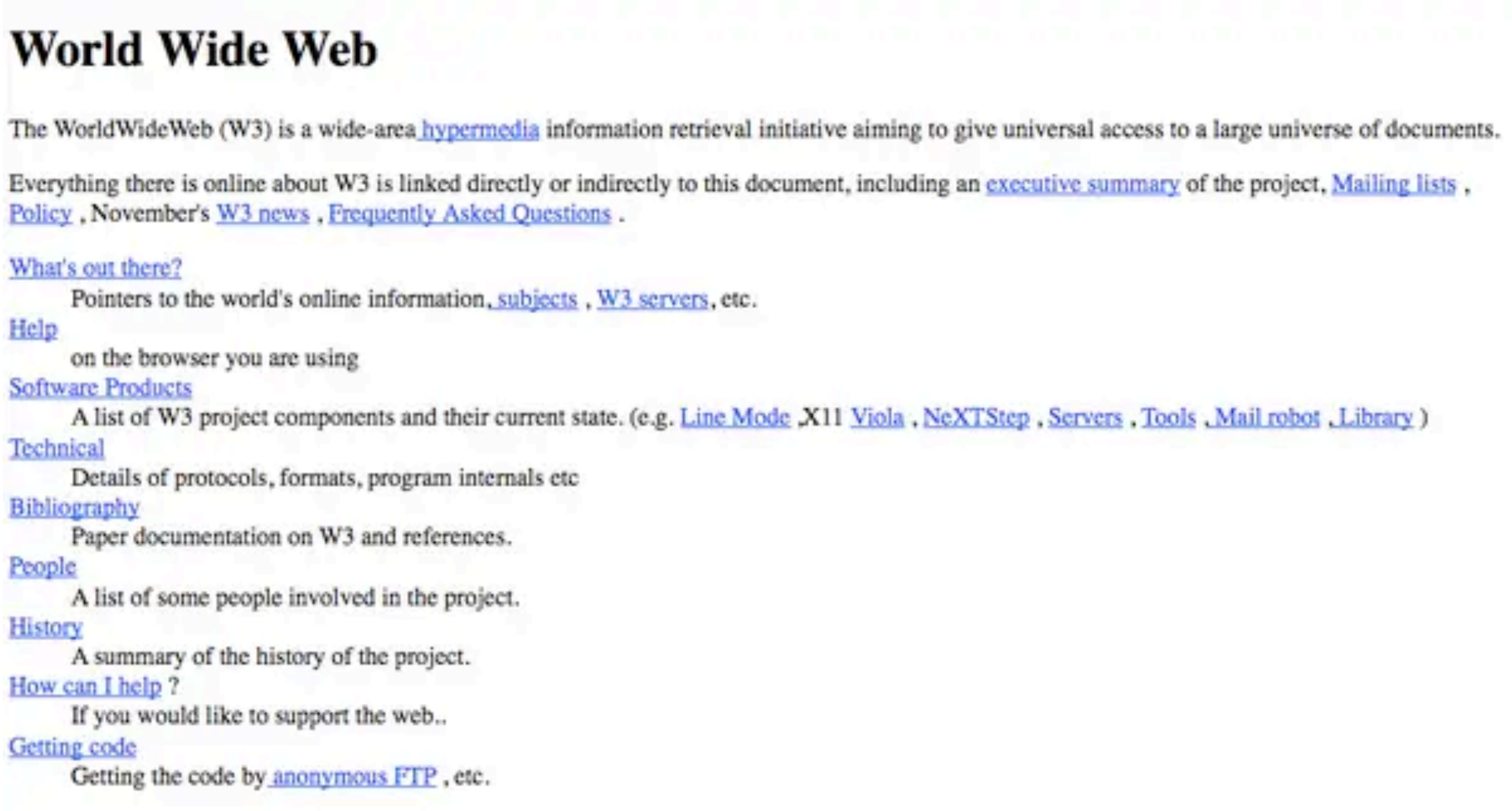
Web Protocol Evolution

CS249i The Modern Internet

Stanford
University

Evolution of the Web

- Earliest websites provided static content with little additional media
- First Website, August 6, 1991:



World Wide Web

The WorldWideWeb (W3) is a wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents.

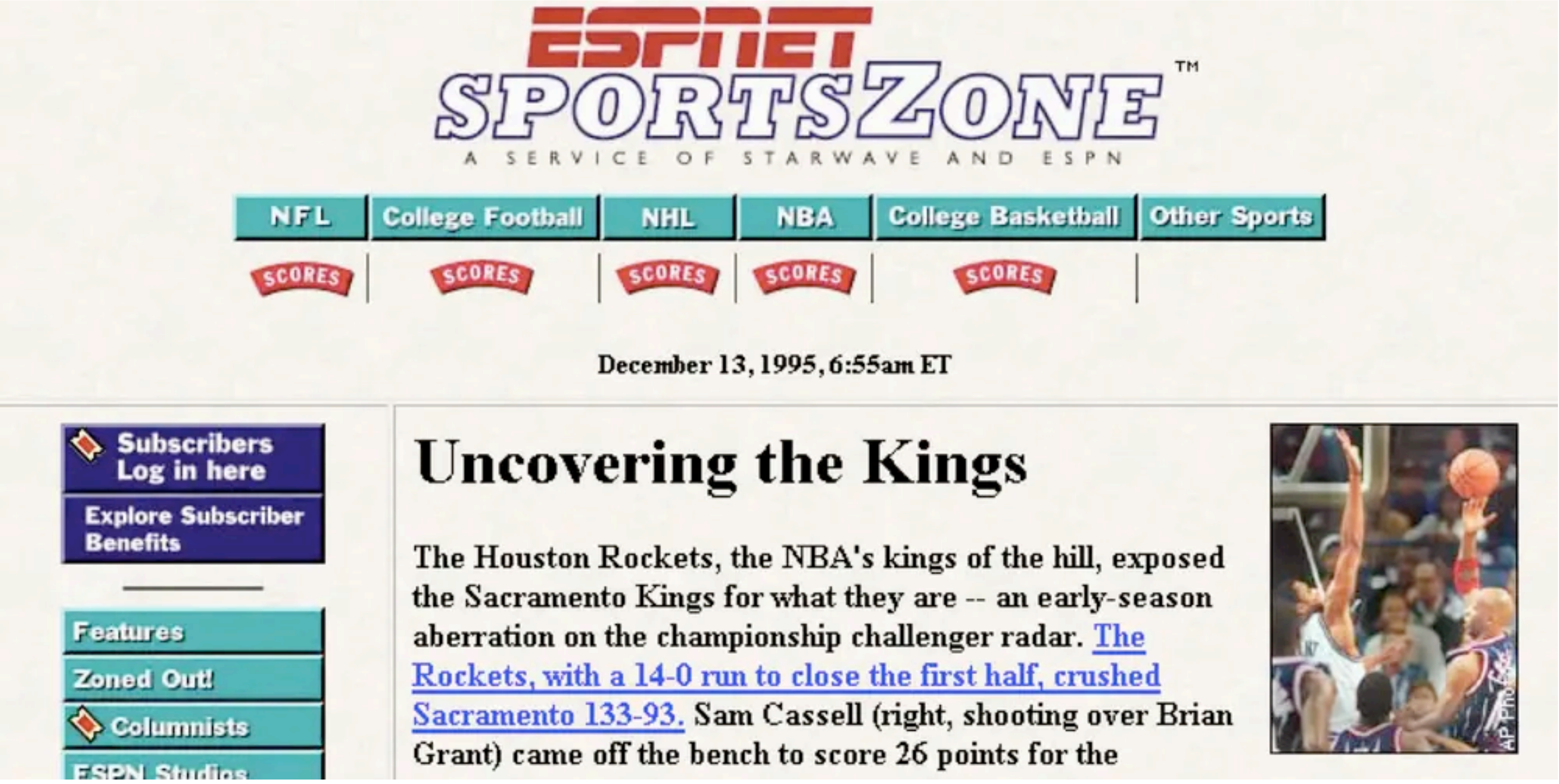
Everything there is online about W3 is linked directly or indirectly to this document, including an executive summary of the project, Mailing lists , Policy , November's W3 news , Frequently Asked Questions .

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 Viola , NeXTStep , Servers , Tools , Mail robot , 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*



December 13, 1995, 6:55am ET

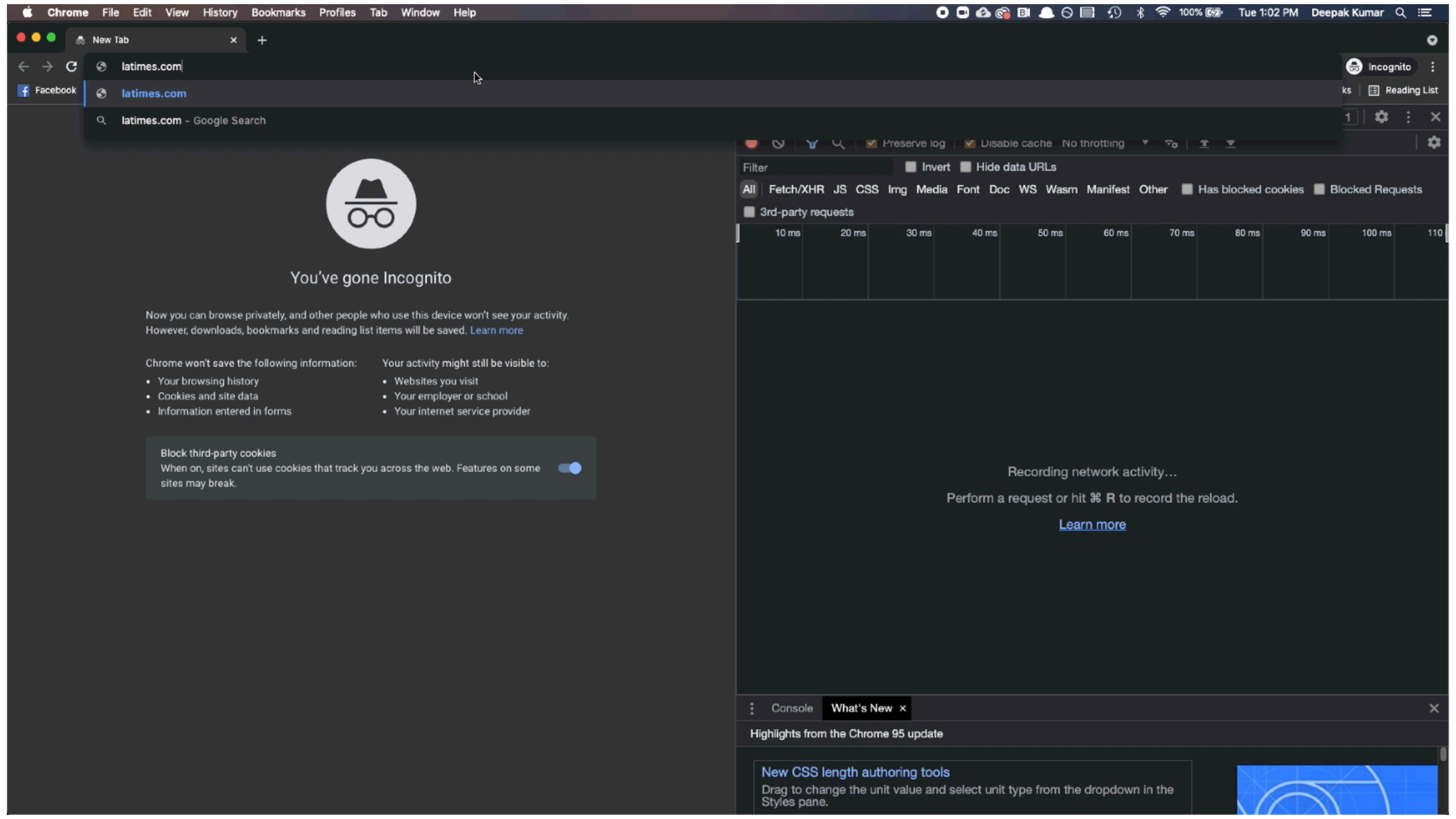
Uncovering the Kings

The Houston Rockets, the NBA's kings of the hill, exposed the Sacramento Kings for what they are -- an early-season aberration on the championship challenger radar. The Rockets, with a 14-0 run to close the first half, crushed Sacramento 133-93. Sam Cassell (right, shooting over Brian Grant) came off the bench to score 26 points for the

ESPN in 1996

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



You've gone Incognito

Now you can browse privately, and other people who use this device won't see your activity. However, downloads, bookmarks and reading list items will be saved. Learn more

Chrome won't save the following information:

- Your browsing history
- Cookies and site data
- Information entered in forms

Your activity might still be visible to:

- Websites you visit
- Your employer or school
- Your internet service provider

Block third-party cookies
When on, sites can't use cookies that track you across the web. Features on some sites may break.

Recording network activity…

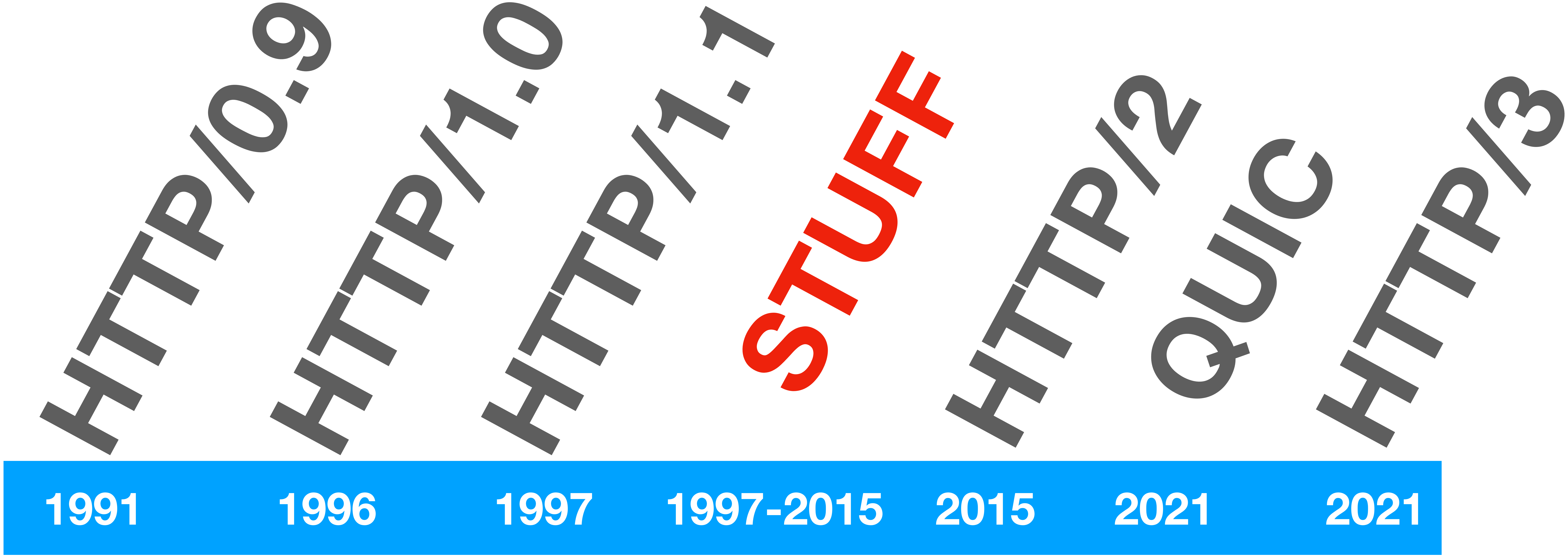
Perform a request or hit ⌘ R to record the reload.

Learn more

Highlights from the Chrome 95 update

New CSS length authoring tools
Drag to change the unit value and select unit type from the dropdown in the Styles pane.

A History of Web Protocols



HTTP/0.9	1991
HTTP/1.0	1996
HTTP/1.1	1997
STUFF	1997-2015
HTTP/2	2015
QUIC	2021
HTTP/3	2021

Interfacing with the Web

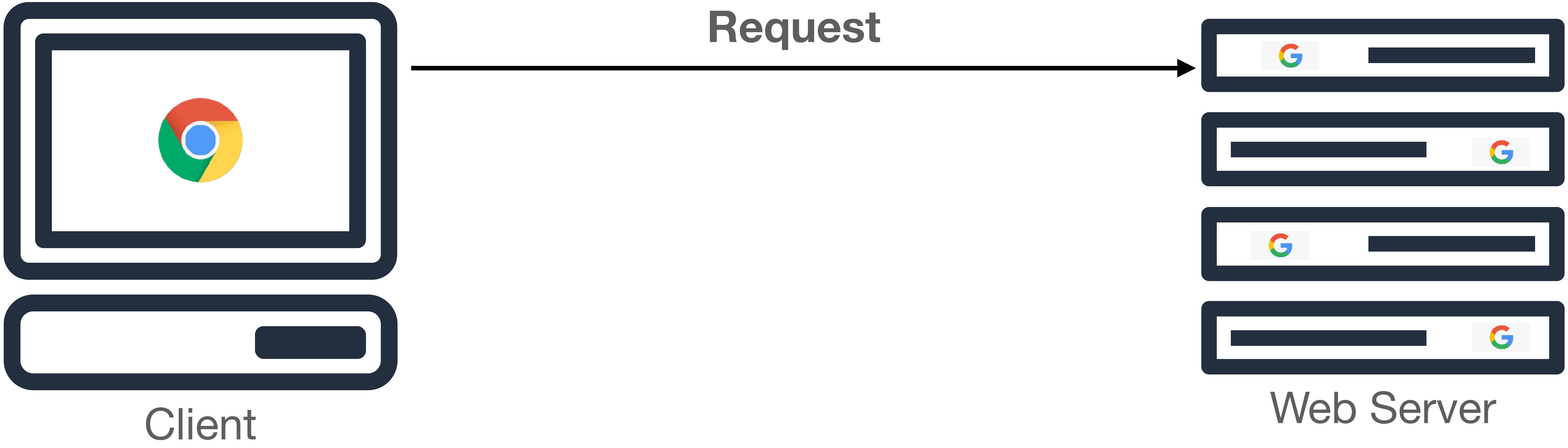
Client / Server Model

Client

Web Server

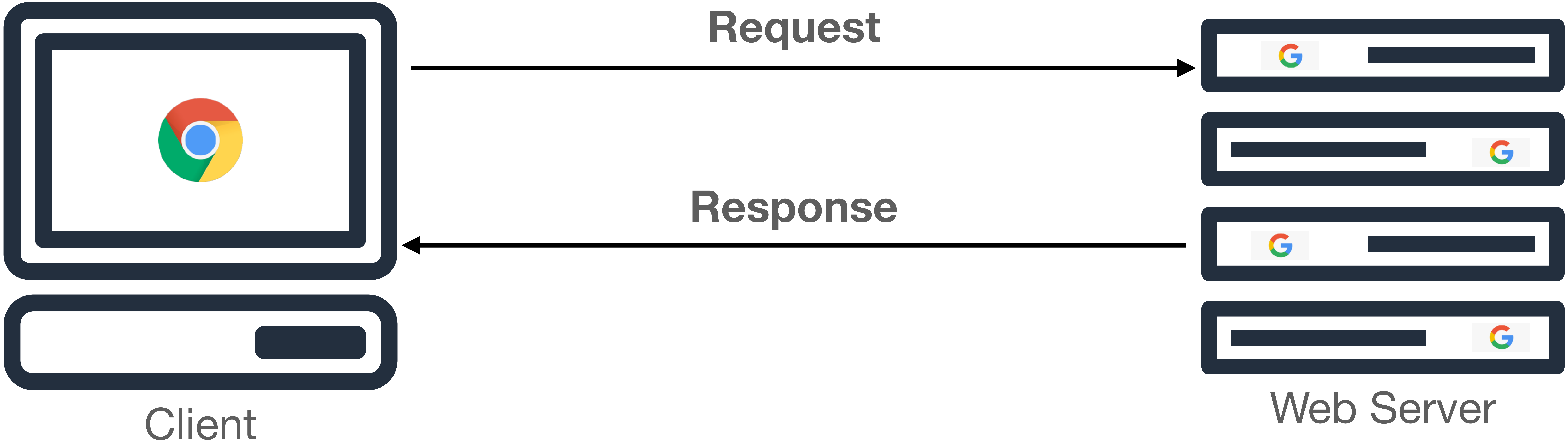
Interfacing with the Web

Client / Server Model

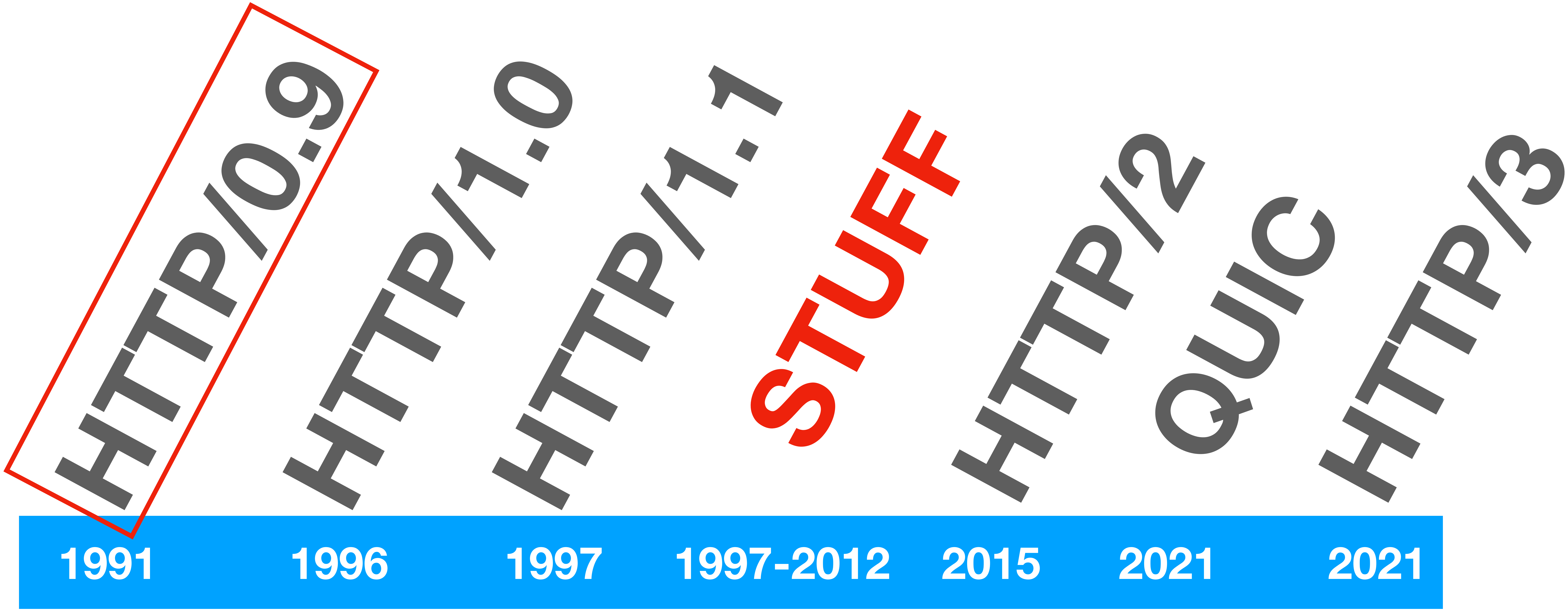


Interfacing with the Web

Client / Server Model



A History of Web Protocols



HTTP/0.9	HTTP/1.0	HTTP/1.1	STUFF	HTTP/2	QUIC	HTTP/3
1991	1996	1997	1997-2012	2015	2021	2021

HTTP/0.9

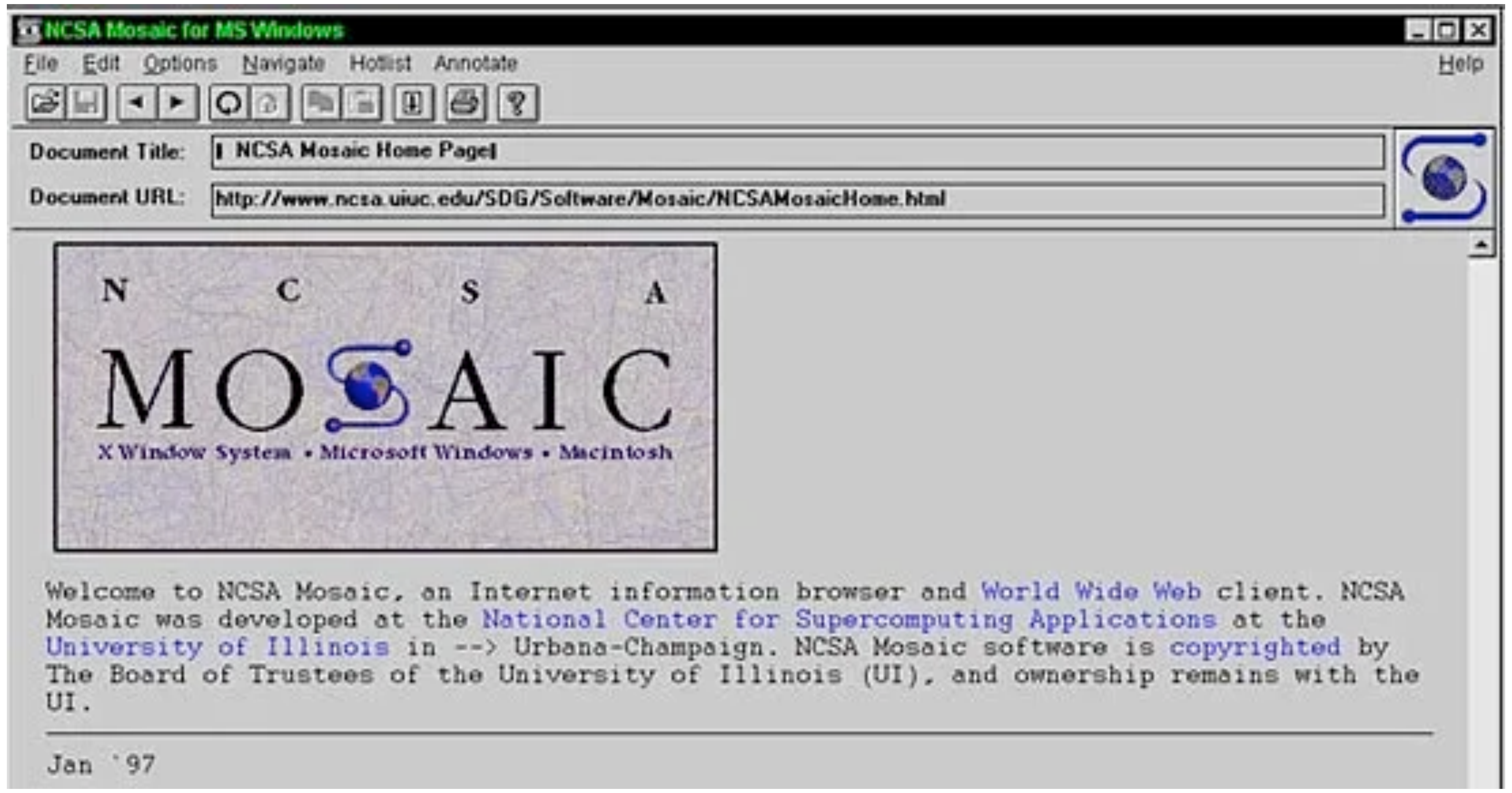
Single Line Protocol

- In 1991, Tim-Berners Lee needed a simple protocol to test his new invention "The Mesh" → "The World Wide Web"
    - The first web browser was also called "WorldWideWeb"
- 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 meta-data
- 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"


NCSA Mosaic for MS Windows
File
Edit
Options
Navigate
Hotlist
Annotate
Help
N C S A
MOSAIC
X Window System • Microsoft Windows • Macintosh

Document Title: NCSA Mosaic Home Page

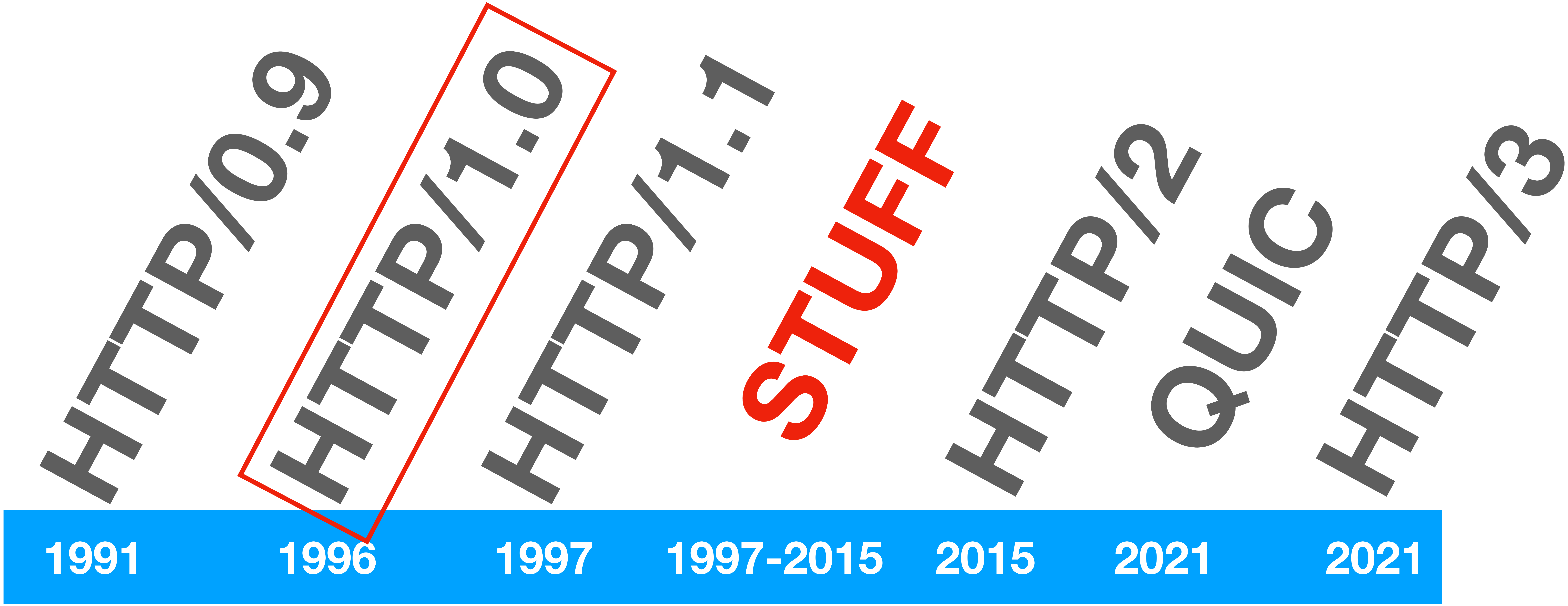
Document URL: http://www.ncsa.uiuc.edu/SDG/Software/Mosaic/NCSAMosaicHome.html

Welcome to NCSA Mosaic, an Internet information browser and World Wide Web client. NCSA Mosaic was developed at the National Center for Supercomputing Applications at the University of Illinois in --> Urbana-Champaign. NCSA Mosaic software is copyrighted by The Board of Trustees of the University of Illinois (UI), and ownership remains with the UI.

Jan '97

Chronicle / Carlos Avila Gonzalez

A History of Web Protocols



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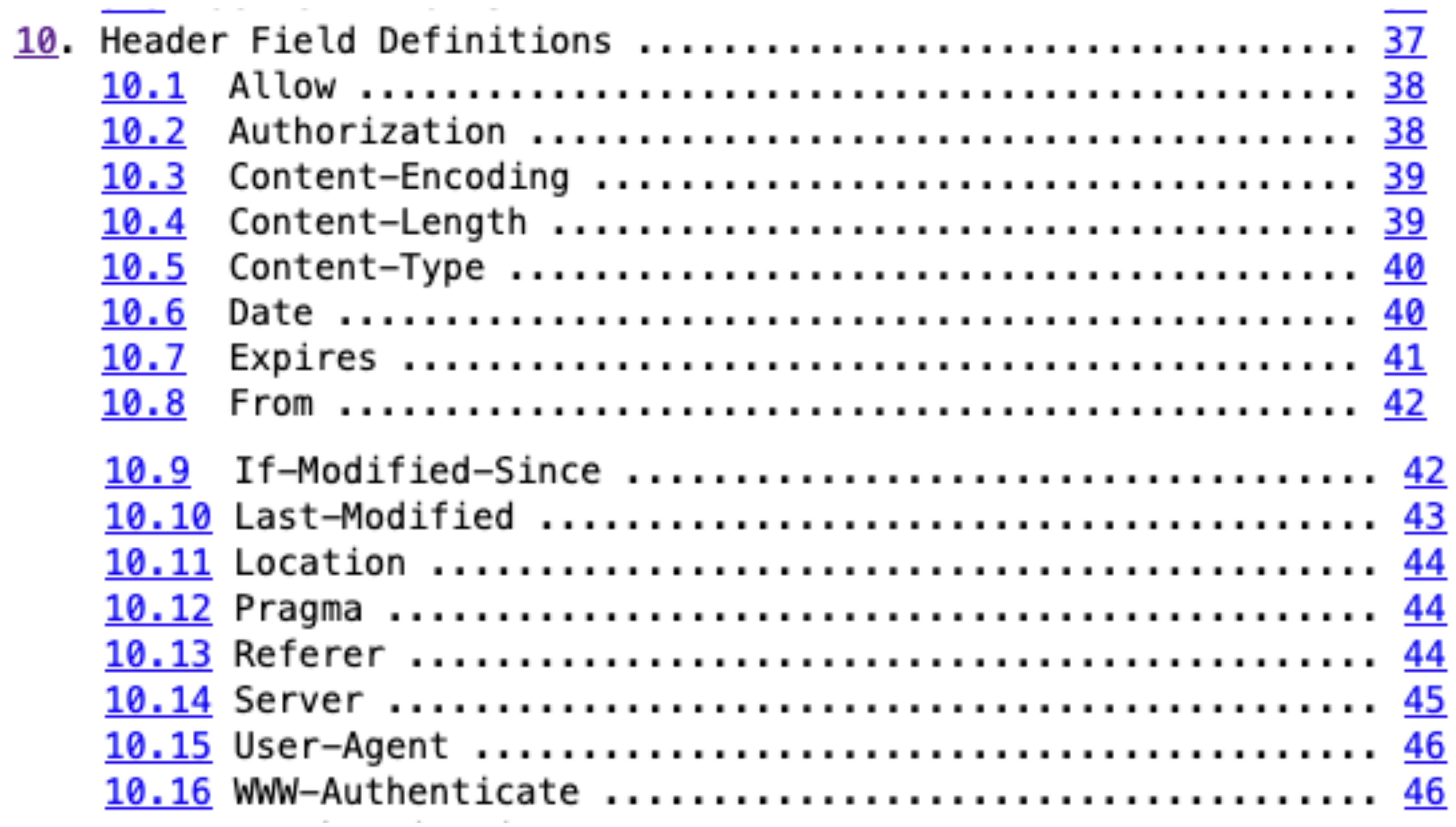
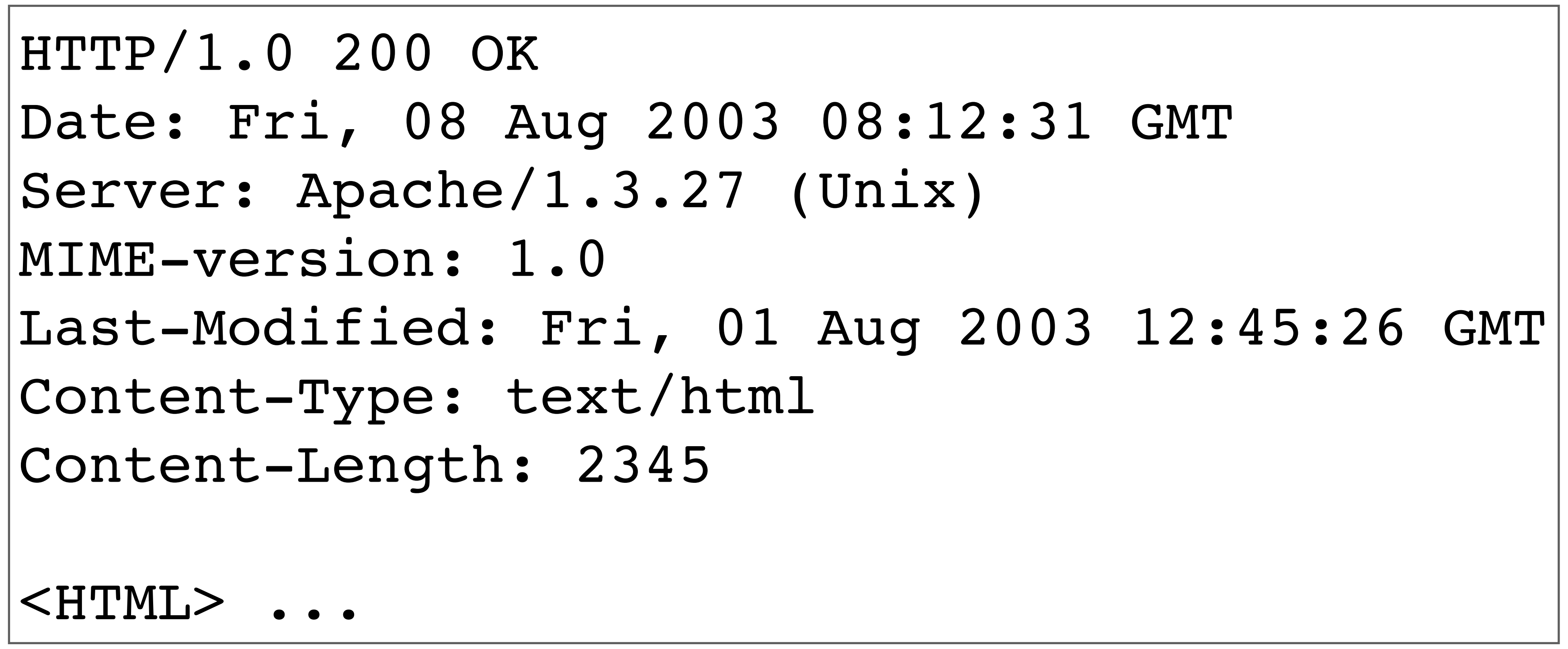
HTTP/1.0

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/1.0 200 OK
Date: Fri, 08 Aug 2003 08:12:31 GMT
Server: Apache/1.3.27 (Unix)
MIME-version: 1.0
Last-Modified: Fri, 01 Aug 2003 12:45:26 GMT
Content-Type: text/html
Content-Length: 2345

<HTML> ...
```

HTTP/1.0

Mired with Problems

- Connections were closed after requesting a single resource = Slow
    - 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

December 13, 1995, 6:55am ET

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The Houston Rockets, the NBA's kings of the hill, exposed the Sacramento Kings for what they are -- an early-season aberration on the championship challenger radar. The Rockets, with a 14-0 run to close the first half, crushed Sacramento 133-93. Sam Cassell (right, shooting over Brian Grant) came off the bench to score 26 points for the

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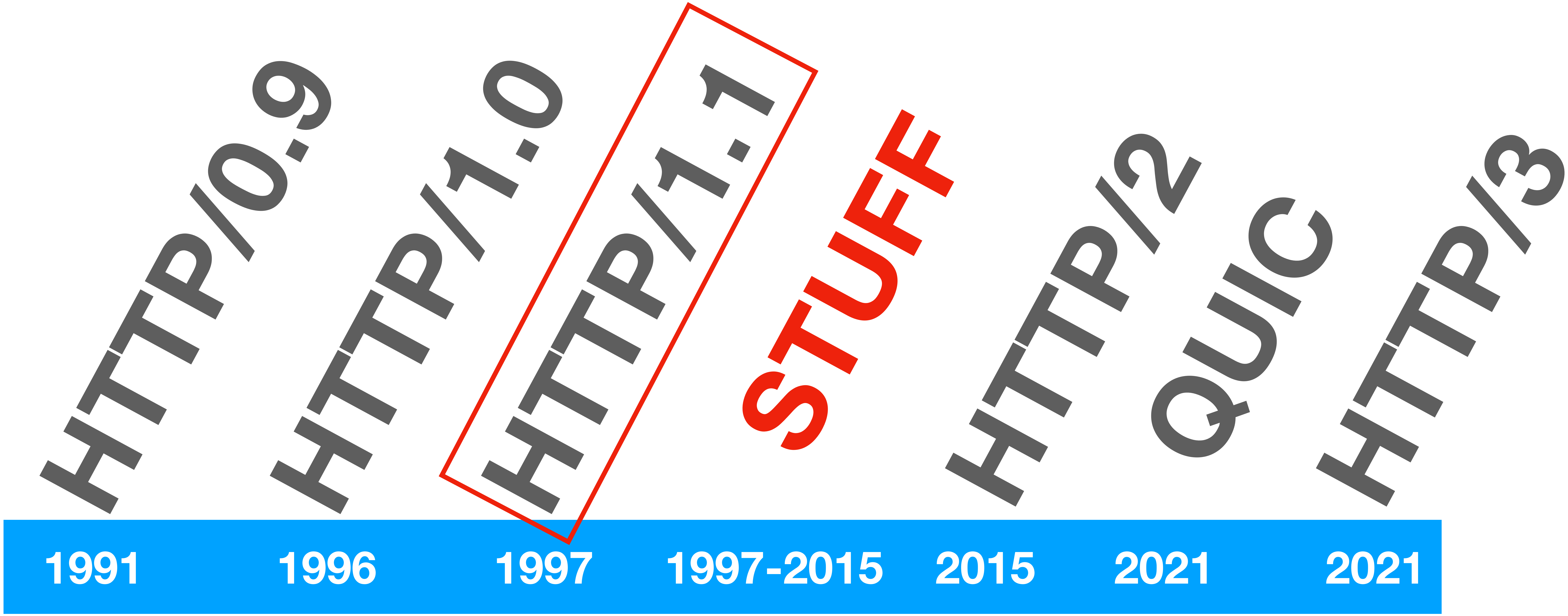

HTTP/0.9

HTTP/1.0

HTTP/1.1

STUFF

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QUIC

HTTP/3

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HTTP/1.1

A New Era

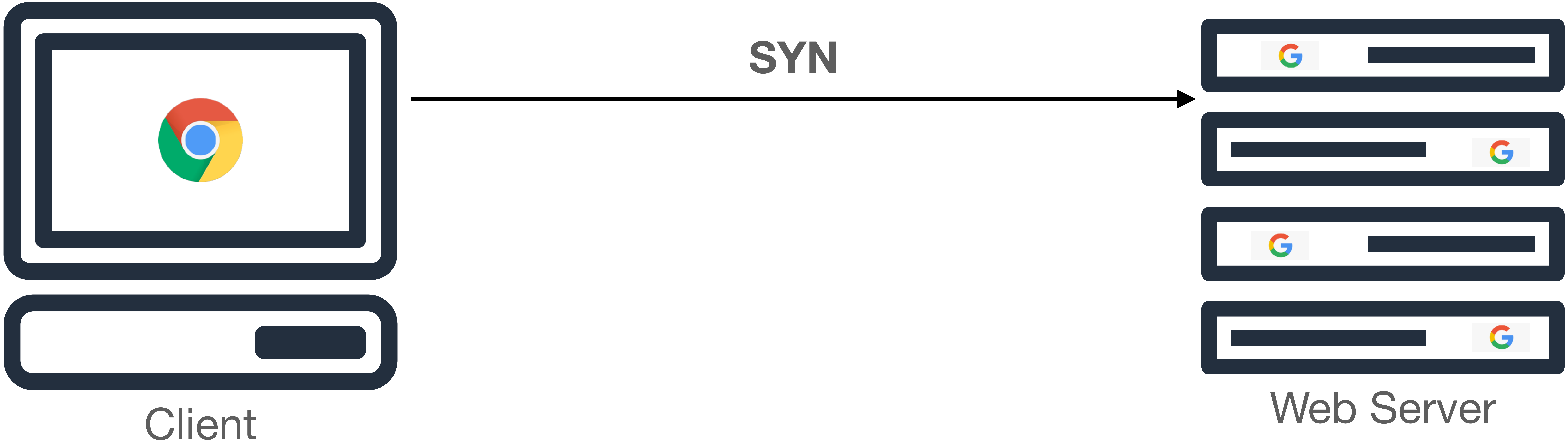
- HTTP/1.1 fixed many problems and challenges with early versions
  - Added the Host header (to enable multiple websites with different domains to be served from the same IP address)
  - Allowed for **persistent connections**
    - Allowed chunked responses
    - Enabled pipelining of requests

HTTP/1.1

Persistent Connections

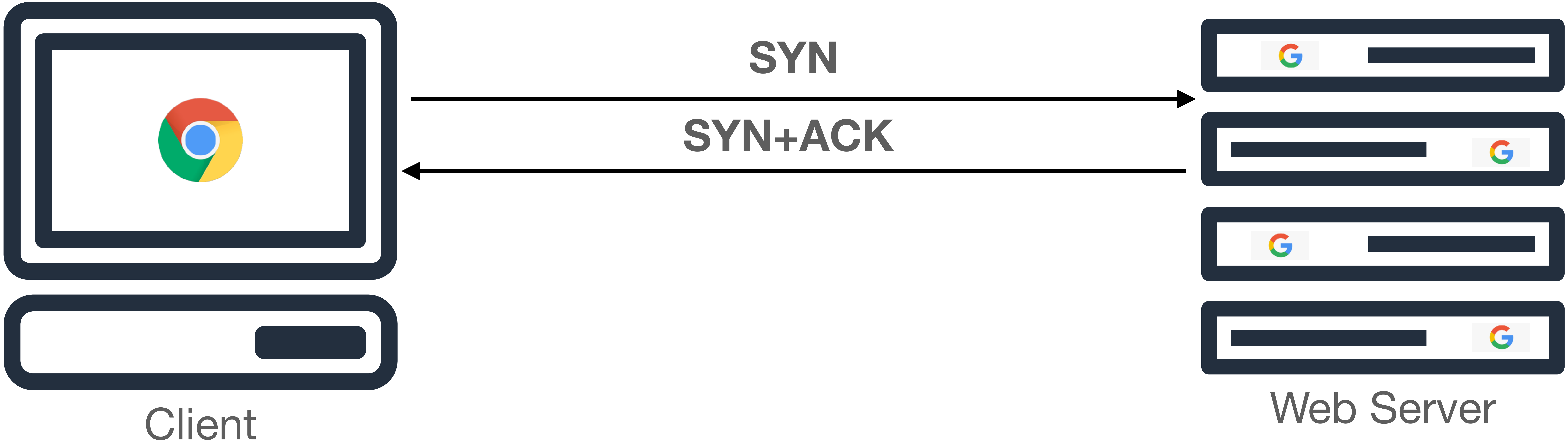
HTTP/1.1

Persistent Connections



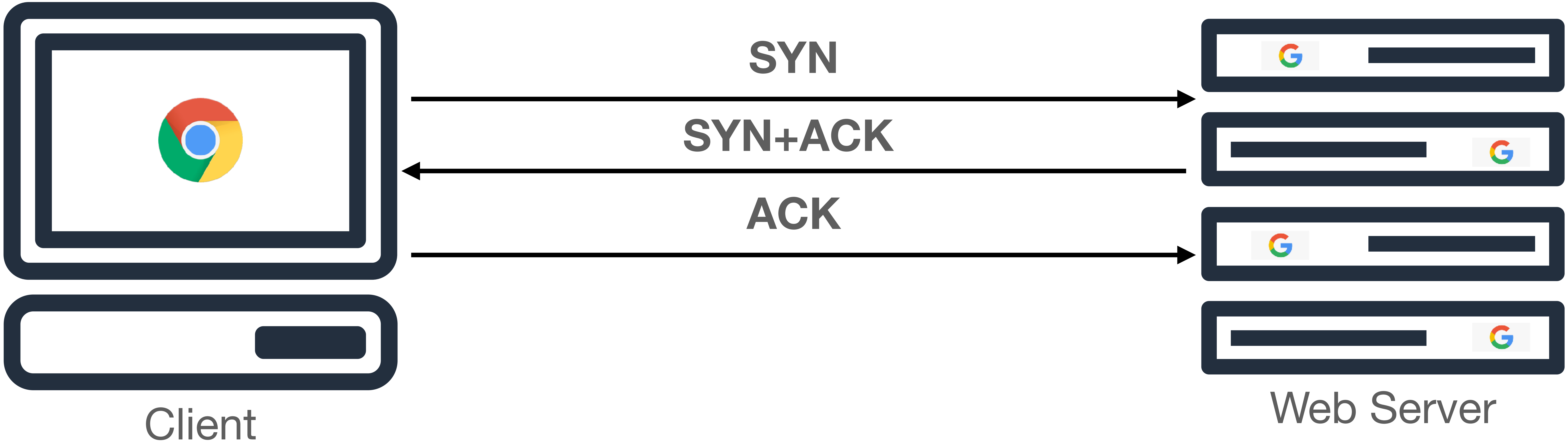
HTTP/1.1

Persistent Connections



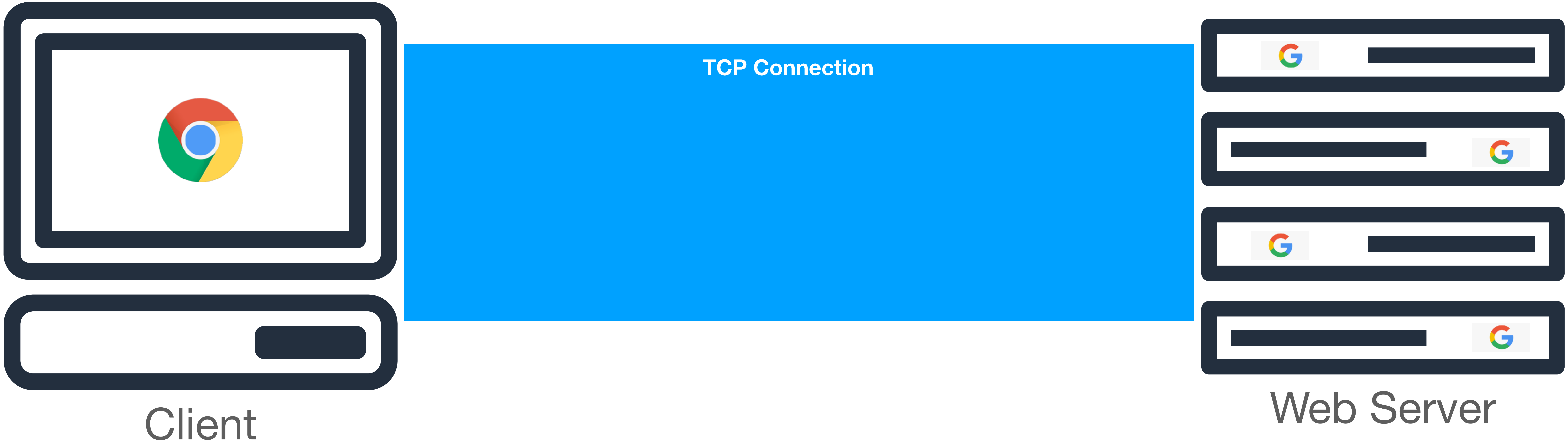
HTTP/1.1

Persistent Connections



HTTP/1.1

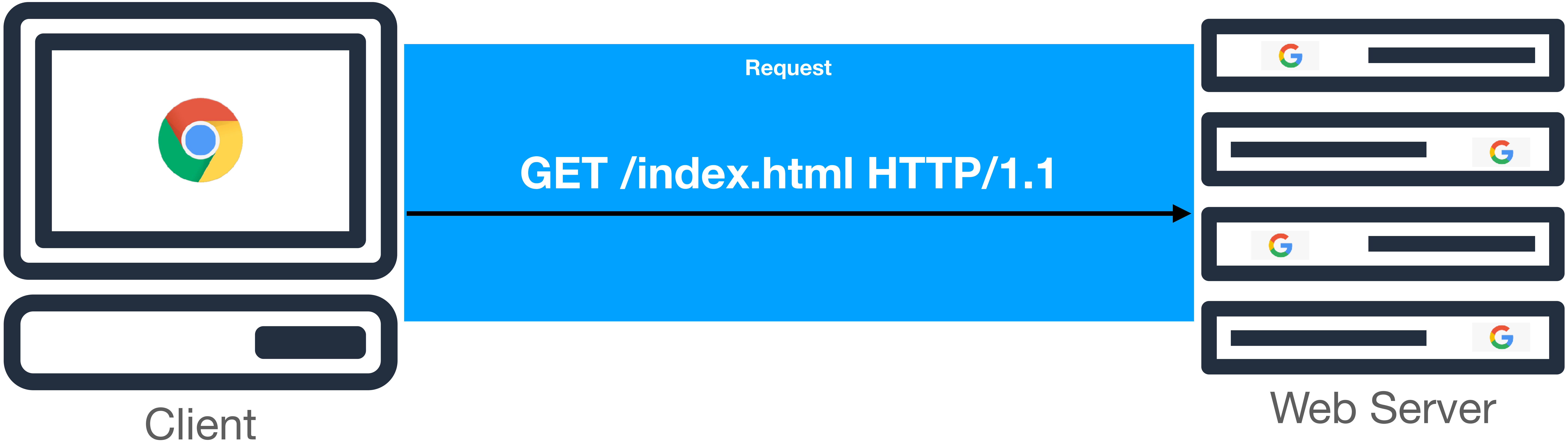
Persistent Connections



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
```



Request

GET /index.html HTTP/1.1

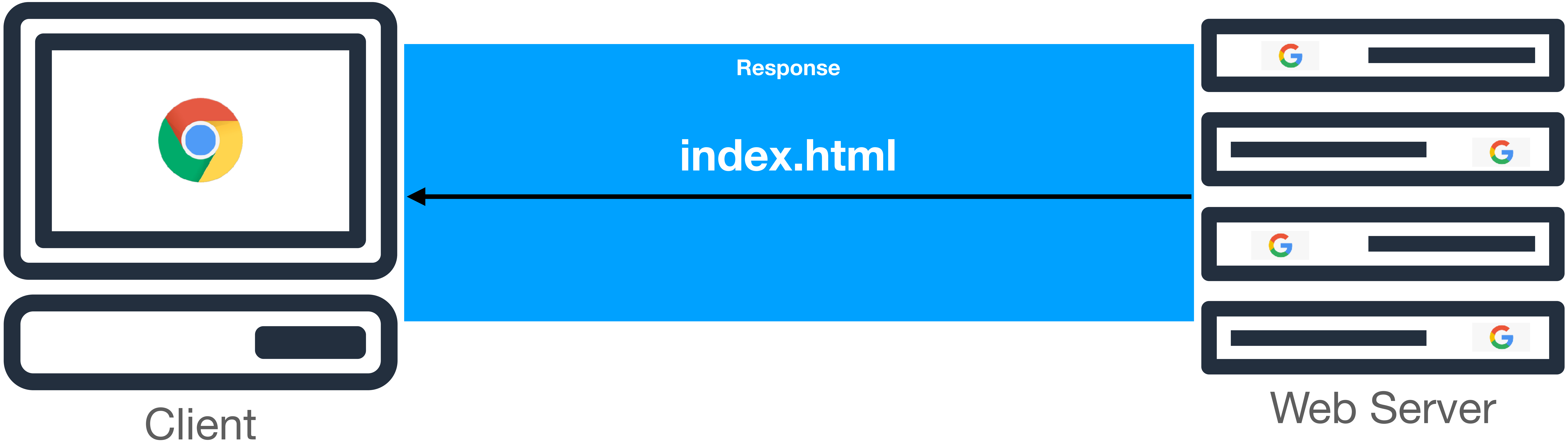
Client

Web Server

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

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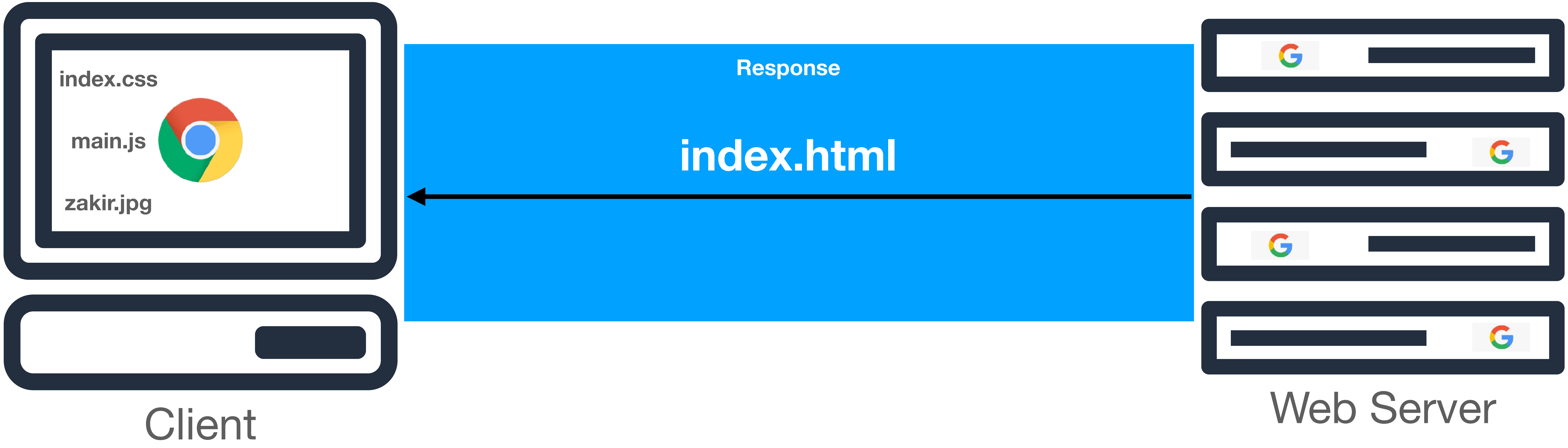
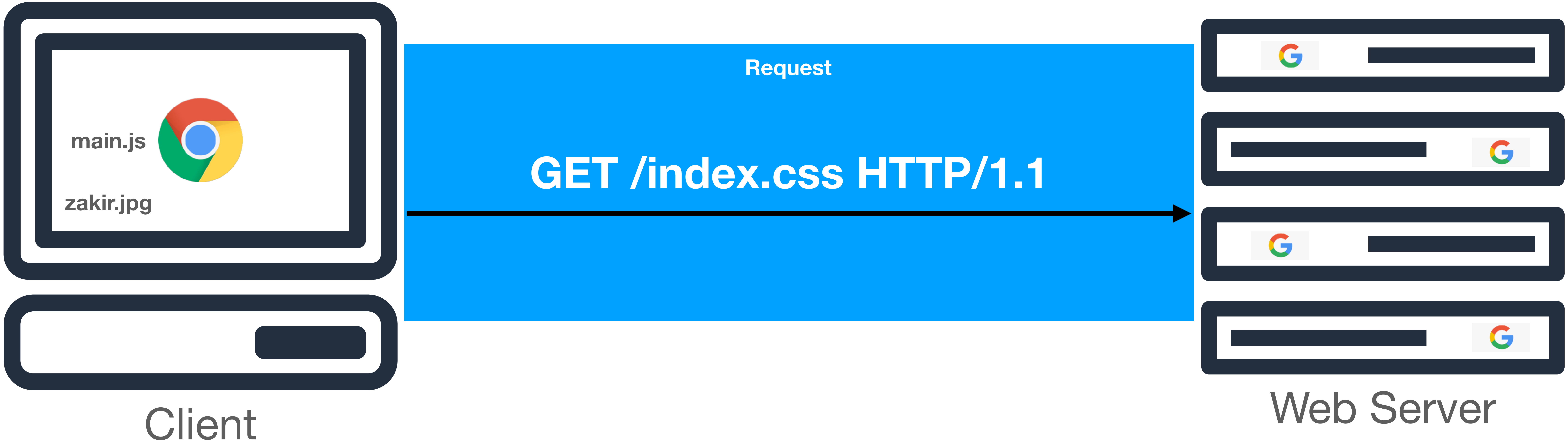


HTTP/1.1

Persistent Connections



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

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

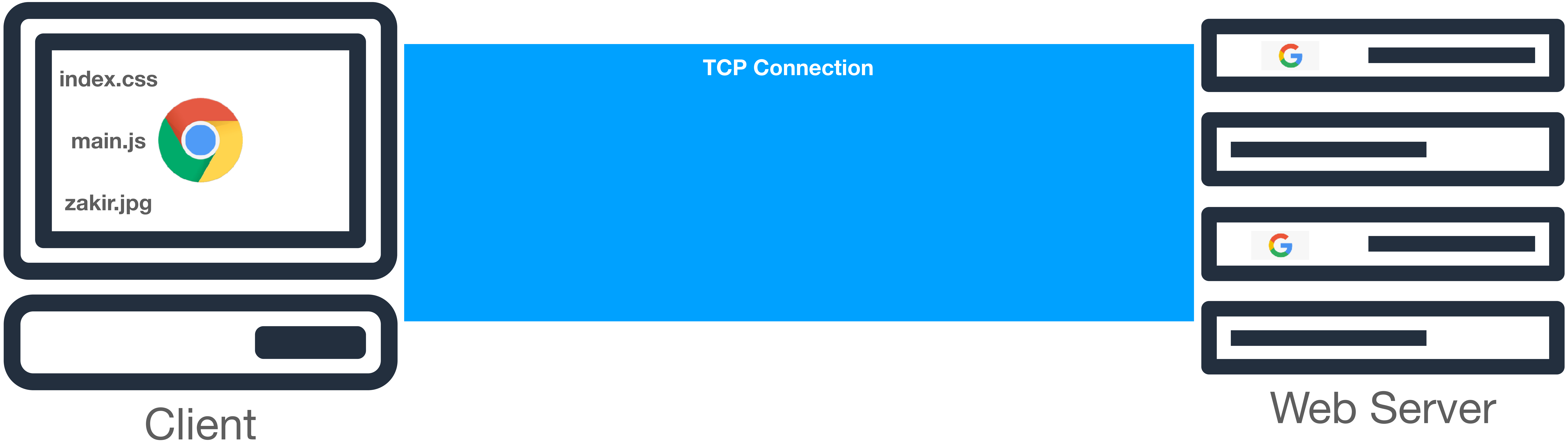
HTTP/1.1

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

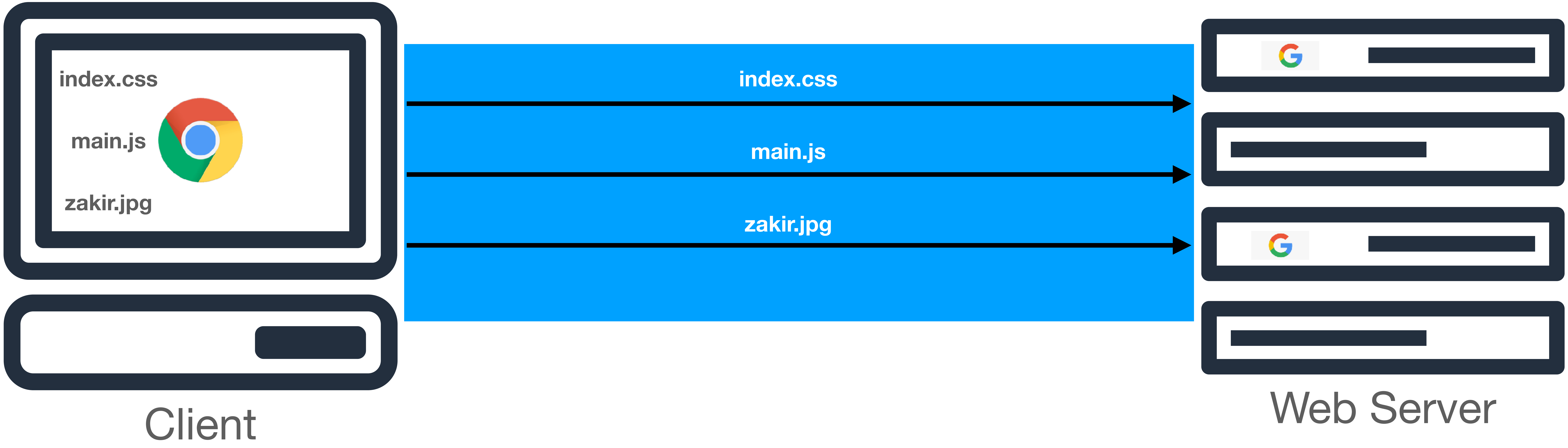
Pipelining



HTTP/1.1

Pipelining

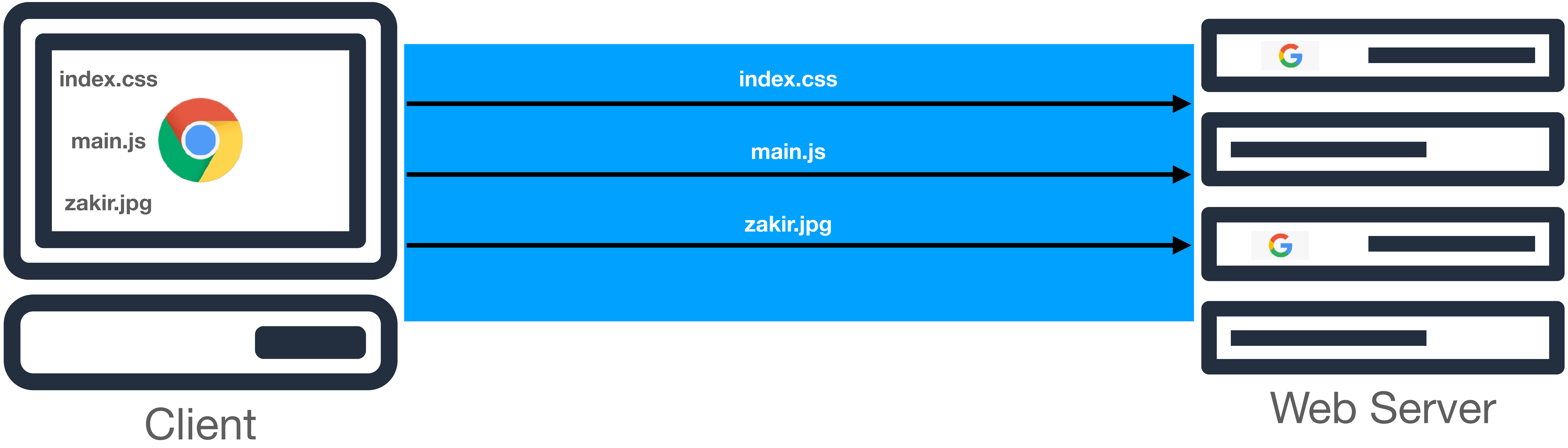
With pipelining, I can use just one TCP connection!



HTTP/1.1

Pipelining

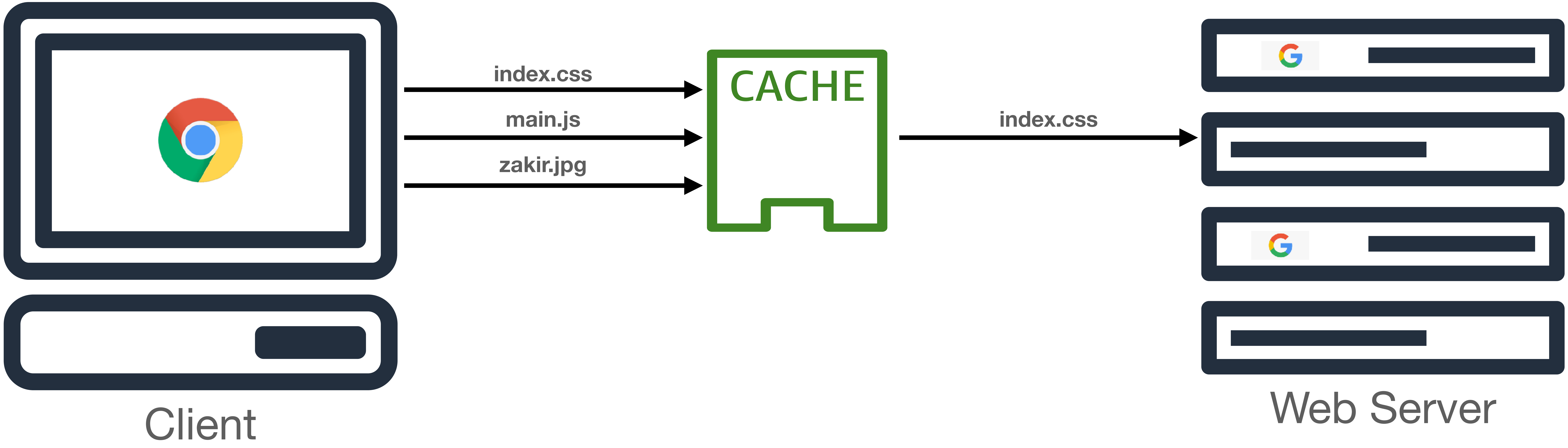
But what happens if index.css takes a long time to retrieve?



HTTP/1.1

Pipelining

Also, what about HTTP proxies?



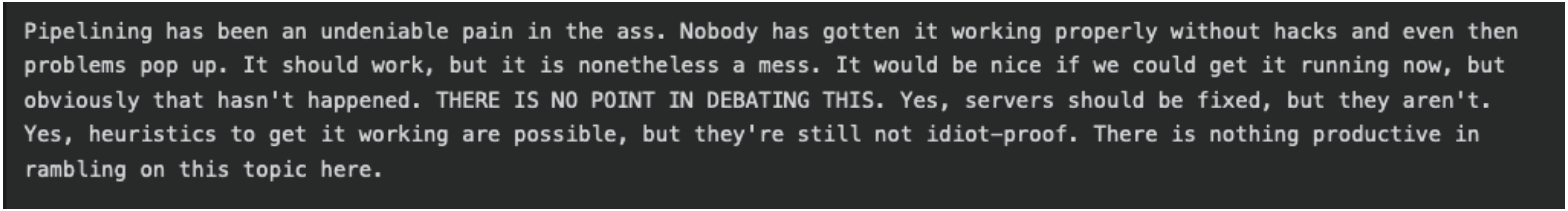
HTTP/1.1

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

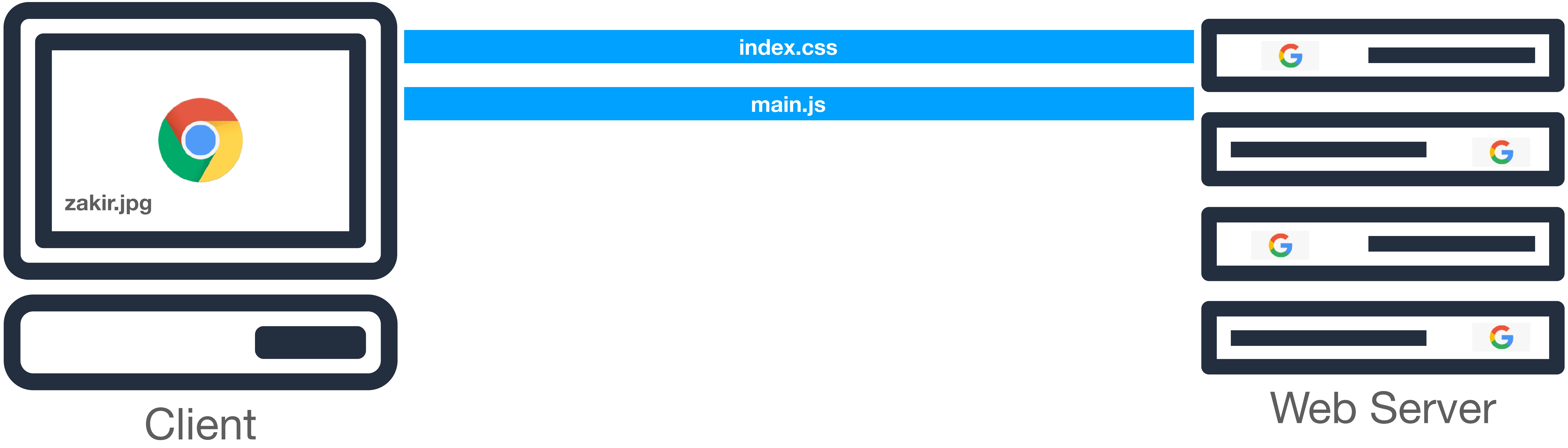


Pipelining has been an undeniable pain in the ass. Nobody has gotten it working properly without hacks and even then problems pop up. It should work, but it is nonetheless a mess. It would be nice if we could get it running now, but obviously that hasn't happened. THERE IS NO POINT IN DEBATING THIS. 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.

https://bugzilla.mozilla.org/show_bug.cgi?id=264354

HTTP/1.1

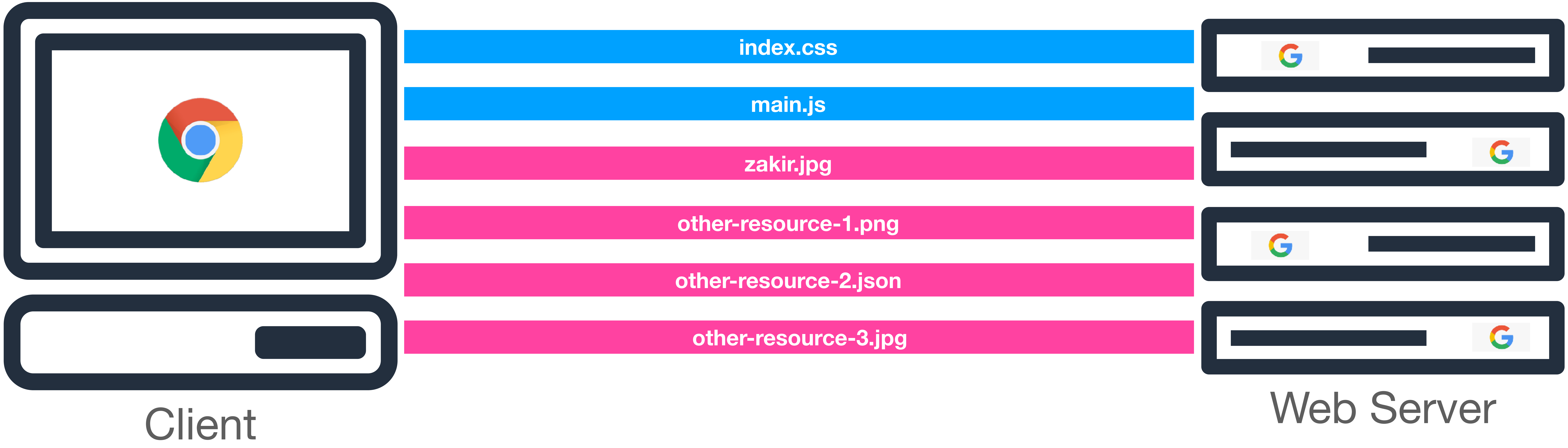
Persistent Connections



HTTP/1.1

Persistent Connections

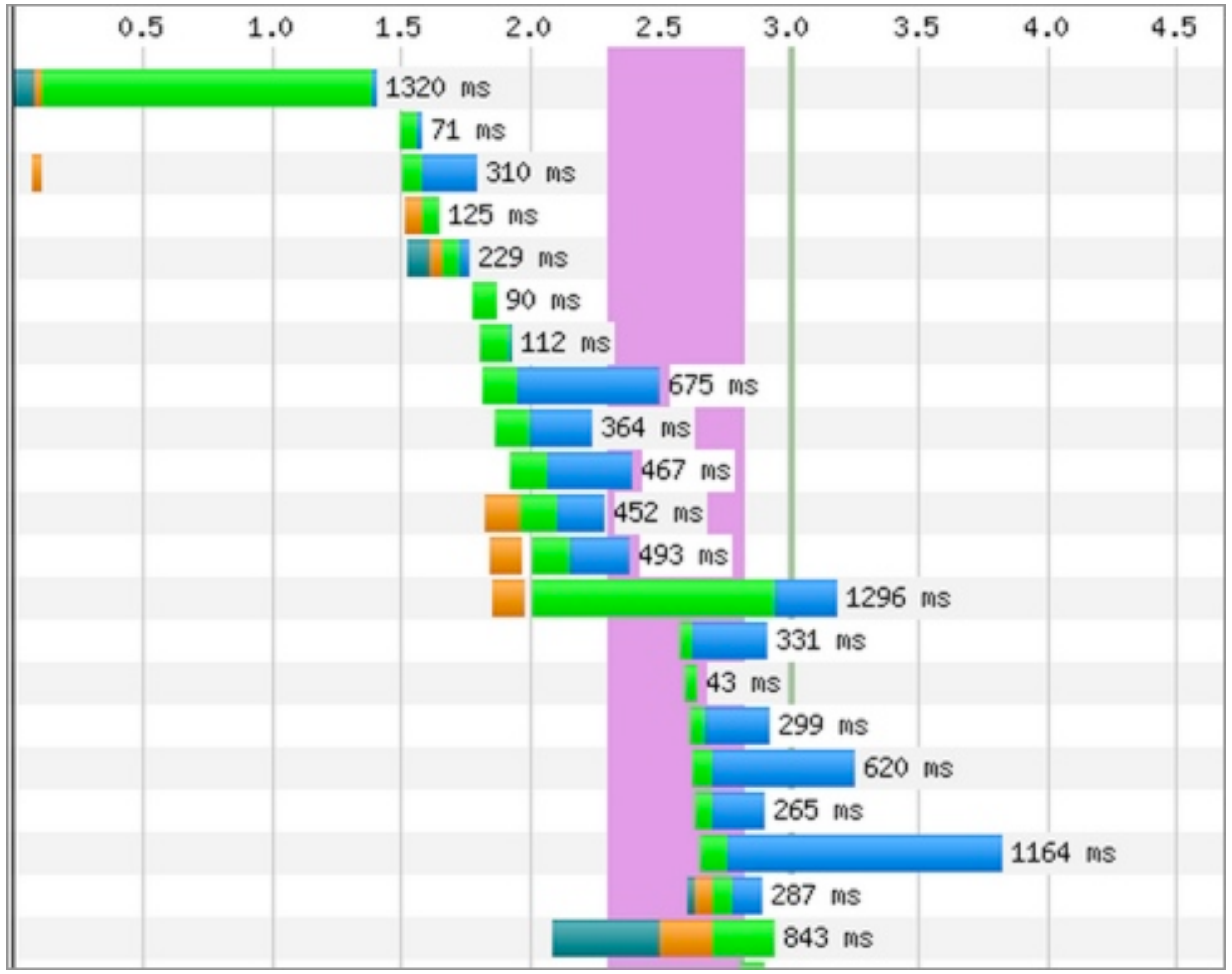
*Modern browsers will open up to **6 TCP connections per host**, plus **4 external TCP connections** at a time*



HTTP/1.1

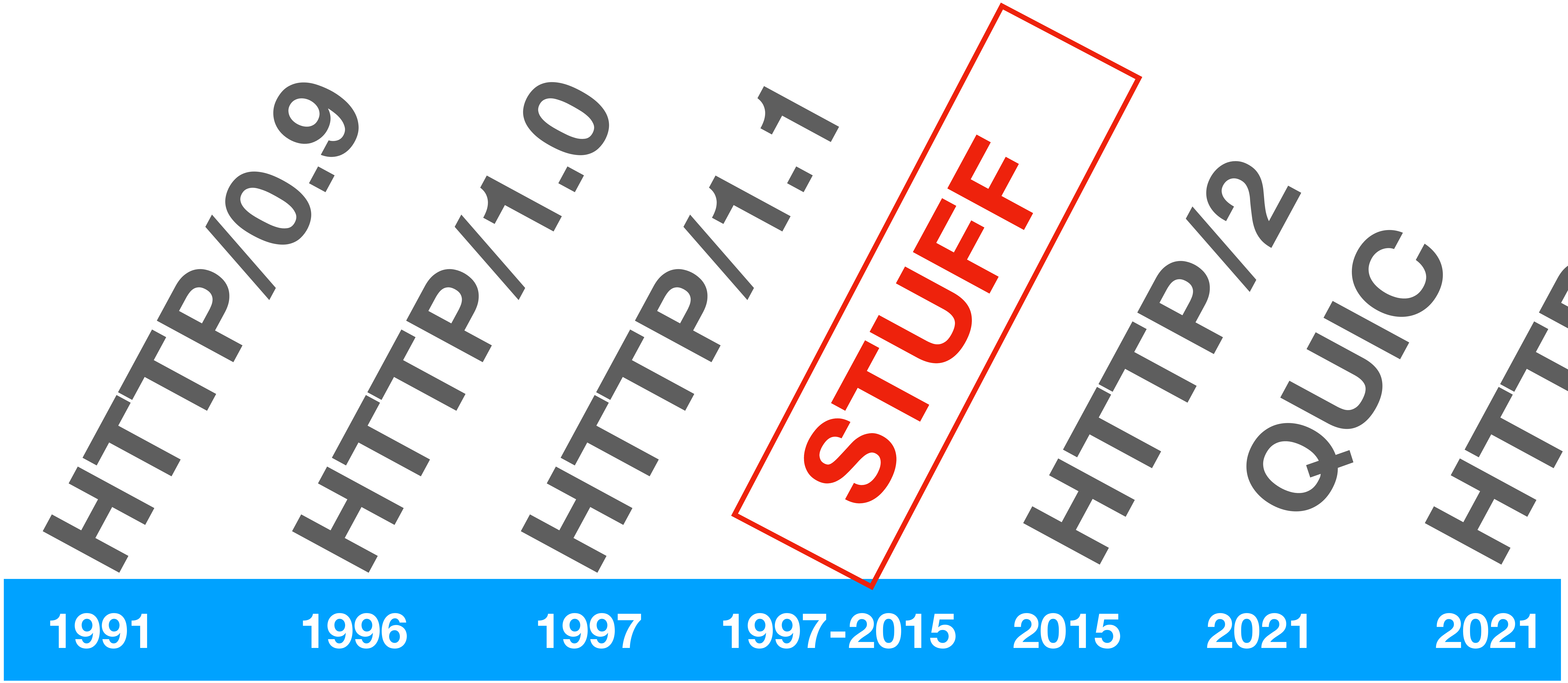
Head of Line Blocking

- Head of Line blocking is **broader** than pipelining
- Modern browsers still only open a maximum of 6 connections and have to wait for requests to finish before issuing new ones
- This is still pretty slow



https://www.merkleinc.com/blog/http2-electric-boogaloo-0

A History of Web Protocols



HTTP/0.9 — 1991

HTTP/1.0 — 1996

HTTP/1.1 — 1997

STUFF — 1997-2015

HTTP/2 — 2015

QUIC — 2021

HTTP/3 — 2021

What Happened from 1997 – 2012?

- 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 different objects
- Internet speeds and infrastructure significantly improved, networks matured
    - **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

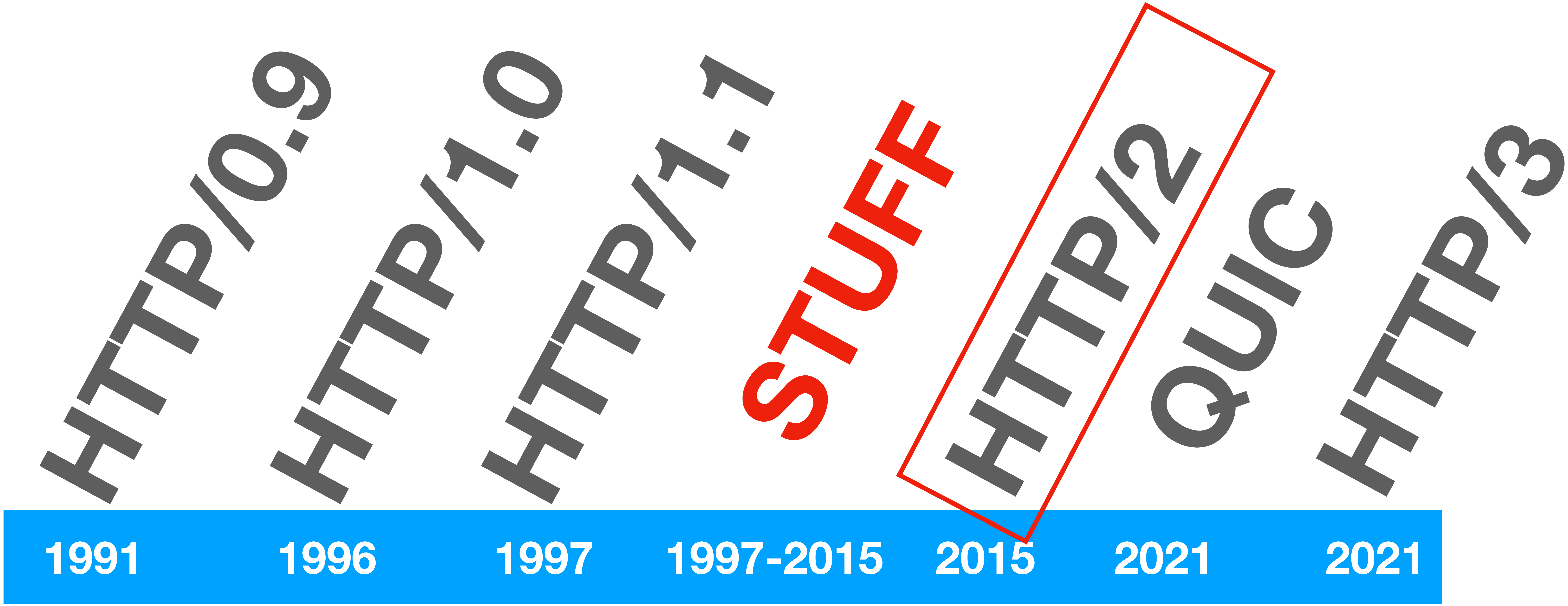
- SPDY was a *translation layer* between HTTP clients and servers and sat in front of HTTP on both ends

    - 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

A History of Web Protocols



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HTTP/2

Design Goals

1. Eliminate Head-of-Line (HOL) blocking by multiplexing HTTP requests over a single TCP connection

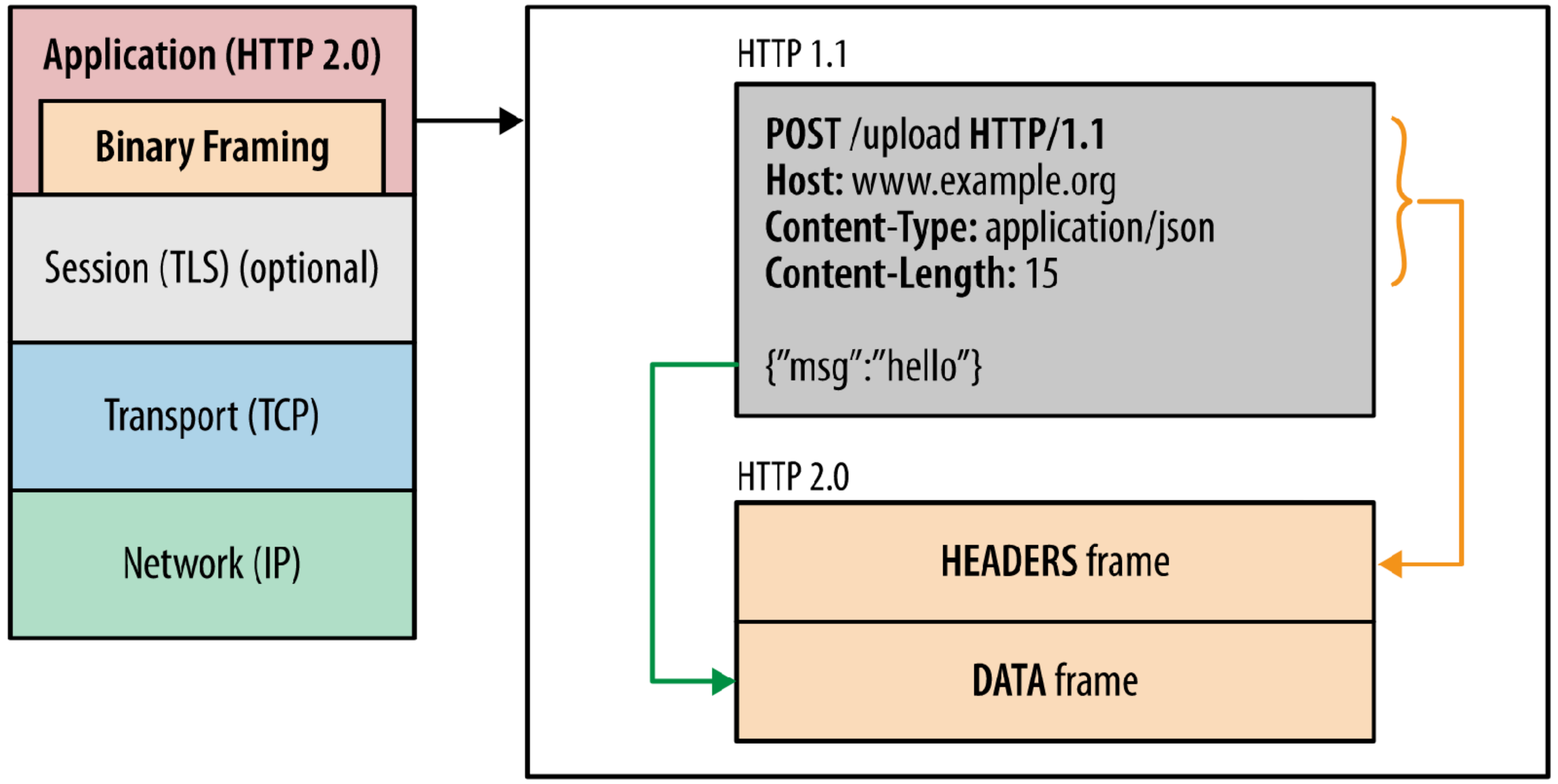
2. Give servers more agency (e.g., allow them to *push* content over persistent connections)

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 ***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



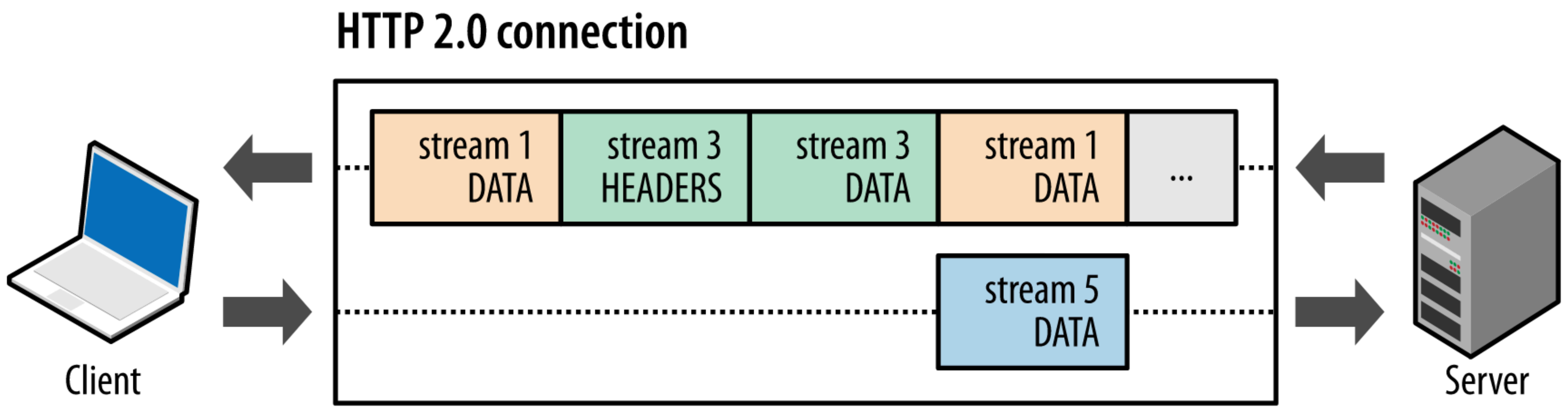
```
POST /upload HTTP/1.1
Host: www.example.org
Content-Type: application/json
Content-Length: 15

{"msg":"hello"}
```

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!

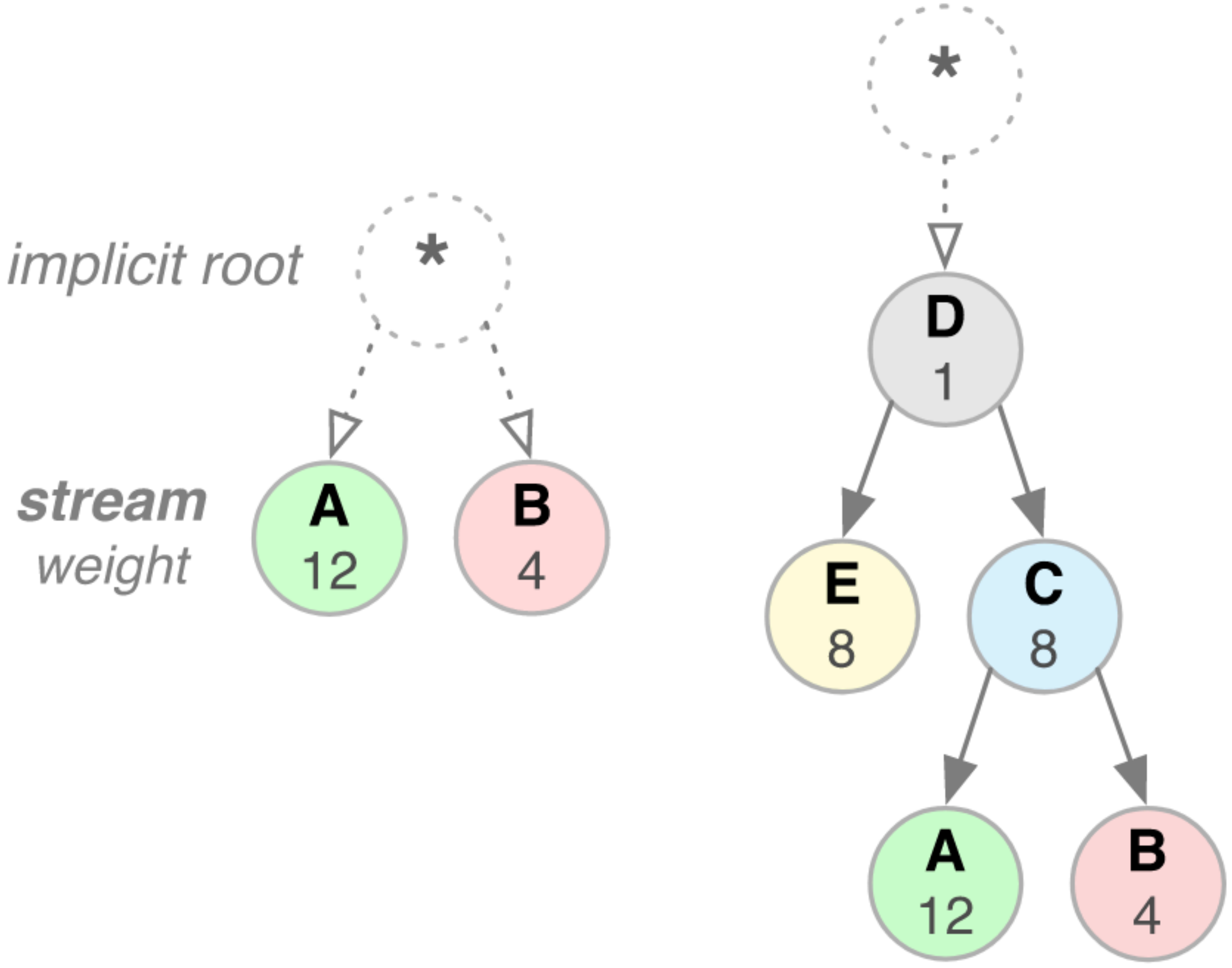


https://developers.google.com/web/fundamentals/performance/http2

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 support *prioritization of streams,* which is a mechanism that allows the client to ask for specific streams ahead of others
  - 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

Design Goals

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

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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

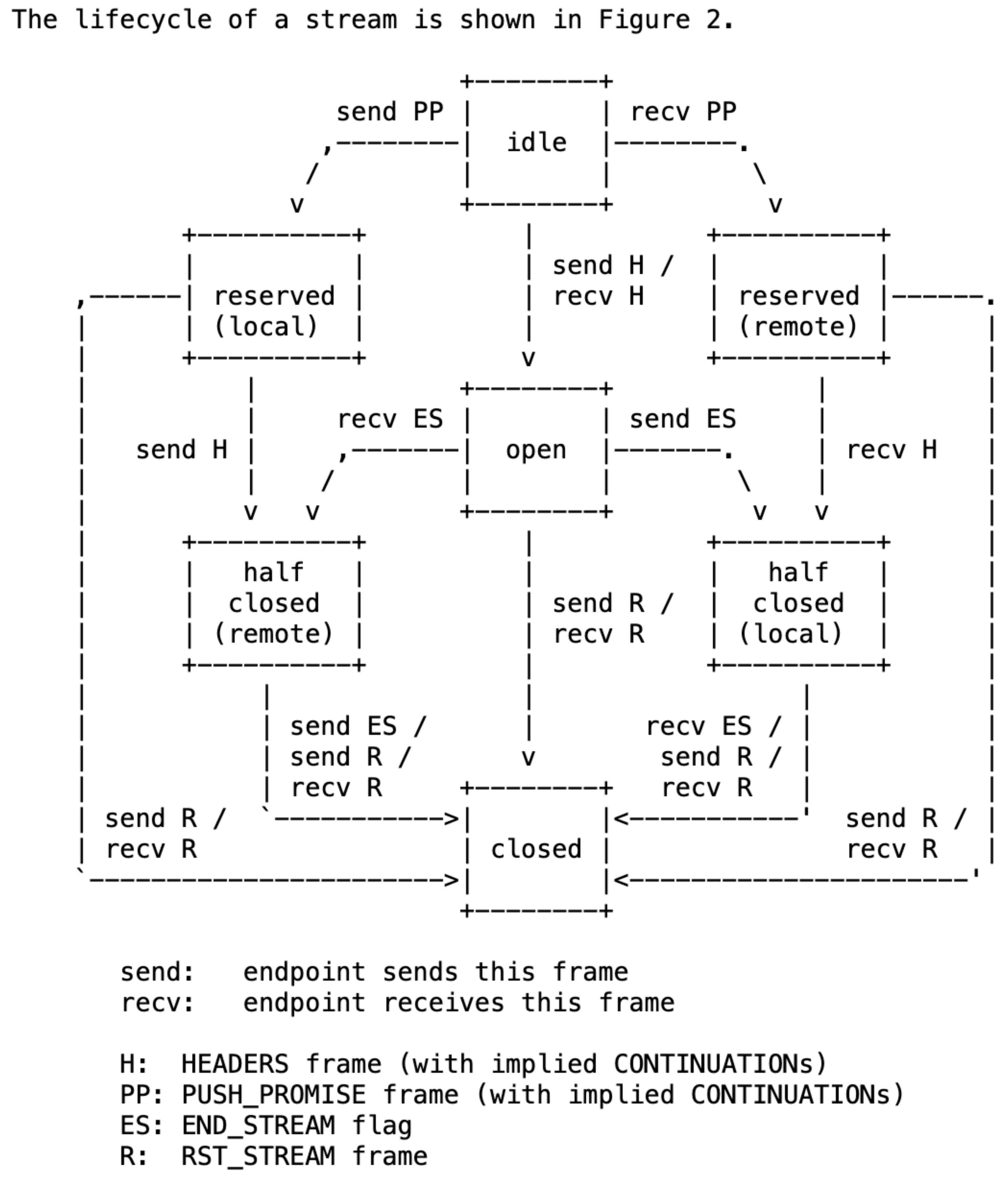
Goal 2: Giving servers more agency

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

- 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



```
The lifecycle of a stream is shown in Figure 2.

                                +--------+
                        send PP |        | recv PP
                       ,--------|  idle  |--------.
                      /         |        |         \
                     v          +--------+          v
              +----------+          |           +----------+
              |          |          | send H /  |          |
       ,------| reserved |          | recv H    | reserved |------.
       |      | (local)  |          |           | (remote) |      |
       |      +----------+          v           +----------+      |
       |          |             +--------+             |          |
       |          |     recv ES |        | send ES     |          |
       |   send H |     ,-------|  open  |-------.     | recv H   |
       |          |    /        |        |        \    |          |
       |          v   v         +--------+         v   v          |
       |      +----------+          |           +----------+      |
       |      |   half   |          |           |   half   |      |
       |      |  closed  |          | send R /  |  closed  |      |
       |      | (remote) |          | recv R    | (local)  |      |
       |      +----------+          |           +----------+      |
       |           |                |                 |           |
       |           | send ES /      |       recv ES / |           |
       |           | send R /       v        send R / |           |
       |           | recv R     +--------+   recv R   |           |
       | send R /  `----------->|        |<-----------'  send R / |
       | recv R                 | closed |               recv R   |
       `----------------------->|        |<----------------------'
                                +--------+

   send:   endpoint sends this frame
   recv:   endpoint receives this frame

   H:  HEADERS frame (with implied CONTINUATIONs)
   PP: PUSH_PROMISE frame (with implied CONTINUATIONs)
   ES: END_STREAM flag
   R:  RST_STREAM frame
```

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)

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

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

Index	Header Name	Header Value
1	:authority	
2	:method	GET
3	:method	POST
…		
28	content-length	
38	host	
61	www-authenticate	
62	Host	kumarde.com

HTTP/2

Design Goals

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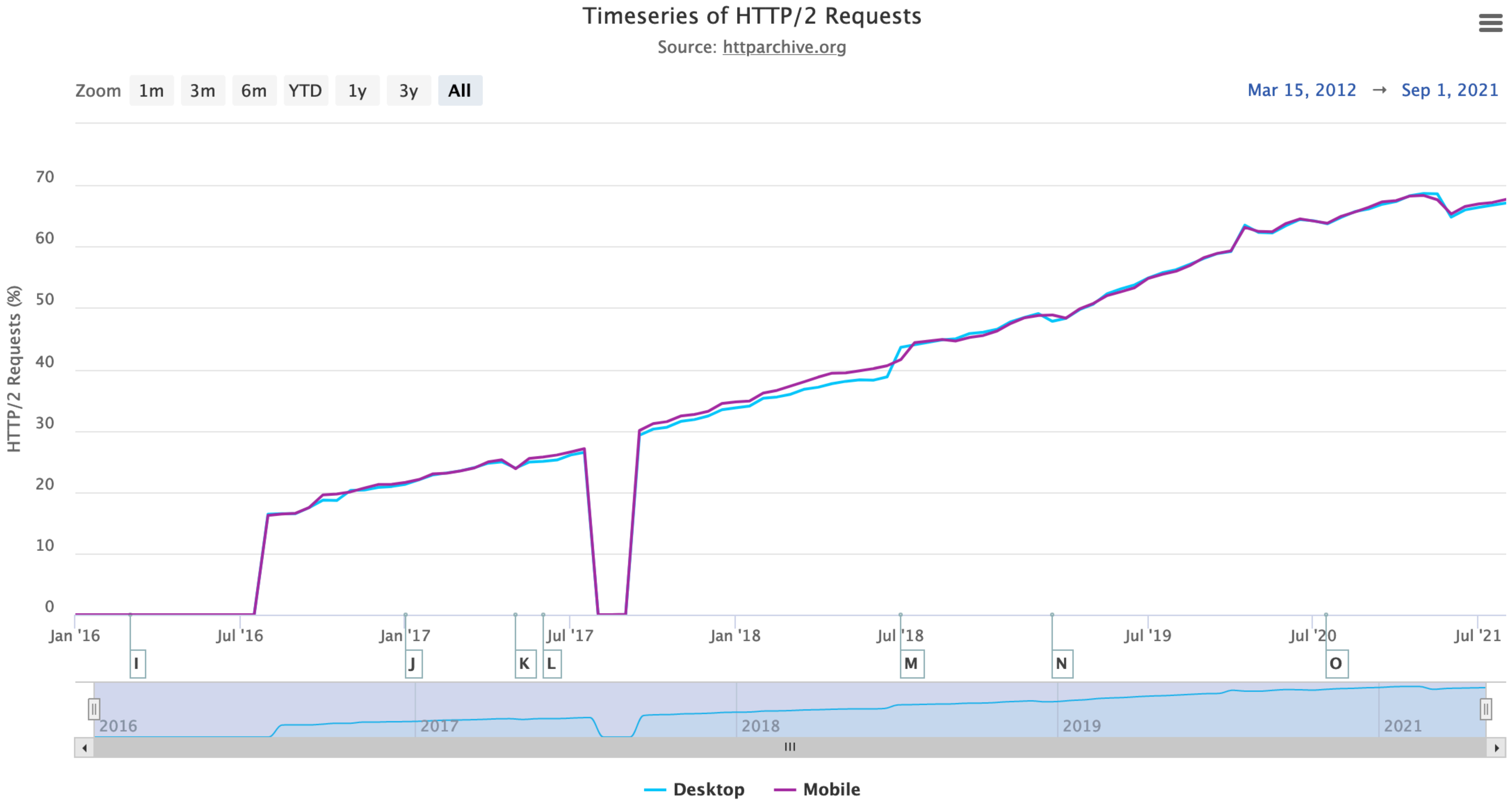
HTTP/2

Adoption is booming



Timeseries of HTTP/2 Requests

Source: httparchive.org

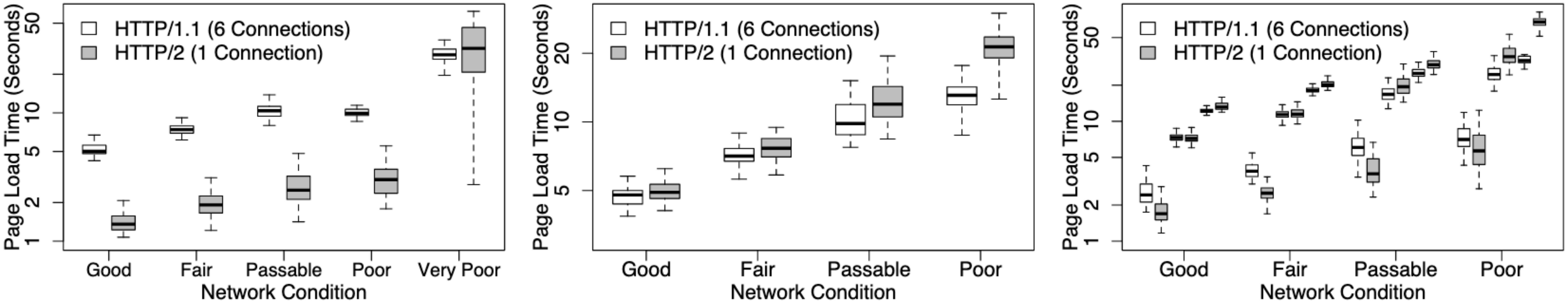
HTTP/2

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?



(a) 365 objects of 2 KB each (b) 10 objects of 435 KB each (c) 136 objects of 1 KB to 620 KB each

Figure 1: Distribution of page load times when loaded over h1 and h2 under various network conditions.

- "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

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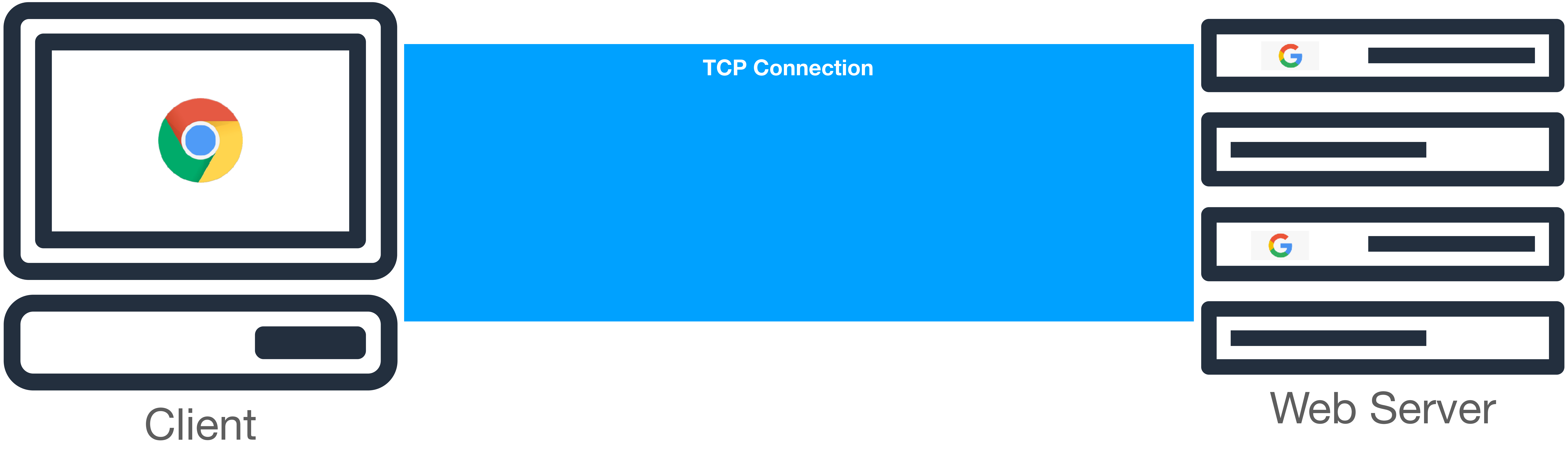

HTTP/2

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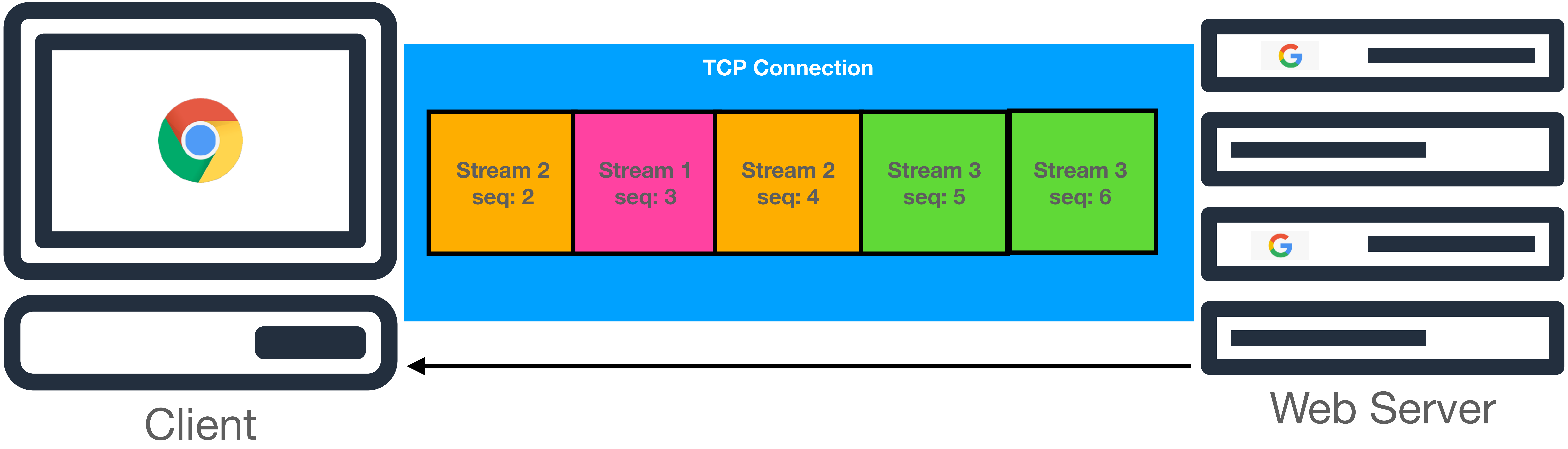

HTTP/2

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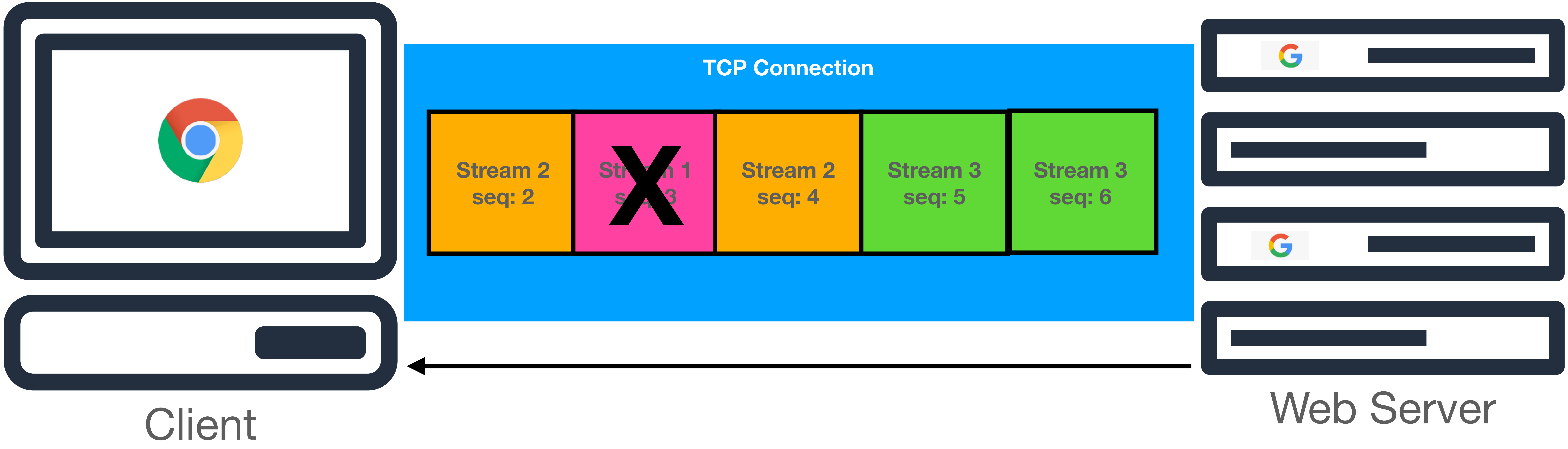
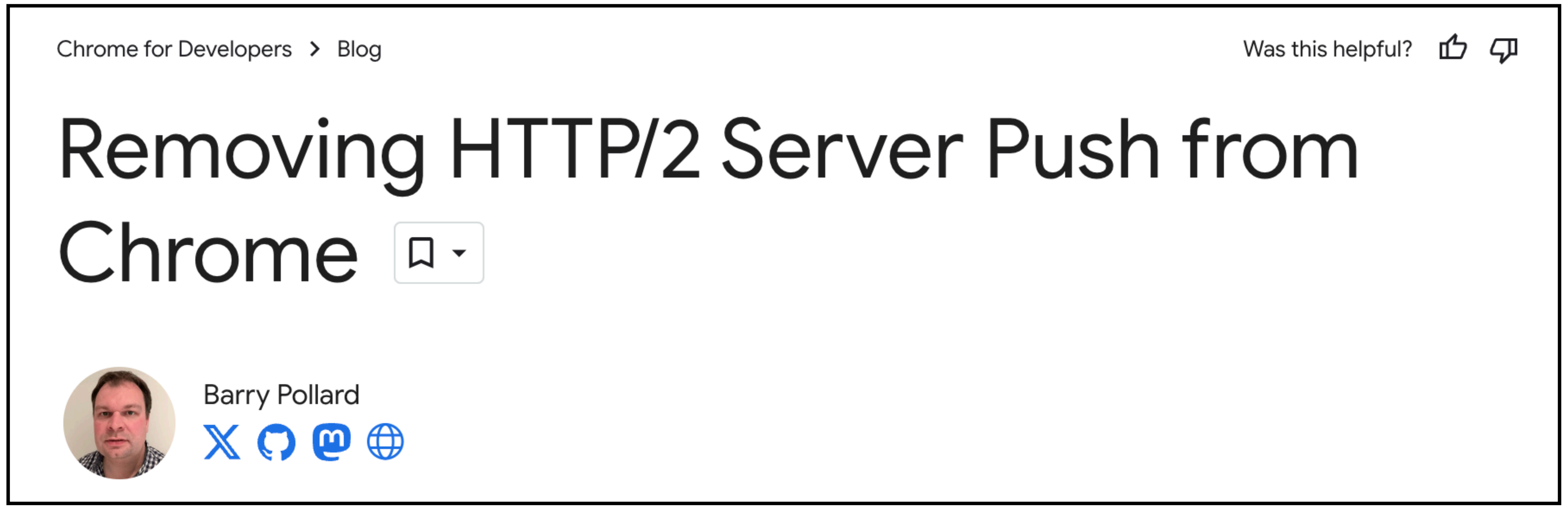


HTTP/2 — Removing Server Push

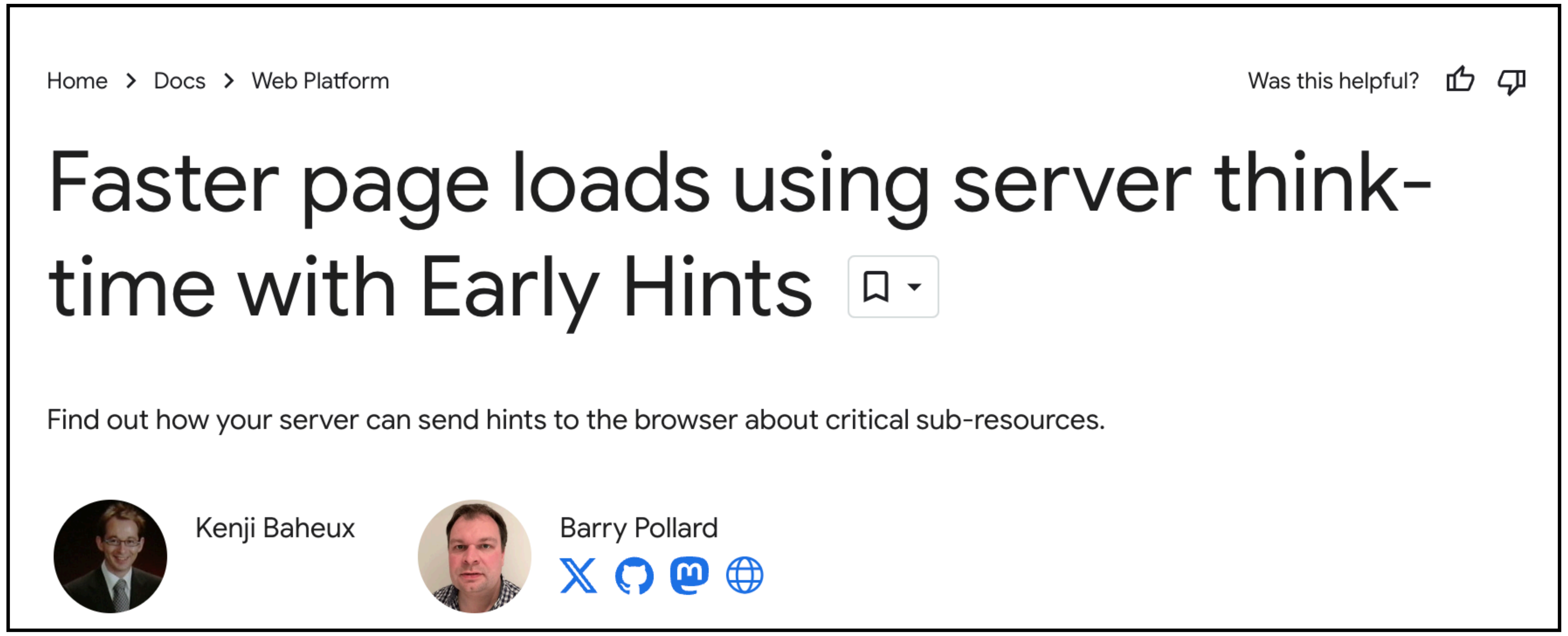


Chrome for Developers › Blog

Was this helpful?

Removing HTTP/2 Server Push from Chrome

Barry Pollard



Home › Docs › Web Platform

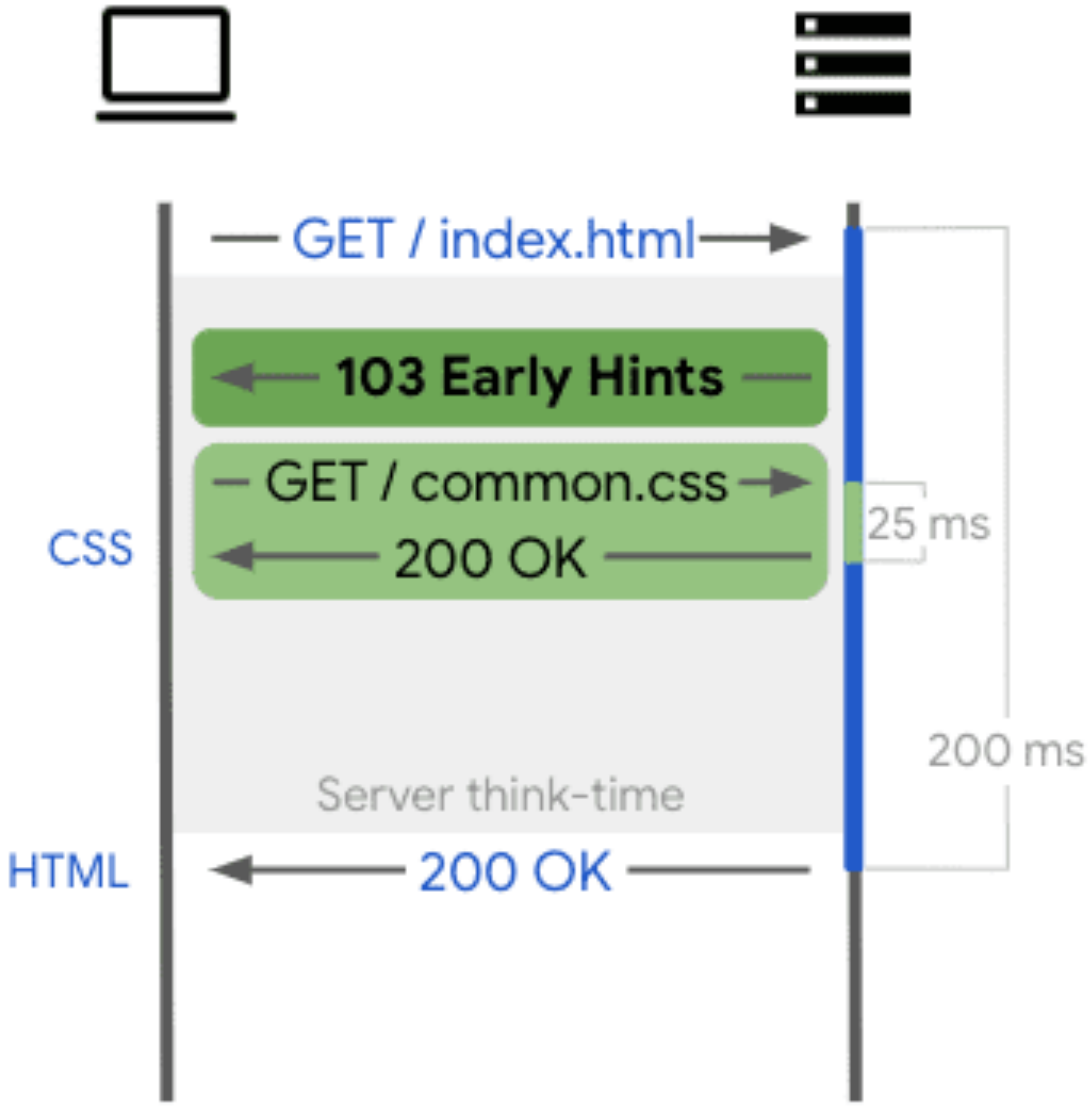
Was this helpful?

Faster page loads using server think-time with Early Hints

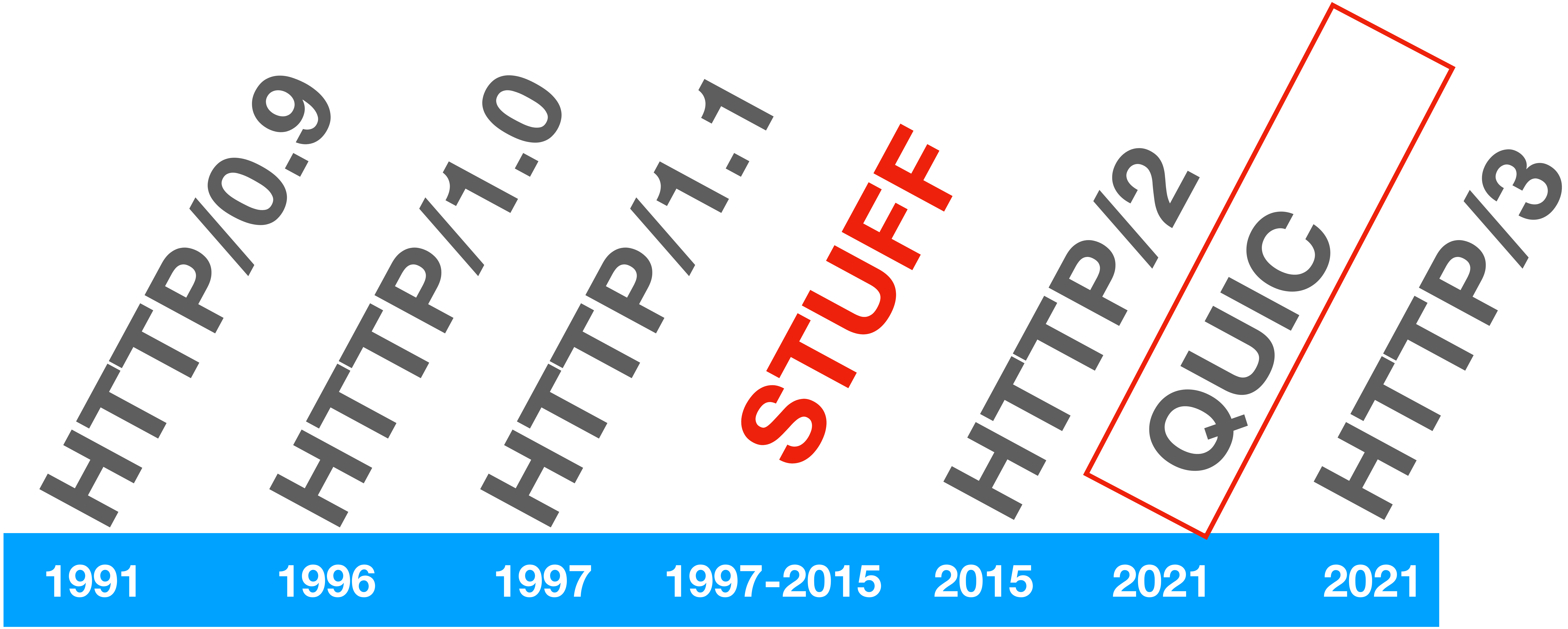
Find out how your server can send hints to the browser about critical sub-resources.

Kenji Baheux

Barry Pollard



A History of Web Protocols



HTTP/0.9 — 1991

HTTP/1.0 — 1996

HTTP/1.1 — 1997

STUFF — 1997-2015

HTTP/2 — 2015

QUIC — 2021

HTTP/3 — 2021

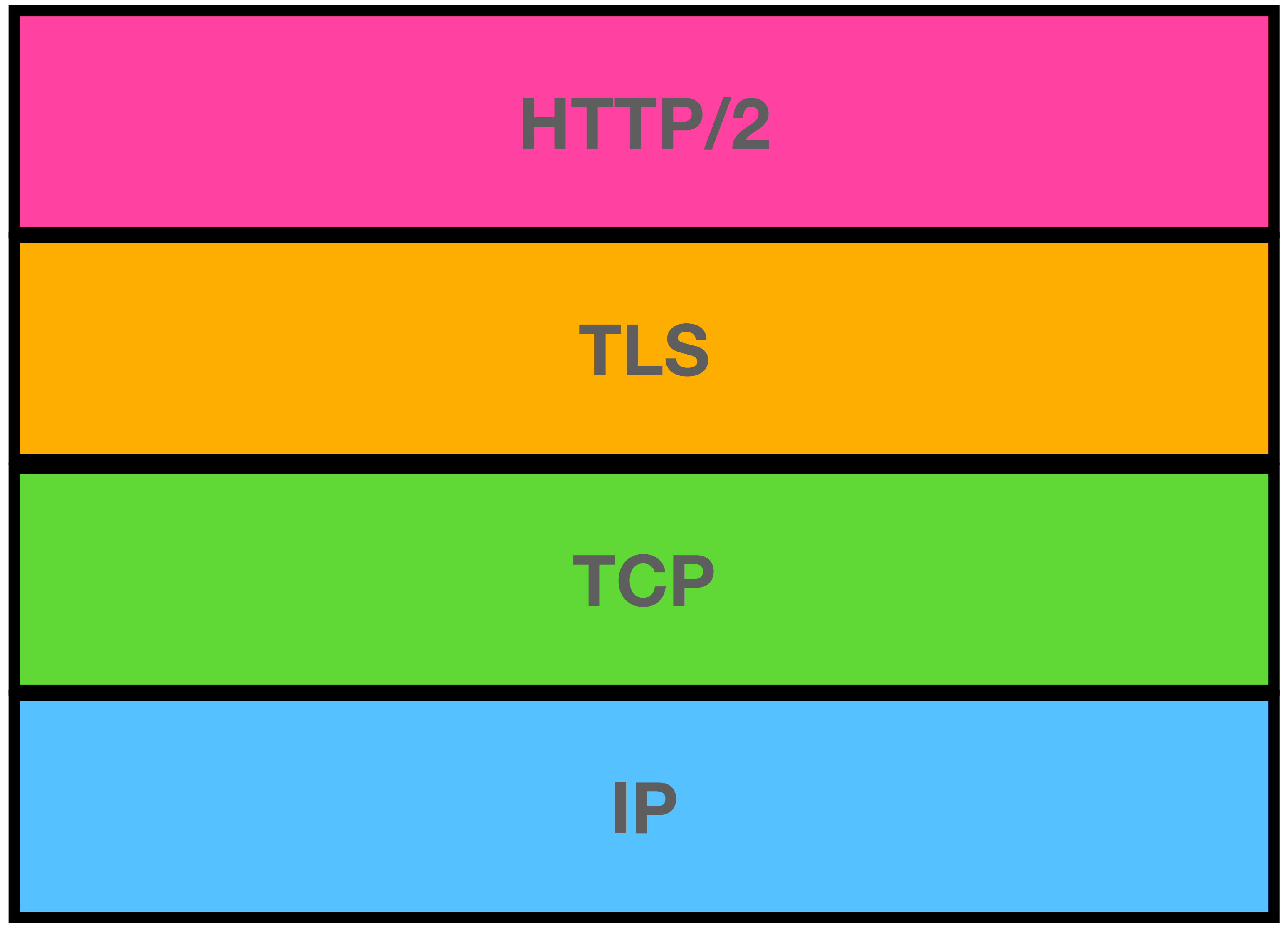
QUIC

A New Way Forward

- A core problem with HTTP (of all versions) 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?

QUIC

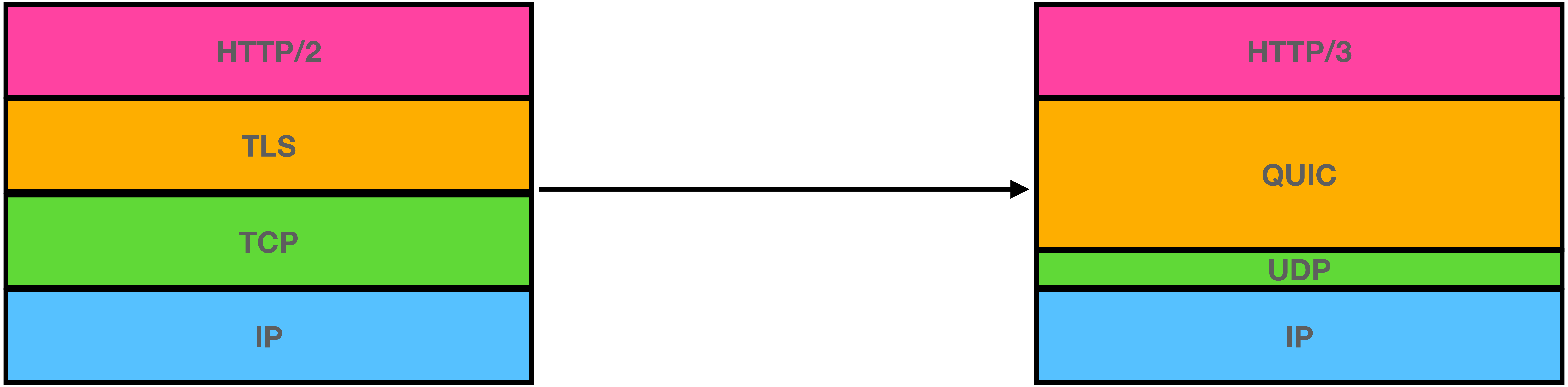
A New Transport Layer



The current world

QUIC

A New Transport Layer



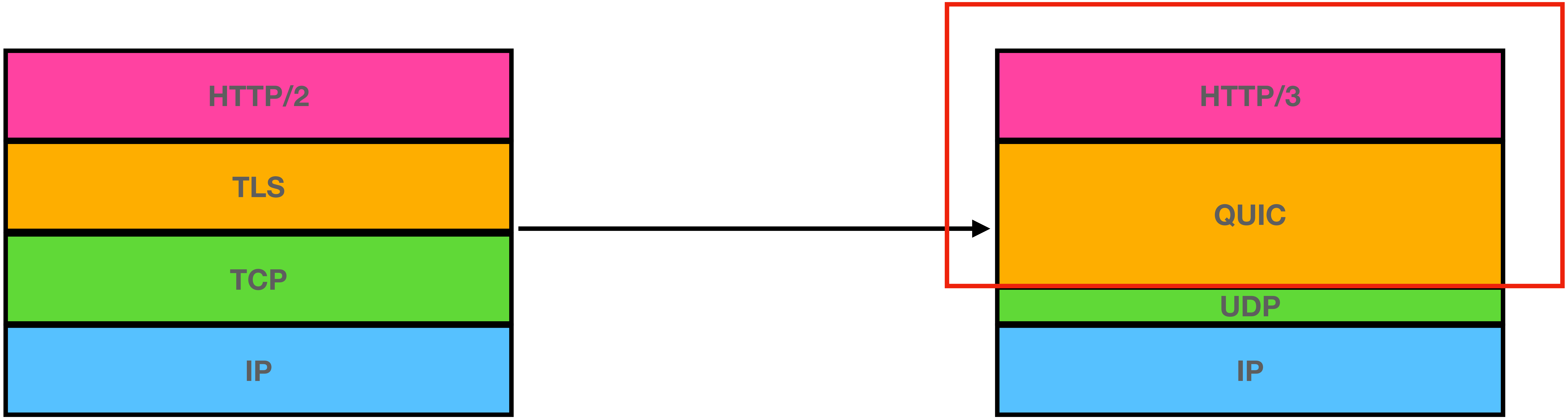
The current world

A QUICer world

QUIC

A New Transport Layer

This is all user space!!!



The current world

A QUICer world

QUIC

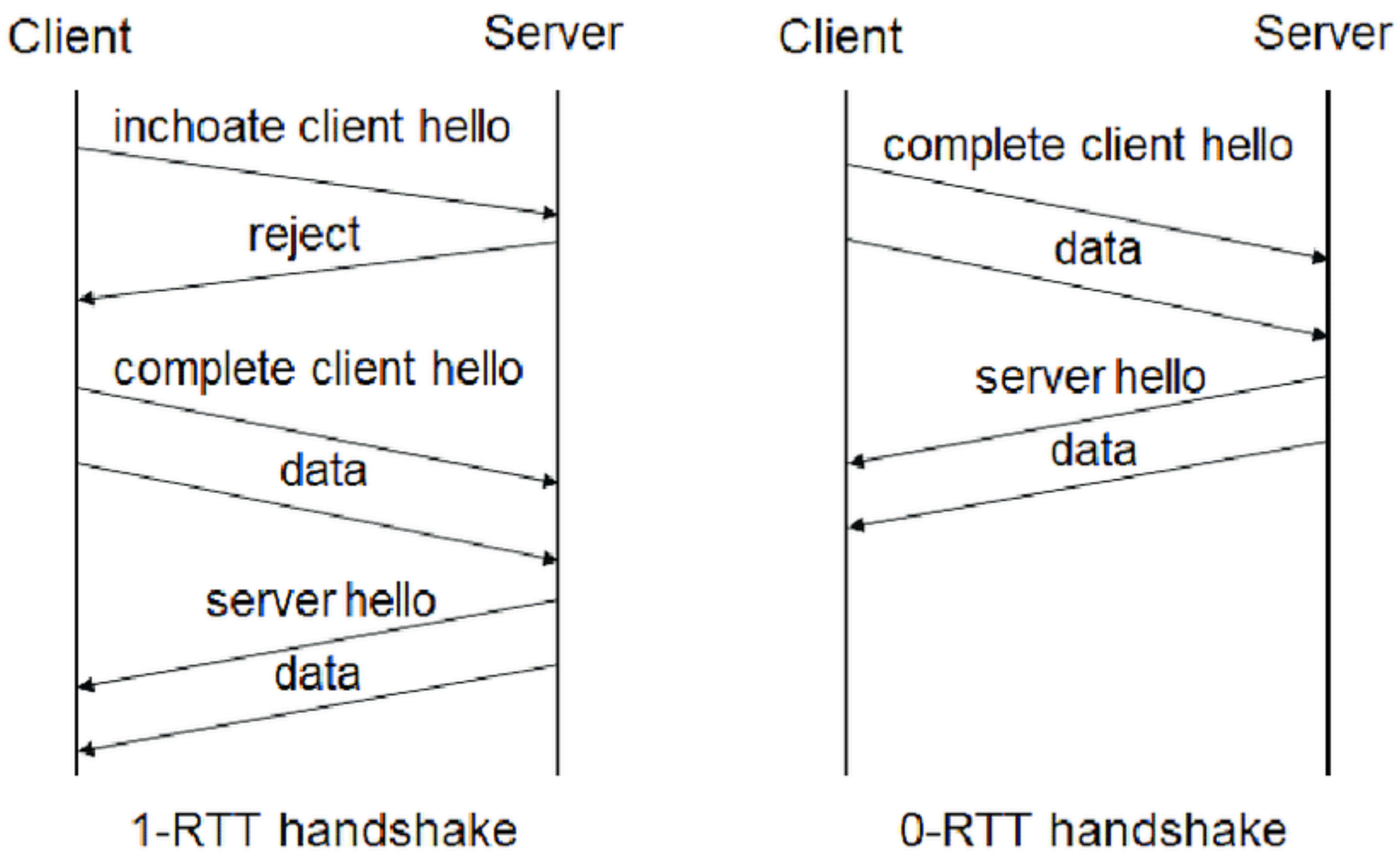
Design Goals

- 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

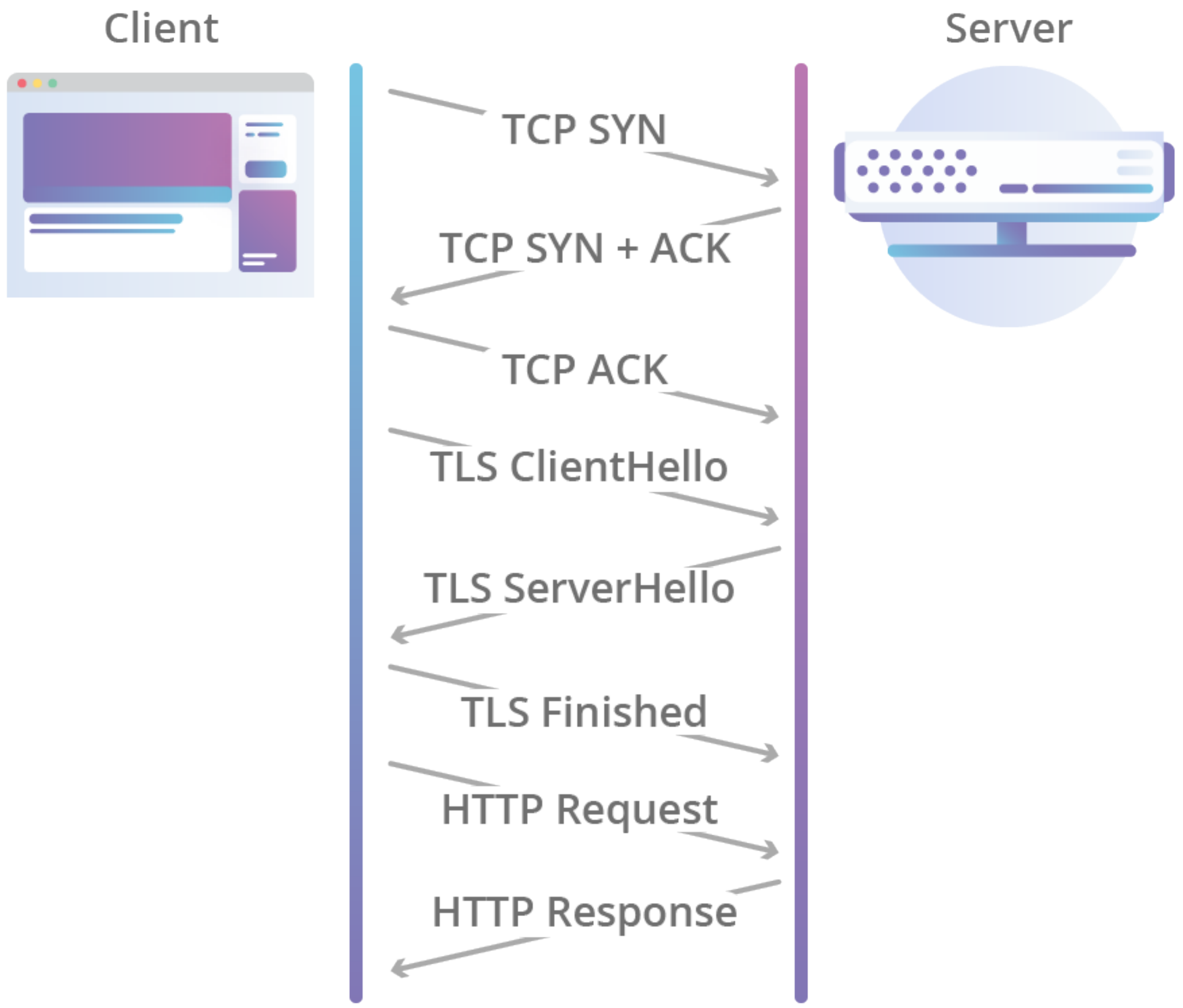
Establishing a Connection

- The first time a client wants to communicate with a server, it send 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 vs. TLS + HTTP

HTTP Request Over TCP + TLS



Client

Server

TCP SYN

TCP SYN + ACK

TCP ACK

TLS ClientHello

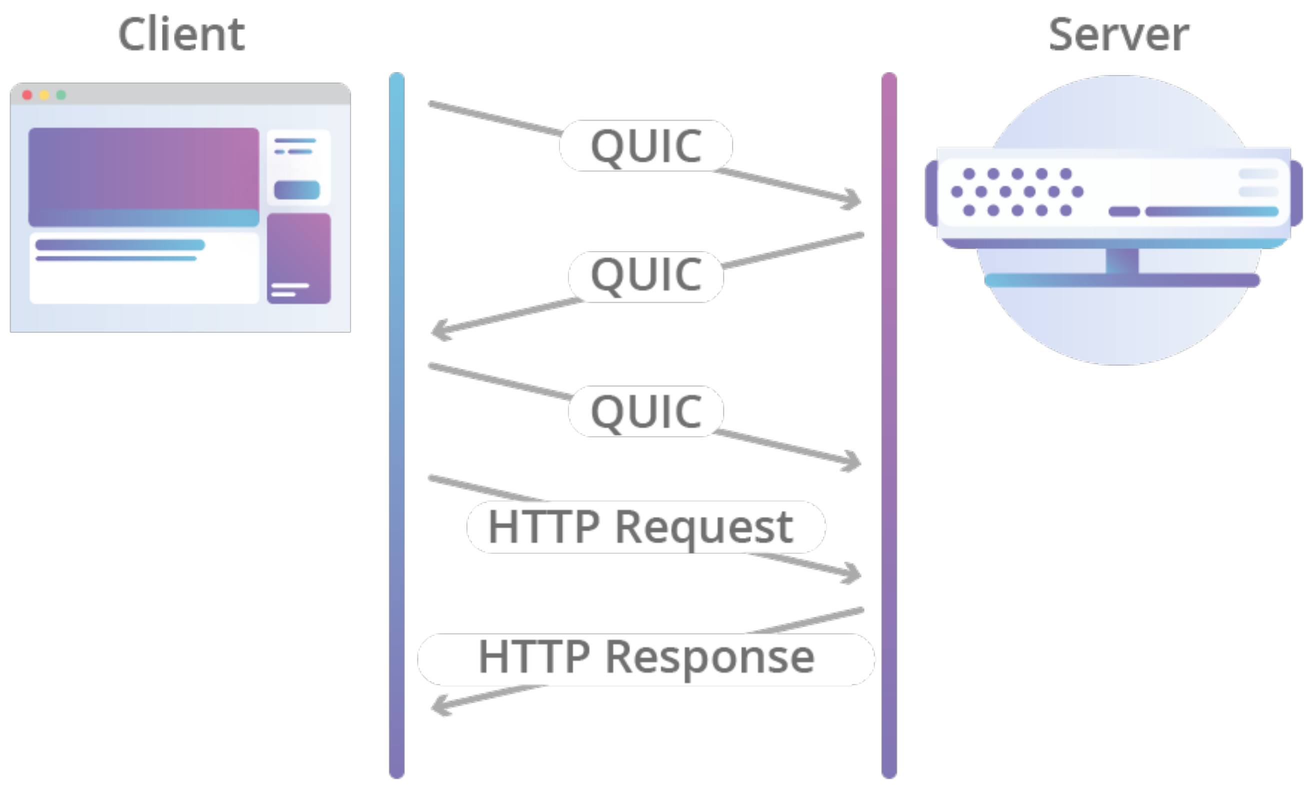
TLS ServerHello

TLS Finished

HTTP Request

HTTP Response

HTTP Request Over QUIC



Client

Server

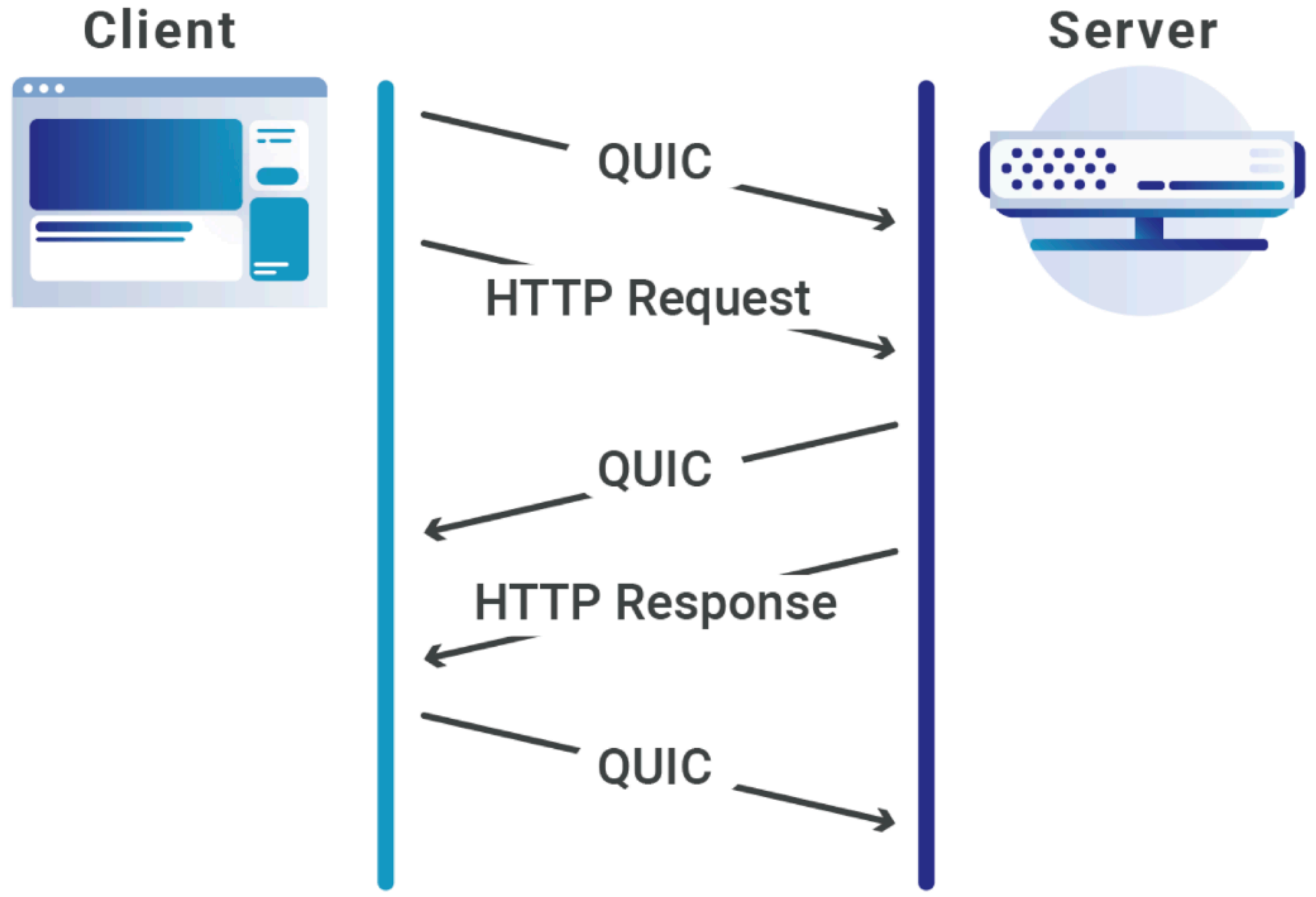
QUIC

QUIC

QUIC

HTTP Request

HTTP Response



Client

Server

QUIC

HTTP Request

QUIC

HTTP Response

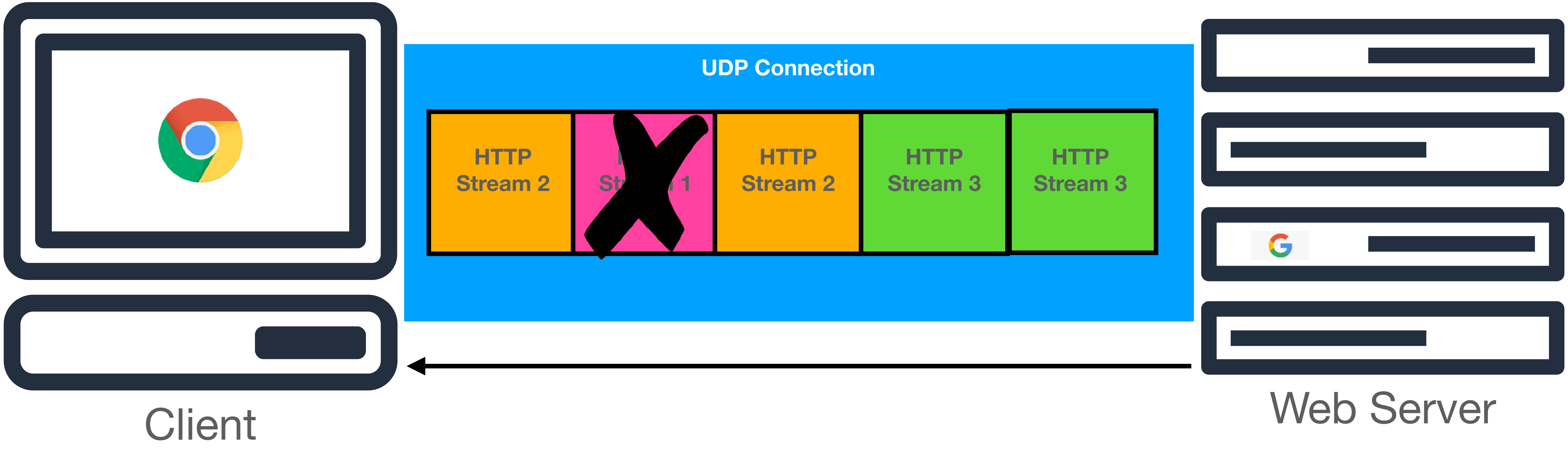
QUIC

Warning! Application data sent during 0-RTT can be captured by an on-path attacker and then replayed multiple times to the same server.

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

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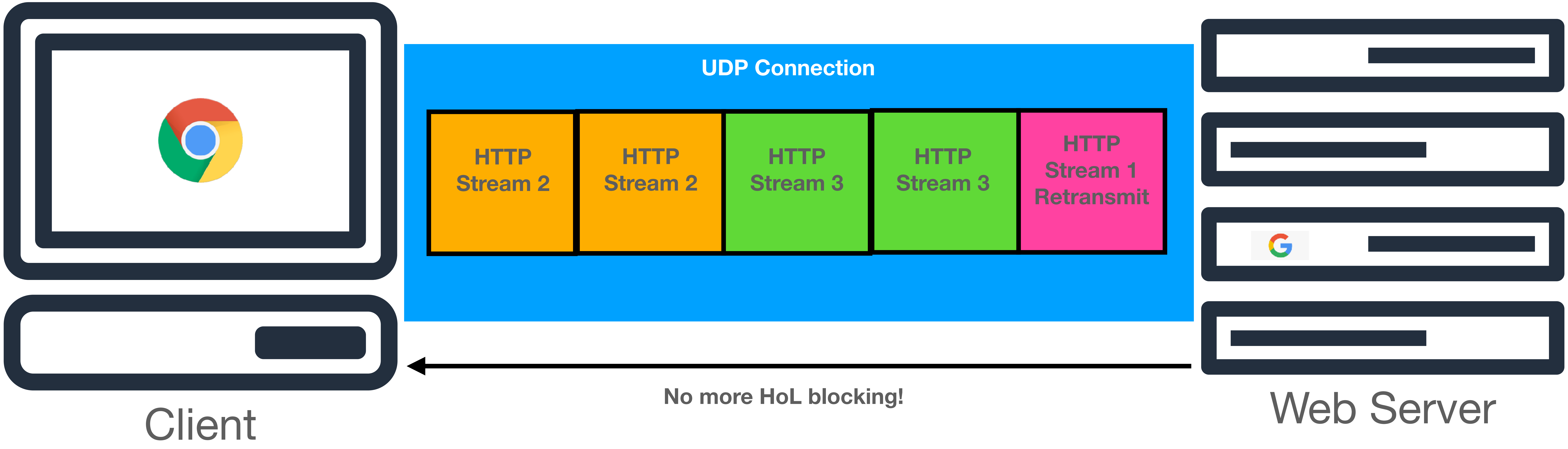
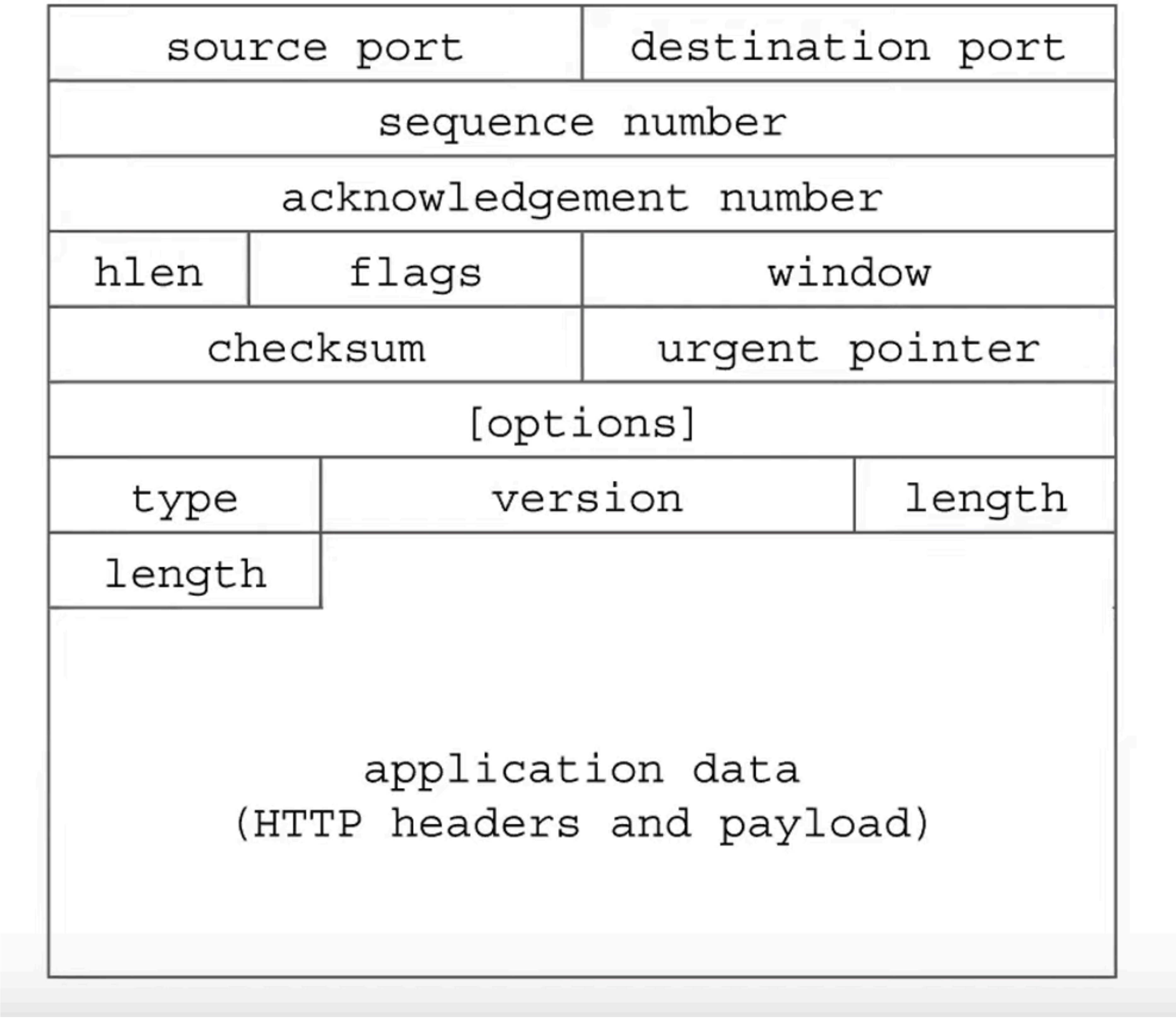


QUIC

Encrypt as much as possible

HTTP w/ TLS + TCP



source port | destination port

sequence number

acknowledgement number

hlen | flags | window

checksum | urgent pointer

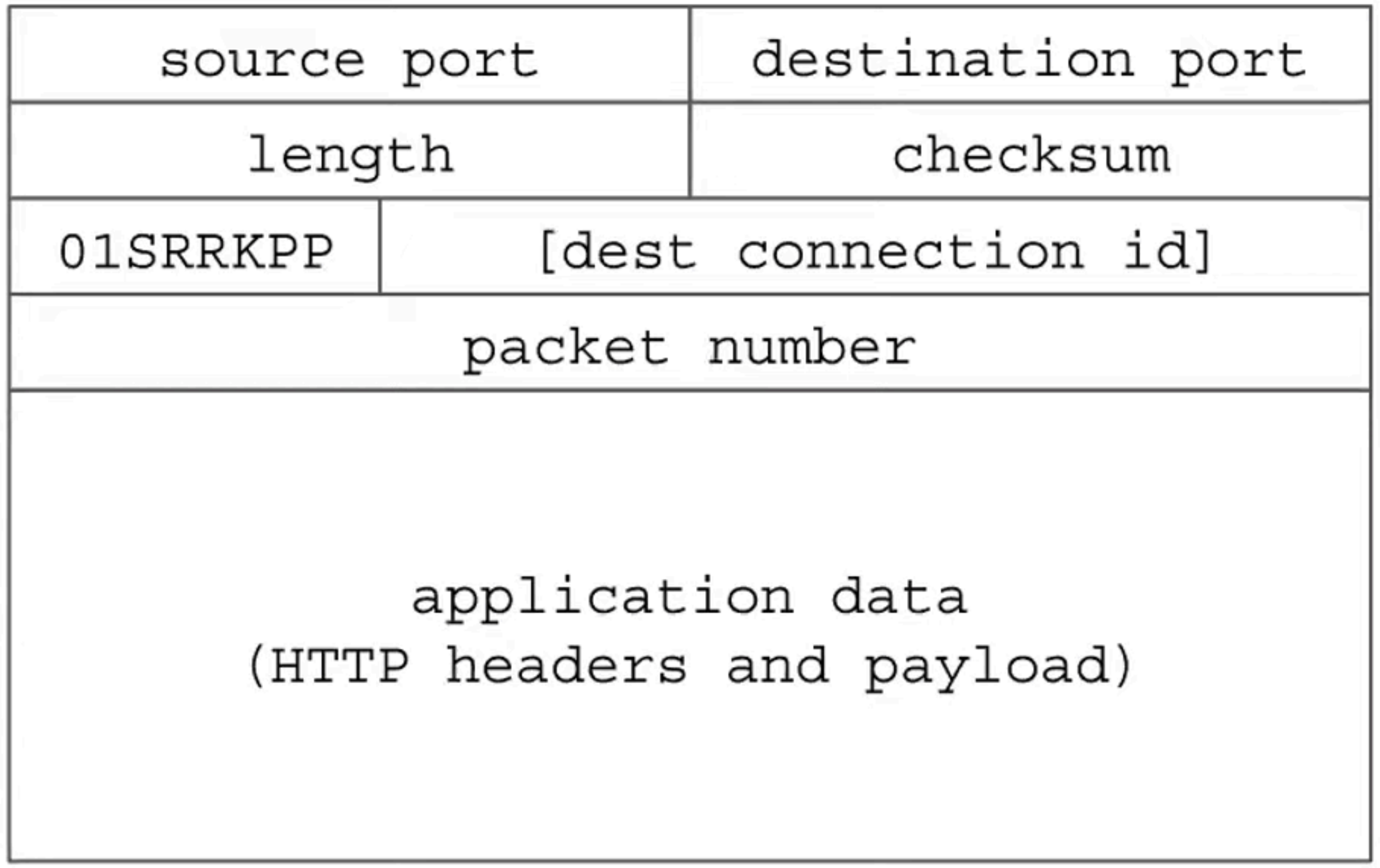
[options]

type | version | length

length

application data
(HTTP headers and payload)

HTTP w/ QUIC



source port | destination port

length | checksum

01SRRKPP | [dest connection id]

packet number

application data
(HTTP headers and payload)

Slide stolen from: https://www.youtube.com/watch?v=31J8PoLW9iM&t=9104s

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

https://tools.ietf.org/id/draft-ietf-quic-recovery-27.html

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!)

HTTP/3 is HTTP/2 over QUIC!