# Computer Networks and Applications

COMP 3331/COMP 9331

Week 3

## Application Layer (DNS, P2P, Video Streaming and CDN)

**Reading Guide: Chapter 2, Sections 2.4 -2.7**

# 2. Application Layer: outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP

2.4 DNS

2.5 P2P applications

2.6 video streaming and content distribution networks (CDNs)

2.7 socket programming with UDP and TCP

A nice overview https://www.thegeeksearch.com/beginners-guide-to-dns/

# DNS: Domain Name System

*people:* many identifiers:

- SSN, name, passport #

*Internet hosts, routers:*

- IP address (32 bit) - used for addressing datagrams
- "name", e.g., cs.umass.edu - 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"

# DNS: History

- Initially all host-address mappings were in a hosts.txt file (in /etc/hosts):
  - Maintained by the Stanford Research Institute (SRI)
  - Changes were submitted to SRI by email
  - New versions of hosts.txt periodically FTP'd from SRI
  - An administrator could pick names at their discretion

- As the Internet grew this system broke down:
  - SRI couldn't handle the load; names were not unique; hosts had inaccurate copies of hosts.txt

- The Domain Name System (DNS) was invented to fix this

Jon Postel

http://www.wired.com/2012/10/joe-postel/

# 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

## *Q: Why not centralize DNS?*

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

## *A: doesn't scale!*

- Comcast DNS servers alone: 600B DNS queries per day

# Goals

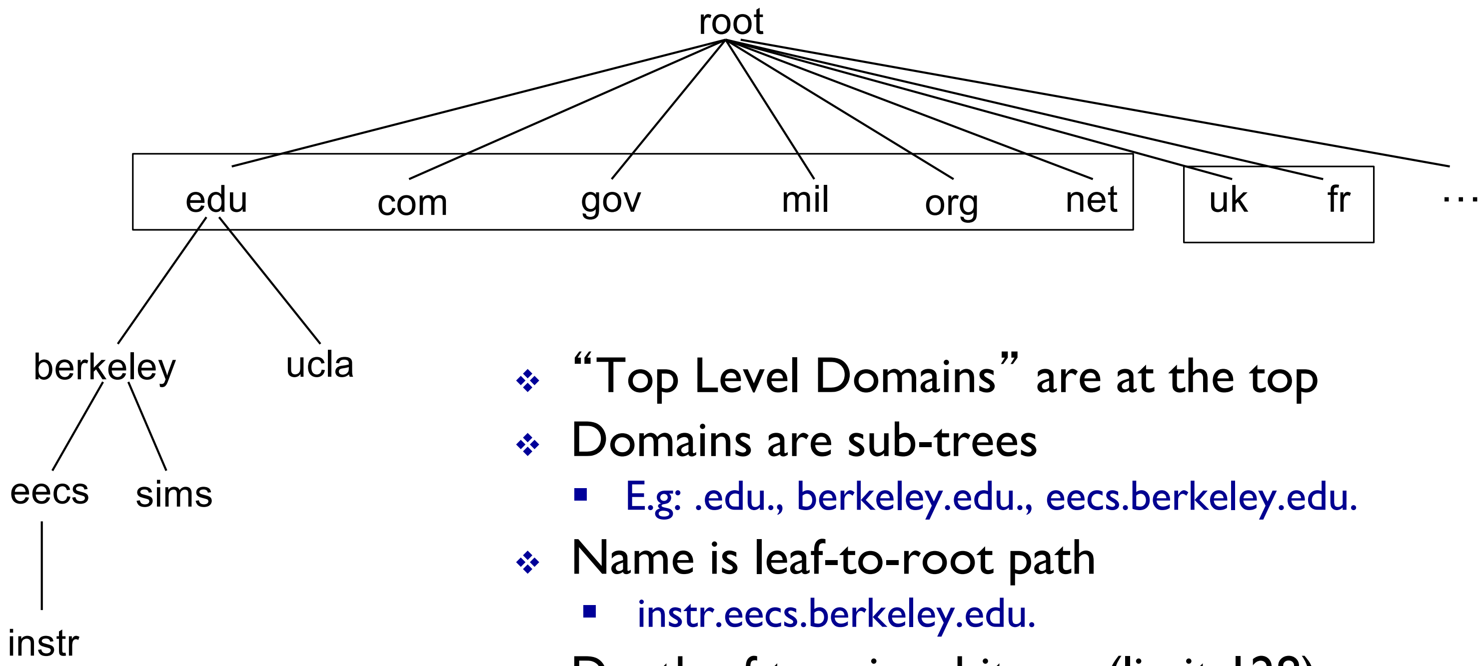
- No naming conflicts (uniqueness)
- Scalable
  - many names
  - (secondary) frequent updates
- Distributed, autonomous administration
  - Ability to update my own (domains') names
  - Don't have to track everybody's updates
- Highly available
- Lookups should be fast

# Key idea: Hierarchy

Three intertwined hierarchies

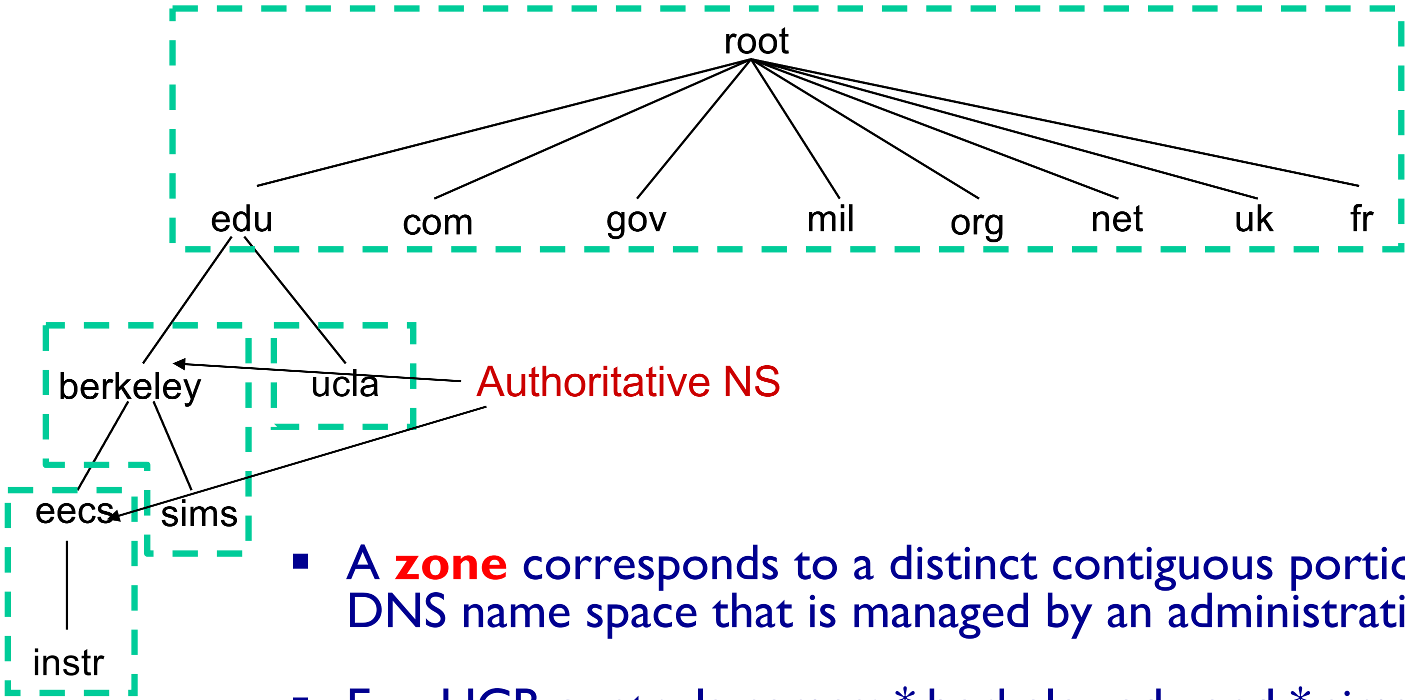
- Hierarchical namespace
  - As opposed to original flat namespace
- Hierarchically administered
  - As opposed to centralised
- (Distributed) hierarchy of servers
  - As opposed to centralised storage

# Hierarchical Namespace




- "Top Level Domains" are at the top
- Domains are sub-trees
  - E.g: .edu., berkeley.edu., eecs.berkeley.edu.
- Name is leaf-to-root path
  - instr.eecs.berkeley.edu.
- Depth of tree is arbitrary (limit 128)
- Name collisions trivially avoided
  - each domain is responsible

# Hierarchical Administration




- A **zone** corresponds to a distinct contiguous portion of the DNS name space that is managed by an administrative authority
- E.g., UCB controls names: *.berkeley.edu and *.sims.berkeley.edu
- E.g., EECS controls names: *.eecs.berkeley.edu

# Server Hierarchy

- Top of hierarchy: Root servers
  - Location hardwired into other servers
- Next Level: Top-level domain (TLD) servers
  - .com, .edu, etc. (several new TLDs introduced recently)
  - Managed professionally
- Bottom Level: Authoritative DNS servers
  - Store the name-to-address mapping
  - Maintained by the corresponding administrative authority

# Server Hierarchy

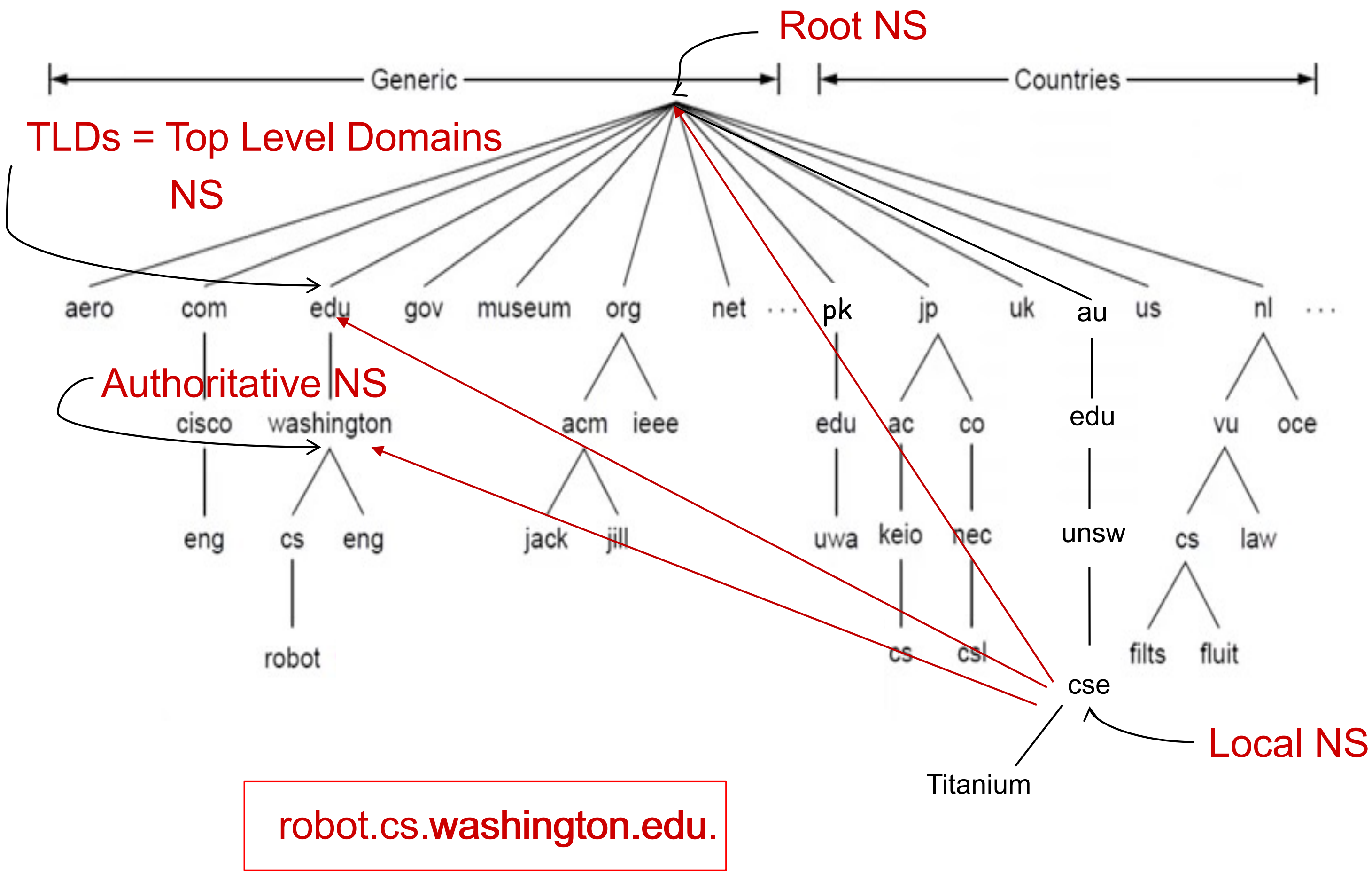
- Each server stores a (small!) subset of the total DNS database

- An authoritative DNS server stores "resource records" for all DNS names in the domain that it has authority for

- Each server can discover the server(s) that are responsible for the other portions of the hierarchy
  - Every server knows the root server(s)
  - Root server(s) knows about all top-level domains

Credits: Prof David Wetherall, UoW

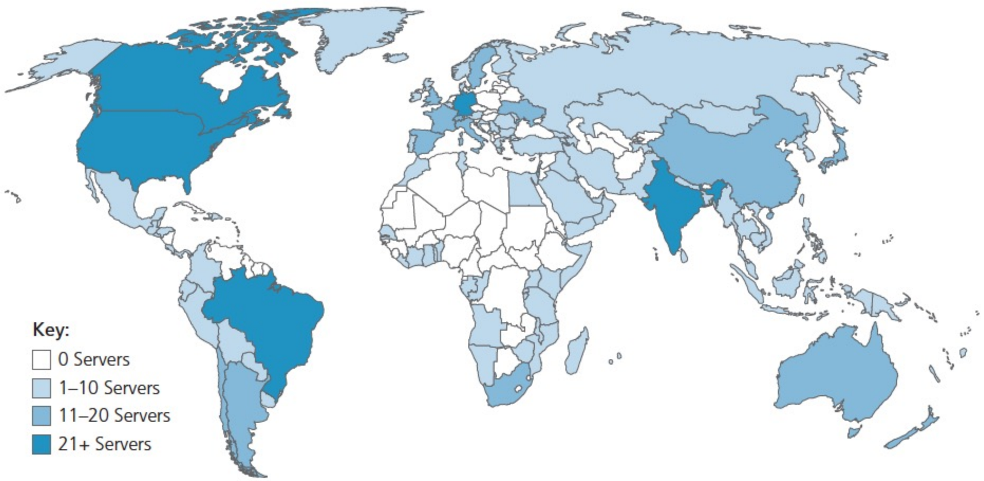
# DNS: a distributed, hierarchical database



# DNS: root name servers

- official, contact-of-last-resort by name servers that can not resolve name
- *incredibly important* Internet function
  - Internet couldn't function without it!
  - DNSSEC – provides security (authentication and message integrity)
- ICANN (Internet Corporation for Assigned Names and Numbers) manages root DNS domain

13 logical root name "servers" worldwide each "server" replicated many times (~200 servers in US)



# DNS: root name servers


As of 2018-08-01, the root server system consists of 931 instances operated by the 12 independent root server operators.

www.root-servers.org

# 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.: .cn, .uk, .fr, .ca, .jp
- Network Solutions: authoritative registry for .com, .net TLD
- Educause: .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 servers

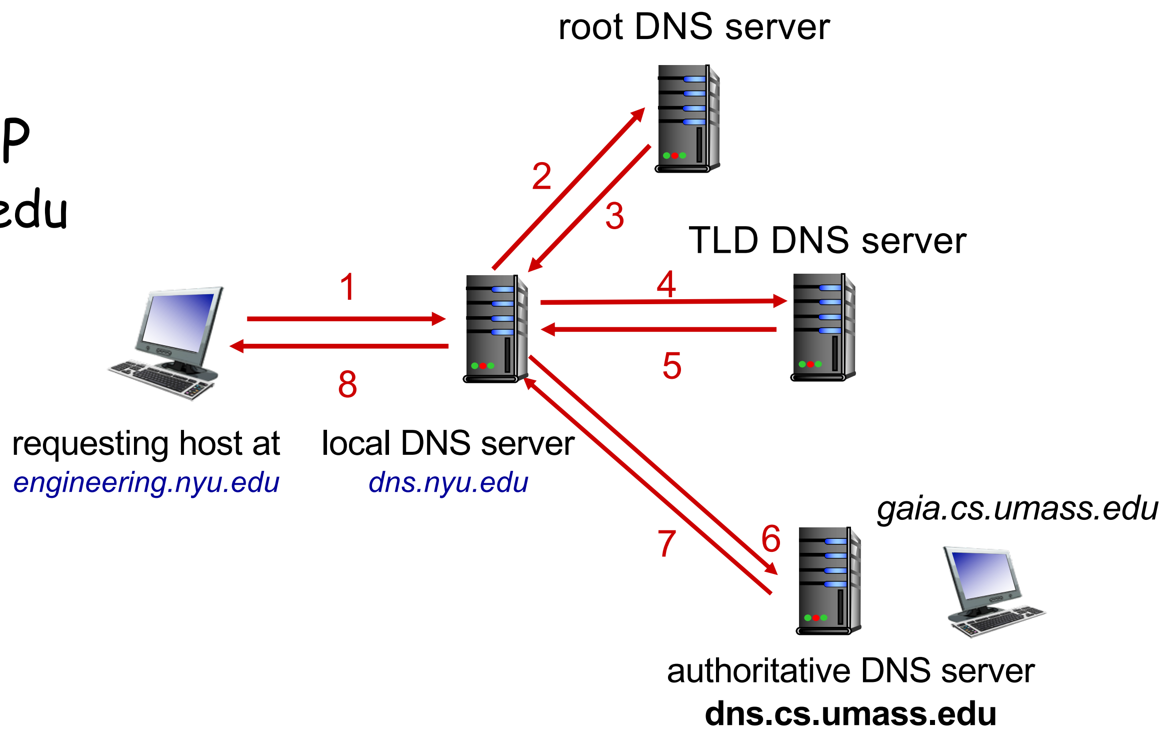
- does not strictly belong to hierarchy
- each ISP (residential ISP, company, university) has one
  - also called "default name server"
- Hosts learn server via a host configuration protocol (e.g., DHCP)
- Client application
  - Obtain hostname (e.g., from URL)
  - Do **gethostbyname()** to trigger DNS request to its local DNS 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: iterated query

Example: host at engineering.nyu.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"

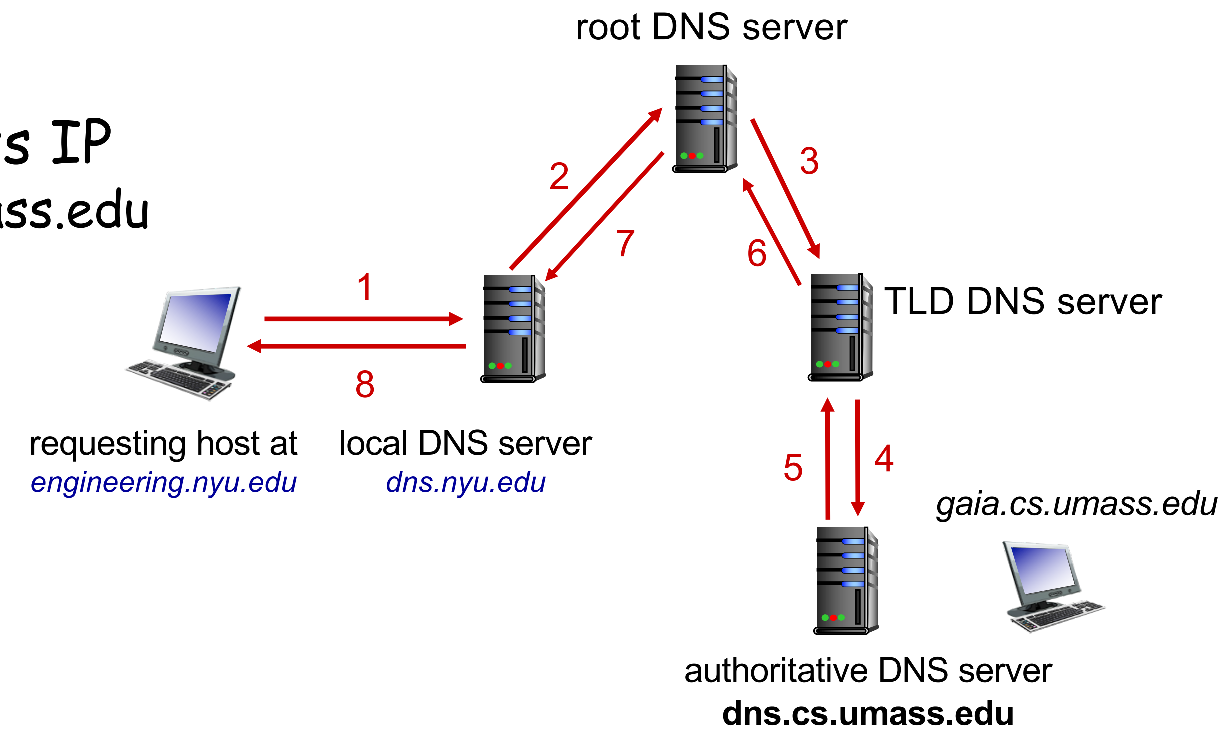


# DNS name resolution: recursive query

Example: host at engineering.nyu.edu wants IP address for gaia.cs.umass.edu

Recursive query:

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



# Caching, Updating DNS 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
- Negative caching (optional)
  - Remember things that don't work
  - E.g., misspellings like www.cnn.comm and www.cnnn.com

# DNS records

**DNS:** distributed database 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

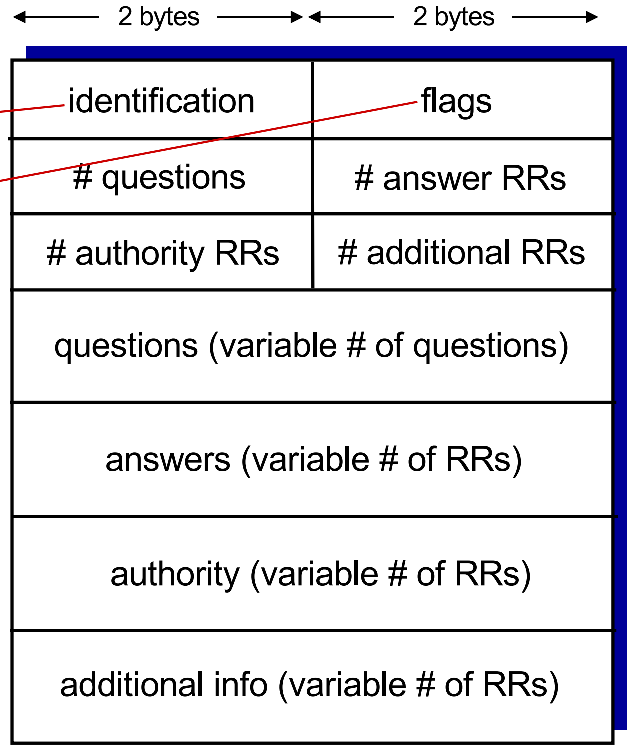
- `value` is name of mailserver associated with `name`

# DNS protocol messages

DNS *query* and *reply* messages, both have same *format:*

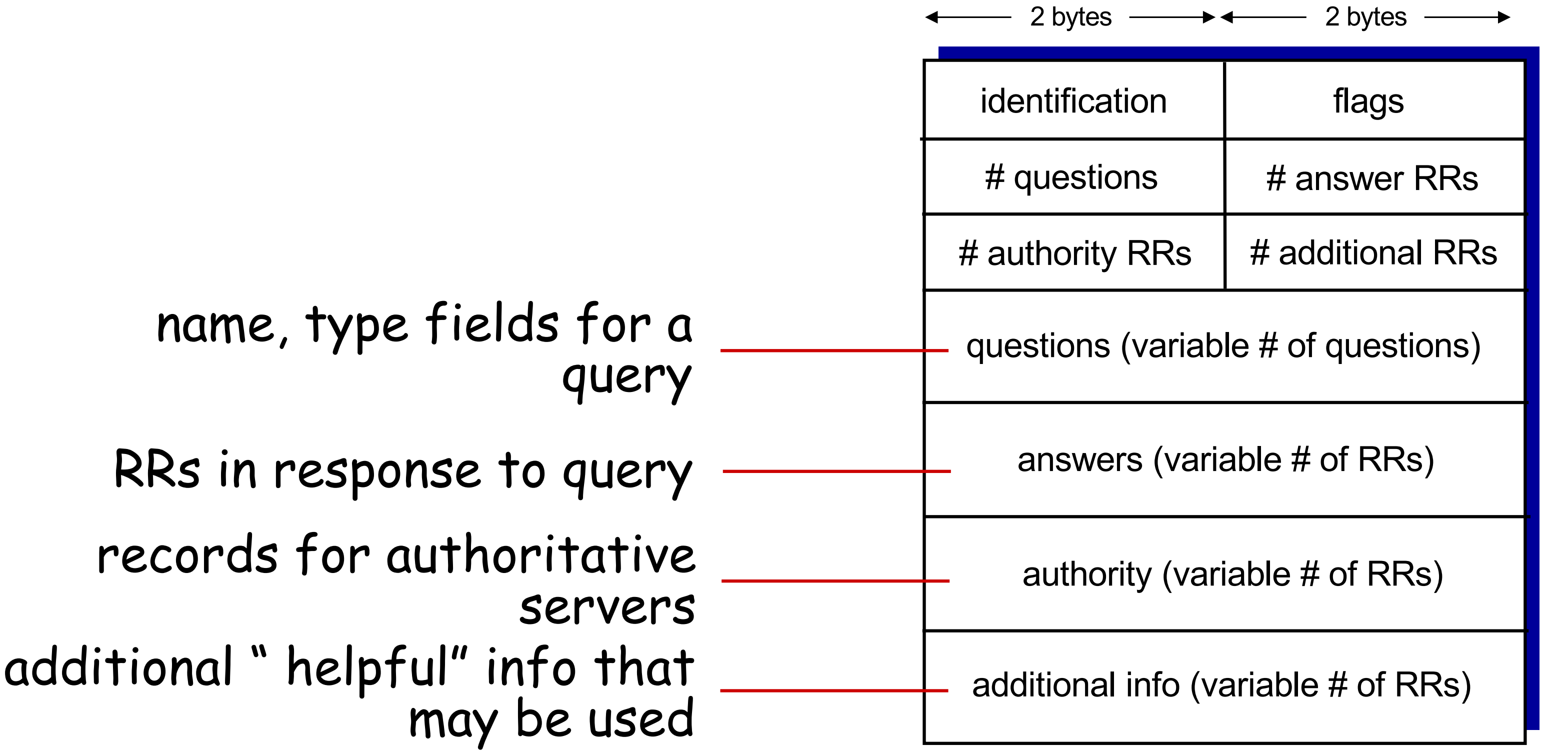
message header:

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



# DNS protocol messages

DNS *query* and *reply* messages, both have same *format:*



# An Example

Try this out yourself. Part of Lab 3

```
salilk@wagner:~$ dig www.oxford.ac.uk

; <<>> DiG 9.9.5-9+deb8u19-Debian <<>> www.oxford.ac.uk
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 23390
;; flags: qr rd ra; QUERY: 1, ANSWER: 4, AUTHORITY: 4, ADDITIONAL: 6

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 4096
;; QUESTION SECTION:
;www.oxford.ac.uk.              IN      A

;; ANSWER SECTION:
www.oxford.ac.uk.       300     IN      A       151.101.194.133
www.oxford.ac.uk.       300     IN      A       151.101.2.133
www.oxford.ac.uk.       300     IN      A       151.101.66.133
www.oxford.ac.uk.       300     IN      A       151.101.130.133

;; AUTHORITY SECTION:
oxford.ac.uk.           86400   IN      NS      dns2.ox.ac.uk.
oxford.ac.uk.           86400   IN      NS      dns0.ox.ac.uk.
oxford.ac.uk.           86400   IN      NS      dns1.ox.ac.uk.
oxford.ac.uk.           86400   IN      NS      ns2.ja.net.

;; ADDITIONAL SECTION:
ns2.ja.net.             81448   IN      A       193.63.105.17
ns2.ja.net.             17413   IN      AAAA    2001:630:0:45::11
dns0.ox.ac.uk.          42756   IN      A       129.67.1.190
dns1.ox.ac.uk.          908     IN      A       129.67.1.191
dns2.ox.ac.uk.          908     IN      A       163.1.2.190

;; Query time: 544 msec
;; SERVER: 129.94.242.2#53(129.94.242.2)
;; WHEN: Mon Sep 28 10:55:27 AEST 2020
;; MSG SIZE  rcvd: 285
```

# 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 NS, A RRs into .com TLD server:

    `(networkutopia.com, dns1.networkutopia.com, NS)`

    `(dns1.networkutopia.com, 212.212.212.1, A)`
- create authoritative server locally with IP address `212.212.212.1`
  - Containing type A record for www.networkuptopia.com
  - Containing type MX record for networkutopia.com

# Updating DNS records

- Remember that old records may be cached in other DNS servers (for up to TTL)
- General guidelines
  - Record the current TTL value of the record
  - Lower the TTL of the record to a low value (e.g., 30 seconds)
  - Wait the length of the previous TTL
  - Update the record
  - Wait for some time (e.g., 1 hour)
  - Change the TTL back to your previous time

# Reliability

- DNS servers are replicated (primary/secondary)
  - Name service available if at least one replica is up
  - Queries can be load-balanced between replicas
- Usually, UDP used for queries
  - Need reliability: must implement this on top of UDP
  - Spec supports TCP too, but not always implemented
- DNS uses port 53
- Try alternate servers on timeout
  - Exponential backoff when retrying same server
- Same identifier for all queries
  - Don’t care which server responds

# CDN example (more later)

```
bash-3.2$ dig www.mit.edu

; <<>> DiG 9.10.6 <<>> www.mit.edu
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 17913
;; flags: qr rd ra; QUERY: 1, ANSWER: 3, AUTHORITY: 8, ADDITIONAL: 8

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 4096
;; QUESTION SECTION:
;www.mit.edu.                   IN      A

;; ANSWER SECTION:
www.mit.edu.            924     IN      CNAME   www.mit.edu.edgekey.net.
www.mit.edu.edgekey.net. 54     IN      CNAME   e9566.dscb.akamaiedge.net.
e9566.dscb.akamaiedge.net. 14   IN      A       23.77.154.132

;; AUTHORITY SECTION:
dscb.akamaiedge.net.    623     IN      NS      n0dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n2dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n7dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n6dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n1dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n3dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n5dscb.akamaiedge.net.
dscb.akamaiedge.net.    623     IN      NS      n4dscb.akamaiedge.net.

;; ADDITIONAL SECTION:
n0dscb.akamaiedge.net.  1241    IN      A       88.221.81.192
n0dscb.akamaiedge.net.  1124    IN      AAAA    2600:1480:e800::c0
n1dscb.akamaiedge.net.  842     IN      A       23.32.5.76
n2dscb.akamaiedge.net.  749     IN      A       23.32.5.84
n4dscb.akamaiedge.net.  1399    IN      A       23.32.5.177
n6dscb.akamaiedge.net.  702     IN      A       23.32.5.98
n7dscb.akamaiedge.net.  1208    IN      A       23.206.243.54

;; Query time: 46 msec
;; SERVER: 129.94.172.11#53(129.94.172.11)
;; WHEN: Mon Sep 28 13:15:28 AEST 2020
;; MSG SIZE  rcvd: 421
```

Many well-known sites are hosted by CDNs. A simple way to check using dig is shown here.

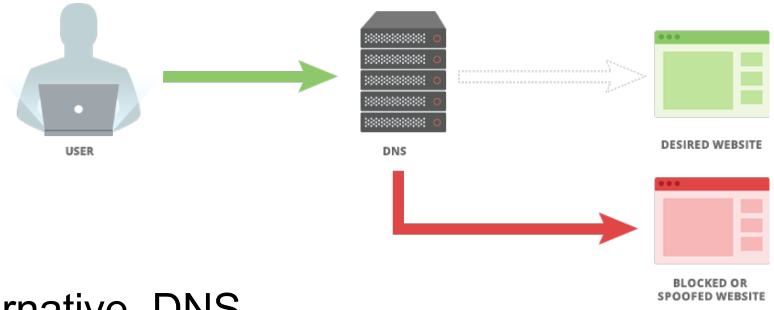
# WWW vs non-WWW domains

- E.g., www.metalhead.com or metalhead.com
- Non-www referred to as apex or naked domains (metalhead.com)
- Technically either can serve as primary (for search engines) and the other is redirected to primary (HTTP 301)
- There are 2 main advantages of using www
  - DNS requires apex domains to always point to type A and that CNAME record cannot coexist with other RR types
  - With www domains, offloading to a CDN is easy:
    - www.metalhead.com CNAME somecdn.com
    - metalhead.com A 156.23.34.252
    - Note: Some CDN providers have workarounds for the above
  - Cookies of the apex domain are automatically passed down to sub-domains (metalhead.com to static.metalhead.com and mail.metalhead.com)
    - Unnecessary cookies hurt performance
    - Also, a security issue (out of scope of our discussion)

More reading at: https://www.bjornjohansen.com/www-or-not

# Do you trust your DNS server?

- Censorship




https://wikileaks.org/wiki/Alternative_DNS

- Logging
  - IP address, websites visited, geolocation data and more
  - E.g., Google DNS:

https://developers.google.com/speed/public-dns/privacy

# DNS security

## 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 DNS 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

DNSSEC [RFC 4033]

# DNS Cache Poisoning

- Suppose you are a bad guy  and you control the name server for drevil.com. Your name server receives a request to resolve www.drevil.com. and it responds as follows:

;; QUESTION SECTION:
;www.drevil.com. IN A

;; ANSWER SECTION:
www.drevil.com 300 IN A 129.45.212.42

;; AUTHORITY SECTION:
drevil.com 86400 IN NS dns1.drevil.com.
drevil.com 86400 IN NS google.com

A drevil.com machine, **not** google.com

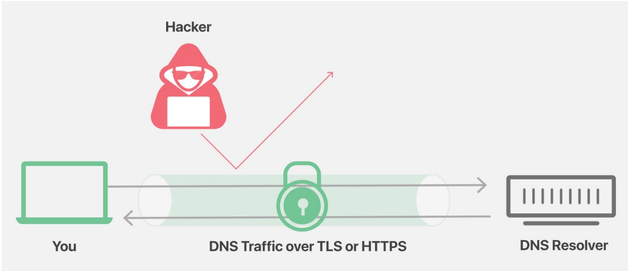
;; ADDITIONAL SECTION:
google.com 600 IN A 129.45.212.222

- Solution: Do not allow DNS servers to cache IP address mappings unless they are from authoritative name servers

DNS Cache Poisoning Test - https://www.grc.com/dns/dns.htm

**NOT ON EXAM**

# DoH (RFC 8484) and DoT (RFC 7858)




- DoT: DNS over Transport Layer Security (TLS)
- DoH: DNS over HTTPS (or HTTP2)
- Increase user privacy and security
- DoT: port 853, DoH: port 443
- DoH traffic masked with other HTTPS traffic
- Cloudflare, Google, etc. have publicly accessible DoT resolvers and OS support is also available
- Chrome and Mozilla support DoH, OS support coming soon (or already there)
- DoT: https://developers.google.com/speed/public-dns/docs/dns-over-tls
- DoH: https://developers.cloudflare.com/1.1.1.1/dns-over-https

# Quiz: DNS

- If a local DNS server has no clue about where to find the address for a hostname then the_____

a) Server starts crying

b) Server asks the root DNS server

c) Server asks its neighbouring DNS server

d) Request is not processed

**Answer: B**

**www.pollev.com/salil**

# Quiz: DNS

- Which of the following are respectively maintained by the client-side ISP and the domain name owner?

  a) Root DNS server, Top-level domain DNS server
  b) Root DNS server, Local DNS server
  c) Local DNS server, Authoritative DNS server
  d) Top-level domain DNS server, Authoritative DNS server
  e) Authoritative DNS server, Top-level domain DNS server

**Answer: C**

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# Quiz: DNS

- Suppose you open your email program and send an email to salil@unsw.edu.au, your email program will trigger which type of DNS query?

  a) A
  b) NS
  c) CNAME
  d) MX
  e) All of the above

**Answer: D**

**www.pollev.com/salil**

## Quiz: DNS

- You open your browser and type www.pollev.com. The minimum number of DNS requests sent by your local DNS server to obtain the corresponding IP address is:

A. 0

B. 1

C. 2

D. 3

E. 42

**Answer: A**

**www.pollev.com/salil**

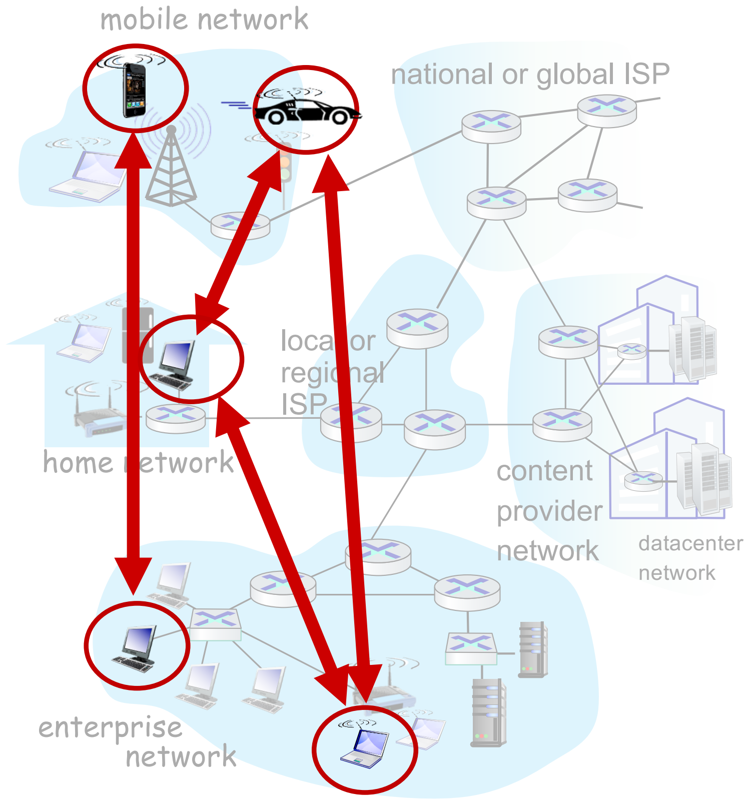
# 2. Application Layer: outline

2.1 principles of network applications
2.2 Web and HTTP
2.3 electronic mail
- SMTP

2.4 DNS
2.5 P2P applications
2.6 video streaming and content distribution networks (CDNs)
2.7 socket programming with UDP and TCP

# Peer-to-peer (P2P) architecture

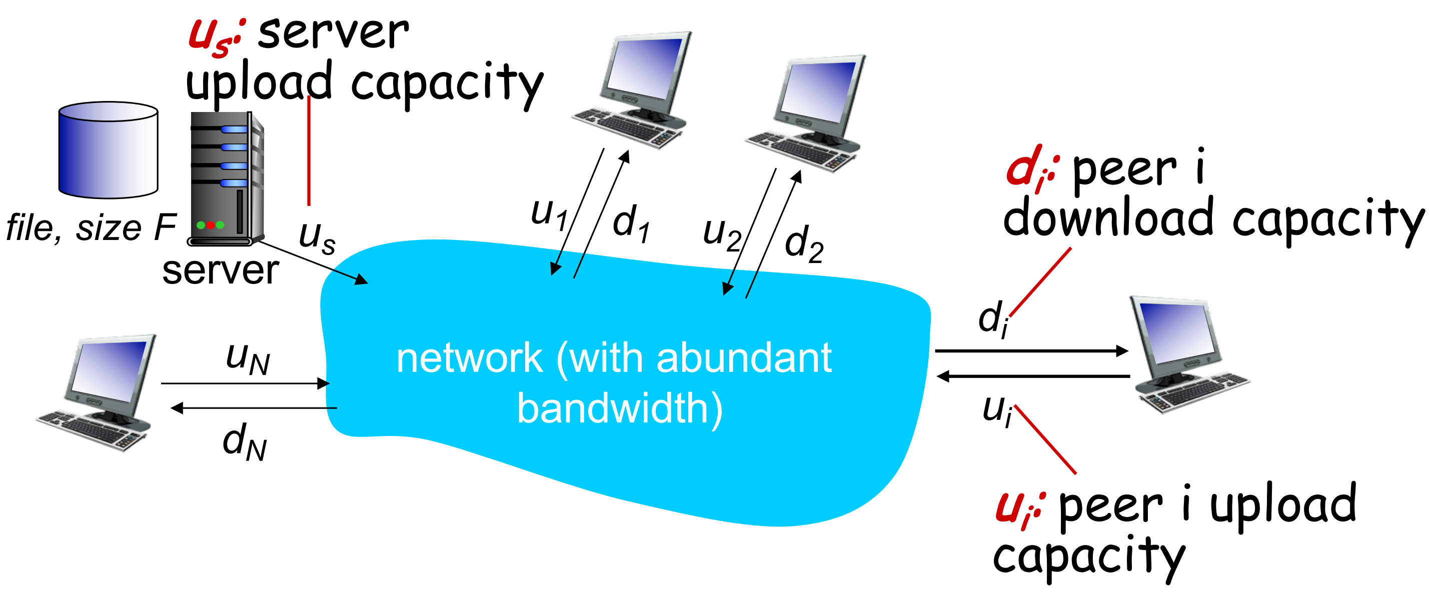
- *no* always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, and new service demands
- peers are intermittently connected and change IP addresses
  - complex management
- examples: P2P file sharing (BitTorrent), streaming (KanKan), VoIP (Skype), Cryptocurrency (Bitcoin)



# File distribution: client-server vs P2P

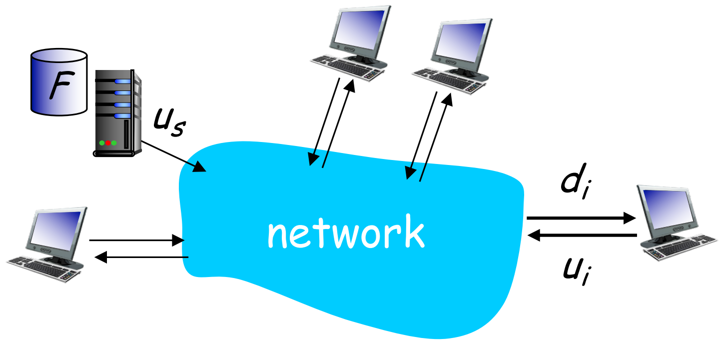
*Q:* how much time to distribute file (size *F*) from one server to *N peers*?

- 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
  - $d_{min}$ = min client download rate
  - min client download time: $F/d_{min}$



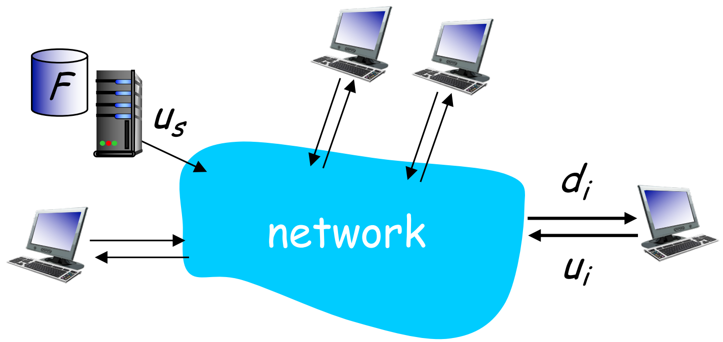

*time to distribute F to N clients using client-server approach*

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

increases linearly in N

# 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 $u_s + \Sigma u_i$



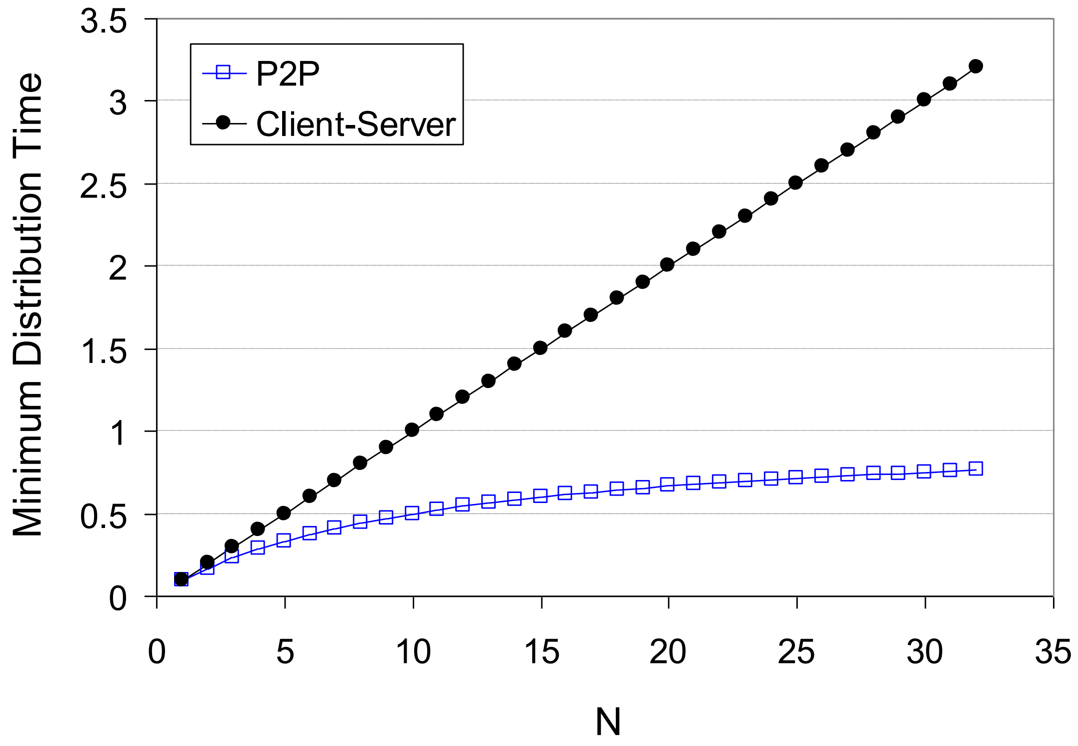

*time to distribute F to N clients using P2P approach*

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

increases linearly in $N$ …
… but so does this, as each peer brings service capacity

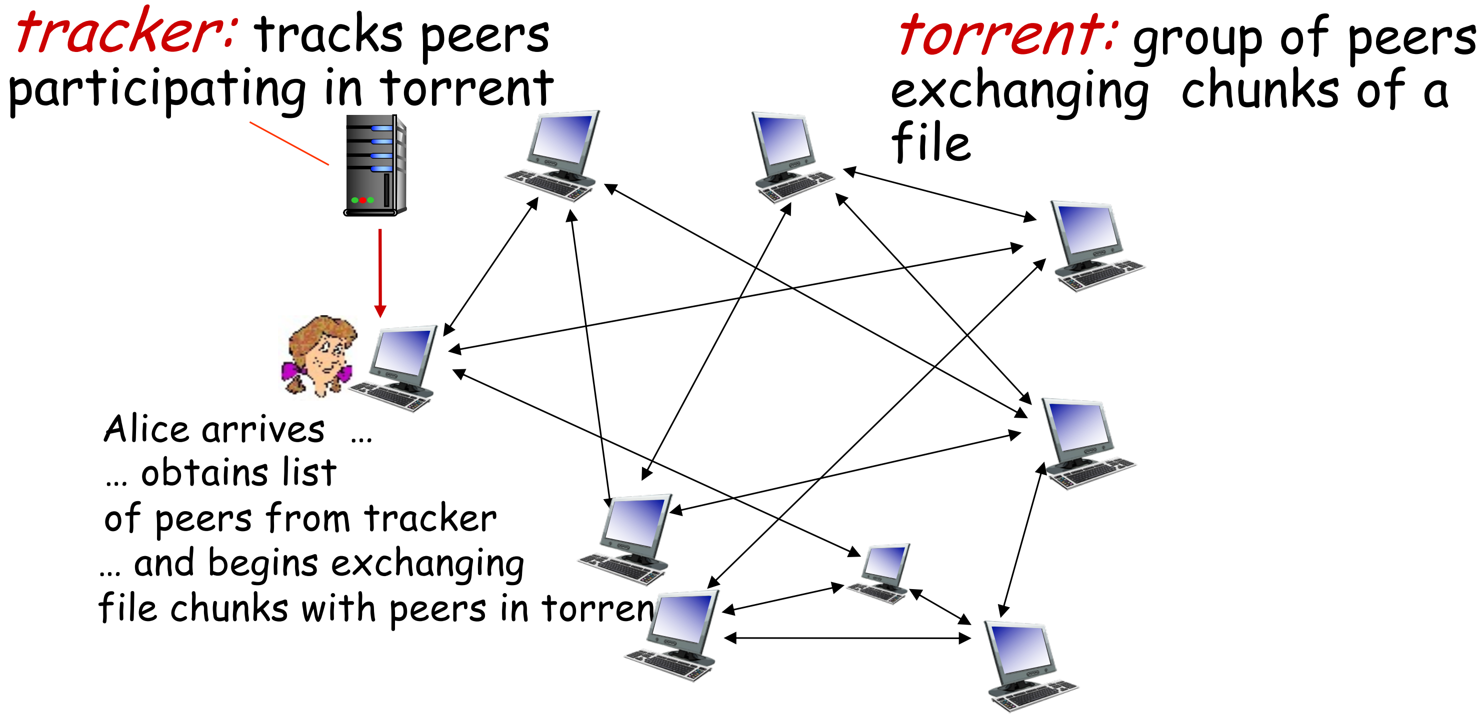
# Client-server vs. P2P: example

client upload rate = $u$, $F/u$ = 1 hour, $u_s = 10u$



# P2P file distribution: BitTorrent

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

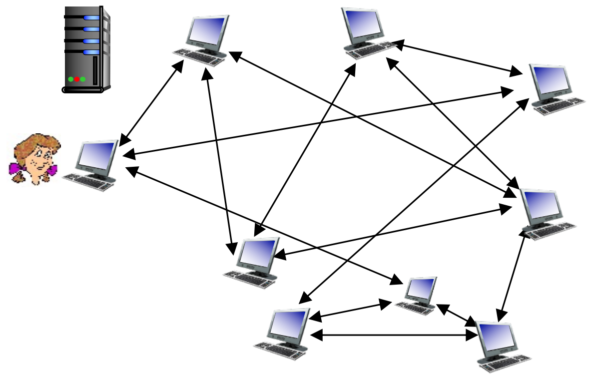


# Torrent files

- Contains address of trackers for the file
  - Where can I find other peers?
- Contain a list of file chunks and their cryptographic hashes
  - This ensures that chunks are not modified

| **Title** | **Trackers** |
|---|---|
| The Boys Season 2 | Tracker1-url |
| Walking Dead Season 10 | Tracker2-url |
| Game of Thrones Season 8 | Tracker2-url,Tracker3-url |

# 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:

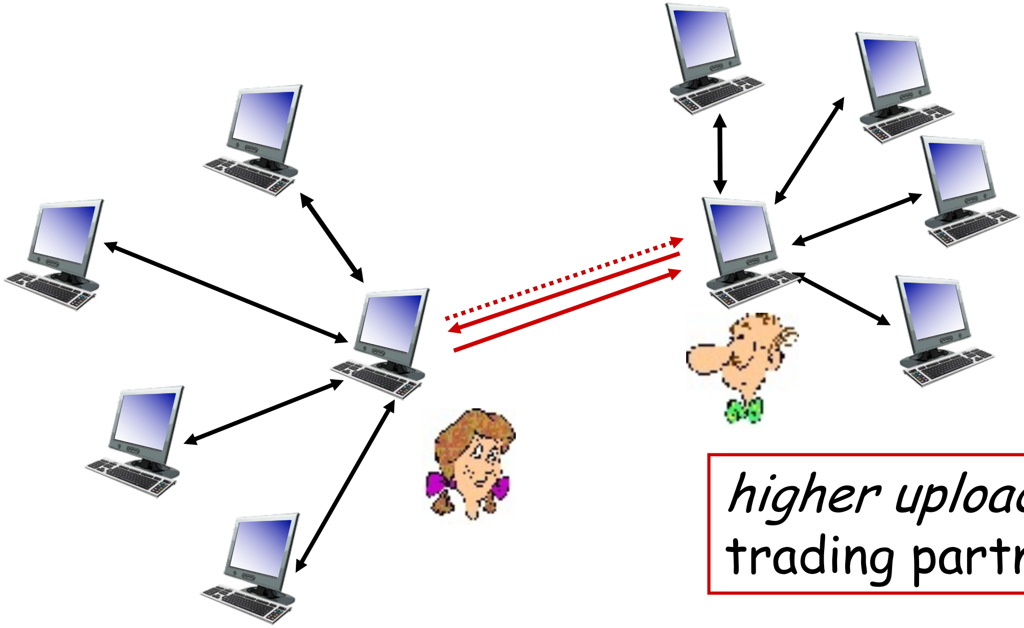
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first (why?)

## 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 every10 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 !

*Original Research Paper on BitTorrent added to lecture notes: NOT MANDATORY READING*

# Distributed Hash Table (DHT)

- DHT: a *distributed P2P database*
- database has (key, value) pairs; examples:
  - key: TFN number; value: human name
  - key: file name; value: IP addresses of peers (BitTorrent Tracker)
- Distribute the (key, value) pairs over many peers
- a peer queries DHT with key
  - DHT returns values that match the key
- peers can also insert (key, value) pairs

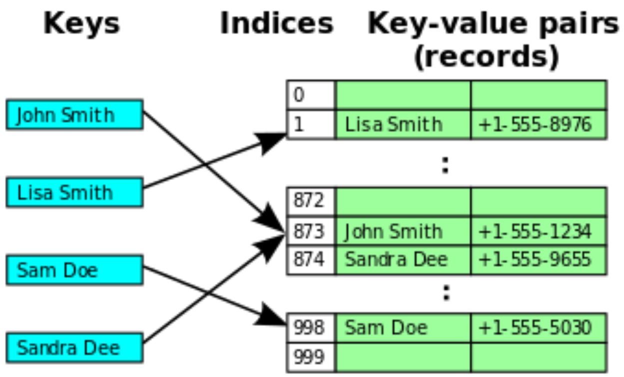
**Content available in 6th Edition of the textbook Section 2.6.2, Added to Lecture Notes**

# Q: how to assign keys to peers?

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

# DHT identifiers: Consistent Hashing

- assign integer identifier to each peer in range $[0,2^n-1]$ for some *n*-bit hash function
  - E.g., node ID is hash of its IP address
- require each key to be an integer in **same range**
- to get integer key, hash original key
  - e.g., key = hash("The Boys Season 2")
  - therefore, it is referred to as a *distributed "hash" table*



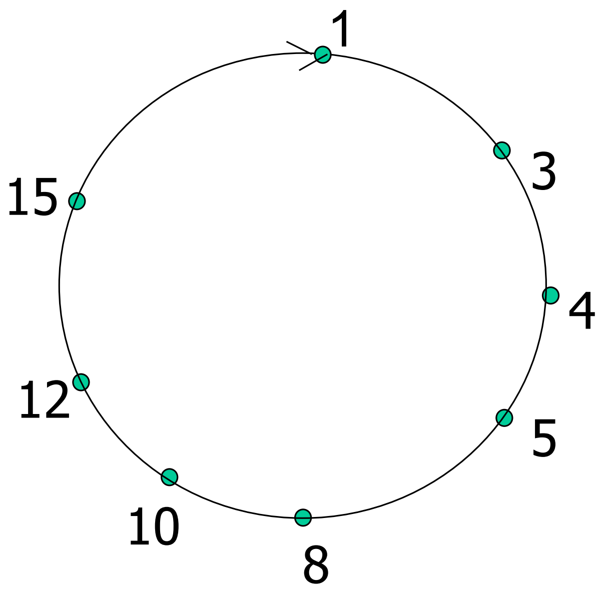
# Assign keys to peers

- rule: assign key to the peer that has the *closest* ID.
- common convention: closest is the *immediate successor* of the key.
- e.g., $n$=4; all peers & key identifiers are in the range [0-15], peers: 1,3,4,5,8,10,12,14;
  - key = 13, then successor peer = 14
  - key = 15, then successor peer = 1

Question: How is the peer-to-peer network organised?

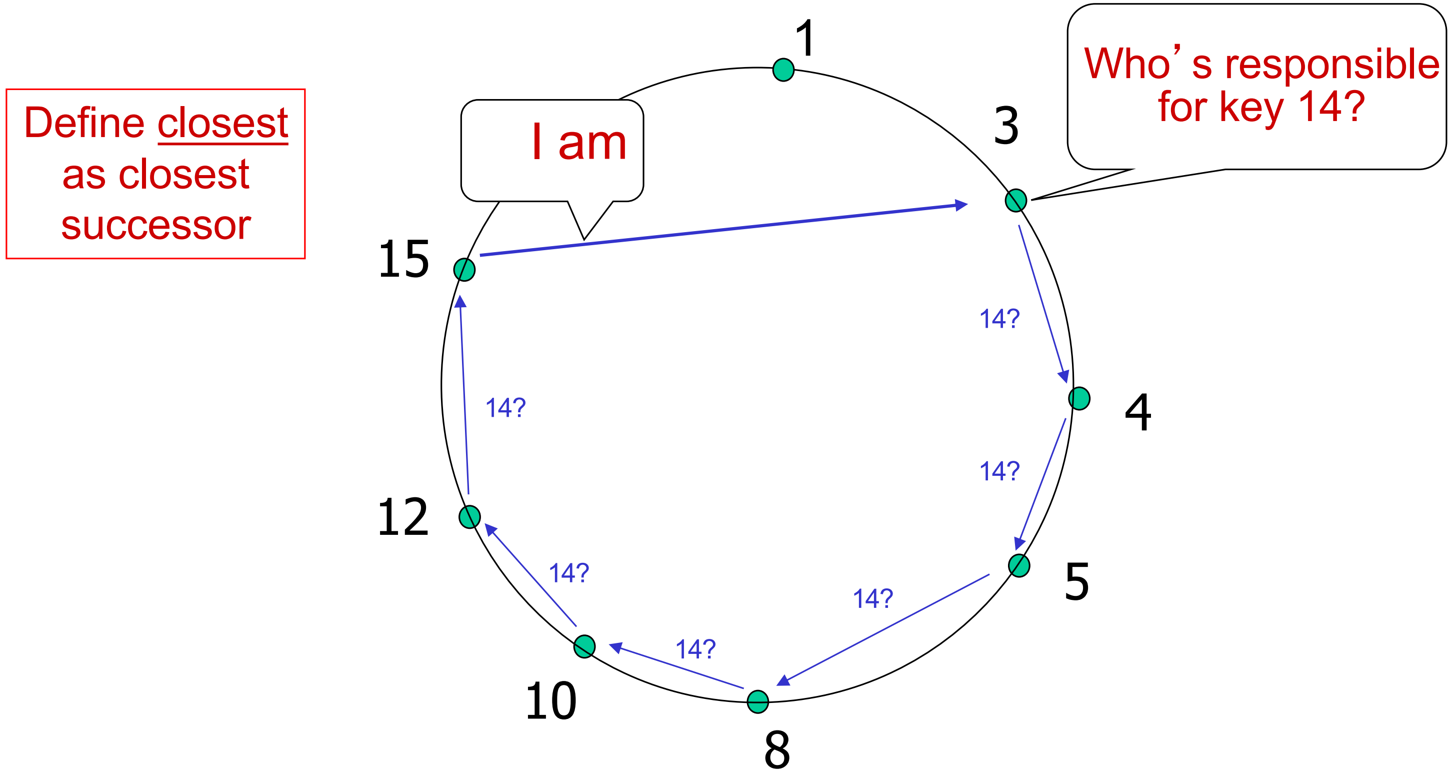
One way could be to require each peer to be aware of every other peer, but this would not scale.

# Circular DHT (1)



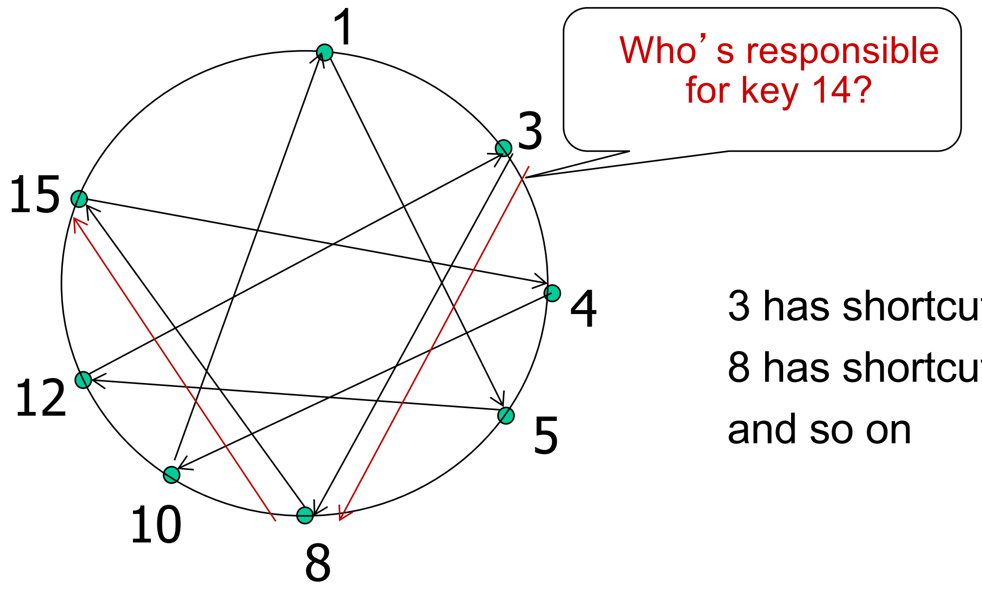

- each peer *only* aware of immediate successor and predecessor
- "overlay network"
- queries typically propagate in clockwise direction

# Circular DHT (2)




- Each peer maintains 2 neighbours
- In this example, 6 query messages are sent
- Worst case: N messages, Average: N/2 messages

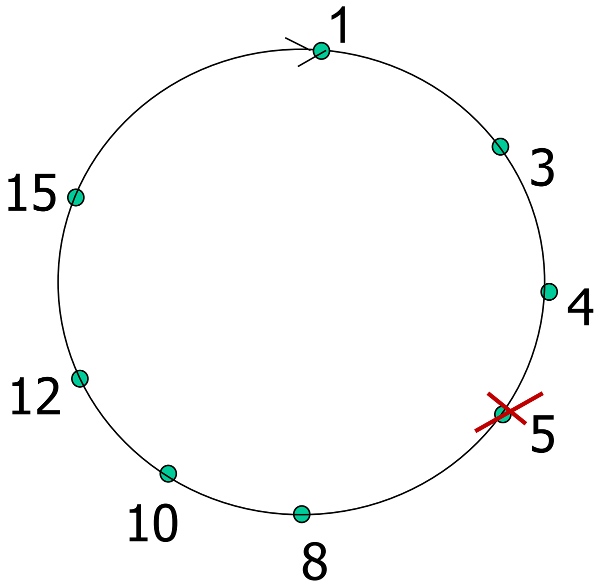
# Circular DHT with shortcuts




3 has shortcut to 8
8 has shortcut to 15
and so on

- 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)* neighbours, *O(log N)* messages in query

# 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.

# More DHT info

- How do nodes join?
- How does cryptographic hashing work?
- How much state does each node store?

Research Papers (on the lectures page):
Chord: A Scalable Peer-to-Peer Lookup Service for Internet Applications
*NOT MANDATORY READING*

## Quiz: BitTorrent

- BitTorrent uses tit-for-tat in each round to

  a) Determine which chunks to download
  b) Determine from which peers to download chunks
  c) Determine to which peers to upload chunks
  d) Determine which peers to report to the tracker as uncooperative
  e) Determine whether or how long it should stay after completing download

**Answer: C**

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# 2. Application Layer: outline

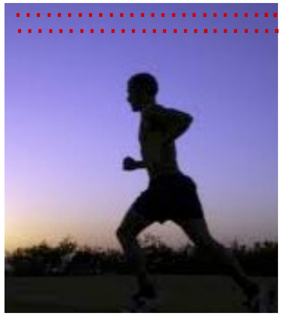
# Video Streaming and CDNs: context

- stream video traffic: major consumer of Internet bandwidth
  - Netflix, YouTube, Amazon Prime: 80% of residential ISP traffic (2020)
- challenge: scale - how to reach ~1B users?
  - single mega-video server won't work (why?)
- challenge: heterogeneity
  - different users have different capabilities (e.g., wired versus mobile; bandwidth rich versus bandwidth poor)
- *solution: distributed, application-level infrastructure*

# Multimedia: video

- video: sequence of images displayed at constant rate
  - e.g., 24 images/sec
- digital image: array of pixels
  - each pixel represented by bits
- coding: use redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)

*spatial coding example:* instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values (*N)



frame *i*

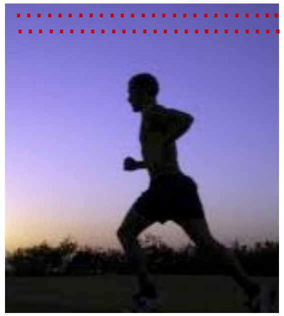
*temporal coding example:* instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

# Multimedia: video

- **CBR: (constant bit rate):** video encoding rate fixed
- **VBR: (variable bit rate):** video encoding rate changes as amount of spatial, temporal coding changes
- **examples:**
  - MPEG 1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, 64Kbps – 12 Mbps)

*spatial coding example:* instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values* (N)



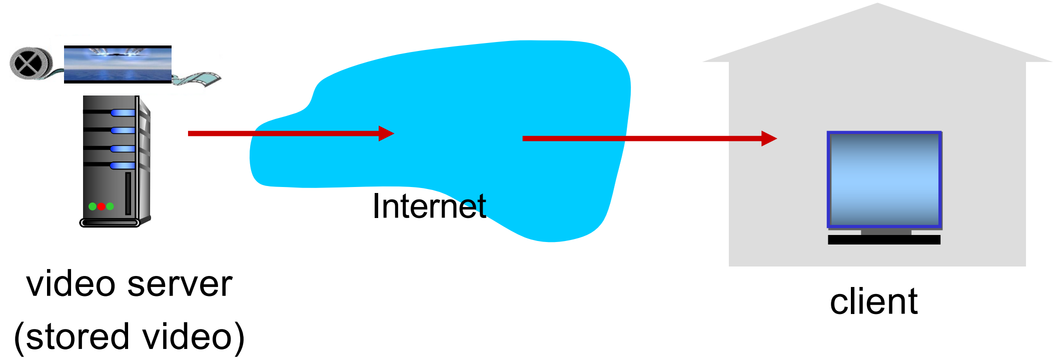
frame *i*

*temporal coding example:* instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

# Streaming stored video

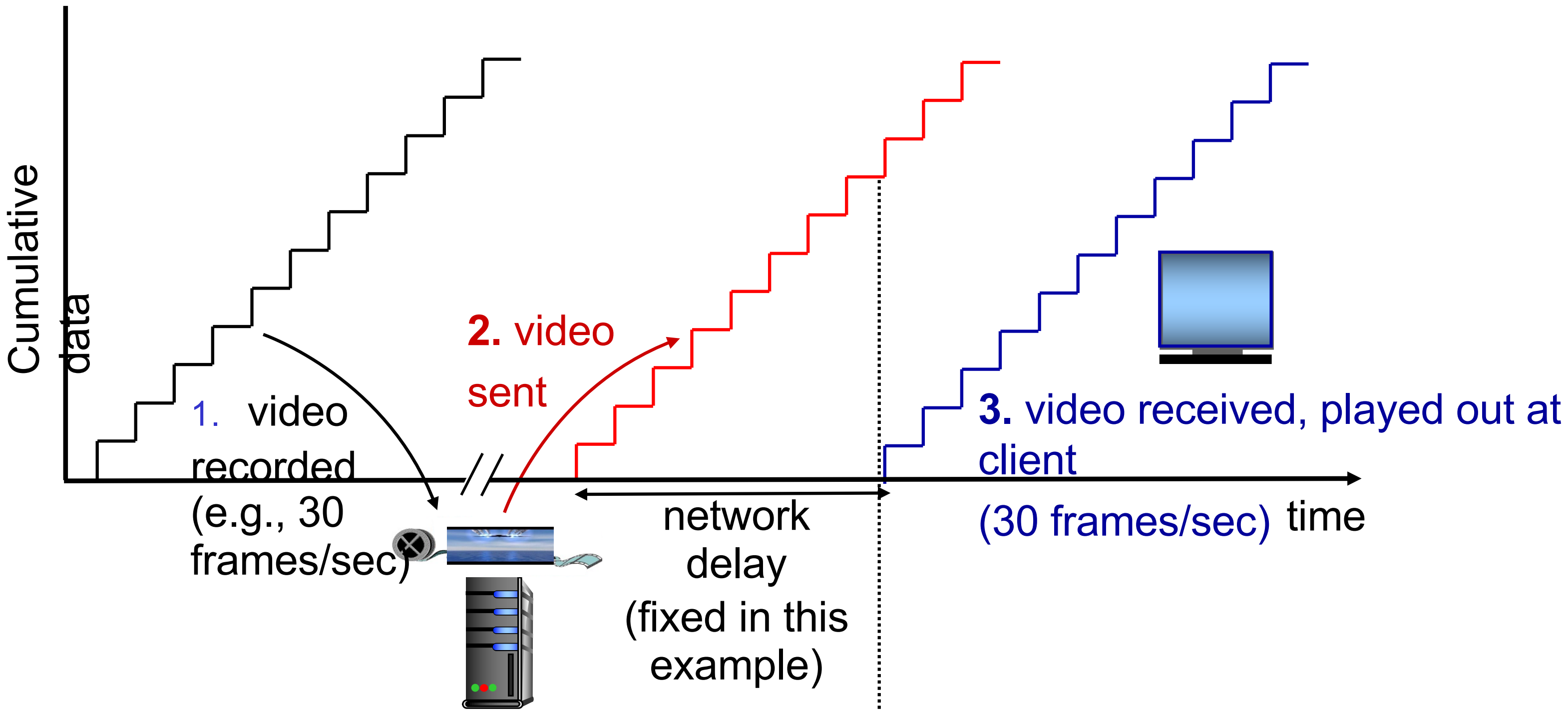
simple scenario:




Main challenges:

- server-to-client bandwidth will *vary* over time, with changing network congestion levels (in house, in access network, in network core, at video server)
- packet loss and delay due to congestion will delay playout, or result in poor video quality

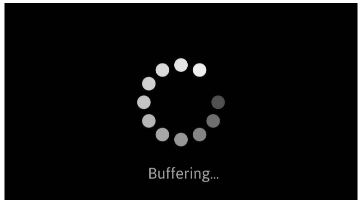
# Streaming stored video




streaming: at this time, client playing out early part of video, while server still sending later part of video

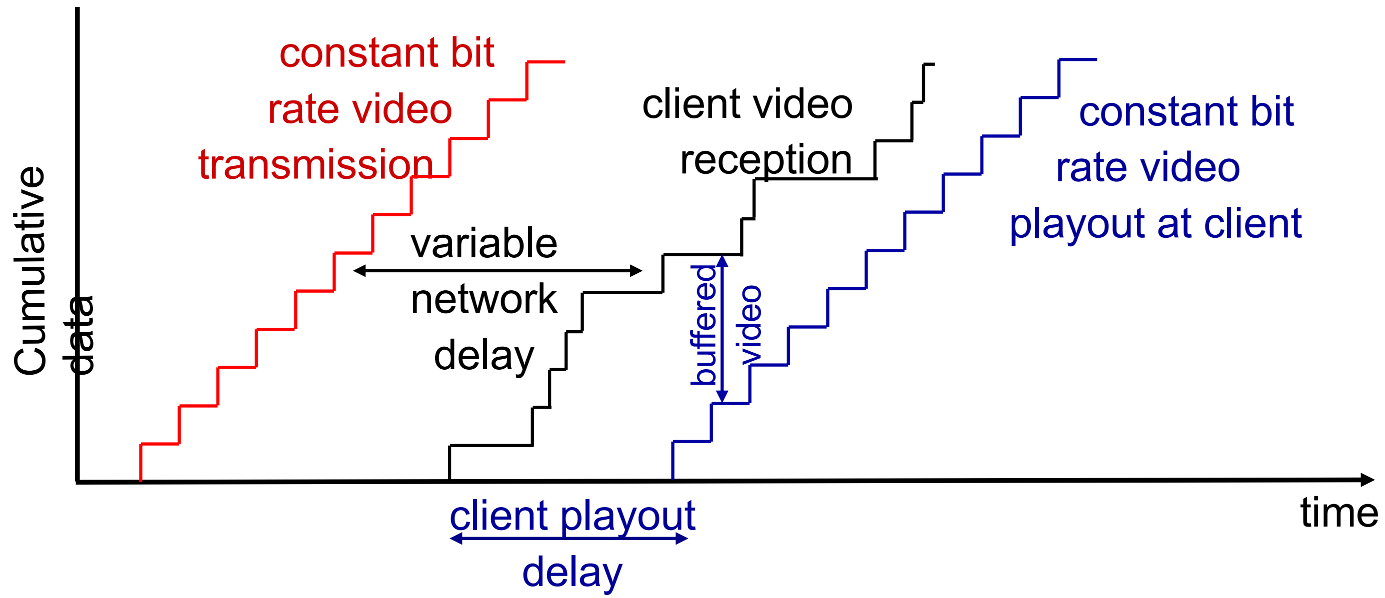
# Streaming stored video: challenges

- continuous playout constraint: once client playout begins, playback must match original timing
  - … but network delays are variable (jitter), so will need client-side buffer to match playout requirements




- other challenges:
  - client interactivity: pause, fast-forward, rewind, jump through video
  - video packets may be lost, retransmitted

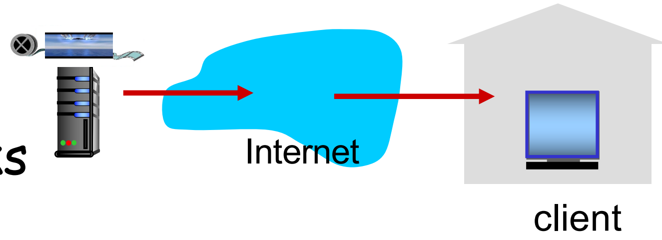
# Streaming stored video: playout buffering




- *client-side buffering and playout delay:* compensate for network-added delay, delay jitter

# Streaming multimedia: DASH

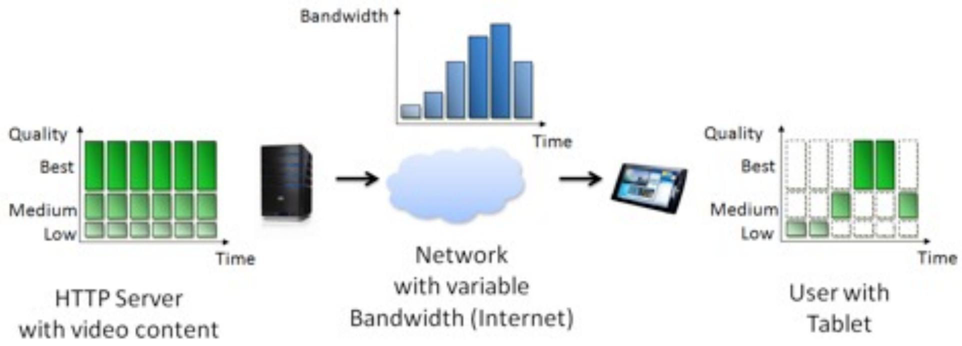
- *DASH: D*ynamic, *A*daptive *S*treaming over *H*TTP
- *server:*
  - divides video file into multiple chunks
  - each chunk stored, encoded at different rates
  - *manifest file:* provides URLs for different chunks




- *client:*
  - periodically measures server-to-client bandwidth
  - consulting manifest, requests one chunk at a time
    - chooses maximum coding rate sustainable given current bandwidth
    - can choose different coding rates at different points in time (depending on available bandwidth at time)

# Streaming multimedia: DASH

- *"intelligence"* at client: client determines
  - *when* to request chunk (so that buffer starvation, or overflow does not occur)
  - *what encoding rate* to request (higher quality when more bandwidth available)
  - *where* to request chunk (can request from URL server that is "close" to client or has high available bandwidth)




Streaming video = encoding + DASH + playout buffering

# Content distribution networks (CDNs)

- *challenge:* how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?
- option 1: single, large "mega-server"
  - single point of failure
  - point of network congestion
  - long path to distant clients
  - multiple copies of video sent over outgoing link

....quite simply: this solution *doesn't scale*

# Content distribution networks (CDNs)

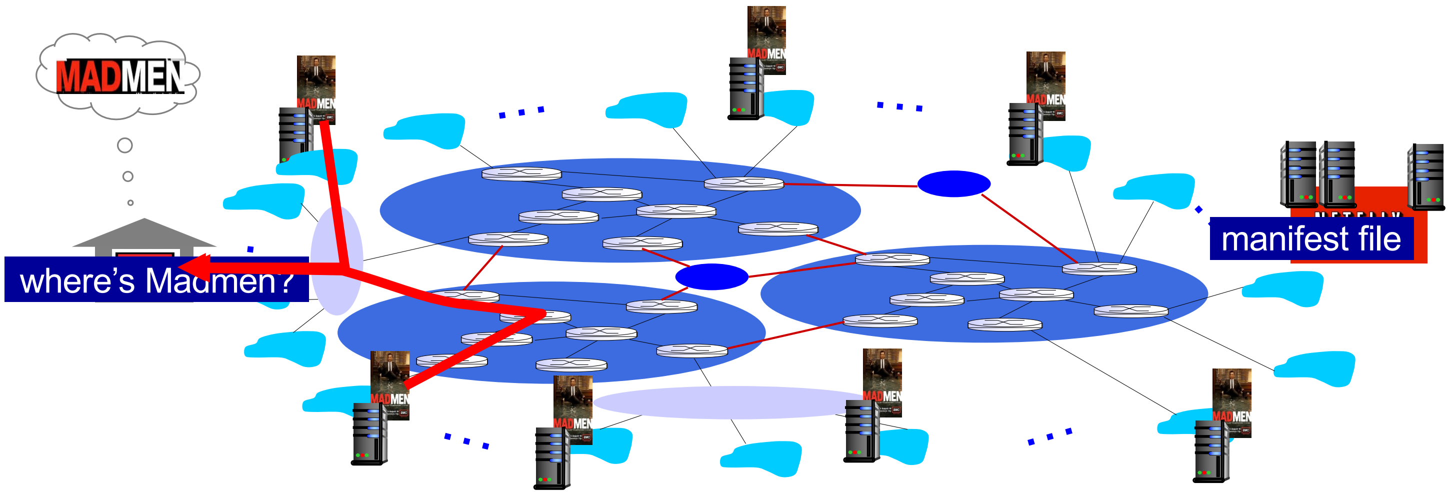
- *challenge:* how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?
- option 2: store/serve multiple copies of videos at multiple geographically distributed sites *(CDN)*
  - *enter deep:* push CDN servers deep into many access networks
    - close to users
    - Akamai: 240,000 servers deployed in more than 120 countries (2015)
  - *bring home:* smaller number (10's) of larger clusters in POPs near (but not within) access networks
    - used by Limelight

Akamai

Limelight NETWORKS

# Content distribution networks (CDNs)

- CDN: stores copies of content at CDN nodes
  - e.g., Netflix stores copies of MadMen
- subscriber requests content from CDN
  - directed to nearby copy, retrieves content
  - may choose different copy if network path congested



# Content distribution networks (CDNs)

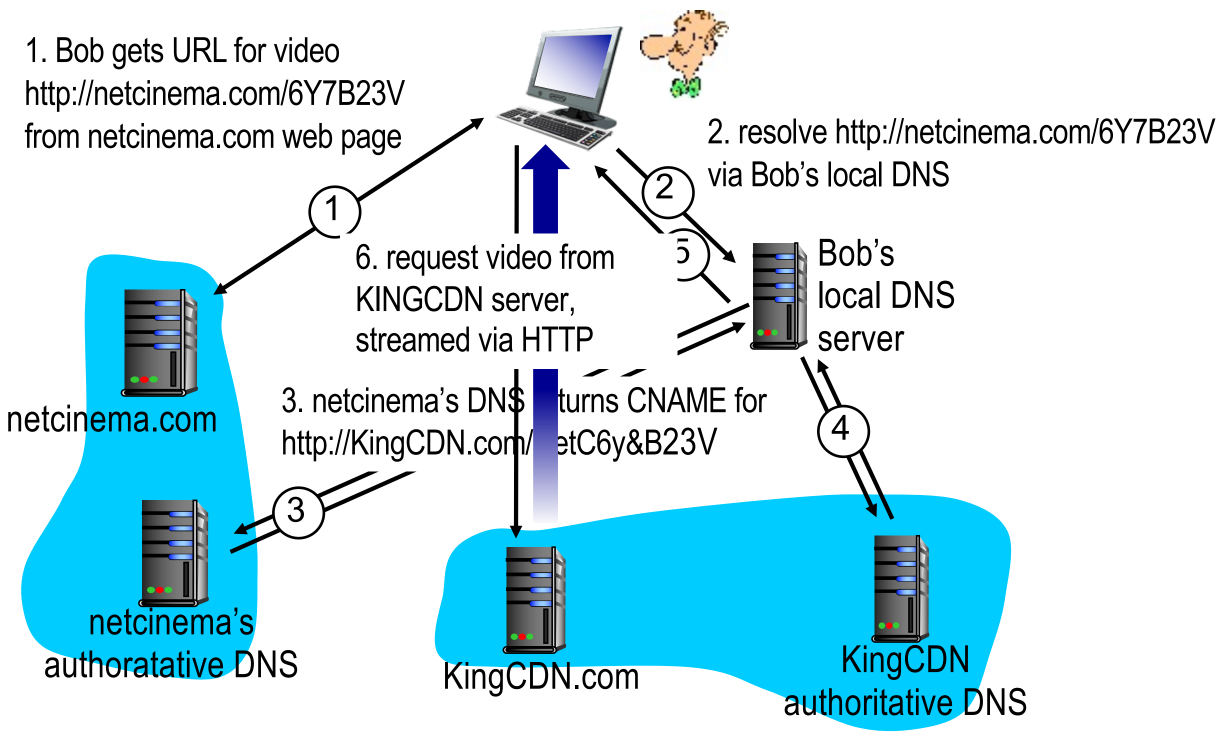

*OTT challenges:* coping with a congested Internet

- from which CDN node to retrieve content?
- viewer behavior in presence of congestion?
- what content to place in which CDN node?

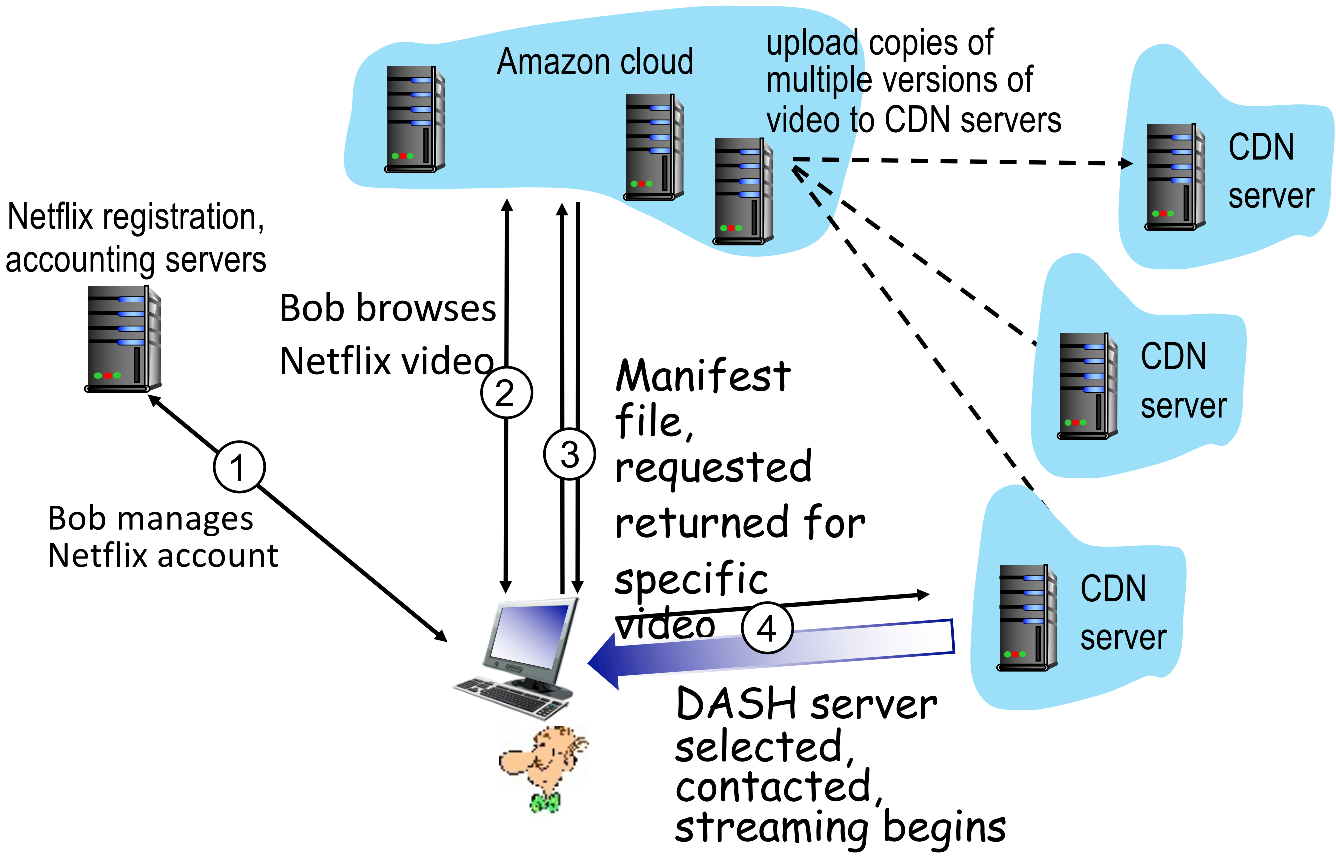
# CDN content access: a closer look

Bob (client) requests video http://netcinema.com/6Y7B23V

- video stored in CDN at http://KingCDN.com/NetC6y&B23V



# Case study: Netflix



## Quiz: CDN

- The role of the CDN provider's authoritative DNS name server in a content distribution network, simply described, is:
  a) to provide an alias address for each browser access to the "origin server" of a CDN website
  b) to map the query for each CDN object to the CDN server closest to the requestor (browser)
  c) to provide a mechanism for CDN "origin servers" to provide paths for clients (browsers)
  d) none of the above, CDN networks do not use DNS

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**Answer: B**

# 2. Application Layer: outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP

2.4 DNS

2.5 P2P applications

2.6 video streaming and content distribution networks (CDNs)

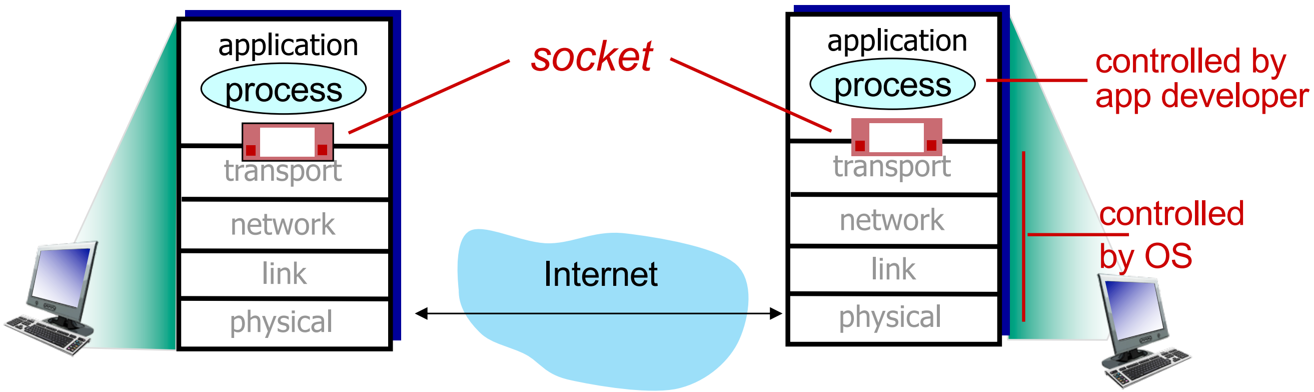
2.7 socket programming with UDP and TCP

**Please see example code (C, Java, Python) on course website**
**Labs 2 & 3 will include a socket programming exercise**

# 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 with UDP

## UDP: no "connection" between client & server

- no handshaking before sending data
- sender explicitly attaches IP destination address and port # to each packet
- receiver 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

# Pseudo code UDP client

- Create socket
- Loop
  - (Send UDP datagram to known port and IP addr of server)

  - (Receive UDP datagram as a response from server)
- Close socket

# Pseudo code UDP server

- Create socket
- Bind socket to a specific port where clients can contact you
- Loop
  - (Receive UDP datagram from client X)
  - (Send UDP datagram as reply to client X)
- Close socket

Note: The IP address and port number of the client must be extracted from the client's message

# 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:**

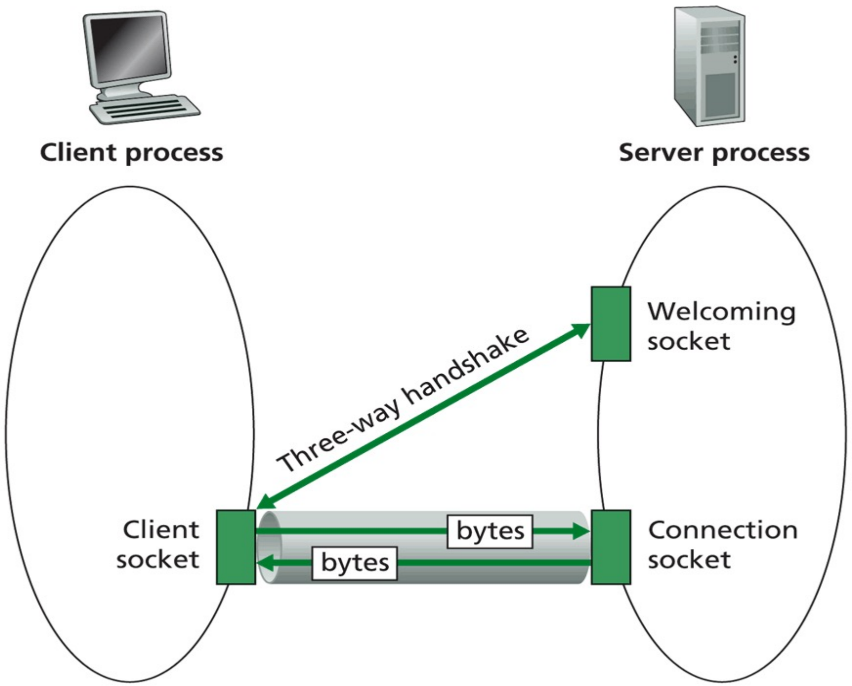
- Creating TCP socket, specifying IP address, port number of server process
- *when client creates socket:* client TCP establishes connection to server TCP

- 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 when we study TCP)

**Application viewpoint**

TCP provides reliable, in-order byte-stream transfer ("pipe") between client and server

# TCP Sockets



Client process
Server process
Welcoming socket
Three-way handshake
Client socket
bytes
bytes
Connection socket

# Pseudo code TCP client

- Create socket (ConnectionSocket)
- Do an active connect specifying the IP address and port number of server
- Read and write data into ConnectionSocket to communicate with client
- Close ConnectionSocket

# Pseudo code TCP server

- Create socket (WelcomingSocket)
- Bind socket to a specific port where clients can contact you
- Register with the OS your willingness to listen on that socket for clients to contact you
- Loop
  - Accept new connection(ConnectionSocket)
  - Read and write data into ConnectionSocket to communicate with client
  - Close ConnectionSocket
- Close WelcomingSocket

# Queues

- While the server socket is busy, incoming connection requests are stored in a queue
- Once the queue fills up, further incoming connections are refused
- This is clearly a problem
  - Example: HTTP servers
- Solution
  - Concurrency

# Concurrent TCP Servers

- Benefit comes in ability to hand off interaction with a client to another process
- Parent process creates the WelcomingSocket and waits for clients to request connection
- When a connection request is received, fork off a child process to handle that connection so that the parent process can return to waiting for connections as soon as possible
- Multithreaded server: same idea, just spawn off another thread rather than a process

# 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
  - SMTP, IMAP
  - DNS
  - P2P: BitTorrent, DHT
- video streaming, CDNs
- socket programming:
  TCP, UDP sockets