Design and Verification of the TLS 1.3 Handshake State Machine in LibreSSL

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TLS Basics

TLS stands for Transport Layer Security.
Successor of the SSL (Secure Socket Layer) protocol.

Client wants to connect to a server.

- Establishes a connection
- Negotiates connection with server (TLS handshake)
- Application data
- End of connection

We will take a closer look at the handshake later on.

History

SSL protocol developed in the mid nineties by Netscape.

- Legacy versions:
  - SSL 1.0 (never released)
  - SSL 2.0 (1995–2011)
  - SSL 3.0 (1996–2015)
  - TLS 1.0 (1999–2020?)
  - TLS 1.1 (2006–2020?)
- Current versions:
  - TLS 1.2 RFC 5246 (2008), refined in RFC 6176 (2011).
  - TLS 1.3 RFC 8446 (2018).

TLS 1.2 vs TLS 1.3

TLS 1.2 is still fine.

TLS 1.3 brings some improvements:

- Legacy algorithms removed
- Better elliptic curve support (no point format negotiation)
- Forward secrecy
- Optimized handshake state machine
- Much more...

Summary: improved cryptography and performance.

The TLS 1.2 handshake

The TLS 1.2 handshake takes two full round trips:

1. Client initiates handshake: ClientHello.
2. Server responds:
   ServerHello, Certificate, ServerKeyExchange, ServerHelloDone
3. Client responds:
   ClientKeyExchange, ChangeCipherSpec, Finished
4. Server finishes up:
   ChangeCipherSpec, Finished

This usually takes 300 – 500 milliseconds.

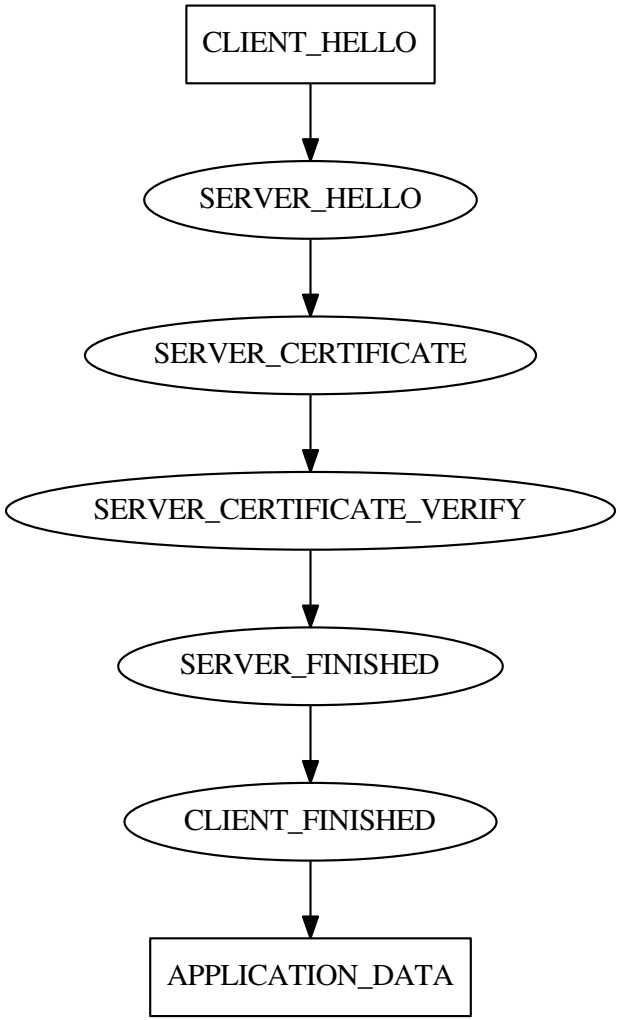
The TLS 1.3 handshake

The TLS 1.3 handshake takes only one round trip:

1. The ClientHello includes the client key exchange.
2. Server sends ServerHello, Certificate, CertificateVerify, ServerFinished.
3. Client sends ClientFinished

Takes about 200 – 350 milliseconds.

Visualization



Basic design of the state machine

Fundamental observation: while the RFC's state machine has a loop, it can be modeled on a directed acyclic graph (DAG).

Therefore it is possible to enumerate all legal paths.

Linearized in a static table.

Design based on s2n's state machine.

Main property

At every point we know what message comes next and we can call a specialized handler.

Almost... After the encrypted extensions there is no way to know whether the server will send a certificate request or a certificate message. Needs an ugly workaround.

By design, we are safe from out-of-order messages (cf. libssh).

The message types

```
enum tls13_message_type {
        INVALID,
        CLIENT_HELLO,
        SERVER_HELLO,
        CLIENT_HELLO_RETRY,
        ...
        APPLICATION_DATA,
        TLS13_NUM_MESSAGE_TYPES,
};
```

The handshake actions

Every message type has an associated action:

```
struct tls13_handshake_action {
        uint8_t handshake_type;
        uint8_t sender;
        uint8_t handshake_complete;
        uint8_t preserve_transcript_hash;

        int (*send)(struct tls13_ctx *ctx);
        int (*sent)(struct tls13_ctx *ctx);
        int (*recv)(struct tls13_ctx *ctx);
};
```

Example:

```
[CLIENT_HELLO] = {
        .handshake_type = TLS13_MT_CLIENT_HELLO,
        .sender = TLS13_HS_CLIENT,
        .send = tls13_client_hello_send,
        .recv = tls13_client_hello_recv,
},
```

The handshakes table

```
enum tls13_message_type handshakes[]
        [TLS13_NUM_MESSAGE_TYPES] = {
    ...
            [NEGOTIATED | WITHOUT_CR] = {
                    CLIENT_HELLO,
                    SERVER_HELLO,
                    SERVER_ENCRYPTED_EXTENSIONS,
                    SERVER_CERTIFICATE,
                    SERVER_CERTIFICATE_VERIFY,
                    SERVER_FINISHED,
                    CLIENT_FINISHED,
                    APPLICATION_DATA,
            },
    ...
```

Advancing the state machine

Simply increment a value:

```
int
tls13_handshake_advance_state_machine
    (struct tls13_ctx *ctx)
{
        if (++ctx->handshake_stage.message_number
            >= TLS13_NUM_MESSAGE_TYPES)
                return 0;

        return 1;
}
```

Regress tests

The handshakes table is generated by code in the regress test.

```
$ cd /usr/src/regress/lib/libssl/handshake
$ make print
```

Tests are run daily by bluhm@ on his regress machines.

Visualization

Regress target to generate graphics in various formats. Uses the math/graphviz package (thanks, edd@).

```
$ cd /usr/src/regress/lib/libssl/handshake
$ doas pkg_add graphviz
$ make handshake.png
```

References

- RFC 8446
- A Detailed Look at RFC 8446
- Source code: lib/libssl, regress/lib/libssl/handshake
- Tweet thread by Colm MacCárthaigh

Status of TLS 1.3 in LibreSSL

About 60% there.

The client side is mostly done

Work on the server side has not yet started

Thanks

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- bluhm@
- schwarze@
- sthen@

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