# MTAT.07.017
# Applied Cryptography

Transport Layer Security (TLS)

University of Tartu

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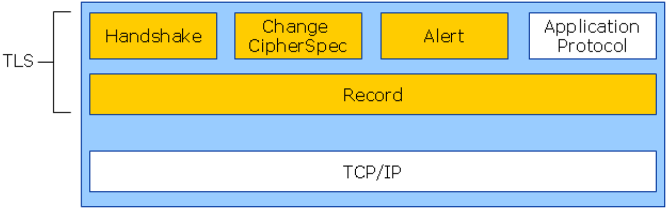
# Transport Layer Security (TLS)

"TLS is a cryptographic protocol that provides communication security over the Internet."

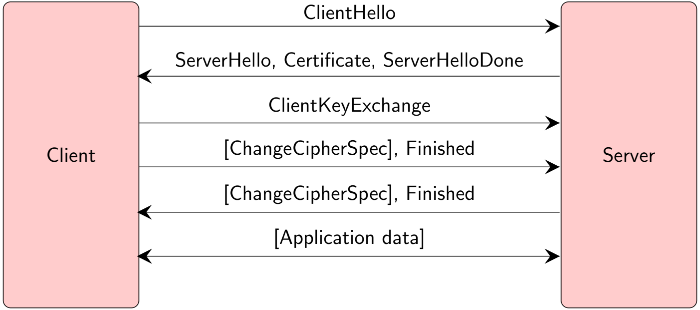
- Provides confidentiality, integrity and server authentication
- The most successful and widely used cryptographic protocol (!!!)
- Any application protocol can be encapsulated in TLS



# TLS version history

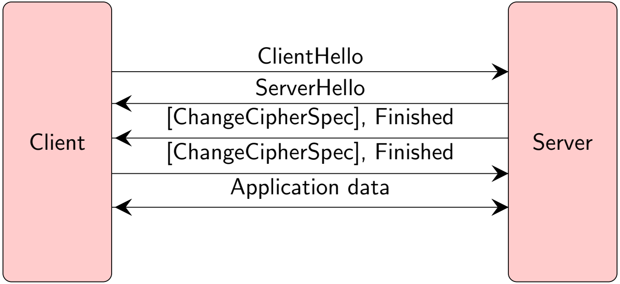
- SSL 1.0 – never publicly released
- SSL 2.0 – Netscape (1995)
- SSL 3.0 – Netscape (1996)
- TLS 1.0 (SSL 3.1) – RFC 2246 (1999)
- TLS 1.1 – RFC 4346 (2006)
- **TLS 1.2** – RFC 5246 (2008)
- TLS 1.3 – RFC 8446 (2018)

# TLS handshake




- Client verifies server's X.509 certificate
- Client extracts the server's public key from the certificate
- Client encrypts a random symmetric key using the server's public key
- Only the server can decrypt the symmetric key
- Now the client and server share the same symmetric key
- Symmetric key is used for the actual data encryption/authentication

# TLS session resumption

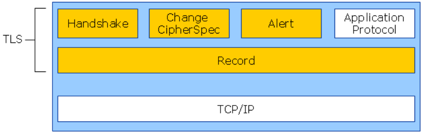


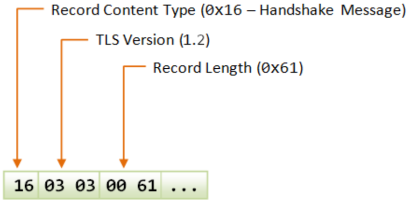

- Resumed TLS connections share the same "master secret"
- Several TLS *connections* can belong to the same TLS *session*
- If TLS connection fails, the TLS session becomes non-resumable
- Abbreviated handshake improves performance, saving:
  - 1 round-trip time across the network
  - 1 asymmetric crypto operation

# TLS Record Layer

`[Type] [Version] [Length] [Data]`

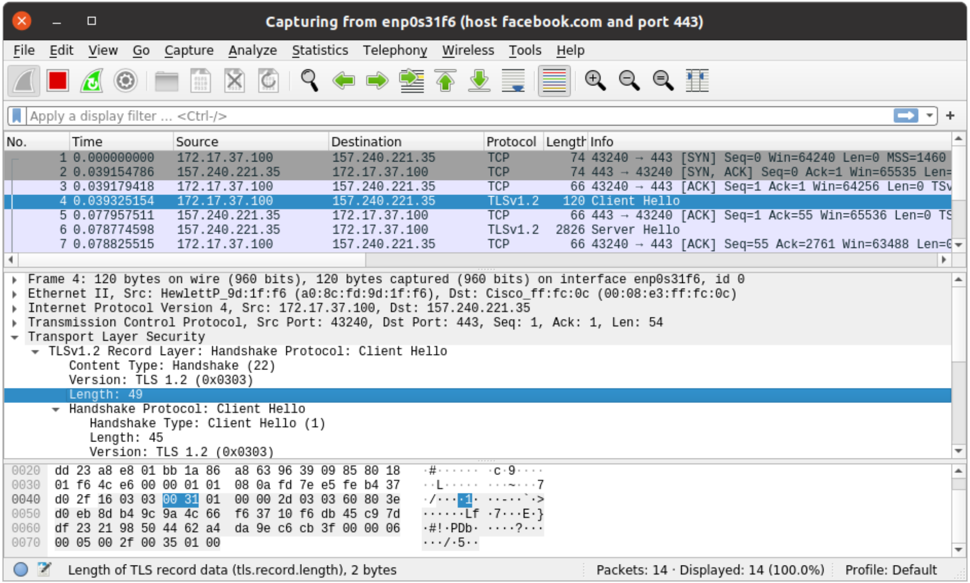
- Type: type of encapsulated data:
  - Handshake message (`0x16`)
  - Change Cipher Spec message (`0x14`)
  - Alert message (`0x15`)
  - Application data (`0x17`)
- Protocol version: 0x0303 (for TLS v1.2)
- Length: length of the data (2 bytes)
- Data: encapsulated data
  - Can contain several same type messages




TLS record header is never encrypted!

# Dissecting TLS with Wireshark



# Alert message

Signals about TLS related issues to other party

`[Level] [Description]`

- Level (1 byte):
  - Warning (0x01)
  - Fatal (0x02)
- Description (1 byte):

```
close_notify(0),
unexpected_message(10),
bad_record_mac(20),
decryption_failed(21),
handshake_failure(40),
bad_certificate(42),
unsupported_certificate(43),
certificate_revoked(44),
certificate_expired(45),
illegal_parameter(47),
unknown_ca(48),
access_denied(49),
decrypt_error(51),
user_canceled(90),
...
```

```
▾ TLSv1.2 Record Layer: Alert (Level: Fatal, Description: Certificate Unknown)
    Content Type: Alert (21)
    Version: TLS 1.2 (0x0303)
    Length: 2
  ▾ Alert Message
      Level: Fatal (2)
      Description: Certificate Unknown (46)
```

# Change Cipher Spec message

Signals to other party that from now on, the negotiated cipher suite will be used to protect outgoing messages

`[0x01]`

```
▾ TLSv1.2 Record Layer: Change Cipher Spec Protocol: Change Cipher Spec
    Content Type: Change Cipher Spec (20)
    Version: TLS 1.2 (0x0303)
    Length: 1
    Change Cipher Spec Message
```

# Application data

Contains (most likely encrypted) application data in a form as required by the application protocol (e.g., HTTP request/response etc.)

`[Application Data]`

```
▾ TLSv1.2 Record Layer: Application Data Protocol: http-over-tls
    Content Type: Application Data (23)
    Version: TLS 1.2 (0x0303)
    Length: 38
    Encrypted Application Data: f48f13030665f43f3d9a07ba27dcc824c4dc8dfbe9e1
```

# Handshake message

Contains protocol handshake parameters

`[Type] [Length] [Body]`

- Type: message type:

```
hello_request(0), client_hello(1), server_hello(2),
certificate(11), server_key_exchange (12),
certificate_request(13), server_hello_done(14),
certificate_verify(15), client_key_exchange(16),
finished(20)
```

- Length: length of the body (3 bytes)
- Body: message body
  - Can be split over several TLS records

# Handshake message: ClientHello

- The highest TLS version supported (2 bytes)
- Client randomness (32 bytes)
  - Timestamp in first 4 bytes
- Session ID length (1 byte) + session ID
- Cipher suites length (2 bytes)
- List of cipher suites supported:
  - 0x0005 – TLS_RSA_WITH_RC4_128_SHA
  - 0x002f – TLS_RSA_WITH_AES_128_CBC_SHA
  - 0x0035 – TLS_RSA_WITH_AES_256_CBC_SHA
  - 0x0039 – TLS_DHE_RSA_WITH_AES_256_CBC_SHA
- Compression methods length (1 byte)
- List of compression methods supported:
  - 0x00 – null (mandatory)
  - 0x01 – DEFLATE (gzip)
- Extensions (optional)

```
▾ TLSv1.2 Record Layer: Handshake Protocol: Client Hello
    Content Type: Handshake (22)
    Version: TLS 1.2 (0x0303)
    Length: 49
  ▾ Handshake Protocol: Client Hello
      Handshake Type: Client Hello (1)
      Length: 45
      Version: TLS 1.2 (0x0303)
    ▾ Random: 60803ad638faf11c374c0607f5df0fd3e592e0d3569c18
        GMT Unix Time: Apr 21, 2021 17:46:46.000000000 EEST
        Random Bytes: 38faf11c374c0607f5df0fd3e592e0d3569c18
      Session ID Length: 0
      Cipher Suites Length: 6
    ▾ Cipher Suites (3 suites)
        Cipher Suite: TLS_RSA_WITH_RC4_128_SHA (0x0005)
        Cipher Suite: TLS_RSA_WITH_AES_128_CBC_SHA (0x002f)
        Cipher Suite: TLS_RSA_WITH_AES_256_CBC_SHA (0x0035)
      Compression Methods Length: 1
    ▾ Compression Methods (1 method)
        Compression Method: null (0)
```

# Handshake message: ServerHello

- TLS version selected (2 bytes)
- Server randomness (32 bytes)
  - Timestamp in first 4 bytes
- Session ID length (1 byte) + session ID
- Cipher suite selected (2 bytes)
- Compression method selected (1 byte)
- Extensions (optional)

```
▾ TLSv1.2 Record Layer: Handshake Protocol: Server Hello
    Content Type: Handshake (22)
    Version: TLS 1.2 (0x0303)
    Length: 74
  ▾ Handshake Protocol: Server Hello
      Handshake Type: Server Hello (2)
      Length: 70
      Version: TLS 1.2 (0x0303)
    ▾ Random: 60803c7e5b8903bc2ee3981a90f4ee8ee7b5a2451bdd7e8a
        GMT Unix Time: Apr 21, 2021 17:53:50.000000000 EEST
        Random Bytes: 5b8903bc2ee3981a90f4ee8ee7b5a2451bdd7e8
      Session ID Length: 32
      Session ID: 47c681a76422c7a046a0a2ac1d318305e70caa7856e4
      Cipher Suite: TLS_RSA_WITH_AES_128_CBC_SHA (0x002f)
      Compression Method: null (0)
```

# Handshake message: Certificate

- Length of certificate list (3 bytes)
- List of certificates
  - Certificate length (3 bytes)
  - DER encoded certificate
- The first is server's certificate
- Other certificates are optional
  - Usually intermediate CA certificates

```
▾ TLSv1.2 Record Layer: Handshake Protocol: Certificate
    Content Type: Handshake (22)
    Version: TLS 1.2 (0x0303)
    Length: 2986
  ▾ Handshake Protocol: Certificate
      Handshake Type: Certificate (11)
      Length: 2982
      Certificates Length: 2979
    ▾ Certificates (2979 bytes)
        Certificate Length: 1768
      ▸ Certificate: 308206e4308205cca00302010202100a9ce9bf5
        Certificate Length: 1205
      ▸ Certificate: 308204b130820399a00302010202100 4e1e7a4d
```

# Handshake message: ServerHelloDone

- Empty message body
- Indicates that there will be no more messages from the server in this protocol round

```
▾ TLSv1.2 Record Layer: Handshake Protocol: Server Hello Done
    Content Type: Handshake (22)
    Version: TLS 1.2 (0x0303)
    Length: 4
  ▾ Handshake Protocol: Server Hello Done
      Handshake Type: Server Hello Done (14)
      Length: 0
```

# Handshake message: ClientKeyExchange

Contains an (two-byte length-prefixed) encrypted 48-byte random “pre-master secret”

- Encrypted using the public key from the server’s certificate
- Encrypted according to PKCS#1 v1.5
- The first two bytes in the pre-master secret contain the TLS version
  - Must be checked by the server
  - Prevents some attacks (?)
- Next 46 bytes are truly random bytes

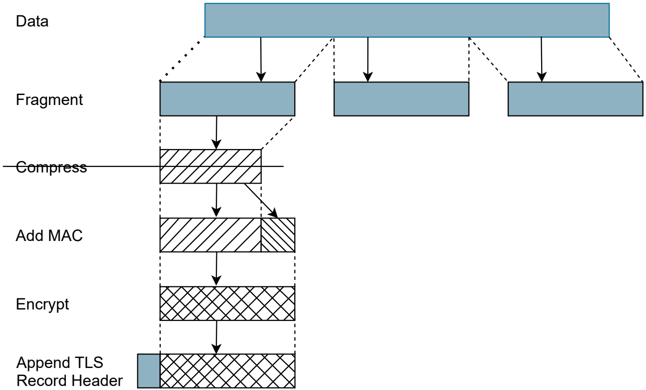
```
▾ TLSv1.2 Record Layer: Handshake Protocol: Client Key Exchange
    Content Type: Handshake (22)
    Version: TLS 1.2 (0x0303)
    Length: 262
  ▾ Handshake Protocol: Client Key Exchange
      Handshake Type: Client Key Exchange (16)
      Length: 258
    ▾ RSA Encrypted PreMaster Secret
        Encrypted PreMaster length: 256
        Encrypted PreMaster: cab3417a3aaac5a3299df9f35c197ec6
```

# Handshake message: Finished

- The first encrypted message
- Serves to verify whether encryption works
- Contains a hash of the concatenation of all previous handshake messages (excluding the TLS record header)
  - Must be verified by other party to detect downgrade attacks

```
▾ TLSv1.2 Record Layer: Handshake Protocol: Encrypted Handshake Message
    Content Type: Handshake (22)
    Version: TLS 1.2 (0x0303)
    Length: 36
    Handshake Protocol: Encrypted Handshake Message
```

# TLS encryption process




- How many symmetric keys are needed?
  - MAC & encrypt (+ IV for block ciphers)
  - Separate keys for each direction
- How do we derive these keys from the 48-byte pre-master secret?

# Key derivation

- TLS defines PRF() (pseudo-random function)
  - Uses SHA256
  - Produces infinitely long pseudo-random output
- From the 48-byte “pre-master secret” a 48-byte “master secret” is derieved:

```
master_secret = PRF(premaster + 'master secret' + client_random + server_random, 48)
```

- From the “master secret” a key block in the size needed is derived:

```
key_block = PRF(master_secret + 'key expansion' + server_random + client_random, 136)
```

- The key block is split into the keys needed:

```
client_mac_key = key_block[:20]
server_mac_key = key_block[20:40]
client_enc_key = key_block[40:56]
server_enc_key = key_block[56:72]
client_iv = ...
...
```

# MAC calculation

```
HMAC_hash(key, seq + type + version + length + data)
```

- hash: hash algorithm from the negotiated cipher suite
- key: client/server MAC key
- seq: client/server sequence number (8 bytes)
  - Starts from 0
  - Incremented for every TLS record sent
- type: TLS record type
- version: TLS protocol version (2 bytes)
- length: length of the data (2 bytes)
- data: TLS record payload

# Task: TLS getcert

Implement a TLS v1.2 client that can retrieve a server's certificate:

```
$ ./tls_getcert.py https://facebook.com/ --certificate server.pem
--> ClientHello()
<--- Handshake()
        <--- ServerHello()
        [+] server randomness: 14CEF697777BB51D0AFA367E78689AF86152BDF47D8D7C71B0BB6C2AD279FE32
        [+] server timestamp: 1981-01-23 17:24:23
        [+] TLS session ID: 2AF350EFDBC0FEC91D55E68B837C58E86FEA4140632508D7B6C8217F43765757
        [+] Cipher suite: TLS_RSA_WITH_AES_128_CBC_SHA
<--- Handshake()
        <--- Certificate()
        [+] Server certificate length: 1768
        [+] Server certificate saved in: server.pem
<--- Handshake()
        <--- ServerHelloDone()
--> Alert()
[+] Closing TCP connection!

$ openssl x509 -in server.pem -text | grep 'Subject:'
        Subject: C = US, ST = California, L = Menlo Park, O = "Facebook, Inc.", CN = *.facebook.com
```

| | | | | | | |
|---|---|---|---|---|---|---|
| 4 | 0.038276599 | 172.17.37.100 | 157.240.221.35 | TLSv1.2 | 120 | Client Hello |
| 5 | 0.076361047 | 157.240.221.35 | 172.17.37.100 | TCP | 66 | 443 → 42240 [ACK] Seq=1 Ack=55 Win=65536 Len=0 TSval=2489148823 TSecr=4247465819 |
| 6 | 0.077064049 | 157.240.221.35 | 172.17.37.100 | TLSv1.2 | 2826 | Server Hello |
| 7 | 0.077076735 | 172.17.37.100 | 157.240.221.35 | TCP | 66 | 42240 → 443 [ACK] Seq=55 Ack=2761 Win=63488 Len=0 TSval=4247465858 TSecr=2489148823 |
| 8 | 0.077064098 | 157.240.221.35 | 172.17.37.100 | TLSv1.2 | 385 | Certificate, Server Hello Done |
| 9 | 0.077090855 | 172.17.37.100 | 157.240.221.35 | TCP | 66 | 42240 → 443 [ACK] Seq=55 Ack=3080 Win=63232 Len=0 TSval=4247465858 TSecr=2489148823 |
| 10 | 0.086159677 | 172.17.37.100 | 157.240.221.35 | TLSv1.2 | 73 | Alert (Level: Fatal, Description: Certificate Unknown) |

# Task: TLS getcert

```
$ ./tls_getcert.py https://twitter.com/
--> ClientHello()
<--- Handshake()
        <--- ServerHello()
        [+] server randomness: B5319D1EAF32F2E74B7867D6A871B062FBC5A78DE7E4551E6076A128B30BA7B6
        [+] server timestamp: 2066-05-01 11:19:42
        [+] TLS session ID:
        [+] Cipher suite: TLS_RSA_WITH_AES_128_CBC_SHA
<--- Handshake()
        <--- Certificate()
        [+] Server certificate length: 1606
<--- Handshake()
        <--- ServerHelloDone()
--> Alert()
[+] Closing TCP connection!

$ ./tls_getcert.py https://live.com/
--> ClientHello()
<--- Handshake()
        <--- ServerHello()
        [+] server randomness: 608023ADFD820BF1FEEDC57B939263DB5BF2A3F3A4BD2589DEC1FFAB64EDF075
        [+] server timestamp: 2021-04-21 16:07:57
        [+] TLS session ID: D73D00004387C0F7403F8D97241972CDDF7E108D61A1B8E24F48A8FE538E187B
        [+] Cipher suite: TLS_RSA_WITH_AES_256_CBC_SHA
        <--- Certificate()
        [+] Server certificate length: 2015
        <--- ServerHelloDone()
--> Alert()
[+] Closing TCP connection!
```

# Task: TLS getcert

- Use Wireshark to see what bytes are actually sent out over the network
  - Use capture filters `'host twitter.com and port 443'`
- NB! One TLS record can contain several handshake messages
- Unix timestamp can be obtained using `int(time.time())`
- Unix timestamp can be printed using:

```
datetime.datetime.fromtimestamp(int(time.time())).strftime('%Y-%m-%d %H:%M:%S')
```

# Task: TLS client (next homework)

Implement a TLS v1.2 client that can obtain an HTTP GET response:

```
$ ./tls_client.py https://127.0.0.1:4433/
--> ClientHello()
<--- Handshake()
        <--- ServerHello()
        [+] server randomness: 60828BA632D28C1E49A5532585E14F6A46390AC448E0F4F0AF99654F3D979BC9
        [+] server timestamp: 2021-04-23 11:56:06
        [+] TLS session ID:
        [+] Cipher suite: TLS_RSA_WITH_RC4_128_SHA
<--- Handshake()
        <--- Certificate()
        [+] Server certificate length: 554
<--- Handshake()
        <--- ServerHelloDone()
--> ClientKeyExchange()
--> ChangeCipherSpec()
--> Finished()
<--- ChangeCipherSpec()
<--- Handshake()
        <--- Finished()
--> Application_data()
GET / HTTP/1.0
<--- Application_data()
HTTP/1.0 200 OK
Content-Length: 6

Hello!
[+] Closing TCP connection!
```

# Task: TLS client

- Client has to support `TLS_RSA_WITH_RC4_128_SHA` cipher suite
- Template contains fully implemented `PRF()`, `derive_master_secret()`, `derive_keys()`, `encrypt()`, `decrypt()` and client/server Finished hash calculation code
  - Make sure that the correct inputs are provided to these functions (!!!)
- Grading:
  - 3 points if the server accepts your ClientKeyExchange message
  - 2 points if the server accepts your Finished message
  - 2 points if your code can show the HTTP response
- `tls_server` binary can be used for development (port 4433)
- Wireshark: “Decode As” → “TCP Destination 4433” → “TLS”

# Debugging

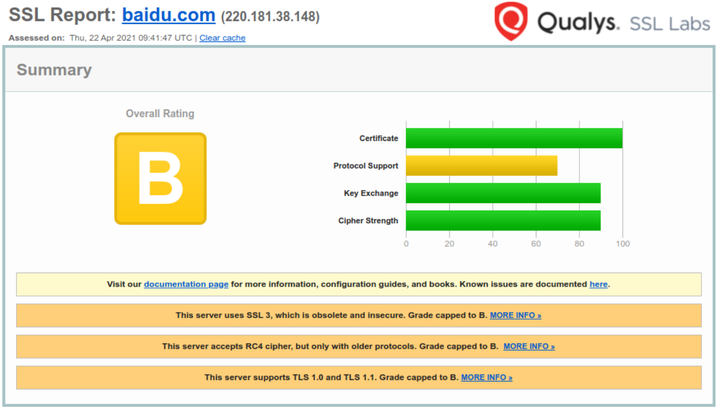
```
$ ./tls_server --port 4433
[+] Connection from 127.0.0.1:36098
<--- Handshake()
        <--- ClientHello()
        [+] version: 0303
        [+] client randomness: 60828BA6C11163C5B41E3DB1DE4717B83F12ED088844DEB424A6DBB2C3415DD4
        [+] client timestamp: 2021-04-23 11:56:06
        [+] TLS session ID:
        [+] Cipher suites:
                TLS_RSA_WITH_RC4_128_SHA
        [+] Compression methods:
                null
        [+] Extensions length: 0
--> ServerHello()
        [+] server randomness: 60828BA632D28C1E49A5532585E14F6A46390AC448E0F4F0AF99654F3D979BC9
        [+] server timestamp: 2021-04-23 11:56:06
        [+] TLS session ID:
        [+] Cipher suite: TLS_RSA_WITH_RC4_128_SHA
--> Certificate()
        [+] Server certificate length: 554
--> ServerHelloDone()
<--- Handshake()
        <--- ClientKeyExchange()
        [+] PreMaster length: 128
        [+] PreMaster (encrypted): 61897cea2123d2a5a0b4811da54f134e454ba12a9fa0ae42cf6c9c6a4cc8406151e6f3683738522695e37be0574937d472666efbe500ac597d569afb00d7a9
        [+] PreMaster: 03039e1742dfe8ab14cbe4ffd13aef7ea43a73dab09a6bfc38ec4e34700b2044f50984a56f1005d34325e3473db4b98a
<--- ChangeCipherSpec()
        [+] Applying cipher suite:
                [+] master_secret = PRF(03039e1742dfe8ab14cbe4ffd13aef7ea43a73dab09a6bfc38ec4e34700b2044f50984a56f1005d34325e3473db4b98a, "master secret" + 60828
                [+] master_secret: 5b16adaa3647949e0d5227295515421cec049d5635787ff4da00651fc070bf16a8a83650393aa5535fbe51dcdb1e6d59
                [+] client_mac_key: 6fdc0e10aa5d2e9128571d46a4f57a762882827c
                [+] server_mac_key: e864f54aefa6ecb29d81617d68afa4d49bcd00ee
                [+] client_enc_key: 912d2a8d4db049e4eed821c3aae43a04
                [+] server_enc_key: b2a9d386372dd9e253c420e0c459731d
<--- Handshake()
        <--- Finished()
        [+] client_verify (received): 04b3cb0ef05733b0da3c27d6
        [+] client_verify (calculated): 04b3cb0ef05733b0da3c27d6
--> ChangeCipherSpec()
--> Finished()
<--- Application_data()
GET / HTTP/1.0
```

# RC4 (TLS_RSA_WITH_RC4_128_SHA)

```
$ ./tls_client.py https://facebook.com/
--> ClientHello()
<--- Alert()
        [-] fatal: 40

$ ./tls_client.py https://twitter.com/
--> ClientHello()
<--- Alert()
        [-] fatal: 40

$ ./tls_client.py https://baidu.com/
--> ClientHello()
<--- Handshake()
        <--- ServerHello()
        [+] server randomness: 91F35EC232AAB567
        [+] server timestamp: 2047-08-05 22:23:
        [+] TLS session ID: D9C239963DB4654D544
        [+] Cipher suite: TLS_RSA_WITH_RC4_128_
<--- Handshake()
        <--- Certificate()
        [+] Server certificate length: 1753
<--- Handshake()
        <--- ServerHelloDone()
--> ClientKeyExchange()
--> ChangeCipherSpec()
--> Finished()
<--- ChangeCipherSpec()
<--- Handshake()
        <--- Finished()
--> Application_data()
GET / HTTP/1.0
<--- Alert()
        [-] warning: 0
[+] Closing TCP connection!
```



# Most common pitfalls

- Server fails to verify MAC of client's Finished message
  - Make sure client's Finished message is encrypted using the correct keys. Compare keys – if they are different make sure the key derivation receives the correct premaster secret and client and server randomness values.
  - Make sure that MAC is calculated using the TLS record type and not the handshake message type
- Server fails to verify hash in client's Finished message
  - Make sure all handshake messages sent and received are appended to the `handshake_messages` variable
- Client fails to verify hash in server's Finished message
  - Plaintext version of client's Finished message must be appended to the `handshake_messages`
- Server returns fatal Alert "decryption failed" after receiving client's Finished message
  - Make sure the server did not choose a non-RC4 cipher suite