Chapter 2
Application Layer

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Computer Networking:
Jim Kurose, Keith Ross
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Chapter 2: Application layer

- 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
Chapter 2: Application Layer

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

- social networks
- web over IP
- instant messaging
- voice over IP
- P2P file sharing
- multi-user network games
- streaming stored video clips
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
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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
Google Data Centers

- Estimated cost of data center: $600M
- Google spent $2.4B in 2007 on new data centers
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
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 messages to socket
- 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:
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 &

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

**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
### 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</td>
<td>Telnet [RFC 854]</td>
<td>TCP</td>
</tr>
<tr>
<td>access</td>
<td>HTTP [RFC 2616]</td>
<td>TCP</td>
</tr>
<tr>
<td>Web</td>
<td>FTP [RFC 959]</td>
<td>TCP</td>
</tr>
<tr>
<td>file transfer</td>
<td>HTTP (e.g., Youtube),</td>
<td>TCP or UDP</td>
</tr>
<tr>
<td>streaming multimedia</td>
<td>RTP [RFC 1889]</td>
<td></td>
</tr>
<tr>
<td>Internet telephony</td>
<td>SIP, RTP, proprietary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(e.g., Skype)</td>
<td>typically UDP</td>
</tr>
</tbody>
</table>
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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

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

[Diagram showing client-server model with HTTP request and response]
HTTP overview (continued)

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

HTTP is “stateless”
- server maintains no information about past client requests

Aside

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

- Persistent HTTP
  - Multiple objects can be sent over a single connection.
  - Connection between client and server.
Nonpersistent HTTP

Suppose user enters URL

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

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

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

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

4. HTTP server closes TCP connection.


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
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
HTTP request message

- two types of HTTP messages: request, response
- HTTP request message:
  - ASCII (human-readable format)
  - request line (GET, POST, HEAD commands)
    - GET /somedir/page.html HTTP/1.1
    - Host: www.someschool.edu
    - User-agent: Mozilla/4.0
    - Connection: close
    - Accept-language: fr
  - header lines
  - Carriage return, line feed
    - (extra carriage return, line feed)
  - indicates end of message
HTTP request message: general format

```
method sp URL sp version cr lf
header field name : value cr lf
... header lines ...
header field name : value cr lf

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
- POST
- HEAD
- DELETE

- uploads file in entity body to path specified in URL field
- asks server to leave requested object out of response
- 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, e.g.,
requested
HTML file
data data data data data data ...
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:

   \texttt{telnet cis.poly.edu}
   \texttt{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:

   \texttt{GET /~ross/}
   \texttt{HTTP/1.1}
   \texttt{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
Cookies: keeping “state” (cont.)

client

cookie file

ebay 8734

usual http request msg

ebay 8734
amazon 1678

usual http response
Set-cookie: 1678

usual http response msg

ebay 8734
amazon 1678

one week later:

usual http request msg

cookie: 1678

usual http response msg

server

Amazon server creates ID 1678 for user

create entry

backend database

cookie-specific action

access

access

cookie-specific action

2: Application Layer
Cookies (continued)

What cookies can bring:
- authorization
- shopping carts
- recommendations
- user session state

How to keep “state”:
- protocol endpoints: maintain state at sender/receiver over multiple transactions
- cookies: http messages carry state

Aside

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

Diagram:
- Client
- Proxy server
- Origin server
- HTTP request
- HTTP response
More about Web caching

Why Web caching?
- cache acts as both client and server
- 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

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%
Caching example (cont)

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 (cont)

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
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
  
  ![Diagram of Conditional GET](image)
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FTP: the file transfer protocol

- FTP: the file transfer protocol
- FTP server: port 21
- FTP user interface
- FTP client
- user at host
- file transfer
- client/server model
  - client: side that initiates transfer (either to/from remote)
  - server: remote host
- ftp: RFC 959
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.
- 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:

- statusASCII text over control channel
- USER username OK, password required
- PASS password connection already open; transfer starting
- LIST return list of file in current directory
- 425 Can’t open data connection
- RETR filename retrieves file
- STOR filename stores (puts) file onto remote host
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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
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

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

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

Above lets you send email without using email client (reader)
SMTP: final words

Comparison with HTTP:

- SMTP uses persistent connections
- HTTP: pull
- SMTP: push
- SMTP server uses CRLF.CRLF to determine end of message
- 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 messages
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)
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

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

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 folders.
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DNS: Domain Name System

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

Internet hosts, routers:
- IP address (32 bit) - used for addressing datagrams
- “name”, e.g., ww.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
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!
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

13 root name servers worldwide:

- a Verisign, Dulles, VA
- b USC-ISI Marina del Rey, CA
- c Cogent, Herndon, VA (also LA)
- d U Maryland College Park, MD
- e NASA Mt View, CA
- f Internet Software C. Palo Alto, CA (and 36 other locations)
- g US DoD Vienna, VA
- h ARL Aberdeen, MD
- i Autonomica, Stockholm (plus 28 other locations)
- j Verisign, (21 locations)
- k RIPE London (also 16 other locations)
- l ICANN Los Angeles, CA
- m WIDE Tokyo (also Seoul, Paris, SF)
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?

Diagram:
- Requesting host: cis.poly.edu
- Local DNS server: dns.poly.edu
- Root DNS server
- TLD DNS server: dns.cs.umass.edu
- Authoritative DNS server: gaia.cs.umass.edu
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
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

- **Type=CNAME**
  - *name* is alias name for some “canonical” (the real) name
    - www.ibm.com is really servereast.backup2.ibm.com
  - *value* is canonical name

- **Type=MX**
  - *value* is name of mailserver associated with *name*
DNS protocol, messages

DNS protocol: query and reply messages, both with

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

<table>
<thead>
<tr>
<th>Identification</th>
<th>Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of questions</td>
<td>number of answer RRs</td>
</tr>
<tr>
<td>number of authority RRs</td>
<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)
DNS protocol, messages

Name, type fields for a query

RRs in response to query

records for authoritative servers

additional “helpful” info that may be used

**DNS** protocol, messages

<table>
<thead>
<tr>
<th>identification</th>
<th>flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of questions</td>
<td>number of answer RRs</td>
</tr>
<tr>
<td>number of authority RRs</td>
<td>number of additional RRs</td>
</tr>
<tr>
<td>questions (variable number of questions)</td>
<td></td>
</tr>
<tr>
<td>answers (variable number of resource records)</td>
<td></td>
</tr>
<tr>
<td>authority (variable number of resource records)</td>
<td></td>
</tr>
<tr>
<td>additional information (variable number of resource records)</td>
<td></td>
</tr>
</tbody>
</table>
Inserting records into DNS

- example: new startup “Network Utopia”
- register name networkuptopia.com at DNS registrar (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts two RRs into com TLD server:
    - (networkutopia.com, dns1.networkutopia.com, NS)
    - (dns1.networkutopia.com, 212.212.212.1, A)

- create authoritative server Type A record for www.networkuptopia.com; Type MX record for networkutopia.com
Chapter 2: Application layer

- 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
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
**File Distribution: Server-Client vs P2P**

**Question**: How much time to distribute file from one server to \( N \) peers?

\[
\begin{align*}
\text{Server} & \quad \text{Network (with abundant bandwidth)} \\
\text{File, size } F & \quad uN \\
\text{\( u \)} & \quad dN \\
\end{align*}
\]

\( u_s \): 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:
  - $NF/us$ time
- client i takes $F/d_i$ time to download

Time to distribute $F$ to $N$ clients using client/server approach $= \text{dcs} = \max \{ NF/us, \frac{F}{\min(d_i)} \}$

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

- server must send one copy: $F/us$ time
- client $i$ takes $F/d_i$ time to download
- $NF$ bits must be downloaded (aggregate)

- Fastest possible upload rate: $us + \sum_{i} u_i$

$$d_{P2P} = \max \{ F/us, F/min(d_i), NF/(us + \sum_{i} u_i) \}$$
Server-client vs. P2P: example

Client upload rate = u, $F/u = 1$ hour, $us = 10u$, $d_{\text{min}} \geq us$
File distribution: BitTorrent

- P2P file distribution

tracker: tracks peers participating in torrent

Torrent: group of peers exchanging chunks of a file

peer

obtain list of peers

trading chunks
BitTorrent (1)

- 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
BitTorrent (2)

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

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, \(key = h(\text{"Led Zeppelin IV"})\)
  - 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

Who’s resp for key 1110?

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.

Who’s resp for key 1110?
Peer Churn

- 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.

- 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.
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;
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.
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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

socket

A *application-created, OS-controlled* interface (a “door”) into which application process can both send and receive messages to/from another application process
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.
- 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.
Socket 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

application viewpoint

UDP provides unreliable transfer of groups of bytes (“datagrams”) between client and server

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
**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)

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

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

Client process

client UDP socket
Example: Java client (UDP)

```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();
```

1. Create input stream
2. Create client socket
3. Translate hostname to IP address using DNS

4. Send data
5. Receive data
6. Close connections

```java
```

2: Application Layer
Example: Java client (UDP), cont.

Create datagram with data-to-send, length, IP addr, port

Send datagram to server

Read datagram from server

DatagramPacket sendPacket =
new DatagramPacket(sendData, sendData.length, IPAddress, 9876);

clientSocket.send(sendPacket);

DatagramPacket receivePacket =
new DatagramPacket(receiveData, receiveData.length);

clientSocket.receive(receivePacket);

String modifiedSentence =
new String(receivePacket.getData());

System.out.println("FROM SERVER:" + modifiedSentence);

clientSocket.close();
}
Example: Java server (UDP)

```java
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);

            DatagramPacket receivePacket = new DatagramPacket(receiveData, receiveData.length);
            serverSocket.receive(receivePacket);
        }
    }
}
```
Example: Java server (UDP), cont

String sentence = new String(receivePacket.getData());

InetAddress IPAddress = receivePacket.getAddress();

int port = receivePacket.getPort();

String capitalizedSentence = sentence.toUpperCase();

sendData = capitalizedSentence.getBytes();

DatagramPacket sendPacket =
    new DatagramPacket(sendData, sendData.length, IPAddress, port);

serverSocket.send(sendPacket);

Get IP addr, port #, of sender

Create datagram to send to client

Write out datagram to socket

End of while loop, loop back and wait for another datagram
UDP observations & questions

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

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

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

application viewpoint

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

Server (running on hostid)

Client

create socket, port=x, for incoming request
requestSocket = ServerSocket()

wait for incoming connection request
connectionSocket = welcomeSocket.accept()

read request from connectionSocket

write reply to connectionSocket

close connectionSocket

TCP connection setup

create socket, connect to hostid, port=x
clientSocket = Socket()

send request using clientSocket

read reply from clientSocket

close clientSocket
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.
Socket programming with TCP

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)

```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());
    }
}
```
Example: Java client (TCP), cont.

```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)

```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()));

            String clientSentence = inFromClient.readLine();
            clientSentence = clientSentence.trim();
            capitalizedSentence = clientSentence.toUpperCase();

            System.out.println(capitalizedSentence);
        }
    }
}
```
Example: Java server (TCP), cont

Create output stream, attached to socket

Read in line from socket

Write out line to socket

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

clientSentence = inFromClient.readLine();

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

outToClient.writeBytes(capitalizedSentence);

End of while loop, loop back and wait for another client connection
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?
Chapter 2: Summary

our study of network apps now complete!

- application architectures
  - client-server
  - P2P
  - hybrid

- application service requirements:
  - reliability, bandwidth, delay

- specific protocols:
  - HTTP
  - FTP
  - SMTP, POP, IMAP
  - DNS
  - P2P: BitTorrent, Skype

- socket programming
Chapter 2: Summary

Most importantly: learned about protocols

- typical request/reply message exchange:
  - client requests info or service
  - server responds with data, status code

- message formats:
  - headers: fields giving info about data

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”