

# Web Security

## Secure Socket Layer and Transport Layer Security

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# Outline

## Secure Socket Layer (SSL)

- Introduction

- Overview of SSL

## Transport Layer Security (TLS)

- Overview of TLS

- The handshake protocol

- The record protocol

- Alert messages

## Applications

## Security of TLS

# Secure Socket Layer (SSL)

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# Secure Sockets Layer (SSL)

SSL, developed by Netscape Communications, is a protocol whose primary purpose is to establish a private communication channel between two applications to ensure:

- Privacy of data;
- Authentication of the parties;
- Integrity.

A bit of history:

- SSL 1.0 was never released because of serious security flaws;
- SSL 2.0, released in Feb 1995, was shortly discovered to contain security and usability flaws;
- Version 3.0 released in Nov 1996 is a complete reconstruction of the SSL protocol, being the basis for further developments.

# SSL 3.0

Version 3.0 of SSL was produced by Paul Kocher, working with Netscape engineers, when Taher ElGamal was Chief Scientist at Netscape Communications:

*“Taher had a clear vision for SSL 3.0, but had many other things on his platter as well, so he made arrangements for me and Phil Karlton to do the main work of designing the protocol.”*

*Paul Kocher*

SSL is a significant contribution to the practice of cryptography:

*“The entire Internet population benefits from the work of Kocher and ElGamal every day.”*

*Dr. Vinton Cerf, Chair of the Marconi Society*

Guglielmo Marconi (1874-1937), the inventor of radio, shared the 1909 Nobel Prize in Physics with Karl Braun.

# The 2019 Marconi prize



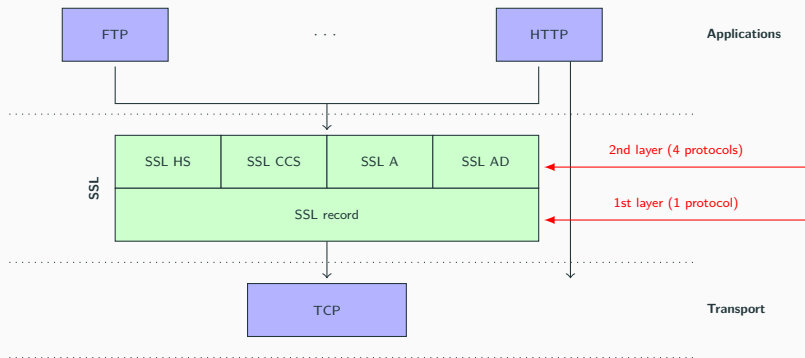
**Figure 1:** Paul Kocher (left) and Taher ElGamal (right) awarded the 2019 Marconi prize for their contributions to the security of communications.

# SSL in a nutshell

Even though SSL 3.0 has been implemented and used since 1996, the first complete document published appeared only in Aug 2011 (Freier et al. (2011)). Some points of reference on it:

1. **Primary goal:** to provide a private channel between communicating applications to ensure:
  - Privacy of data;
  - Authentication of the parties;
  - Integrity;
2. **SSL does not provide non-repudiation;**
3. **SSL is socket-oriented:** all or none of the data that is sent or received from a socket are protected in the same way, i.e., there is no way to sign individual pieces of data;
4. **SSL is application independent.**

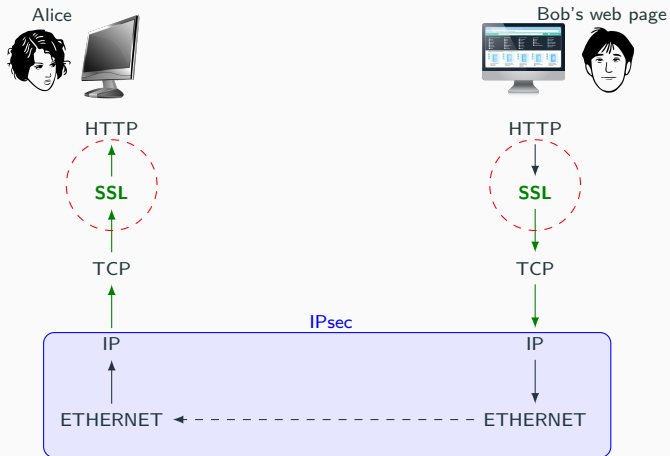
# SSL in the TCP/IP protocol stack



SSL provides security services to any TCP-based application protocol (e.g., HTTP, FTP etc.).



# Usage scenario



# Transport Layer Security (TLS)

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# Transport Layer Security (TLS)

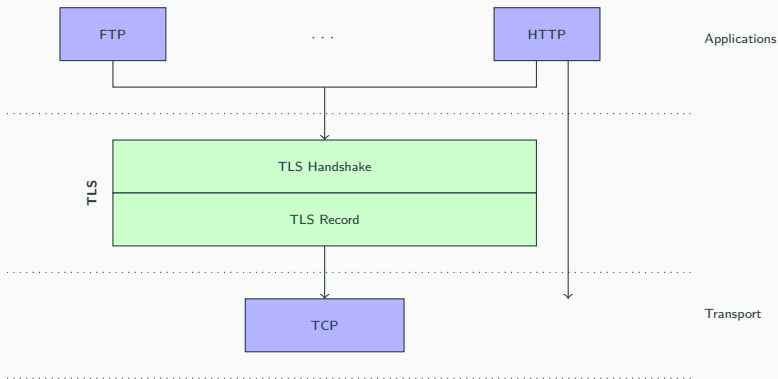
- 1996: The IETF Transport Layer Security (TLS) working group was created to unify and standardize the SSL 3.0 protocol and similar variants such as PCT/STLP. The final result would be called TLS;
- TLS Standards:
  - TLS 1.0 – 1999 (RFC 2246);
  - TLS 1.1 – 2006 (RFC 4346);
  - TLS 1.2 – 2008 (RFC 5246);
  - TLS 1.3 – 2018 (RFC 8446);
- TLS has a similar structure to SSL but added **significant changes** from standard to standard:
  - Removed broken features (e.g., compression);
  - Improved the crypto architecture of the protocol: HMAC, AEAD, HKDF, etc.;
  - Improved latency (e.g., handshake in **1-RTT** or even **0-RTT**);
  - Improved security and privacy (e.g., forward secrecy).

# TLS 1.3

- **TLS 1.3** – work started on April 2014 (draft-00) and completed on Aug 10, 2018 (draft-29);
- **Already in** Firefox, Chrome, Safari, Opera, Cloudflare, Google, Facebook, OpenSSL, etc.;
- **Vibrant research topic**: more than 40 papers have been dedicated to the understanding, analysis, and implementation of this standard:
  - HKDF = HMAC-based key derivation functions;
  - SIGMA = SIGn and MAC;
  - AEAD = Authenticated Encryption with Associated Data: allow the message to contain “associated data” (AD) which is not made confidential, but its integrity is protected. A typical example: the header of a network packet that contains the destination address;
  - Symbolic verification in Tamarin;
  - Computational analysis and verification.

# TLS in the TCP/IP protocol stack

Major components of TLS 1.3:



# Sessions and connections

- Session

- Association between two communicating peers;
- Defines a set of cryptographic parameters which can be shared among multiple connections;
- Created by the handshake protocol;
- Primarily used to avoid expensive negotiation of new security parameters for each connection;

- Connection

- Transport (in the OSI layering model definition) that provides a suitable type of service;
- Each connection is associated with one session.

Multiple simultaneous sessions between a pair of parties may coexist.

# TLS handshake protocol

The [handshake protocol](#) is the most complex protocol of TLS. It allows parties to:

- Agree on a protocol version;
- Negotiate cryptographic algorithms;
- Establish shared secret keying material;
- Authenticate each other.

Once the handshake is complete, the peers use keying material to derive the [application data traffic keys](#).

# TLS handshake protocol

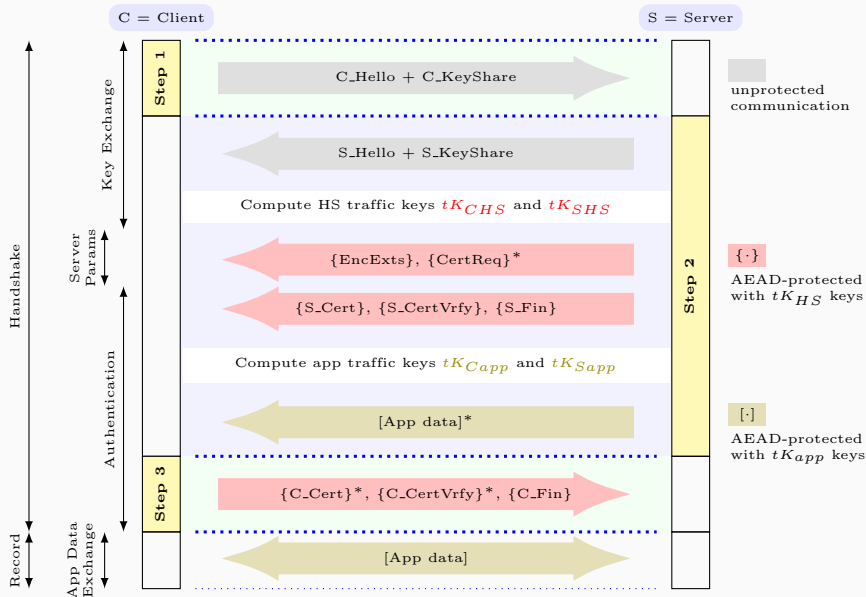
TLS supports two basic key exchange modes, one of which has two variants:

1. (EC)DHE mode. This is the standard handshake mode that does not use pre-shared secrets;
2. Pre-shared key (PSK) based mode. This is based on pre-shared keys. It may come in two variants:
  - 2.1 PSK-only, which does not provide forward secrecy;
  - 2.2 PSK with (EC)DHE, which provides forward secrecy.

When clients and servers share a PSK (either obtained externally or via a previous handshake), TLS 1.3 allows clients to send data on the first flight (early data). The client uses the PSK to authenticate the server and to encrypt the early data.



# Basic full handshake

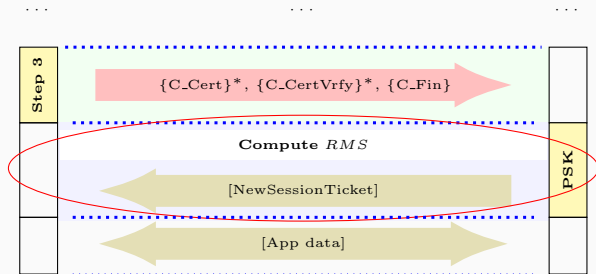


# Establishing a PSK in a previous connection

C = Client

S = Server

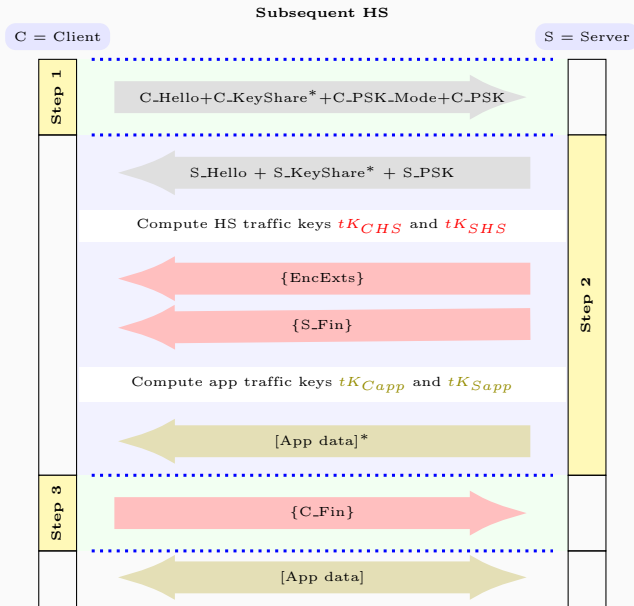
Initial HS



Once a HS has completed, S can send to C a **NewSessionTicket** message to create a unique association between the ticket value and a secret PSK derived from the **Resumption Master Secret (RMS)**.

The client **may use** this PSK for future HS. A server **may send** multiple tickets on a single connection!

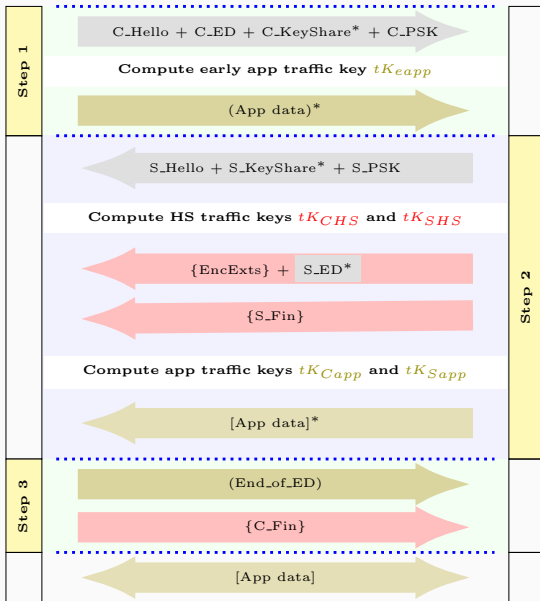
# PSK-based handshake



# PSK-based handshake with early data: 0-RTT

C = Client

S = Server



(·)

AEAD-protected with  $tK_{eapp}$  derived from PSK

# HMAC-based key derivation

TLS 1.3 uses a **HMAC-based key derivation function** (HKDF) (RFC 5869) that, starting with an initial keying material (IKM) generates an output keying material (OKM) following the two steps **extract-and-expand** paradigm:

1. In the first stage, it takes IKM and “extracts” from it a fixed-length pseudorandom key  $K$ . Formally,

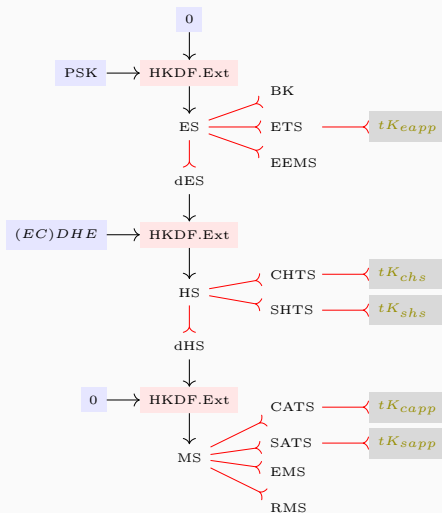
$$K \leftarrow \text{HKDF.Ext}(\text{salt}, \text{IKM})$$

(salt = practice jargon for “random non-secret quantity”);

2. In the second stage, based on some optional context and application-specific information, “expands” the key  $K$  into OKM of some length  $L$

$$\text{OKM} \leftarrow \text{HKDF.Exp}(K, \text{info}, L)$$

# Key derivation flow



ES = Early Secret  
 BK = Binder Key  
 ETS = Early Traffic Secret  
 $tK_{eapp}$  = Early App Traffic Key  
 EEMS = Early Exporter Master Secret  
 dES = Derived Early Secret

HS = Handshake Secret  
 CHTS = Client Handshake Traffic Secret  
 $tK_{chs}$  = Client Handshake Traffic Key  
 SHTS = Server Handshake Traffic Secret  
 $tK_{shs}$  = Server Handshake Traffic Key  
 dHS = Derived Handshake Secret

MS = Master Secret  
 CATS = Client App Traffic Secret  
 $tK_{capp}$  = Client App Traffic Key  
 SATS = Server App Traffic Secret  
 $tK_{sapp}$  = Server App Traffic Key  
 EMS = Exporter Master Secret  
 RMS = Resumption Master Secret

Note: The red “arrows” means application of the HKDF.Exp function. For instance,  $ETS = \text{HKDF.Exp}(ES, X, Y)$ , for some X and Y

# Handshake properties (1)

1. **Establishing the same session keys** on both sides of the handshake, provided that it completes successfully on each endpoint;
2. **Secrecy of the session keys**: The shared session keys should be known only to the communicating parties and not to the attacker;
3. **Peer authentication**: Server side of the channel is always authenticated; the client side is optionally authenticated;
4. **Uniqueness of the session keys**: Any two distinct handshakes should produce distinct, unrelated session keys. Individual session keys produced by a handshake should also be distinct and independent;
5. **Downgrade protection**: The cryptographic parameters should be the same on both sides and should be the same as if the peers had been communicating in the absence of an attack;

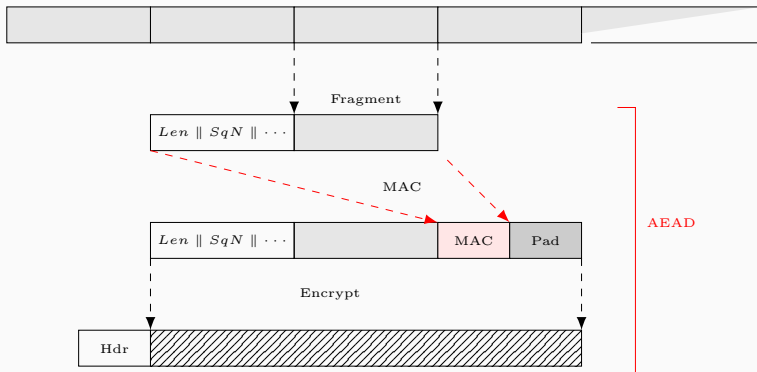
## Handshake properties (2)

6. **Forward secret with respect to long-term keys:** protect the secrecy of past sessions so that a session stays secret going forward;
7. **Key compromise impersonation resistance:** In a mutually authenticated connection with certificates, compromising the long-term secret of one actor should not break that actor's authentication of their peer in the given connection. For example, if a client's signature key is compromised, it should not be possible to impersonate arbitrary servers to that client in subsequent handshakes;
8. **Protection of endpoint identities:** The server's identity (certificate) should be protected against passive attackers. The client's identity should be protected against both passive and active attackers.



# The record protocol

Application data



# Alert messages

- Alert messages convey closure information and errors;
- Alert messages are encrypted in accordance with the current connection state;
- In contrast to the previous versions, the severity of the alert in TLS 1.3 is implicit in the type of alert being sent;
- There are two types of alerts:
  - **Closure alerts:**
    - **close\_notify**: notifies the recipient that the sender will not send any more messages on this connection;
    - **user\_canceled**: notifies the recipient that the sender is canceling the handshake for some reason unrelated to a protocol failure;
  - **Error alerts** indicate abortive closure of the connection. Examples: **unexpected\_message**, **bad\_record\_mac**, **handshake\_failure**, etc.

# Applications

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# Applications

- HTTPS (HTTP + SSL/TLS + TCP);
- FTPS (FTP + TLS);
- Software update programs: in more recent versions of Windows, Windows Update is a custom app secured by TLS. Many other online software update programs, such as the getPlus program used by Adobe, use TLS connections for security;
- Client security with TLS: client side certificates can be used with TLS to prove the identity of the client to the server, and vice-versa. This is called “two-way TLS” and requires the client and server both provide certificates to each other;
- Server-to-Server security with TLS: many server-to-server connections offer TLS as an option;
- TLS based VPN.

# Security of TLS

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# Security of TLS

1. The study of TLS 1.3 protocol security is a hot research topic with paramount practical importance;
2. Many research articles and doctoral theses have been written in this direction;
3. Special sessions at conferences and workshops focused on cryptography and information security have been dedicated to TLS 1.3;
4. The two primary directions are the study of TLS 1.3 security in the:
  - 4.1 Symbolic model: Horvat (2015); Cremers et al. (2017); Hoyland (2018); van der Merwe (2018); Scott (2018);
  - 4.2 Computational model: Jager et al. (2012); Giesen et al. (2013); Kohlar et al. (2013); Dowling et al. (2021); Aviram et al. (2021); Bhargavan et al. (2022); Davis et al. (2022).

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