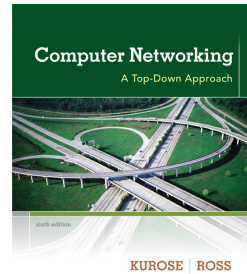


Chapter 2

Application Layer



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**Computer
Networking: A Top
Down Approach**
6th edition
Jim Kurose, Keith Ross
Addison-Wesley
March 2012

Application Layer 2-1

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

Application Layer 2-2

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

Application Layer 2-3

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
- ❖ ...
- ❖ ...

Application Layer 2-4

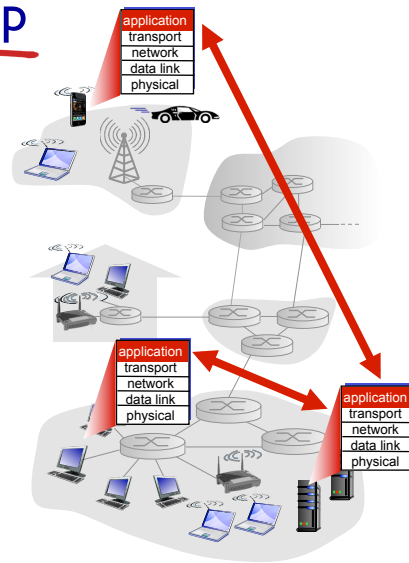
Creating a network app

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 Layer 2-5

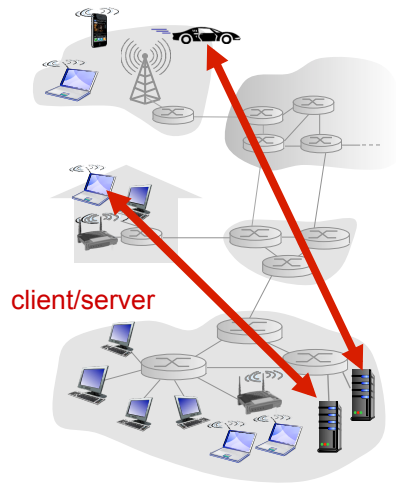
Application architectures

possible structure of applications:

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

Application Layer 2-6

Client-server architecture



server:

- ❖ always-on host
- ❖ permanent IP address
- ❖ data centers for scaling

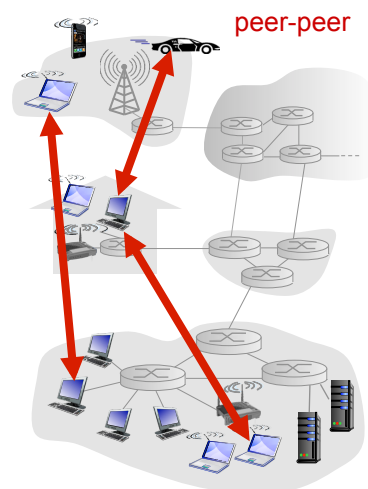
clients:

- ❖ communicate with server
- ❖ may be intermittently connected
- ❖ may have dynamic IP addresses
- ❖ do not communicate directly with each other

Application Layer 2-7

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



Application Layer 2-8

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

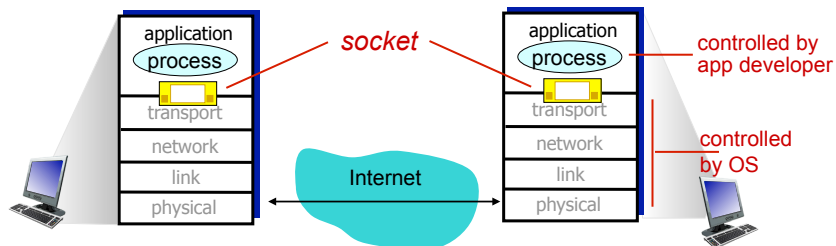
server process: process that waits to be contacted

- ❖ aside: applications with P2P architectures have client processes & server processes

Application Layer 2-9

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



Application Layer 2-10

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...

Application Layer 2-11

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

Application Layer 2-12

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, ...

Application Layer 2-13

Transport service requirements: common apps

| application | data loss | throughput | time sensitive |
|-----------------------|---------------|---|-----------------------------------|
| file transfer | no loss | elastic | no |
| e-mail | no loss | elastic | no |
| Web documents | no loss | elastic | no |
| real-time audio/video | loss-tolerant | audio: 5kbps-1Mbps video: 10kbps-5Mbps | yes, 100' s msec |
| stored audio/video | loss-tolerant | same as above | |
| interactive games | loss-tolerant | few kbps up | yes, few secs |
| text messaging | no loss | elastic | yes, 100' s msec yes and no |

Application Layer 2-14

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?

Application Layer 2-15

Internet apps: application, transport protocols

| application | application layer protocol | underlying transport protocol |
|------------------------|--------------------------------------|-------------------------------|
| e-mail | SMTP [RFC 2821] | TCP |
| remote terminal access | Telnet [RFC 854] | TCP |
| Web | HTTP [RFC 2616] | TCP |
| file transfer | FTP [RFC 959] | TCP |
| streaming multimedia | HTTP (e.g., YouTube), RTP [RFC 1889] | TCP or UDP |
| Internet telephony | SIP, RTP, proprietary (e.g., Skype) | TCP or UDP |

Application Layer 2-16

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

Chapter 2: outline

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Application Layer 2-18

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.,

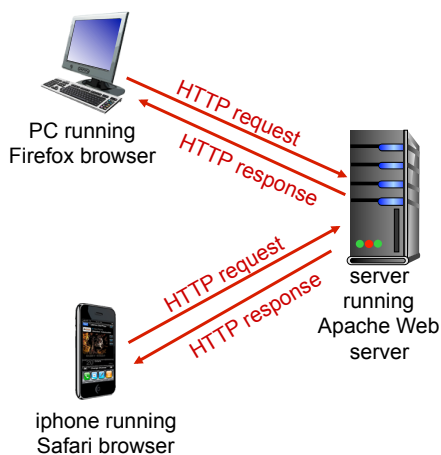
www.someschool.edu / someDept/pic.gif
host name path name

Application Layer 2-19

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



Application Layer 2-20

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

Application Layer 2-21

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

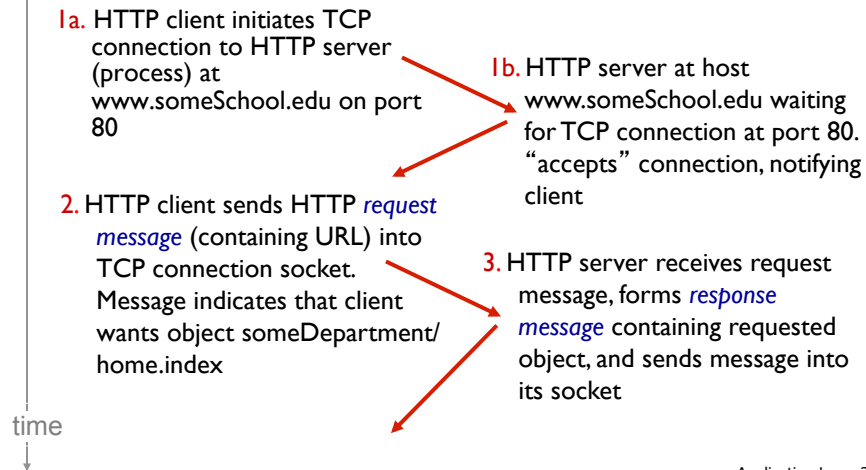
Application Layer 2-22

Non-persistent HTTP

suppose user enters URL:

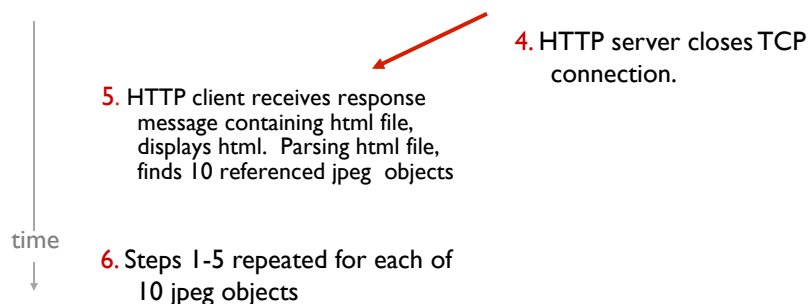
`www.someSchool.edu/someDepartment/home.index`

(contains text,
references to 10
jpeg images)



Application Layer 2-23

Non-persistent HTTP (cont.)



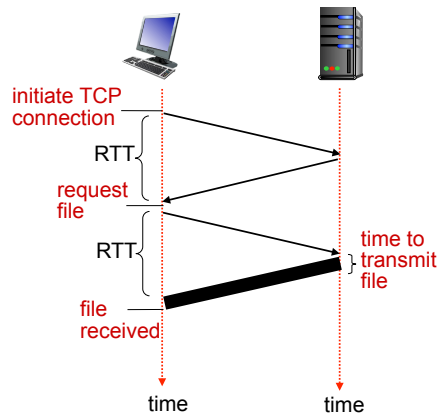
Application Layer 2-24

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 =
 $2\text{RTT} + \text{file transmission time}$



Application Layer 2-25

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

Application Layer 2-26

HTTP request message

❖ two types of HTTP messages: *request, response*

❖ **HTTP request message:**

- ASCII (human-readable format)

request line
(GET, POST,
HEAD commands)

header
lines

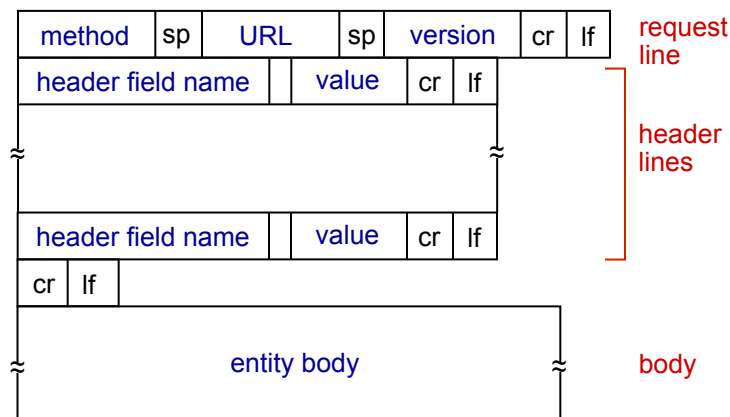
carriage return,
line feed at start
of line indicates
end of header lines

```
GET /index.html HTTP/1.1\r\n
Host: www-net.cs.umass.edu\r\n
User-Agent: Firefox/3.6.10\r\n
Accept: text/html,application/xhtml+xml\r\n
Accept-Language: en-us,en;q=0.5\r\n
Accept-Encoding: gzip,deflate\r\n
Accept-Charset: ISO-8859-1,utf-8;q=0.7\r\n
Keep-Alive: 115\r\n
Connection: keep-alive\r\n
\r\n
```

carriage return character
line-feed character

Application Layer 2-27

HTTP request message: general format



Application Layer 2-28

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`

Application Layer 2-29

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

Application Layer 2-30

HTTP response message

status line
(protocol
status code
status phrase)

header
lines

data, e.g.,
requested
HTML file

```
HTTP/1.1 200 OK\r\n
Date: Sun, 26 Sep 2010 20:09:20 GMT\r\n
Server: Apache/2.0.52 (CentOS)\r\n
Last-Modified: Tue, 30 Oct 2007 17:00:02 GMT\r\n
ETag: "17dc6-a5c-bf716880"\r\n
Accept-Ranges: bytes\r\n
Content-Length: 2652\r\n
Keep-Alive: timeout=10, max=100\r\n
Connection: Keep-Alive\r\n
Content-Type: text/html;\r\n
charset=ISO-8859-1\r\n
\r\n
data data data data data ...
```

Application Layer 2-31

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**

Application Layer 2-32

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)

Application Layer 2-33

User-server state: cookies

many Web sites use cookies

four components:

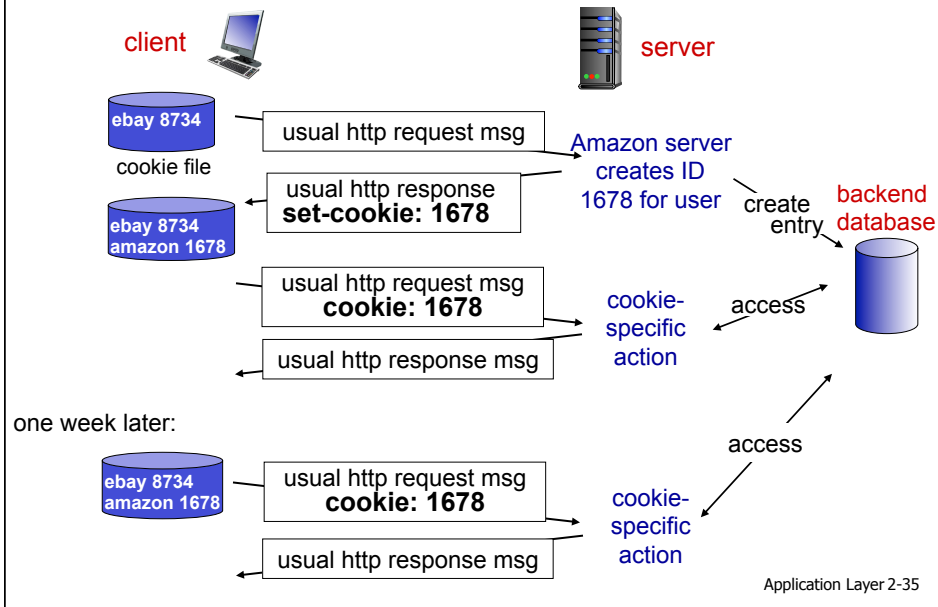
- 1) cookie header line of HTTP *response* message
- 2) cookie header line in next HTTP *request* message
- 3) cookie file kept on user's host, managed by user's browser
- 4) back-end database at Web site

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

Application Layer 2-34

Cookies: keeping “state” (cont.)



Cookies (continued)

what cookies can be used for:

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

cookies and privacy: aside

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

how to keep “state”:

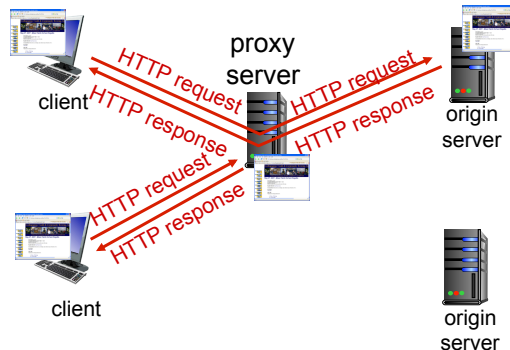
- ❖ protocol endpoints: maintain state at sender/receiver over multiple transactions
- ❖ cookies: http messages carry state

Application Layer 2-36

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



Application Layer 2-37

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)

Application Layer 2-38

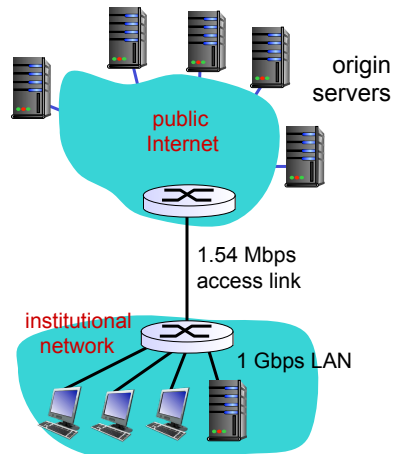
Caching example:

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%
- ❖ access link utilization = **99%** *problem!*
- ❖ total delay = Internet delay + access delay + LAN delay
= 2 sec + minutes + usecs



Application Layer 2-39

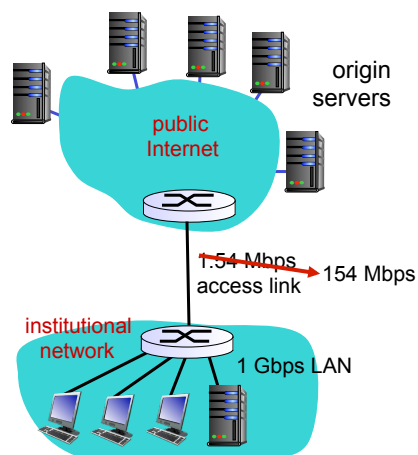
Caching example: fatter access link

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~~ → 154 Mbps

consequences:

- ❖ LAN utilization: 15%
- ❖ access link utilization = ~~99%~~ → 9.9%
- ❖ total delay = Internet delay + access delay + LAN delay
= 2 sec + ~~minutes~~ → msecs



Cost: increased access link speed (not cheap!)

Application Layer 2-40

Caching example: install local cache

assumptions:

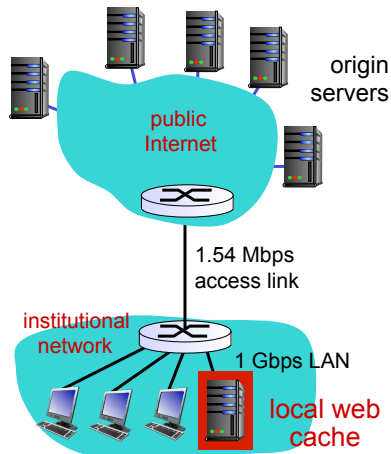
- ❖ avg object size: 100K bits
- ❖ avg request rate from browsers to origin servers: 15/sec
- ❖ avg data rate to browsers: 1.50 Mbps
- ❖ RTT from institutional router to any origin server: 2 sec
- ❖ access link rate: 1.54 Mbps

consequences:

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

How to compute link utilization, delay?

Cost: web cache (cheap!)

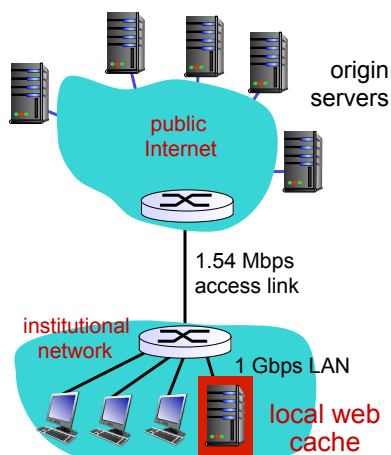


Application Layer 2-41

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
 - = $0.6 \times 1.50 \text{ Mbps} = .9 \text{ Mbps}$
 - utilization = $0.9 / 1.54 = .58$
- ❖ total delay
 - = $0.6 \times (\text{delay from origin servers}) + 0.4 \times (\text{delay when satisfied at cache})$
 - = $0.6 (2.01) + 0.4 (\sim \text{msecs})$
 - = $\sim 1.2 \text{ secs}$
 - less than with 154 Mbps link (and cheaper too!)



Application Layer 2-42

Conditional GET

- ❖ **Goal:** don't send object if cache has up-to-date cached version

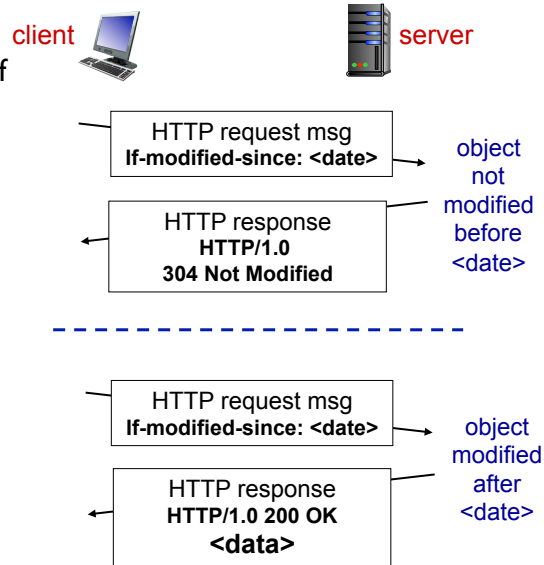
- no object transmission delay
- lower link utilization

- ❖ **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



Application Layer 2-43

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- SMTP, POP3, IMAP

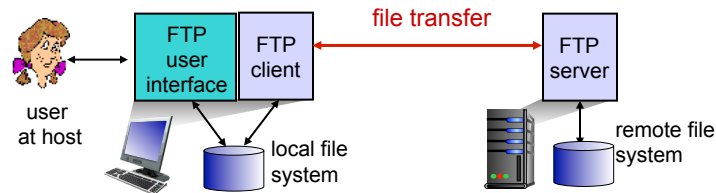
2.5 DNS

2.6 P2P applications

2.7 socket programming with UDP and TCP

Application Layer 2-44

FTP: the file transfer protocol

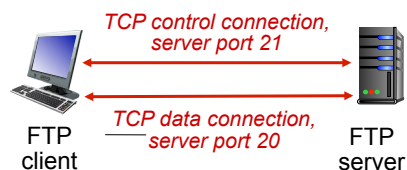


- ❖ transfer file to/from remote host
- ❖ client/server model
 - *client*: side that initiates transfer (either to/from remote)
 - *server*: remote host
- ❖ ftp: RFC 959
- ❖ ftp server: port 21

Application Layer 2-45

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



Application Layer 2-46

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 2-47

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Application Layer 2-48

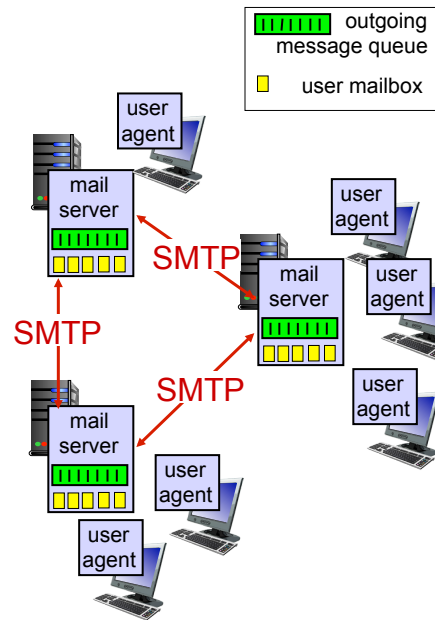
Electronic mail

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

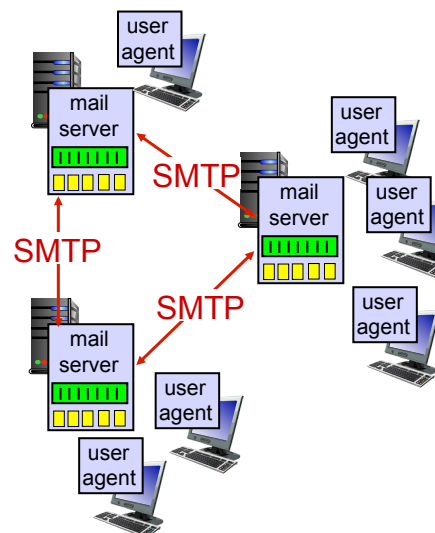


Application Layer 2-49

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



Application Layer 2-50

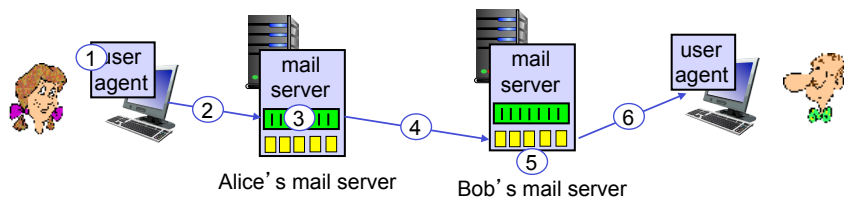
Electronic Mail: SMTP [RFC 2821]

- ❖ 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

Application Layer 2-51

Scenario: Alice sends message to Bob

- 1) Alice uses UA to compose message "to" bob@school.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



Application Layer 2-52

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
```

Application Layer 2-53

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)

Application Layer 2-54

SMTP: final words

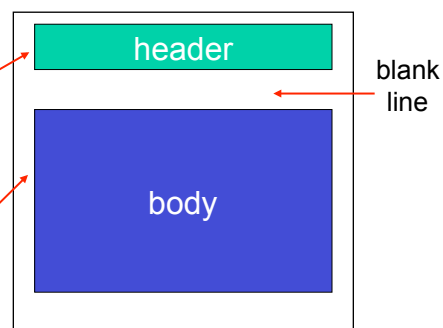
- ❖ SMTP uses persistent connections
 - ❖ SMTP requires message (header & body) to be in 7-bit ASCII
 - ❖ SMTP server uses CRLF.CRLF to determine end of message
- comparison with HTTP:*
- ❖ HTTP: pull
 - ❖ SMTP: push
 - ❖ both have ASCII command/response interaction, status codes
 - ❖ HTTP: each object encapsulated in its own response msg
 - ❖ SMTP: multiple objects sent in multipart msg

Application Layer 2-55

Mail message format

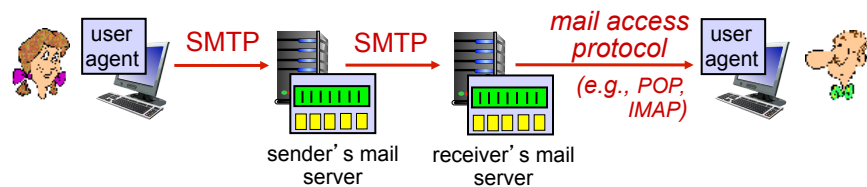
SMTP: protocol for exchanging email msgs
RFC 822: standard for text message format:

- ❖ header lines, e.g.,
 - To:
 - From:
 - Subject:
- different from SMTP MAIL FROM, RCPT TO: commands!*
- ❖ Body: the “message”
 - ASCII characters only



Application Layer 2-56

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.

Application Layer 2-57

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
  
```

Application Layer 2-58

POP3 (more) and IMAP

more about POP3

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

IMAP

- ❖ 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

Application Layer 2-59

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

Application Layer 2-60

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: how to map between IP address and name, and vice versa ?

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”

Application Layer 2-61

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

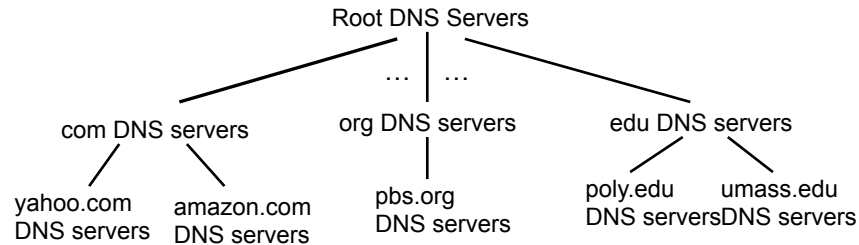
why not centralize DNS?

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

A: *doesn't scale!*

Application Layer 2-62

DNS: a distributed, hierarchical database



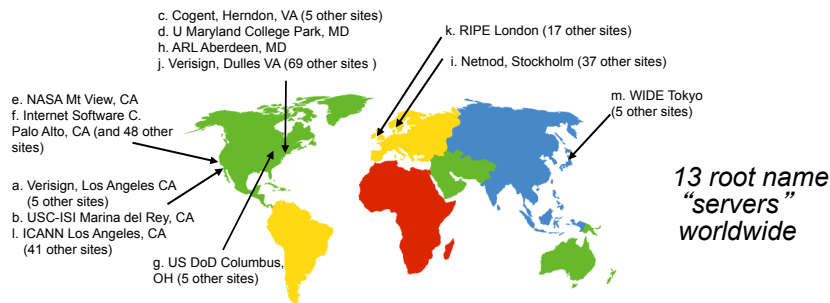
client wants IP for www.amazon.com; 1st approx:

- ❖ 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

Application Layer 2-63

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



Application Layer 2-64

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

Application Layer 2-65

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

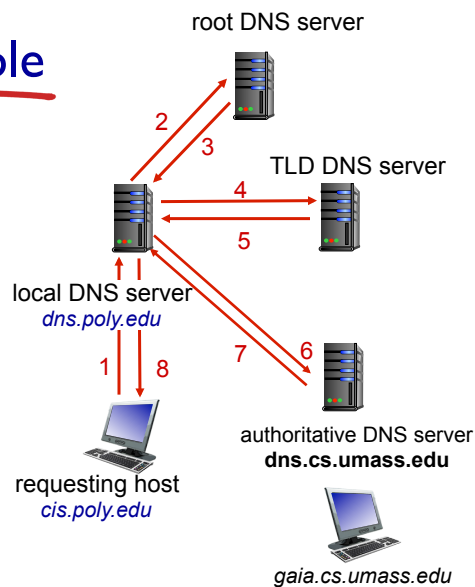
Application Layer 2-66

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”

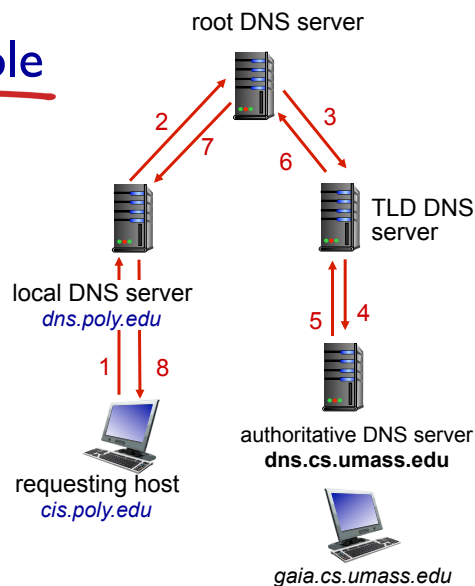


Application Layer 2-67

DNS name resolution example

recursive query:

- ❖ puts burden of name resolution on contacted name server
- ❖ heavy load at upper levels of hierarchy?



Application Layer 2-68

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

Application Layer 2-69

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
- **www.ibm.com** is really **servereast.backup2.ibm.com**
- **value** is canonical name

type=MX

- **value** is name of mailserver associated with **name**

Application Layer 2-70

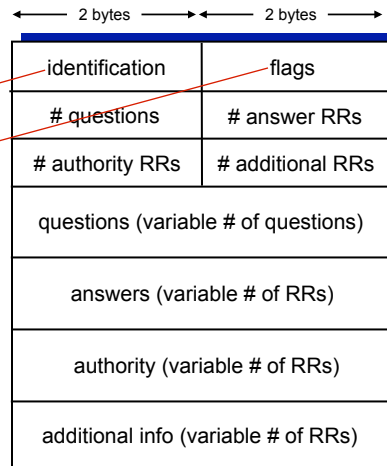
DNS protocol, messages

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

msg header

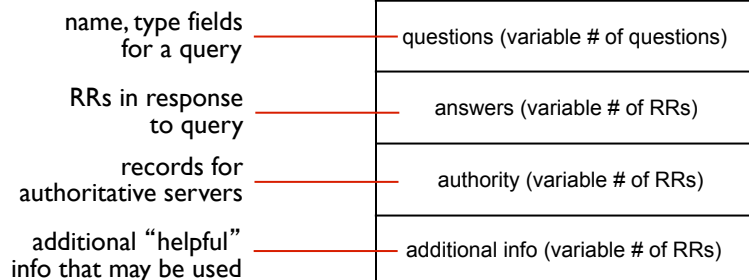
- ❖ **identification**: 16 bit # for query, reply to query uses same #

- ❖ **flags**:
 - query or reply
 - recursion desired
 - recursion available
 - reply is authoritative



Application Layer 2-71

DNS protocol, messages



Application Layer 2-72

Inserting records into DNS

- ❖ example: new startup “Network Utopia”
- ❖ register name networkutopia.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

Application Layer 2-73

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 replies to DNS server, which caches

Exploit DNS for DDoS

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

Application Layer 2-74

Chapter 2: outline

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2.5 DNS

2.6 P2P applications

2.7 socket programming with UDP and TCP

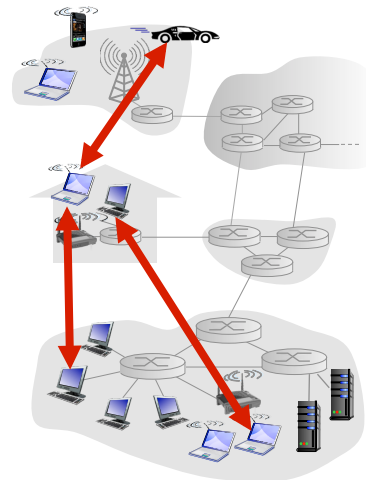
Application Layer 2-75

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)

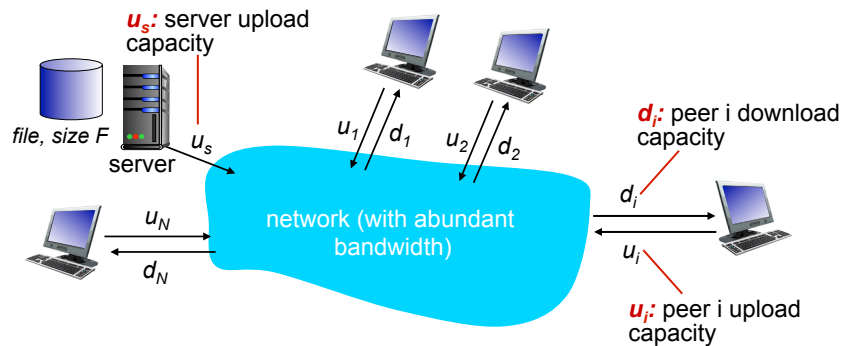


Application Layer 2-76

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



Application Layer 2-77

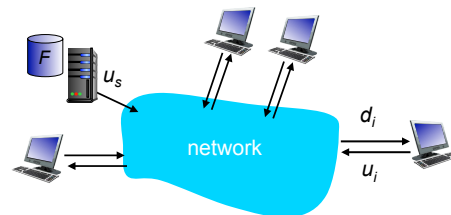
File distribution time: client-server

- ❖ **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_{\min} = min client download rate
- min client download time: F/d_{\min}



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

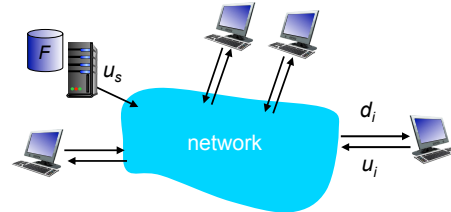
$$D_{c-s} \geq \max\{NF/u_s, F/d_{\min}\}$$

increases linearly in N

Application Layer 2-78

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_{\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

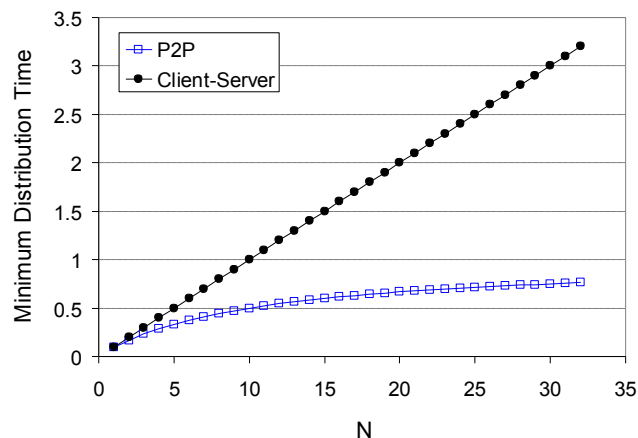
$$D_{P2P} \geq \max\{F/u_s, F/d_{\min}, NF/(u_s + \sum u_i)\}$$

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 , $F/u = 1$ hour, $u_s = 10u$, $d_{\min} \geq u_s$



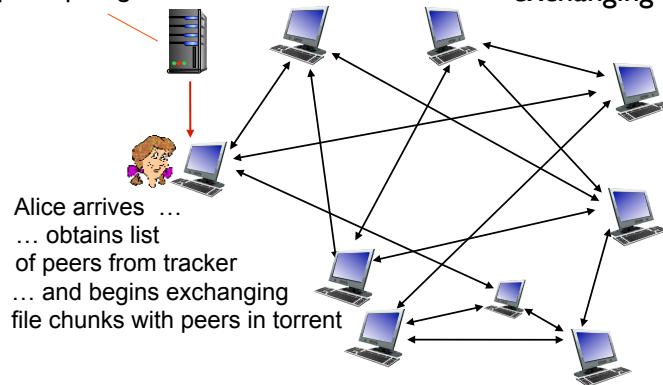
Application Layer 2-80

P2P file distribution: BitTorrent

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

tracker: tracks peers participating in torrent

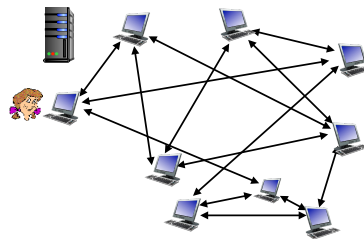
torrent: group of peers exchanging chunks of a file



Application Layer 2-81

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



Application Layer 2-82

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

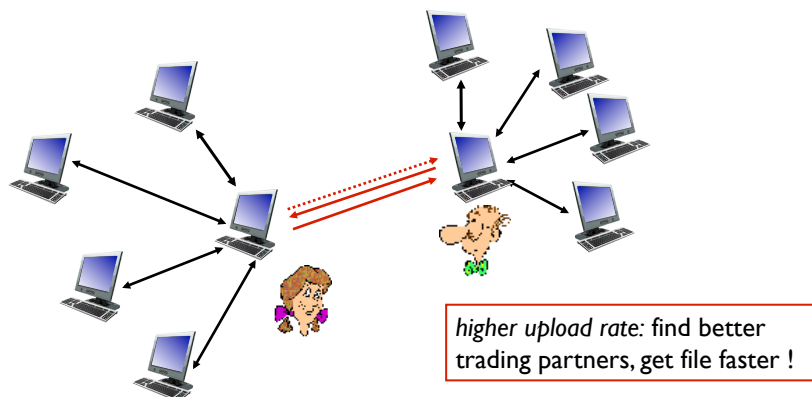
sending chunks: tit-for-tat

- ❖ 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

Application Layer 2-83

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



Application Layer 2-84

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

Application 2-85

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

Application 2-86

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., key = **hash**("Led Zeppelin IV")
 - this is why its is referred to as a *distributed "hash" table*

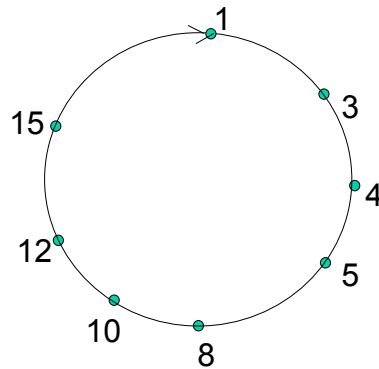
Application 2-87

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

Application 2-88

Circular DHT (I)

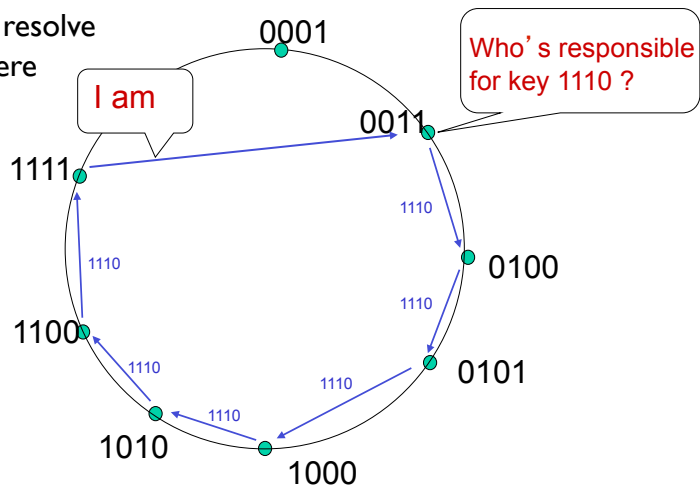


- ❖ each peer *only* aware of immediate successor and predecessor.
- ❖ “overlay network”

Application 2-89

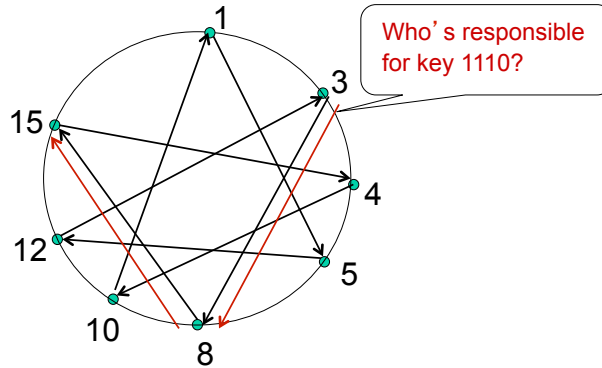
Circular DHT (I)

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



Application 2-90

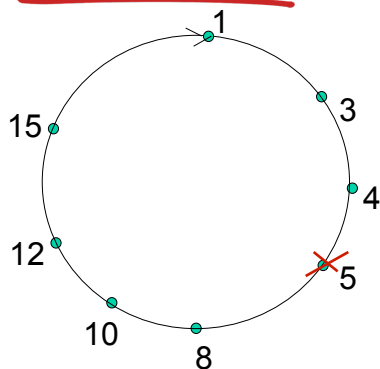
Circular DHT with shortcuts



- ❖ 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

Application 2-91

Peer churn



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

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?

Application 2-92

Chapter 2: outline

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2.5 DNS

2.6 P2P applications

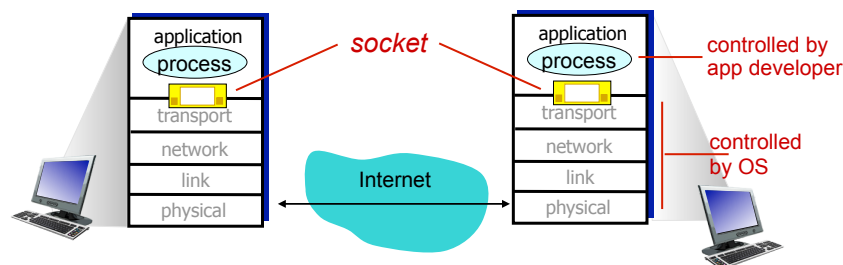
2.7 socket programming with UDP and TCP

Application Layer 2-93

Socket programming

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

socket: door between application process and end-end-transport protocol



Application Layer 2-94

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.

Application Layer 2-95

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

Application Layer 2-96

Client/server socket interaction: UDP

server (running on serverIP)

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

read datagram from
`serverSocket`

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

client

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

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

read datagram from
`clientSocket`

close
`clientSocket`

Application 2-97

Berkeley Socket API for UDP (in C):

Server

```
int socket(int family, int type,  
int protocol);  
int bind(int sockfd,  
struct sockaddr *myaddr,  
int addrlen);
```

```
int recvfrom(int sockfd, char *buff,  
int nbytes, int flags,  
struct sockaddr *from,  
int *addrlen);
```

```
int sendto(...);
```

```
int close(int fd);
```

Client

```
int socket(...);  
int bind(...);
```

```
int sendto(int sockfd, char *buff,  
int nbytes, int flags,  
struct sockaddr *to, int addrlen);
```

```
int recvfrom(...);
```

```
int close(...);
```

2: Application Layer 98

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

Application Layer 2-99

Client/server socket interaction: TCP

server (running on `hostid`)

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

wait for incoming
connection request
`connectionSocket =`
`serverSocket.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

Application Layer 2-100

Sketch of a C Client

```

bzero((char *)&serv_addr, sizeof(serv_addr));
serv_addr.sin_family = AF_INET;
serv_addr.sin_addr.s_addr = htonl(SERVER_HOST_IP_ADDRESS);
serv_addr.sin_port = htons(SERVER_TCP_PORT);

if (( sockfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    perror("client: can't open stream socket");

if (connect(sockfd, (struct sockaddr *)&serv_addr, sizeof(serv_addr)) < 0)
    perror("client: cannot connect to server");

/* send request to server, receive reply */

close(sockfd);
}

```

Specifying
Server Info

Create a TCP
socket

Connect socket to
the server

2: Application Layer 101

Sketch of a TCP Server (in C)

```

if (( sockfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    perror("server: can't open stream socket");

bzero((char *)&serv_addr, sizeof(serv_addr));
serv_addr.sin_family = AF_INET;
serv_addr.sin_addr.s_addr = htonl(INADDR_ANY); /* host to network long */
serv_addr.sin_port = htons(SERV_TCP_PORT); /* host to network short */

if (bind(sockfd, (struct sockaddr *)&serv_addr, sizeof(serv_addr)) < 0)
    perror("server: can't bind local address");

listen(sockfd, 5);

while(1){
    newsockfd = accept(sockfd, (struct sockaddr *)&cli_addr, &clilen);

    /* receive request from client, send reply */

    close(newsockfd);
}

```

Create a TCP
socket

Specify info for
the server socket

Bind the info to the
socket

Set the queue length
for incoming connect request
from clients

Accept a connect req from
a client and return a new
socket for that connection

2: Application Layer 102

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

Application Layer 2-103

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”

Application Layer 2-104