ADVANCED INFORMATION SYSTEM SECURITY

Hoping to get a better grade this time around.

Fabio Lorenzato

October 17, 2024

Contents

Chapter 1

Transport Layer Security

TLS, or Transport Layer Security, was originally proposed by Netscape in 1995 as a way to secure communications between a web browser and a web server. It is the successor to SSL, or Secure Sockets Layer, which was first introduced by Netscape in 1995. The two terms are often used interchangeably, but TLS is the more modern and secure protocol.
The main goal of SSL was to create secure network channel, almost at session level(4.5), between two parties, to provide some security services that neither TCP nor IP provides:

- **peer authentication** based on asymmetric challenge-response authentication(the challenge for the service is implicit, while for the client is explicit). Server authentication is alway compulsory, while client authentication is optional and requested by the server.
- **message confidentiality** base on symmetric encryption
- **message integrity** and authentication based on MAC computed on the trasmitted data
- **replay, filtering and reordering attack protection** using implicit record numbers(the correct order of transmission is provided by TCP, for this reason the number is implicit). This number is used also in the MAC computation.

You can see the TLS packet structure in figure 1.1. The TLS handshake protocol is used to establish a new session or reestablish an existing session. The TLS change cipher spec protocol is used to trigger the change of the algorithms to be used for message protection, or most notably to pass from the previous unprotected session to a protected one. The TLS alert protocol is used to signal errors or signal the end of the connection. The TLS record protocol contains the generic protocols informations and its content depend of the state of the connection and the protocol it is tunneling.

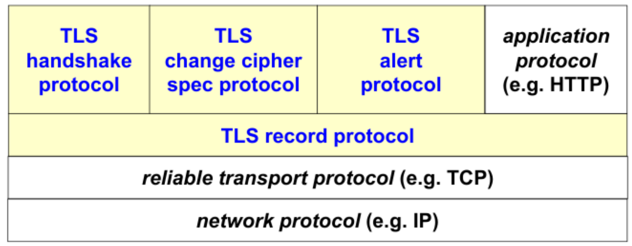


Figure 1.1: TLS packet structure.

1.1 TLS session and connection

It is important to make a clear distinction between TLS session and connections.
TLS sessions a **logical association** between client and server, created via an handshake protocol and its shared between different TLS connections(1:N).
TLS connections are a **transient TLS channel** between client and server, which means that each connection is associated with only one specific TLS session(1:1).

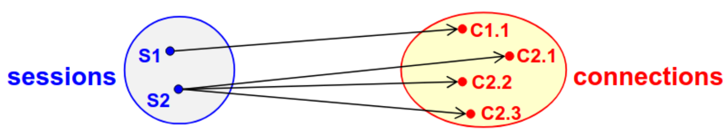


Figure 1.2: TLS session and connection.

1.2 TLS handshake protocol

The TLS handshake protocol is used to establish a new session or reestablish an existing session. It's a critical part of the TLS protocol, because the channel pass from an unprotected state to a protected one. During this phase the two parts agree agree on a set of algorithms for confidentiality and integrity, exchange random numbers between the client and the server to be used for the subsequent generation of the keys, establish a symmetric key by means of public key operations (originally RSA and DHKE, but nowadays the elliptic curve versions of algorithms are used) and negotiate the session-id and exchange the necessary public keys certificates for the asymmetric challenge-response authentication.

1.3 Achieving Data protection

Data protection is achieved by using symmetric encryption algorithms to encrypt the data and Message Authentication Codes(MAC) to ensure the integrity of the data and the authentication of the sender.
Figure 1.3 shows how the data protection is achived in TLS using authenticate-then-encrypt approachm, but also encrypt-then-authenticate is possible.
The MAC is computed over the data(compressed or not), the TLS sequence number and the key used for the MAC computation. The padding is also part of the MAC computation to avoid those attacks that change the padding.

The MAC is then encrypted with the dedicated symmetric key and a suitable initialization vector(IV)

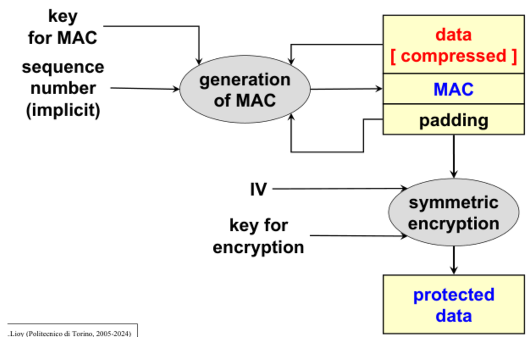


Figure 1.3: TLS data protection.

The keys are **directional**, so there are two keys(one for client to server and one for server to client) to protect against reuse of the sequence number in the opposite direction.

1.4 Relationship among keys and sessions

When a new session is created using the handshake protocol, a new **pre-master secret** is established using public key cryptography. Then from the session a new connection is created, which requires a random number to be generated, and exchanged between the client and the server. Those two values are combined via a KDF, usually HHKDF(HMAC-based key derivation function) to generate the **master secret**. This computation is done only once, and the secret is common to several connections.
The pre-master secret is then discarded, and the keys necessary for the MAC computation, encryption and, if necessary, IVs will be derived from the master secret.
You can notice that the master secret is common to any connections inside a session, but the per-connection keys are different every time. This is another important feature to avoid replay attacks, possible because numbering is per-connection. This solution also allows to reduce the cost of establishing new keys for each connection.

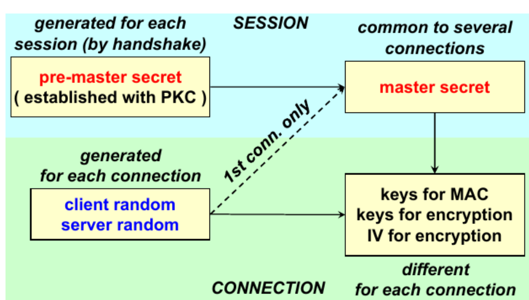


Figure 1.4: Relationship among keys and sessions.

1.5 Perfect Forward Secrecy

Since the keys are generated from symmetric crypto, if the private key used to perform encryption and decryption of the pre-master secret is compromised, all the previous communication can be decrypted because it is possible to derive the master-secret. This is only possible if the server has a certificate valid for both signature and encryption In this context, perfect forward secrecy is desirable.

> **Perfect Forward Secrecy** is a property of key-agreement protocols ensuring that the compromise of the secret key used for will compromise only current (and eventually future) traffic but not the past one

The most common way to achieve this is to use **ephemeral keys**, which are one-time asymmetric keys(used for key exchange). This means that the key pair used for key exchange is not a long term key pair, but a temporary one generated on-the-fly when necessary.
The ephemeral key needs to be authenticated, so only for this purpose the long-term key is used for signing the ephemeral key. This is done using DHKE instead of RSA because the latter one is really slow, while the former one is faster with the compromise of only using the established key for a certain number of session.
Let's now go over some considerations: if the temporary key is compromised, perfect forward secrecy of the communication is still valid because he can only decrypt the traffic exchanged using the temporary key. On the contrary, if the long-term key is compromised, no secret is really disclosed, because no traffic has been exchanged using it for encryption, but is still a problem for server authentication.

1.6 The protocol

The TLS handshake is always initiated by the client.

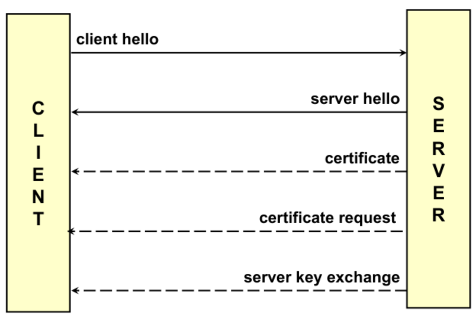
1.6.1 Client Hello and Server Hello

In version 1.2 the client sends a **Client Hello**, which contains:

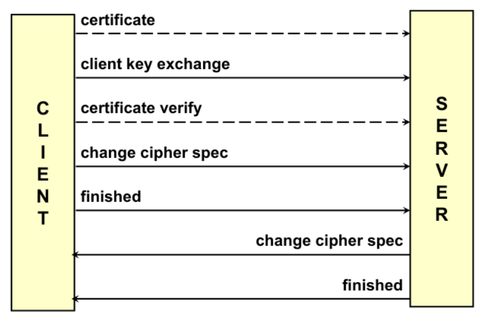
- the SSL version preferred by the client, and the highest supported(2=SSL-2, 3.0=SSL-3, 3.1=TLS-1.0, . . .)
- a 28 bytes pseudo-random number, which is the client random
- a session-id, which is *0* if the client is starting a new session, and *1* if the client is trying to resume a previous session
- a list of cipher suites supported by the client, in order to let the server choose the most secure one (the set of algorithms used for encryption, for key exchange, and for integrity)
- a list of compression methods supported by the client (supported only up to TLS 1.2)

And then a **server hello** is sent back, which contains:

- the SSL version chosen by the server, the highest one supported by both the client and the server
- a 28 bytes pseudo-random number, which is the server random
- a session identifier(session-id), which is a new one if the server is starting a new session, and the same as the client's if the server is resuming a previous session
- the cipher suite chosen by the server, the strongest common one between the client and the server
- the compression method chosen by the server



(a) The TLS handshake protocol(TLS 1.2).



(b) The TLS handshake protocol(TLS 1.3).

1.6.2 Cipher suite

A cipher suite is a string which contains the set of cryptographic algorithms used in the TLS protocol. A typical cipher suite consists of a key exchange algorithm, the symmetric encryption algorithm, and the hash function used for generating MACs. Some example of those are:

- SSL_NULL_WITH_NULL_NULL (no protection, used for the record protocol to be used in the handshake)
- SSL_RSA_WITH_NULL_SHA
- SSL_RSA_EXPORT_WITH_RC2_CBC_40_MD5
- SSL_RSA_WITH_3DES_EDE_CBC_SHA

1.6.3 Certificates

After the initial exchange, the server is ready to authenticate itself.
The server sends its long-term public key certificate to the client for server authentication. Actually, the whole certificate chain, up to the root CA, must be sent. Furthermore , the subject of the certificate must match the server name.
Server authentication is implicit, because its private key is used to decrypt the pre-master secret, while client authentication is always explicit.

> The implicit server authentication is based on the fact that the MAC is computed trough the key derived trough knowledge of the private key, so only the server can compute it.

Optionally, the server can request a certificate from the client for client authentication. In this case the server specifies the list of trusted CA's, and the client sends its certificate chain. The browsers show to the users (for a connection) only the certificates issued by trusted CAs. If client certificate verification is required, an explicit request to send the hash computed over all the handshake messages before this one and encrypted with the client private key is sent to the client.

1.6.4 Key exchange

The key exchange is the most important part of the handshake protocol. If the server is using RSA for key exchange, the client generates a pre-master secret, encrypts it with the server's public key(which can be ephemeral or from its x.509 certificate) and sends it to the server. If RSA is no used, DHKE can be used to generate the pre-master secret, and in this case the server computes the value independently and the two parts can derive the master secret.
Another option is to use FORTEZZA, which is a key exchange algorithm based on DH.

1.6.5 Certificate verify

In case the server requested client authentication, the client will be required to send the certificate to prove that he is the owner of it's private key. The message to be signed is the hash of all the messages exchanged up to this point in the handshake protocol. This is to avoid replay attacks too.

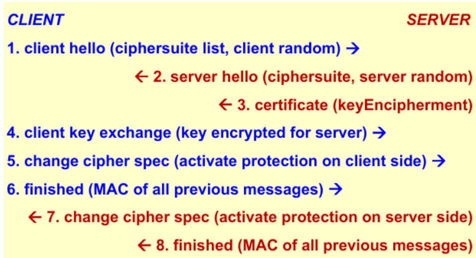
1.6.6 Change cipher spec

The change cipher spec message used to trigger the change of the algorithms to be used for message protection. It allows to pass from the previous unprotected messages to the protection of the next messages with algorithms and keys just negotiated, thus is technically a protocol on its own and not part of the handshake. Some analysis even say that it could be removed from it.

1.6.7 Finished message

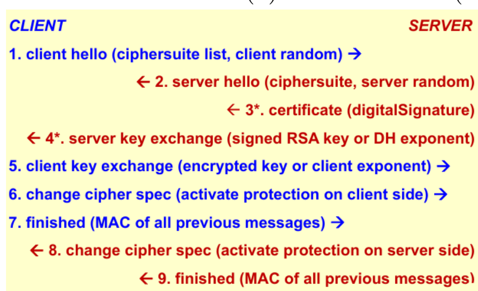
The finished message is the last message of the handshake protocol, and the first message protected by the negotiated keys and algorithms. It is necessary to ensure that the handshake has not been tampered with, and it contains contains a MAC computed over all the previous handshake messages (but change cipher spec) using as a key the master secret. Notice that the finished message is different for the client and the server, because the MAC is computed over different messages.

This allows to prevent rollback man-in-the-middle attacks (version downgrade or ciphersuite downgrade)



(a) TLS handshake(no ephemeral, no client authN).

(b) TLS handshake(no ephemeral, client authN).

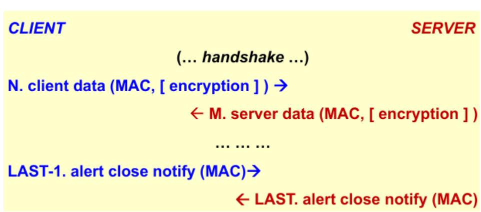


(c) TLS handshake(ephemeral, no client authN).

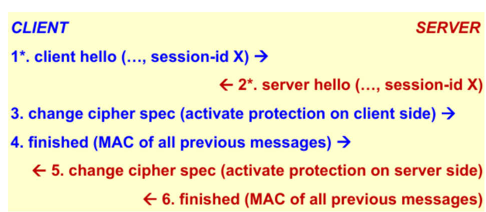
Figure 1.6: TLS handshake protocol.

1.7 Setup Time

The setup time is the time required to establish a secure connection between the client and the server. TLS depends on TCP, so the TCP handshake must be taken into account. Then the TLS handshake is performed, meaning that typically 3 RTTs (1 for TCP and 2 for TLS) are required to establish a secure connection. Usually after 180ms the two parties are ready to send protected data(assuming 30ms delay one-way).



(a) TLS link teardown.



(b) TLS resume session.

Figure 1.7: TLS link teardown and resume session.

1.8 TLS versions

1.8.1 TLS 1.0

TLS 1.0, or SSL 3.1, was released in 1999. It is the first version of the protocol, and it is based on SSL 3.0. Previous version were using proprietary solutions, so the adoption of open standards was strongly encouraged.

1.8.2 TLS 1.1

TLS 1.1 was released in 2006, and it introduced some security fixes especially to protect against CBC attacks. In fact, the implicit IV is replaced with an explicit IV to protect against CBC attacks. Also protection against padding oracle attacks were introduces to reduce the information leaks. For this reason Passing errors now use the bad_record_mac alert message (rather than the decryption_failed one). Furthermore, premature closes no longer cause a session to be non- resumable.

1.8.3 TLS 1.2

TLS 1.2 was released in 2008, and it introduced some new features and improvements. The chipersuite also specifies the pseudo random function instead of leaving the choice to the implementation. The sha-1 algorithm was replaced with SHA-256, and its also added support for authenticated encryption, such as AES in GCN or CCM mode.

All the chipersuites tat use IDEA and DES are deprecated.

1.9 TLS attacks

1.9.1 Heartbleed

Heartbleed is a security bug in the OpenSSL cryptography library, which is a widely used implementation of the TLS protocol. It was able to exploit the fact that the heartbeat extension keeps the connection alive without the need to negotiate the SSL session again. The attacker could send a heartbeat request, but the length of the response is much longer(up to 64KB) than the actual data sent by the client. This attack could then allow to leak memory contents.

1.9.2 Bleichenbacher attack

Blackenbacker is a 1998 attack and it's the so-called the million message attack because it exploited a vulnerability in the way the RSA encryption was done. RSA requires the padding to be done in a certain way, because if it is unoptimally done, it could cause some issues.
The attacker could perform an RSA private key operation with a server's private key by sending a million or so well-crafted messages and looking for differences in the error codes returned. By basically knowing the public key and trying to decrypt a message with some guessed private keys, the different responses obtained were giving hints about which bits were correct and which bits were wrong.
Later one the RSA implementations moved to RSA-OAEP, which is a padding scheme that is provably secure against chosen-ciphertext attacks.
In 2017 another variant of this attack was discovered, called ROBOT(Return Of Bleichenbacher's Oracle Threat), to which many major websites, like Facebook, were vulnerable.

1.9.3 Other attacks against SSL/TLS

Some other attacks against SSL/TLS are CRIME, BREACH, BEAST and POODLE.
Crime is an attack against the **compression algorithm** used in **SSL/TLS**, which by injection chosen plaintext in the user requests, for example by using a form or choosing fraudulently an username that is displayed, and then measure the size of the encrypted traffic, an attacker could recover specific plaintext parts exploiting information leaked from the compression, and this is part of the reason why the compression is deprecated in TLS 1.3.
BREACH is an attack against the **HTTP compression** to deduce a secret within the HTTP response provided by the server. It is different from Crime because the former is an attack against the compression algorithm used in SSL/TLS, while the latter is an attack against the HTTP compression.
BEAST is an attack that exploits a vulnerability in the way the **CBC** mode of operation is used in SSL/TLS. The attack is possible if **IV concatenation**is used, meaning that the initial vector for the next encryption is taken from the end of the previous encryption. A MITM may decrypt HTTP headers with a blockwise-adaptive chosen-plaintext attack, and by doing so, he's able to decrypt HTTPS requests and steal information such as session cookies.
POODLE, or Padding Oracle On Downgraded Legacy Encryption, is an attack that exploits the fact that SSL 3.0 uses a padding scheme that is vulnerable to a **padding oracle attack**, by acting as a MITM. This is done by exploiting SSL-3 fallbacks to decrypt data. This is also the only attack among those that still works today.
FREAK, or Factoring RSA Export Keys, is an attack that exploits the downgrades on TLS to export-level RSA keys to a factorizable bit length(512 bits). It is also possible to carry this out by downgrading the symmetric key too and then perform a brute force attack(40-bit). As you can see from figure 1.8, in the first phase the random and the supported elliptic curve are not altered by the MITM, but only the supported cipher suites are altered(to export level ones). Usually 40 bits chiper suits should not be configured at all, but some misconfigurations may happen. The third phase is where the magic happen: we have theoretically the MAC in the FINISHED message to protect against tampering (recall that the MAC will be computed over all the handshake messages) but since the MAC is protected with the master secret, the master secret is only 40 bits. The attacker can then brute force the master secret on-the-fly, recompute the MAC so that the server will accept the message. Since the attacker have access to the premaster secret and the master secret, all traffic beyond this point is encrypted with a weak shared key and the middleman can read and even modify the traffic.
For all those reasons SSL-3 has been disabled on most browsers, but its still needed for some browsers, for example IE6 by Microsoft, which is outlasting its expected life span, because its the default browser on Windows XP, which is still used today unfortunately, meaning that the window of exposure for those attacks is still open.

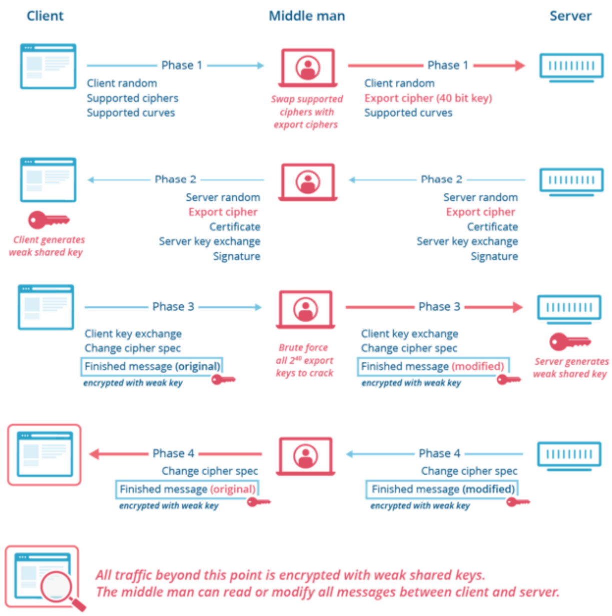


Figure 1.8: FREAK attack.

1.10 ALPN extension

The ALPN extension, or Application-Layer Protocol Negotiation, is an extension that allow to negotiate the application protocol to speed up the connection creation, avoiding additional round-trips for application negotiation. It is used to negotiate the protocol to be used on top of the TLS connection, such as HTTP/2, SPDY, or QUIC, before the connection is established. This is useful because it saves time, obviously, because after the connection is established, the client and server could still fail to communicate because the application protocol is not supported by the server.
The extension is inserted in the client hello message, by setting the ALPN flag to true and providing a list of supported protocols in the client HELLO message. The server will respond with the ALPN flag set to true(if it supports the extension) and the selected protocol.
This is also useful for those servers that use different certificates for the different application protocols.

1.11 TLS False Start

TLS False Start is another extension that allows the client can send application data together with the ChangeCipherSpec and Finished messages, in a single segment, without waiting for the corresponding server messages. The biggest advantage of using this is the reduction of the latency to 1 RTT. In theory this should work without changes, but to use this in Chrome and Firefox they require the ALPN and the Forward Secrecy enabled, while Safari requires forward secrecy.

1.12 The TLS downgrade problem

In theory, when negotiating the TLS version to be used, the client sends (in ClientHello) the highest supported version, while the server notifies (in ServerHello) the version to be used (highest in common with client).
For example if the client support up to SSL 3.3(TLS 1.2) and the server support the same version, the connection will be established using TLS 1.2. But if the server supports only SSL 3.2(TLS 1.1), the connection will be established using SSL TLS 1.1.
Some servers, instead of sending the highest version supported, just close the connection, forcing the client to retry with a lower version of the protocol. An attacker could exploit this behavior to force the client to use an older version of the protocol, by repeatedly closing the connection, and then exploit the vulnerabilities of the older version of the protocol.

> This means that its not a problem of the protocol itself, but of the implementation of the server.

1.12.1 TLS Fallback Signalling Cipher Suite Value (SCSV)

This behavior is not always an attack, for example there could be and error in the channel, which is closed by the server. This means that there's a need to distinguish between a real attack and a simple error.
The **TLS Fallback SCSV** is a **special value** that is used to prevent the protocol downgrade attacks, not only chiper suite. It do so by sending a new (dummy) ciphersuite value(TLS_FALLBACK_SCSV) which is sent by the client when opening a downgraded connection as the last value in the chipersuite list.
If the server receives this value and still supports an higher version of the protocol, it will know that the client is trying to downgrade the connection, and it will refuse to establish the connection by sending a **inappropriate_fallback** alert message an closing the channel. This notify the client that he should retry with the highest version of the protocol supported by himself.
Many servers do no support SCSV yet, but most servers have fixed their behavior when the client requests a version higher than the supported one so browsers can now disable insecure downgrade

1.13 TLS session tickets

We know that session resumption is possible with TLS, but the server needs to keep a cache of session IDs, which may become very large for high traffic servers. For this reason, the **TLS session tickets** were introduced, which are an extension allowing the server to send the session data to the client encrypted with a server secret key. This data is stored by the client, which will send it again when it wants to resume a session. This allows to move the cache to the client side. Obviously, this data has to be encrypted with a server secret key.
Even if this behaviour is desirable for the server, it still need to be supported by the browser (it's an extension after all) and needs a mechanism to share keys among the servers in a load-balancing heavy environment.

1.14 The Virtual Server Problem

Nowadays, virtual servers are very common in web hosting, because they allows to have different logical names associated with the same IP address(ie: home.myweb.it=10.1.2.3, food.myweb.it=10.1.2.3). This is easy to manage in HTTP/1.1 but quite troublesome with HTTPS, because TLS is activated before the HTTP request is sent, which makes it difficult to know which certificate should be provided in advance. The solutions are quire simple:

- use a wildcard certificate, which is a certificate that is valid for all the subdomains of a domain (ie: *.myweb.it)
- use the SNI (Server Name Indication) extension, which is an extension that allows the client to specify the hostname of the server it is trying to connect to, allowing the server to provide the correct certificate. This is sent in the ClientHello message.
- provide a certificate with a list of servers in subjectAltName, which allow to share the same private key for different servers.

1.15 TLS 1.3

TLS 1.3 was released in 2018, and it introduced some new features while solving some of the most common problems of the previous versions:

- **reduce** the **handshake latency** in general
- **encrypting** more of the **handshake** (for security and privacy, after all up to TLS 1.2 the handshake was in clear text)
- **improving resiliency** to cross-protocol attacks
- removing legacy features

We will now go over the main changes in TLS 1.3.

1.15.1 Key exchange

In this version, the support for static RSA and DH key exchange was removed for many reasons:

- it does not implement forward secrecy
- its difficult to implement correctly, which is a problem because it exposes the system to many attacks like Bleichenbacher

Now Diffie-Hellman ephemeral (DHE) and Elliptic Curve Diffie-Hellman Ephemeral (ECDHE) are the only key exchange methods supported, with some required parameters(some implementations weren't really up to the standards, ie: used DH with small numbers(just 512 bits) or generated values without the required mathematical properties).

1.15.2 Message protection

TLS 1.3 greatly improves message protection by eliminating several vulnerabilities present in earlier versions. Previously, issues arose from using CBC mode with authenticate-then-encrypt, which led to attacks like Lucky13 and POODLE. The use of RC4 also allowed plaintext recovery due to measurable biases, and compression enabled the CRIME attack.
TLS 1.3 addresses these weaknesses by removing CBC mode and enforcing AEAD modes for stronger security. Insecure algorithms such as RC4, 3DES, Camellia, MD5, and SHA-1 have been dropped, and compression is no longer used, ensuring a more secure cryptographic environment.

1.15.3 Digital signature

In TLS 1.3, digital signatures have been strengthened to address earlier vulnerabilities. Previously, RSA signatures were used on ephemeral keys with the outdated PKCS#1v1.5 schema, leading to potential flaws. The handshake was authenticated using a MAC instead of a proper digital signature, which exposed the protocol to attacks like FREAK.
TLS 1.3 improves this by using the modern, secure RSA-PSS signature scheme. Additionally, the entire handshake is signed, not just the ephemeral keys, providing more comprehensive security. The protocol also adopts modern signature schemes, enhancing the overall strength of the cryptographic process.

1.15.4 Ciphersuites

TLS 1.3 simplifies the protocol by reducing the complexity seen in earlier versions, which had a long list of cryptographic options that grew exponentially with each new algorithm. This complexity made configuration and security management difficult.
To address this, TLS 1.3 specifies only essential, orthogonal elements: a cipher (and mode) combined with an HKDF hash function. It no longer ties the protocol to specific certificate types (like RSA, ECDSA, or EdDSA) or key exchange methods (such as DHE, ECDHE, or PSK).
Moreover, TLS 1.3 narrows the selection to just five ciphersuites:

- TLS_AES_128_GCM_SHA256
- TLS_AES_256_GCM_SHA384
- TLS_CHACHA20_POLY1305_SHA256
- TLS_AES_128_CCM_SHA256
- TLS_AES_128_CCM_8_SHA256 (deprecated but yet supported for computational environments with low capacity)

1.15.5 EdDSA

EdDSA, or Edwards-curve Digital Signature Algorithm, is a digital signature scheme using the EdDSA signature scheme, which is a variant of the standard elliptic curve DSA schema. The EdDSA scheme, unlike standard DSA, doesnt require a PRNG, which could in some

cases leak the private key if the underlying generation algorithm is broken or predictable.
EdDSA picks a nonce based on a **hash of the private key** and the **message**, which means after the private key is generated there's no need anymore for random number generators. Another advantage is that the EdDSA is faster in signature generation and verification than the standard DSA, because it implements simplified point addition and doubling.
EdDSA is using an n-bit private and public keys and will generate a signature which has a size which is the double of the keys size. As per the RFC stipulations, EdDSA must support the Ed25519 and Ed448 curves, which are based on the Edwards-curve Digital Signature, which uses respectively SHA-2 and SHA-3 as hash functions. Among those two, Ed25519 is the most used, which is also used for an implementation of EcDH.
When it comes to the RFCs there's an issue: there are two RFCs that are slightly different, one is the RFC 8032, which is for general internet implementations, with the implementational details left to the developers, and there's also FIPS 186-5, which specifies not only the mathematics behind an algorithm but also implementation details because it is a standard for the US government.

1.15.6 Other improvements

TLS 1.3 introduces several key improvements to enhance security and efficiency. One major change is that all handshake messages sent after the ServerHello are now encrypted, ensuring better confidentiality during the handshake process, even if the keys have not been enstablished(we will go over the details later). The new **EncryptedExtensions** message allows additional extensions, which were previously sent in cleartext during ServerHello, to also benefit from encryption, improving privacy.
Additionally, key derivation functions have been redesigned to support easier cryptographic analysis due to their clear key separation properties. HKDF is now used as the underlying primitive for key derivation, providing a robust and flexible method.
The handshake state machine has also been overhauled, making it more consistent by removing unnecessary messages, such as **ChangeCipherSpec**, which is now only retained for compatibility with older systems. This restructuring streamlines the handshake process, reducing complexity and improving protocol efficiency.

1.15.7 HKDF in TLS 1.3

HKDF is one of the novelties of TLS 1.3, and is a HMAC-based extract-and-expand Key Derivation Function. As a normal key derivation function, it takes 4 inputs: the salt, the input keying material(which is basically a secret key), the info string and the output length. It basically takes the first 2 inputs to derive a key which will be used to derive a pseudorandom key .Then the second stage expands this key into several additional pseudorandom keys, which are the output of the KDF. So multiple outputs can be generated from the single IKM value by using different values info strings.
By calling the function repeatedly call the HMAC function with with PR keys and the info string as the input message, and then concatenate the results, by appending the output of the HMAC function to the previous output and incrementing an 8-bit counter.
This means that from one call we can generate at most $256(2^8)$ different keys.
The finished message is not protected with the master secret as it was in TLS 1.2, but with

the specific key, which is created with expand starting from the base key and putting as info the text "finished" and then the desired length. The pre-shared key to protect the ticket contains the word "resumption". So you start with some basic key material and then by using different labels, you are able to generate the different keys.

```
HKDF-Expand( HKDF-Extract ( salt, IKM ), info, length )
```

Listing 1: HKDF-Expand pseudocode.

1.15.8 TLS-1.3 handshake

Even the handshake in TLS 1.3 was changed. The first thing that we notice is that the change chiper specs has been removed from the standard.
At first, as you can see from figure 1.9, the connection starts with an hello message from the client, which will also send it's list of chipersuites and the key share material , in which the client will send it's DH parameters(it is still needed after all). All this data is sent in the same message to save some RTTs and to allow the middleboxes with lower TLS version support to understand the message, interpreting them as an extension of the client hello and thus skipping them. In fact most of the TLS 1.3 features are implemented in message extensions.
The following messages are just the specular ones but sent from the server this time. After this point it is possible to have confidentiality of the communication, because a shared key has been established(the curly braces in the picture are just for that).

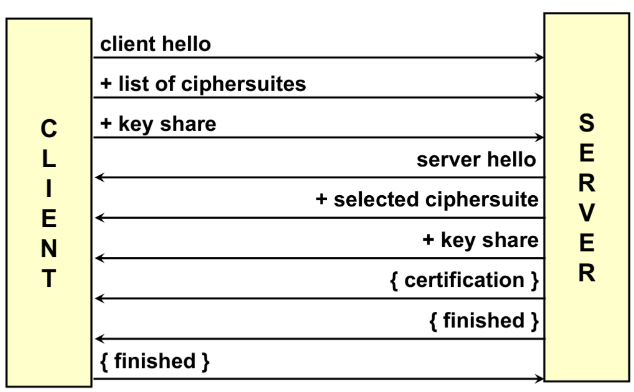


Figure 1.9: TLS 1.3 handshake.

Client request

The client hello message contains the **client random**, the highest supported protocol version(which is 1.2), client random, the supported cipher suites and compression methods(no compression allows but still necessary for backward compatibility) and of course the session id.
The supported extensions are:

- key_share = client (EC)DHE share

- signature_algorithms = list of supported algorithms
- psk_key_exchange_modes = list of supported modes for the pre-shared key exchange
- pre_shared_key = list of PSKs offered, which are not the real keys, are just an index label for the pre-shared keys available

Recall that if the extension is not supported by the server or middlebox it will be ignored.

Server response

The server will respond with it's parameters, some of which will already be encrypted because the key has been established. The key exchange material will be sent in clear of course(the key_share and the pre_shared_key).
The servers parameters are present too and encrypted, which are

- { EncryptedExtensions } = responses to non-crypto client extensions
- { CertificateRequest } = request for client certificate, optional and encrypted for privacy

Even the server authentication parameters are sent in the same message:

- { Certificate } = X.509 certificate (or raw key, RFC-7250, useful for low power IoT devices)
- { CertificateVerify } = signature over the entire handshake
- { Finished } = MAC over the entire handshake

Finally, the server can immediately send application data, if needed, which will be encrypted with the key derived for data protection, not the one derived for the handshake.

Client finish

The client will respond with the last messages, which are:

- { Certificate } = X.509 certificate (or raw key, RFC-7250)
- { CertificateVerify } = signature over the entire handshake
- { Finished } = MAC over the entire handshake

Pre-shared keys

In TLS, the pre-shared key (PSK) replaces the session ID and session ticket. PSKs are agreed upon during a full handshake and can be reused for multiple connections.

> Pre-shared keys are only used if a previous session has been established.

They can be combined with (EC)DHE to achieve forward secrecy, where the PSK is used for authentication and (EC)DHE for key agreement. While PSKs can be generated out-of-band (OOB) from a passphrase, this is risky due to the potential lack of randomness, making brute-force attacks feasible. Therefore, using OOB PSKs is generally discouraged.

0-RTT connections

In TLS 1.3, when using a pre-shared key (PSK), a client can send "early data" with its initial message, which is protected by a specific key. However, this approach lacks forward secrecy because it relies solely on the PSK and could be vulnerable to replay attacks. While some complex mitigations exist, they are particularly challenging for multi-instance servers.

Incorrect share

In TLS 1.3, if a client sends a list of (EC)DHE groups that the server does not support, the server responds with a HelloRetryRequest, prompting the client to restart the handshake with different groups. If the new groups are also unacceptable, the handshake will be aborted, and the server will send an appropriate alert.

1.16 TLS and PKI

Even with TLS 1.3, public key certificates are required, meaning TLS has a connection with Public Key Infrastructure (PKI), as certificates are typically issued by a PKI. PKI is always needed for server authentication and optionally for client authentication unless using "true" PSK (Pre-Shared Key) authentication. In this case, "true" refers to manually pre-installed shared keys between the client and server, which is rare, often limited to certain embedded systems.

When a peer (server or client) sends its certificate to the other peer:

- The entire certificate chain is sent, which includes the peer's certificate and certificates of intermediate CAs (Certification Authorities). However, the root CA certificate is not sent, as it should already be trusted and present on the other side. Some attackers may attempt to send a fake root CA certificate; if the receiving peer accepts it without proper verification, the attack is successful. For instance, in TLS monitoring systems, it's crucial to ensure that the certificate chain never includes the root CA.

- The receiving peer must validate each certificate in the chain. A potential vulnerability is when some browsers and servers only validate the peer's end certificate, neglecting the intermediate CAs, which could be invalid. Proper validation must recursively verify each certificate in the chain, including checking the correctness of signatures, issue, and expiration dates.

- It's also essential to verify whether a seemingly valid certificate has been revoked. This can be done using either:
  - **CRL (Certificate Revocation List):** A list of revoked certificates, though the list can be large, making downloading and storing CRLs cumbersome—especially since a separate CRL is needed for each step in the chain.
  - **OCSP (Online Certificate Status Protocol):** More efficient performance-wise, as it allows querying an OCSP server to check if a certificate is valid. However, this method raises privacy concerns, as the OCSP server gains visibility into the servers being visited.

Both CRL and OCSP add additional network requests and delays to the setup, as the certificates must be validated before the session begins. For example, OCSP can introduce a median delay of +300ms, with an average of +1 second. Therefore, privacy and performance trade-offs must be considered.

1.17 TLS and certificate status

What should be done if the CRL or OCSP servers are unreachable? This could happen due to server or network failures, or even because a firewall is blocking access—common in companies with strict firewall rules due to security policies. Another reason could be that OCSP responses are sent in clear text, even though they are signed. The potential responses to this situation are:

- **Hard fail:** The page is not displayed, and the user is shown a security warning. For instance, "Sorry, we cannot display this page because we couldn't verify its revocation status." While this is the most secure option, it is also the most inconvenient for users. It could also result from a (D)DoS attack on the OCSP or CRL server.
- **Soft fail:** The page is shown regardless of whether the certificate's revocation status can be verified, assuming the certificate is still valid.

Both approaches lead to extra load time, often longer than just waiting for an OCSP response. This happens because the system needs to wait for the timeout after initiating a TCP connection. To address these issues, two different solutions are typically used.

1.17.1 Pushed CRL

In most cases, revoked certificates result from a compromised intermediate CA. When this happens, all certificates issued by that CA must be revoked, which can be a significant number. As a result, browser vendors have chosen to push updates containing only major revoked certificates. If an intermediate CA becomes invalid, it is promptly marked as invalid, and the CRL containing this information is distributed through a browser update. Here are some examples of how different browsers handle this:

- **Internet Explorer:** Updates its revoked certificate list with each browser update, which isn't ideal. If an update is delayed, the user may not be informed about the CA revocation in a timely manner.
- **Firefox:** Uses a system called *oneCRL*, which is part of its blocklist management process. This list, maintained by Firefox's developers, is updated nightly and includes CRLs of revoked intermediate CAs as well as known malicious websites.
- **Chrome:** Utilizes *CRLsets* to manage these CRLs, which are pushed with each browser update. On startup, Chrome checks for new CRLsets.

1.18 OSCP Stapling

Let's now look at how browsers and servers manage OCSP-related issues, which can affect both verification and privacy. The term "Stapling" refers to keeping things together.

- Automatic downloads of CRL and OCSP are often disabled because they take too long. As a result, browsers may be vulnerable to attacks using revoked certificates.
- Pushed CRLs only include a subset of revoked certificates; otherwise, the list would become too large.
- Browser behavior varies significantly in this area. Depending on the browser, different features may be available, and there is no standardized method for handling certificate revocation.

To improve this, instead of relying on the client to fetch revocation information, the server takes responsibility through a process called *OCSP stapling*. When the server sends its certificate, it also provides recent revocation information via an OCSP response (essentially saying, "Here's my certificate, and here's proof it's valid"). This allows the client to skip making a separate OCSP request, as the necessary information is included in the initial TLS handshake.

OCSP Stapling is a TLS extension, meaning it is not part of the standard handshake and must be supported by both the server and the client. It is announced during the TLS handshake when the server sends the *Server Hello* message, indicating to the client that it will be using this extension.
The first version of OCSP Stapling is defined in RFC-6066 (extension **status_request**), while version two is in RFC-6961 (extension **status_request_v2**) with the value **CertificateStatusRequest**. The TLS server pre-fetches the OCSP response from an OCSP server and includes it in the handshake as part of the server's certificate message. This message contains not only the certificate chain but also the OCSP responses for each certificate in the chain. As a result, the message size increases since there must be an OCSP response for each certificate, which validates that the certificates have not been revoked. This process "staples" the OCSP responses to the certificates.

The main advantage is improved privacy for the client, as it no longer needs to request information directly from the OCSP server—this is handled by the TLS server, meaning the OCSP server remains unaware of which clients are requesting access. Additionally, the client avoids having to establish a separate connection to the OCSP server, improving both speed and privacy.

However, a downside is that the freshness of the OCSP responses can be an issue. Since the OCSP response is pre-fetched by the server, it may not always be up-to-date (the server might store the response for a few minutes). This delay creates a small window of opportunity for attacks. For example, an attacker could retrieve the valid certificate and OCSP response, then attack the server to steal the private key and set up a fake server. When users connect to this fake server, the attacker can still present a valid certificate and OCSP response until the browser accepts it (would a browser accept an OCSP response from 30 minutes ago?).

OCSP stapling is typically handled automatically by the server, though the client can explicitly request it. When the client connects, it may not know whether the server supports OCSP stapling, so the client can send a *Certificate Status Request* (CSR) as part of the *ClientHello* message to request the OCSP responses in the TLS handshake.

This process is optional: even if the client requests OCSP responses, the server may not support stapling. In this case, the server might return the OCSP responses for its certificate chain in a separate message called *CertificateStatus*.

The issues include:

- Servers may ignore the status request; they are not obligated to provide a response.
- Clients may proceed with the handshake even if no OCSP response is provided.

Although the technology exists, there is uncertainty about whether it is widely implemented. It is important to monitor the process to verify whether OCSP responses are being provided, requested, or ignored, as this offers insight into the actual security status, not just the theoretical one. To address this uncertainty, a newer solution called *OCSP Must Staple* has been introduced, which forces OCSP stapling.

1.18.1 OCSP Must Staple

When a server requests a certificate from a certification authority, it may declare that it will always provide OCSP responses to clients, even if not explicitly requested. This information can be included in the certificate. Such servers present a certificate to the client that contains a certificate extension called **TLSFeatures**, as defined in RFC-7633. This extension informs the client that every time it connects to that server, it must receive a valid OCSP response as part of the TLS handshake. If the client does not receive an OCSP response, it should reject the server's certificate. Essentially, the server promises to always send both its certificate and the OCSP response. If the server does not provide the OCSP response, it can be considered a fraudulent server.

The benefit of this approach is that the client no longer needs to query the OCSP responder, and it enhances security by preventing attacks that block OCSP responses for a specific client or DoS attacks against the OCSP responder.

Key actors and their responsibilities

- **Certification Authority (CA)**: Must include the **TLSFeatures** extension in the server certificate if requested by the server's owner.
- **OCSP Responder**: Must be available 24/7 to provide valid OCSP responses. This requires a robust infrastructure with multiple network access points, backup servers, and resilience against DoS attacks. Otherwise, servers would not be able to establish connections, as they must provide OCSP responses.
- **TLS Client**: Must send the Certificate Status Request (CSR) extension in the *ClientHello* message, recognize the OCSP Must-Staple extension (if present in the server's certificate), and reject the server's certificate if no OCSP response is provided when promised.
- **TLS Server**: Must pre-fetch and cache OCSP responses for a certain period, and include an OCSP response in the TLS handshake. It must also handle errors when communicating with OCSP responders, in case the responder is temporarily unavailable.

- **Server Administrators**: Should configure their servers to use OCSP Stapling and request a server certificate that includes the OCSP Must-Staple extension.

One potential issue is the duration of the OCSP stapled response (for example, Cloudflare has a validity of 7 days). A window of 7 days may be problematic if a server is compromised, as there is potential exposure during that time.

1.19 Questions and answers

Question 1

what of the following remarks regarding TLS are possibly true?

- ✓ has been established a session S1 that involved connection C1 and C2 at time t1
- ✓ has been established a session S2 that involved connection C1, C2 and C3, at different and non- overlapping time intervals
- × connection C5 has been used initially in session S3 and then re-used in session S4 for performance-sake
- × in connection C1.1 of session S1 has been used AES192, while in Connection C1.2 of the same session S1 has been used AES128 since regarded less sensible information

Question 2

focusing on TLS Connections and Sessions

- ✓ sessions are typically relatively long-life in respect to connections
- × connections allow to re-use cryptographic parameters defined during handshake, thus reducing significantly the handshake phase
- × by using resumption mechanisms, the client can resume a connections decreasing the overall connection time
- ✓ each connection has its own specific set of parameters like seguence numbers and keys for integrity and confidentiality

Question 3

focusing on Perfect Forward Secrecy

- ✓ starting from version TLS version 1.3, it must be always enabled
- × using RSA mechanisms in TLS, it would be theoretically impossible to achieve
- ✓ using RSA mechanisms in TLS, it would be impractical to achieve
- × using ECDH mechanisms in TLS, it would be impractical due to the length of the key parameters

Question 4

Which of the following properties is NOT directly related to Perfect Forward Secrecy in a TLS context?

× the use of ephemeral keys

✓ protection against replay attacks

× security of past sessions if the server's private key is compromised

× independent session keys for each connection

Question 5

In the context of TLS 1.3, what is the role of PFS in session resumption mechanisms like O-RTT?

× O-RTT resumption is vulnerable to replay attacks, thus does not support PFS

× O-RTT session resumption uses pre-shared keys that provide Perfect Forward Secrecy.

✓ O-RTT session resumption compromises Perfect Forward Secrecy for faster handshakes.

× O-RTT session resumption reuses the original session's ephemeral keys

Question 6

Which TLS feature was introduced to specifically mitigate downgrade attacks?

× HSTS (HTTP Strict Transport Security)

× OCSP Stapling

× Certificate Pinning

✓ TLS FALLBACK SCSV

Question 7

Given the following packet capture:

× indicate a

× might be the initial phase of a secured real-time data exchange (like video streaming)

× It refers to an aborted TLS session, due to the impossibility to verify the x509v3 certificate

✓ lt refers to an aborted TLS session, due to TLS version mismatch between the versions supported by the server and by the client

Chapter 2

SSH

SSH, or Secure Shell, is a **network protocol** that allows for **secure communication** between two computers, which makes it a *"competitor"* of the much more used TLS protocol. It has been introduced in 1995 by Tatu Ylönen, a Finnish computer science student, as a response to a security incident per which the FTP credentials of his university were sniffed, but it has been commercialized since so it was not open source anymore. A open source fork called OpenSSH has been introduced in OpenBSD in 1999, and has been standardized in 2006 by the IETF in RFC 4251, referred to it as SSH-2.

> As it is the most used version, here we will always refer to SSH-2 (unless otherwise noted)

2.1 Architecture

From an architectural point of view, SSH is a three layer architecture, which means it is simpler than TLS. SSH uses TCP as the Transport Layer Protocol, but the SSH transport layer provides a nice set of features, which are **initial connection**, **server authentication**, **confidentiality** and **integrity** and **key re-exchange** (RFC-4253 recommends after 1GB of data transmitted or after 1 hour of transmission, notice that this does not refer specifically to SSH bu to any encrypted channel) which is crucial for long running connections.

> Beware that the SSH transport layer is not the same as the TCP transport layer, but it is a layer that is built on top of the TCP transport layer, even though they have similar names.

There's also a specific protocol for **user authentication**, compulsory with SSH, and a **connection protocol** too, which supports supports multiple connections (channels) over a single secure channel (implemented with the transport layer protocol). This means that SSH can act as a site-to-site VPN.

2.1.1 SSH Transport Layer Protocol

The general schema of an SSH connection is shown in figure 2.1.
The connection is setup with TCP, by default on port 22, on which the client initiates the

connection.
Then the SSH version string is exchanges by both sides, which contains the security features supported. Both sides must send a **version string** of the following form(the pipe symbol is used to separate the fields):

```
SSH-protoversion-softwareversion|SP|comments|CR|LF
```

SP is a space character, CR is a carriage return character and LF is a line feed character. If the comments are omitted, the SP is also omitted.
Its also used to triggers compatibility extensions and to advertise the protocol implementation capabilities.
A **key exchange** follows, which includes algorithm negotiation for the key exchange itself. After this point data can be exchanged, and the connection is closed when the data exchange is finished.
The termination of the TCP connection is not part of the protocol itself, but it's performed by TCP itself.

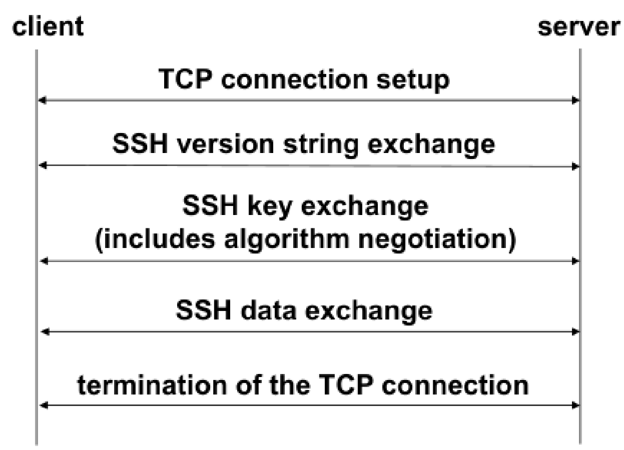


Figure 2.1: SSH Transport Layer Protocol

Binary Packet Protocol

All packets that follow the version string exchange is sent using the Binary Packet Protocol, which is roughly the basic unit on transmission. Every message in this kind of packet is sent as a sequence of bytes. The Binary Packet Protocol is pretty simple, it consists of:

- the **length** of the **packet** (4 bytes), which does not include the MAC and the packet length field itself
- the **padding length** (1 byte), which is the length of the random padding field
- the **payload**, which may be compressed. Its size is the length of the packet minus the length of the length field minus 1 (for the padding length field), up to a maximum uncompressed size of 32768 bytes(32KB)

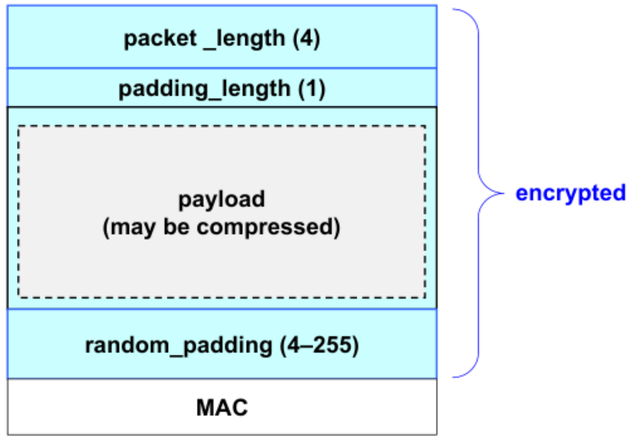


Figure 2.2: Binary Packet Protocol

- the **random padding**, minimum 4 bytes, up to the entire size of one block, and random to add confusion to the packet
- the **MAC**, computed over the clear text packet and the implicit sequence number

The first 4 fields are encrypted.

Key exchange

Another essential part of the SSH protocol is the key exchange, which is used to established the keys and to negotiate the algorithms to been used.
One peculiarity of the SSH protocol is that the algorithms used are selected based on directionality, which means that it is possible to use different algorithms for the client-to-server and server-to-client communication.
SSH-2 allows to select the key exchange function as well as the hash algorithm to be used in the key derivation function.

> This means that the two parties have *"full"* control over the algorithms to be used(if supported).

Another interesting aspect of the protocol is that, as it was proposed as an alternative to the Telnet protocol, it included negotiation of the language to be used, because of the text-only nature of the protocol.
The last field of the key exchange(first key exchange packet follows) contains an attempt to guess the agreed key exchange algorithm.
It contains the following fields:

- SSH_MSG_KEXINIT
- cookie (16 random bytes)
- kex_algorithms
  - eg:diffie-hellman-group1-sha1, ecdh-sha2-OID_of_curve

- server_host_key_algorithms: used for the server authentication
  - eg:ssh-rsa, ssh-dss, ecdsa-sha2-NISTP256
- encryption_algorithms_client_to_server, ... server_to_client
  - aes-128-cbc, aes-256-ctr, aead_aes_128_gcm
- mac_algorithms_client_to_server, ... server_to_client
  - hmac-sha1, hmac-sha2-256, aead_aes_128_gcm
- compression_algorithms_client_to_server, ... server_to_client
  - none, zlib
- languages_client_to_server, ... server_to_client
- first_kex_packet_follows (flag)

Keep in mind that because of the negotiation of the protocols to be used, SSH is potentially vulnerable to downgrade attacks.

> A complete list of the supported algorithms can be found **here**

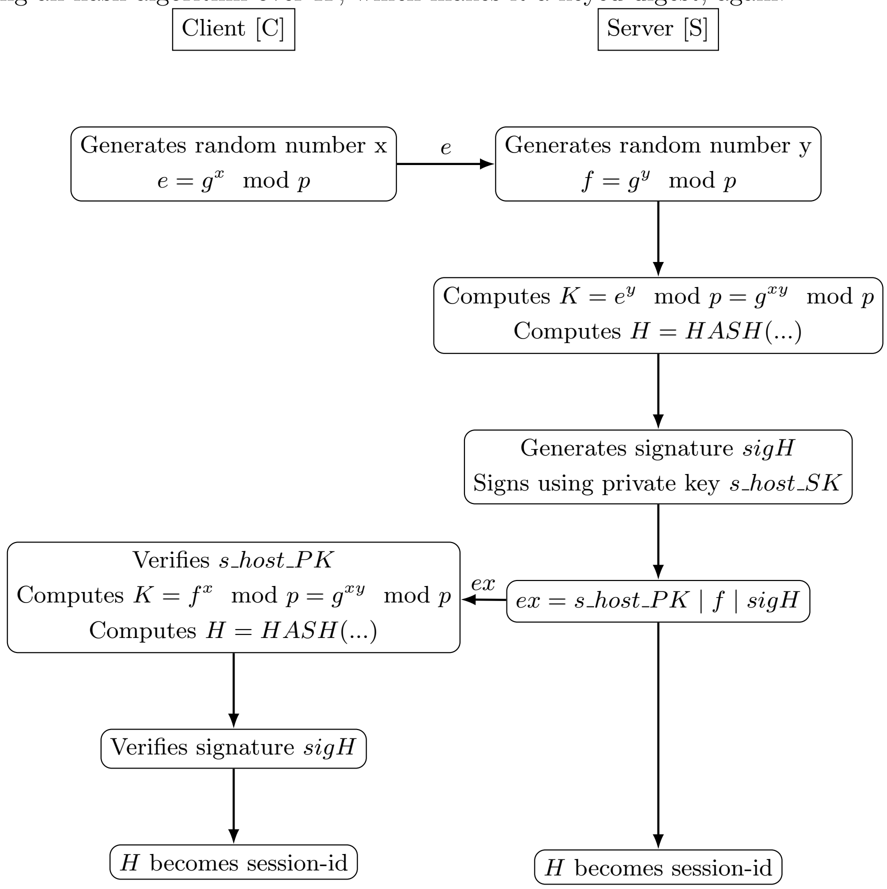
Diffie-Hellman key agreement

This is also an **implicit authentication** of the server, due to the fact that the server can compute the correct premaster secret using the private key.
In this phase the client generates a random number x and computes $e = g^x \mod p$ and sends it to the server. The server generates a random number y and computes $f = g^y \mod p$ and sends it to the client. At this point the key K has been established. The server computes the **exchange hash** H over many fields(which makes it basically a keyed digest):

- the client version string
- the server version string
- the client's KEXINIT message
- the server's KEXINIT message
- the shared secret K
- the exchange value f
- the exchange value e
- the host public key

and signs it with its private key to generate the signature $sigH$.
Those two values, together with the host public key in a raw format, are sent to the client, which verifies the signature and computes the same hash value. Notice that because the public key is sent in a raw format, the client must have a copy of the server's public key stored locally, and this is one of the major attack vectors of SSH.

Notice also that, because many algorithms need an initialization vector, which is computed using an hash algorithm over H, which makes it a keyed digest, again.



Key derivation

Many keyed digest require a initialization vector.
Starting with those exchanged values, if there is any kind of algorithm that requires an IV (nearly all), then the initial IV is:

- From client to server: HASH(K || H || "A" || session_id), where K is the key that has been negotiated and "A" is simply a letter.
- From server to client: HASH(K || H || "B" || session_id).

The encryption key is generated as follows:

- From client to server: HASH(K || H || "C" || session_id).
- From server to client: HASH(K || H || "D" || session_id).

The integrity key:

- From client to server: HASH(K || H || "E" || session_id).
- From server to client: HASH(K || H || "F" || session_id).

The HASH algorithm is the one used to create all these keys, and this could be a weak point because it would be much better to generate keys using a KDF (Key Derivation Function).

2.1.2 Encryption

Encryption is compulsory in SSH, which algorithms are negotiated during the key exchange. The supported algorithms are:

- (required for backward compatibility) 3des-cbc (w/ three keys, i.e. 168 bit key)
- (recommended) aes128-cbc
- (optional) blowfish-cbc, twofish256-cbc, twofish192-cbc, twofish128-cbc, aes256-cbc, aes192-cbc, serpent256-cbc, serpent192-cbc, serpent128-cbc, arcfour, idea-cbc, cast128-cbc, none

The key and initialization vector needed are established during the key exchange and all packets sent in one direction is a single data stream, meaning that the first packet sent has got an initialization vector, which is the one that was created with the key derivation function. But in the following ones, the IV is passed in the packet from the end of one to the beginning of the next one. In fact, there are two cases:

- if **CBC mode** is used, the IV for next packet is the last encrypted block of the previous packet
- if **CTR mode** is used, the IV for the next packet is the incremented value of the last IV

2.1.3 MAC

The MAC algorithm and the key are negotiated during the key exchange and they can be different in each direction.
The basic set of algorithms are:

- hmac-sha1 (required for backward compatibility) [key length = 160-bit]
- hmac-sha1-96 (recomm) [key length = 160-bit]
- hmac-md5 (opt) [key length = 128-bit]
- hmac-md5-96 (opt) [key length = 128-bit]

> The mac is computed using the key for the right direction over the sequence number concatenated with the packet in clear text.

The sequence number is implicit, as in TLS, and its possible because of TCP. It is represented as a 32-bit unsigned integer, which is incremented by one for each packet sent.
This value is never reset, even if keys and algorithms are re-negotiated, which means that when the maximum value is reached, the channel has to be reset.

2.1.4 Peer authentication

The **server** is authenticated using an **asymmetric challenge-response** mechanism, which requires and explicit server signature of the key exchange hash H. (The challenge is implicit, the signature is implicit).
The client locally stores the public keys of the server, which are usually stored in the `known_hosts` file in the `.ssh` directory.
When connecting to a server not listed in that file, the client is asked to store the public key of the server in the file, following a **TOFU** (Trust On First Use) policy.
Because of this, a good practice is to protect the `known_hosts` file for authentication and integrity, and to periodic audit/review all the known_hosts files to quickly detect added/deleted hosts or changed keys.
Client authentication can be performed by two methods. The first one is based on **credentials**(username and password), which are exchanged only after the protected channel is established. This method protects against sniffing attacks, but not other ones like password guessing.
The second method is based on **asymmetric challenge-response**. In that case, the server must locally store the public keys of the users allowed to connect, typically in the `authorized_keys` file in the `.ssh` directory.
As per the server authentication process, as a good practice, the `authorized_keys` file should be protected for authentication and integrity, and periodically audited/reviewed to quickly detect added/deleted keys or changed keys.

2.2 Port forwarding

We already mentioned that SSH can act as a site-to-site VPN, but rather than creating a general purpose VPN, SSH can be used to perform **port forwarding** or **tunneling**.

> Port forwarding is a technique that allows to forward unprotected TCP traffic through a secure SSH channel.

This allows to secure unprotected service like POP3, SMTP or HTTP while also allowing the application to perform their normal authentication over an encrypted channel.
There are two types of port forwarding, **local** and **remote**, but both use the Connection Protocol to encapsulate a TCP channel inside a SSH one.

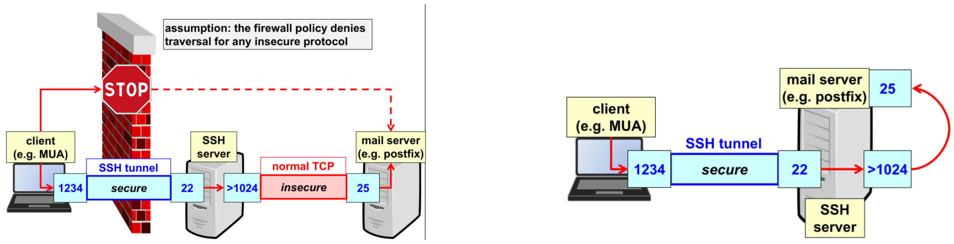
2.2.1 Local port forwarding

The concert of local port forwarding is to forward a local port to a remote one, which means that the client listens on a local port and forwards the traffic to a remote port.
For example, let's suppose to be behind a firewall that blocks access to an external mail server because only secure traffic is permitted. An SSH tunnel can be created to forward the local port 110 to the remote port 25 using the following command:

```
ssh -L 1234:mail_server:25 user@ssh_server
```

the traffic to port 1234 on the (internal) client will be forwarded to port 25 on the mail_server

by using a tunnel to the (external) ssh_server.
The firewall will see the traffic as SSH traffic, but the user has still to configure the mail user agent to use the local port 1234 to connect as the outgoing mail server.

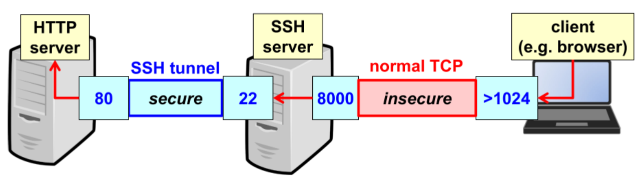


2.2.2 Remote port forwarding

Remote port forwarding is the opposite of local port forwarding, which means that the client listens on a remote port and forwards the traffic to a local port.
For example, let's suppose to have a web server on a local machine that is behind a firewall, and the user wants to make it available to the public internet. The user can create a tunnel to the remote machine with the following command:

```
ssh -R 8000:localhost:80 user@ssh_server
```

The traffic to port 8000 on the remote machine will be forwarded to port 80 on the local machine.
The user can now access the web server on the local machine by connecting to the remote machine on port 8000.



2.2.3 Causes of insecurity

In general, the biggest causes of insecurity for SSH are direct trust in the public keys. In fact, x.509 certificates are not used, but some commercial SSH implementations support them and openSSH has SSH certificates, which are a different thing.
Furthermore, blindly trusting the public keys can lead to a MITM attack. The server could also have a weak platform security(worms, malicious software, rootkits, etc.) as well as the client (malware, keyloggers, etc.).
One last point is that any connection to a local forwarded port will be tunneled, even if coming from another node. This is undesirable, as such it is recommended to specify the binding address when creating a tunnel:

```
ssh -L 127.0.0.1:1234:mail_server:25 user@ssh_server
```

2.3 Attacks on SSH

2.3.1 BothanSpy

BothanSpy is believed to be a CIA tool, according to information released by Wikileaks on July 6, 2017, as part of their Vault 7 disclosure. This malware targets Xshell, a Windows-based SSH client widely used in the USA and South Korea. BothanSpy operates by injecting a malicious DLL into the Xshell process, enabling it to steal sensitive information from SSH connections. Specifically, it collects:

- Usernames and passwords from password-authenticated connections.
- Usernames, private key filenames, and passphrases from public-key authenticated connections.

BothanSpy is designed to work with the ShellTerm attack framework, featuring:

- A covert communication channel with a Command and Control (C&C) server.
- DLL injection capabilities for direct C&C communication, with no data written to disk, making it difficult to detect using traditional anti-malware solutions.
- An offline mode, where the collected data is written to disk, encrypted with AES for later retrieval.

2.3.2 Gyrfalcon

Gyrfalcon is another suspected CIA tool, as revealed by Wikileaks on July 6, 2017, in their Vault 7 release. This malware specifically targets OpenSSH on enterprise Linux systems, such as RedHat and CentOS. Gyrfalcon operates by pre-loading a malicious DLL to intercept plaintext traffic, capturing information both before encryption and after decryption. The tool is capable of capturing:

- Usernames and passwords.
- Actual data transmitted over SSH connections.

Key features of Gyrfalcon include:

- An encrypted configuration file.
- An encrypted file for storing captured data.

While Gyrfalcon requires root access for installation, it notably does not integrate with a Command and Control (C&C) server. Instead, it freely reads and writes files on disk, potentially exploiting the limited use of anti-malware solutions on Linux platforms. Despite these capabilities, Gyrfalcon is not particularly stealthy or sophisticated compared to other tools.

2.3.3 Brute force attack

Brute force attacks can exploit the false sense of security provided by secure communication channels, especially when insecure authentication methods like reusable passwords are employed. In a typical brute-force attack, an attacker systematically attempts to guess a password by trying all possibilities from a dictionary of commonly used passwords.

An illustrative example of such an attack occurred in September 2016:

- Two servers, one with an IPv4 address and the other with an IPv6 address, were activated in the cloud to test SSH brute-force attacks.
- The IPv4 server was immediately targeted and compromised within just 12 minutes, primarily because the root password was set to "password."
- Once compromised, the server was quickly used in a Distributed Denial of Service (DDoS) attack.
- In contrast, after one week, the IPv6 server remained unscathed, as it had not even been attacked.

This example demonstrates the risks of relying on weak passwords and highlights the disparity in attack frequency between IPv4 and IPv6 networks.

Protection from brute-force attacks

To mitigate the risk of SSH brute-force attacks on Linux systems, several strategies can be implemented:

- **Account Lockout**: Automatically lock accounts after a certain number of failed authentication attempts using tools like `pam_tally2` or `pam_faillock`.
- **TCP Wrappers**: Use TCP wrappers to restrict SSH access by permitting or denying connections from specific hosts or networks.
- **SSH Rate Control**: Implement rate limiting for SSH connections using IPtables, for example, by allowing only 5 connection attempts per minute.
- **Disable Root Access**: Deny direct SSH access to the root account to limit exposure.
- **Change Default SSH Port**: Move SSH from the default port 22 to another port to reduce the chances of automated scans and attacks.
- **Fail2ban**: Use `Fail2ban` to monitor log files and blacklist IP addresses after a defined number of authentication failures.
- **Two-Factor Authentication (2FA)**: Implement 2FA, such as Google Authenticator, for an added layer of security.
- **Disable Password-Based Authentication**: Disable password-based authentication altogether in favor of more secure methods like public-key authentication.

These measures can significantly reduce the effectiveness of brute-force attacks and improve the overall security of SSH services.

2.4 Main Applications of SSH

SSH (Secure Shell) is widely used for a variety of secure applications due to the encryption and authentication mechanisms it offers. The main applications include:

- **Remote Interactive Access**: SSH allows users to securely connect to remote systems with a text-based interface, enabling command-line interaction.
- **Remote Command Execution**: SSH facilitates the secure execution of commands on remote systems, making it ideal for system administration and automation tasks.
- **Tunneling**: SSH can create secure tunnels for various applications, such as forwarding network traffic, encrypting data, or creating virtual private networks (VPNs).

Keep in mind that SSH is now natively available on Linux, macOS, and Windows, providing both client and server functionality on these platforms.
All of these functions benefit from the security properties inherent to SSH, including confidentiality, integrity, and authentication.

Chapter 3

The X.509 standard and PKI

3.1 Public-key certificate (PKC)

Lets begin with a definition:

> A **public-key certificate** is a data structure to securely bind a public key to some attributes

A PKC is said to ”securely bind” a public key to some attributes because it is signed by a trusted entity, the **Certificate Authority**, but other techniques for certification exists (e.g. blockchain, direct trust and personal signature).
The attributes in the certificate are those employed in the transaction being protected by the PKC, which are difficult to decide a-priori without knowing the context.
PKC are most important to achieve **non-repudiation** and **digital signature** in a secure way.

3.1.1 Key Generation in Public Key Cryptography (PKC)

Key generation in public key cryptography (PKC) involves complex algorithms and often relies on random number generators (RNGs) to ensure strong, unpredictable keys. Once a key is generated, the private key must be securely protected in various contexts:

- **Storage**: The private key needs to be securely stored to prevent unauthorized access.
- **Usage**: The private key must also be protected when being used, as it could be exposed during operations.
- **Software Application**: In software environments (e.g., web browsers), the trustworthiness of the computing platform must be considered, as it may be vulnerable to malware or weak implementations. This is true both for the context of key generation and use.
- **Dedicated Hardware**: Storing and using keys in dedicated hardware, such as a smart card, offers enhanced protection but comes with limitations in terms of algorithm updates or vulnerability patching(which may be difficult or even impossible).

- **Key Injection**: Keys may be generated in software and injected into hardware devices, a process that can be useful for key recovery, but should be restricted to encryption keys to maintain security. This is most important for the private key.

PKC key management requires careful consideration of both security and operational challenges, especially when dealing with long-term security mechanisms.

3.1.2 Certification architecture

In Public Key Infrastructure (PKI), several key entities are responsible for managing the lifecycle of Public Key Certificates (PKCs):

- **Certification Authority (CA)**: The CA is responsible for generating and revoking PKCs. It also publishes PKCs and maintains information about their status, such as whether they are valid or revoked, or even suspended.
- **Registration Authority (RA)**: The RA plays a critical role in verifying the claimed identity and attributes of a certificate requestor. It authorizes the issuance or revocation of PKCs but does not generate them itself.
- **Validation Authority (VA)**: The VA provides services that allow third parties to verify the validity status of a PKC, because some responsibilities or the RA may be delegated to it. This may involve downloading Certificate Revocation Lists (CRLs) or querying an Online Certificate Status Protocol (OCSP) responder to check the certificate's status in real-time.
- **Revocation Authority**: Although not an official term, this role may be assigned to either the RA or CA. The revocation authority is delegated to revoke certificates, often on a more urgent basis than their issuance (they are available most of the time), ensuring that compromised or invalid certificates are promptly rendered unusable.

These entities work together to ensure the security and trustworthiness of PKC-based systems by handling key tasks such as certificate issuance, verification, and revocation.

3.1.3 Certificate generation

The general When an actor want to generate a certificate, it must first generate a key pair (public and private key). The private key is stored locally and protected(encrypted) as strong as possible, while the public key is sent to the CA with some attributes that help identify the actor. The CA then requires that the attributes are correct and are associated with the actor, which requires authentication of the actor. At this point the CA generates the certificate, signs it with its private key and sends it back to the actor while also storing it in its repository.
As you may noticed, the verification is only on the attributes, and not of the possession of the private key, which will be discussed later.

In addition to what just discussed, alternative architectures for certificate generation exist:

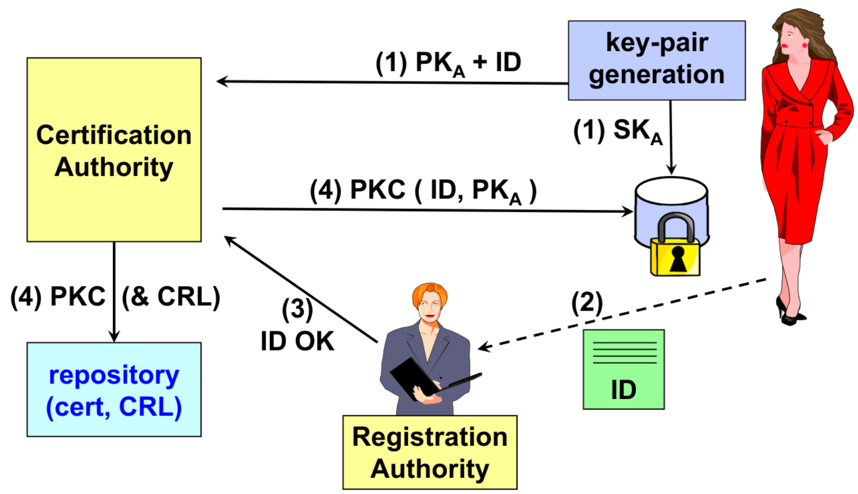


Figure 3.1: Certificate generation

- **Key Pair Generation by RA**: In some architectures, the Registration Authority (RA) generates the key pair on behalf of the user, obtains the Public Key Certificate (PKC), and securely distributes the key pair and certificate to the user via a secure device, such as a smart card. This approach is often used in large companies where the employees are already known to the organization.

- **User Authentication via Code**: Another common method involves the user visiting the RA to obtain a code that can be used to authenticate their certificate request to the Certification Authority (CA). The code is typically calculated as a Message Authentication Code (MAC) using the shared secret key between the RA and CA:

$$\text{code} = \text{MAC}(K, ID)$$

  where K is a shared secret key between the RA and CA, and ID is the user's identity. The user then submits this code to the CA to validate the certificate request.

These alternative methods provide flexibility for organizations with different security needs, allowing for centralized key generation and secure certificate distribution.

3.1.4 X.509 certificates

X.509 is an ITU-T standard that defines the format of public key certificates used to verify the identity of a key owner in cryptographic systems. The development of X.509 certificates has undergone several versions:

- **v1 (1988)**: The initial version of the standard.
- **v2 (1993)**: A minor update with small improvements.
- **v3 (1996)**: Added extensions and introduced version 1 of the attribute certificate.
- **v3 (2001)**: Further enhancements, including version 2 of the attribute certificate, which are not used anymore.

X.509 is part of the larger X.500 standard for directory services, often referred to as "white pages," which are used for managing information about entities in a structured way(directory services). X.509 provides a solution to the problem of securely identifying the owner of a cryptographic key.

The certificates and their structures are defined using **ASN.1** (Abstract Syntax Notation One), a standard interface for defining data structures exchanged in networking environments in a neutral and platform-independent way.

3.1.5 PKC Scope

A Public Key Certificate (PKC) contains information that uniquely associates a cryptographic key with an entity. This binding between the key and the entity is ensured by a **Trusted Third Party (TTP)**, typically referred to as a Certification Authority (CA), which digitally signs each certificate to guarantee its authenticity.

The liability associated with a PKC may be restricted to specific applications or purposes, as outlined in the CA's certification policy. This policy defines the intended usage and limits the scope of the certificate, ensuring it is applied within the proper legal and technical contexts.

3.1.6 Certificate Policy (CP) and Certification Practice Statement (CPS)

According to RFC-3647, "Internet X.509 Public Key Infrastructure Certificate Policy and Certification Practices Framework," both the Certificate Policy (CP) and Certification Practice Statement (CPS) play key roles in defining the use and management of Public Key Certificates (PKCs):

- **Certificate Policy (CP)**: A CP is a named set of rules that defines the applicability of a PKC to a specific community or class of applications with common security requirements. It establishes the minimum requirements for the issuance and management of certificates and can be followed by multiple Certification Authorities (CAs). For example, a government CP may apply to all certification providers issuing certificates for official use.
- **Certification Practice Statement (CPS)**: A CPS outlines the specific practices that a CA follows when issuing PKCs. While a CP specifies the general rules, the CPS provides detailed implementation procedures. Each CA develops its own CPS, which is tailored to its operations and describes how it meets the requirements set forth in the CP.

3.1.7 X.500 Directory Service

The X.500 directory service was the first application to use X.509v1 certificates, providing a framework for managing information about entities in a network. However, three major problems were encountered with this early system:

- **Lack of Guarantees on the Quality of the CA**: There were no clear policies to ensure the reliability and trustworthiness of the Certification Authorities (CAs), leading to concerns about the security of issued certificates.
- **Lack of an X.500 Infrastructure**: A fully developed X.500 infrastructure did not exist, making it difficult to access certificates or distribute them effectively across networks.
- **Difficulty in Establishing Certification Paths**: Establishing a certification path between two arbitrary users was challenging, as the relationships between different CAs were not well-defined or standardized.

These issues hindered the widespread adoption of X.500 and highlighted the need for more robust certification frameworks.

Remedies for x.509v1

To address those problems, the X.509v1 standard was revised to include the following features:

- force the semantics in the application or in any case in the context external to the certificate (eg: RFC-1422 (PEM))
- make the certificate more flexible and expressive(more htan the identifier and the key). This was solved in X.509v3.

3.1.8 RFC-1422

RFC-1422 introduced a hierarchical certification infrastructure rooted at the **Internet Policy Registration Authority (IPRA)**, which oversaw the certification hierarchy. The framework defined special types of Certification Authorities (CAs) to manage and enforce certificate policies:

- **Policy Certification Authority (PCA)**: PCAs were responsible for establishing and enforcing the policies used to issue certificates. They ensured that subordinate CAs followed the defined security practices and policies.
- **Name Subordination**: CAs were required to issue certificates within a specific subset of the naming hierarchy, ensuring structured and consistent name allocation. For example:
  - **CA n.1**: C=IT (country-level CA for Italy)
  - **CA n.2**: C=IT, O=Politecnico di Torino (organizational-level CA within Italy)

This hierarchical model helped structure the certification infrastructure, defining clear roles and responsibilities for issuing and managing certificates.

Unfortunately this was a failure for many reasons:

- the hierarchical infrastructure limits the flexibility
- the name subordination introduces undesired limits to the assignment of X.500 names

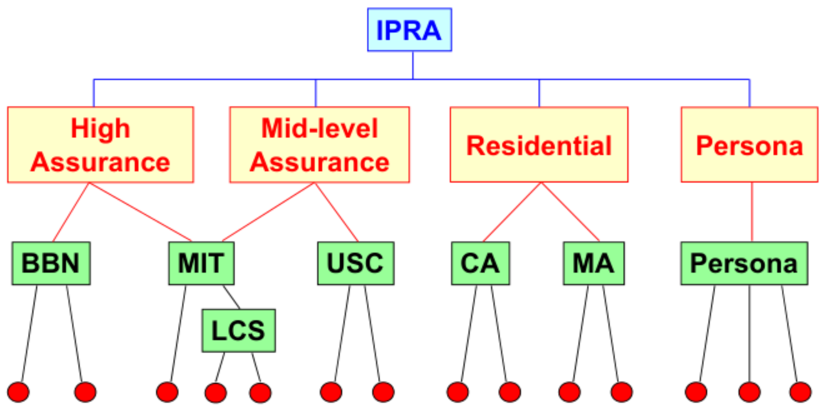


Figure 3.2: Internet PEM hierarchy (RFC-1422)

- the use of the PCA concept is not flexible in commercial applications, where the participation of an operator to take a decision is impractical, because no-one was willing to trust a global PCA.

3.2 X.509 Version 3

X.509 Version 3 is a standard that was completed in June 1996 through a collaborative effort between ISO/ITU and the IETF. Its primary goal was to define certificates that are suitable for Internet applications. This version consolidates all modifications necessary to extend the definitions of certificates and Certificate Revocation Lists (CRLs) into a single document.
Key features of X.509 Version 3 include:

- **Types of Extensions**:
  - **Public Extensions**: These are defined by the standard and made publicly available for anyone to use.
  - **Private Extensions**: These are tailored to specific user communities and are not publicly available. Those are considered as blobs if not understand er and discarded
- **Certificate Profile**: This refers to a set of extensions designed for a specific purpose, ensuring that certificates meet particular requirements for different applications. An example of a certificate profile is given by RFC-5280, titled "Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile," which outlines standard practices for X.509 certificates and CRLs.

3.2.1 Base syntax

3.2.2 Critical Extensions

In the context of X.509 certificates, extensions can be classified as critical or non-critical, each affecting the certificate verification process differently:

- **Critical Extensions**: If a certificate contains an unrecognized critical extension, it **MUST** be rejected during the verification process. This ensures that any essential information required for proper validation is recognized and handled appropriately.
- **Non-Critical Extensions**: Conversely, a non-critical extension **MAY** be ignored if it is unrecognized. This allows flexibility in certificate processing, as non-critical information does not impede the overall verification of the certificate.

The responsibility for handling these extensions lies entirely with the entity performing the verification, referred to as the **Relying Party (RP)**. The RP must implement logic to correctly interpret and respond to both critical and non-critical extensions in accordance with their definitions.

3.2.3 Public Extensions

X.509 version 3 defines four classes of public extensions that enhance the functionality and applicability of certificates:

- **Key and Policy Information**: Extensions in this class provide additional information regarding the key usage and policies applicable to the certificate, guiding how the key should be used within specific contexts.
- **Certificate Subject and Certificate Issuer Attributes**: These extensions include attributes related to both the subject of the certificate (the entity that the certificate represents) and the issuer (the Certification Authority), enabling more detailed identification and classification.
- **Certificate Path Constraints**: These extensions define rules and limitations regarding the certification path, ensuring that certificates can only be used in certain contexts or under specific conditions, enhancing security within the certificate hierarchy.
- **CRL Distribution Points**: This extension indicates where the Certificate Revocation List (CRL) can be found, providing necessary information for relying parties to check the revocation status of the certificate efficiently.

3.2.4 Key and policy information

Authority key identifier

Key and policy information extensions in X.509 v3 provide crucial details about the public keys associated with certificates. One significant component is the **Authority Key Identifier (AKI)**, which serves the following purposes:

- **Identification of the Signing Key**: The AKI identifies a specific public key used to sign a certificate, ensuring that the verification process can accurately trace the certificate's authenticity back to the correct authority.
- **Identification Methods**: The identification can be achieved through:
  - A **key identifier**, typically represented as the digest of the public key (PK).

  - The combination of **issuer-name** and **serial-number**, allowing a clear reference to the issuing CA's key.

- **Usage**: The AKI is particularly useful in scenarios where the same CA might utilize multiple keys (e.g., for different assurance levels like low and high assurance).
- **Non-Critical Extension**: While the AKI is classified as non-critical, its presence can be vital in certain applications, especially when building the certificate chain is necessary for verifying trust and authenticity.

Subject key identifier

The **Subject Key Identifier** (SKI) extension in X.509 v3 serves to identify a specific public key associated with a certificate. Key features include:

- **Identification of Public Key**: The SKI uniquely identifies a particular public key used in an application. This is especially important in scenarios where the public key may be updated or replaced over time.
- **Non-Critical Extension**: The SKI is classified as a non-critical extension, meaning that while it provides valuable identification information, its absence does not necessarily prevent the certificate from being considered valid.

key usage

The **Key Usage** (KU) extension in X.509 v3 specifies the application domains in which a public key may be utilized. Key characteristics include:

- **Application Domain Identification**: The KU extension identifies the specific purposes for which the associated public key can be employed, ensuring that it is used appropriately within defined contexts.
- **Critical or Non-Critical**: The Key Usage extension can be classified as either critical or non-critical:
  - If marked as **critical**, the certificate may only be used for the specific purposes indicated in the Key Usage extension. Any usage outside the defined scopes would render the certificate invalid.
  - If marked as **non-critical**, the certificate can be used more flexibly, potentially allowing usage beyond the defined applications without invalidating the certificate.
- **Permitted Cryptographic Operations**: The following cryptographic operations can be defined within the Key Usage extension:
  - **digitalSignature**: Allowed for both Certificate Authorities (CAs) and users.
  - **nonRepudiation**: Specifically permitted for users.
  - **keyEncipherment**: Permitted for users.
  - **dataEncipherment**: Allowing encryption of data.

  - **keyAgreement**: Involves:
    * **encipherOnly**: Restricting use to enciphering operations.
    * **decipherOnly**: Restricting use to deciphering operations.
  - **keyCertSign**: Specifically permitted for Certificate Authorities (CAs).
  - **cRLSign**: Also permitted for Certificate Authorities (CAs) for signing Certificate Revocation Lists (CRLs).

Private key usage period

The **Private Key Usage Period** extension in X.509 v3 specifies the time frame during which the associated private key may be used. Key features include:

- **Usage Period Definition**: This extension defines the period during which the private key can be actively utilized, helping to enforce time-based restrictions on key usage.
- **Non-Critical Extension**: The Private Key Usage Period extension is always classified as non-critical, meaning that its absence does not invalidate the certificate. However, the information it provides can be important for managing key lifecycles.
- **Usage Discouraged**: While this extension is available, its use is generally discouraged in practice. Organizations often prefer to manage key lifetimes through other means, such as regular key rotation, rather than relying on a specified usage period within the certificate.

Certificate policies

The **Certificate Policies** extension in X.509 v3 outlines the specific policies that were adhered to during the issuance of the certificate and defines the purposes for which the certificate can be utilized. Key aspects include:

- **Policy Listing**: This extension provides a comprehensive list of the policies that govern the certificate issuance process, ensuring clarity regarding its intended use.
- **Indication Methods**: Certificate policies can be indicated using various formats, including:
  - **Object Identifier (OID)**: A unique identifier for the policy.
  - **Uniform Resource Identifier (URI)**: A link to a location where the policy can be reviewed.
  - **Text Message**: A textual description of the policy.
- **Critical or Non-Critical**: The Certificate Policies extension can be classified as either critical or non-critical:
  - If marked as **critical**, the certificate must only be used in accordance with the specified policies; otherwise, it may be considered invalid.
  - If marked as **non-critical**, the certificate can be used more flexibly, although the policies still provide guidance for its intended use.

- **Support for Authentication and Authorization**: The use of this extension can enhance not only the authentication of users and entities but also facilitate authorization processes, providing a clearer understanding of the permissible actions associated with the certificate.

Policy mappings

The **Policy Mappings** extension in X.509 v3 establishes a correspondence between policies across different certification domains. Key aspects include:

- **Mapping of Policies**: This extension indicates how policies from one certification authority (CA) correspond to policies from another, facilitating interoperability and trust among different certificate frameworks.
- **Presence in CA Certificates**: The Policy Mappings extension is typically present only in CA certificates, allowing certification authorities to define and communicate relationships between their policies and those of other authorities.
- **Non-Critical Extension**: The Policy Mappings extension is classified as non-critical, meaning its absence does not invalidate the certificate. However, it serves as an important tool for enhancing the understanding and usability of certificates across different domains.

3.3 Private extensions

The **Private Extensions** in X.509 v3 allow for the definition of extensions that are specific to a particular user community, facilitating tailored applications within closed groups. Key aspects include:

- **Definition of Private Extensions**: Private extensions are custom extensions that can be defined for use by a specific community or group of users, enabling flexibility and specificity in certificate applications.
- **Examples from IETF-PKIX**: The Internet Engineering Task Force Public Key Infrastructure (IETF-PKIX) has defined three notable private extensions for the Internet user community:
  - **Subject Information Access**: Provides information about how to access subject-related data.
  - **Authority Information Access**: Offers details on how to access information related to the certificate authority.
  - **CA Information Access**: Supplies information about accessing resources associated with the CA.