Modern Web Protocols

cs249i
Evolution of the Web

- Earliest websites provided static content with little additional media

World Wide Web

The WorldWideWeb (WWW) is a wide-area hypertext information retrieval initiative aiming to give universal access to a large universe of documents.

Everything there is online about W3 is linked directly or indirectly to this document, including an executive summary of the project, Mailing lists, Policy, November's W3 news, Frequently Asked Questions.

What's out there?
- Pointers to the world's online information, subjects, W3 servers, etc.
- Help on the browser you are using

Software Products
- A list of W3 project components and their current state. (e.g. Line Mode, X11 Viewer, NoX3Server, Search, Tools, Mailing) Library

Technical
- Details of protocols, formats, program internals etc.

Bibliography
- Paper documentation on W3 and references.

People
- A list of some people involved in the project.

History
- A summary of the history of the project.

How can I help?
- If you would like to support the web

Getting code
- Getting the code by anonymous FTP, etc.

Ostensibly the first website ever
Evolution of the Web

• Earliest websites provided static content with little additional media

• Over time, websites grew to include many more things, like deepening the web structure (adding more pages), adding images, logos, and even started serving some dynamic content
Evolution of the Web

- Earliest websites provided static content with little additional media

- Over time, websites grew to include many more things, like deepening the web structure (adding more pages), adding images, logos, and even started serving some dynamic content

- Modern websites are incredibly complex are rely on often hundreds of resources to properly function
A History of Web Protocols

HTTP/0.9: 1991
HTTP/1.0: 1996
HTTP/1.1: 1997
HTTP/2: 1997-2015
QUIC: 2015
HTTP/3: 2021
STUFF: 2021
Websites are growing up. So should our protocols.
Interfacing with the Web
Client / Server Model
Interfacing with the Web

Client / Server Model

Client

Request

Web Server
Interfacing with the Web
Client / Server Model

Client

Request

Response

Web Server
A History of Web Protocols

- HTTP/0.9
- HTTP/1.0
- HTTP/1.1
- HTTP/2
- QUIC
- HTTP/3

Timeline:
- 1991: HTTP/0.9
- 1996: HTTP/1.0
- 1997: HTTP/1.1
- 1997-2012: STUFF
- 2015: HTTP/2
- 2021: QUIC
- 2021: HTTP/3
HTTP/0.9
Single Line Protocol

• In 1991, Tim-Berners Lee needed a simple protocol to test his new invention (the web)

• Request was a single line command, supported only retrieving HTML content
  - GET /index.html

• Response was the file data itself!

• HTTP/0.9 was built on top of TCP, for reliable transport of data, and the connection was closed after every single request
The Web Catches On

Moar Content

- The web started catching on, and people started to build out software that could interact with other types of content (e.g., images) and share other types of metadata

- HTML specification started to show a lot of progress

- The first browsers started showing up around 1994 – Netscape (first browser) was developed as an academic project at NSCA in Champaign, IL
  - Began the first “browser wars”
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STUFF: 1997-2015
HTTP/1.0
Specification Improvements

- Goals: “generic, stateless, object-oriented protocol which can be used for many tasks, such as name servers and distributed object management systems” (from RFC1945)

- Added versioning, a number of new methods (POST, HEAD, PUT, DELETE, LINK, UNLINK), supported myriad different content-types (no longer just HTML!), and included headers to accompany each request and response
HTTP/1.0
Mired with Problems

• Connections were closed after requesting a single resource, this made things frustrating, slow, and expensive as websites started hosting dozens of files

• Internet connection speeds were slow, and TCP slow start had just been rolled out widely

• People wanted to host multiple websites at the same IP address, which wasn’t possible (e.g., colocation services)
A History of Web Protocols

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- QUIC: 2021
- HTTP/3: 2021
HTTP/1.1
A New Era

• HTTP/1.1 fixed many problems and challenges with early versions of the protocol
  • Added the Host header (to enable multiple websites with different domains to be served from the same IP address)
  • Allowed for **persistent connections**
    • Allowed chunked responses
    • Enabled pipelining of requests
HTTP/1.1
Persistent Connections

Client

Web Server
HTTP/1.1
Persistent Connections
HTTP/1.1
Persistent Connections

Client → Web Server
SYN
SYN+ACK

Client
Web Server
HTTP/1.1
Persistent Connections

Client

Web Server

SYN
SYN+ACK
ACK
HTTP/1.1
Persistent Connections
HTTP/1.1
Persistent Connections

Client

Request

GET /index.html HTTP/1.1

Web Server
HTTP/1.1 Persistent Connections

GET /index.html HTTP/1.1
Host: kumarde.com
User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X 10.9; rv:50.0)
Gecko/20100101 Firefox/50.0
Accept: text/html,application/xhtml+xml,application/xml;q=0.9,*/*;q=0.8
Accept-Language: en-US,en;q=0.5
Accept-Encoding: gzip, deflate, br
Referer: https://developer.mozilla.org/testpage.html
Connection: keep-alive
HTTP/1.1
Persistent Connections

Client

Web Server

Response

index.html
HTTP/1.1 Persistent Connections

200 OK
Access-Control-Allow-Origin: *
Connection: Keep-Alive
Content-Encoding: gzip
Content-Type: text/html; charset=utf-8
Date: Mon, 18 Jul 2016 16:06:00 GMT
Keep-Alive: timeout=5, max=997
Last-Modified: Mon, 18 Jul 2016 02:36:04 GMT
Server: Apache
Transfer-Encoding: chunked
HTTP/1.1 Persistent Connections

Client

Web Server

index.html

Response

200 OK
Access-Control-Allow-Origin: *
Connection: Keep-Alive
Content-Encoding: gzip
Content-Type: text/html; charset=utf-8
Date: Mon, 18 Jul 2016 16:06:00 GMT
Keep-Alive: timeout=5, max=997
Last-Modified: Mon, 18 Jul 2016 02:36:04 GMT
Server: Apache
Transfer-Encoding: chunked
HTTP/1.1
Persistent Connections

Client

GET /index.css HTTP/1.1

Web Server
HTTP/1.1
Persistent Connections

Client

Web Server
index.css
main.js
zakir.jpg
HTTP/1.1
Persistent Connections

Modern browsers will open up to 6 TCP connections per host, plus 4 external TCP connections at a time.
HTTP/1.1

Chunking

• With persistent connections, servers could also now **chunk** data by sending a Transfer-Encoding: Chunked header

• Essentially, this means that servers can break up their responses into independent chunks – each chunk does not need to know about the other chunks in order to send correctly (e.g., this is good for TCP)

• This enabled the transfer of large files via HTTP, and also enabled streaming data (e.g., video content streaming, which is typically TCP based)
HTTP/1.1

Pipelining

• Another great feature for HTTP innovation was pipelining, essentially the ability for clients to make additional requests before the response to previous requests arrived

• Requirement: Servers needed to send back responses in the order they were received
  • HTTP/1.1 specification dictated that servers MUST implement pipelining
  • On the server side, this simply amount to keeping network buffers open and know to look for more HTTP requests on the TCP connection before response

• Clients did not want to deal with HTTP pipelining… why?
HTTP/1.1

Pipelining

Client

Web Server
HTTP/1.1

Pipelining

Without pipelining, I have to open three separate TCP connections
HTTP/1.1 Pipelining

With pipelining, I can use just one TCP connection!
HTTP/1.1

Pipelining

But what happens if index.css takes a long time to retrieve?
HTTP/1.1

Pipelining

Also, what about HTTP proxies?
HTTP/1.1
Head of Line Blocking

• Big problem with HTTP/1.1 pipelining is a concept called head of line blocking (HOL) which essentially means that subsequent resources on a shared connection need to **wait for the first request to be serviced** before they can be served.

• In theory, pipelining is a good idea, but there are some thorny edge cases:
  - If proxies do not support pipelining, clients need to retransmit or fall-back to non-pipelining, which is hard to identify and causes delays.
  - This crippled HTTP/1.1 pipelining, so much so that no browsers currently support it and browser developers get angry when you bring it up.
HTTP/1.1
Head of Line Blocking

Pipelining has been an undeniable pain in the ass. Nobody has gotten it working properly without hacks and even then problems pop up. It should work, but it is nonetheless a mess. It would be nice if we could get it running now, but obviously that hasn't happened. THERE IS NO POINT IN DEBATING THIS. Yes, servers should be fixed, but they aren't. Yes, heuristics to get it working are possible, but they're still not idiot-proof. There is nothing productive in rambling on this topic here.
HTTP/1.1
Head of Line Blocking

• Head of Line blocking is broader than pipelining – today, modern browsers still only open a maximum of 6 connections and have to wait for requests to finish before issuing new ones.

• This is obviously slow,
A History of Web Protocols

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HTTP/2 1997-2015
QUIC 2015
HTTP/3 2021
STUFF 2021
Stuff that Happened from 1997 – 2012

Context

• Modern websites exploded with dynamic content and an increased reliance on web resources to provide new online experiences
  
  • In 2011, median number of requests per modern webpage was 40, with some requesting up to 100 different
  
  • Internet speeds and infrastructure significantly improved, networks matured quite a lot
  
  • Millions of people were accessing the Internet (and the web) for the first time, adding significantly to load
  
  • We needed to figure out how to meet the demands of a growing web, and HTTP/1.1 was not cutting it.
SPDY
Google’s solution

• Google engineers decided to try and modernize how web content was shared, and developed SPDY (pronounced “speedy”), which was largely motivated by reducing page load times for websites

• SPDY was a translation layer between HTTP clients and servers and sat in front of HTTP on both ends
  • Shipped in Chrome, Firefox also implemented SPDY shortly after

• At its peak, SPDY served the majority of traffic to Google services and a whole host of other Internet services

• SPDY formed the foundation for what would eventually be HTTP/2, SPDY is now deprecated
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HTTP/2  2015
QUIC  2021
HTTP/3  2021
HTTP/2
Design Goals

1. Eliminate HoL blocking by multiplexing HTTP requests over a single TCP connection

2. Give servers more agency (e.g., allow them to *push* content over persistent connections)

3. Reduce unnecessary duplicate bytes sent over the wire (e.g., static headers)
HTTP/2

Goal 1: Multiplexing Requests

• Core idea: Move away from an ASCII-based request / response cycle for data transfer, and move towards a binary stream of data

  • Not backwards compatible with HTTP/1.x

• New terminology

  • Streams: A bidirectional flow of bytes which can carry one or more messages, denoted by an integer \textit{stream_id}

  • Message: Complete sequence of frames that map to a logical request or response

  • Frame: Smallest unit of data, can contain either header information or content information

https://developers.google.com/web/fundamentals/performance/http2
HTTP/2

Goal 1: Multiplexing Requests

- HTTP/2 uses a **single** TCP connection for any number of arbitrary HTTP requests and responses
  - Everything is logically separated by stream_id (4 byte integer)
- This means that if the server takes significant amounts of time for one request (say, the first one), other requests can still be completed while we wait for that one!
HTTP/2

Goal 1: Multiplexing Requests
HTTP/2
Stream Lifecycle

• All streams start in an “idle” state

• Upon receiving or sending a HEADERS Frame (H), the stream becomes open, and anyone can send or receive data on it

• Can send frames of any type on the stream until an END_STREAM (ES) flag is sent

• RFC specifies that one full HTTP request / response pair must put the stream into a “closed” state
HTTP/2
Stream Prioritization

- Either the client or server can create a new stream, but the ordering of streams may matter to some applications.
- HTTP/2 also supports prioritization of streams, which is a mechanism that allows the client to ask for specific streams ahead of the streams.
  - Clients can build a stream prioritization tree, which is essentially weights on a graph sent to the server along with each stream request.
  - Asking the server: “If you can, please process stream 8 before you process stream 12”, but it’s not a guarantee.
HTTP/2
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HTTP/2
Goal 2: Giving servers more agency

• HTTP/2 offers a new feature called Server Push, which enables the server to send data to the client that it hasn’t even requested yet.

• Why might we want this?
HTTP/2

Goal 2: Giving servers more agency

• HTTP/2 offers a new feature called Server Push, which enables the server to send data to the client that \textit{it hasn't even requested yet}.

• \textbf{Why might we want this?}

• Despite the fact that websites are highly dynamic, they still serve lots of static content

  • e.g., index.css, main.js

• The server knows the client will need these assets to load the page, so why not just give it to them in advance?
HTTP/2

Goal 2: Giving servers more agency
HTTP/2
Goal 2: Giving servers more agency

- Server Push is implemented using a PUSH_PROMISE frame on a new stream
- Essentially asking to reserve an HTTP/2 stream for pushing additional data to the client
- Clients can still, however, reject the push by sending a RST_STREAM frame, which means “I don’t want this resource.”
- Could be because the resource is in the cache already, or client is too busy, or whatever the application demands
HTTP/2
Design Goals

1. Eliminate HoL blocking by multiplexing HTTP requests over a single TCP connection

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HTTP/2

Goal 3: Remove duplicate information as much as possible

- In HTTP/1.x, headers are always sent as plain text, despite the fact that many are static and unchanging
  
  - We already compress application data (e.g., with Content-Encoding: gzip), but we don’t do this for headers @ the protocol level

- HTTP/2 solves this with a new compression algorithm, HPACK, which has two main ideas
  
  - Compress header data (Huffman coding)
  
  - Keep a shared compression table on the client + server that is dynamically updated with new requests every on every request / response
HTTP/2
HPACK Compression Table

• HPACK encodes a static table with 61 entries for the most common HTTP headers (and some other freebies, like GET, POST) into every client and server

  • You no longer have to send these headers in cleartext, you can just send the encoded value of the index instead

  • After this, every subsequent request is dynamically encoded and added to the shared table, which reduces the amount of data required to be sent over the wire for subsequent requests

<table>
<thead>
<tr>
<th>Index</th>
<th>Header Name</th>
<th>Header Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>:authority</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>:method</td>
<td>GET</td>
</tr>
<tr>
<td>3</td>
<td>:method</td>
<td>POST</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>content-length</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>host</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>www-authenticate</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>Host</td>
<td>kumarde.com</td>
</tr>
</tbody>
</table>
HTTP/2
Design Goals

- Eliminate HoL blocking by multiplexing HTTP requests over a single TCP connection
- Give servers more agency (e.g., allow them to push content over persistent connections)
- Reduce unnecessary duplicate bytes sent over the wire (e.g., static headers)
HTTP/2
Adoption is booming
HTTP/2

Does it work?

• Generally, HTTP/2 will show performance benefits over HTTP/1.1 for well-resourced, high bandwidth channels

• Financial Times reported speedups of 25 – 50% in a direct comparison between HTTP/1.x and HTTP/2

• But turns out this isn’t universally true…
HTTP/2
Does it work?

- "HTTP/2 Performance in Cellular Networks", from Montana State + Akamai, showed that in poor network conditions, HTTP/2 performed worse than HTTP/1.1, especially for larger objects. Why?
HTTP/2
A New Problem

- HTTP/2 solves the HTTP-level HoL blocking problems associated with older versions of HTTP... but introduces a new problem at a lower layer
HTTP/2
A New Problem

- HTTP/2 solves the HTTP-level HoL blocking problems associated with older versions of HTTP... but introduces a new problem at a **lower layer**
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HTTP/2
A New Problem

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- HTTP/1.0
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- HTTP/2
- QUIC
- HTTP/3

- 1991
- 1996
- 1997
- 1997-2015
- 2015
- 2021
- 2021
QUIC
A New Way Forward

• A core problem with HTTP up to this point is a fundamental limitation of reliable transport

  • We want to have reliability guarantees, but the way this is implemented in the layering model (e.g., in TCP) makes it such that applications don’t have flexibility to define what reliability means!

• We could try to change TCP?
  
  • But that requires updating every router in the world. Way too hard.

• QUIC idea: What if we re-envisioned what we needed from lower network layers?
The current world
QUIC
A New Transport Layer

The current world

A QUICer world
QUIC
A New Transport Layer

This is all user space!!!
QUIC

Design Goals

• A new, reliable transport layer

• Easily deployable and evolvable
  • Make this something that exists in userspace and something that doesn’t require us to update every router ever

• Security by default
  • Build in encryption, integrity checks, and authentication into the transport layer itself

• Reduce unnecessary delays imposed by strict layering
  • Handshake delays (e.g., TLS handshake), HoL blocking (HTTP, TCP)
QUIC
Establishing a Connection

- The first time a client wants to communicate with a server, it sends an *inchoate client hello* in cleartext, which will initiate a REJ (reject) from the server.
  - The server will send back a number of details, including a certificate chain (for server authentication) and other server metadata.
- The client will then use the server information provided to send a *complete client hello*, and immediately start sending encrypted data.
- Client *caches* server details (based on origin), so for any future connection, the client can simply use the server data to send encrypted messages moving forward. This is known as a **0-RTT protocol**.
QUIC

Two Types of Headers

Figure 1: QUIC Long Header

QUIC

Two Types of Headers

Figure 2: QUIC Short Header

# QUIC

Encrypt as much as possible

## HTTP w/ TLS + TCP

<table>
<thead>
<tr>
<th>source port</th>
<th>destination port</th>
</tr>
</thead>
<tbody>
<tr>
<td>sequence number</td>
<td></td>
</tr>
<tr>
<td>acknowledgement number</td>
<td></td>
</tr>
<tr>
<td>hlen</td>
<td>flags</td>
</tr>
<tr>
<td>checksum</td>
<td>urgent pointer</td>
</tr>
<tr>
<td>[options]</td>
<td></td>
</tr>
<tr>
<td>type</td>
<td>version</td>
</tr>
</tbody>
</table>

application data  
(HTTP headers and payload)

## HTTP w/ QUIC

<table>
<thead>
<tr>
<th>source port</th>
<th>destination port</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td></td>
</tr>
<tr>
<td>checksum</td>
<td></td>
</tr>
<tr>
<td>01SRRKPP</td>
<td>[dest connection id]</td>
</tr>
<tr>
<td>packet number</td>
<td></td>
</tr>
</tbody>
</table>

application data  
(HTTP headers and payload)

Slide stolen from: https://www.youtube.com/watch?v=31J8PoLW9IM&t=9104s
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application data

(HTTP headers and payload)
**QUIC**

Encrypt as much as possible

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<td></td>
</tr>
<tr>
<td>acknowledgement number</td>
<td></td>
</tr>
<tr>
<td>hlen flags window</td>
<td></td>
</tr>
<tr>
<td>checksum urgent pointer</td>
<td></td>
</tr>
</tbody>
</table>

| [options] |
| type version length |

### HTTP w/ QUIC

<table>
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<th>destination port</th>
</tr>
</thead>
<tbody>
<tr>
<td>length checksum</td>
<td></td>
</tr>
</tbody>
</table>

01S [dest connection id]
QUIC
Maintaining the Stream Abstraction

- QUIC uses the idea of a stream (with a stream_id) as a baseline abstraction for sending data between two endpoints, similar to HTTP/2
QUIC
Maintaining the Stream Abstraction

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Maintaining the Stream Abstraction

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TCP vs. QUIC
Recovering from Losses

- TCP uses sequence numbers + acknowledgement numbers to identify whether or not a packet has been lost, and needs to be retransmitted.

- Unfortunately, sequence numbers mean two things: reliability and the order at which the bytes are supposed to be delivered to the receiver.

- On top of this, TCP retransmissions use the same sequence number, so it becomes very hard to know whether an ACK was sent for first transmission or a retransmission.

- TCP conflates transmission ordering AND delivery ordering in one number.
TCP vs. QUIC

Recovering from Losses

- QUIC decouples transmission and delivery ordering through its use of *streams*
  - Each packet contains a packet number, which is **unique and monotonically increasing**, even on retransmission
  - Clients will ACKNOWLEDGE packet numbers, and the server can identify if an outstanding packet has not been acknowledged... you can find the details at the link below
  - Each frame in a stream contains a *stream offset*, which alerts the client of how to properly reorder the packets on the delivery side
  - Enables simpler loss detection than TCP

QUIC
Connection Rebinding

• Because QUIC connections are over UDP, they can persist beyond traditional network boundaries, like your home NAT

• No more resetting connection when your underlying network changes

• QUIC does this through the use of several unique variable length Connection IDs to identify the connection, with a protocol in place to verify the connection through a network change

• See RFC for notes on address spoofing + off-path packet attackers (something they’ve considered!)
QUIC
NATs, Middleboxes, Deployment Challenges

• Typically, NATs keep track of TCP connections by using a 5-tuple (src_port, src_ip, dst_port, dst_ip, protocol), and can maintain state because they have access to TCP headers

• Not all NATs speak QUIC yet, and even if they did, header information is encrypted, so they default to processing UDP packets, which could cause short timeouts and routing issues

• UDP-based protocols are susceptible to reflection attacks, where attackers use UDP servers with spoofed source ports to amplify their attack, and QUIC can be asymmetric on inchoate client hello

• This is why QUIC has a REJ packet to start, but this increases the number of round trips required on initial connection. Probably a decent trade off.
QUIC Deployment
QUICly eating the world

• QUIC was officially ratified by the IETF in May 2021 (RFC 9000)

• QUIC support already existed in Chrome for a while, but is now available in Firefox as well

• QUIC is being deployed everywhere
  • 6% of websites use QUIC, but will grow post RFC ratification
  • Google apps all use QUIC, 75% of Facebook uses QUIC
  • Some ISPs have reported that 20% of their packets were over QUIC

https://w3techs.com/technologies/details/ce-quic
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HTTP/3 is HTTP over QUIC!
Recap

- The web has drastically changed over time, with developers doing more than ever before and websites becoming increasingly complex.

- But for a long time, our protocols didn’t match the growing complexity of the world.

- New protocols like SPDY, HTTP/2 were useful in working within our paradigm, but there is **change** afoot!

- People are not liking TCP as much, and companies like Google are starting to throw their weight around in envisioning a new future for layering requirements.

- We are redefining “end-to-end” abstractions… let’s see how it goes :)