socket clientSocket = new Socket("hostname", 6789);
        DataOutputStream outToServer =
            new DataOutputStream(clientSocket.getOutputStream());
        BufferedReader inFromServer =
            new BufferedReader(new InputStreamReader(clientSocket.getInputStream()));
        String line = inFromUser.readLine();
        outToServer.writeUTF(line.toUpperCase());
        System.out.println(inFromServer.readLine());
    }
}
```
Example: Java client (TCP) – (2/4)

```java
BufferedReader inFromServer = new BufferedReader(new InputStreamReader(clientSocket.getInputStream()));
sentence = inFromUser.readLine();
outToServer.writeBytes(sentence + '\n');
modifiedSentence = inFromServer.readLine();
System.out.println("FROM SERVER: " + modifiedSentence);
clientSocket.close();
```

Example: Java server (TCP) – (3/4)

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

class TCPServer {
    public static void main(String argv[]) throws Exception {
        String clientSentence;
        String capitalizedSentence;
        ServerSocket welcomeSocket = new ServerSocket(6789);

        while(true) {
            Socket connectionSocket = welcomeSocket.accept();
            BufferedReader inFromClient =
            new BufferedReader(new
            InputStreamReader(connectionSocket.getInputStream()));
```
Example: Java server (TCP) – (4/4)

Create output stream, attached to socket

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

Read in line from socket

`clientSentence = inFromClient.readLine();`

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

Write out line to socket

`outToClient.writeBytes(capitalizedSentence);`

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

TCP observations & questions

- Server has two types of sockets:
  - `ServerSocket` and `Socket`

- When client knocks on `serverSocket`'s “door,” server creates `connectionSocket` and completes TCP conx.

- Dest IP and port are not explicitly attached to segment.

- Can multiple clients use the server?
Application Layer: Summary (1/2)

our study of network apps now complete!

- application architectures
  - client-server
  - P2P
  - hybrid
- application service requirements:
  - reliability, bandwidth, delay
- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP
- specific protocols:
  - HTTP
  - FTP
  - SMTP, POP, IMAP
  - DNS
  - P2P: BitTorrent, Skype
- socket programming
Application Layer: Summary (2/2)

Most importantly: learned about protocols

- typical request/reply message exchange:
  - client requests info or service
  - server responds with data, status code
- message formats:
  - headers: fields giving info about data
  - data: info being communicated

Important themes:
- control vs. data msgs
  - in-band, out-of-band
- centralized vs. decentralized
- stateless vs. stateful
- reliable vs. unreliable msg transfer
- “complexity at network edge”

Assignments & Readings

- Readings
  - Chapter 2
- Assignment #2