

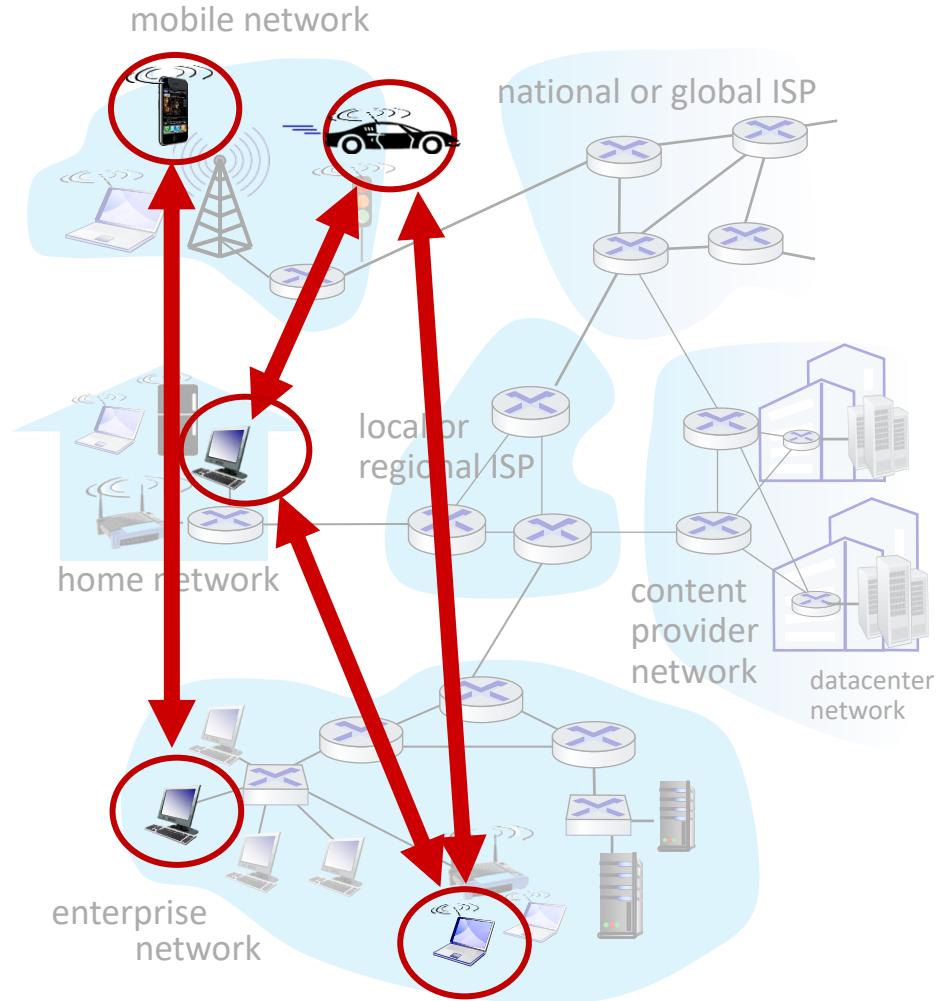
Application Layer: Overview

- Principles of network applications
- Web and HTTP
- E-mail, SMTP, IMAP
- The Domain Name System
DNS
- P2P applications



Peer-to-peer (P2P) architecture

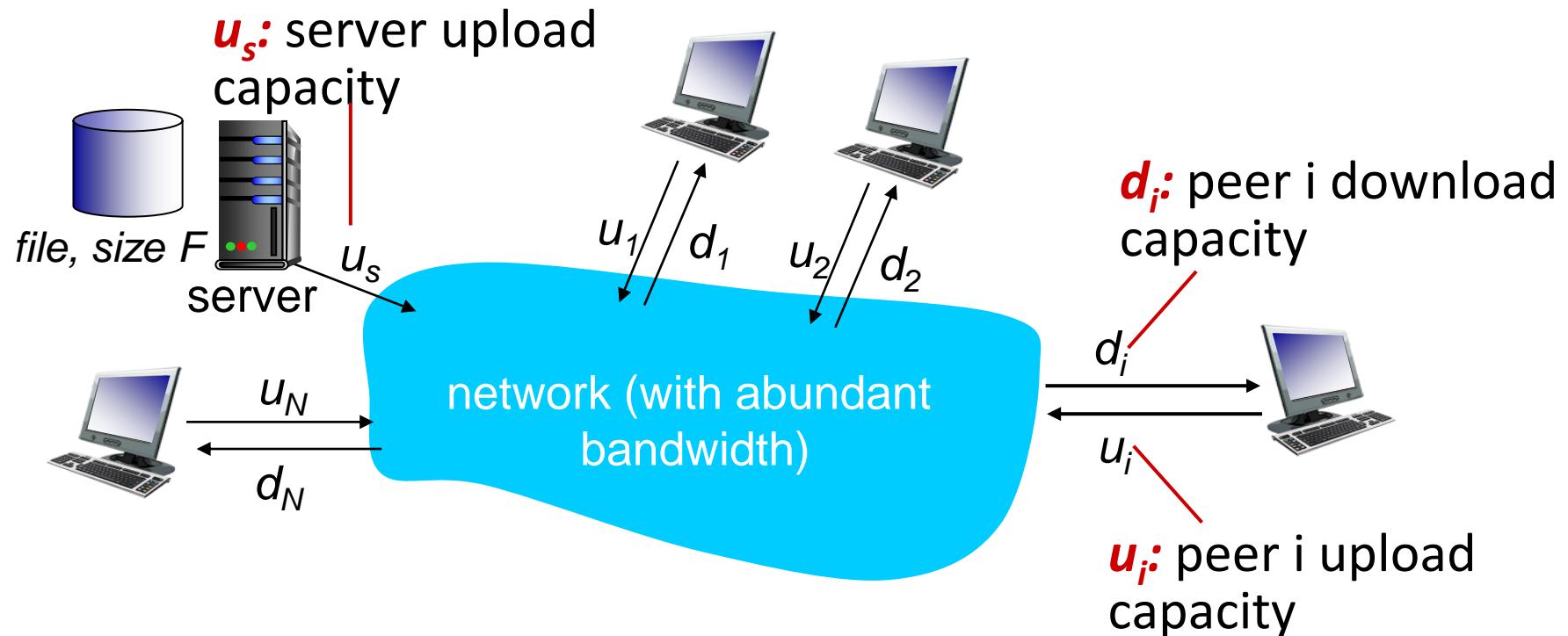
- no always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
 - *self scalability* – new peers bring new service capacity, and new service demands
- peers are intermittently connected and change IP addresses
 - complex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



File distribution: client-server vs P2P

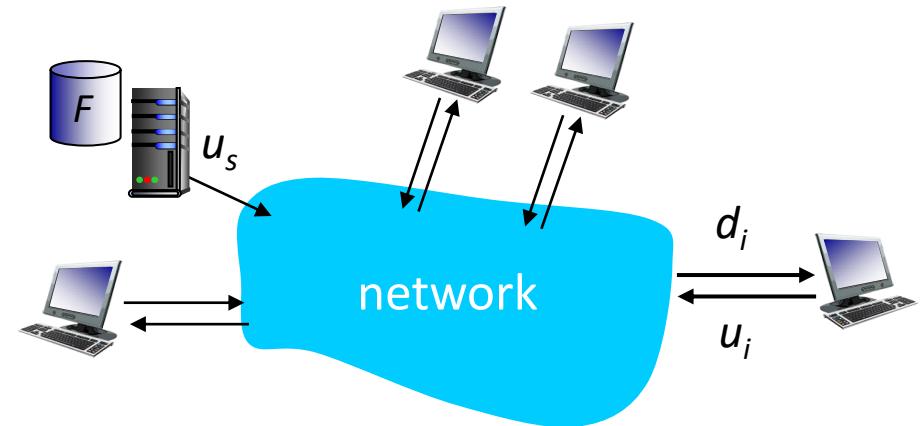
Q: how much time to distribute file (size F) from one server to N peers?

- 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}



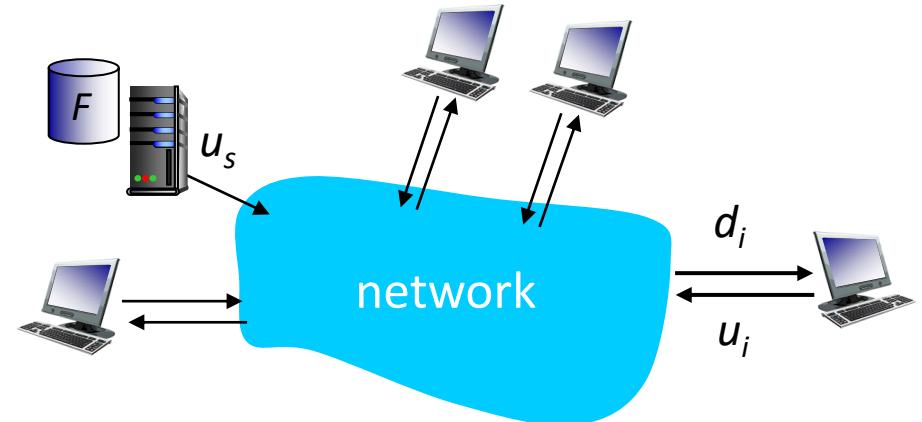
*time to distribute F
to N clients using
client-server approach*

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

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 $u_s + \sum u_i$



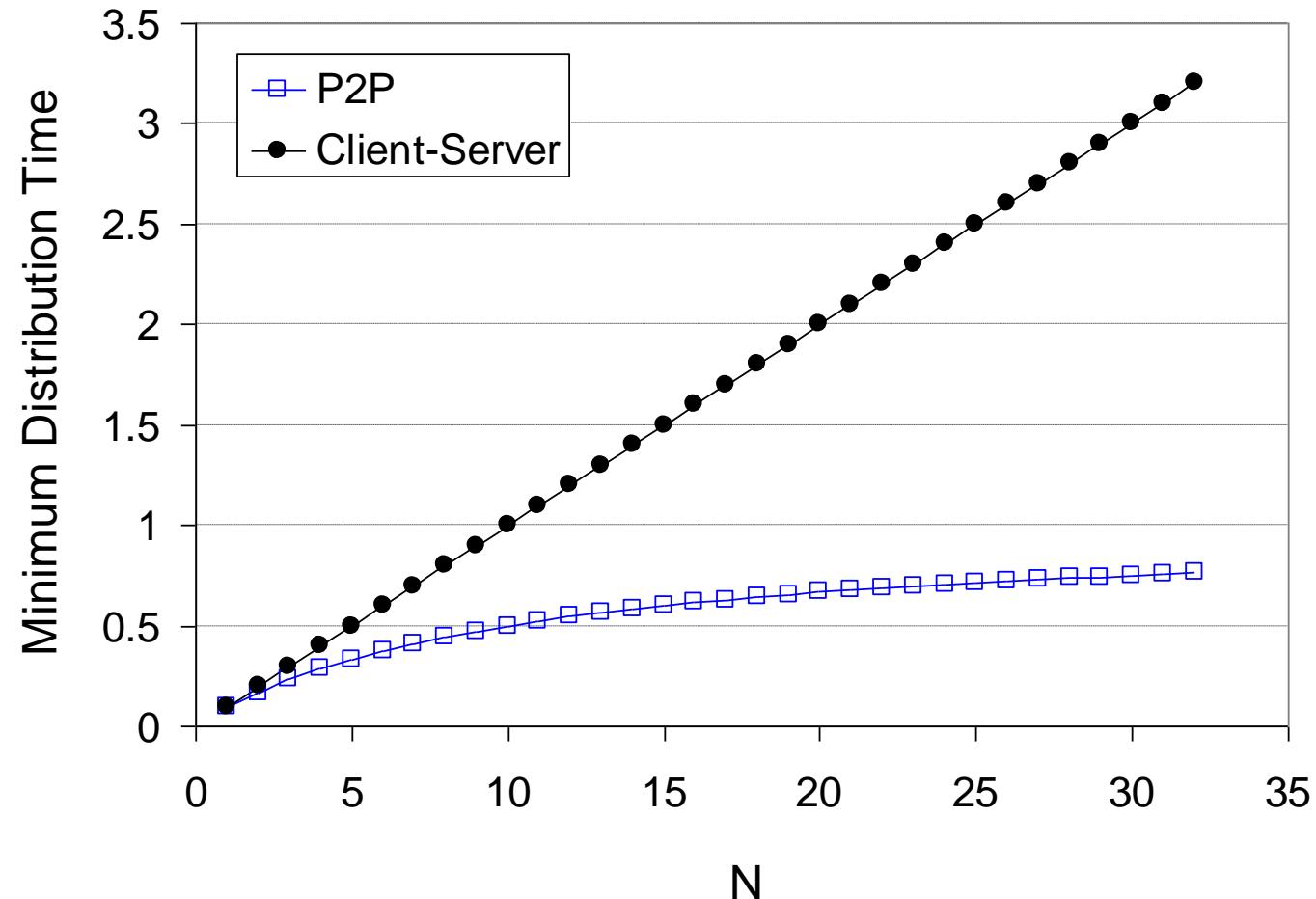
time to distribute F
to N clients using
P2P approach

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

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

Client-server vs. P2P: example

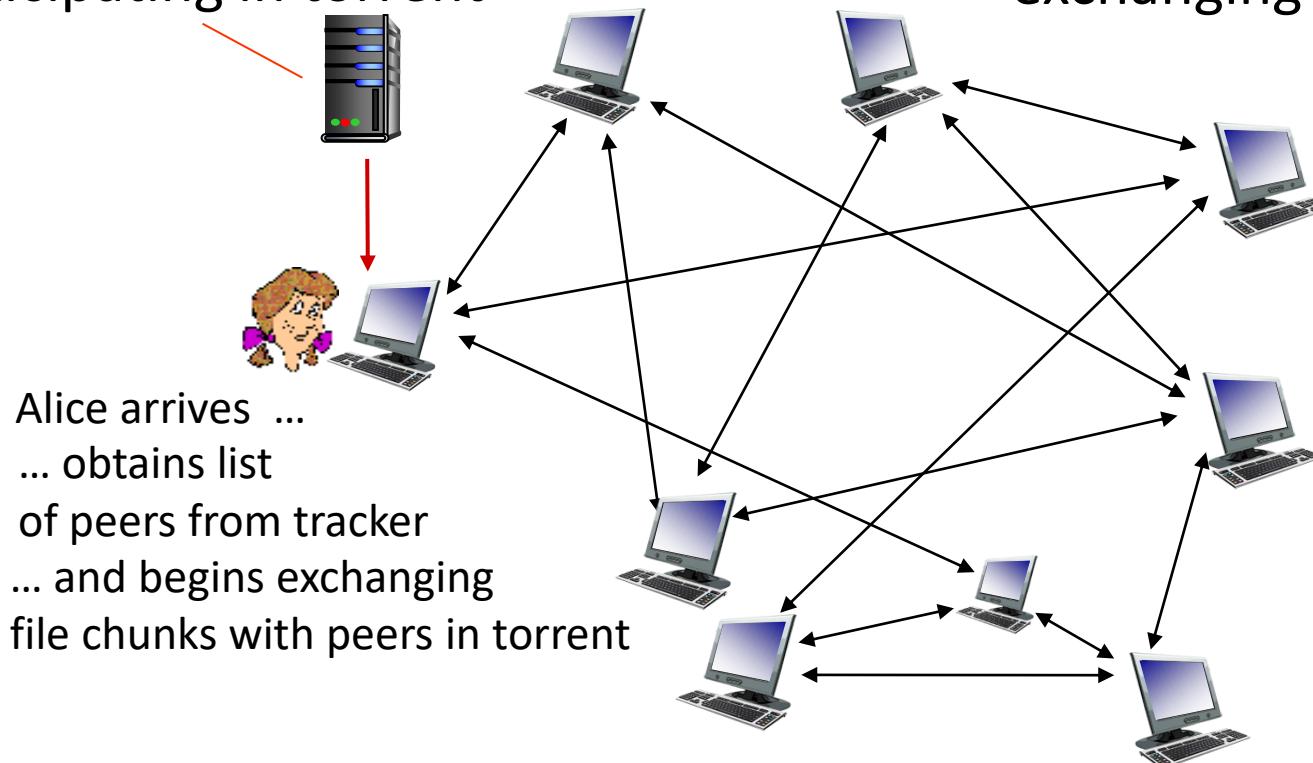
client upload rate = u , $F/u = 1$ hour, $u_s = 10u$, $d_{min} \geq u_s$



P2P file distribution: BitTorrent

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

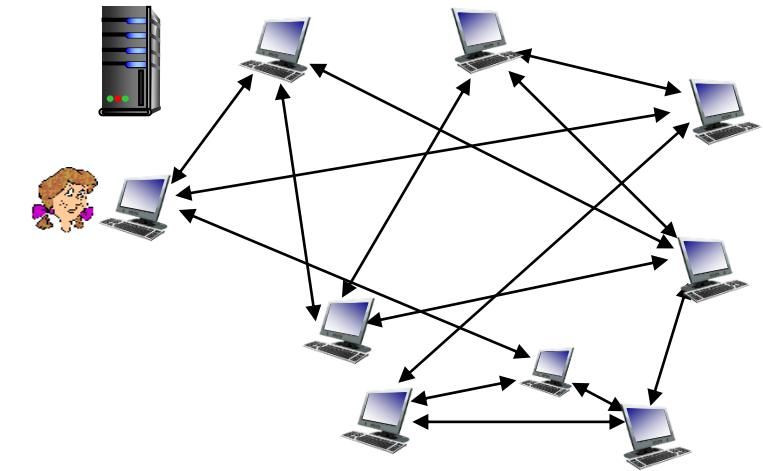
tracker: tracks peers
participating in torrent



torrent: group of peers
exchanging chunks of a file

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:

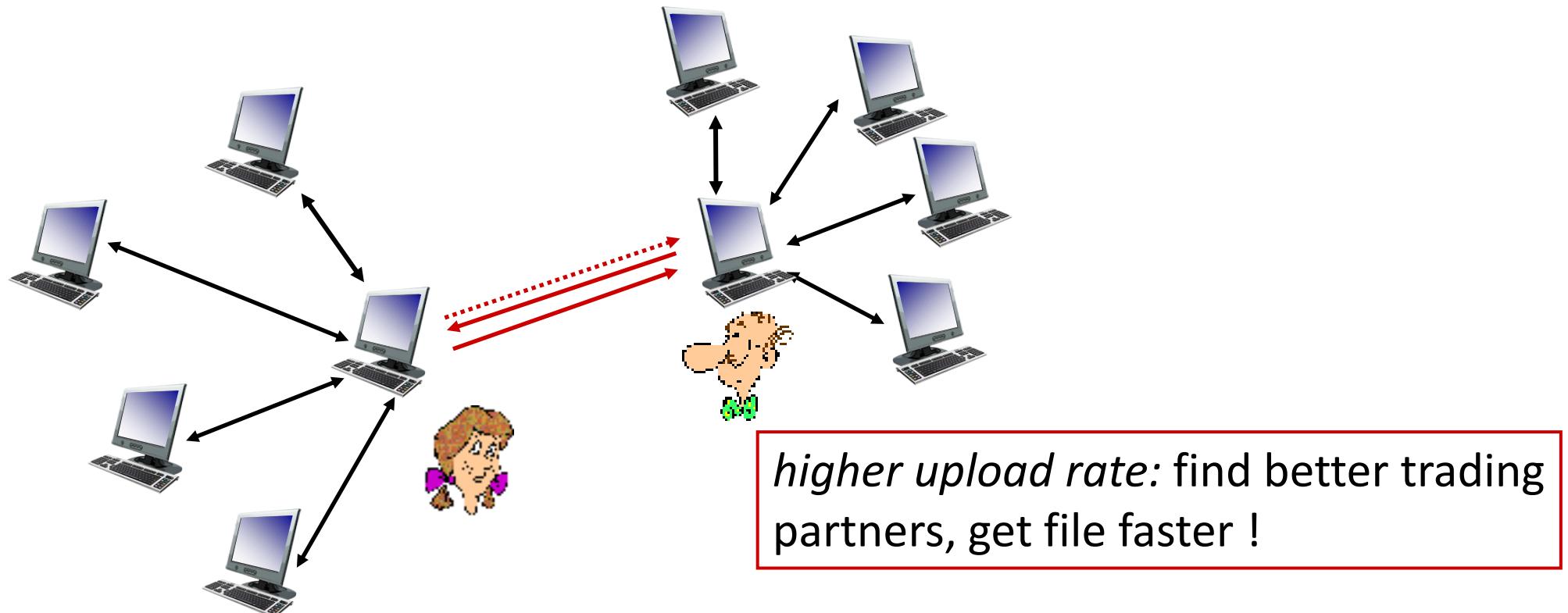
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

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 unchoke” Bob
- (2) Alice becomes one of Bob’s top-four providers; Bob reciprocates
- (3) Bob becomes one of Alice’s top-four providers



P2P Applications

- File Sharing and Distribution
 - BitTorrent
- Cryptocurrency Networks
 - Bitcoin
 - Ethereum
- P2P Gaming
- Decentralized Market Places
- P2P VPN
- P2P Cloud Storage
- P2P Video Streaming

Application layer: overview

- Principles of network applications
- Web and HTTP
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- The Domain Name System DNS
- P2P applications
- video streaming and content distribution networks
- socket programming with UDP and TCP



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?
- *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

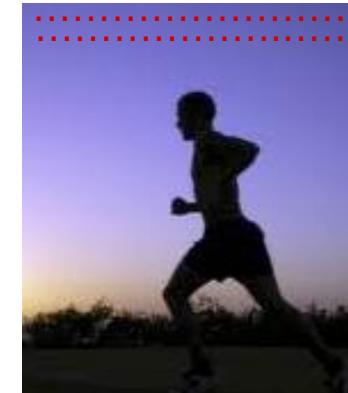


frame $i+1$

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

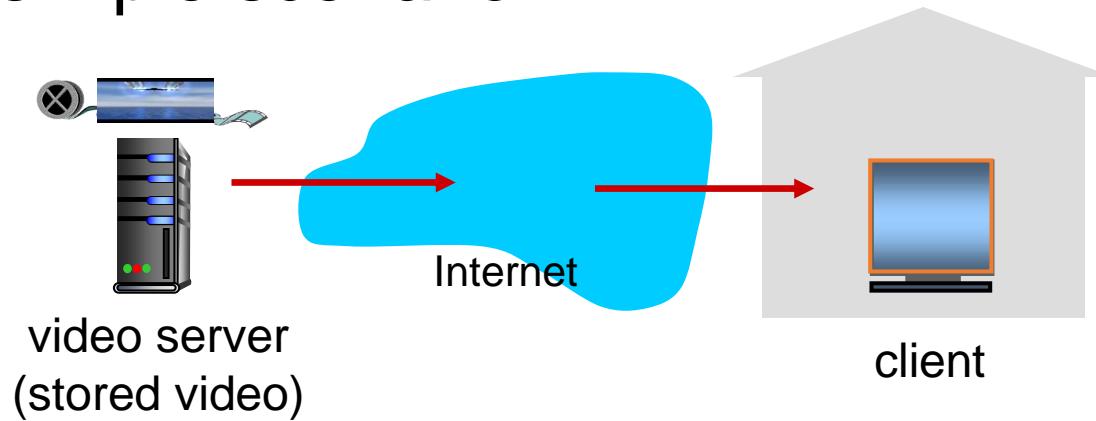
temporal coding example: instead of sending complete frame at $i+1$, send only differences from frame i



frame $i+1$

Streaming stored video

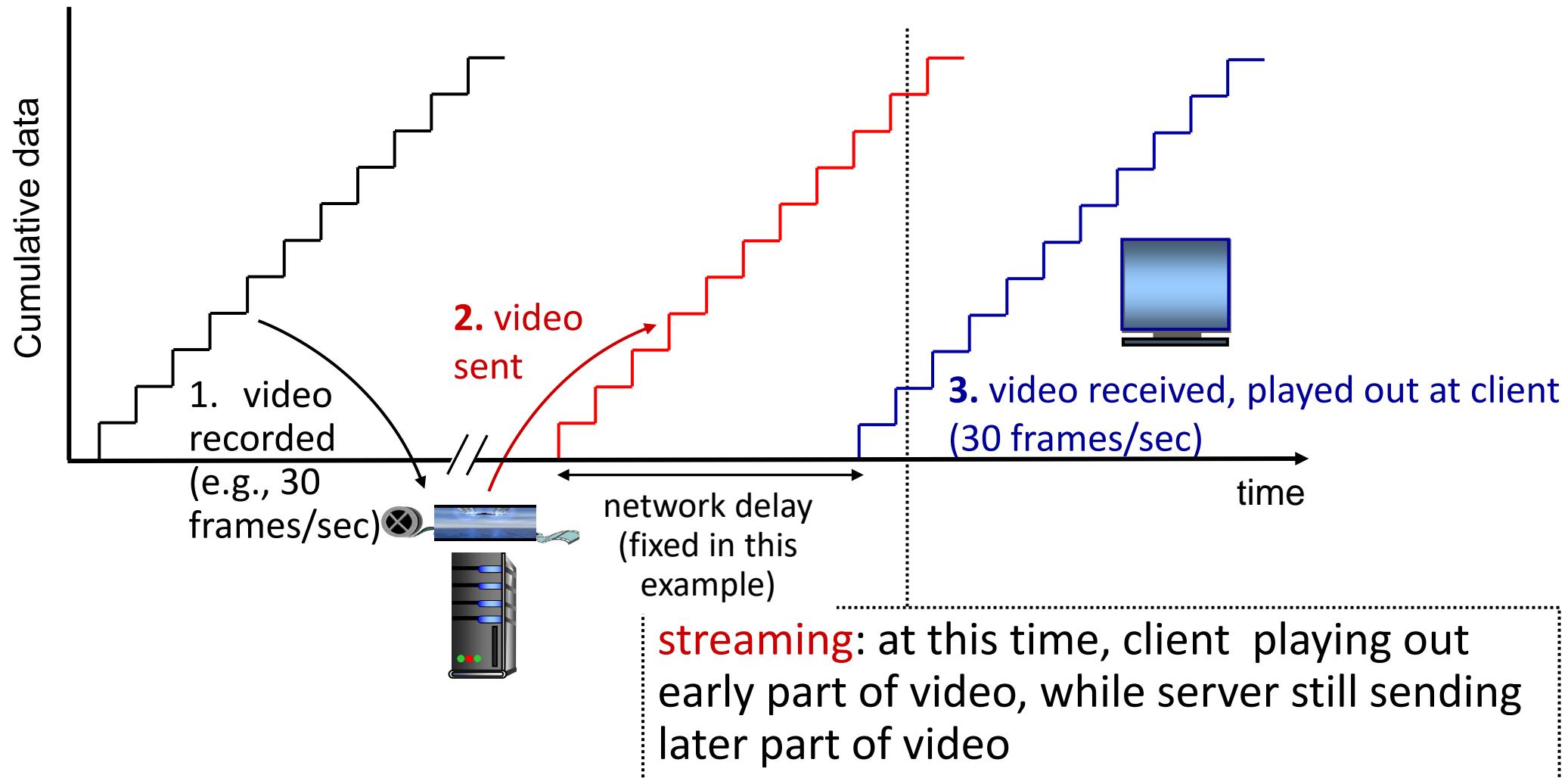
simple scenario:



Main challenges:

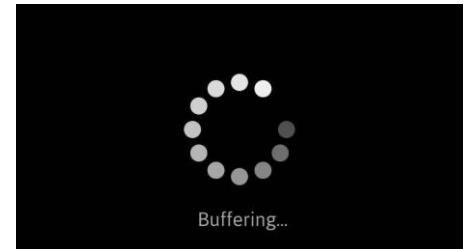
- server-to-client bandwidth will *vary* over time, with changing network congestion levels (in house, access network, network core, video server)
- packet loss, delay due to congestion will delay playout, or result in poor video quality

Streaming stored video

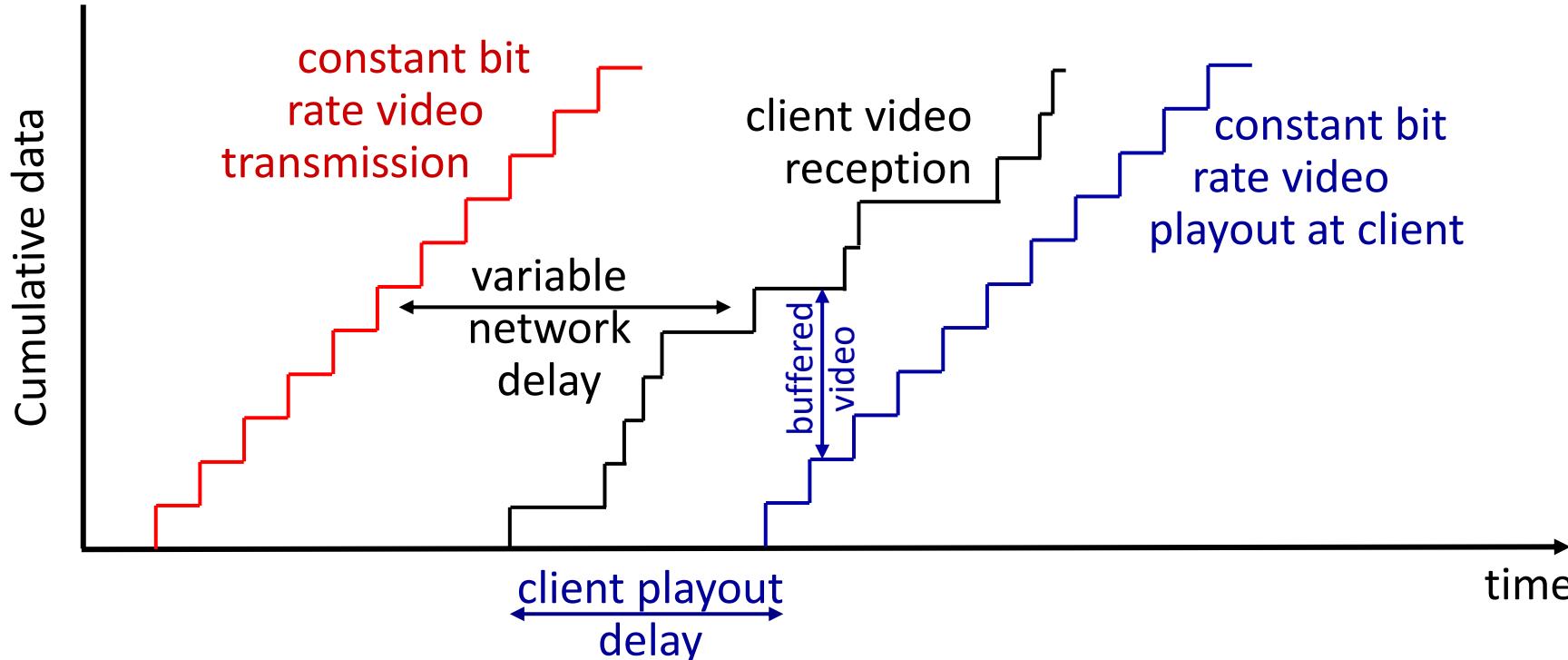


Streaming stored video: challenges

- **continuous playout constraint:** during client video playout, playout timing must match original timing
 - ... but **network delays are variable** (jitter), so will need **client-side buffer** to match continuous playout constraint
- 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

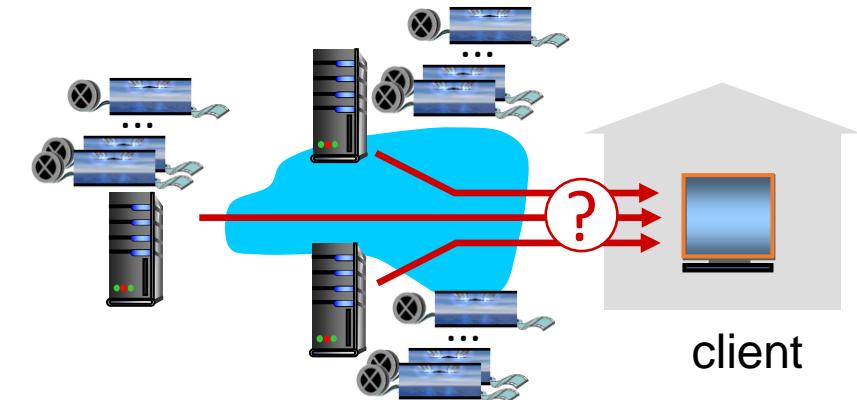
*Dynamic, Adaptive
Streaming over HTTP*

server:

- divides video file into multiple chunks
- each chunk encoded at multiple different rates
- different rate encodings stored in different files
- files replicated in various CDN nodes
- *manifest file*: provides URLs for different chunks

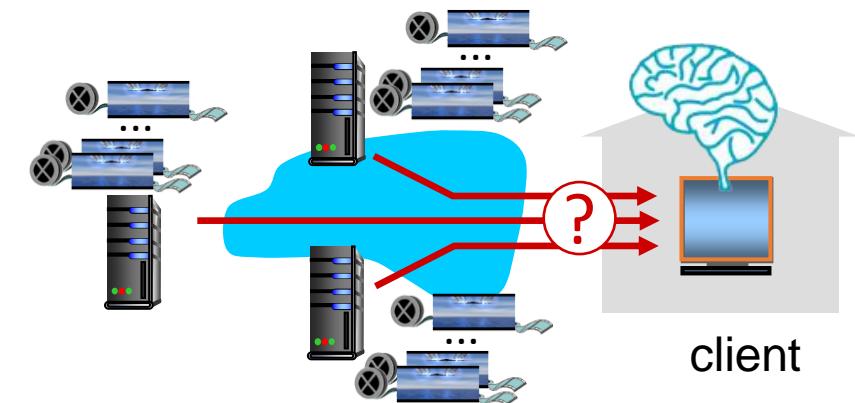
client:

- periodically estimates 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), and from different servers



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 (and possibly congested) path to distant clients

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

Content distribution networks (CDNs)

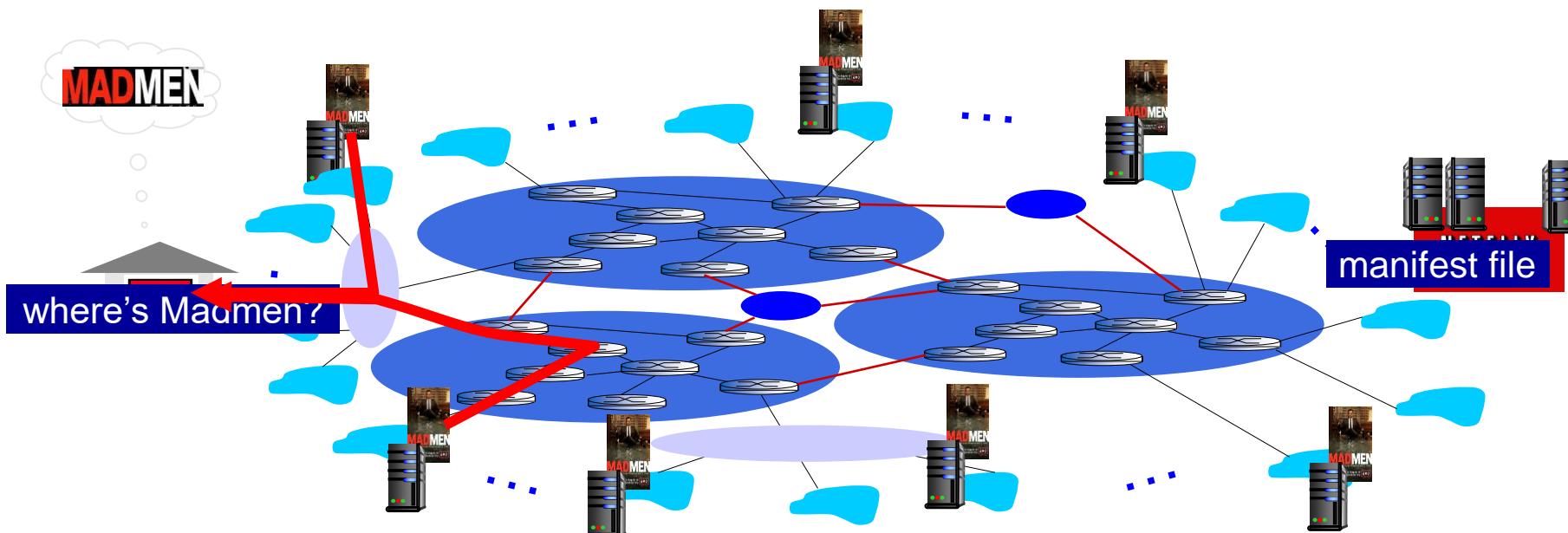
challenge: how to stream content (selected from millions of videos) to hundreds of thousands of *simultaneous* users?

- *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 > 120 countries (2015)
 - *bring home:* smaller number (10's) of larger clusters in POPs near access nets
 - used by Limelight



Content distribution networks (CDNs)

- CDN: stores copies of content (e.g. MADMEN) at CDN nodes
- subscriber requests content, service provider returns manifest
 - using manifest, client retrieves content at highest supportable rate
 - may choose different rate or copy if network path congested



Content distribution networks (CDNs)



OTT challenges: coping with a congested Internet from the “edge”

- what content to place in which CDN node?
- from which CDN node to retrieve content? At which rate?

Application Layer: Overview

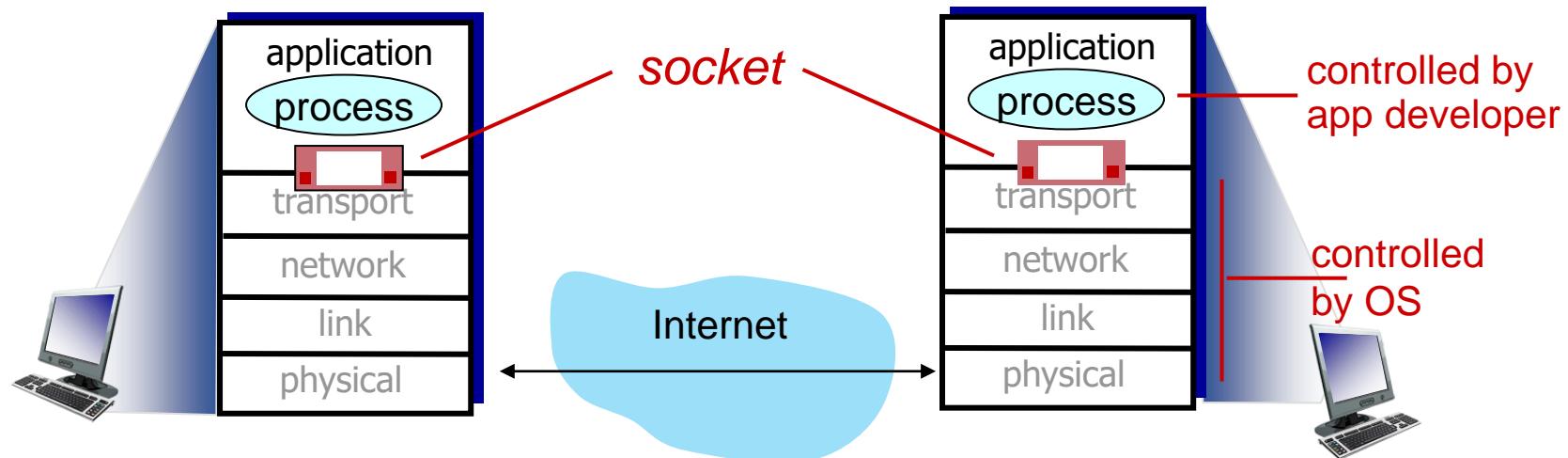
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- video streaming and content distribution networks
- **socket programming with UDP and TCP**



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 data to server
2. server receives the data and converts characters to uppercase
3. server sends modified data to client
4. client receives modified data and displays line on its screen

Socket programming with UDP

UDP: no “connection” between client
and 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 processes

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 serverIP address
And port=x; send datagram via
clientSocket

read datagram from
clientSocket
close
clientSocket

Example app: UDP client

Python UDPCClient

```
include Python's socket library → from socket import *
serverName = 'hostname'
serverPort = 12000
create UDP socket for server → clientSocket = socket(AF_INET,
                                                    SOCK_DGRAM)
get user keyboard input → message = raw_input('Input lowercase sentence:')
attach server name, port to message; send into socket → clientSocket.sendto(message.encode(),
                           (serverName, serverPort))
read reply characters from socket into string → modifiedMessage, serverAddress =
                                               clientSocket.recvfrom(2048)
print out received string and close socket → print modifiedMessage.decode()
                                              clientSocket.close()
```

Example app: UDP server

Python UDPServer

```
from socket import *
serverPort = 12000
create UDP socket → serverSocket = socket(AF_INET, SOCK_DGRAM)
bind socket to local port number 12000 → serverSocket.bind(("", serverPort))
                                         print ("The server is ready to receive")
loop forever → while True:
Read from UDP socket into message, getting →   message, clientAddress = serverSocket.recvfrom(2048)
client's address (client IP and port)           modifiedMessage = message.decode().upper()
                                               serverSocket.sendto(modifiedMessage.encode(),
send upper case string back to this client →   clientAddress)
```

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 processes

Client/server socket interaction: TCP



server (running on hostid)



client

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

TCP
connection setup

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

send request using
clientSocket

read reply from
clientSocket

close
clientSocket

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.encode())
modifiedSentence = clientSocket.recv(1024)
print ('From Server:', modifiedSentence.decode())
clientSocket.close()
```

create TCP socket for server,
remote port 12000 → clientSocket = socket(AF_INET, SOCK_STREAM)

No need to attach server name, port → modifiedSentence = clientSocket.recv(1024)

Example app: TCP server

Python TCP Server

```
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 True:
    connectionSocket, addr = serverSocket.accept()
    sentence = connectionSocket.recv(1024).decode()
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence.
                           encode())
connectionSocket.close()
```

create TCP welcoming socket → from socket import *

server begins listening for incoming TCP requests → serverPort = 12000
→ serverSocket = socket(AF_INET,SOCK_STREAM)
→ serverSocket.bind(("","serverPort"))
→ serverSocket.listen(1)

loop forever → print 'The server is ready to receive'
→ while True:

server waits on accept() for incoming requests, new socket created on return → connectionSocket, addr = serverSocket.accept()

read bytes from socket (but not address as in UDP) → sentence = connectionSocket.recv(1024).decode()
→ capitalizedSentence = sentence.upper()
→ connectionSocket.send(capitalizedSentence.
 encode())

close connection to this client (but *not* welcoming socket) → connectionSocket.close()

Chapter 2: Summary

our study of network application layer is 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
- video streaming, CDNs
- 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(payload) being communicated

important themes:

- centralized vs. decentralized
- stateless vs. stateful
- scalability
- reliable vs. unreliable message transfer
- “complexity at network edge”

Questions