Middleware Architectures 1
Lecture 4: HTTP/2

doc. Ing. Tomáš Vitvar, Ph.D.
tomas@vitvar.com • @TomasVitvar • https://vitvar.com

Czech Technical University in Prague
Faculty of Information Technologies • Software and Web Engineering • https://vitvar.com/lectures

Modified: Sun Oct 30 2022, 21:06:34
Humla v1.0

Overview

- Introduction
- HTTP/2
- HTTP/3

Overview

- Developed from SPDY (2009) experimental protocol by Google
  - *May 2015: RFC 7540 (HTTP/2) and RFC 7541 (HPACK)*
  - *HTTP/2 standards extend (not replace) the previous HTTP standards*
- HTTP/1.x limitations
  - *HTTP/1.x clients need to use multiple connections to achieve concurrency*
  - *unnecessary network traffic – request and response headers not compressed*
  - *no effective resource prioritization*
- Primary goals
  - *Reduction of latency*
  - *enabling full request and response multiplexing*
  - *minimize protocol overhead via efficient compression of HTTP header fields*
  - *support for request prioritization and server push*
- HTTP/2 does not modify application semantics of HTTP
  - *HTTP metods, URIs, header fields are the same*
  - *HTTP/2 modifies **how data is formatted and transported** in communication*
- Literature and source
  - *I. Grigorik: High Performance Browser Networking, O'Reilly Media, Inc. 2013. ISBN: 9781449344757*

Establishing a HTTP/2 Connection

- Negotiating HTTP/2 via a secure connection with TLS and ALPN
  - *Client sends a protocol (HTTP/2) in a TLS `ClientHello` message.*
- Upgrading a plaintext connection to HTTP/2 without prior knowledge
  - *Client starts HTTP/1.1 and then sends an upgrade request*

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

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

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

          (or)

HTTP/1.1 101 Switching Protocols
Connection: Upgrade
Upgrade: h2c

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

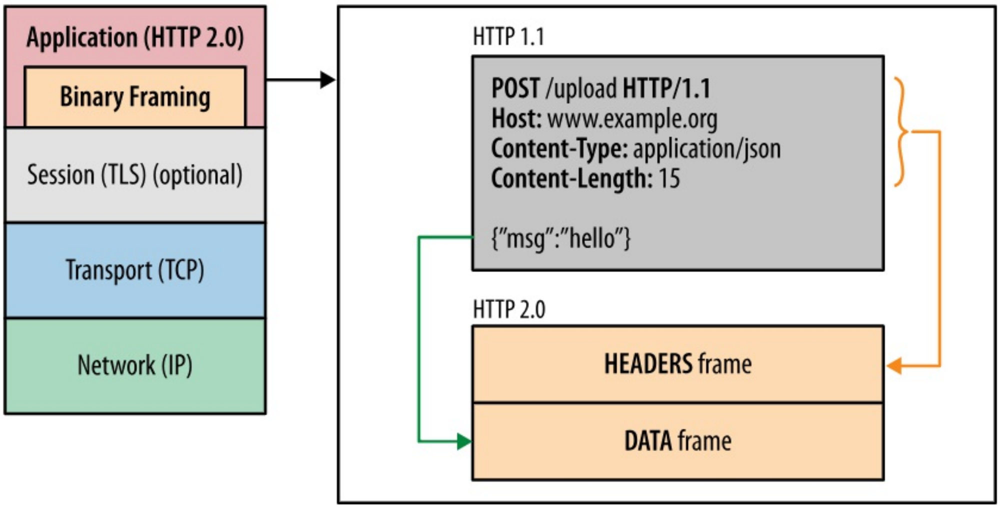
- Initiating a plaintext HTTP/2 connection with prior knowledge
  - *Client gets information about server's HTTP/2 via DNS or manual configuration.*
  - *Client initiates HTTP/2 and if it does not work, it falls back to HTTP/1.1*

Overview

- Introduction
- HTTP/2
  - *Binary Framing*
  - *Stream Prioritization*
  - *Flow Control*
  - *Server Push*
  - *Header Compression*
  - *HTTP/2 Analysis*
- HTTP/3

Binary Framing Layer

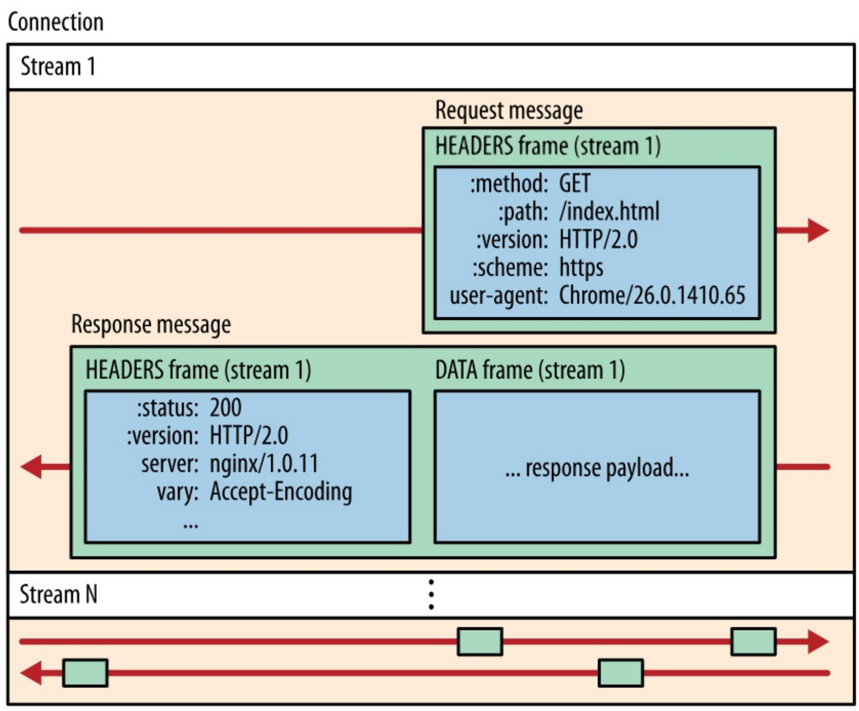
- Binary framing layer
  - *defines how HTTP messages are encapsulated and transferred*
  - *communication is split into messages and frames in binary format*



HTTP/2 Communication

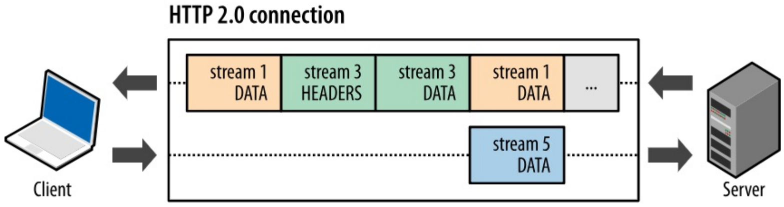
- Data exchange between the client and server
  - *break down of the communication into frames*
  - *frames are mapped to messages that belong to a particular stream*
  - *communication is* ***multiplexed within a single TCP connection****.*
- Stream
  - *bi-directional flow of bytes in a connection*
  - *may carry one or more messages*
  - *may have a priority*
- Message
  - *a sequence of frames*
  - *it maps to logical request or response message*
- Frame
  - *the smallest unit of communication*
  - *each has a frame header which identifies a stream to which it belongs.*

Streams, Messages, and Frames



Request and Response Multiplexing

- Parallel requests
  - *HTTP/1.x can use HTTP pipelining; they open multiple connections*
    - → *browser typically opens up six connections*
    - → *One response can be delivered at a time (response queuing) per connection*
      - → *Head of line blocking problem*
  - *HTTP/2 allows full request and response multiplexing*
    - → *Allows for parallel in-flight streams*
    - → *There are 3 parallel streams in the below example:*



- Performance benefits
  - *Interleave requests/responses in parallel without blocking any one.*
  - *Deliver lower page load times by eliminating unnecessary latency*
  - *Improve utilization of available network capacity*

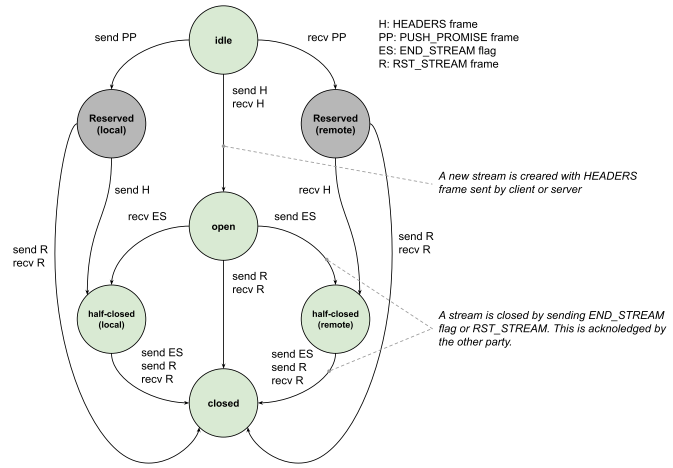
Binary Framing – Frame Header

- 9-byte frame header

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

- Fields
  - `length` – *24 bits, allows a frame to carry* 2^{24} *bytes of data.*
  - `type` – *8 bits, determines the format and semantics of the frame.*
    - → *Frame types:* `DATA`, `HEADERS`, `PRIORITY`, `RST_STREAM`, `SETTINGS`, `PUSH_PROMISE`, `PING`, `GOAWAY`, `WINDOW_UPDATE`, `CONTINUATION`
  - `flags` – *8 bits, defines frame-type specific boolean flags.*
  - `stream identifier` – *31 bits, uniquely identifies the HTTP/2 stream.*

Stream Lifecycle



- HTTP/2 doesn't reuse the same stream IDs
  – *A stream's lifecycle corresponds to request/response messages interaction.*
- A new id is assigned until it reaches `2`^{31}
  – *When the last id is used, the browser sends* `GOAWAY` *frame to initialize a new TCP connection, and the stream ID is reset.*

Initiating a New Stream

```
▼ 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

  – *New stream created with request metadata*
  – *HEADERS and DATA frames sent separately*

Sending Application Data

```
▼ HyperText Transfer Protocol 2
  ▼ Stream: DATA, Stream ID: 1, Length 5
      Length: 5
      Type: DATA (0)
    ▼ Flags: 0x00
        .... ...0 = End Stream: False
        .... 0... = Padded: False
        0000 .00. = Unused: 0x00
      0... .... .... .... .... .... .... .... = Reserved: 0x00000000
      .000 0000 0000 0000 0000 0000 0000 0001 = Stream Identifier: 1
      [Pad Length: 0]
      Data: 48656c6c6f

0000  02 00 00 00 45 00 00 42  89 06 40 00 40 06 00 00   ....E..B ..@.@...
0010  7f 00 00 01 7f 00 00 01  1f 90 d8 eb 8a 94 78 19   ........ ......x.
0020  7d b6 67 50 80 18 23 dd  fe 36 00 00 01 01 08 0a   }.gP..#. .6......
0030  6a 78 1f ec 6a 78 1f ec  00 00 05 00 00 00 00 00   jx..jx.. ........
0040  01 48 65 6c 6c 6f                                  .Hello
```

– *App data sent in DATA frame*
– *There are more frames that carry the data (i.e.* `END_STREAM` *flag is not set)*
  → *The small frame size allows for efficient multiplexing*
– *The app data is loaded by application according to the used encoding mechanism (plain text, gzip, etc.).*

Request and Response Multiplexing Benefits

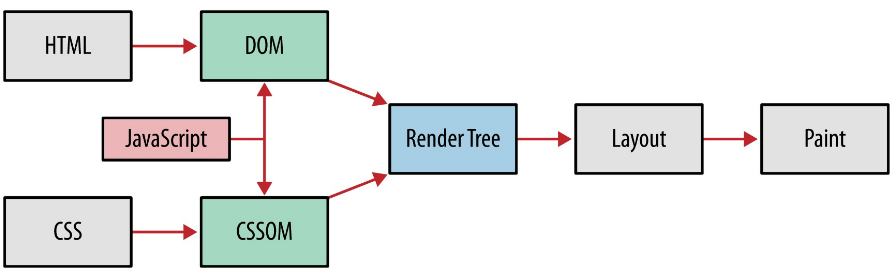
- Interleave multiple requests and responses
  – *Requests or responses are not blocked on any other requests or response*
- A single TCP connection
  – *Multiple requests and responses can be delivered in parallel*
- Remove HTTP/1.x workarounds
  – *Concatenated files*
  – *Image sprites*
  – *Domain sharding*
- Deliver lower page load times
  – *Eliminates unnecessary latency*
  – *Improves utilization of available newtork capacity*

Overview

- Introduction
- HTTP/2
  – *Binary Framing*
  – *Stream Prioritization*
  – *Flow Control*
  – *Server Push*
  – *Header Compression*
  – *HTTP/2 Analysis*
- HTTP/3

Browser Request Prioritization

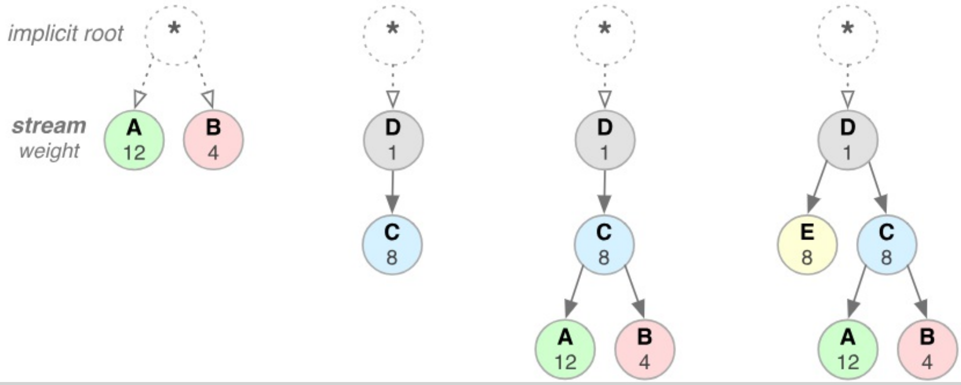
- Not all resources have equal priority when rendering a page
  – *HTTP/2 stream prioritization*
  – *Requests are prioritized based on type of asset, location on the page, and learned priority from previous visits*
    → *If page loading was blocked on an asset, the asset priority gets increased*
- DOM, CSSOM and JavaScript



  – *HTML document is critical to construct DOM*
  – *CCS is required to construct CSSOM*
  – *Both DOM and CSSOM construction can be blocked on JavaScript resources*
    → *A script can issue* `doc.write` *and block DOM parsing and construction*
    → *A script can query for a computed style of an object; the script can block on CSS*

Stream Prioritization

- Purpose
  - *Messages split into **frames** which are delivered in multiplexed **streams***
  - *The order in which frames are delivered is important for a good performance*
  - *Client can define stream prioritization*
    → *optimizations in the browser, change prioritization based on user interaction*
- Streams' weights and dependency
  - *Each stream can be assigned an integer weight between 1 and 256.*
  - *Each stream may be given an explicit dependency on another stream.*

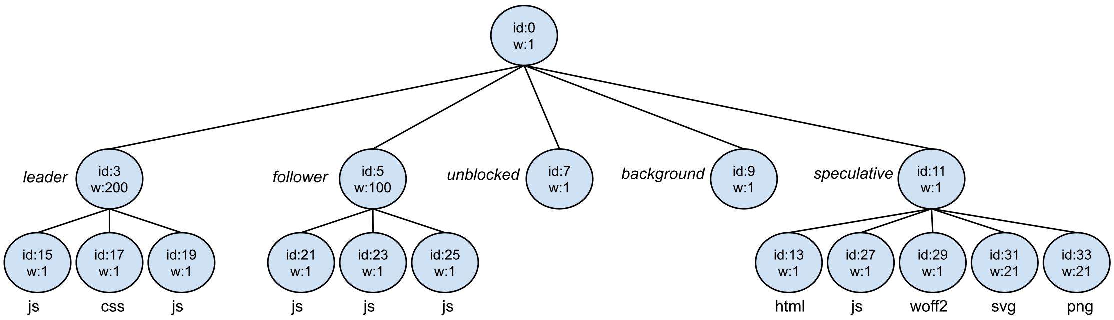


Stream Prioritization (cont.)

- Dependency
  - *referencing the unique identifier of another stream as its parent*
  - *if the identifier is omitted the stream is dependent on the "root stream"*
  - *The parent stream should be allocated resources ahead of its dependencies.*
    → *"Please process and deliver response D before response C"*
- Weights
  - *Sibling streams have resources allocated as per their weights*
  - *Example*
    → *Sum all the weights:* `4 + 12 = 16`
    → *Divide each stream weight by the total weight:* `A = 12/16`, `B = 4/16`
    → *Stream* `A` *receives* `3/4` *and stream* `B` *receives* `1/4` *of available resources;*

Dependency priorities

- Grouping streams
  - *Streams that are never opened with HEADERS frame*
  - *They exist as nodes in the dependency tree that other streams depend on*
- Dependency groups in Firefox
  - *Five fixed dependency groups*
  - *crearted with `PRIORITY` frame when a session is established.*
  - *Every new stream depends on them*
- Example (from a sample http2 packets)



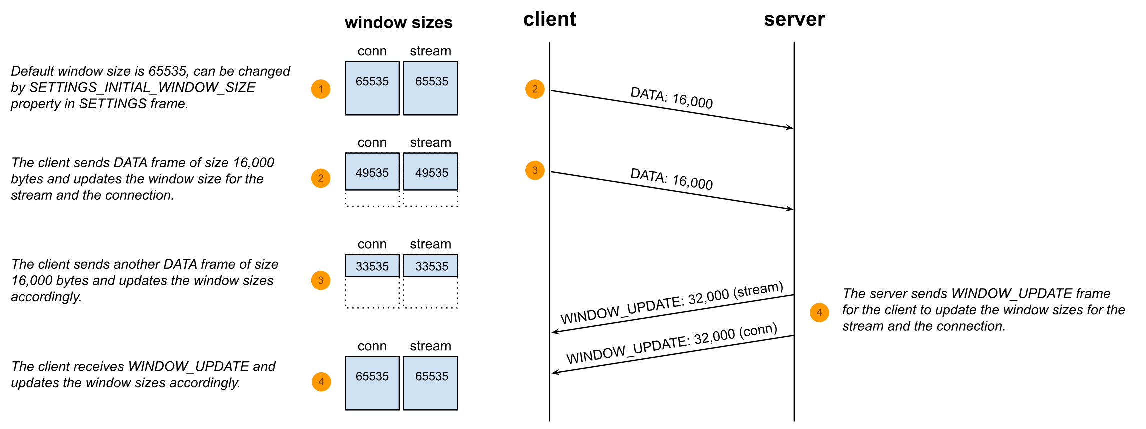
Overview

- Introduction
- HTTP/2
  - *Binary Framing*
  - *Stream Prioritization*
  - *Flow Control*
  - *Server Push*
  - *Header Compression*
  - *HTTP/2 Analysis*
- HTTP/3

Flow control

- Prevent sender from receiving data it doest not want
  - *Receiver is busy or under heavy load*
  - *Receiver is willing to allocate fixed amount of resources for a stream*
- Examples
  - *Client request a video stream; a user pauses the stream*
    → the client wants to pause the stream delivery to avoid buffering
  - *A proxy server has a fast downstream and slow upstream*
    → the proxy server can control how quickly the downstream delivers data to match the speed of upstream
    → better control of resource usage
  - *Similar problems as in TCP flow control*
    → TCP flow control has no app-level API to regulate delivery of streams
- Flow control
  - *Sender and receiver both advertise stream flow control window in bytes*
    = the size of the available buffer space to hold the incoming data
  - *exhanged by special* `SETTINGS` *and* `WINDOW_UPDATE` *frames*
  - *Flow control is hop-by-hop, not end-to-end*
    → an intermediary can set its own flow control

Flow Control Example



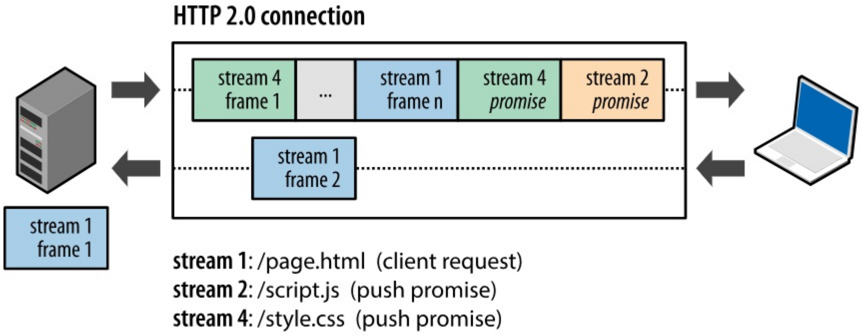
- Window size
  - *The client and server maintains the window size for each stream and a connection.*
  - *How much data the client can still send to the server and vise-versa.*
  - `WINDOW_UPDATE` *provides an increment of the current window size.*
  - *When the window size is zero, no data is sent until the other party changes it.*

Overview

- Introduction
- HTTP/2
  - *Binary Framing*
  - *Stream Prioritization*
  - *Flow Control*
  - *Server Push*
  - *Header Compression*
  - *HTTP/2 Analysis*
- HTTP/3

Server push

- Ability to send multiple responses for a single request
  - *A response to the request is sent back*
  - *Additonal resources can be pushed without client requesting them*
  - *Hypertext – "server knows what the client will need"*



- Similar to resource inlining
  - *A resource is pushed to the client in HTML/CSS resource*
- Performance benefits
  - *Cached by the client, reused across pages, multiplexed, declined by the client*

Push promise

- `PUSH_PROMISE` frames
  - *A singnal that the server intents to push resources to the client*
  - *The client needs to know which resources the server intends to push to avoid creating duplicate requests for these resources.*
- After the client receives `PUSH_PROMISE`
  - *it may decline the stream (via `RST_STREAM` frame)*
    - → *For example, when the resource is already in the cache*
    - → *As for inline resources, this is not possible, the client always receives them*
  - *it can limit the number of concurrently pushed streams*
  - *it can adjust the initial flow control window to control how much data is pushed when the stream is first opened*
  - *it can disable server push entirely*
- pushed resources must obey the same-origin policy

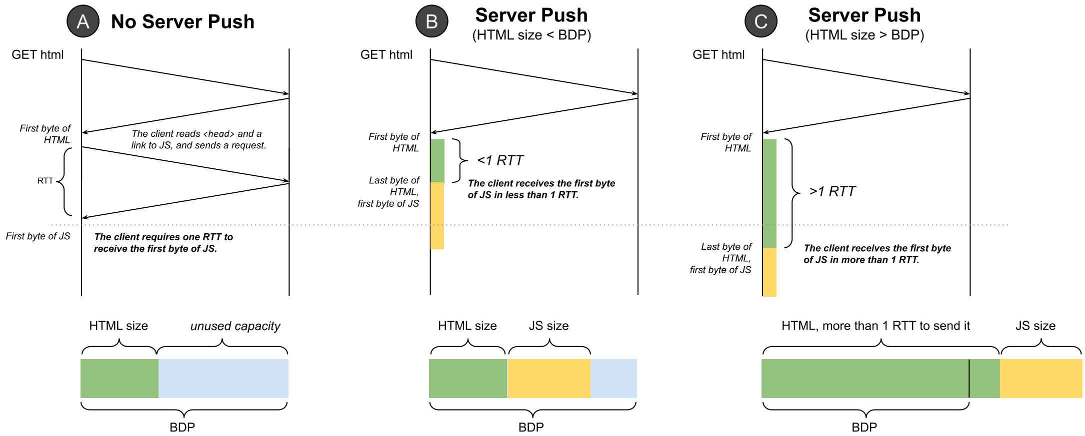
Implementation

- You need to implement Server Push at the app level
  - *Your server may provide a library/API to do so*
    - → *Node express middleware:* `http2-express-autopush`
    - → *Nginx: http2 server push*

```
server {
    # Ensure that HTTP/2 is enabled for the server
    listen 443 ssl http2;

    ssl_certificate ssl/certificate.pem;
    ssl_certificate_key ssl/key.pem;

    root /var/www/html;

    # whenever a client requests demo.html, also push
    # /style.css, /image1.jpg and /image2.jpg
    location = /demo.html {
        http2_push /style.css;
        http2_push /image1.jpg;
        http2_push /image2.jpg;
    }
}
```

Rules for server push

- Performance analysis by Google
  – *see Rules of Thumb for HTTP/2 Push*
- Server push may not always lead to a better performance, such as:
  – *Push just enough resources to fill idle network time, and no more.*



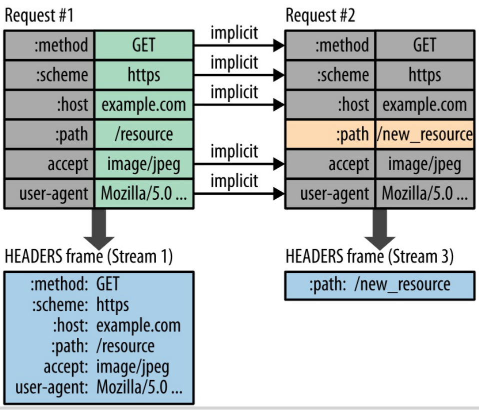
  – *(A) may be better than (C) when* `HTML size > BDP`
  BDP = Bandwidth-delay product

Overview

- Introduction
- HTTP/2
  – *Binary Framing*
  – *Stream Prioritization*
  – *Flow Control*
  – *Server Push*
  – *Header Compression*
  – *HTTP/2 Analysis*
- HTTP/3

Header compression

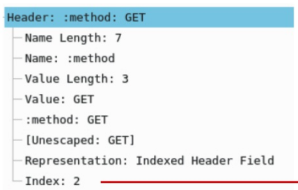
- Purpose
  - *Each HTTP request/response contains a set of headers (metadata)*
  - *HTTP/1.x – metadata sent as plain text, adds 500-800 bytes per transfer*
- HTTP/2 provides
  - *Request and response metadata are compressed using HPACK format*
    - *→ header fields encoded via a static Huffman code – reduces size*
    - *→ client and server maintain an* ***indexed list of previously seen header fields*** *in static and dynamic tables*



Static and Dynamic Tables

- Static table
  - *Pre-defined table of* `61` *header fiedls and values where each has assigned an index*
  - *Defined in HPACK: Header Compression for HTTP/2*

GET header field in HEADERS frame



Static table

Index	Header Name	Header Value
1	:authority	
2	:method	GET
3	:method	POST
4	:path	/
5	:path	/index.html

  - *Decompressed size is* `10` *bytes (*`name+value` *length)*
  - *The real size is* `1` *byte.*
- Dynamic table
  - *Dynamically created table of header fields that do not exist in the static table.*
  - *It is maintained by the client and the server*
  - *There are entries starting with index* `62`

Overview

- Introduction
- HTTP/2
  - *Binary Framing*
  - *Stream Prioritization*
  - *Flow Control*
  - *Server Push*
  - *Header Compression*
  - *HTTP/2 Analysis*
- HTTP/3

nghttp

- Command line tool
  - `nghttp` *displays frames and a summary information about each frame*

```
$ nghttp -vvv -n https://w20.vitvar.com/lecture1.html
[  0.071] Connected
The negotiated protocol: h2
[  0.137] send SETTINGS frame <length=12, flags="0x00," stream_id="0">
          (niv=2)
          [SETTINGS_MAX_CONCURRENT_STREAMS(0x03):100]
          [SETTINGS_INITIAL_WINDOW_SIZE(0x04):65535]
[  0.137] send PRIORITY frame <length=5, flags="0x00," stream_id="3">
          (dep_stream_id=0, weight=201, exclusive=0)
[  0.137] send PRIORITY frame <length=5, flags="0x00," stream_id="5">
          (dep_stream_id=0, weight=101, exclusive=0)
[  0.137] send PRIORITY frame <length=5, flags="0x00," stream_id="7">
          (dep_stream_id=0, weight=1, exclusive=0)
[  0.137] send PRIORITY frame <length=5, flags="0x00," stream_id="9">
          (dep_stream_id=7, weight=1, exclusive=0)
[  0.137] send PRIORITY frame <length=5, flags="0x00," stream_id="11">
          (dep_stream_id=3, weight=1, exclusive=0)
[  0.137] send HEADERS frame <length=49, flags="0x25," stream_id="13">
          ; END_STREAM | END_HEADERS | PRIORITY
          (padlen=0, dep_stream_id=11, weight=16, exclusive=0)
          ; Open new stream
          :method: GET
          :path: /lecture1.html
          :scheme: https
          :authority: w20.vitvar.com
          accept: */*
          accept-encoding: gzip, deflate
          user-agent: nghttp2/1.42.0
[  0.180] recv SETTINGS frame <length=6, flags="0x00," stream_id="0">
          (niv=1)
          [SETTINGS_MAX_CONCURRENT_STREAMS(0x03):100]
[  0.180] recv WINDOW_UPDATE frame <length=4, flags="0x00," stream_id="0">
          (window_size_increment=16711681)
[  0.180] recv SETTINGS frame <length=0, flags="0x01," stream_id="0">
          ; ACK
          (niv=0)
[  0.180] recv (stream_id=13) :status: 200
[  0.180] recv (stream_id=13) server: GitHub.com
...
```

Wireshark and HTTP/2 Traffic

- HTTP/2 is encrypted
  – *You can capture packets in Wireshark/tcpdump but they are encrypted*
  – *The browser (FF, Chrome, Opera) can dump keys in NSS Key Log Format*
  – *You can use the log to decrypt the communication in Wireshark*
- Demo at `https://kde.vitvar.com`

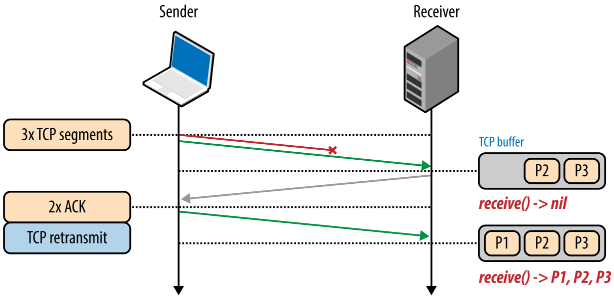
  1. *Configure an env variable* `SSLKEYLOGFILE` *to point to a file on the filesystem*
  2. *Start **firefox** browser; check the keylog file was created.*
  3. *Start **wireshark**; configure the keylog file in pre-master secret log filename*
  4. *Start packet capture on* `eth0` *using the filter:*
     ```
     ((dst host 185.199 and src host 192.168) or
     (dst host 192.168 and src host 185.199))
     ```
     – *This captures the packets in both directions between the client and the server and back*
  5. *Point **firefox** to https://vitvar.com*
  6. *Check captured packets in the **wireshark***
     – *There should be decrypted HTTP/2 communication.*

Overview

- Introduction
- HTTP/2
- HTTP/3

HTTP/2 Drawbacks

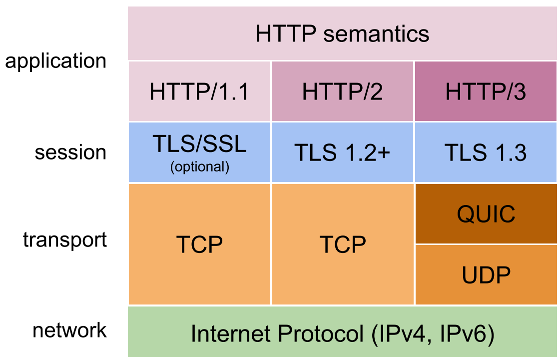
- HTTP/2 is dependant on TCP
- TCP head-of-line blocking



  – *When TCP segment does not arrive, it needs to be transmitted*
  – *This may delay all HTTP/2 streams*
- There must always be TLS handshake after TCP hanshake
  – *HTTP/2 can only be used with TLS*

HTTP/3

- Protocol stack



- HTTP semantic does not change across HTTP versions
- New transport protocol QUIC
  – *Based on UDP*
  – *Reduced connection establishment time*
  – *Multiplexing without head of line blocking*
  – *Connection migration*