Chapter 2
Application Layer

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Computer Networking: A Top Down Approach
6th edition
Jim Kurose, Keith Ross
Addison-Wesley
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Chapter 2: outline

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 and TCP
Chapter 2: application layer

**our goals:**

- conceptual, implementation aspects of network application protocols
  - transport-layer service models
  - client-server paradigm
  - peer-to-peer paradigm

- learn about protocols by examining popular application-level protocols
  - HTTP
  - FTP
  - SMTP / POP3 / IMAP
  - DNS

- creating network applications
  - socket API
Some network apps

- e-mail
- web
- text messaging
- remote login
- P2P file sharing
- multi-user network games
- streaming stored video (YouTube, Hulu, Netflix)
- voice over IP (e.g., Skype)
- real-time video conferencing
- social networking
- search
- ...
- ...
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
Application architectures

possible structure of applications:

- client-server
- peer-to-peer (P2P)
Client-server architecture

server:
- always-on host
- permanent IP address
- data centers for scaling

clients:
- communicate with server
- may be intermittently connected
- may have dynamic IP addresses
- do not communicate directly with each other
P2P architecture

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

**clients, servers**

**client process**: process that initiates communication

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

- aside: 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 to deliver message to socket at receiving process

![Diagram of socket and network layers](Image)
Addressing processes

- to receive messages, process must have *identifier*
- host device has unique 32-bit IP address
- **Q:** does IP address of host on which process runs suffice for identifying the process?
  - **A:** no, *many* processes can be running on same host

- *identifier* includes both IP address and port numbers associated with process on host.
- example port numbers:
  - HTTP server: 80
  - mail server: 25
- to send HTTP message to gaia.cs.umass.edu web server:
  - IP address: 128.119.245.12
  - port number: 80
- **more shortly…**
App-layer protocol defines

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

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

proprietary protocols:
- e.g., Skype
What transport service does an app need?

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

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

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

security
- encryption, data integrity, …
# Transport service requirements: common apps

<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</td>
<td>yes, 100’s msec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>video:10kbps-5Mbps</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>same as above</td>
<td></td>
</tr>
<tr>
<td>stored audio/video</td>
<td>loss-tolerant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>interactive games</td>
<td>loss-tolerant</td>
<td>few kbps up</td>
<td>yes, few secs</td>
</tr>
<tr>
<td>text messaging</td>
<td>no loss</td>
<td>elastic</td>
<td>yes, 100’s msec</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>yes and no</td>
</tr>
</tbody>
</table>
**Internet transport protocols services**

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

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

**Q:** why bother? Why is there a UDP?
## 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 (e.g., 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>TCP or UDP</td>
</tr>
</tbody>
</table>
Securing TCP

TCP & UDP
- no encryption
- cleartext passwds sent into socket traverse Internet in cleartext

SSL
- provides encrypted TCP connection
- data integrity
- end-point authentication

SSL is at app layer
- Apps use SSL libraries, which “talk” to TCP

SSL socket API
- cleartext passwds sent into socket traverse Internet encrypted
- See Chapter 7

Application Layer 2-17
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   ▪ app requirements
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Web and HTTP

First, a review...

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

  www.someschool.edu/someDept/pic.gif

  - host name
  - path name
HTTP overview

HTTP: hypertext transfer protocol

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

uses TCP:

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

HTTP is “stateless”

- server maintains no information about past client requests

Aside:

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

**non-persistent HTTP**
- at most one object sent over TCP connection
  - connection then closed
- downloading multiple objects required multiple connections

**persistent HTTP**
- multiple objects can be sent over single TCP connection between client, server
Non-persistent HTTP

suppose user enters URL:
www.someSchool.edu/someDepartment/home.index  
(contains text, references to 10 jpeg images)

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
Non-persistent HTTP (cont.)

4. HTTP server closes TCP connection.


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

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

HTTP response time:
- one RTT to initiate TCP connection
- one RTT for HTTP request and first few bytes of HTTP response to return
- file transmission time
- non-persistent HTTP response time = 2RTT + file transmission time
Persistent HTTP

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

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

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

```
GET /index.html HTTP/1.1\r\nHost: www-net.cs.umass.edu\r\nUser-Agent: Firefox/3.6.10\r\nAccept: text/html,application/xhtml+xml\r\nAccept-Language: en-us,en;q=0.5\r\nAccept-Encoding: gzip,deflate\r\nAccept-Charset: ISO-8859-1,utf-8;q=0.7\r\nKeep-Alive: 115\r\nConnection: keep-alive\n\r\n```
HTTP request message: general format

```
method  sp  URL  sp  version  cr  lf

header field name  value  cr  lf

header field name  value  cr  lf

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
  - 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
Date: Sun, 26 Sep 2010 20:09:20 GMT
Server: Apache/2.0.52 (CentOS)
Last-Modified: Tue, 30 Oct 2007 17:00:02 GMT
ETag: "17dc6-a5c-bf716880"
Accept-Ranges: bytes
Content-Length: 2652
Keep-Alive: timeout=10, max=100
Connection: Keep-Alive
Content-Type: text/html; charset=ISO-8859-1

data data data data data data data data ...

header lines
HTTP response status codes

- status code appears in 1st line in server-to-client response message.

- some sample codes:
  
  200 OK
  - request succeeded, requested object later in this msg
  
  301 Moved Permanently
  - requested object moved, new location specified later in this msg
    (Location:)
  
  400 Bad Request
  - request msg not understood by server

  404 Not Found
  - requested document not found on this server

  505 HTTP Version Not Supported
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!

   (or use Wireshark to look at captured HTTP request/response)
User-server state: cookies

many Web sites use cookies

four components:

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

example:

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

**client**

- ebay 8734 cookie file
- ebay 8734 amazon 1678

**server**

- usual http request msg
- usual http response msg
- set-cookie: 1678

Amazon server creates ID 1678 for user

create entry

backend database

**one week later:**

- usual http request msg
- cookie: 1678
- cookie-specific action

**access**

- ebay 8734 amazon 1678
- cookie-specific action
Cookies (continued)

what cookies can be used for:
- 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
  - server for original requesting client
  - client to origin server

- typically cache is installed by ISP (university, company, residential ISP)

why Web caching?

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

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

**consequences:**
- LAN utilization: 15%  
  - problem!
- access link utilization = 99%
- total delay = Internet delay + access delay + LAN delay
  = 2 sec + minutes + usecs
Caching example: fatter access link

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

**consequences:**
- LAN utilization: 15%
- access link utilization = 99%
- total delay = Internet delay + access delay + LAN delay
  = 2 sec + minutes + usecs
- 154 Mbps

**Cost:** increased access link speed (not cheap!)
**Caching example: install local cache**

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

**consequences:**
- LAN utilization: 15%
- access link utilization = ?
- total delay = ?

*How to compute link utilization, delay?*

**Cost:** web cache (cheap!)
Caching example: install local cache

Calculating access link utilization, delay with cache:

- Suppose cache hit rate is 0.4
  - 40% requests satisfied at cache, 60% requests satisfied at origin

- Access link utilization:
  - 60% of requests use access link

- Data rate to browsers over access link:
  \[ 0.6 \times 1.50 \text{ Mbps} = 0.9 \text{ Mbps} \]
  - Utilization: \[ \frac{0.9}{1.54} = 0.58 \]

- Total delay:
  \[ 0.6 \times (\text{delay from origin servers}) + 0.4 \times (\text{delay when satisfied at cache}) \]
  \[ = 0.6 \times 2.01 + 0.4 \times (\sim \text{msecs}) \]
  \[ = \sim 1.2 \text{ secs} \]
  - Less than with 154 Mbps link (and cheaper too!)
Conditional GET

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

Object not modified before `<date>`

Object modified after `<date>`
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  ▪ SMTP, POP3, IMAP

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2.7 socket programming with UDP and TCP
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, using TCP
- client authorized over control connection
- client browses remote directory, sends commands over control connection
- when server receives file transfer command, server opens 2nd TCP data 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
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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., Outlook, Thunderbird, iPhone mail client
- outgoing, incoming messages stored on server
Electronic mail: mail servers

mail servers:

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

![Diagram of mail servers and SMTP protocol](image)
Electronic Mail: SMTP [RFC 2821]

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

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

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

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

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

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

6) Bob invokes his user agent to read message
Sample SMTP interaction

S: 220 hamburger.edu
C: HELO crepes.fr
S: 250 Hello crepes.fr, pleased to meet you
C: MAIL FROM: <alice@crepes.fr>
S: 250 alice@crepes.fr... Sender ok
C: RCPT TO: <bob@hamburger.edu>
S: 250 bob@hamburger.edu ... Recipient ok
C: DATA
S: 354 Enter mail, end with "." on a line by itself
C: Do you like ketchup?
C: How about pickles?
C: .
S: 250 Message accepted for delivery
C: QUIT
S: 221 hamburger.edu closing connection
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 MAIL FROM, RCPT TO: commands!
- Body: the “message”
  - ASCII characters only
Mail access protocols

- **SMTP**: delivery/storage to receiver’s server
- mail access protocol: retrieval from server
  - **POP**: Post Office Protocol [RFC 1939]: authorization, download
  - **IMAP**: Internet Mail Access Protocol [RFC 1730]: more features, including manipulation of stored msgs on server
  - **HTTP**: 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
```
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

- keeps all messages in one place: at server
- allows user to organize messages in folders
- keeps user state across sessions:
  - names of folders and mappings between message IDs and folder name
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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., www.yahoo.com - used by humans

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

**Q:** how to map between IP address and name, and vice versa?
DNS: services, structure

DNS services
- hostname to IP address translation
- host aliasing
  - canonical, alias names
- mail server aliasing
- load distribution
  - replicated Web servers: many IP addresses correspond to one name

why not centralize DNS?
- single point of failure
- traffic volume
- distant centralized database
- maintenance

A: doesn’t scale!
DNS: a distributed, hierarchical database

client wants IP for www.amazon.com; 1st approx:

- client queries 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
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

- 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 at upper levels of hierarchy?
DNS: caching, updating records

- once (any) name server learns mapping, it *caches* mapping
  - cache entries timeout (disappear) after some time (TTL)
  - TLD servers typically cached in local name servers
    - thus root name servers not often visited
- cached entries may be *out-of-date* (best effort name-to-address translation!)
  - if name host changes IP address, may not be known Internet-wide until all TTLs expire
- update/notify mechanisms proposed IETF standard
  - RFC 2136
**DNS records**

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

RR format: \((\text{name}, \text{value}, \text{type}, \text{ttl})\)

- **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
  - **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

- *query* and *reply* messages, both with same *message format*

**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># questions</td>
<td># answer RRs</td>
</tr>
<tr>
<td># authority RRs</td>
<td># additional RRs</td>
</tr>
<tr>
<td>questions (variable # of questions)</td>
<td></td>
</tr>
<tr>
<td>answers (variable # of RRs)</td>
<td></td>
</tr>
<tr>
<td>authority (variable # of RRs)</td>
<td></td>
</tr>
<tr>
<td>additional info (variable # of RRs)</td>
<td></td>
</tr>
</tbody>
</table>
DNS protocol, messages

- Identification
- Flags
- # Questions
- # Answer RRs
- # Authority RRs
- # Additional RRs
- Questions (variable # of questions)
- Answers (variable # of RRs)
- Authority (variable # of RRs)
- Additional info (variable # of RRs)

- Name, type fields for a query
- RRs in response to query
- Records for authoritative servers
- Additional “helpful” info that may be used

2 bytes 2 bytes

Application Layer 2-72
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
Attacking DNS

DDoS attacks

- Bombard root servers with traffic
  - Not successful to date
  - Traffic Filtering
  - Local DNS servers cache IPs of TLD servers, allowing root server bypass
- Bombard TLD servers
  - Potentially more dangerous

Redirect attacks

- Man-in-middle
  - Intercept queries
- DNS poisoning
  - Send bogus relies to DNS server, which caches

Exploit DNS for DDoS

- Send queries with spoofed source address: target IP
- Requires amplification
Chapter 2: outline

2.1 principles of network applications
   ▪ app architectures
   ▪ app requirements
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 and TCP
Pure P2P architecture

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

**examples:**
- file distribution (BitTorrent)
- Streaming (KanKan)
- VoIP (Skype)
File distribution: client-server vs P2P

**Question:** how much time to distribute file (size $F$) from one server to $N$ peers?

- peer upload/download capacity is limited resource
File distribution time: client-server

- **server transmission**: must sequentially send (upload) $N$ file copies:
  - time to send one copy: $F/u_s$
  - time to send $N$ copies: $NF/u_s$

- **client**: each client must download file copy
  - $d_{\text{min}} = \min \text{ client download rate}$
  - min client download time: $F/d_{\text{min}}$

\[
D_{c-s} \geq \max\{NF/u_s, F/d_{\text{min}}\}
\]

**time to distribute $F$ to $N$ clients using client-server approach**

increases linearly in $N$
File distribution time: P2P

- **server transmission**: must upload at least one copy
  - time to send one copy: \( F/u_s \)
- **client**: each client must download file copy
  - min client download time: \( F/d_{\text{min}} \)
- **clients**: as aggregate must download \( NF \) bits
  - max upload rate (limiting max download rate) is \( u_s + \sum u_i \)

Time to distribute \( F \) to \( N \) clients using P2P approach

\[
D_{P2P} \geq \max\{F/u_s, F/d_{\text{min}}, NF/(u_s + \sum u_i)\}
\]

Increases linearly in \( N \) …

… but so does this, as each peer brings service capacity

Application Layer 2-79
Client-server vs. P2P: example

client upload rate = \( u \), \( \frac{F}{u} = 1 \) hour, \( u_s = 10u \), \( d_{min} \geq u_s \)
P2P file distribution: BitTorrent

- file divided into 256Kb chunks
- peers in torrent send/receive file chunks

**tracker**: tracks peers participating in torrent

**torrent**: group of peers exchanging chunks of a file

Alice arrives ...
... obtains list of peers from tracker
... and begins exchanging file chunks with peers in torrent
P2P file distribution: BitTorrent

- peer joining torrent:
  - has no chunks, but will accumulate them over time from other peers
  - registers with tracker to get list of peers, connects to subset of peers (“neighbors”)
- while downloading, peer uploads chunks to other peers
- peer may change peers with whom it exchanges chunks
- **churn**: peers may come and go
- once peer has entire file, it may (selfishly) leave or (altruistically) remain in torrent
BitTorrent: requesting, sending file chunks

**requesting chunks:**
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

**sending chunks: tit-for-tat**
- Alice sends chunks to those four peers currently sending her chunks *at highest rate*
  - other peers are choked by Alice (do not receive chunks from her)
  - re-evaluate top 4 every 10 secs
- every 30 secs: randomly select another peer, starts sending chunks
  - “optimistically unchoke” this peer
  - newly chosen peer may join top 4
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

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

- DHT: a *distributed P2P database*

- database has *(key, value)* pairs; examples:
  - key: ss number; value: human name
  - key: movie title; value: IP address

- Distribute the *(key, value)* pairs over the *(millions of peers)*

- a peer *queries* DHT with key
  - DHT returns values that match the key

- peers can also *insert* *(key, value)* pairs
Q: how to assign keys to peers?

- central issue:
  - assigning (key, value) pairs to peers.

- basic idea:
  - convert each key to an integer
  - Assign integer to each peer
  - put (key, value) pair in the peer that is closest to the key
DHT identifiers

- assign integer identifier to each peer in range \([0, 2^n - 1]\) for some \(n\).
  - each identifier represented by \(n\) bits.

- require each key to be an integer in same range
- to get integer key, hash original key
  - e.g., \(\text{key} = \text{hash}(\text{“Led Zeppelin IV”})\)
  - this is why it's is referred to as a distributed “hash” table
Assign keys to peers

- rule: assign key to the peer that has the closest ID.
- convention in lecture: closest is the immediate successor of the key.
- e.g., $n=4$; 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”
Circular DHT (I)

$O(N)$ messages on average to resolve query, when there are $N$ peers

Who’s responsible for key 1110?

I am

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.

Who’s responsible for key 1110?
Peer churn

example: peer 5 abruptly leaves

- peer 4 detects peer 5 departure; 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?

handling peer churn:
- peers may come and go (churn)
- each peer knows address of its two successors
- each peer periodically pings its two successors to check aliveness
- if immediate successor leaves, choose next successor as new immediate successor
Chapter 2: outline

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2.7 socket programming with UDP and TCP
Socket programming

**goal:** learn how to build client/server applications that communicate using sockets

**socket:** door between application process and end-end-transport protocol
Socket programming

Two socket types for two transport services:
- **UDP**: unreliable datagram
- **TCP**: reliable, byte stream-oriented

Application Example:
1. Client reads a line of characters (data) from its keyboard and sends the data to the server.
2. The server receives the data and converts characters to uppercase.
3. The server sends the modified data to the client.
4. The client receives the modified data and displays the line on its screen.
Socket programming with UDP

UDP: no “connection” between client & server

- no handshaking before sending data
- sender explicitly attaches IP destination address and port # to each packet
- rcvr extracts sender IP address and port# from received packet

UDP: transmitted data may be lost or received out-of-order

Application viewpoint:
- UDP provides unreliable transfer of groups of bytes (“datagrams”) between client and server
Client/server socket interaction: UDP

(C/C++ System calls shown in green)

server (running on serverIP)

create socket, port= x:
serverSocket =
socket(AF_INET,SOCK_DGRAM)

( socket(2) )  ( bind(2) )

read datagram from serverSocket

( recvfrom(2) )
write reply to serverSocket
specifying ( sendto(2) )
client address, port number

( See also ip(7), udp(7) )

client

create socket:
clientSocket = ( socket(2) )
socket(AF_INET,SOCK_DGRAM)

Create datagram with server IP and port=x; send datagram via clientSocket ( sendto(2) )

read datagram from clientSocket ( recvfrom(2) )

close clientSocket ( close(2) )
Example app: UDP client

Python UDPClient

```
from socket import *
serverName = ‘hostname’
serverPort = 12000
clientSocket = socket(socket.AF_INET,
                      socket.SOCK_DGRAM)
message = raw_input(‘Input lowercase sentence:’)
clientSocket.sendto(message,(serverName, serverPort))
modifiedMessage, serverAddress =
  clientSocket.recvfrom(2048)
print modifiedMessage
clientSocket.close()
```
Example app: UDP server

Python UDPServer

```python
from socket import *
s
serverPort = 12000

serverSocket = socket(AF_INET, SOCK_DGRAM)
serverSocket.bind(('', serverPort))

print("The server is ready to receive")

while 1:
    message, clientAddress = serverSocket.recvfrom(2048)
    modifiedMessage = message.upper()
    serverSocket.sendto(modifiedMessage, clientAddress)
```

create UDP socket
bind socket to local port number 12000
loop forever
Read from UDP socket into message, getting client’s address (client IP and port)
send upper case string back to this client
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 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 that particular 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 byte-stream transfer (“pipe”) between client and server
Client/server socket interaction: TCP

server (running on hostid)

create socket, port=x, for incoming request:
serverSocket = socket()

socket(2)

bind(2), listen(2)

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

accept(2)

TCP

connection setup

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

socket(2), connect(2)

send request using clientSocket

send(2)

read request from connectionSocket

recv(2)

write reply to connectionSocket

send(2)

read reply from clientSocket

recv(2)

close connectionSocket

close(2)

( See also ip(7), tcp(7) )
Example app: TCP client

Python TCPClient

```
from socket import *
serverName = 'servername'
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName, serverPort))
sentence = raw_input('Input lowercase sentence:')
clientSocket.send(sentence)
modifiedSentence = clientSocket.recv(1024)
print 'From Server:', modifiedSentence
clientSocket.close()
```
Example app: TCP server

Python TCPServer

from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind(('',serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while 1:
    connectionSocket, addr = serverSocket.accept()
sentence = connectionSocket.recv(1024)
capitalizedSentence = sentence.upper()
connectionSocket.send(capitalizedSentence)
connectionSocket.close()
Chapter 2: summary

our study of network apps now complete!

- application architectures
  - client-server
  - P2P
- 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, DHT
- socket programming: TCP, UDP sockets
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
  - 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”