SAC Summer School 2016

Implementation and analysis of cryptographic protocols

Part 2: The TLS Protocol

Dr. Douglas Stebila

McMaster University

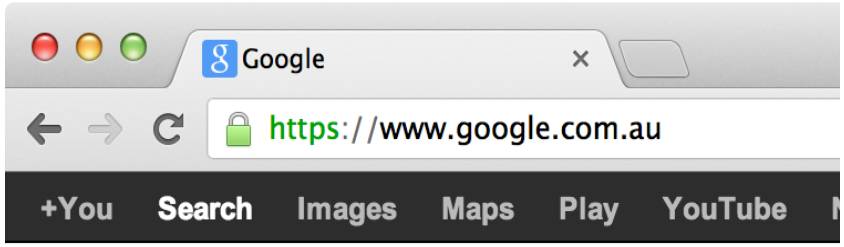
https://www.douglas.stebila.ca/teaching/sac-2016

Terminology

- SSL: Secure Sockets Layer
- Proposed by Netscape
  - SSLv2: 1995
  - SSLv3: 1996

- TLS: Transport Layer Security
- IETF Standardization of SSL
  - TLSv1.0 = SSLv3: 1999
  - TLSv1.1: 2006
  - TLSv1.2: 2008
  - TLSv1.3: 2017?

- HTTPS: HTTP (Hypertext Transport Protocol) over SSL



Security goals of TLS

- Provides **authentication** based on public key certificates
  - server-to-client (always)
  - client-to-server (optional)
- Provides **confidentiality** and integrity of message transmission

- But only protects confidentiality if authentication is correct.

IETF Internet Protocol suite

TLS adds encryption to many application level protocols

Layer	Examples
Application	web (HTTP, HTTPS) email (SMTP, POP3, IMAP) login (SSH, Telnet)
Transport	connection-oriented (TCP) connectionless (UDP)
Internet	addressing and routing: • IPv4, IPv6 control (ICMP) security (IPsec)
Link	packet framing (Ethernet) physical connection • WLAN • ADSL • GSM/3G

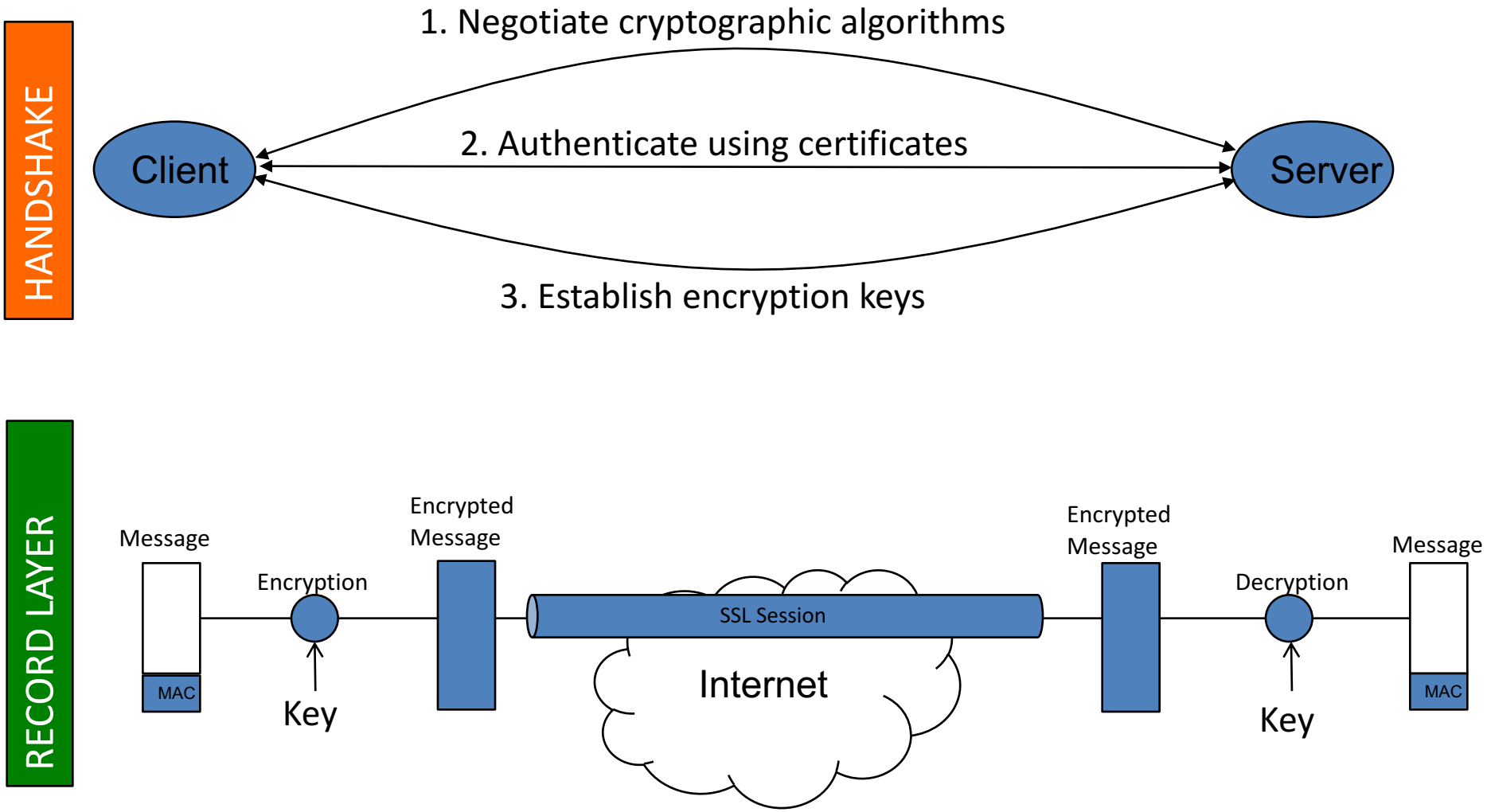
TLS

TLS and HTTP

- TLS can be used to provide protection for HTTP communications:
  - Port 443 is reserved for HTTP over TLS
- HTTPS is the name of the URL scheme used with this port.

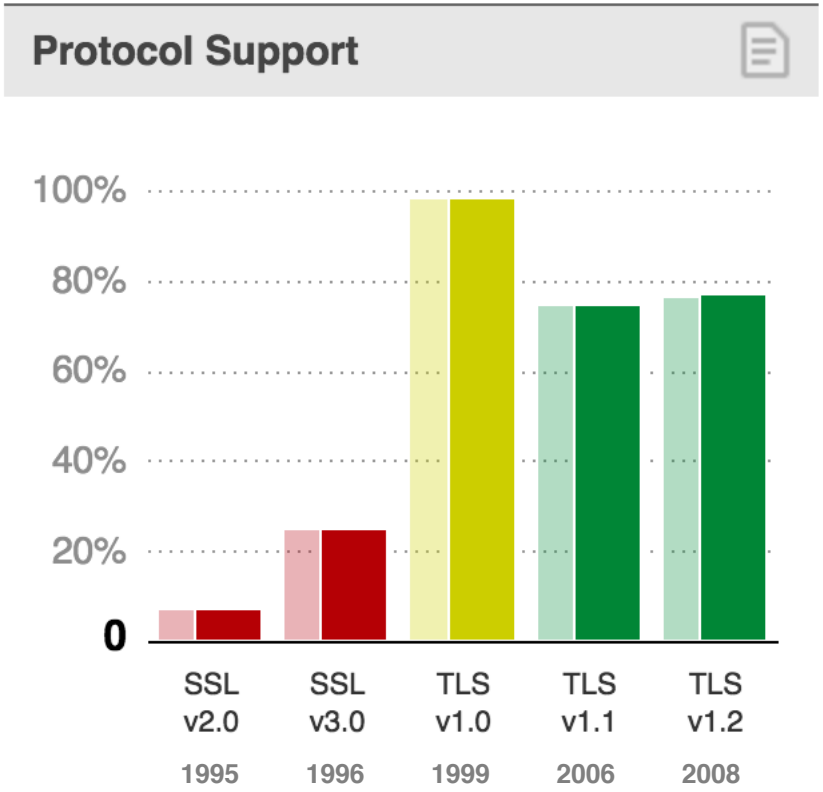
- http://www.develop.com implies the use of standard HTTP using port 80.
- https://www.develop.com implies the use of HTTP over TLS using port 443.

SSL/TLS Protocol



What is TLS?

- 5 protocol versions
- vast array of standards
- many implementations!
- 300+ combinations of cryptographic primitives
- different levels of security
- different modes of authentication
- additional functionality:
  - alerts & errors
  - session resumption
  - renegotiation
  - compression



https://www.trustworthyinternet.org/ssl-pulse/
June 1, 2016

The current approved version of TLS is version 1.2, which is specified in:

- RFC 5246: “The Transport Layer Security (TLS) Protocol Version 1.2”.

The current standard replaces these former versions, which are now considered obsolete:

- RFC 2246: “The TLS Protocol Version 1.0”.
- RFC 4346: “The Transport Layer Security (TLS) Protocol Version 1.1”.

as well as the never standardized SSL 3.0:

- RFC 6101: “The Secure Sockets Layer (SSL) Protocol Version 3.0”.

Other RFCs subsequently extended TLS.

Extensions to TLS 1.0 include:

- RFC 2595: “Using TLS with IMAP, POP3 and ACAP”. Specifies an extension to the IMAP, POP3 and ACAP services that allow the server and client to use transport-layer security to provide private, authenticated communication over the Internet.
- RFC 2712: “Addition of Kerberos Cipher Suites to Transport Layer Security (TLS)”. The 40-bit cipher suites defined in this memo appear only for the purpose of documenting the fact that those cipher suite codes have already been assigned.
- RFC 2817: “Upgrading to TLS Within HTTP/1.1”, explains how to use the Upgrade mechanism in HTTP/1.1 to initiate Transport Layer Security (TLS) over an existing TCP connection. This allows unsecured and secured HTTP traffic to share the same well known port (in this case, http: at 80 rather than https: at 443).
- RFC 2818: “HTTP Over TLS”, distinguishes secured traffic from insecure traffic by the use of a different 'server port'.
- RFC 3207: “SMTP Service Extension for Secure SMTP over Transport Layer Security”. Specifies an extension to the SMTP service that allows an SMTP server and client to use transport-layer security to provide private, authenticated communication over the Internet.
- RFC 3268: “AES Ciphersuites for TLS”. Adds Advanced Encryption Standard (AES) cipher suites to the previously existing symmetric ciphers.
- RFC 3546: “Transport Layer Security (TLS) Extensions”, adds a mechanism for negotiating protocol extensions during session initialisation and defines some extensions. Made obsolete by RFC 4366.
- RFC 3749: “Transport Layer Security Protocol Compression Methods”, specifies the framework for compression methods and the DEFLATE compression method.
- RFC 3943: “Transport Layer Security (TLS) Protocol Compression Using Lempel-Ziv-Stac (LZS)”.
- RFC 4132: “Addition of Camellia Cipher Suites to Transport Layer Security (TLS)”.
- RFC 4162: “Addition of SEED Cipher Suites to Transport Layer Security (TLS)”.
- RFC 4217: “Securing FTP with TLS”.
- RFC 4279: “Pre-Shared Key Ciphersuites for Transport Layer Security (TLS)”, adds three sets of new cipher suites for the TLS protocol to support authentication based on pre-shared keys.

Extensions to TLS 1.1 include:

- RFC 4347: “Datagram Transport Layer Security” specifies a TLS variant that works over datagram protocols (such as UDP).
- RFC 4366: “Transport Layer Security (TLS) Extensions” describes both a set of specific extensions and a generic extension mechanism.
- RFC 4492: “Elliptic Curve Cryptography (ECC) Cipher Suites for Transport Layer Security (TLS)”.
- RFC 4507: “Transport Layer Security (TLS) Session Resumption without Server-Side State”.
- RFC 4680: “TLS Handshake Message for Supplemental Data”.
- RFC 4681: “TLS User Mapping Extension”.
- RFC 4785: “Pre-Shared Key (PSK) Ciphersuites with NULL Encryption for Transport Layer Security (TLS)”.
- RFC 5054: “Using the Secure Remote Password (SRP) Protocol for TLS Authentication”. Defines the TLS-SRP ciphersuites.
- RFC 5081: “Using OpenPGP Keys for Transport Layer Security (TLS) Authentication”, obsoleted by RFC 6091.

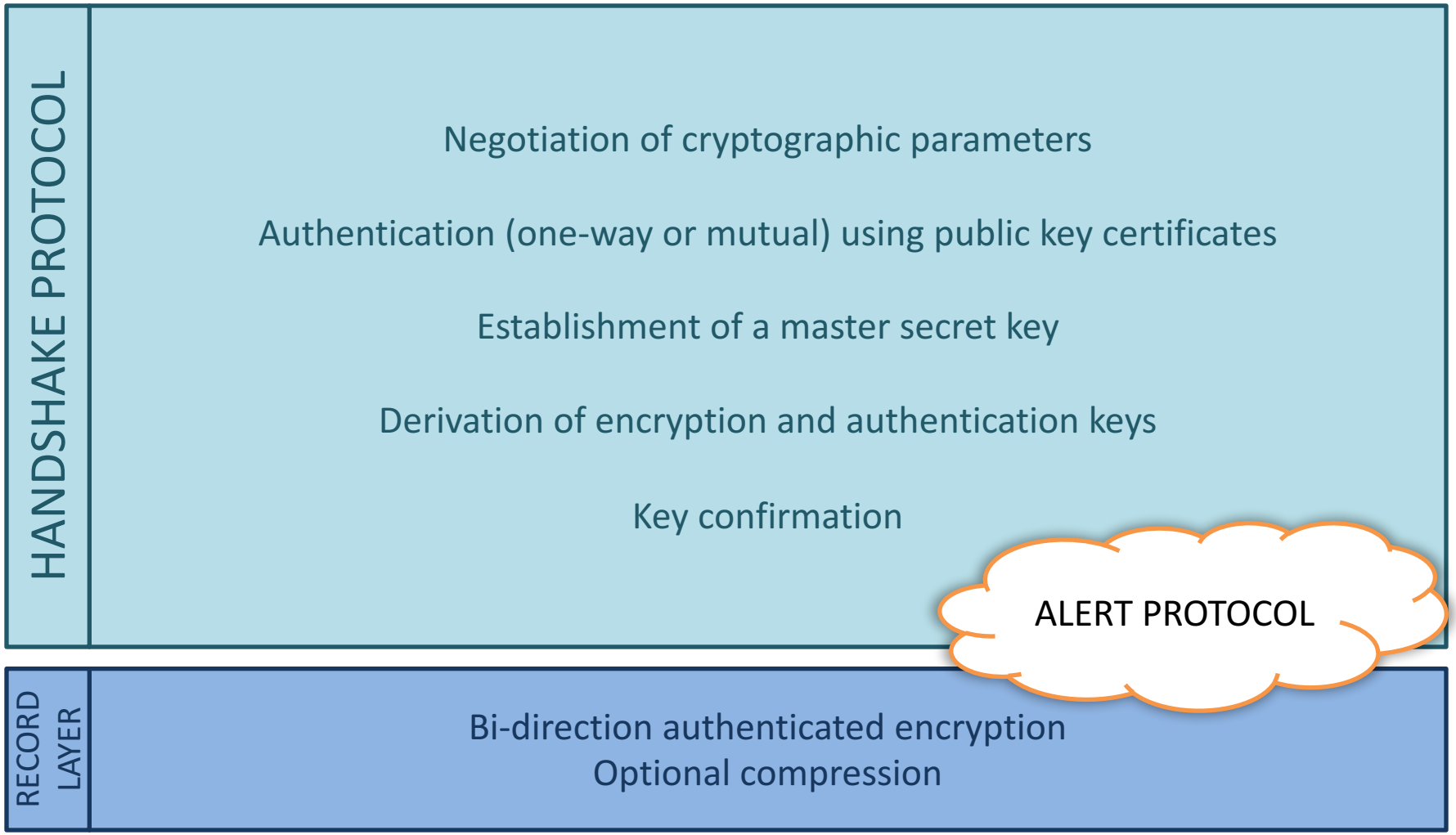
Extensions to TLS 1.2 include:

- RFC 5746: “Transport Layer Security (TLS) Renegotiation Indication Extension”.
- RFC 5878: “Transport Layer Security (TLS) Authorization Extensions”.
- RFC 6091: “Using OpenPGP Keys for Transport Layer Security (TLS) Authentication“.
- RFC 6176: “Prohibiting Secure Sockets Layer (SSL) Version 2.0”.
- RFC 6209: “Addition of the ARIA Cipher Suites to Transport Layer Security (TLS)”.

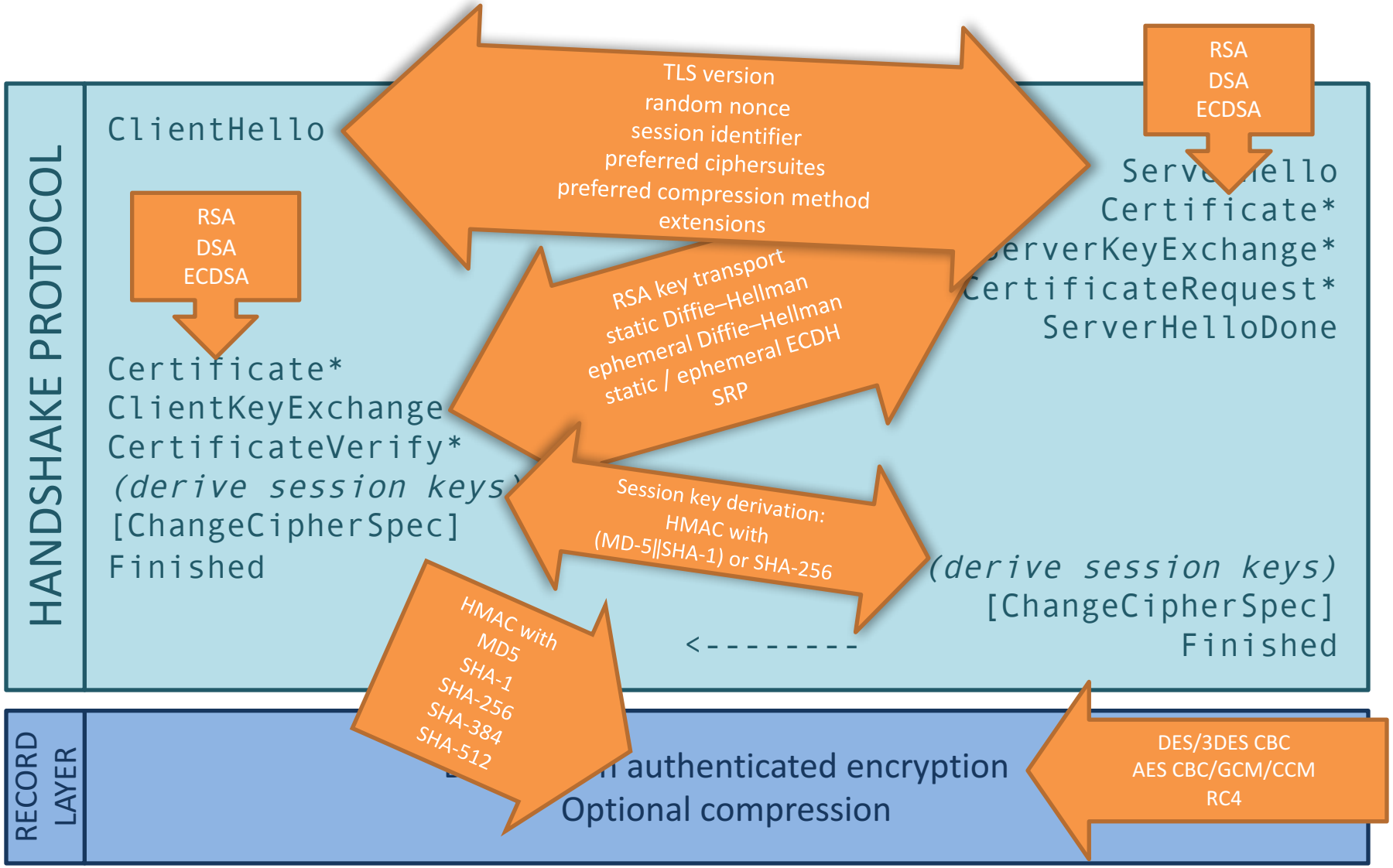
What is TLS?

http://en.wikipedia.org/wiki/Transport_Layer_Security

Structure of TLS



Structure of TLS



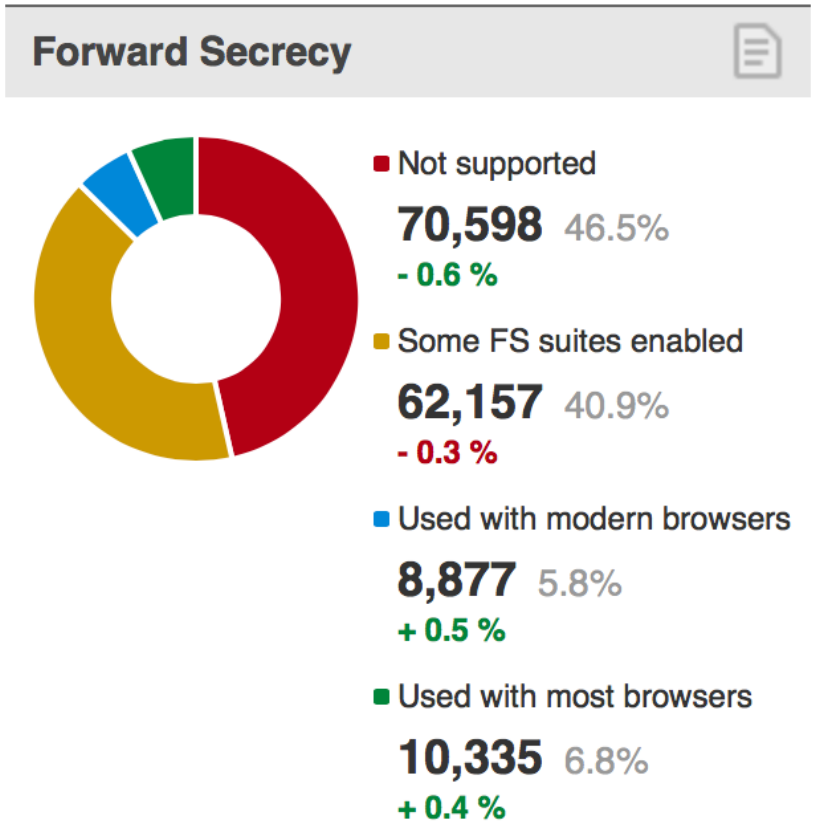
TLS_NULL_WITH_NULL_NULL TLS_RSA_WITH_NULL_MD5 TLS_RSA_WITH_NULL_SHA TLS_RSA_EXPORT_WITH_RC4_40_MD5 TLS_RSA_WITH_RC4_128_MD5 TLS_RSA_WITH_RC4_128_SHA TLS_RSA_EXPORT_WITH_RC2_CBC_40_MD5
TLS_RSA_WITH_IDEA_CBC_SHA TLS_RSA_EXPORT_WITH_DES40_CBC_SHA TLS_RSA_WITH_DES_CBC_SHA TLS_RSA_WITH_3DES_EDE_CBC_SHA TLS_DH_DSS_EXPORT_WITH_DES40_CBC_SHA TLS_DH_DSS_WITH_DES_CBC_SHA
TLS_DH_DSS_WITH_3DES_EDE_CBC_SHA TLS_DH_RSA_EXPORT_WITH_DES40_CBC_SHA TLS_DH_RSA_WITH_DES_CBC_SHA TLS_DH_RSA_WITH_3DES_EDE_CBC_SHA TLS_DHE_DSS_EXPORT_WITH_DES40_CBC_SHA
TLS_DHE_DSS_WITH_DES_CBC_SHA TLS_DHE_DSS_WITH_3DES_EDE_CBC_SHA TLS_DHE_RSA_EXPORT_WITH_DES40_CBC_SHA TLS_DHE_RSA_WITH_DES_CBC_SHA TLS_DHE_RSA_WITH_3DES_EDE_CBC_SHA
TLS_DH_anon_EXPORT_WITH_RC4_40_MD5 TLS_DH_anon_WITH_RC4_128_MD5 TLS_DH_anon_EXPORT_WITH_DES40_CBC_SHA TLS_DH_anon_WITH_DES_CBC_SHA TLS_DH_anon_WITH_3DES_EDE_CBC_SHA
TLS_KRB5_WITH_DES_CBC_SHA TLS_KRB5_WITH_3DES_EDE_CBC_SHA TLS_KRB5_WITH_RC4_128_SHA TLS_KRB5_WITH_IDEA_CBC_SHA TLS_KRB5_WITH_DES_CBC_MD5 TLS_KRB5_WITH_3DES_EDE_CBC_MD5
TLS_KRB5_WITH_RC4_128_MD5 TLS_KRB5_WITH_IDEA_CBC_MD5 TLS_KRB5_EXPORT_WITH_DES_CBC_40_SHA TLS_KRB5_EXPORT_WITH_RC2_CBC_40_SHA TLS_KRB5_EXPORT_WITH_RC4_40_SHA
TLS_KRB5_EXPORT_WITH_DES_CBC_40_MD5 TLS_KRB5_EXPORT_WITH_RC2_CBC_40_MD5 TLS_KRB5_EXPORT_WITH_RC4_40_MD5 TLS_PSK_WITH_NULL_SHA TLS_DHE_PSK_WITH_NULL_SHA TLS_RSA_PSK_WITH_NULL_SHA
TLS_RSA_WITH_AES_128_CBC_SHA TLS_DH_DSS_WITH_AES_128_CBC_SHA TLS_DH_RSA_WITH_AES_128_CBC_SHA TLS_DHE_DSS_WITH_AES_128_CBC_SHA TLS_DHE_RSA_WITH_AES_128_CBC_SHA
TLS_DH_anon_WITH_AES_128_CBC_SHA TLS_RSA_WITH_AES_256_CBC_SHA TLS_DH_DSS_WITH_AES_256_CBC_SHA TLS_DH_RSA_WITH_AES_256_CBC_SHA TLS_DHE_DSS_WITH_AES_256_CBC_SHA
TLS_DHE_RSA_WITH_AES_256_CBC_SHA TLS_DH_anon_WITH_AES_256_CBC_SHA TLS_RSA_WITH_NULL_SHA256 TLS_RSA_WITH_AES_128_CBC_SHA256 TLS_RSA_WITH_AES_256_CBC_SHA256 TLS_DH_DSS_WITH_AES_128_CBC_SHA256
TLS_DH_RSA_WITH_AES_128_CBC_SHA256 TLS_DHE_DSS_WITH_AES_128_CBC_SHA256 TLS_RSA_WITH_CAMELLIA_128_CBC_SHA TLS_DH_DSS_WITH_CAMELLIA_128_CBC_SHA TLS_DH_RSA_WITH_CAMELLIA_128_CBC_SHA
TLS_DHE_DSS_WITH_CAMELLIA_128_CBC_SHA TLS_DHE_RSA_WITH_CAMELLIA_128_CBC_SHA TLS_DH_anon_WITH_CAMELLIA_128_CBC_SHA TLS_DHE_RSA_WITH_AES_128_CBC_SHA256 TLS_DH_DSS_WITH_AES_256_CBC_SHA256
TLS_DH_RSA_WITH_AES_256_CBC_SHA256 TLS_DHE_DSS_WITH_AES_256_CBC_SHA256 TLS_DHE_RSA_WITH_AES_256_CBC_SHA256 TLS_DH_anon_WITH_AES_128_CBC_SHA256 TLS_DH_anon_WITH_AES_256_CBC_SHA256
TLS_RSA_WITH_CAMELLIA_256_CBC_SHA TLS_DH_DSS_WITH_CAMELLIA_256_CBC_SHA TLS_DH_RSA_WITH_CAMELLIA_256_CBC_SHA TLS_DHE_DSS_WITH_CAMELLIA_256_CBC_SHA TLS_DHE_RSA_WITH_CAMELLIA_256_CBC_SHA
TLS_DH_anon_WITH_CAMELLIA_256_CBC_SHA TLS_PSK_WITH_RC4_128_SHA TLS_PSK_WITH_3DES_EDE_CBC_SHA TLS_PSK_WITH_AES_128_CBC_SHA TLS_PSK_WITH_AES_256_CBC_SHA TLS_DHE_PSK_WITH_RC4_128_SHA
TLS_DHE_PSK_WITH_3DES_EDE_CBC_SHA TLS_DHE_PSK_WITH_AES_128_CBC_SHA TLS_DHE_PSK_WITH_AES_256_CBC_SHA TLS_RSA_PSK_WITH_RC4_128_SHA TLS_RSA_PSK_WITH_3DES_EDE_CBC_SHA
TLS_RSA_PSK_WITH_AES_128_CBC_SHA TLS_RSA_PSK_WITH_AES_256_CBC_SHA TLS_RSA_WITH_SEED_CBC_SHA TLS_DH_DSS_WITH_SEED_CBC_SHA TLS_DH_RSA_WITH_SEED_CBC_SHA TLS_DHE_DSS_WITH_SEED_CBC_SHA
TLS_DHE_RSA_WITH_SEED_CBC_SHA TLS_DH_anon_WITH_SEED_CBC_SHA TLS_RSA_WITH_AES_128_GCM_SHA256 TLS_RSA_WITH_AES_256_GCM_SHA384 TLS_DHE_RSA_WITH_AES_128_GCM_SHA256
TLS_DHE_RSA_WITH_AES_256_GCM_SHA384 TLS_DH_RSA_WITH_AES_128_GCM_SHA256 TLS_DH_RSA_WITH_AES_256_GCM_SHA384 TLS_DHE_DSS_WITH_AES_128_GCM_SHA256 TLS_DHE_DSS_WITH_AES_256_GCM_SHA384
TLS_DH_DSS_WITH_AES_128_GCM_SHA256 TLS_DH_DSS_WITH_AES_256_GCM_SHA384 TLS_DH_anon_WITH_AES_128_GCM_SHA256 TLS_DH_anon_WITH_AES_256_GCM_SHA384 TLS_PSK_WITH_AES_128_GCM_SHA256
TLS_PSK_WITH_AES_256_GCM_SHA384 TLS_DHE_PSK_WITH_AES_128_GCM_SHA256 TLS_DHE_PSK_WITH_AES_256_GCM_SHA384 TLS_RSA_PSK_WITH_AES_128_GCM_SHA256 TLS_RSA_PSK_WITH_AES_256_GCM_SHA384
TLS_PSK_WITH_AES_128_CBC_SHA256 TLS_PSK_WITH_AES_256_CBC_SHA384 TLS_PSK_WITH_NULL_SHA256 TLS_PSK_WITH_NULL_SHA384 TLS_DHE_PSK_WITH_AES_128_CBC_SHA256 TLS_DHE_PSK_WITH_AES_256_CBC_SHA384
TLS_DHE_PSK_WITH_NULL_SHA256 TLS_DHE_PSK_WITH_NULL_SHA384 TLS_RSA_PSK_WITH_AES_128_CBC_SHA256 TLS_RSA_PSK_WITH_AES_256_CBC_SHA384 TLS_RSA_PSK_WITH_NULL_SHA256 TLS_RSA_PSK_WITH_NULL_SHA384
TLS_RSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_DH_DSS_WITH_CAMELLIA_128_CBC_SHA256 TLS_DH_RSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_DHE_DSS_WITH_CAMELLIA_128_CBC_SHA256
TLS_DHE_RSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_DH_anon_WITH_CAMELLIA_128_CBC_SHA256 TLS_RSA_WITH_CAMELLIA_256_CBC_SHA256 TLS_DH_DSS_WITH_CAMELLIA_256_CBC_SHA256
TLS_DH_RSA_WITH_CAMELLIA_256_CBC_SHA256 TLS_DHE_DSS_WITH_CAMELLIA_256_CBC_SHA256 TLS_DHE_RSA_WITH_CAMELLIA_256_CBC_SHA256 TLS_DH_anon_WITH_CAMELLIA_256_CBC_SHA256
TLS_EMPTY_RENEGOTIATION_INFO_SCSV TLS_ECDH_ECDSA_WITH_NULL_SHA TLS_ECDH_ECDSA_WITH_RC4_128_SHA TLS_ECDH_ECDSA_WITH_3DES_EDE_CBC_SHA TLS_ECDH_ECDSA_WITH_AES_128_CBC_SHA
TLS_ECDH_ECDSA_WITH_AES_256_CBC_SHA TLS_ECDHE_ECDSA_WITH_NULL_SHA TLS_ECDHE_ECDSA_WITH_RC4_128_SHA TLS_ECDHE_ECDSA_WITH_3DES_EDE_CBC_SHA TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA TLS_ECDH_RSA_WITH_NULL_SHA TLS_ECDH_RSA_WITH_RC4_128_SHA TLS_ECDH_RSA_WITH_3DES_EDE_CBC_SHA TLS_ECDH_RSA_WITH_AES_128_CBC_SHA
TLS_ECDH_RSA_WITH_AES_256_CBC_SHA TLS_ECDHE_RSA_WITH_NULL_SHA TLS_ECDHE_RSA_WITH_RC4_128_SHA TLS_ECDHE_RSA_WITH_3DES_EDE_CBC_SHA TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA
TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA TLS_ECDH_anon_WITH_NULL_SHA TLS_ECDH_anon_WITH_RC4_128_SHA TLS_ECDH_anon_WITH_3DES_EDE_CBC_SHA TLS_ECDH_anon_WITH_AES_128_CBC_SHA
TLS_ECDH_anon_WITH_AES_256_CBC_SHA TLS_SRP_SHA_WITH_3DES_EDE_CBC_SHA TLS_SRP_SHA_RSA_WITH_3DES_EDE_CBC_SHA TLS_SRP_SHA_DSS_WITH_3DES_EDE_CBC_SHA TLS_SRP_SHA_WITH_AES_128_CBC_SHA
TLS_SRP_SHA_RSA_WITH_AES_128_CBC_SHA TLS_SRP_SHA_DSS_WITH_AES_128_CBC_SHA TLS_SRP_SHA_WITH_AES_256_CBC_SHA TLS_SRP_SHA_RSA_WITH_AES_256_CBC_SHA TLS_SRP_SHA_DSS_WITH_AES_256_CBC_SHA
TLS_ECDHE_ECDSA_WITH_AES_128_CBC_SHA256 TLS_ECDHE_ECDSA_WITH_AES_256_CBC_SHA384 TLS_ECDH_ECDSA_WITH_AES_128_CBC_SHA256 TLS_ECDH_ECDSA_WITH_AES_256_CBC_SHA384
TLS_ECDHE_RSA_WITH_AES_128_CBC_SHA256 TLS_ECDHE_RSA_WITH_AES_256_CBC_SHA384 TLS_ECDH_RSA_WITH_AES_128_CBC_SHA256 TLS_ECDH_RSA_WITH_AES_256_CBC_SHA384
TLS_ECDHE_ECDSA_WITH_AES_128_GCM_SHA256 TLS_ECDHE_ECDSA_WITH_AES_256_GCM_SHA384 TLS_ECDH_ECDSA_WITH_AES_128_GCM_SHA256 TLS_ECDH_ECDSA_WITH_AES_256_GCM_SHA384
TLS_ECDHE_RSA_WITH_AES_128_GCM_SHA256 TLS_ECDHE_RSA_WITH_AES_256_GCM_SHA384 TLS_ECDH_RSA_WITH_AES_128_GCM_SHA256 TLS_ECDH_RSA_WITH_AES_256_GCM_SHA384 TLS_ECDHE_PSK_WITH_RC4_128_SHA
TLS_ECDHE_PSK_WITH_3DES_EDE_CBC_SHA TLS_ECDHE_PSK_WITH_AES_128_CBC_SHA TLS_ECDHE_PSK_WITH_AES_256_CBC_SHA TLS_ECDHE_PSK_WITH_AES_128_CBC_SHA256 TLS_ECDHE_PSK_WITH_AES_256_CBC_SHA384
TLS_ECDHE_PSK_WITH_NULL_SHA TLS_ECDHE_PSK_WITH_NULL_SHA256 TLS_ECDHE_PSK_WITH_NULL_SHA384 TLS_RSA_WITH_ARIA_128_CBC_SHA256 TLS_RSA_WITH_ARIA_256_CBC_SHA384
TLS_DH_DSS_WITH_ARIA_128_CBC_SHA256 TLS_DH_DSS_WITH_ARIA_256_CBC_SHA384 TLS_DH_RSA_WITH_ARIA_128_CBC_SHA256 TLS_DH_RSA_WITH_ARIA_256_CBC_SHA384 TLS_DHE_DSS_WITH_ARIA_128_CBC_SHA256
TLS_DHE_DSS_WITH_ARIA_256_CBC_SHA384 TLS_DHE_RSA_WITH_ARIA_128_CBC_SHA256 TLS_DHE_RSA_WITH_ARIA_256_CBC_SHA384 TLS_DH_anon_WITH_ARIA_128_CBC_SHA256 TLS_DH_anon_WITH_ARIA_256_CBC_SHA384
TLS_ECDHE_ECDSA_WITH_ARIA_128_CBC_SHA256 TLS_ECDHE_ECDSA_WITH_ARIA_256_CBC_SHA384 TLS_ECDH_ECDSA_WITH_ARIA_128_CBC_SHA256 TLS_ECDH_ECDSA_WITH_ARIA_256_CBC_SHA384
TLS_ECDHE_RSA_WITH_ARIA_128_CBC_SHA256 TLS_ECDHE_RSA_WITH_ARIA_256_CBC_SHA384 TLS_ECDH_RSA_WITH_ARIA_128_CBC_SHA256 TLS_ECDH_RSA_WITH_ARIA_256_CBC_SHA384 TLS_RSA_WITH_ARIA_128_GCM_SHA256
TLS_RSA_WITH_ARIA_256_GCM_SHA384 TLS_DHE_RSA_WITH_ARIA_128_GCM_SHA256 TLS_DHE_RSA_WITH_ARIA_256_GCM_SHA384 TLS_DH_RSA_WITH_ARIA_128_GCM_SHA256 TLS_DH_RSA_WITH_ARIA_256_GCM_SHA384
TLS_DHE_DSS_WITH_ARIA_128_GCM_SHA256 TLS_DHE_DSS_WITH_ARIA_256_GCM_SHA384 TLS_DH_DSS_WITH_ARIA_128_GCM_SHA256 TLS_DH_DSS_WITH_ARIA_256_GCM_SHA384 TLS_DH_anon_WITH_ARIA_128_GCM_SHA256
TLS_DH_anon_WITH_ARIA_256_GCM_SHA384 TLS_ECDHE_ECDSA_WITH_ARIA_128_GCM_SHA256 TLS_ECDHE_ECDSA_WITH_ARIA_256_GCM_SHA384 TLS_ECDH_ECDSA_WITH_ARIA_128_GCM_SHA256
TLS_ECDH_ECDSA_WITH_ARIA_256_GCM_SHA384 TLS_ECDHE_RSA_WITH_ARIA_128_GCM_SHA256 TLS_ECDHE_RSA_WITH_ARIA_256_GCM_SHA384 TLS_ECDH_RSA_WITH_ARIA_128_GCM_SHA256
TLS_ECDH_RSA_WITH_ARIA_256_GCM_SHA384 TLS_PSK_WITH_ARIA_128_CBC_SHA256 TLS_PSK_WITH_ARIA_256_CBC_SHA384 TLS_DHE_PSK_WITH_ARIA_128_CBC_SHA256 TLS_DHE_PSK_WITH_ARIA_256_CBC_SHA384
TLS_RSA_PSK_WITH_ARIA_128_CBC_SHA256 TLS_RSA_PSK_WITH_ARIA_256_CBC_SHA384 TLS_PSK_WITH_ARIA_128_GCM_SHA256 TLS_PSK_WITH_ARIA_256_GCM_SHA384 TLS_DHE_PSK_WITH_ARIA_128_GCM_SHA256
TLS_DHE_PSK_WITH_ARIA_256_GCM_SHA384 TLS_RSA_PSK_WITH_ARIA_128_GCM_SHA256 TLS_RSA_PSK_WITH_ARIA_256_GCM_SHA384 TLS_ECDHE_PSK_WITH_ARIA_128_CBC_SHA256 TLS_ECDHE_PSK_WITH_ARIA_256_CBC_SHA384
TLS_ECDHE_ECDSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_ECDHE_ECDSA_WITH_CAMELLIA_256_CBC_SHA384 TLS_ECDH_ECDSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_ECDH_ECDSA_WITH_CAMELLIA_256_CBC_SHA384
TLS_ECDHE_RSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_ECDHE_RSA_WITH_CAMELLIA_256_CBC_SHA384 TLS_ECDH_RSA_WITH_CAMELLIA_128_CBC_SHA256 TLS_ECDH_RSA_WITH_CAMELLIA_256_CBC_SHA384
TLS_RSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_RSA_WITH_CAMELLIA_256_GCM_SHA384 TLS_DHE_RSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_DHE_RSA_WITH_CAMELLIA_256_GCM_SHA384
TLS_DH_RSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_DH_RSA_WITH_CAMELLIA_256_GCM_SHA384 TLS_DHE_DSS_WITH_CAMELLIA_128_GCM_SHA256 TLS_DHE_DSS_WITH_CAMELLIA_256_GCM_SHA384
TLS_DH_DSS_WITH_CAMELLIA_128_GCM_SHA256 TLS_DH_DSS_WITH_CAMELLIA_256_GCM_SHA384 TLS_DH_anon_WITH_CAMELLIA_128_GCM_SHA256 TLS_DH_anon_WITH_CAMELLIA_256_GCM_SHA384
TLS_ECDHE_ECDSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_ECDHE_ECDSA_WITH_CAMELLIA_256_GCM_SHA384 TLS_ECDH_ECDSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_ECDH_ECDSA_WITH_CAMELLIA_256_GCM_SHA384
TLS_ECDHE_RSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_ECDHE_RSA_WITH_CAMELLIA_256_GCM_SHA384 TLS_ECDH_RSA_WITH_CAMELLIA_128_GCM_SHA256 TLS_ECDH_RSA_WITH_CAMELLIA_256_GCM_SHA384
TLS_PSK_WITH_CAMELLIA_128_GCM_SHA256 TLS_PSK_WITH_CAMELLIA_256_GCM_SHA384 TLS_DHE_PSK_WITH_CAMELLIA_128_GCM_SHA256 TLS_DHE_PSK_WITH_CAMELLIA_256_GCM_SHA384
TLS_RSA_PSK_WITH_CAMELLIA_128_GCM_SHA256 TLS_RSA_PSK_WITH_CAMELLIA_256_GCM_SHA384 TLS_PSK_WITH_CAMELLIA_128_CBC_SHA256 TLS_PSK_WITH_CAMELLIA_256_CBC_SHA384
TLS_DHE_PSK_WITH_CAMELLIA_128_CBC_SHA256 TLS_DHE_PSK_WITH_CAMELLIA_256_CBC_SHA384 TLS_RSA_PSK_WITH_CAMELLIA_128_CBC_SHA256 TLS_RSA_PSK_WITH_CAMELLIA_256_CBC_SHA384
TLS_ECDHE_PSK_WITH_CAMELLIA_128_CBC_SHA256 TLS_ECDHE_PSK_WITH_CAMELLIA_256_CBC_SHA384 TLS_RSA_WITH_AES_128_CCM TLS_RSA_WITH_AES_256_CCM TLS_DHE_RSA_WITH_AES_128_CCM
TLS_DHE_RSA_WITH_AES_256_CCM TLS_RSA_WITH_AES_128_CCM_8 TLS_RSA_WITH_AES_256_CCM_8 TLS_DHE_RSA_WITH_AES_128_CCM_8 TLS_DHE_RSA_WITH_AES_256_CCM_8 TLS_PSK_WITH_AES_128_CCM
TLS_PSK_WITH_AES_256_CCM TLS_DHE_PSK_WITH_AES_128_CCM TLS_DHE_PSK_WITH_AES_256_CCM TLS_PSK_WITH_AES_128_CCM_8 TLS_PSK_WITH_AES_256_CCM_8 TLS_PSK_DHE_WITH_AES_128_CCM_8
TLS_PSK_DHE_WITH_AES_256_CCM_8

List of all 314 TLS ciphersuites

(Perfect) Forward secrecy

- An adversary who later learns the server's long-term private key shouldn't be able to read previous transmissions

- RSA key transport: no PFS
- signed Diffie–Hellman: PFS

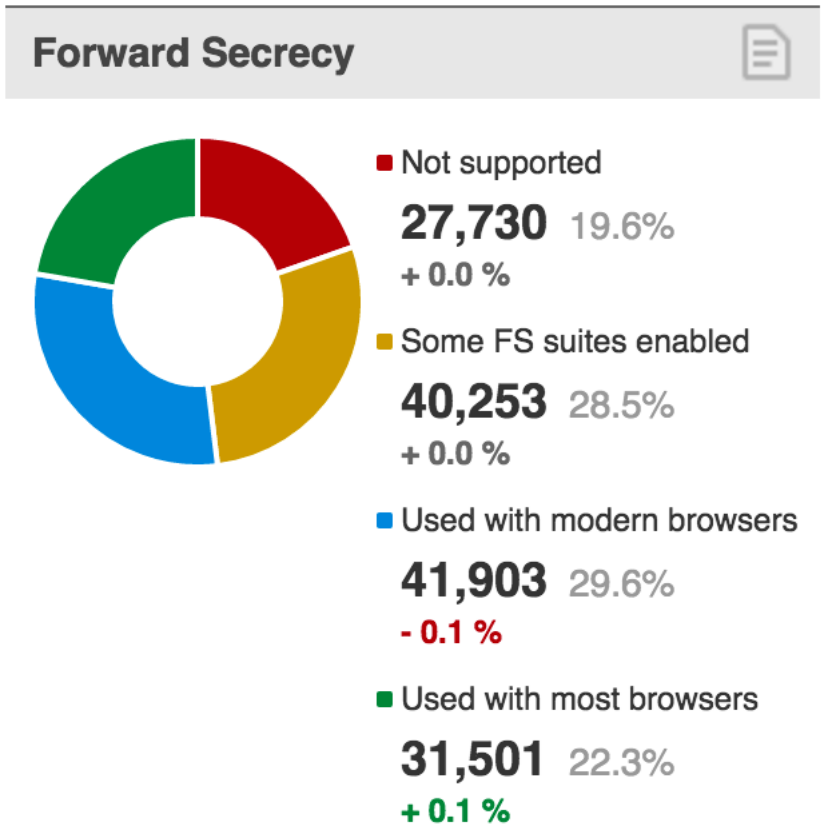


https://www.trustworthyinternet.org/ssl-pulse/ September 4, 2014

(Perfect) Forward secrecy

- An adversary who later learns the server's long-term private key shouldn't be able to read previous transmissions

- RSA key transport: no PFS
- signed Diffie–Hellman: PFS



https://www.trustworthyinternet.org/ssl-pulse/ June 1, 2016

Is TLS secure?

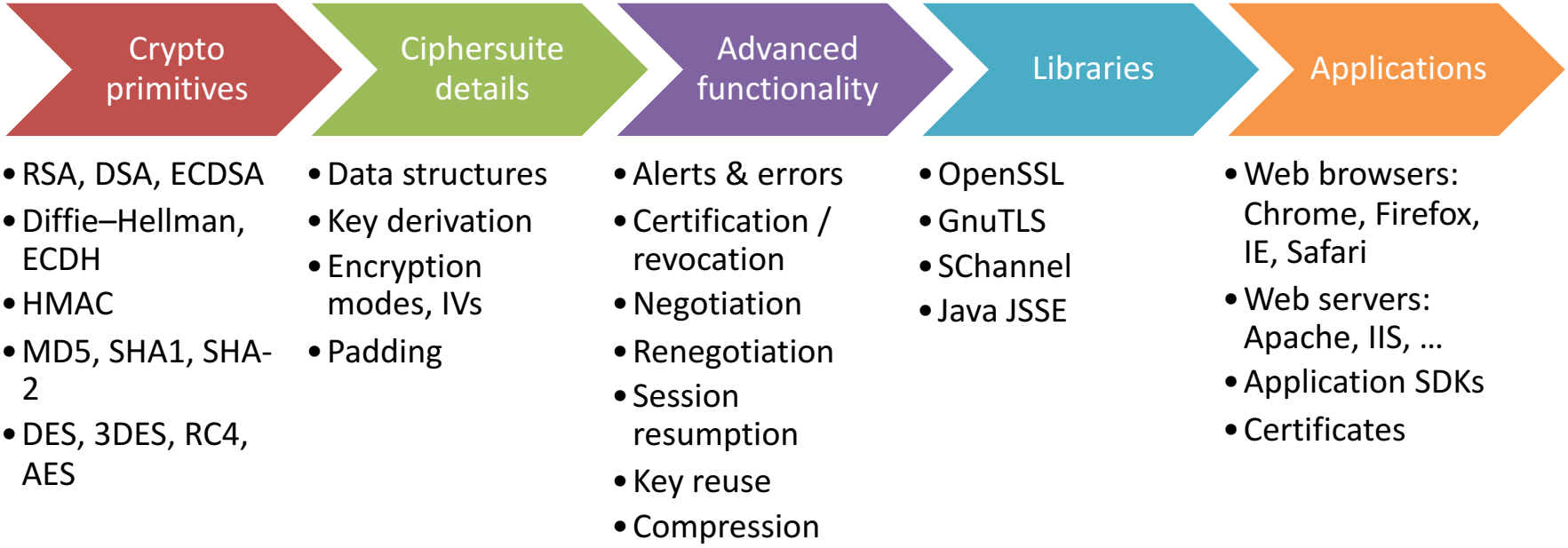
What should TLS do?

- Server-to-client authentication
- Client-to-server authentication (optional)
- Confidential communication with integrity protection

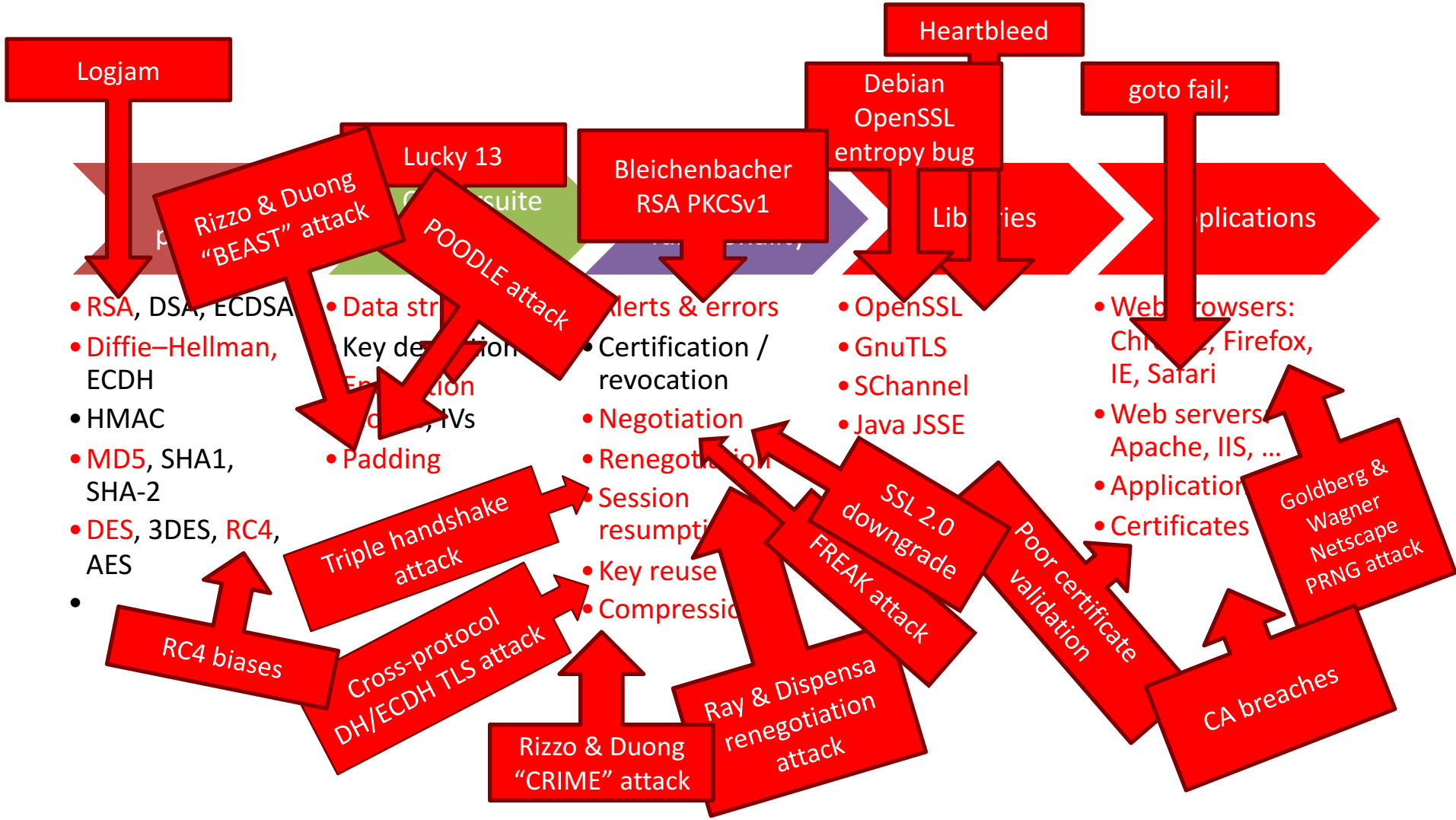
What doesn't TLS do?

- (Trusted creation of certificates)
- Password-based authentication
- Stop denial of service attacks
- Prevent web application vulnerabilities

Components of TLS



Attacks on TLS



Target	Attack Name	Year	Reference
Core cryptography			
RSA PKCS#1v1.5 decryption	Side channel – Bleichenbacher	1998	[24]
DES	Weakness – brute force	1998	[45]
MD5	Weakness – collisions	2005	[83]
RC4	Weakness – biases	2000*, 2013	[51, 86]*, [4]
RSA export keys	FREAK	2015	[14]
DH export keys	Logjam	2015	[3]
RSA-MD5 signatures	SLOTH	2016	[20]
Crypto usage in ciphersuites			
CBC mode encryption	BEAST	2002*, 2011	[96]*, [43]
Diffie–Hellman parameters	Cross-protocol attack	1996*, 2012	[125]*, [90]
MAC-encode-encrypt padding	Lucky 13	2013	[5]
CBC mode encryption + padding	POODLE	2014	[97]
TLS protocol functionality			
Negotiation	Downgrade to weak crypto	1996, 2015	[125, 14, 3]
Termination	Truncation attack	2007, 2013	[13, 118]
Renegotiation	Renegotiation attack	2009	[106]
Compression	CRIME, BREACH	2002*, 2012	[70]*, [111, 105]
Session resumption	Triple-handshake attack	2014	[16]
Implementation – libraries			
OpenSSL – RSA	Side-channel	2005, 2007	[103, 2]
Debian OpenSSL	Weak RNG	2008	[121]
OpenSSL – elliptic curve	Side-channel	2011–14	[28, 27, 127]
Apple – certificate validation	goto fail;	2014	[82]
OpenSSL – Heartbeat extension	Heartbleed	2014	[33, 35]
Multiple – certificate validation	Frankencerts	2014	[26]
NSS – RSA PKCS#1v1.5 signatures	BERserk (Bleichenbacher)	2006*, 2014	[50]*, [79]
Multiple – state machine	CCS injection, SMACK	2014, 2015	[71, 14]
Implementation – HTTP-based applications			
Netscape	Weak RNG	1996	[58]
Multiple – certificate validation	"The most dangerous code..."	2012	[56]
Application-level protocols			
HTTP	SSL stripping	2009	[88]
HTTP server virtual hosts	Virtual host confusion	2014	[36]
IMAP/POP/FTP	STARTTLS command injection	2011	[124]

Table 1.1. Known attacks on SSL/TLS. * denotes theoretical basis for a later practical attack.