Computer Networks X_400487

Lecture 9

Chapter 7: The Application Layer

Q: Latency and packet loss on the Internet today?

Packet loss < 0.4% in most cases, latency below 50ms in most cases*

Lecturer: Jesse Donkervliet
with slides from Lin Wang

Vrije Universiteit Amsterdam

*Source: https://data.fcc.gov/download/measuring-broadband-america/2023/2023-Fixed-Measuring-Broadband-America-Report.pdf

Online Games

A challenge for computer networks: real-time interactive systems

UDP or TCP? What is best for your app?

Discussed in class through a series of comparison videos available as part of a blog post at https://gafferongames.com/post/deterministic_lockstep/. The entire blog is highly recommended reading.

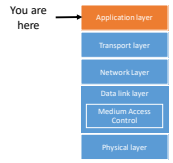
Milestone reached!

Creating large-scale distributed systems is difficult!

We can now ***start*** building applications and systems that communicate over a network!

Advanced courses unlocked:

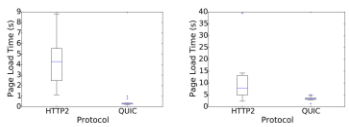
1. Advanced Systems Programming
2. Advanced Computer Networks
3. Distributed systems
   (also requires Computer Organization and Operating Systems)



Now we can finally build applications and no longer worry about networking!

Or so we thought!

SSH IMAP FTP ...
RPC MQTT SMTP
XMPP HTTP QUIC



(a) High Loss, Low Delay

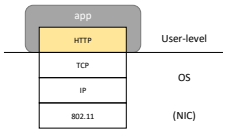
(b) High Loss, High Delay

Figure: Prasenjeet Biswal, Omprakash Gnawali: Does QUIC Make the Web Faster? GLOBECOM 2016

Where The Application Layer Sits

Application layer protocols are often part of an "app"

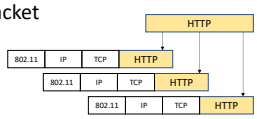
But they don't need a GUI, e.g., DNS



Application Layer Messages

Application layer messages are often split over multiple packets

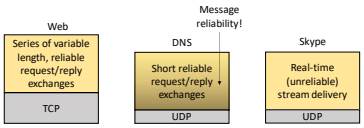
Or may be aggregated in a packet



10

Application Communication Needs

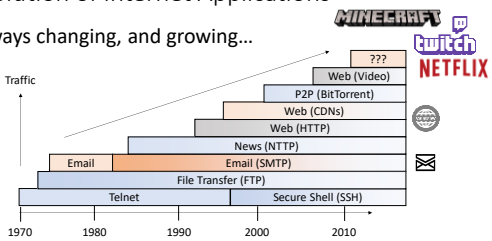
Vary widely with app; must build on Transport services



11

Evolution of Internet Applications

Always changing, and growing…



15

Every minute:

1. 241M emails sent
2. 6.3M Zoom meeting minutes
3. 649k hours video viewed on YouTube
4. 10.4M viewing minutes on Instagram
5. 34k Slack Messages
6. …

16

Application Layer Topics

1. **Domain Name System (DNS)**
2. Email
3. Web (HTTP, Web caching/proxy)
4. Multimedia applications

17

Domain Name System

18

Domain Name System

Port 53

An application used by the network itself!

Machines on the internet are identified by their ***IP address***

These addresses are difficult for humans to remember!

Q: Can you think of another disadvantage?

http://4.31.198.44/rfc/rfc1035.txt

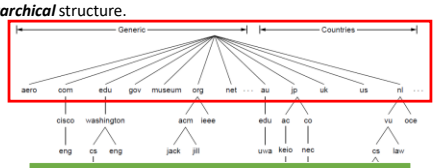
j.j.r.donkervliet@131.180.77.82

DNS translates ***human readable names*** to IP addresses

19

DNS name space

Hierarchical structure.

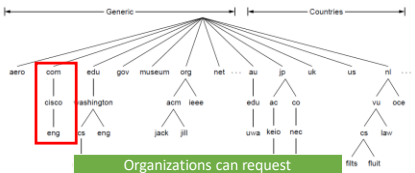


Top level domains controlled by Internet Corporation for Assigned Names and Numbers (ICANN).

20

DNS name space

Hierarchical structure.

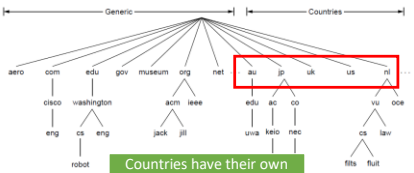


Organizations can request second-level domains from ***registrars***.

21

DNS name space

Hierarchical structure.

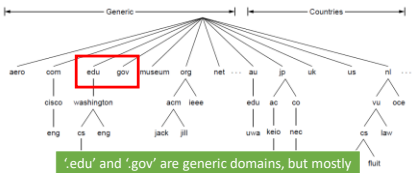


Countries have their own second-level domains.

22

DNS name space

Hierarchical structure.



'.edu' and '.gov' are generic domains, but mostly used by organizations in the United States.

23

DNS name space

If you control a domain, you can specify arbitrary subdomains.

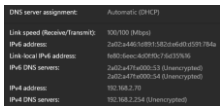
United Kingdom uses
ac.uk. for academic use and
co.uk. for commercial use.

The Netherlands puts everything directly under ***.nl.***.

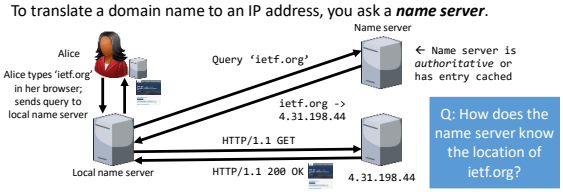
24

Name servers

Q: How does Alice's machine know where to find the name server?



To translate a domain name to an IP address, you ask a ***name server***.



Q: How does the name server know the location of ietf.org?

Location of name servers

Hosts learn about the location of name servers via ***DHCP***

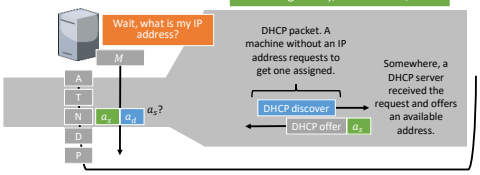
The ***operating system*** keeps track of name servers and dynamically selects which one to use

```
Linux
cat /etc/resolv.conf
Windows
ipconfig /all
```


Dynamic Host Configuration Protocol (DHCP)

MAC addresses are built into NICs. But network addresses are not.

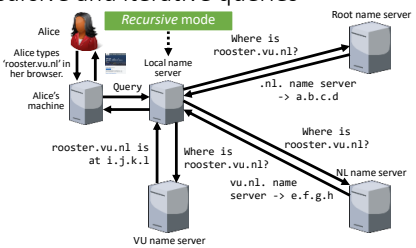
Used to configure other settings such as: ***DNS name servers***, addresses of default gateway, time servers, etc.



Q: How to send DHCP offer back to machine without an address?

Other name servers are in *iterative* mode

Recursive and iterative queries




```
(base) jesse@Jesses-XPS-2022:~$ dig canvas.vu.nl

; <<>> DiG 9.16.1-Ubuntu <<>> canvas.vu.nl
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 41657
;; flags: qr rd ad; QUERY: 1, ANSWER: 5, AUTHORITY: 0, ADDITIONAL: 0
;; WARNING: recursion requested but not available

;; QUESTION SECTION:
;canvas.vu.nl.                  IN      A

;; ANSWER SECTION:
canvas.vu.nl.           0       IN      CNAME   vu-vanity.instructure.com.
vu-vanity.instructure.com. 0    IN      CNAME   canvas-dub-prod-c84-1303699784.eu-west-1.elb.amazonaws.com.
canvas-dub-prod-c84-1303699784.eu-west-1.elb.amazonaws.com. 0 IN A 52.17.144.218
canvas-dub-prod-c84-1303699784.eu-west-1.elb.amazonaws.com. 0 IN A 54.216.29.136
canvas-dub-prod-c84-1303699784.eu-west-1.elb.amazonaws.com. 0 IN A 54.77.55.232

;; Query time: 9 msec
;; SERVER: 172.31.224.1#53(172.31.224.1)
;; WHEN: Mon May 15 14:47:46 CEST 2023
;; MSG SIZE  rcvd: 284
```


DNS Resource Record (RR) Types

Name servers reply with ***domain resource records***.
A record can contain:

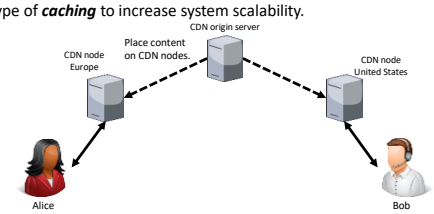
1. **IPv4 address** (record type A)
2. **IPv6 address** (record type AAAA)
3. Domain that accepts **email** (record type MX)
4. **Name server** for this domain (record type NS)
5. **Alias** to Canonical Name (record type CNAME)
6. …

Content Delivery Networks

Content delivery networks

Q: How to make sure users do not all contact the same node?

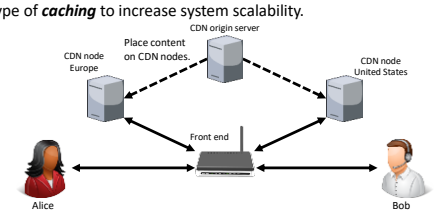
A type of ***caching*** to increase system scalability.



Content delivery networks

Front end forwards requests and distributes load

A type of ***caching*** to increase system scalability.

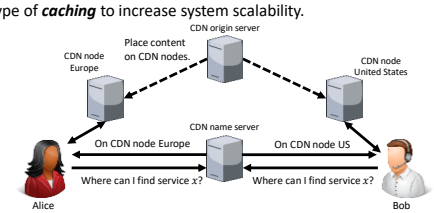


Content delivery networks

Powered by DNS!

DNS can be used for load balancing!

A type of ***caching*** to increase system scalability.



Content delivery networks

Powered by DNS!

```
$ dig @192.5.6.30 ibm.com

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; udp: 4096
;; QUESTION SECTION:
;ibm.com.                       IN      A

;; AUTHORITY SECTION:
ibm.com.        172800  IN      NS      usw2.akam.net.
ibm.com.        172800  IN      NS      usc2.akam.net.
ibm.com.        172800  IN      NS      eur2.akam.net.
ibm.com.        172800  IN      NS      ns1-99.akam.net.
ibm.com.        172800  IN      NS      ns1-206.akam.net.
ibm.com.        172800  IN      NS      asia3.akam.net.
ibm.com.        172800  IN      NS      usc3.akam.net.
ibm.com.        172800  IN      NS      eur5.akam.net.
```


Content delivery networks

Powered by DNS!

```
$ dig @192.5.6.30 ibm.com

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:;
;; QUESTION SECTION:
;ibm.com.
```

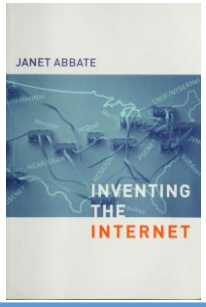
Akamai

'akam' means 'Akamai', a CDN company.

```
;; AUTHORITY SECTION:
ibm.com.        172800  IN      NS      usw2.akam.net.
ibm.com.        172800  IN      NS      usc2.akam.net.
ibm.com.        172800  IN      NS      eur2.akam.net.
ibm.com.        172800  IN      NS      ns1-99.akam.net.
ibm.com.        172800  IN      NS      ns1-206.akam.net.
ibm.com.        172800  IN      NS      asia3.akam.net.
ibm.com.        172800  IN      NS      usc3.akam.net.
ibm.com.        172800  IN      NS      eur5.akam.net.
```

Application Layer Topics

1. Domain Name System (DNS)
2. **Email**
3. Web (HTTP, Web caching/proxy)
4. Multimedia applications



Email

Not too long ago, email was all we had! Now, more options are available.

More than ***240 million*** emails sent every minute!
→ 9 out of 10 emails are spam!

You can send and receive email on ***your own*** domain.

Or you can use a (free) email service provided by a company or organization:

Ziggo TUDelft VU UNIVERSITY AMSTERDAM

1. http://www.visualcapitalist.com/happens-internet-minute-2017/
2. *McAfee Threat Reports: First Quarter 2010*, McAfee Inc., 2010.

Metcalfe's Law

The value of a network is proportional to the square of the number of users.

(I.e., value is proportional to the number of possible connections.)

As networks get larger, there is more value in joining them, making them larger, …

We don't know what will be tomorrow's network applications, but we know that these networks will continue growing.

Mobile, Internet of Things (IoT), …

Email
Message formats

Envelope is used to get message to correct recipient.

Messages contain:
1. An envelope
2. A header
3. A body

From: Alice
To: Bob
Encryption: None

From: Alice
To: Bob
Subject: How does email work?

Hi Bob,

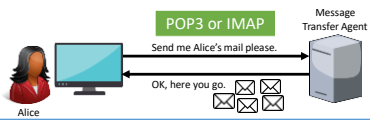
I really want to know how email works. Do you know of any CS courses I could follow to learn more about it?

Other helpful headers:
Message-Id, In-Reply-To, Reply-To, …

Email
How does it work?

Email uses multiple protocols:

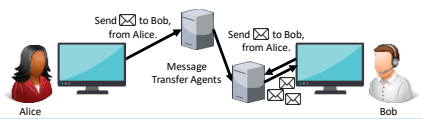
1. Users use ***POP3*** or ***IMAP*** to interact with their ***mailbox***.



Email
How does it work?

Email uses multiple protocols:

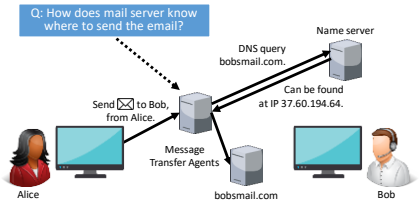
1. Users use ***POP3*** or ***IMAP*** to interact with their ***mailbox***.
2. Users and ***Message Transfer Agents*** use ***SMTP*** to send email from a source to a destination.



Email
How does it work?

Powered by DNS!

Q: How does mail server know where to send the email?

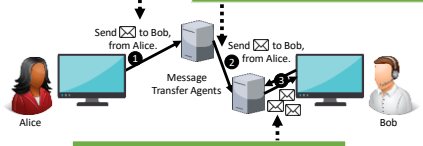


Email
How does it work?

Q: Example of a proprietary protocol used for ***final delivery***?

Mail submission uses SMTP + Extensions (e.g. AUTH).

Message transfer between mail servers uses SMTP.



Final delivery uses IMAP/POP3 or a propriety protocol.

Internet Message Access Protocol (IMAP)

RFC 9000

Ports: 143, 993

Q: Does `gmail.com` use POP3 or IMAP?

Sends commands to ***mail server*** to manipulate mailboxes

Common commands:

1. LOGIN. Log into server
2. FETCH. Fetch messages from a folder
3. CREATE/DELETE. Create or delete a folder
4. EXPUNGE. Remove messages marked for deletion

Uses mostly plain text!

Replaced POP3 protocol

Security through TLS (not covered in the course)

Simple Mail Transfer Protocol (SMTP)

RFC 5321

Ports: 25, 587

SMTP uses ASCII

You can use TELNET to talk to a mail server!

```
        S: 220 ee.uwa.edu.au SMTP service ready
C: HELO abcd.com
        S: 250 cs.washington.edu says hello to ee.uwa.edu.au
C: MAIL FROM: <alice@cs.washington.edu>
        S: 250 sender ok
C: RCPT TO: <bob@ee.uwa.edu.au>
        S: 250 recipient ok
C: DATA
        S: 354 Send mail; end with "." on a line by itself
C: …
```

FROM field ***not*** checked!

Basic SMTP does not support binary data!

Basic SMTP does not include authentication!

Many extensions exist to address these issues.

Multipurpose Internet Mail Extensions (MIME)

Developed for email, now used more broadly

Adds headers to email:

```
MIME-Version
Content-Description
Content-Id
Content-Transfer-Encoding
Content-Type
```

If MIME-Version in header
    check Content-Type
Else
    plain text

MIME Content-Type

1. Text:	text/plain,	text/html
2. Images:	image/jpeg,	image/gif
3. Video:	video/mp4,	video/mpeg
4. Multipart:	multipart/mixed,	multipart/alternative

Used to create messaged with multiple data types (e.g., an email with attachment).

Basic SMTP does not support binary data!

Multipurpose Internet Mail Extensions (MIME)

Developed for email, now used more broadly

Adds headers to email:

```
MIME-Version
Content-Description
Content-Id
Content-Transfer-Encoding
Content-Type
```

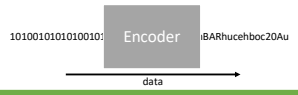
If MIME-Version in header
  check Content-Type
Else
  plain text

Sending binary data via ASCII-only SMTP

Modern SMTP protocol supports binary data

When MIME was introduced, servers were not expecting non-ASCII data.

Q: How to send binary via a server that can only handle ASCII?



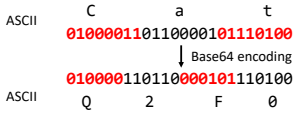
Base64 encoding converts binary data into ASCII

Base64 encoding

Q: How large is the overhead of base64 encoding?

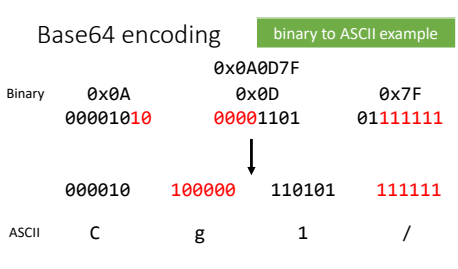
Used to convert binary data to and from ASCII.
Alphabet: `[A-Za-z0-9+/]`
6 bits are translated into 1 character.

ASCII to ASCII example



Base64 encoding

binary to ASCII example

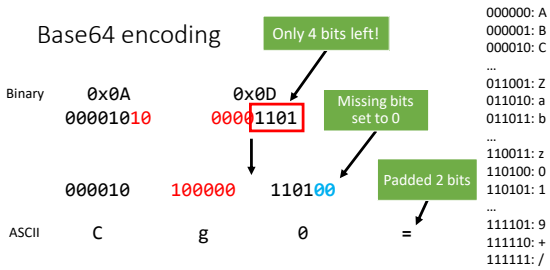


Base64 encoding

Only 4 bits left!

Missing bits set to 0

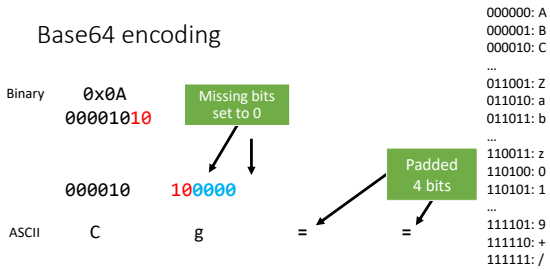
Padded 2 bits



Base64 encoding

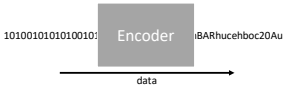
Missing bits set to 0

Padded 4 bits



Base64 encoding to send arbitrary data types

1. Text: text/plain, text/html
2. Images: image/jpeg, image/gif
3. Video: video/mp4, video/mpeg
4. ***Multipart***: multipart/mixed, multipart/alternative



56

Application Layer Topics

1. Domain Name System (DNS)
2. Email
3. **Web (HTTP, QUIC, WebSocket)**
4. Multimedia applications

57

58

Hypertext

Vannevar Bush described the Memex, a device for storing data *associatively*

The idea existed before digital computers and digital media (e.g., libraries)


Vannevar Bush

Hypertext invented by Ted Nelson and Douglas Engelbart


Ted Nelson


Douglas Engelbart

60

The Web
TCP+DNS+Hypertext

Tim Berners-Lee, a computer engineer at CERN, started the modern Web by combining TCP, DNS, and hypertext in 1989

He now directs the World Wide Web Consortium (W3C)


Tim Berners-Lee

61

Page last updated at 10:52 GMT, Wednesday, 14 October 2009 11:52 UK

E-mail this to a friend Printable version

Berners-Lee 'sorry' for slashes

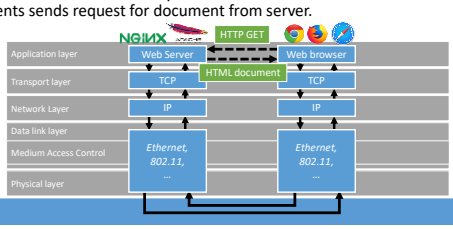
The forward slashes at the beginning of internet addresses have long annoyed net users and now the man behind them has apologised for using them.

Sir Tim Berners-Lee, the creator of the World Wide Web, has confessed that the // in a web address were actually "unnecessary".

Tim Berners-Lee started the web to help scientists communicate

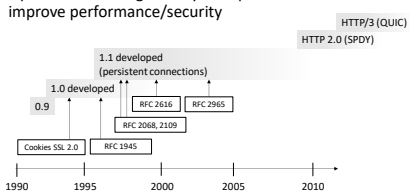
HTTP Request/Response

HTML documents hosted by servers.
Clients sends request for document from server.



Evolution of HTTP

Optimizations are gradually incorporated to improve performance/security



HTTP Protocol

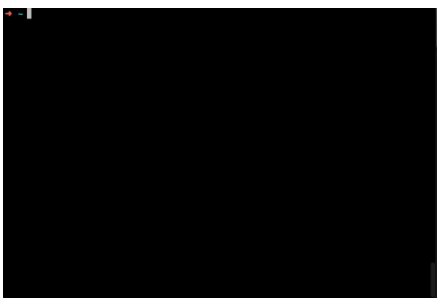
Similar to chat application from the lab!

Originally a simple text-based protocol
Many options added over time

Try it yourself:

```
$ telnet en.wikipedia.org 80
GET wiki/HTML HTTP/1.0
```


HTTP Request via TELNET



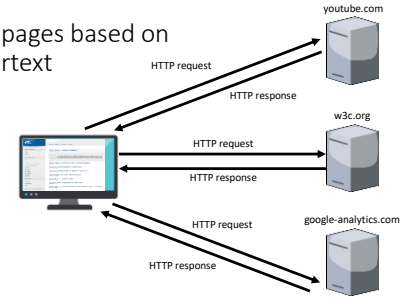
HTTP Request Methods

Methods: GET, POST, PUT, HEAD, …

```
$ curl -v -L --http1.1 https://vu.nl -o /dev/null
…
> GET / HTTP/1.1
> Host: vu.nl
> User-Agent: curl/7.64.1
> Accept: */*
>
…
```

https://**www.w3.org**/**TR/2010/WD-html5-20100624/**
Specifies the **protocol**, the **domain name**, and a **path**.

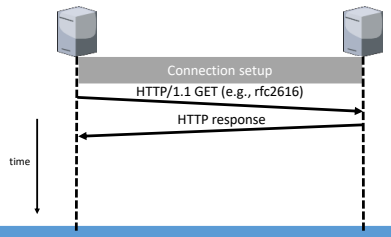
Web pages based on Hypertext



Web and HTTP Performance

The Web and HTTP continues to evolve, with servers sending ***more*** and ***larger*** responses

Single document

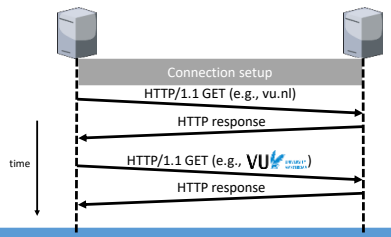


Single document Example

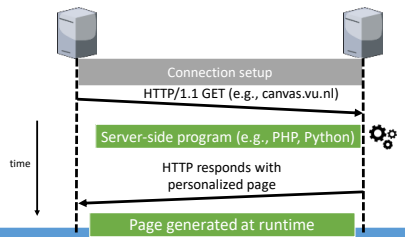
https://www.w3.org/Protocols/rfc2616/rfc2616.html

Name	Domain	Type	Transfer Size	Time

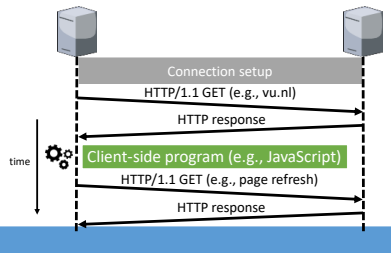
External resources



Server-side programs



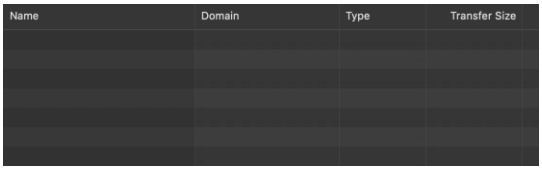
Client-side programs



74

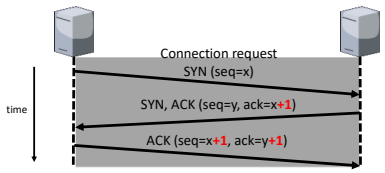
Modern webpages
Many requests

https://canvas.vu.nl/



75

Recap
TCP Connection setup

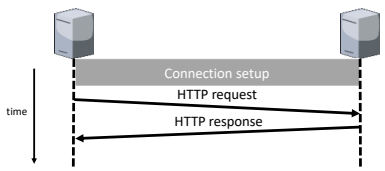


76

Recap
TCP Connection setup

77

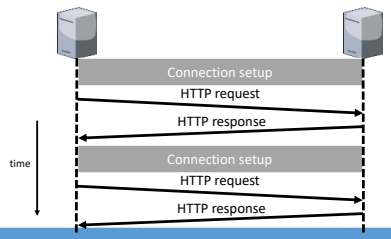
HTTP
Sequential requests



78

`HTTP 1.0`

HTTP
Sequential requests

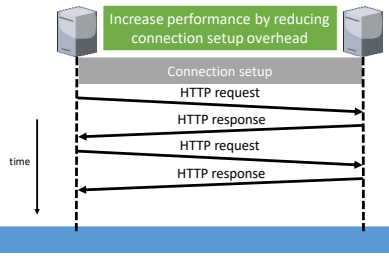


79

HTTP Persistent connection

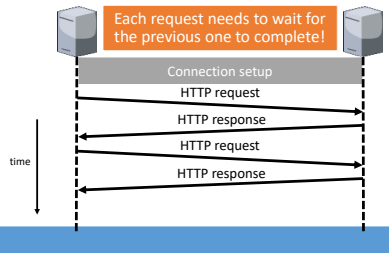
HTTP 1.1

Persistent connections allow browsers to issue multiple requests over the same TCP connection



80

HTTP Performance Problem
Head of Line Blocking (HOL)

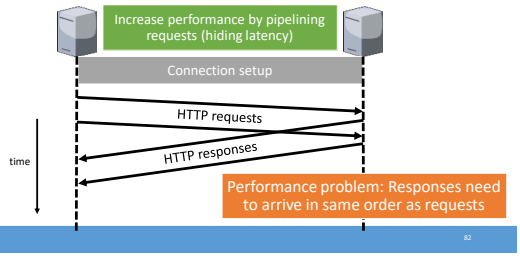


81

HTTP1.1 Pipelined requests

HTTP 1.1

Reduces Head of Line Blocking!



82

HTTP/2

1. Binary instead of plaintext.

WIRESHARK

Easier for machines to parse

More difficult for humans to read

Q: Why would it be easier for machines?

2. Multiplexed streams over a single TCP connection.

Supports out-of-order responses!

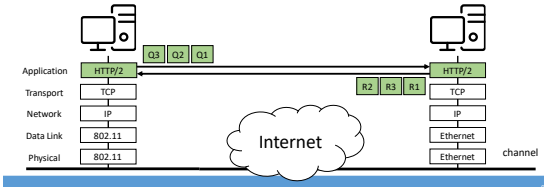
3. Server push allows the server to send resources before the client asks for it explicitly.

https://tools.ietf.org/html/rfc7540

83

Head-of-Line Blocking in HTTP/2

Despite ***pipelining*** (HTTP1.1) and ***out-of-order responses*** (HTTP/2), HTTP/2 performance still suffers from a type of Head of Line blocking



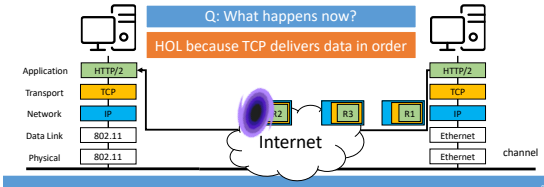
84

Head-of-Line Blocking in HTTP/2

Despite ***pipelining*** (HTTP1.1) and ***out-of-order responses*** (HTTP/2), HTTP/2 performance still suffers from a type of Head of Line blocking

Q: What happens now?

HOL because TCP delivers data in order



85

QUIC orders data per *stream* RFC 9051

HTTP/3 (HTTP + ***QUIC***)

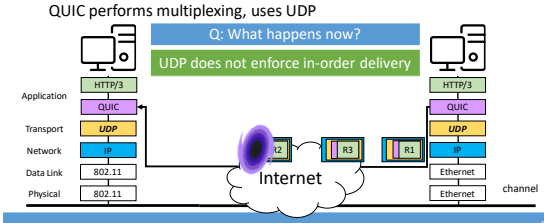
Each HTTP request can use a separate stream; within a stream, data is delivered in order; across streams no such guarantee is made

HTTP/3 uses the ***QUIC*** protocol

QUIC performs multiplexing, uses UDP

Q: What happens now?

UDP does not enforce in-order delivery



RFC 6455

WebSockets

Application layer protocol

Q: Can the application layer contain protocols?

A socket-like interface on the application layer.

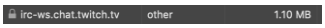
Full-duplex connection between server and client.

Q: Can you think of a use-case?

Increasingly complex 'apps' on the Web that need to send data continuously.

Examples:

1. `irc-ws.chat.twitch.tv`



2. `ws.todoist.com`

RFC 6455

WebSockets

Application layer protocol

A socket-like interface on the application layer.

Full-duplex connection between server and client.

Q: Can you think of a use-case?

Increasingly complex 'apps' on the Web that need to send data continuously.

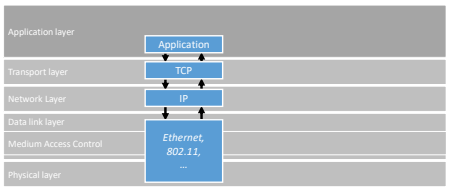
Examples:

1. `irc-ws.chat.twitch.tv`

2. `ws.todoist.com`

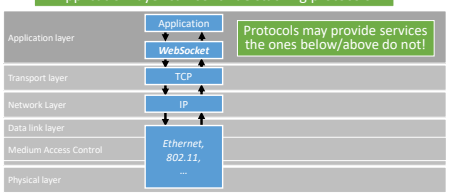
'ws' stands for WebSocket

Stacking
Application layer protocols

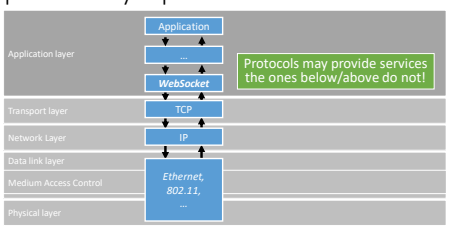


Stacking
Application layer protocols

Application layer can continue stacking protocols



Stacking
Application layer protocols



Starting a WebSocket over HTTP

```
GET /chat HTTP/1.1
Host: example.com:80
Upgrade: websocket
Connection: Upgrade
Sec-WebSocket-Key: dGhlIHNhbXBsZSBub25jZQ==
Sec-WebSocket-Version: 13
```

Client requests to switch to WebSocket protocol

```
HTTP/1.1 101 Switching Protocols
Upgrade: websocket
Connection: Upgrade
Sec-WebSocket-Accept:
s3pPLMBiTxaQ9kYGzzhZRbK+xOo=
```

Reply from server if it accepts

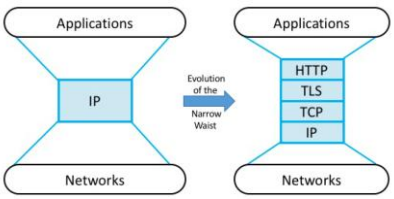
WebSocket frame format

```
Frame format:

 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-------+-+-------------+-------------------------------+
|F|R|R|R| opcode|M| Payload len |    Extended payload length    |
|I|S|S|S|  (4)  |A|     (7)     |             (16/64)           |
|N|V|V|V|       |S|             |   (if payload len==126/127)   |
| |1|2|3|       |K|             |                               |
+-+-+-+-+-------+-+-------------+ - - - - - - - - - - - - - - - +
|     Extended payload length continued, if payload len == 127  |
+ - - - - - - - - - - - - - - - +-------------------------------+
|                               |Masking-key, if MASK set to 1  |
+-------------------------------+-------------------------------+
| Masking-key (continued)       |          Payload Data         |
+-------------------------------- - - - - - - - - - - - - - - - +
:                     Payload Data continued ...                :
+ - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
|                     Payload Data continued ...                |
+---------------------------------------------------------------+
```

https://developer.mozilla.org/en-US/docs/Web/API/WebSockets_API/Writing_WebSocket_servers

HTTP is the new "narrow waist"



E.g., REST APIs

Method	Description
GET	Read a Web page
HEAD	Read a Web page's header
POST	Append to a Web page
PUT	Store a Web page

Q: Advantages over using TCP directly?

Answers include:

- Provides set of methods
- Provides security
- Provides *naming*

Source: Peterson, Larry L., and Bruce S. Davie. *Computer networks: a systems approach*. Elsevier, 2007.

Application Layer Topics

1. Domain Name System (DNS)
2. Email
3. Web (HTTP, QUIC, WebSocket)
4. **Multimedia applications**

Video dominates

Video constitutes around 70 percent of all global mobile network traffic in 2022

- 28,000 people watching Netflix
- 500 hours of content uploaded to YouTube
- 2 million Twitch views
- 3.4 million Snaps created

Source: https://www.visualcapitalist.com/sp/2021-this-is-what-happens-in-an-internet-minute/

Streaming Video Requires Compression

1024 height x 2048 width = 2M pixels

1 pixel = 1 byte

30 frames per second → 60 MB/s = 480 Mbps

Without compression, only possible over wired fiber-optic channels

Compression reduced bandwidth requirement by an order of magnitude

Internet connection speed recommendations

To watch TV shows and movies on Netflix, we recommended having a stable internet connection with a download speed shown below in megabits per second (Mbps).

Video quality	Resolution	Recommended speed
High definition (HD)	720p	3 Mbps or higher
Full high definition (FHD)	1080p	5 Mbps or higher
Ultra high definition (UHD)	4K	15 Mbps or higher

Source: https://help.netflix.com/en/node/306

98

Large compression rates $>\times 10$.

Digital audio compression

Audio typically compressed before sending.

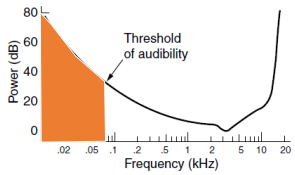
Lossy compression achieves higher compression rates than ***lossless compression***, but ***loses data.***

Q: Why is lossy compression acceptable?

Lossy encoders based on how humans perceive sound.

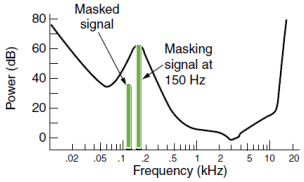
99

Human hearing frequency range



100

Human hearing masked signals



101

Digital video JPEG compression

Changes RGB to YC_bC_r.

Y is luminance.

C_bC_r are chrominances.

Q: Why change to this format?

Eyes are ***less*** sensitive to chrominance than to luminance.

JPEG reduces size of Cb and Cr.
Total compression rate $\times$ 2.

102

Large compression rates $>\times 50$.

Digital video

Q: What is the use of ***bidirectional*** frames?

MPEG compresses over a sequence of frames, further using motion tracking to remove temporal redundancy

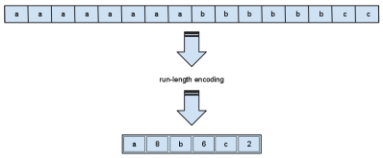
1. I (Intra-coded) frames are self-contained
2. P (Predictive) Looks for comparable ***macro blocks*** in previous frames. How long to search is up to the implementation.
3. B (Bidirectional) frames may base prediction on previous frames and ***future*** frames.

103

Run-Length Encoding

Part of JPEG Compression

A lossless compression technique.



Huffman Encoding

Prefix code: no code word is prefix of other code word

Q: Why is this useful?

String
"application layer"

ASCII
61 70 70 6c 69 63 61 74 69 6f 6e 6c 61 79 65 72 72
(128 bits)

Huffman Encoding
11 101 101 100 0111 0110 11 0101 0111 0100 0011 100 11 0010 0001 0000
(54 bits)

Less than half the original size! $\frac{54}{128} < 0.42$

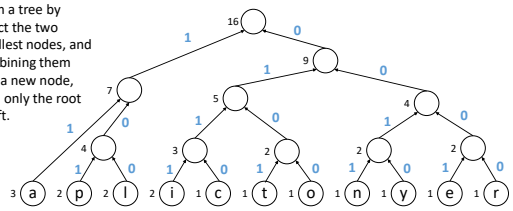
11 101 101 100 0111 0110 11 0101 0111 0100 0011 100 11 0010 0001 0000
(54 bits) "application layer"

Huffman Encoding

Part of JPEG Compression

3 a
frequency symbol

Form a tree by select the two smallest nodes, and combining them into a new node, until only the root is left.



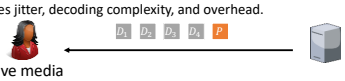
Networking Challenges for Multimedia Applications

Challenge 1
Streaming stored media

YouTube NETFLIX

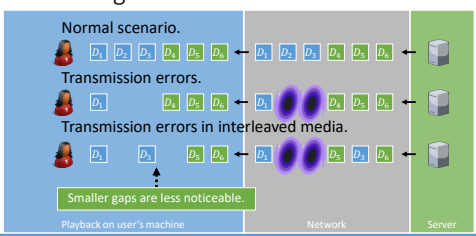
How to handle ***transmission errors***?

1. Use reliable transport (e.g., TCP).
   - Increases jitter significantly.
2. Use ***forward error correction*** (error correction in the application layer).
   - Increases jitter, decoding complexity, and overhead.

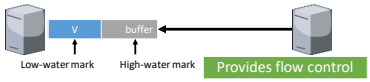


3. Interleave media
   - Slightly increases jitter and decoding complexity.

Masking errors by interleaving media



Challenge 1
Streaming stored media



Low-water mark prevents ***stalls*** in playback.

High-water mark gives client time to prevent ***running out of buffer space***.

Challenge 2
Streaming live media

Streaming live media is similar to the stored case plus:

1. Can't stream faster than ***live rate*** to get ahead
   - Usually need larger buffer to absorb jitter
2. Often have many users viewing at the same time
   - UDP with multicast greatly improves efficiency. It is rarely available, so ***many TCP connections are used***.

Challenge 3
Streaming interactive media

Real-time conferencing has two or more connected live media streams, e.g., voice over IP, Skype video call

Requires low jitter **and** low latency.

1. Benefits from network support (Quality of Service).
2. Large bandwidth (no congestion).

Difficult to provide across long distances/multiple networks

Take-Home Message

- Many responsibilies and pseudo layers hidden in Application Layer
  - From OSI: Presentation, Session. Others: WebSocket, RTP, etc.
- Important behind-the-Scenes applications exist (e.g., DNS)
- Traditional "killer apps" for the Internet:
  - Email
  - The Web
- HTTP is the new "narrow waist"
  - Improved over time (HTTP/2 [SPDY], HTTP/3 [QUIC])
- Today's Internet is increasingly used for multimedia applications
  - Provide new challenges (high bandwidth, low latency, low jitter)