

Chapter 2

Application Layer

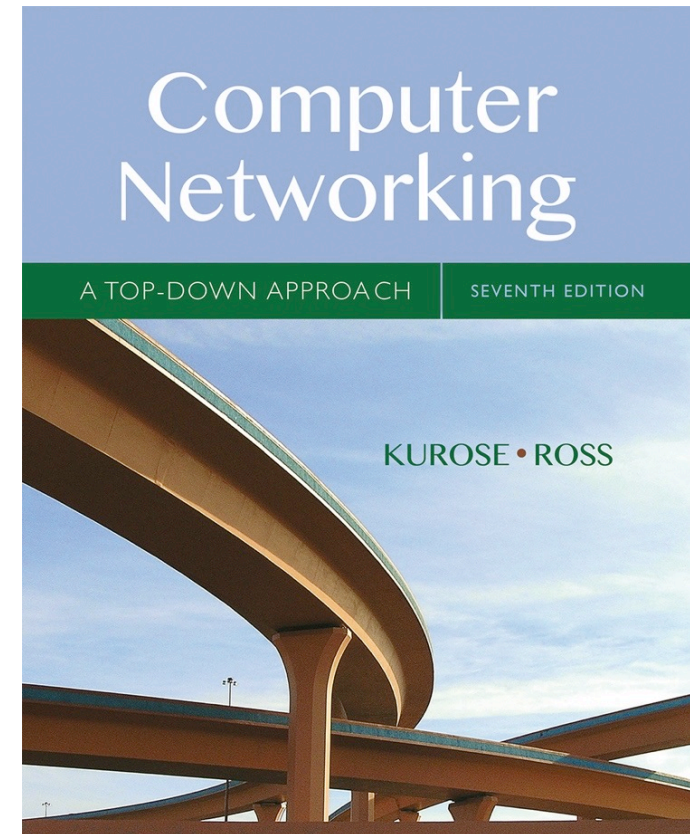
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Computer Networking: A Top Down Approach

7th edition

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Chapter 2: outline

2.1 principles of network applications

2.2 Web and HTTP

2.3 electronic mail

- SMTP, POP3, IMAP

2.4 DNS

2.5 P2P applications

2.6 video streaming and content distribution networks

2.7 socket programming with UDP and TCP

Chapter 2: application layer

our goals:

- conceptual, implementation aspects of network application protocols
 - transport-layer service models
 - client-server paradigm
 - peer-to-peer paradigm
 - content distribution networks
- learn about protocols by examining popular application-level protocols
 - HTTP
 - FTP
 - SMTP / POP3 / IMAP
 - DNS
- creating network applications
 - socket API

Some network types of apps

- e-mail
- web
- text messaging
- remote login
- P2P file sharing
- multi-user network games
- streaming stored video
- IP telephony (voice over IP)
- real-time video conferencing
- social networking
- search
- ...
- ...

The Internet supports a wide variety of network apps and services with distinct characteristics and quality requirements.

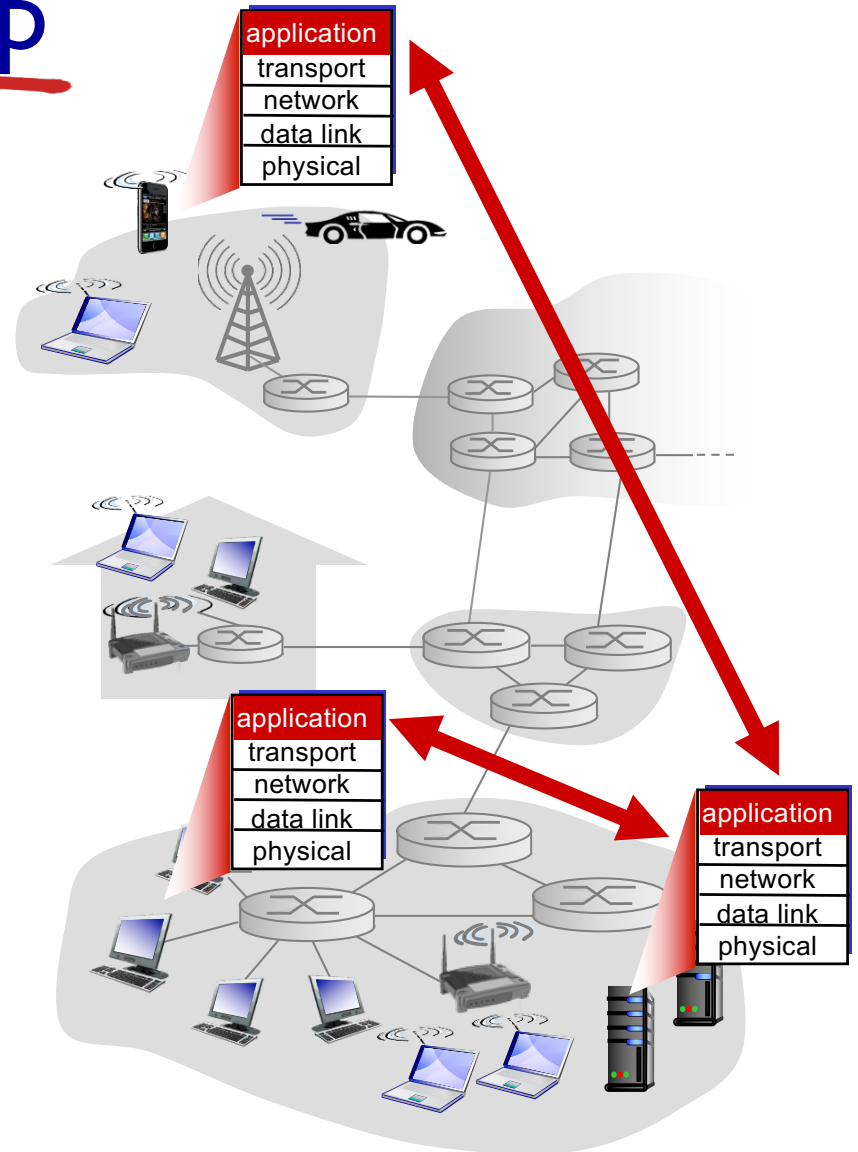
Creating a network app

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



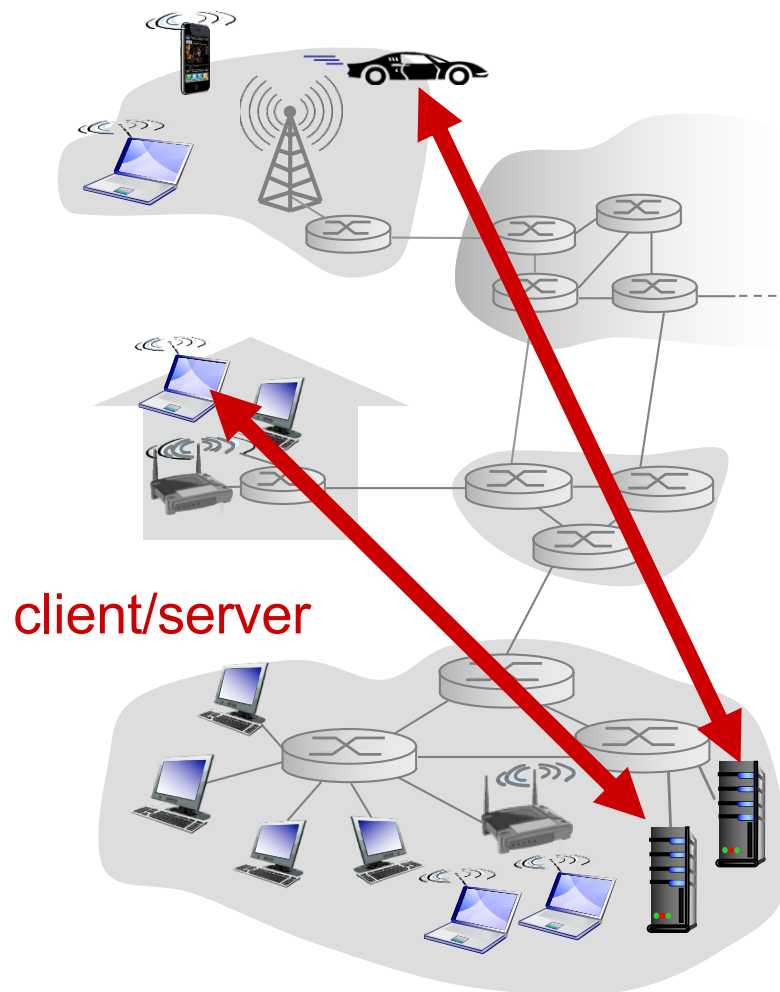
Important concept: The end-to-end principle.

Application architectures

possible structure of applications:

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

Client-server architecture



server:

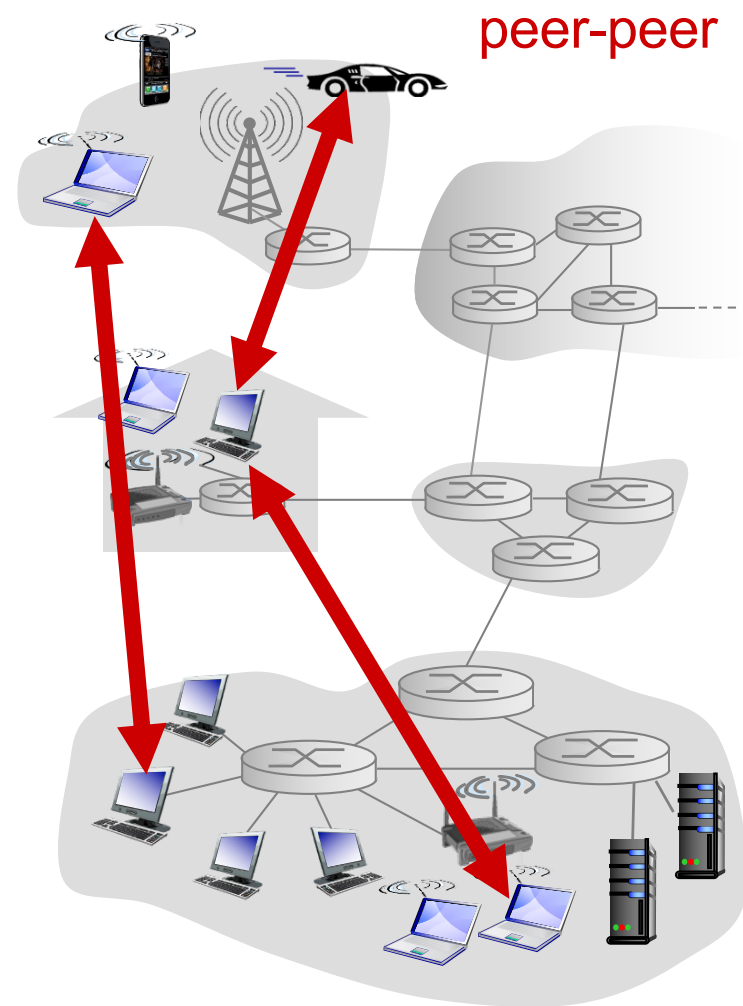
- always-on host
- permanent IP address
- data centers for scaling

clients:

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

P2P architecture

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



Processes communicating

process: program running within a host

- within same host, two processes communicate using *inter-process communication* (defined by OS)
- processes in different hosts communicate by exchanging *messages*

clients, servers

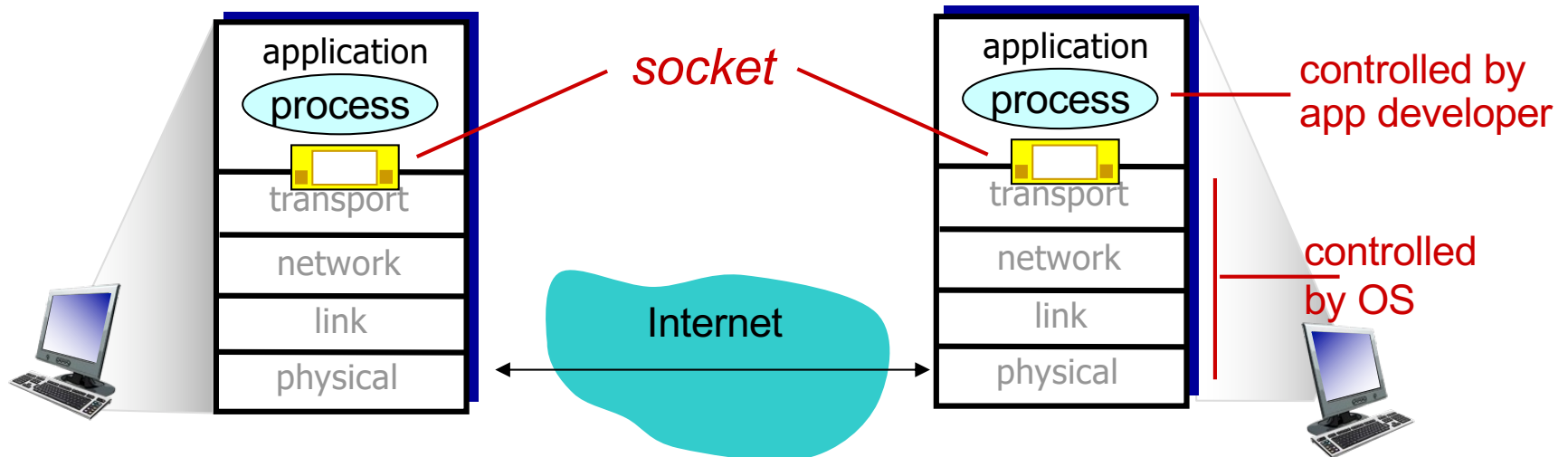
client process: process that initiates communication

server process: process that waits to be contacted

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

Sockets

- process sends/receives messages to/from its **socket**
- socket analogous to door
 - sending process shoves message out door
 - sending process relies on transport infrastructure on other side of door to deliver message to socket at receiving process



Addressing processes

- to receive messages, process must have *identifier*
- host device has unique 32-bit IP address
- Q: does IP address of host on which process runs suffice for identifying the process?
 - A: no, *many* processes can be running on same host
- *identifier* includes both **IP address** and **port numbers** associated with process on host.
- example port numbers:
 - HTTP server: 80
 - mail server: 25
- to send HTTP message to gaia.cs.umass.edu web server:
 - **IP address**: 128.119.245.12
 - **port number**: 80
- more shortly...

App-layer protocol defines

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

open protocols:

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

proprietary protocols:

- e.g., Skype, Zoom

What transport service does an app need?

data integrity

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

timing

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

throughput

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

security

- encryption, data integrity, ...

Transport service requirements: common apps

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: kbps-1Mbps video: 10kbps-5Mbps	yes, 10's msec
stored audio/video	loss-tolerant	same as above	yes, few secs
interactive games	loss-tolerant	few kbps up	yes, 10's msec
messaging	no loss	elastic	yes and no

Internet transport protocols services

TCP service:

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

UDP service:

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

Q: why bother? Why is there a UDP?

Internet apps: application, transport protocols

application	application layer protocol	underlying transport protocol
e-mail	SMTP [RFC 5321]	TCP
remote terminal access	Telnet [RFC 854]	TCP
Web contents	HTTP/1.1 [RFC 7320]	TCP
	HTTP/3 [RFC 9114]	QUIC, UDP
file transfer	FTP [RFC 959]	TCP
streaming multimedia	HTTP 1.1 [RFC 7320], DASH	TCP
Internet telephony	SIP [3261], RTP [RFC 3550], or proprietary	UDP (or TCP)

Securing TCP

- Vanilla TCP & UDP sockets:
 - no encryption
 - cleartext passwords sent into socket traverse Internet in cleartext (!)
- Transport Layer Security (TLS)
 - provides encrypted TCP connections
 - data integrity
 - end-point authentication
- TLS implemented in application layer
 - apps use TLS libraries, that use TCP in turn
 - cleartext sent into “socket” traverse Internet *encrypted*

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2.5 P2P applications

2.6 video streaming and content distribution networks

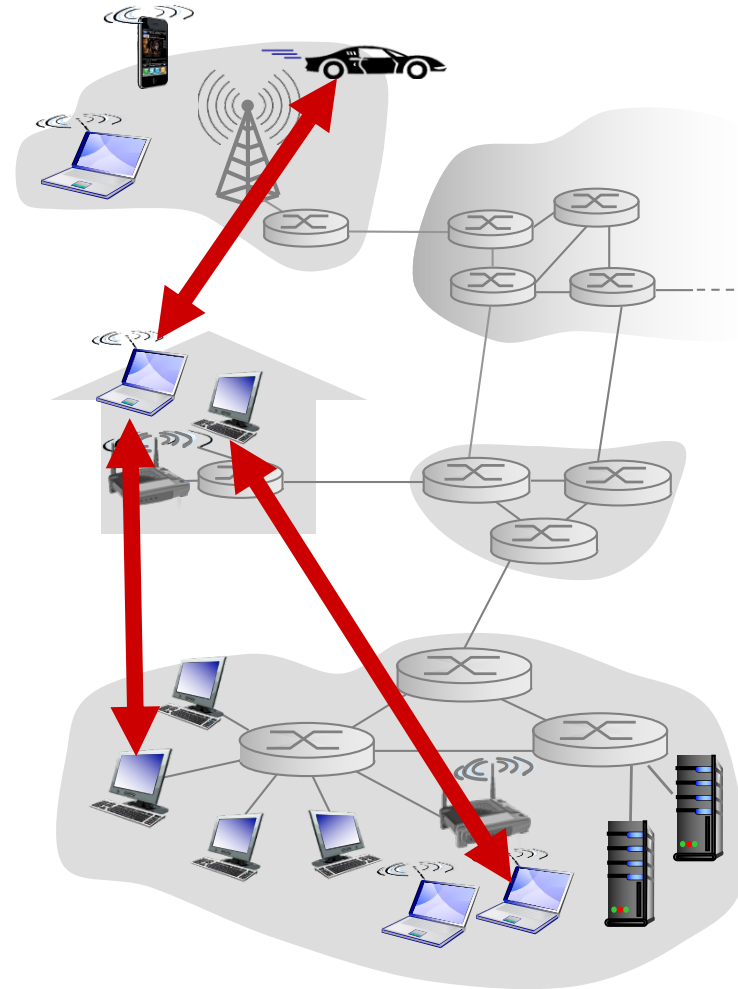
2.7 socket programming with UDP and TCP

Pure P2P architecture

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

examples:

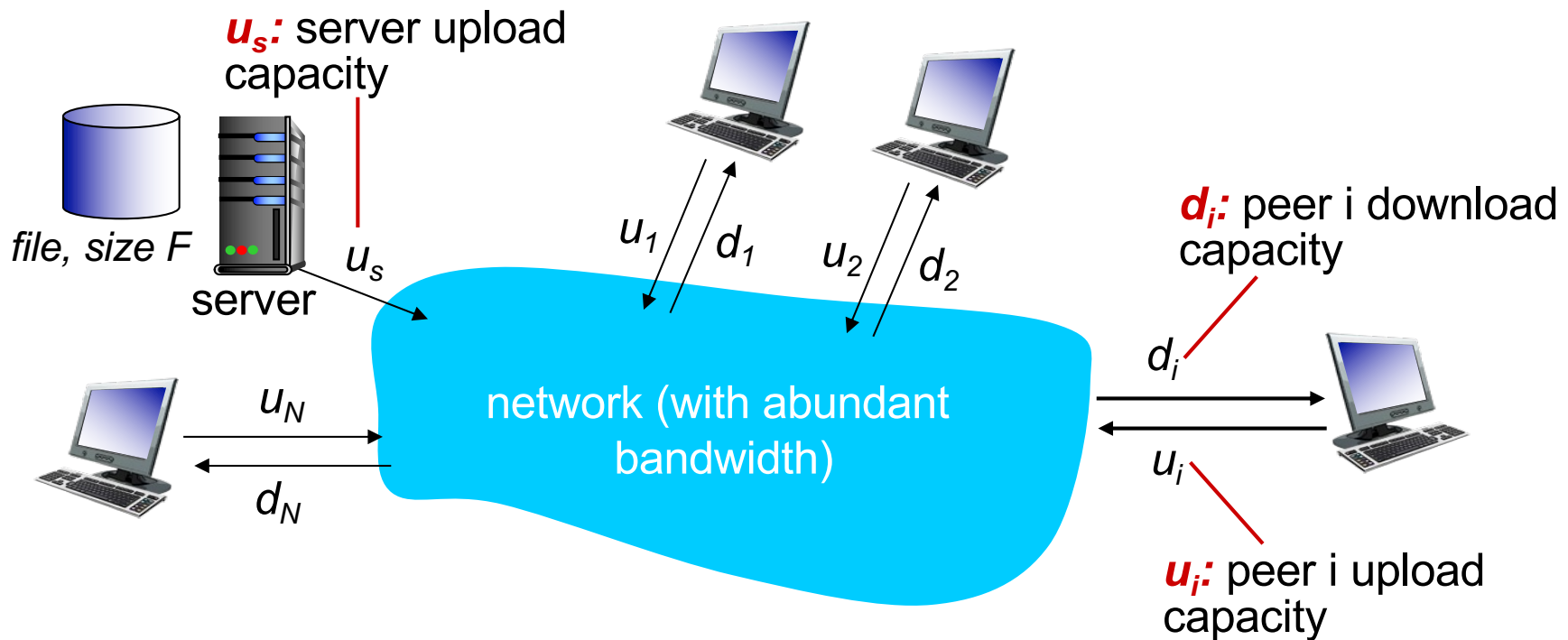
- file distribution (BitTorrent)
- Streaming (KanKan)
- VoIP (Skype)



File distribution: client-server vs P2P

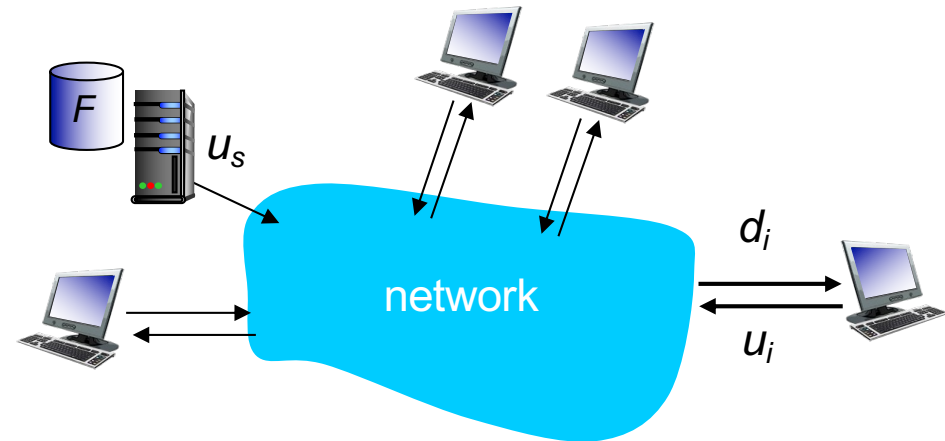
Question: how much time to distribute file (size F) from one server to N peers?

- peer upload/download capacity is limited resource



File distribution time: client-server

- **server transmission:** must sequentially send (upload) N file copies:
 - time to send one copy: F/u_s
 - time to send N copies: NF/u_s
- **client:** each client must download file copy
 - d_{min} = min client download rate
 - min client download time: F/d_{min}



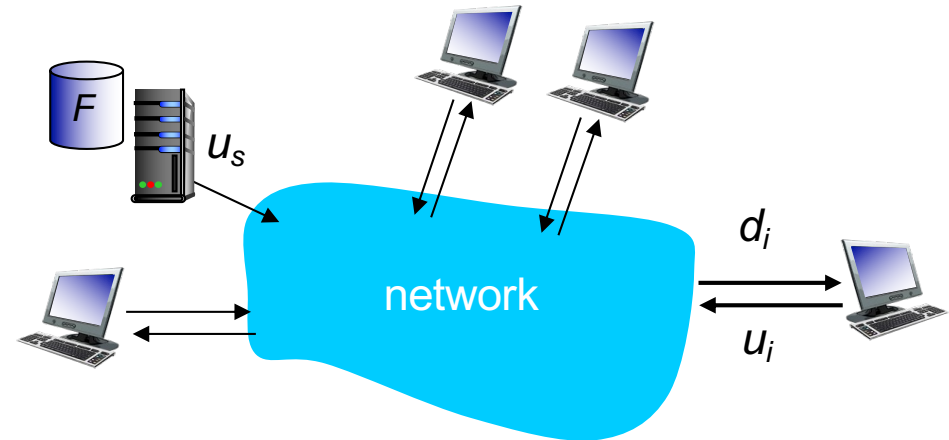
*time to distribute F
to N clients using
client-server approach*

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

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

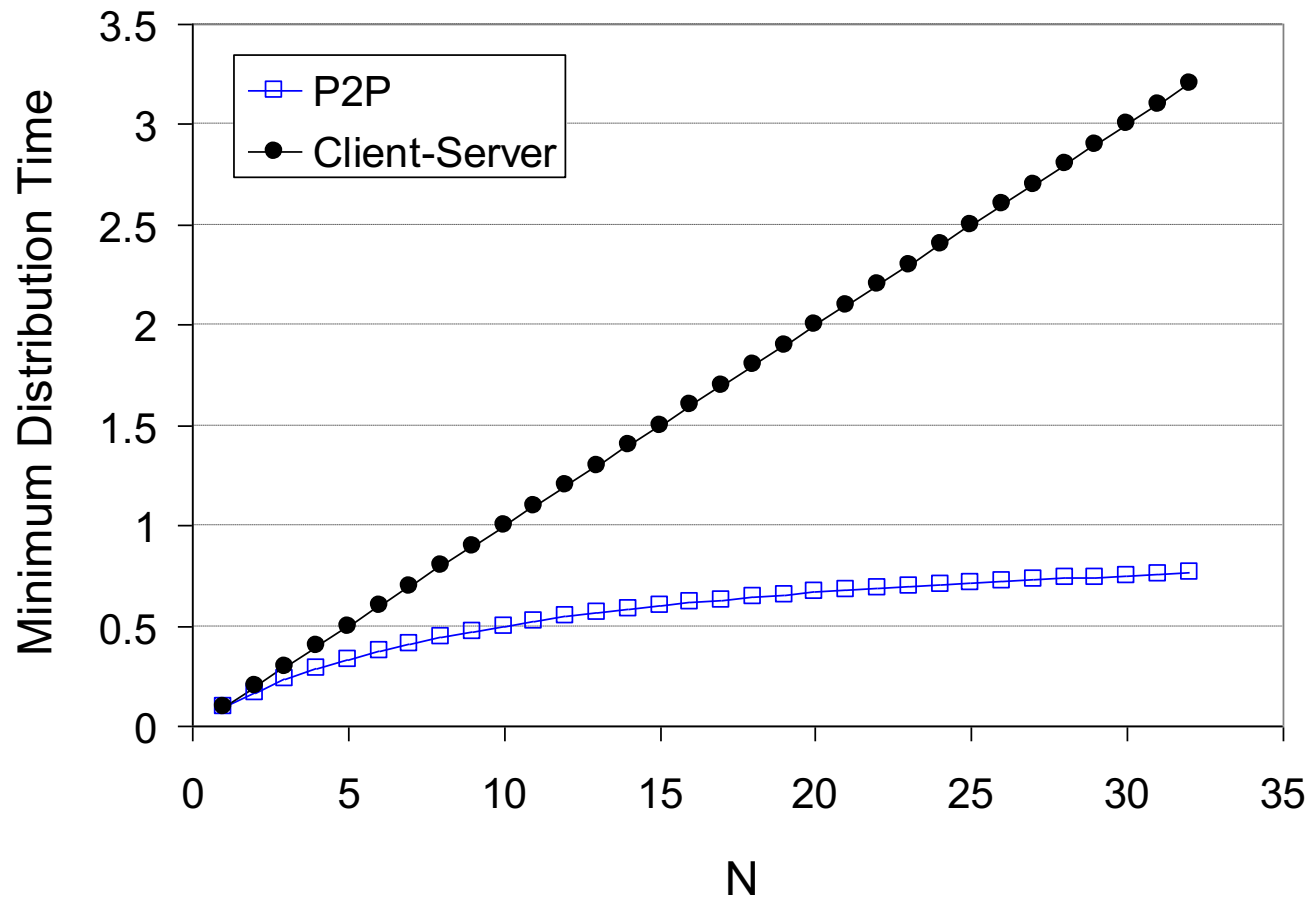
$$D_{P2P} \geq \max\{F/u_s, F/d_{\min}, NF/(u_s + \sum u_i)\}$$

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, $u_s = 10u$, $d_{min} \geq u_s$

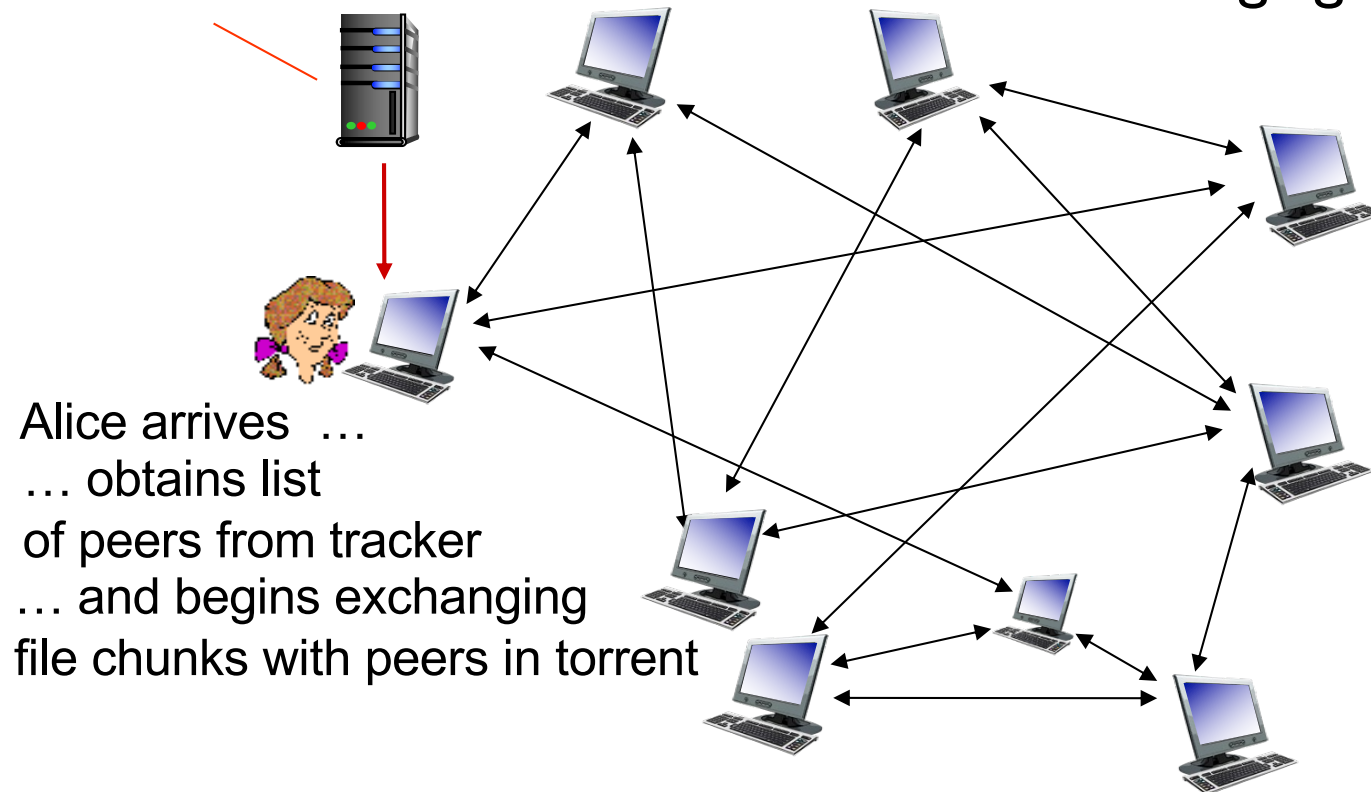


P2P file distribution: BitTorrent

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

tracker: tracks peers participating in torrent

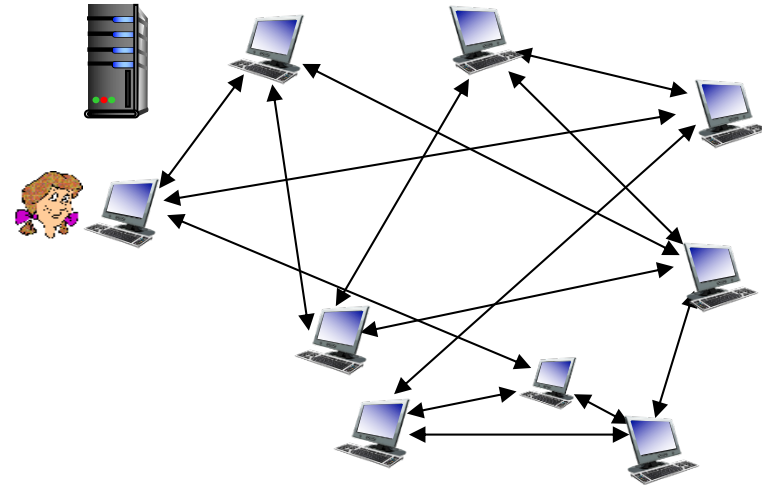
torrent: group of peers exchanging chunks of a file



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

P2P file distribution: BitTorrent

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



BitTorrent: requesting, sending file chunks

requesting chunks:

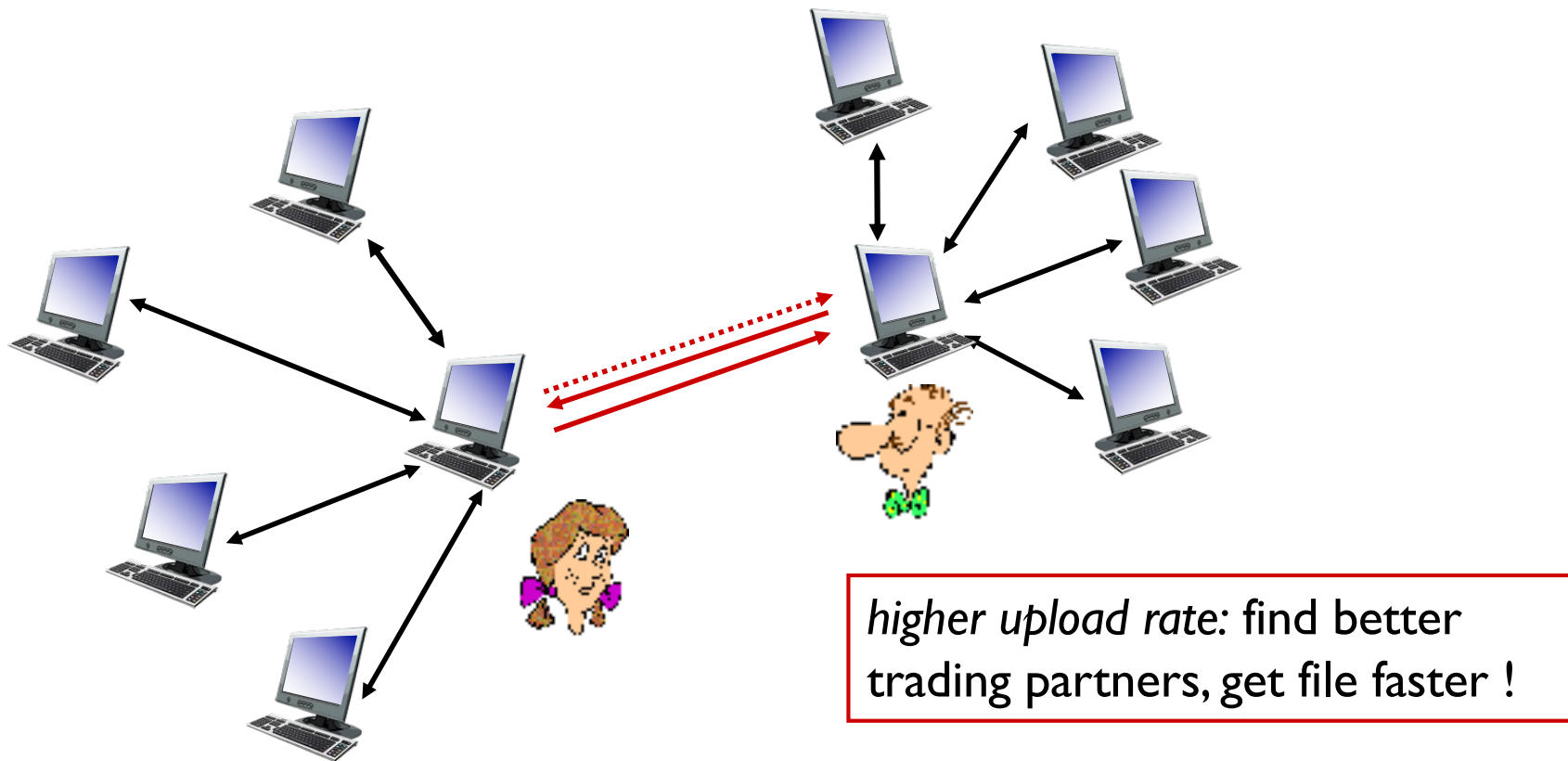
- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

sending chunks: tit-for-tat

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

BitTorrent: tit-for-tat

- (1) Alice “optimistically unchokes” Bob
- (2) Alice becomes one of Bob’s top-four providers; Bob reciprocates
- (3) Bob becomes one of Alice’s top-four providers



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Video Streaming and CDNs: context

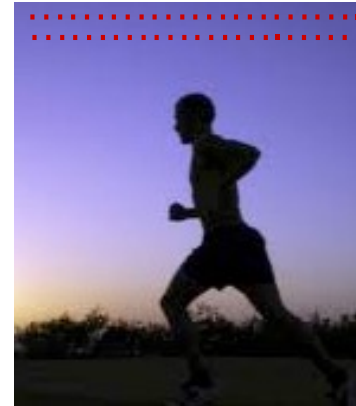
- video traffic: major consumer of Internet bandwidth
 - Netflix, YouTube, Amazon Prime... > 80% overall traffic (Oct, 2021)
 - ~2B YouTube users, ~210M Netflix subscribers (Oct. 2021)
- challenge: scale - how to reach ~2B users?
 - single mega-video server won't work (why?)
- challenge: heterogeneity
 - 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

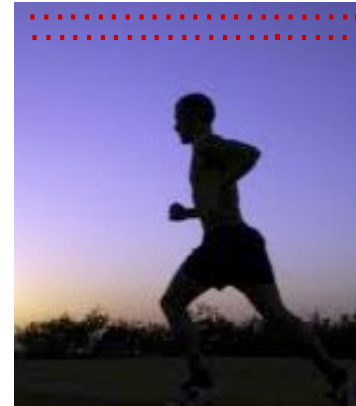


frame $i+1$

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 I (CD-ROM) 1.5 Mbps
 - MPEG2 (DVD) 3-6 Mbps
 - MPEG4 (often used in Internet, 64k to 12Mbps)

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

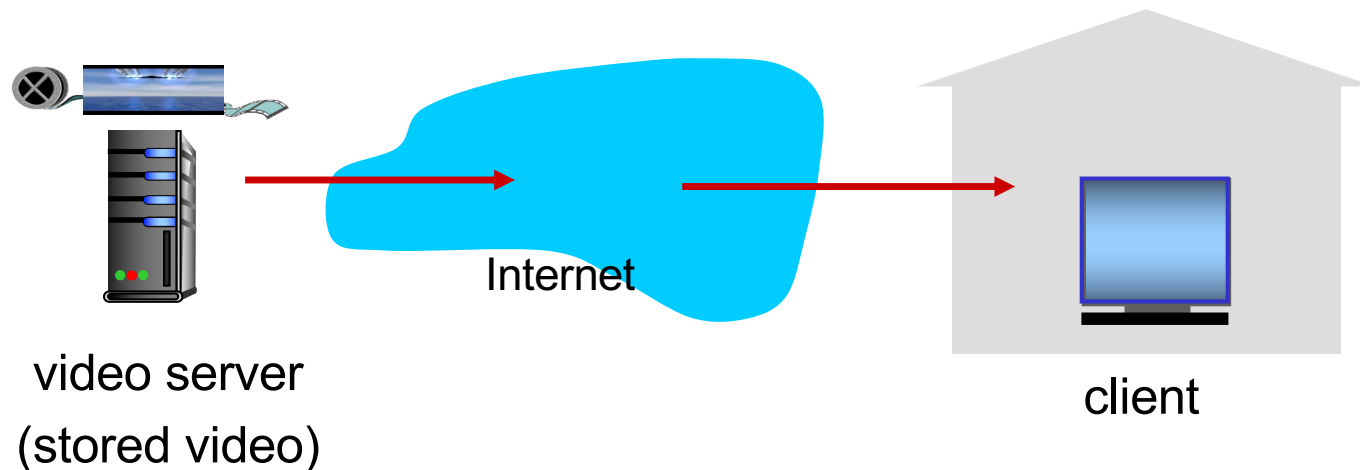
temporal coding example:
instead of sending complete frame at $i+1$,
send only differences from frame i



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 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

- *DASH: Dynamic, Adaptive Streaming over HTTP*
- “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)

Content distribution networks

- *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

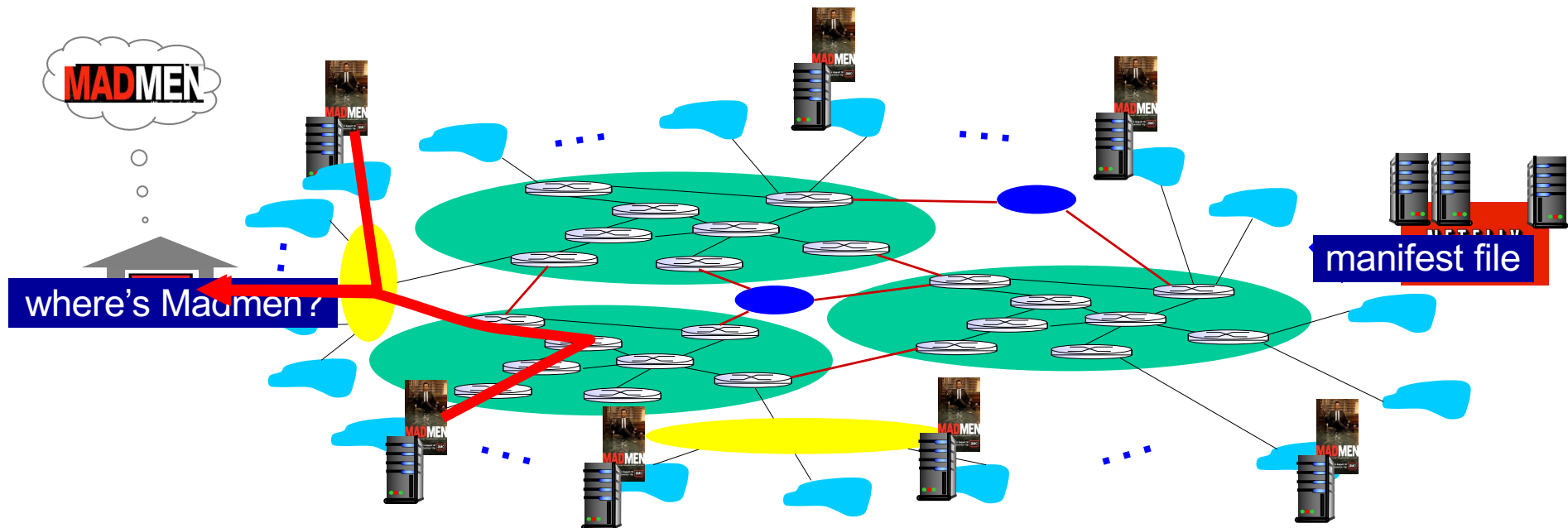
....quite simply: this solution *doesn't scale*

Content distribution networks

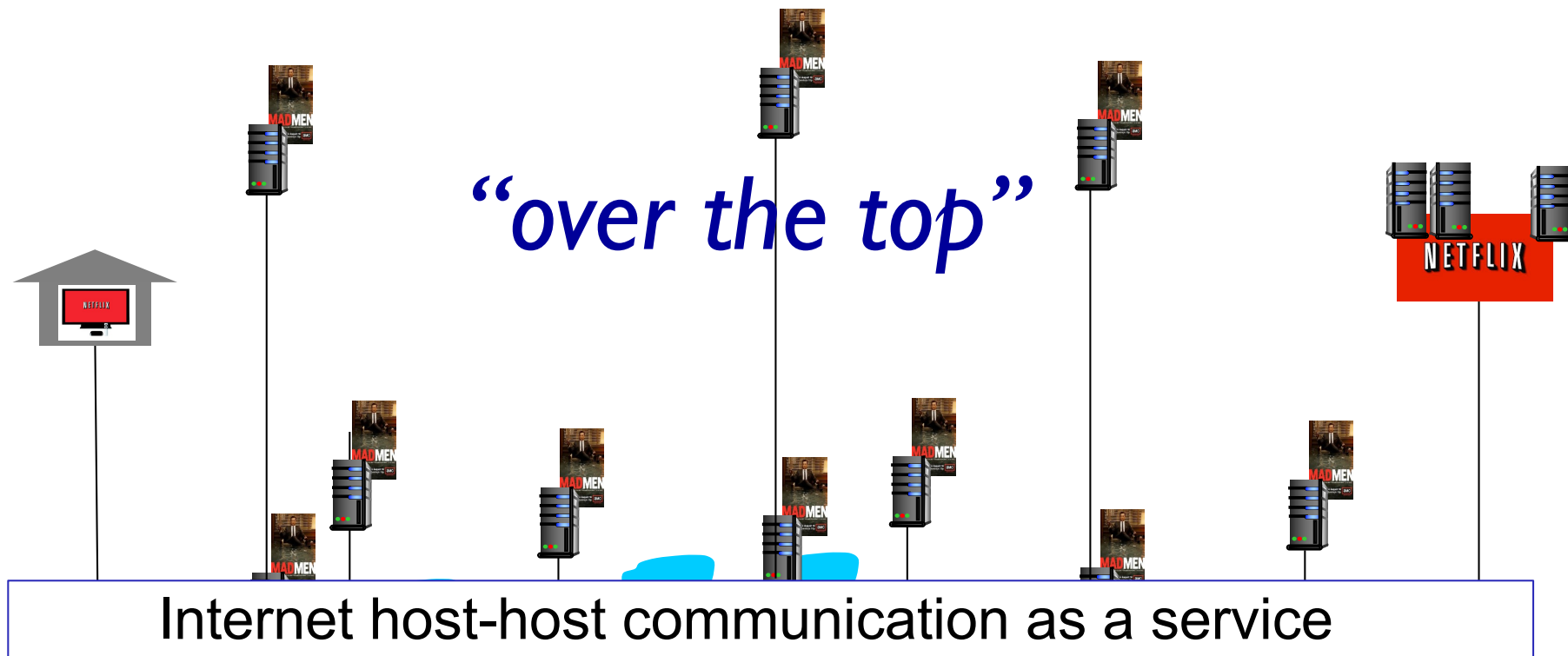
- *challenge*: how to stream content (selected from millions of videos) to hundreds of thousands of simultaneous users?
- *option 2*: store/serve multiple copies of videos at multiple geographically distributed sites (*CDN*)
 - *enter deep*: push CDN servers deep into many access networks
 - close to users (tentative single hop)
 - used by Akamai, ~325000 servers, >135 countries, 100Tbps (2021)
 - *bring home*: smaller number (10's) of larger clusters in POPs near (but not within) access networks
 - used by Limelight

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

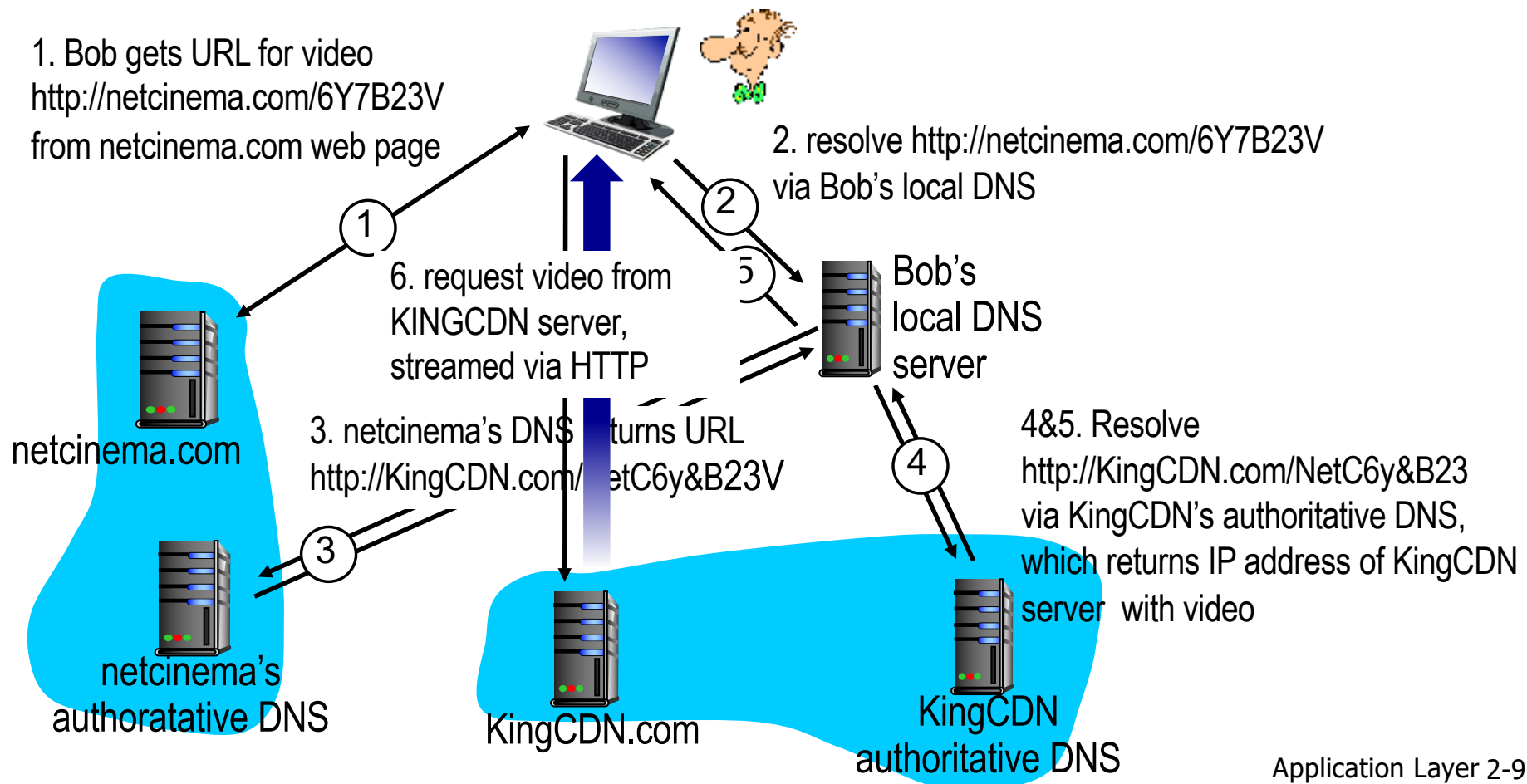
- from which CDN node to retrieve content?
- viewer behavior in presence of congestion?
- what content to place in which CDN node? at which rate?

more .. in chapter 7

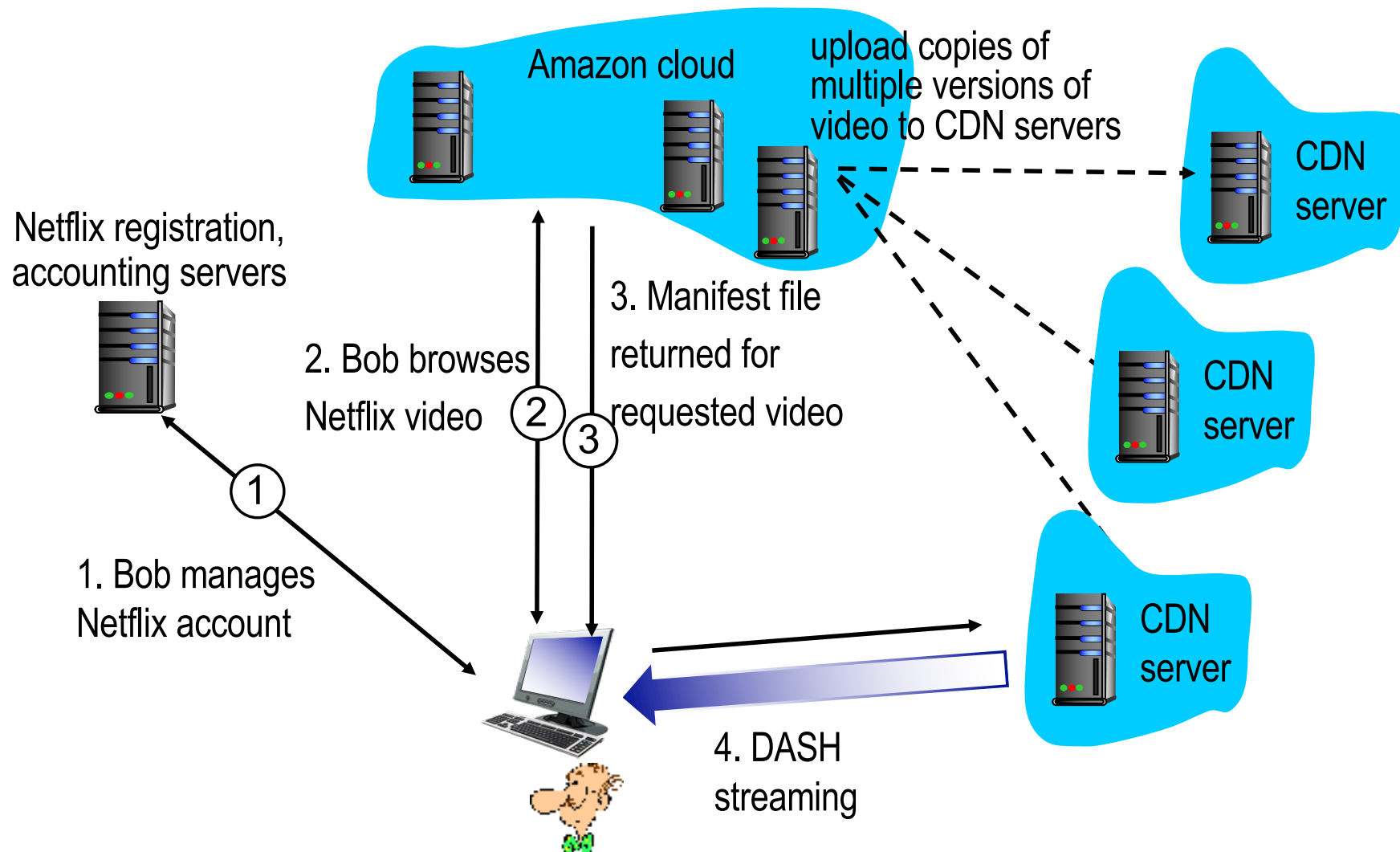
CDN content access: a closer look

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

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



Case study: Netflix



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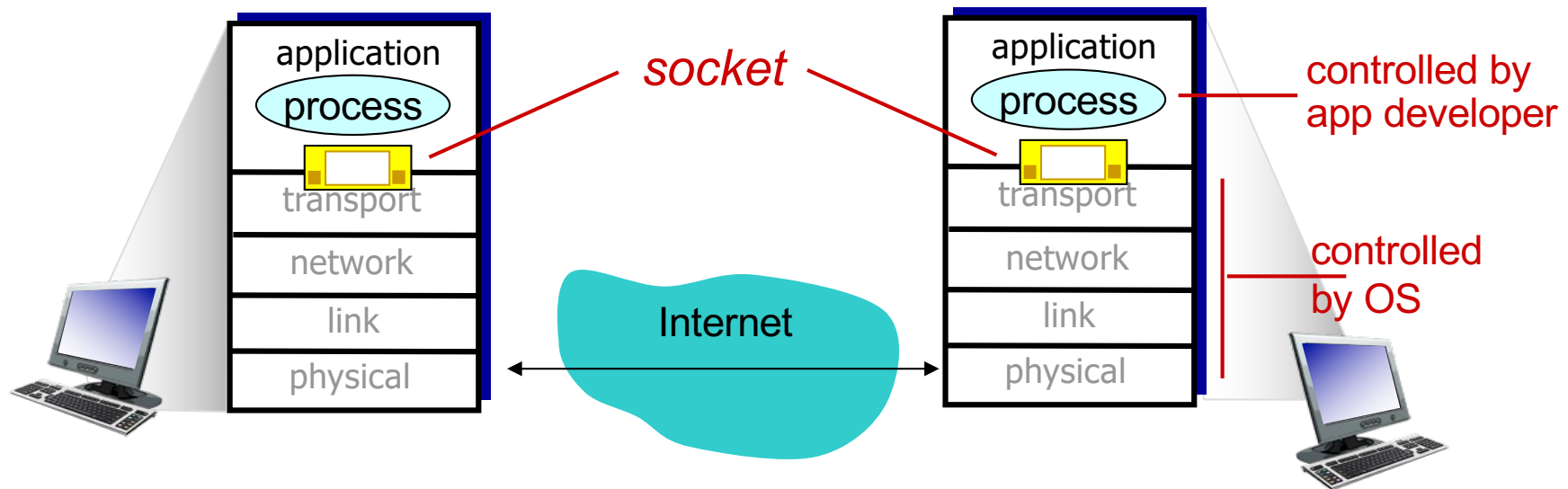
2.6 video streaming and content distribution networks

2.7 socket programming with UDP and TCP

Socket programming

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

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



Socket programming

Two socket types for two transport services:

- **UDP:** unreliable datagram
- **TCP:** reliable, byte stream-oriented

Application Example:

1. client reads a line of characters (data) from its keyboard and sends 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 & 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

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`

Example app: UDP client

Python UDPClient

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 client's
address (client IP and port) → `message, clientAddress = serverSocket.recvfrom(2048)`
`modifiedMessage = message.decode().upper()`

send upper case string
back to this client → `serverSocket.sendto(modifiedMessage.encode(),
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)

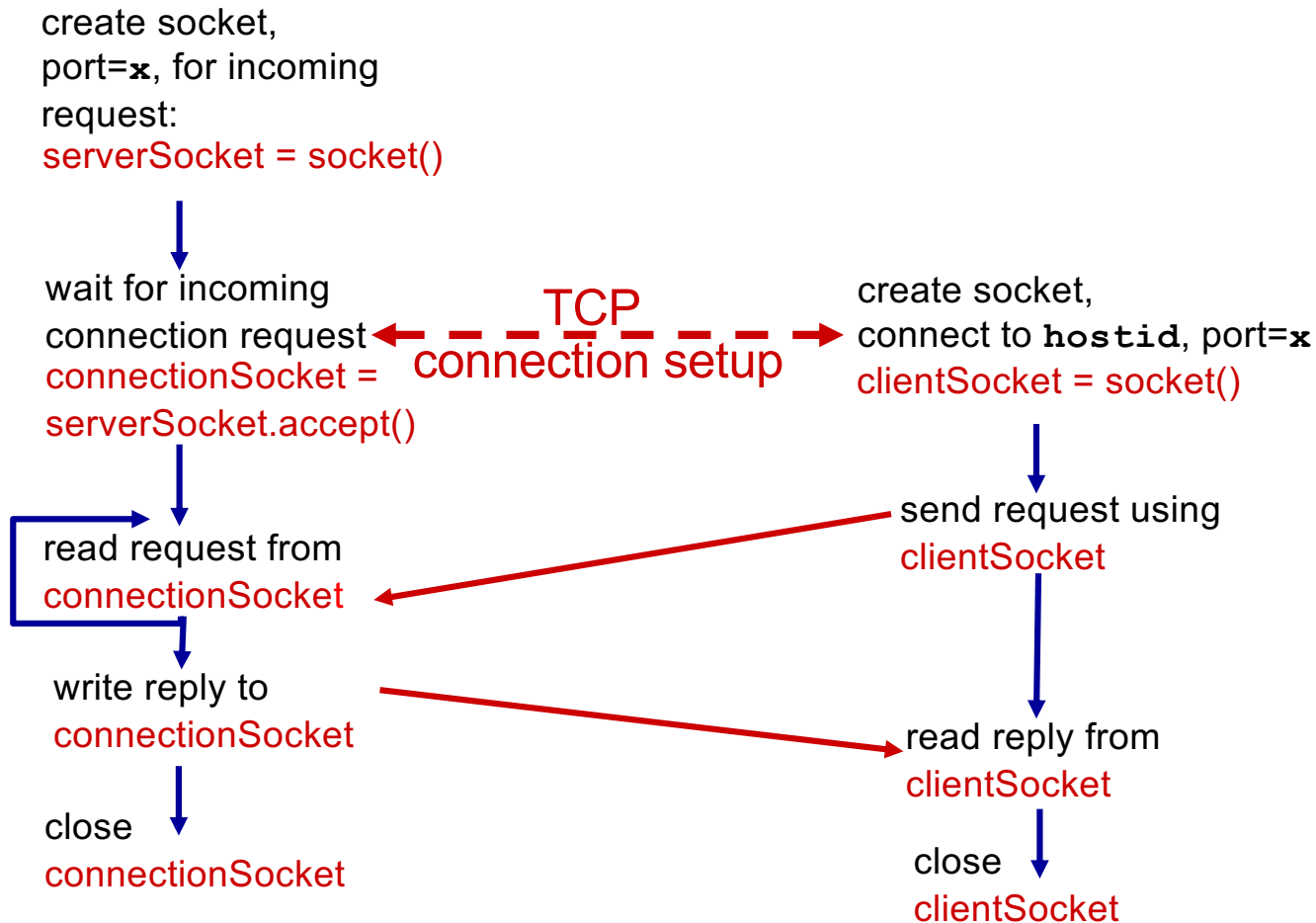
application viewpoint:

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

Client/server socket interaction: TCP

server (running on `hostid`)

client



Example app: TCP client

Python TCPClient

```
from socket import *
```

```
serverName = 'servername'
```

```
serverPort = 12000
```

create TCP socket for
server, remote port 12000

→ `clientSocket = socket(AF_INET, SOCK_STREAM)`

```
clientSocket.connect((serverName,serverPort))
```

```
sentence = raw_input('Input lowercase sentence:')
```

No need to attach server
name, port

→ `clientSocket.send(sentence.encode())`

```
modifiedSentence = clientSocket.recv(1024)
```

```
print ('From Server:', modifiedSentence.decode())
```

```
clientSocket.close()
```

Example app: TCP server

Python TCPServer

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET, SOCK_STREAM)
serverSocket.bind(('', serverPort))
serverSocket.listen(1)
print 'The server is ready to receive'

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

create TCP welcoming
socket →

server begins listening for
incoming TCP requests →

loop forever →

server waits on accept()
for incoming requests, new
socket created on return →

read bytes from socket (but
not address as in UDP) →

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

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
 - SMTP, POP, 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:

- control vs. messages
 - in-band, out-of-band
- centralized vs. decentralized
- stateless vs. stateful
- reliable vs. unreliable message transfer
- “complexity at network edge”