Web Server Design

Lecture 10 – HTTP/2 and HTTP/3

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Original slides by Michael L. Nelson

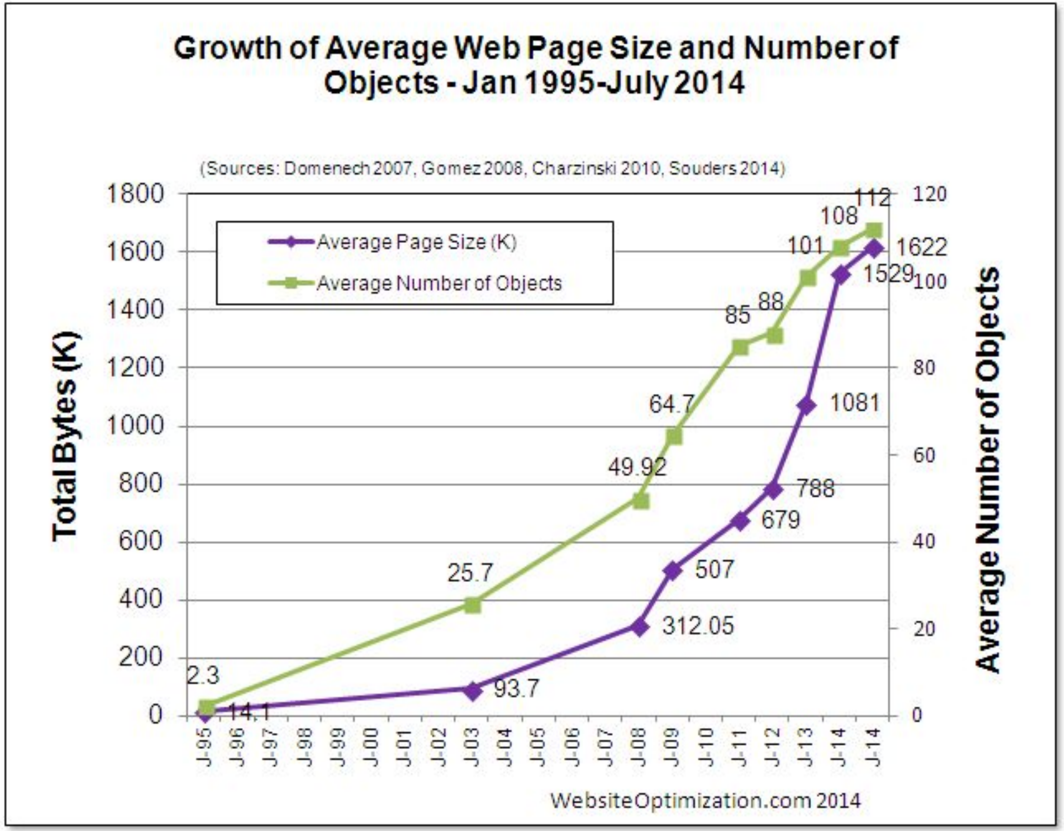
HTTP/1.1 is awesome –
you can’t argue with its deployed footprint.

But there are well-known performance limitations.

HTTP is not a good fit for TCP

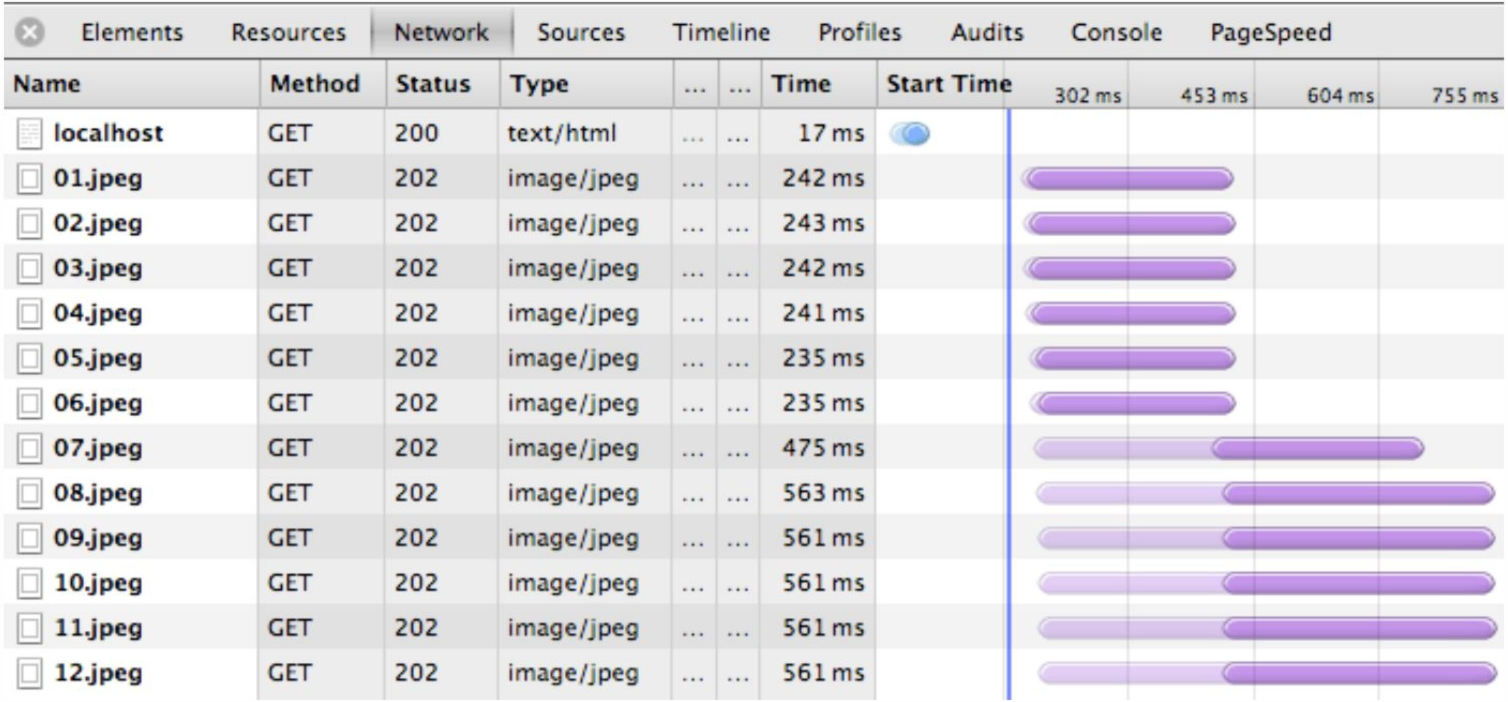
- TCP is designed for long-lived, bulk transfers
  - High-handshake costs, TLS adds even more to startup costs
  - HTTP requests are short and bursty
- Parallelism needed, but:
  - Pipelining has problems with head-of-line-blocking, recovering from failures
  - More TCP connections, more client+server resources to manage the sockets, bandwidth consumed by TCP overhead
  - In practice, browsers limit to six concurrent connections

Parallelism Is Needed Because of Page Bloat



From: https://www.webbloatscore.com/ See also: https://httparchive.org/reports/state-of-the-web

Parallelism Limits In Practice



Elements | Resources | Network | Sources | Timeline | Profiles | Audits | Console | PageSpeed

Name	Method	Status	Type	...	...	Time	Start Time	302 ms	453 ms	604 ms	755 ms
localhost	GET	200	text/html	...	...	17 ms					
01.jpeg	GET	202	image/jpeg	...	...	242 ms					
02.jpeg	GET	202	image/jpeg	...	...	243 ms					
03.jpeg	GET	202	image/jpeg	...	...	242 ms					
04.jpeg	GET	202	image/jpeg	...	...	241 ms					
05.jpeg	GET	202	image/jpeg	...	...	235 ms					
06.jpeg	GET	202	image/jpeg	...	...	235 ms					
07.jpeg	GET	202	image/jpeg	...	...	475 ms					
08.jpeg	GET	202	image/jpeg	...	...	563 ms					
09.jpeg	GET	202	image/jpeg	...	...	561 ms					
10.jpeg	GET	202	image/jpeg	...	...	561 ms					
11.jpeg	GET	202	image/jpeg	...	...	561 ms					
12.jpeg	GET	202	image/jpeg	...	...	561 ms					

Figure 11-5. Staggered resource downloads due to six-connection limit per origin

From: https://hpbn.co/http1x/

HTTP Headers: Metadata >> Data

```
$> curl --trace-ascii - -d'{"msg":"hello"}' http://www.igvita.com/api

== Info: Connected to www.igvita.com
=> Send header, 218 bytes 1
POST /api HTTP/1.1
User-Agent: curl/7.24.0 (x86_64-apple-darwin12.0) libcurl/7.24.0 ...
Host: www.igvita.com
Accept: */*
Content-Length: 15 2
Content-Type: application/x-www-form-urlencoded
=> Send data, 15 bytes (0xf)
{"msg":"hello"}

<= Recv header, 134 bytes 3
HTTP/1.1 204 No Content
Server: nginx/1.0.11
Via: HTTP/1.1 GWA
Date: Thu, 20 Sep 2012 05:41:30 GMT
Cache-Control: max-age=0, no-cache
```

1. HTTP request headers: 218 bytes
2. 15-byte application payload ({"msg":"hello"})
3. 204 response from the server: 134 bytes

Here, 15 bytes of json + 352 bytes of request and response headers

From: https://hpbn.co/http2/

HTTP/1.1 Optimizations

Image Sprites

Send one large image of all flags, use CSS to “cut out” the flag you need

From: https://daniel.haxx.se/http2/

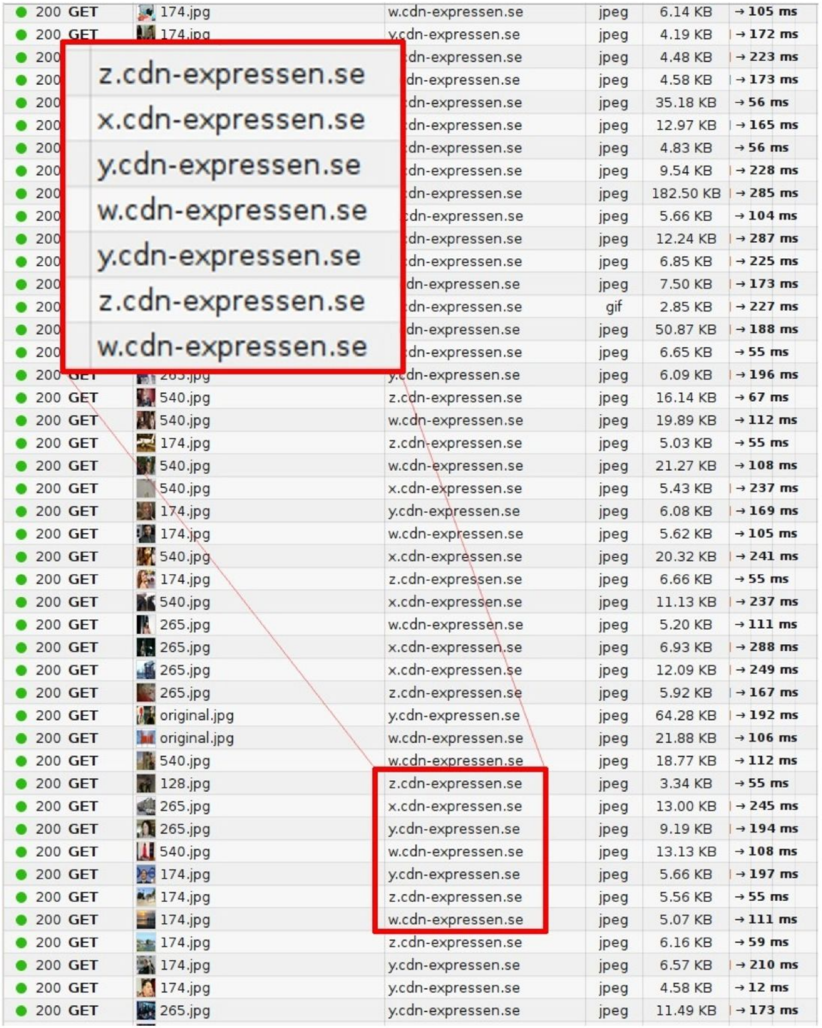
Inlining & Concatenation

- Inlining: send small images as base64

```
<img src="data:image/png;base64,iVBORw0KGgoAAA
ANSUhEUgAAAAUAAAAFCAYAAACNbyblAAAAHElEQVQI12P4
//8/w38GIAXDIBKE0DHxgljNBAAO9TXL0Y4OHwAAAABJRU
5ErkJggg==" alt="Red dot" />
```

https://en.wikipedia.org/wiki/Data_URI_scheme

- Concatenation: put all of your .js/.css files into a single, large .js/.css file
  - Probably sends more than you need
  - Small changes in one file means changes in the entire file



Domain Sharding

Six connections per domain,
But with the overhead of additional DNS lookups.

From: https://daniel.haxx.se/http2/

Evolution from SPDY to HTTP/2

- November 2009: Google begins work on SPDY to address performance limitations of HTTP/1.1
- September 2010: SPDY supported in Chrome
- January 2011: SPDY deployed for all Google services
- March 2012: Twitter supports SPDY
- March 2012: Call for proposals for HTTP/2
- June 2012: NGINX supports SPDY
- July 2012: Facebook announces planned support for SPDY
- November 2012: First draft of HTTP/2 (based on SPDY)
- August 2014: HTTP/2 draft-17 and HPACK draft-12 are published
- August 2014: Working Group last call for HTTP/2
- February 2015: IESG approved HTTP/2 and HPACK drafts
- May 2015: RFC 7540 (HTTP/2) and RFC 7541 (HPACK) are published

Collected from: https://en.wikipedia.org/wiki/SPDY, https://hpbn.co/http2/

Google Deprecates SPDY

"HTTP/2's primary changes from HTTP/1.1 focus on improved performance. Some key features such as multiplexing, header compression, prioritization and protocol negotiation evolved from work done in an earlier open, but non-standard protocol named SPDY. Chrome has supported SPDY since Chrome 6, but since most of the benefits are present in HTTP/2, it's time to say goodbye. We plan to remove support for SPDY in early 2016, and to also remove support for the TLS extension named NPN in favor of ALPN in Chrome at the same time. Server developers are strongly encouraged to move to HTTP/2 and ALPN.

We're happy to have contributed to the open standards process that led to HTTP/2, and hope to see wide adoption given the broad industry engagement on standardization and implementation."

Quoted in: https://hpbn.co/http2/ Original: https://blog.chromium.org/2015/02/hello-http2-goodbye-spdy.html

High-level semantics of HTTP
don’t change in HTTP/2,
but the method of packaging and transport do.

Binary Framing Layer

No more hand-crafted telnet sessions – boo!!!!!

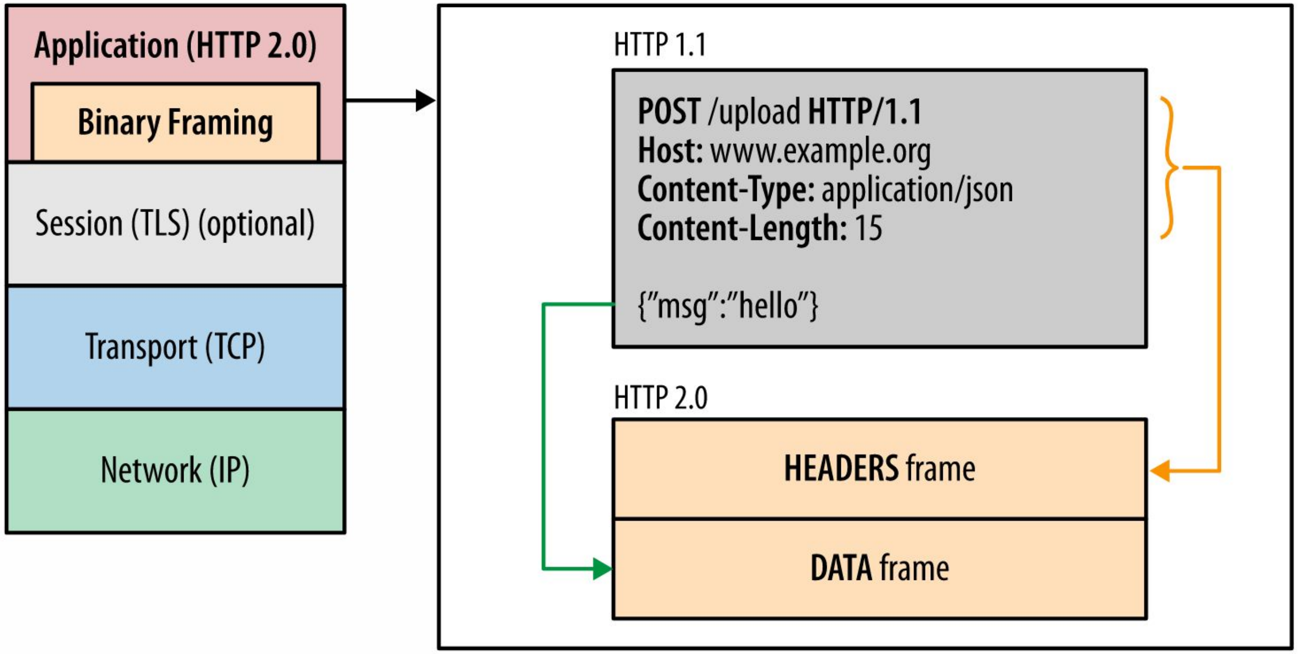


Figure 12-1. HTTP/2 binary framing layer

From: https://hpbn.co/http2/

Streams, Messages, Frames

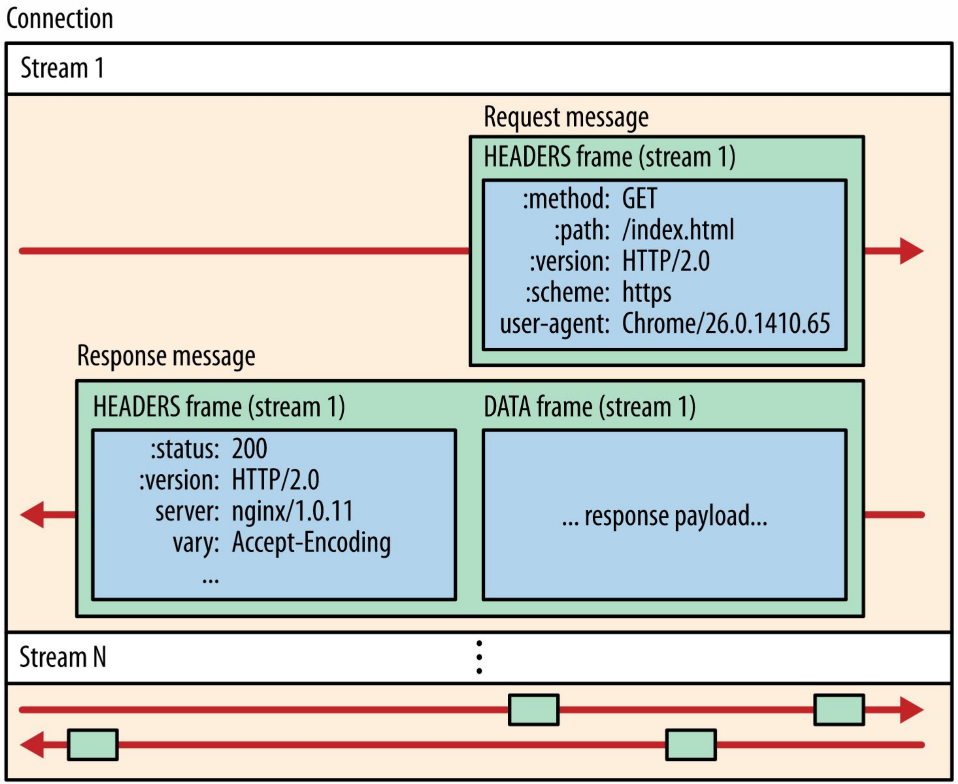


Figure 12-2. HTTP/2 streams, messages, and frames

Stream: bi-directional connection, with 1 or more messages

Message: logically complete request or response

Frame: typed, atomic unit of communication

From: https://hpbn.co/http2/

Request & Response Multiplexing

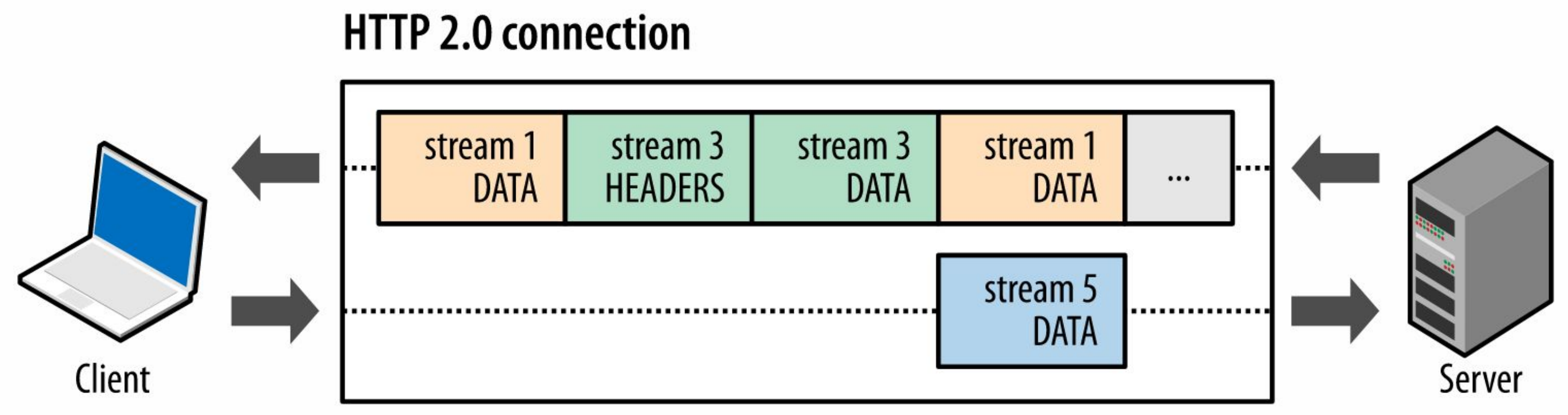


Figure 12-3. HTTP/2 request and response multiplexing within a shared connection

- Interleave multiple requests in parallel without blocking on any one
- Interleave multiple responses in parallel without blocking on any one
- Use a single connection to deliver multiple requests and responses in parallel
- Remove unnecessary HTTP/1.x workarounds (such as concatenated files, image sprites, and domain sharding)
- Deliver lower page load times by eliminating unnecessary latency and improving utilization of available network capacity

Note: frames cannot be received out of order!

From: https://hpbn.co/http2/

Stream Dependencies & Weights

A gets ¾ of bandwidth, B gets ¼
A & B are dependent on the "root" stream (i.e., no dependencies)

C depends on D, service D first (weights trumped by dependency)

D before C, C before A & B, weight A & B as before

D before C, C & E equally Before A & B, weight A & B as before

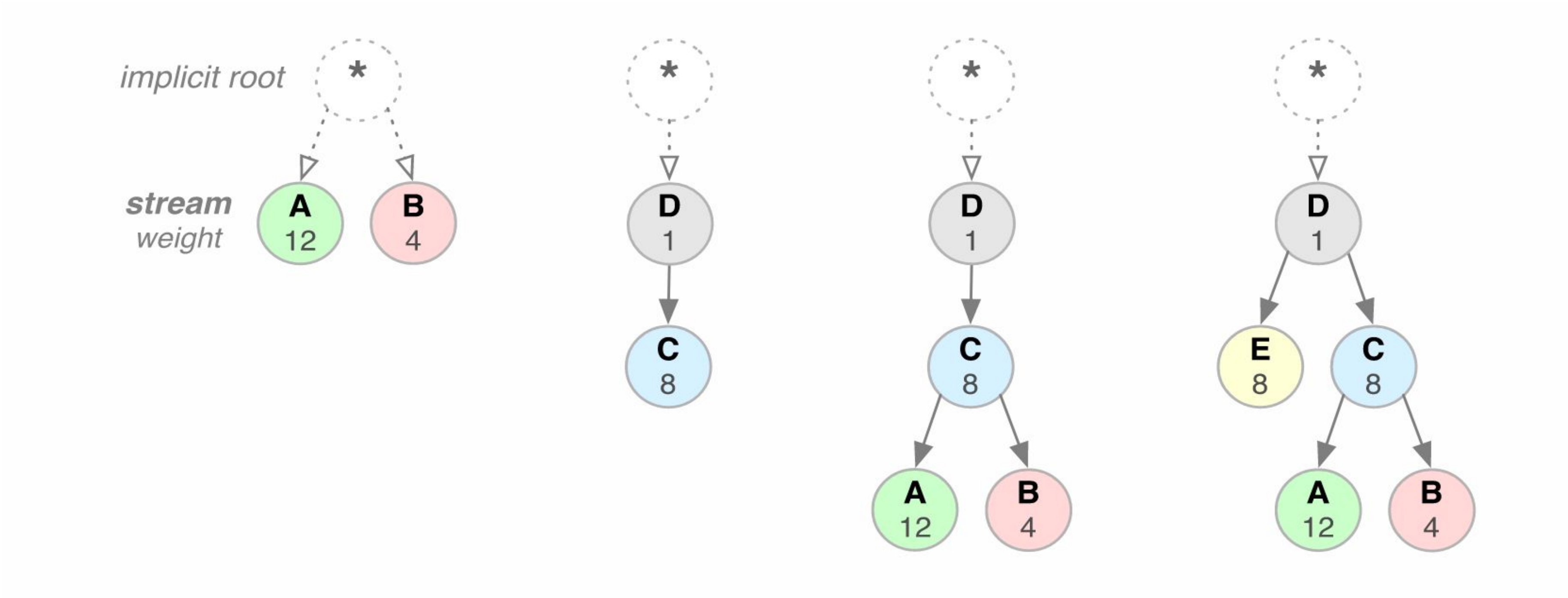


Figure 12-4. HTTP/2 stream dependencies and weights

From: https://hpbn.co/http2/

Server Push: 1 Request, N Responses

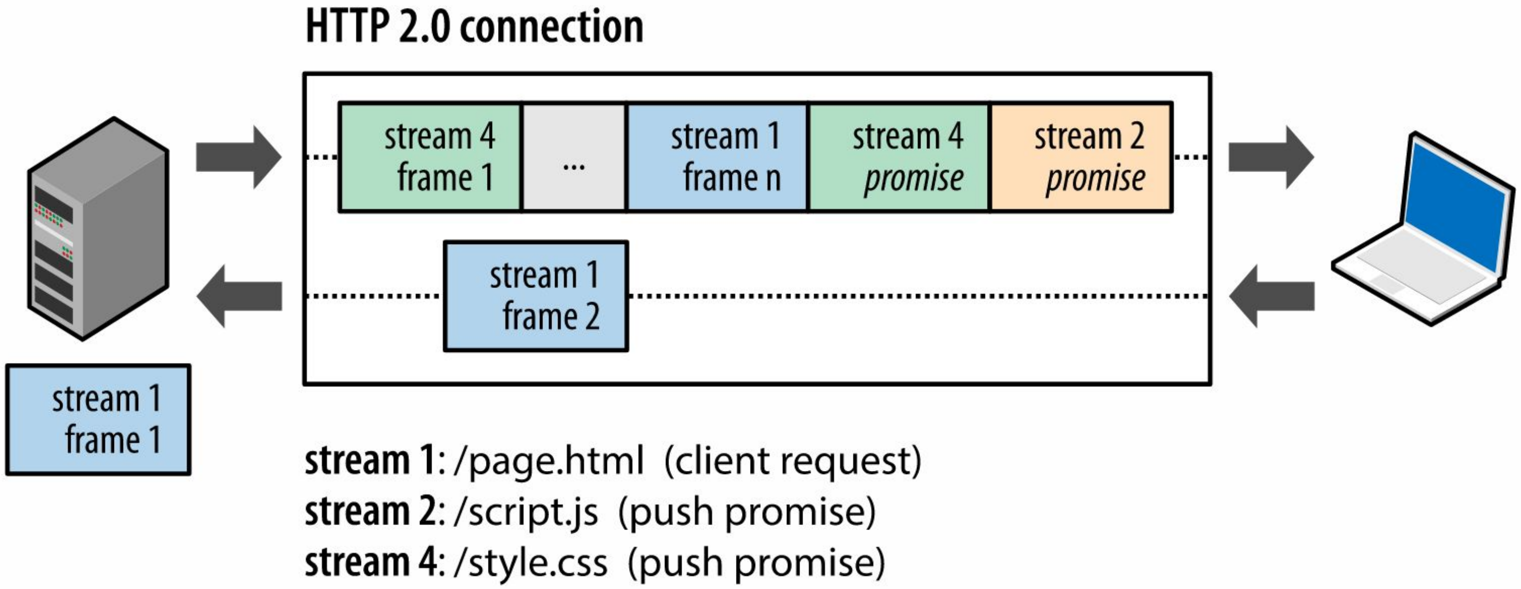


Figure 12-5. Server initiates new streams (promises) for push resources

See discussion of HTTP/2 push in:
https://daniel.haxx.se/blog/2018/11/11/http-3/

Conceptually similar to inlining, rel="preload", rel="prefetch", etc.
Can only push with same-origin policy.

From: https://hpbn.co/http2/

Header Repetitiveness Allows Compression

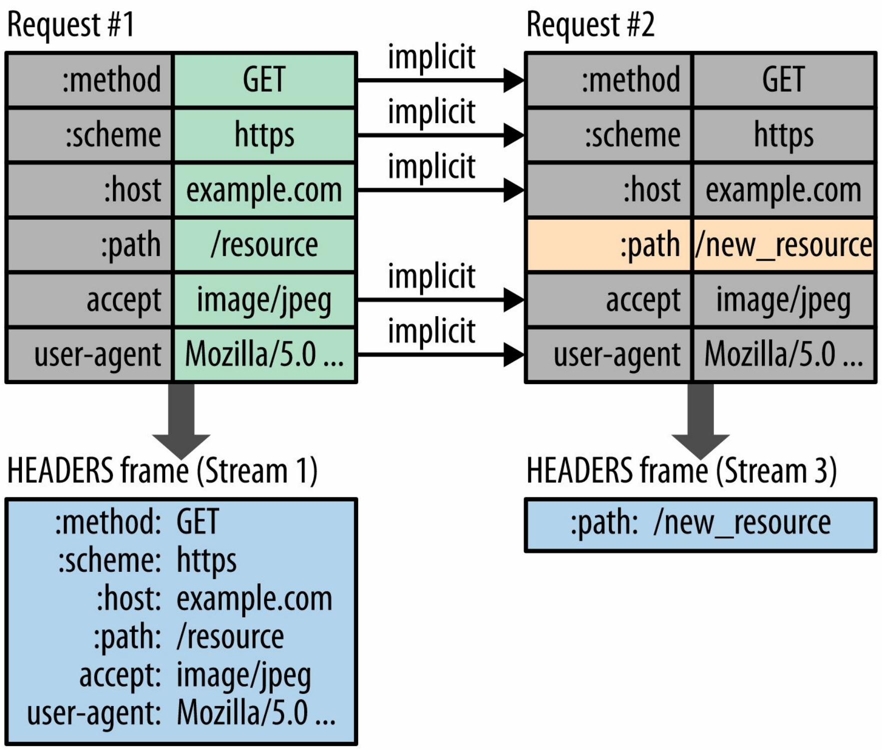


Figure 12-6. HPACK: Header Compression for HTTP/2

Note: headers beginning with ":" are "pseudo-headers" (RFC 7540, 8.1.2.1); or "things-that-should-have-been-headers-in-HTTP/1.1"
Pseudo-headers have to be listed before real headers.

From: https://hpbn.co/http2/

HTTP/1.1 □ HTTP/2 Upgrade

```
GET /page HTTP/1.1
Host: server.example.com
Connection: Upgrade, HTTP2-Settings
Upgrade: h2c (1)
HTTP2-Settings: (SETTINGS payload) (2)

HTTP/1.1 200 OK (3)
Content-length: 243
Content-type: text/html

(... HTTP/1.1 response ...)

          (or)

HTTP/1.1 101 Switching Protocols (4)
Connection: Upgrade
Upgrade: h2c

(... HTTP/2 response ...)
```

1. Initial HTTP/1.1 request with HTTP/2 upgrade header
2. Base64 URL encoding of HTTP/2 SETTINGS payload
3. Server declines upgrade, returns response via HTTP/1.1
4. Server accepts HTTP/2 upgrade, switches to new framing

Note:
"h2" = HTTP/2 over TLS
"h2c" = HTTP/2 over clear text TCP

From: https://hpbn.co/http2/

9 Byte Frame Header

Bit	+0..7	+8..15	+16..23	+24..31
0	Length			Type
32	Flags			
40	R	Stream Identifier		
...	Frame Payload			

Figure 12-7. Common 9-byte frame header

Note: frames cannot be received out of order! Stream id, but not frame id.

Note

Technically, the `Length` field allows payloads of up to 2^{24} bytes (~16MB) per frame. However, the HTTP/2 standard sets the default maximum payload size of DATA frames to 2^{14} bytes (~16KB) per frame and allows the client and server to negotiate the higher value. Bigger is not always better: smaller frame size enables efficient multiplexing and minimizes head-of-line blocking.

From: https://hpbn.co/http2/

Header Types:

- DATA - Used to transport HTTP message bodies
- HEADERS - Used to communicate header fields for a stream
- PRIORITY - Used to communicate sender-advised priority of a stream
- RST_STREAM - Used to signal termination of a stream
- SETTINGS - Used to communicate configuration parameters for the connection
- PUSH_PROMISE - Used to signal a promise to serve the referenced resource
- PING - Used to measure the roundtrip time and perform "liveness" checks
- GOAWAY - Used to inform the peer to stop creating streams for current connection
- WINDOW_UPDATE - Used to implement flow stream and connection flow control
- CONTINUATION - Used to continue a sequence of header block fragments

Example Binary HTTP/2 Request

```
▼ HyperText Transfer Protocol 2
  ▼ Stream: HEADERS, Stream ID: 1, Length 20
      Length: 20
      Type: HEADERS (1)
    ▼ Flags: 0x05
        .... ...1 = End Stream: True
        .... .1.. = End Headers: True
        .... 0... = Padded: False
        ..0. .... = Priority: False
        00.0 ..0. = Unused: 0x00
      0... .... .... .... .... .... .... .... = Reserved: 0x00000000
      .000 0000 0000 0000 0000 0000 0000 0001 = Stream Identifier: 1
      [Pad Length: 0]
      Header Block Fragment: 8682418aa0e41d139d09b8f01e078453032a2f2a
      [Header Length: 100]
    ▶ Header: :scheme: http
    ▶ Header: :method: GET
    ▶ Header: :authority: localhost:8080
    ▶ Header: :path: /
    ▼ Header: accept: */*
        Name Length: 6
        Name: accept
        Value Length: 3
        Value: */*
        Representation: Literal Header Field with Incremental Indexing - Indexed Name
        Index: 19
```

common frame header

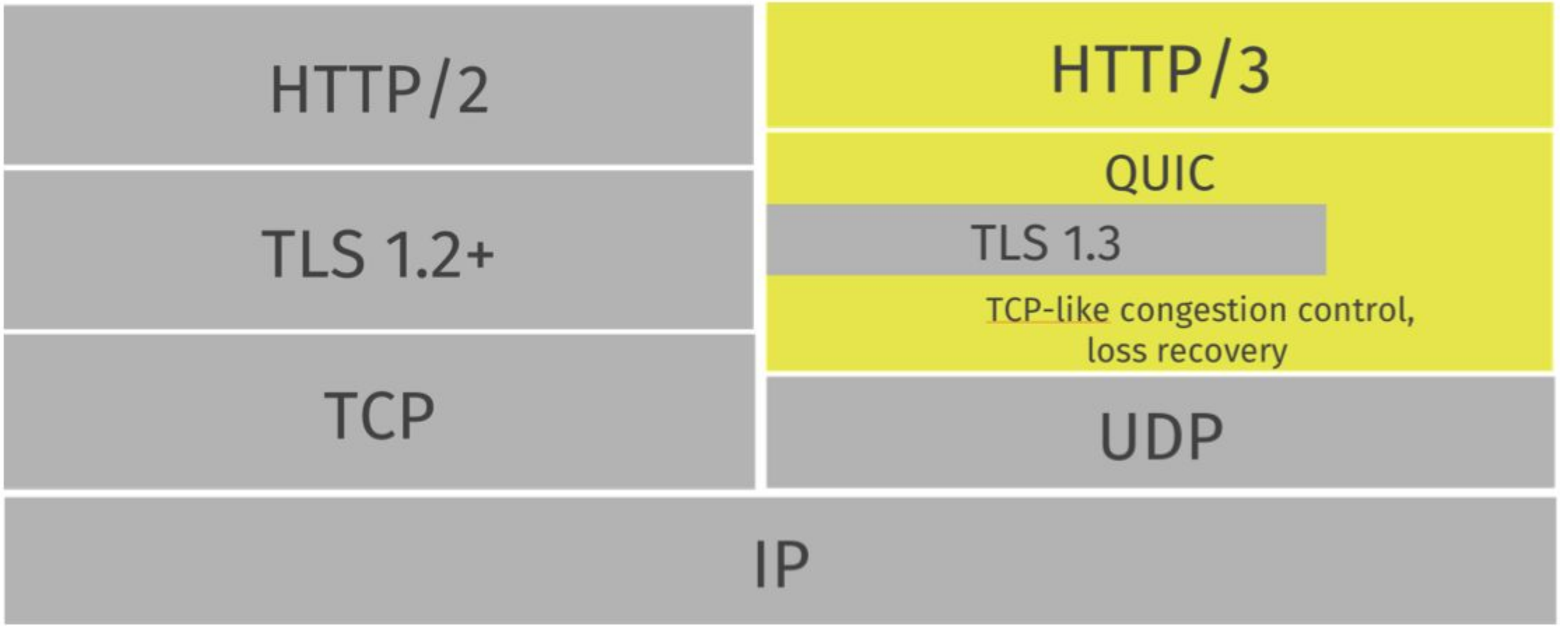
HPACK encoded headers

Figure 12-8. Decoded HEADERS frame in Wireshark

From: https://hpbn.co/http2/

HTTP/3 Network Stack

HTTP/2 optimizes within TCP context (e.g., binary, streams & frames), HTTP/3 *replaces* TCP



From: https://daniel.haxx.se/blog/2018/11/26/http3-explained/

HTTP/3

- "HTTP-over-QUIC" was renamed to "HTTP/3" (Nov 2018)
  - https://daniel.haxx.se/blog/2018/11/11/http-3/
- HTTP/3 became Standard Track RFC in June 2022
  - https://datatracker.ietf.org/doc/html/rfc9114
  - Deployment is growing gradually
- Major changes:
  - Streams are moved from the HTTP layer to the QUIC layer
    - HTTP/2 fixes HTTP head-of-line blocking, but not TCP head-of-line blocking (i.e., streams in TCP can still be held up by dropped TCP packets)
  - Since streams are independent, header compression changes
  - There is no clear-text version of HTTP/3 (integral TLS 1.3)
  - QUIC has faster handshakes than TCP + TLS

https://http3-explained.haxx.se/