The Hyper Text Transfer Protocol (HTTP)

Christian Grothoff
Part I
The Hyper Text Transfer Protocol (HTTP)

- Initially standardized in RFC 2616
- HTTP/0.9 (1990), HTTP/1.0 (1996), HTTP/1.1 (1999), HTTP/2 (2016)
- Runs over TCP (port 80) or as HTTPS over TLS (port 443)
Uniform Resource Locators (URLs)

http://www.example.com:80/path?key=value#anchor

PROTOCOL://HOST:PORT/PATH?QUERY#FRAGMENT
Anatomy of an HTTP request

The HTTP Request

Server Activity:
- Establish Connection
- Send First Byte
- Send Last Byte

Client Activity:
- DNS Lookup
- Initial Connection
- Initial HTTP Request
- Send Data (KB)
- Receive First Byte
- Receive Last Byte

Steps:
- Get IP
- Open Socket
- Time to First Byte
- Content Download
GET / HTTP/1.0
Key1: value1
Key2: value2
Key3: value3
  value3 may be continued here
Key4: value4

- Each line SHOULD be terminated by CRLF, but MAY be terminated only by CR or LF.
- The header ends with an empty line by itself.
- HTTP does not specify a maximum header length
Exercise 1: HTTP/1.0, GET

$ telnet grothoff.org 80
GET / HTTP/1.0
HTTP Methods (or verbs)

GET is just one HTTP method. Other common HTTP/1.0 methods include:

- HEAD
- PUT
- POST
- OPTIONS
- PUT
- DELETE
- TRACE
- CONNECT
## HTTP Methods: Safety and Idempotence

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Idempotent</th>
<th>Safe</th>
</tr>
</thead>
<tbody>
<tr>
<td>GET</td>
<td>Fetch resource</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HEAD</td>
<td>Fetch header only</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>PUT</td>
<td>Store entity</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>POST</td>
<td>Accept entity as subordinate</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>OPTIONS</td>
<td>Return supported HTTP methods</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DELETE</td>
<td>Delete resource</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>PATCH</td>
<td>Change resource</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>TRACE</td>
<td>Echo request back to client</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CONNECT</td>
<td>Convert connection to tunnel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Exercise 2: HTTP/1.0 HEAD

$ telnet grothoff.org 80
HEAD / HTTP/1.0

What happens if you use “HTTP/1.1” instead of “HTTP/1.0”? 
HTTP Responses

A HTTP response generally consists of three parts:

1. HTTP Status code line (version, numeric status code, human readable status code)
2. HTTP (response) headers, followed by empty line
3. HTTP response body
HTTP Status Codes

The numeric range of the HTTP status code is already meaningful:

1. Informational 1xx: Indicate a provisional response
2. Successful 2xx: Indicate that the client request was successful
3. Redirection 3xx: Indicates that further action is needed
4. Client Error 4xx: Indicates when the client seems to have erred
5. Internal Server Error 5xx: Indicates cases in which the server is aware that it has erred
Common HTTP Status Codes

100  Continue
200  Ok
301  Moved Permanently
304  Not Modified
400  Bad Request
401  Authentication Required
402  Payment Required
403  Forbidden
404  Not Found
500  Internal Server Error
Exercise 3: HTTP/1.1

$ telnet grothoff.org 80
GET / HTTP/1.1
Host: grothoff.org
Multiple HTTP requests

- Traditional (HTTP/1.0)

- With Keep-Alive (HTTP/1.1)
Multiple HTTP requests

**Traditional (HTTP/1.0)**

**With Keep-Alive (HTTP/1.1)**
Exercise 4: HTTP/1.1, Connection: close

GET / HTTP/1.1
Host: grothoff.org
Connection: close
Exercise 5: HTTP/1.0, Connection: Keep-alive

GET / HTTP/1.0
Connection: Keep-alive
HTTP/1.1 pipelining

no pipelining

client

open

server

close

pipelining

client

open

server

close

time
HTTP Headers

HTTP headers are used in many ways:

▶ control the connection (Keep-alive)
▶ control caching
▶ provide meta data (content-length, content-type, content-encoding)
▶ request and provide authentication

HTTP knows four types of headers:

▶ General header: can be used in both request and response
▶ Request header: only applicable to request messages
▶ Response header: only applicable to response messages
▶ Entity header: define meta-information about the body
HTTP 1.x Response Format

HTTP/1.1 200 OK
Server: some advertisement
Date: Sun, 31 Aug 1999 24:00:00 GMT
Content-Type: text/html
Content-Length: 11
Connection: close

Hello World

All of the above headers are technically optional.
HTTP and Mobile Systems?

- HTTP(S) is the new IP — tunnel traffic over HTTP
- HTTP + HTML are a fast and portable way to create a GUI
- Full-blown HTTP Servers (Apache, etc.) are often overkill
- Extending Apache only natural with P-languages

Need a lightweight way to create HTTP servers!
GNU libmicrohttpd

- Free software (GNU LGPL or GPL + eCoS)
- Fully HTTP/1.0 and HTTP/1.1 compliant
- Supports all common HTTP features
- Just HTTP(S) server, small footprint
- Makes limited assumptions about event handling:
  - External select/poll loop
  - Internal select/poll loop
  - One thread per connection
  - Thread pool
MHD: Security

- Optional support for HTTPS, full X.509 support
- HTTP basic and digest authentication
- Access to client certificates
- Ability to selectively bind sockets
- Limiting number of connections (overall, per IP), custom timeouts
- Limit memory consumption per connection
- Did very well in three independent external security audits
MHD: Performance

- No busy waiting, ever
- Zero copy, wherever possible
- Stream processing (GET, POST, PUT)
- Minimize malloc, handle all errors
- No re-inventing strchr, strcmp, etc.
- Clean C code, no code duplication
MHD: Scales up and down!

- Library binary can be as small as 32k
- We reportedly have users on systems with 50 Mhz processors with HTTPS
- We have users working with MHD on systems with 64 kb RAM

“I also ran oprofile on the system while streaming about 7gbps to (simulated) ipads and while ramping up 1000s of streams (which causes high rate of HTTP requests to read the Apple HLS playlists). libmicrohttpd barely registers as cpu usage.” – MHD user
Applications using MHD

- GNUnet, P4P Portal
- Gnome Music Player Client, Kiwix, XMBC, OpenVAS
- Psensor, Disk Nukem, Flat8, Fawkes, Conky, CallHome
- OpenDIAS, Techne, Cables communication project
- Open Lightning Architecture, OpenZWave, libhttpserver
- Plus many non-free applications (such as TVs, surveillance cameras, network appliances, etc.)
$ wget https://ftp.gnu.org/gnu/libmicrohttpd/\ libmicrohttpd-0.9.55.tar.gz
$ tar xvf libmicrohttpd-0.9.55.tar.gz
$ cd libmicrohttpd-0.9.55
$ ./configure --prefix=$HOME
$ make install
Exercise 7: Start MHD HTTPD

$ cd doc/examples/
$ gcc -I$HOME/include -L$HOME/lib \
    hellobrowser.c -lmicrohttpd -o hellobrowser
$ export LD_LIBRARY_PATH=$HOME/lib
$ ./hellobrowser  # in another shell
The MHD API

- **Daemon**
  - start
  - handler-cb
  - queue

- **Connection**
  - accept
  - handler-cb
  - queue

- **Response**
  - create
  - 1

- **RC**
Launching MHD: The code

```c
#include <microhttpd.h>

int main ()
{
    struct MHD_Daemon *daemon =
        = MHD_start_daemon ( MHD_USE_AUTO | MHD_USE_INTERNAL_POLLING_THREAD, 8888, NULL, NULL, &answer_to_connection, NULL, MHD_OPTION_END );

    if (NULL == daemon)
        return 1;
    (void) getchar ();
    MHD_stop_daemon (daemon);
    return 0;
}
```
Responding to requests: The code

```c
static int
answer_to_connection ( void *cls,
    struct MHD_Connection *connection,
    const char *url, const char *method,
    const char *version,
    const char *upload_data, size_t *upload_data_size,
    void **con_cls)
{
    const char *page
    = "<html><body>Hello, _browser!</body></html>";
    int ret;
    struct MHD_Response *response
    = MHD_create_response_from_buffer ( strlen ( page ),
        (void *) page, MHD_RESPMEM_PERSISTENT);
    ret = MHD_queue_response ( connection, MHD_HTTP_OK,
        response);
    MHD_destroy_response ( response);
    return ret;
}
```
Exercise 8: Setting Response Headers

response = MHD_create_response (...);
MHD_add_response_header (response,
MHD_HTTP_HEADER_CONTENT_TYPE,
"text/html");

ret = MHD_queue_response (connection,
MHD_HTTP_OK,
response);

MHD_destroy_response (response);

Test it with telnet! Which headers does the response include?
MHD Response Generation

- Static buffer in memory
- Data stream (known or unknown size)
- Data stream with long polling
- From file at offset
- From file with `sendfile()`
- With custom HTTP headers — and trailers
# Exercise 9: sendfile()

```c
int fd;
struct stat sbuf;

if (0 != strcmp(method, "GET")) return MHD_NO;
if ((-1 == (fd = open("picture.png", O_RDONLY))) ||
    (0 != fstat(fd, &sbuf))) {
    if (fd != -1) close(fd);
    return report_error(connection);
}
struct MHD_Response *response =
    MHD_create_response_from_fd_at_offset(sbuf.st_size, fd, 0);
MHD_add_response_header(response,
    "Content-Type", "image/png");
ret = MHD_queue_response(connection, MHD_HTTP_OK, response);
```
Interlude: Benchmarking

Web performance is complex:
- number of requests required per Web page in total
- parallel TCP connections used by browser
- static content vs. dynamic content generation
- impact of caching, proxies, network speed
- HTTP vs. HTTPS
- Use of “Connection: Keep-alive”
- Browser HTML parsing and rendering

We will focus on a few simple tools for the server.
Excercise 10: siege

apt-get install siege

$ siege -t5S http://grothoff.org/

Transactions: 876 hits
Availability: 100.00 %
Elapsed time: 4.64 secs
Data transferred: 0.17 MB
Response time: 0.01 secs
Transaction rate: 188.79 trans/sec
Throughput: 0.04 MB/sec
Concurrency: 2.22
Successful transactions: 878
Failed transactions: 0
Longest transaction: 0.05
Shortest transaction: 0.00
Excercise 11: Apache Benchmark (ab)

apt-get install apache2-utils

$ ab –c 25 –t5 http://grothoff.org/
Excercise 11: Apache Benchmark (ab)

```
apt-get install apache2-utils

$ ab -c 25 -t5 http://grothoff.org/
```

Time taken for tests: 5.000 seconds
Complete requests: 14096
Failed requests: 0
Non-2xx responses: 14096
Total transferred: 5300096 bytes
HTML transferred: 2607760 bytes
Requests per second: 2819.09 [#/sec] (mean)
Time per request: 8.868 [ms] (mean)
Time per request: 0.355 [ms] (mean, across all concurrent requests)
Transfer rate: 1035.14 [Kbytes/sec] received
Lesson learned:

- HTTP servers are very fast
- You may be benchmarking the client
- You may be benchmarking the bandwidth
- You may be benchmarking the network latency
Exercise 12: Benchmark your server

- top
- time BINARY
- strace -c BINARY
- iotop (requires root)
MHD performance tuning

- MHD’s fastest mode is a thread pool with epoll()
- You can re-use struct MHD_Response objects
- You can disable the “Date:” header (MHD_USE_SUPPRESS_DATE_NO_CLOCK)
- You could run HTTP over a UNIX domain socket
- You can enable TCP FASTOPEN (MHD_USE_TCP_FASTOPEN)
- You can enable crazy mode (MHD_USE_TURBO)
- You can disable logging (--disable-messages)

... but, in 99.99% of all cases, your bottleneck will be elsewhere without these!
HTTP/1.1 Responses

- Content-Length header defines body length
- Content-encoding: chunked provides alternative if length not known
- Otherwise, no keep-alive possible (Connection: close header implied)
Content-encoding: chunked

RFC 2616, section 3.6.1 defines chunked encoding:

\[
\text{Chunked-Body} = \ast \text{chunk last-chunk trailer CRLF}
\]

\[
\text{chunk} = \text{chunk-size} [ \text{chunk-extension} ] \text{CRLF}
\]

\[
\text{chunk-data} \text{CRLF}
\]

\[
\text{chunk-size} = 1\ast \text{HEX}
\]

\[
\text{last-chunk} = 1\ast(“0”) [ \text{chunk-extension} ] \text{CRLF}
\]

\[
\text{chunk-extension} = \ast(“;” \text{chunk-ext-name} [ “=” \text{chunk-ext-val} ]
\]

\[
\text{chunk-ext-name} = \text{token}
\]

\[
\text{chunk-ext-val} = \text{token} | \text{quoted-string}
\]

\[
\text{chunk-data} = \text{chunk-size} (\text{OCTET})
\]

\[
\text{trailer} = \ast(\text{entity-header} \text{CRLF})
\]
#include <stdlib.h>

static ssize_t crc (void *cls, uint64_t pos, char *buf, size_t size_max) {
    if (0 == size_max) return 0;
    if (0 == rand() % 1024 * 1024)
        return MHD_CONTENT_READER_END_OF_STREAM;
    *buf = 'b';
    return 1;
}

struct MHD_Response *response
    = MHD_create_response_from_callback
        (MHD_SIZE_UNKNOWN,
         1024,
         &crc, NULL, NULL);
Exercise 13: Generating incremental replies

Using telnet:

▶ What happens if you use the code above with a HTTP/1.0-style request?
▶ What happens if you use the code above with a HTTP/1.1-style request?

Using wget:

▶ What is the output if you use the code above?
▶ What happens on the wire? Use wireshark!
Long polling

HTTP may generate a response incrementally:

- With or without chunked encoding
- MHD_OPTION_CONNECTION_TIMEOUT and MHD_set_connection_option (connection, MHD_CONNECTION_OPTION_TIMEOUT) can control timeout.
- MHD_ContentReaderCallback can return 0 to indicate “more available later”
- MHD_suspend_connection() can suspend handling of network data for a connection.

Request → Response ⇒ Request → Response, [wait, Response]*, fin.
HTTP Caching

HTTP response headers control how long a resource is valid:
▶ Cache-control: max-age=3600
▶ Expires: Mon, 31 Aug 2020 00:00:00 GMT
▶ ETag: "727285929572e8a" — assign unique ID to resource

HTTP request headers can be used to inquire if a resource changed:
▶ If-Modified-Since: Mon, 31 Aug 2000 00:00:00 GMT
▶ If-None-Match: "727285929572e8a"
## HTTP Methods & Caching

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Cacheable</th>
</tr>
</thead>
<tbody>
<tr>
<td>GET</td>
<td>Fetch resource</td>
<td>✓</td>
</tr>
<tr>
<td>HEAD</td>
<td>Fetch header only</td>
<td>✓</td>
</tr>
<tr>
<td>PUT</td>
<td>Store entity</td>
<td>✗</td>
</tr>
<tr>
<td>POST</td>
<td>Accept entity as subordinate</td>
<td>✓(*)</td>
</tr>
<tr>
<td>DELETE</td>
<td>Delete resource</td>
<td>✗</td>
</tr>
<tr>
<td>PATCH</td>
<td>Change resource</td>
<td>✗</td>
</tr>
<tr>
<td>TRACE</td>
<td>Echo request back to client</td>
<td>✗</td>
</tr>
<tr>
<td>CONNECT</td>
<td>Convert connection to tunnel</td>
<td>✗</td>
</tr>
</tbody>
</table>

(*) Only if HTTP response includes explicit freshness information.
HTTP is a “stateless” protocol. Cookies are a mechanism to add state.

```c
const char *value
   = MHD_lookup_connection_value ( connection,
                                  MHD_COOKIE_KIND,
                                  " key");
```

```c
response = ...;
MHD_add_response_header ( response,
                          MHD_HTTP_HEADER_SET_COOKIE,
                          " key=value;OPTIONS" );
```

Modify your code to set cookies and print values of received cookies.
Cookie options

- Expires=DATE — if not set, cookies expire at the end of the session
- Domain=DOMAIN — for which (sub)domain does the cookie apply
- Path=PATH — for which URL paths should the cookie be sent
- Secure — only send cookie over HTTPS
- HttpOnly — only send cookie over HTTP
- SameSite=Strict — do not send along cross-site requests
Range queries

HTTP supports incremental downloads:

GET / HTTP/1.1
Host: grothoff.org
Content-range: 40-42/bytes

206 Partial Content
Content-length: 3
Accept-ranges: bytes
Content-range: 40-42/64
Range queries with MHD

MHD does not (yet) have build-in support, so you need to process range queries manually:

```c
const char *range
    = MHD_lookup_connection_value (connection,
                                   MHD_HEADER_KIND,
                                   MHD_HTTP_HEADER_CONTENT_RANGE);

response = ...;
MHD_add_response_header (response,
                         MHD_HTTP_HEADER_ACCEPT_RANGES,
                         "bytes");
```
HTTP/1.x supports **body** compression

```
GET / HTTP/1.0
Accept-encoding: gzip, deflate

200 OK
Content-encoding: gzip
Content-length: 42
```

The content length is that of the compressed body.
`Compression in C`

```c
#include <zlib.h>

/**
 * Try to compress a response body. Updates @a buf and @a buf_size.
 *
 * @param [in, out] buf pointer to body to compress
 * @param [in, out] buf_size pointer to initial size of @a buf
 * @return true if buf was compressed
 */

int body_compress (void **buf, size_t *buf_size) {
    uLongf cbuf_size = compressBound (*buf_size);
    Bytef *cbuf = malloc (cbuf_size);
    int ret = compress (cbuf, &cbuf_size,
                       (const Bytef *) *buf, *buf_size);
    if ((Z_OK != ret) || (cbuf_size >= *buf_size)) {
        free (cbuf); return false;
    }
    free (*buf);
    *buf = (void *) cbuf;
    *buf_size = (size_t) cbuf_size;
    return true;
}
```
Exercise 14: Add compression support

- Add support for compression to your MHD server.
- Make sure to check the client supports compression.
- You need to link against libz
Part II
<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>GET</td>
<td>Fetch resource</td>
<td>✗</td>
</tr>
<tr>
<td>HEAD</td>
<td>Fetch header only</td>
<td>✗</td>
</tr>
<tr>
<td>PUT</td>
<td>Store entity</td>
<td>✓</td>
</tr>
<tr>
<td>POST</td>
<td>Accept entity as subordinate</td>
<td>✓</td>
</tr>
<tr>
<td>DELETE</td>
<td>Delete resource</td>
<td>✗</td>
</tr>
<tr>
<td>PATCH</td>
<td>Change resource</td>
<td>✓</td>
</tr>
<tr>
<td>TRACE</td>
<td>Echo request back to client</td>
<td>✗</td>
</tr>
<tr>
<td>CONNECT</td>
<td>Convert connection to tunnel</td>
<td>✓</td>
</tr>
</tbody>
</table>
Upload a body may be expensive! HTTP can check if the HTTP server is willing to handle it first!

POST / HTTP/1.1
Host: grothoff.org
Content-length: 1000
Expect: 100-continue

100 Continue

UPLOAD-BODY

200 Ok

RESPONSE-BODY
100 Continue

Uploading a body may be expensive! HTTP can check if the HTTP server is willing to handle it first!

POST / HTTP/1.1
Host: grothoff.org
Content-length: 1000
Expect: 100-continue

100 Continue

UPLOAD-BODY

200 Ok

RESPONSE-BODY
MHD and uploads

```c
int
answer_to_connection ( void *cls,
    struct MHD_Connection *connection,
    const char *url,
    const char *method,
    const char *version,
    const char *upload_data,
    size_t *upload_data_size,
    void **con_cls)
{
}
```

`answer_to_connection` will be called repeatedly!
Exercise 15: Handle uploads

- Write an HTTP server with an upload function
- Reject uploads larger than 8 MB

Why do many HTTP servers include such a limitation?
HTTP Basic authentication

```c
#define DENIED "<html><body>Go away.</body></html>";

char *pass = NULL;
char *user = MHD_basic_auth_get_username_password (connection, &pass);
if (!authentication_ok (user, pass)) {
    response =
        MHD_create_response_from_buffer (strlen (DENIED),
                                            (void *) DENIED,
                                            MHD_RESPMEM_PERSISTENT);
    return MHD_queue_basic_auth_fail_response (connection,
                                                "my_realm",
                                                response);
}
```
HTTP Digest authentication (Part I)

```c
#define MY_OPAQUE_STR "11733b200778ce33060f"

char *username = MHD_digest_auth_get_username(connection);
if (NULL == username) {
    char *response = MHD_create_response_from_buffer(strlen(DENIED),
        DENIED, MHD_RESPMEM_PERSISTENT);
    return MHD_queue_auth_fail_response(connection,
        "my_realm", MY_OPAQUE_STR, response, MHD_NO);
}
```
HTTP Digest authentication (Part II)

```c
int ret = MHD_digest_auth_check (connection, "my_realm", username, password, 300);
if ( (ret == MHD_INVALID_NONCE) ||
    (ret == MHD_NO) )
{
    response = MHD_create_response_from_buffer (strlen (DENIED),
                                                DENIED, MHD_RESPMEM_PERSISTENT);
    return MHD_queue_auth_fail_response (connection,
                                         "my_realm", MY_OPAQUE_STR, response,
                                         (ret == MHD_INVALID_NONCE) ? MHD_YES : MHD_NO);
}
```
Exercise 16: Digest Authentication

- Add support for digest authentication to your MHD server
- Observe the traffic with wireshark
- Attempt a replay attack using telnet or nc or netcat
HTTP Upgrade

- HTTP includes a mechanism to “upgrade” or switch to another protocol
- The client requests the upgrade using the `Connection` header
- The client offers one or more protocols to upgrade to
- The server replies with which protocol it wants to use
- Afterwards, the underlying TCP stream is used bi-directionally for the new protocol
HTTP Upgrade: Web Sockets

GET / HTTP/1.0
Host: example.com
Connection: Upgrade
Upgrade: WebSocket
Sec-WebSocket-Key: HEXCODE==
Sec-WebSocket-Protocol: chat, superchat
Sec-WebSocket-Version: 13

HTTP/1.1 101 Switching Protocols
Upgrade: websocket
Connection: Upgrade
Sec-WebSocket-Accept: HEXCODE=
Sec-WebSocket-Protocol: chat

WEBSOCKET V13.
HTTP Upgrade: HTTP/2

GET / HTTP/1.0
Connection: Upgrade
Upgrade: h2c

HTTP/1.1 101 Switching Protocols
Upgrade: h2c

HTTP2 IN CLEARTEXT.
Virtual hosting

- There are only $\approx 4$ billion IPv4 addresses
- We may not have one for every Web server
- We also may not have a physical machine for every domain

$\Rightarrow$ Goal: allow one IP to host many HTTP domains

Problem: HTTP server needs to know which domain is requested!
Virtual hosting

- There are only \( \approx 4 \) billion IPv4 addresses
- We may not have one for every Web server
- We also may not have a physical machine for every domain

\[\Rightarrow\] Goal: allow one IP to host many HTTP domains

Problem: HTTP server needs to know which domain is requested!

Solution: HTTP/1.1 mandates \texttt{Host:} header to indicate domain.
Sample Apache configuration (sites-enabled/)

```xml
<VirtualHost my-domain.com:80>
    ServerAdmin webmaster@my-comain.com
    ServerName "my-comain.com"
    DocumentRoot /var/www/my-domain/
    <Directory />
        Options FollowSymLinks
        AllowOverride None
    </Directory>
    <Directory "/var/www/my-domain">
        AllowOverride None
        Order allow,deny
        Allow from all
    </Directory>
</VirtualHost>
```
HTTP servers can act as proxies

First, enable the HTTP reverse proxy module:

```bash
# a2enmod mod_proxy
```

Then you can configure the reverse proxy:

```xml
<VirtualHost my-domain.com:80>
    ProxyPass /foo/ http://localhost:58080/
    ProxyPass /bar/ https://localhost:58081/
    ProxyPass /bfh/ https://bfh.ch/
    ProxyPass /ws/ ws://localhost:4242/
</VirtualHost>
```

This is in contrast to an HTTP client using a proxy (such as Squid, Tor or WWWOFFLE).
Exercise 17: Reverse proxy to MHD

- Configure an Apache server for your site
- Redirect a particular path to your MHD instance
- Redirect another (virtual) domain to your MHD instance

Hint: use `/etc/hosts` to map the IP address(es) if you do not have sufficient control over DNS!
X.509 Trust Chains

End-entity Certificate
- Owner's name
- Owner's public key
- Issuer's (CA's) name
- Issuer's signature

Intermediate Certificate
- Owner's (CA's) name
- Owner's public key
- Issuer's (root CA's) name
- Issuer's signature

Root Certificate
- Root CA's name
- Root CA's public key
- Root CA's signature

Sign: owner's private key
Reference: verification of certificate validity
Self-sign: root CA
TLS 1.3: Full Handshake

Diagram showing the sequence of events and timing for the TLS 1.3 full handshake process. The process involves the following steps:

1. Connection Request
2. Client Hello
3. Server Hello
4. Client Key Share
5. Server Key Share
6. Certificate
7. Finished
8. Application Data

The timing is indicated in milliseconds, with the full handshake taking approximately 136ms.
TLS 1.3: Abbreviated Handshake

Connection Request

ClientHello
ClientKeyShare

Finished
Application Data

TCP - 68ms

TLS - 68ms

Time
TLS 1.3: 0.5 RTT Handshake
TLS Protocol Stack

HTTP  FTP  SMTP

TLS

TCP

IP

Record Protocol

Handshake protocol  Cipher Change protocol  Alert protocol
Exercise 18: Enable TLS

- Obtain a TLS certificate via the “Let’s encrypt” CA (you need a global DNS name!):
  
  ```
  # letsencrypt -D DOMAIN.TLD --standalone certonly # or
  # letsencrypt -D DOMAIN.TLD --standalone run # may work
  ```

- Configure your Apache server to use it:
  ```
  SSLEngine on
  SSLProtocol -ALL +TLSv1.2 +TLSv1.1 +TLSv1
  SSLCertificateKeyFile /etc/letsencrypt/live/example.com/privkey.pem
  SSLCertificateChainFile /etc/letsencrypt/live/example.com/fullchain.pem
  SSLCertificateFile /etc/letsencrypt/live/example.com/cert.pem
  ```

- Verify your configuration using
  ```
  https://www.ssllabs.com/ssltest/ and
  https://observatory.mozilla.org/
  ```
HTTP/2

Key changes:

- HTTP/1 is stateless. HTTP/2 is stateful.
- HTTP/1 is human readable. HTTP/2 is binary.
- HTTP/1 is in cleartext. HTTP/2 browsers today require TLS.
- HTTP/1 is reactive. HTTP/2 servers can be proactive.
- HTTP/1 handled requests in order. HTTP/2 allows out of order.
- HTTP/1 is mature. HTTP/2 was rushed to avoid fragmentation.
HTTP/2 Push

Without Push

- Browser requests HTML
- Server sends HTML
- Browser requests CSS
- Server sends CSS

With Push

- Browser requests HTML
- Server sends HTML
- Server pushes CSS
- Browser receives pushed CSS
HOL blocking and prioritization

- Client: open, blocked, close
- Server: open, blocked, close

Time: high priority
Exercise 19: Enable HTTP/2 for Apache

First, enable the HTTP/2 module:

```
# a2enmod http2
```

Then, enable HTTP/2 for your site:

```
<VirtualHost *:443>
  Protocols h2 http/1.1
  ServerAdmin admin@example.com
  ServerName examp.e.com
  ...
</VirtualHost>
```
Exercise 20: Putting it all together

- Configure your site for HTTPS
- Enable HTTP/2
- Reverse proxy to your MHD HTTP instance
- Add Link: headers to add PUSH support:
  
  Link: </assets/styles.css>;rel=preload
Exercise 21: Homework

- Use TLS with MHD directly
- Cross compile MHD for ARM CPUs:
  - Install gcc-arm-linux-gnueabi and binutils-arm-linux-gnueabi or gnueabihf for ARM systems implementing “hardfloat”
  - Configure using ./configure
    --host=arm-linux-gnueabi(hf)
- Implement a RESTful IoT sensor using MHD
- Minimize the MHD binary size by setting configure and gcc options to minimize code size and omit features you do not require
Continuation-Passing Style (CPS)

Continuation-passing style (CPS) is a style of programming in which control is passed explicitly in the form of a continuation.

- In CPS, functions never return!
- Instead, functions takes an extra argument: an explicit “continuation”, i.e. a function of one argument.

When the CPS function has computed its result value, it jumps to the continuation function passing its result value as the argument.
CPS transformation

Programs can always be (automatically) converted to CPS:

- Compilers for functional languages often translate to CPS
- Care must be taken to not use a call stack for the continuations! (See also: tail call)
- Event loops (libev, libevent, glib, GNU-net-SCHEDULER) use a style resembling CPS when code waits for inputs
Event loop: minimal example

```c
static void task (void *cls) {
    const char *text = cls;
    printf ("%s\n", text);
}
static void start (void *cls) {
    GNUNET_SCHEDULE add_now (&task, "Hello_world");
    GNUNET_SCHEDULE add_delayed (TIMEOUT,
                                  &task, "later");
    GNUNET_SCHEDULE add_read_net (TIMEOUT, FD,
                                  &task, "FD_ready");
}
int main () {
    GNUNET_SCHEDULE run (&start, NULL);
}
```
select()

- Traditional API for monitoring multiple file descriptors
- Read `man 2 select`

**Be aware:**
- Most portable API, even available on W32
- Always respect `FD_SETSIZE` when manipulating the sets!
- `FD_SETSIZE` can be **very** small on W32 systems
select() and MHD: minimal example

```c

d = MHD_start_daemon (MHD_USE_ERROR_LOG, 8080,
    NULL, NULL, &handle_req, NULL, MHD_OPTION_END);
while (1) {
    fd_set rs, ws, es;
    int maxposixs = -1;

    FD_ZERO (&rs); FD_ZERO (&ws); FD_ZERO (&es);
    MHD_get_fdset (d, &rs, &ws, &es, &maxposixs);
    MHD_get_timeout (d, &timeout);
    tv.tv_sec = timeout / 1000; /* ms → s */
    tv.tv_usec = (timeout % 1000) * 1000000ULL; /* ms → us */
    select (maxposixs + 1, &rs, &ws, &es, &tv);
    MHD_run (d); // more efficient: MHD_run_from_select();
}
```
poll()

- Instead of using 3 bit-sets, uses an array
- Mostly eliminates restriction on FD_SETSIZE of select()
- Allows more fine-grained control over what events we care about
poll()

#include <poll.h>

struct pollfd fds[2];
fd[0].fd = STDION_FILENO;
fd[0].events = POLLIN;
fd[1].fd = STDOUT_FILENO;
fd[1].events = POLLOUT;
while (1) {
    ppoll (fds, 2, NULL /* timeout */, NULL /* sigmask */);
    if (0 != (fd[0].revents & POLLIN)) do_read ();
    if (0 != (fd[1].revents & POLLOUT)) do_write ();
}
MHD and `poll()`

- MHD can use `ppoll()` internally:
  
  ```c
  MHD_USE_POLL_INTERNAL_THREAD
  ```
Exercise 22: going beyond the FD_SETSIZE limit

Create an MHD service that sends a slow, infinite stream of “A”s to each HTTP client, with a delay of 1s between characters:

- Create a linked list with data about all active connections, store a flag and the connection handle in the list items.
- Add incoming connections to list, use MHD_create_response_from_callback() with a size of MHD_SIZE_UNKNOWN and a pointer to your linked list entry.
- When called, if flag set, return “A” once and clear flag. If flag unset, call MHD_suspend_connection().
- In your main() function, add a loop that once per second goes over the list, sets all flags and calls MHD_resume_connection() on each entry. Make sure to use a mutex to access the list!
Exercise 23: going beyond the FD_SETSIZE limit

Create 2k concurrent clients using wget to test your implementations with select() and ppoll() - based event loops.

▶ What happens if you go beyond 1021 connections with select()?  
▶ What happens if you go beyond \( \approx 1600 \) connections with select()?  
▶ What happens if you go beyond 1021 connections with ppoll()?  
▶ What happens if you go beyond \( \approx 1600 \) connections with ppoll()?  

**Hint:** Read up on listen() and ulimit to explain your findings!
High-performance networking: `epoll()`

- Uses a special file descriptor to represent the FD_SETs
- The epoll-FD is readable when anything is ready in these sets
- Sets are manipulated using system call `epoll_ctl()`
- Read `man 3 epoll`

Be aware:

- Least portable (Linux/FreeBSD-only)
- Best performing for large event sets: $O(1)$
- Requires care when using EPOLLET (edge-triggered) flag
epoll() – minimal example

#include <sys/epoll.h>

struct epoll_event evt;
struct epoll_event events_list[LEN];

epfd = epoll_create1 (EPOLL_CLOEXEC);
evt.events = EPOLLIN;
evt.data.ptr = NULL;
epoll_ctl (epfd, EPOLL_CTL_ADD, some_fd, &evt))

while (1)
{
    ec = epoll_wait (epfd, events_list, LEN, TIMEOUT);
    for (unsigned int i=0; i<ec; i++)
        handle_event (&events_list[i]);
}
MHD and epoll()

- MHD can use epoll() internally:
  MHD_USE_EPOLL_INTERNAL_THREAD

- MHD can give you its epoll() FD: MHD_USE_EPOLL, then ask MHD_get_daemon_info() for MHD_DAEMON_INFO_EPOLL_FD.
Exercise 24: combine select() and epoll()

» Rewrite your external select-based event loop to use MHD’s epoll() FD
Twister Installation

# apt install libtool libltdl-dev autoconf automake libunistring-dev libidn11-dev
$ git clone git://git.gnunet.org/gnunet
# cd gnunet; ./bootstrap
$ ./configure --prefix=$HOME/mc --with-microhttpd=$HOME/mc
$ git clone git://git.taler.net/exchange
$ cd exchange ; ./bootstrap
$ ./configure --prefix=$HOME/mc --with-gnunet=$HOME/mc --with-microhttpd=$HOME/mc
# make install ; cd ..

$ git clone git://git.taler.net/twister
$ cd twister; ./bootstrap
$ ./configure --prefix=$HOME --with-gnunet=$HOME/mc --with-exchange=$HOME/mc \
    --with-microhttpd=$HOME/mc
# make install ; cd ..
The Twister HTTP proxy

# twister.conf
[twister]
# listens here
HTTP_PORT = 8888
# forwards there
DESTINATION_BASE_URL = http://localhost:8080
Driving it

```
# twister.conf
[twister]
# Control channel.
UNIXPATH = /tmp/taler-service-twister.sock
..  

# CLI
$ taler-twister -c twister.conf \
  --flip-ul=child.one
```
#include <taler/taler_twister_service.h>

handle = TALER_TWISTER_connect (CONFIG);

/* Issue char-flipping command */
TALER_TWISTER_flip_upload (handle,
"child.one",
&callback,
NULL);

// ...
TALER_TWISTER_disconnect (handle);
Part IV
RESTful Design

Defined in Roy Fielding’s dissertation “Architectural Styles and the Design of Network-based Software Architectures”. Most of the six REST constraints that guide system design come from HTTP:

- Client-server architecture
- Statelessness
- Cacheability
- Layered system
- Code on demand (optional)
- Uniform interface
Uniform interface

- Resource identification in requests (use URIs)
- Resource manipulation through representations (use HTTP methods)
- Self-descriptive messages (use Content-Type)
- Hypermedia as the engine of application state

The last point is rarely supported by real-world REST APIs.
Resource representation

Common formats for resource representation:

- Server-side: (relational?) database (PostgreSQL)
- Client-side: IndexDB
- Network: ASN.1 formats (BER, DER), Protocol Buffers, XML, JSON
Java Script Object Notation (JSON)

Pros:
- Widely used
- Deterministic encodings available
- Schema-less

Cons:
- Schema-less
- Inefficient compared to binary encodings (solution: BSON!)
Manipulating JSON from C

Do not try to create JSON strings manually in C code.

- String manipulation is notoriously difficult in C
- Memory management becomes a nightmare
- Ensuring syntactic correctness will already be too hard

Solution: libjansson

https://jansson.readthedocs.io/en/2.11/
```
#include <jansson.h>

// construct '{"hello":5, "world":10}'
json_t *j = json_pack("{"hello", s:i, s:i}"), "hello", 5, "world", 10);
// convert to string
char *s = json_dumps (j, 0);
// parse string
json_t *k = json_loads (s, 0, NULL);
// access field
assert (5 == json_integer_value (json_object_get (k, "hello")));
Modify your HTTP server to:

▶ Dynamically generate a JSON-formatted response with a random number
▶ Properly set the “Content-Type” header
▶ Optionally: support body compression
Relational databases

Common relational databases include:

- Sqlite (especially for small systems)
- PostgreSQL
- MariaDB (free software fork of MySQL)
- MySQL (dying due to Oracle acquisition)

We will use PostgreSQL.
Database access from C

Each database comes with a C API:

- libsqlite3
- libpq
- libmysql-client

They are all horrible. We will use the libgmunetpq wrapper around libpq which eliminates the worst atrocities.
libgnunetpq by example

#include <libpq-fe.h>
#include <gnunet/libgnunetpq.h>

PGconn *conn = GNUNET_PQ_connect("postgres://db-name");
// use 'conn' here, finally:
PQfinish(conn);
libgnunetpq by example

```c
struct GNUNET_PQ_ExecuteStatement es[] = {
    GNUNET_PQ_make_execute
    ("DROP TABLE IF EXISTS foo CASCADE;" ),
    GNUNET_PQ_make_execute
    ("CREATE TABLE IF NOT EXISTS bar (key INT4, val BYTEA);" ),
    GNUNET_PQ_make_try_execute
    ("CREATE INDEX bar_index ON bar (key );" ),
    GNUNET_PQ_EXECUTE_STATEMENT_END
};

GNUNET_PQ_exec_statements (conn, es);
```
libgnunetpq by example

```c
struct GNUNET_PQ_PreparedStatement ps[] = {
    GNUNET_PQ_make_prepare("foo_insert",
        "INSERT INTO foo ( key, val ) VALUES ($1, $2 );",
        2),
    GNUNET_PQ_make_prepare("foo_select",
        "SELECT val FROM foo WHERE key = $1 ;",
        1),
    GNUNET_PQ_make_prepare("foo_delete",
        "DELETE FROM foo WHERE key = $1 ;",
        1),
    GNUNET_PQ_PREPARED_STATEMENT_END
};

GNUNET_PQ_prepare_statements(conn, ps);
```
**libgnunetpq by example**

```c
struct GNUNET_PQ_QueryParam params[] = {
    GNUNET_PQ_query_param_uint32 (&key),
    GNUNET_PQ_query_param_end
};

GNUNET_PQ_eval_prepared_non_select (session->conn, 
    "foo_delete", 
    params);
```
libgnunetpq by example

```
struct GNUNET_PQ_QueryParam params[] = {
    GNUNET_PQ_query_param_uint32 (&key),
    GNUNET_PQ_query_param_end
};
char *val; size_t val_size;
struct GNUNET_PQ_ResultSpec rs[] = {
    GNUNET_PQ_result_spec_variable_size ("val",
                                        &val, &val_size),
    GNUNET_PQ_result_spec_end
};

GNUNET_PQ_eval_prepared_singleton_select (session->conn,
                                          "foo_select",
                                          params,
                                          rs);

/* use 'val' here */
GNUNET_PQ_cleanup_result (rs);
```
libgnunetpq by example

```c
struct GNUNET_PQ_QueryParam params[] = {
    GNUNET_PQ_query_param_uint32 (&key),
    GNUNET_PQ_query_param_end
};

GNUNET_PQ_eval_prepared_multi_select (session->conn, "foo_select",
    params, &handle_result, hr_CTX);
```
static void handle_result (void *cls,
    PGresult *result,
    unsigned int num_results) {
    for (unsigned int i=0; i<num_results; i++) {
        char *val; size_t val_size;
        struct GNUNET_PQ_ResultSpec rs[] = {
            GNUNET_PQ_result_spec_variable_size ("val",
                &val, &val_size),
                GNUNET_PQ_result_spec_end
        };

        GNUNET_PQ_extract_result (result, rs, i);
        /* use 'val' here */
        GNUNET_PQ_cleanup_result (rs);
    }
}
Exercise 26: Implement a backup service

Modify your HTTP server to:

▶ Store resources in your database given PUT request
▶ Return resources from database given GET request
▶ Use HTTP features to optimize caching of GET replies
▶ Optionally, use libgnunetutil to:
  ▶ restrict URIs to Crockford base32-encoded EdDSA public keys
  ▶ require signatures by respective private key in separate HTTP header for PUTs
  ▶ support transactional updates by requiring hash of last version to be supplied on PUT
Exercise 27: evaluate performance

Determine the speed of your solution:

- How many stores can you handle per second?
- How many retrievals can you handle per second?
- How much do these two depend on the size of the data?

Use Curl or libcurl to simulate clients. Make sure you measure the service and not the client!
Future Work (aka Bachelor’s thesis topics!)

- Improve usability of MHD API
- Hack on GNU Taler (sync, auditor API, multi-DB support, speed)
Copyright (C) 2012-2018 Christian Grothoff

Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.3 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts.