Network Security: TLS/SSL

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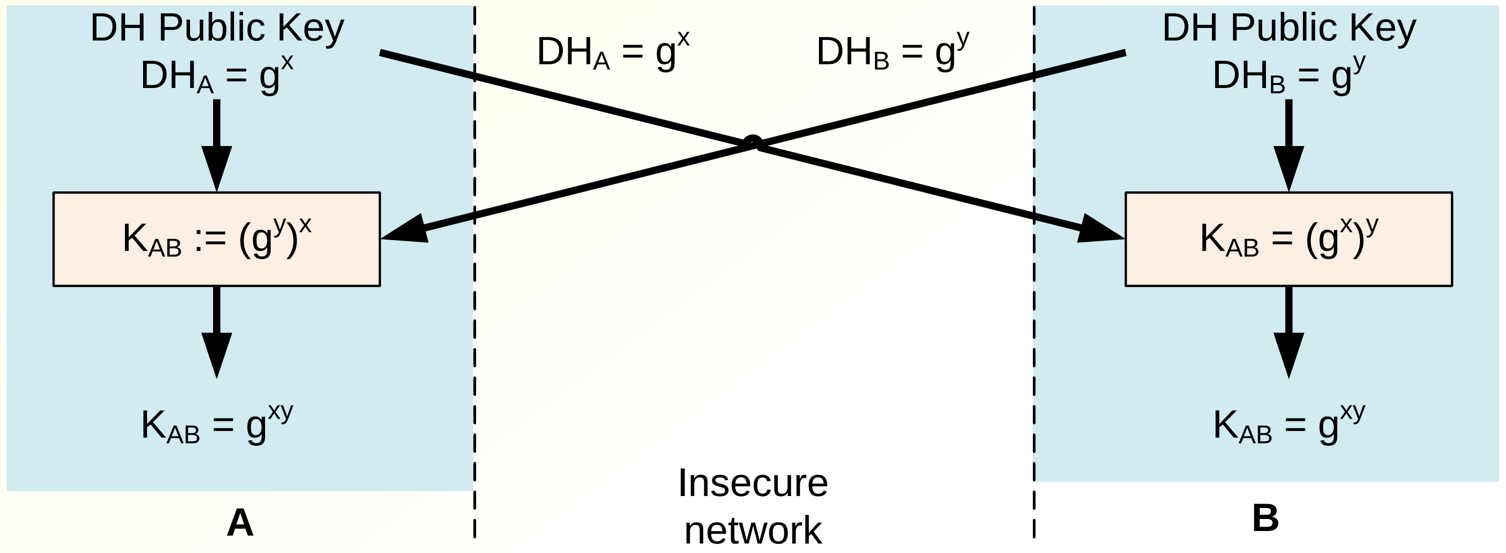
Outline

1. Diffie-Hellman key exchange
2. Key exchange using public-key encryption
3. Goals of authenticated key exchange
4. TLS/SSL
5. TLS handshake
6. TLS record protocol
7. TLS trust model

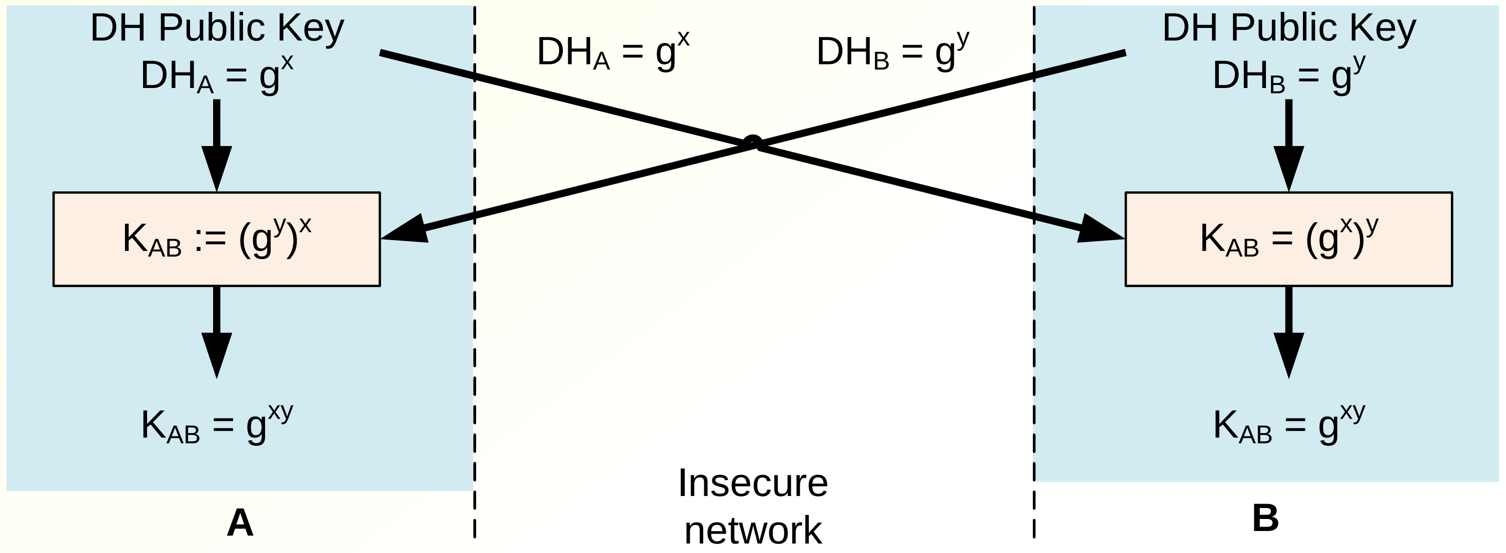
Diffie-Hellman key exchange

Diffie-Hellman



- Key exchange based on commutative public-key operations
  - Each party has its own secret exponent x, y
  - Each party sends or publishes its own public DH key, g^x or g^y
  - Both compute the same shared secret i.e. key material, g^{xy}
- Calculations are done in some pre-agreed finite cyclic group where g is a generating element

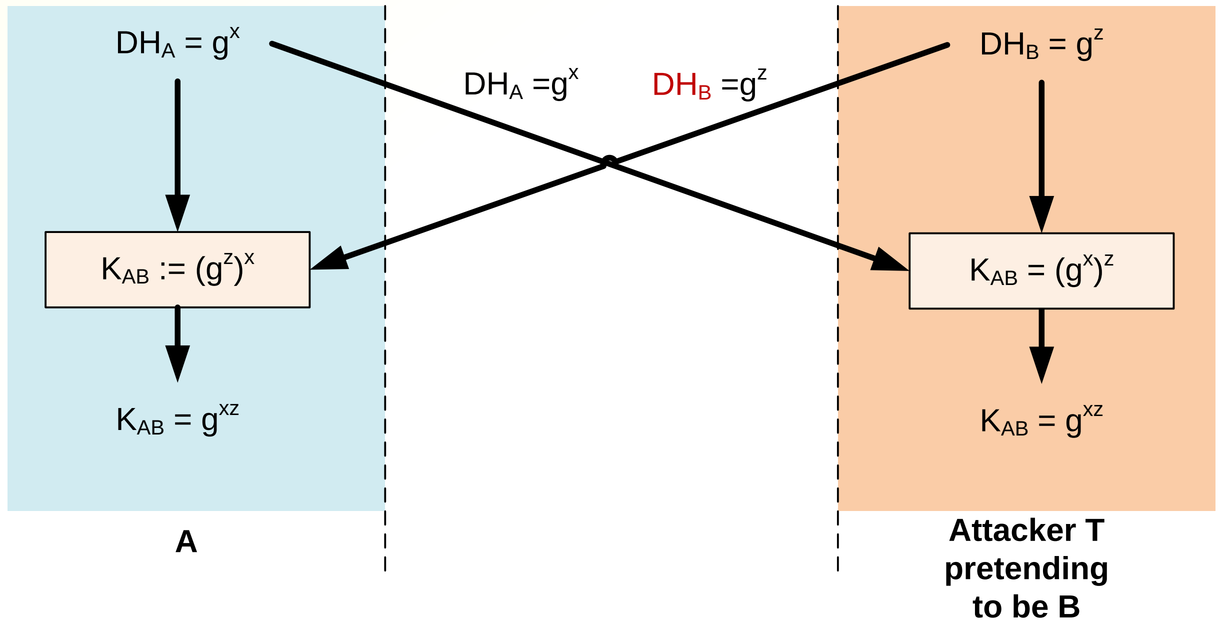
Diffie-Hellman assumption



- Security based on the computational Diffie-Hellman assumption: given g^x and g^y, it is infeasible to solve g^{xy}
- Notations:
  - Public-key: g^x, g^y, DH_A, DH_B, DH-A, DH-B, PK_B, PK_B
  - Shared secret: g^{xy}, SK, K_{AB} , K_{DH} , K_{ses}

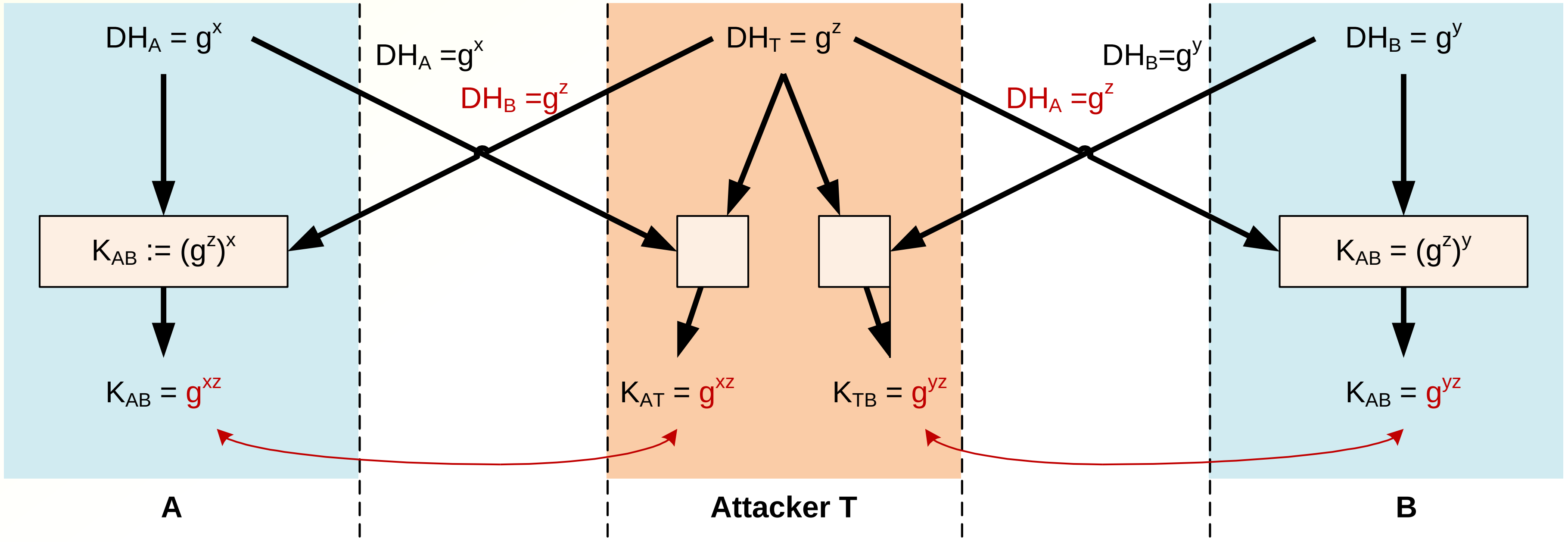
Impersonation attack

- Unauthenticated Diffie-Hellman is secure against passive attackers
  - Not possible to discover the shared secret by sniffing the network
- Vulnerable to an active attack: attacker can pretend to be B (or A) and nothing will stop it



Man-in-the-middle (MitM) attack

- Attacker pretends to be A to B, and B to A
- Attacker shares session keys with both A and B. It can translate session data between the two "secure" sessions, and eavesdrop and modify the data



Alice and Bob notation

- Common informal notation for cryptographic protocols
  - Alice A, Bob B, Carol C, Trent T, Client C, Server S, Initiator I, Responder R, etc.
- Insecure Diffie-Hellman:

  1. $A \rightarrow B$: A, g^x
  2. $B \rightarrow A$: B, g^y

  $SK = h(g^{xy})$
- Impersonation attack:

  $A \rightarrow T(B)$: A, g^x // Trent intercepts the message

  $T(A) \rightarrow B$: A, g^z // Trent spoofs the message
- Man-in-the-middle attack:

  $A \rightarrow T(B)$: A, g^x // Trent intercepts the message

  $T(A) \rightarrow B$: A, g^z // Trent spoofs the message

  $B \rightarrow T(A)$: B, g^y // Trent intercepts the message

  $T(B) \rightarrow A$: B, g^z // Trent spoofs the message

Signed Diffie-Hellman

(Toy examples)

- MitM is prevented by authenticating the DH public keys
- Signed Diffie-Hellman (freshness uncertain):

  1. $A \rightarrow B$: $A, g^x, S_A(A, g^x), Cert_A$
  2. $B \rightarrow A$: $B, g^y, S_B(B, g^y), Cert_B$

  $SK = h(g^{xy})$

  - $Cert_A$ is a standard public-key certificate, e.g. X.509, where the subject key is A's public signature key
- But what about freshness?
  - Freshness solution 1: use fresh random x and y each time
  - Freshness solution 2: nonces (in which case x and y may be reused)

Signed DH with key confirmation

(Somewhat realistic protocol)

- Signed Diffie-Hellman with nonces and key confirmation:

  1. $A \rightarrow B$: $A, B, N_A, g^x, S_A(\text{“Msg1”}, A, B, N_A, g^x), Cert_A$
  2. $B \rightarrow A$: $A, B, N_A, N_B, g^x, g^y, S_B(\text{“Msg2”}, A, B, N_A, N_B, g^x, g^y), Cert_B$
  3. $A \rightarrow B$: $A, B, MAC_{SK}(A, B, \text{“Done.”})$

  $SK = h(N_A, N_B, g^{xy})$

- Mutual entity authentication and key confirmation requires (at least) three messages
- Real protocols are even more complex:
  - Version and algorithm negotiation
  - DoS protection
  - Identity protection

Ephemeral Diffie-Hellman

- Perfect forward secrecy (PFS): session keys and data from past sessions is safe even if the long-term secrets, such as private keys, are later compromised
  - Even participants themselves cannot recover old session keys
  - Called "perfect" for some historical reason; the word means nothing
- General principle of implementing PFS: create a new temporary public key pair for each key exchange and afterwards discard the private key
- Common way to implement PFS is ephemeral DH (DHE): both sides use a new DH exponents in every key exchange and delete the values afterwards
- Cost of exphemeral Diffie-Hellman:
  - Random-number generation for new exponents
  - Computation of new DH public keys g^x and g^y requires exponentiation
  - Cannot cache and reuse previously computed g^{xy}
- Typical trade-off is to replace DH exponents periodically, e.g. once in a day or hour

  → PFS only after the exponents have been deleted

  → nonces are needed freshness

Station-to-station (STS) protocol

- Example of DH-protocol with identity protection
- Signed ephemeral Diffie-Hellman:

  1. $A \rightarrow B$: g, p, g^x
  2. $B \rightarrow A$: $g^y, E_{K_{ses}}(g^y, g, p, g^x, S_B(g^y, g, p, g^x), Cert_B)$
  3. $A \rightarrow B$: $E_{K_{ses}}(g, p, g^x, g^y, S_A(g, p, g^x, g^y), Cert_A)$

  $K_{ses} = h(g^{xy})$
- What could be wrong?
- What does the encryption $E_K(\ldots)$ achieve?
- No known flaws (and STS has been well analyzed)
- Encryption with the DH session key → identity protection
  - Why does it need to be ephemeral DH?

Key exchange using public-key encryption

PK encryption of session key

- Public-key encryption of the session key (insecure):

  1. A → B: A, PK_A
  2. B → A: B, $E_A(SK)$

  SK = session key

  $E_A(\ldots)$ = encryption with A's public key

- Man-in-the-middle attack:

  A → T(B): A, PK_A // Trent intercepts the message

  T(A) → B: A, PK_T // Trent spoofs the message

  B → T(A): B, $E_T(SK)$ // Trent intercepts the message

  T(B) → A: B, $E_A(SK)$ // Trent spoofs the message

Authenticated key exchange

(Somewhat realistic protocol)

- Public-key encryption of the session key:

  $A \rightarrow B$: A,B, N_A, Cert_A

  $B \rightarrow A$: A,B,N_A,N_B,E_A(KM), S_B("Msg2", A,B, N_A,N_B, E_A(KM)), Cert_B

  $A \rightarrow B$: A,B, MAC_{SK}(A,B, "Done.")

  SK = h(N_A,$N_{B,}$KM) (why not SK = KM?)

  KM = random key material generated by B

  Cert_A = certificate for A's public encryption key

  E_A(…) = encryption with A's public key

  Cert_B = certificate for B's public signature key

  S_B(…) = B's signature

- Typically RSA encryption and signatures

Goals of authenticated key exchange

Basic security goals

- Create a good session key:
  - Secret i.e. known only to the intended participants
  - Fresh i.e. never used before
  - Separation of long-term and short-term secrets: long-term secrets such as private keys or master keys are not compromised even if session keys are
- Authentication:
  - Mutual i.e. bidirectional authentication: each party knows with whom it shares the session key
  - Sometimes only unidirectional (one-way) authentication
- Optional properties:
  - Entity authentication: each participant know that the other is online and participated in the protocol
  - Key confirmation: each participant knows that the other knows the session key
  - Perfect forward secrecy: compromise of current secrets should not compromise past session keys
  - Contributory: both parties contribute to the session key; neither can decide the session-key alone

Advanced security goals

- Non-repudiation
  - A party cannot later deny taking part (usually not an explicit goal)
- Plausible deniability
  - No evidence left of taking part (usually not an explicit goal either)
- Integrity check for version and algorithm negotiation
  - Increases difficulty of version fall-back attacks
- Identity protection:
  - Sniffers cannot learn the identities of the protocol participants
  - Usually, one side must reveal its identity first, making it vulnerable to active attacks against identity protection
- Denial-of-service resistance:
  - The protocol cannot be used to exhaust memory or CPU of the participants
  - The protocol cannot be used to flood third parties with data
  - It is not easy to prevent the participants from completing the protocol

TLS/SSL

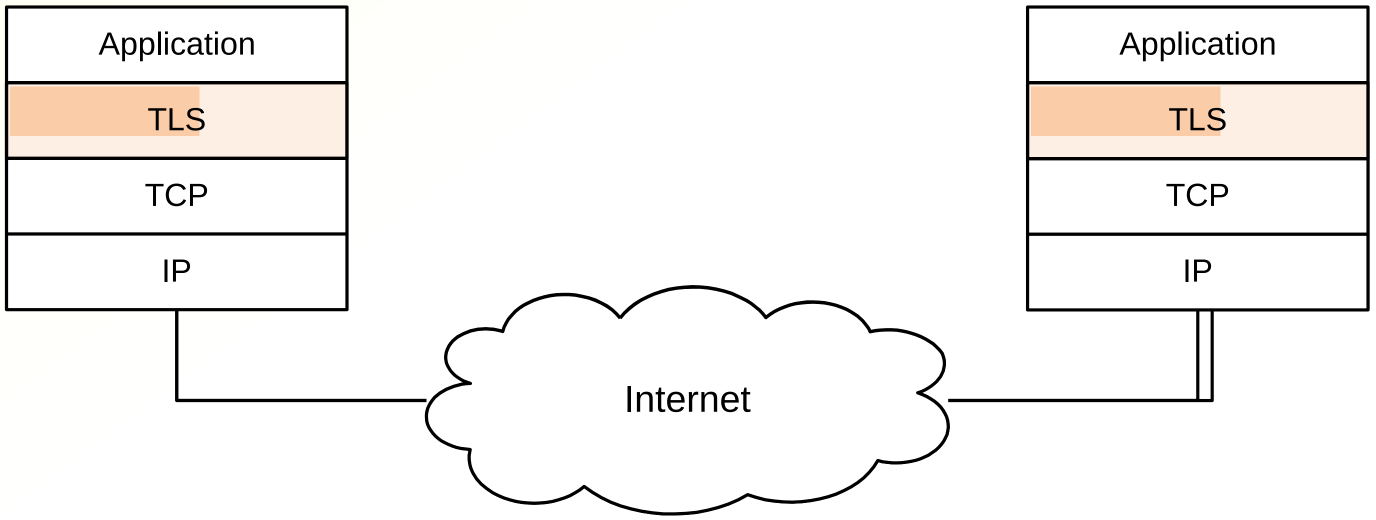
TLS/SSL

- Originally Secure Sockets Layer (SSLv3) by Netscape in 1995
- Originally created to facilitate web commerce:
  - Fast adoption because built into web browsers
  - Encrypt credit card numbers and passwords on the web
- Early resistance, especially in the IETF:
  - Believed that IPSec will eventually replace TLS/SSL
  - TLS/SSL is bad because it slows the adoption of IPSec

  Now SSL/TLS is the dominant encryption standard
- Standardized as Transport-Layer Security (TLS) by IETF [RFC 5246]
  - Minimal changes to SSLv3 implementations but not interoperable

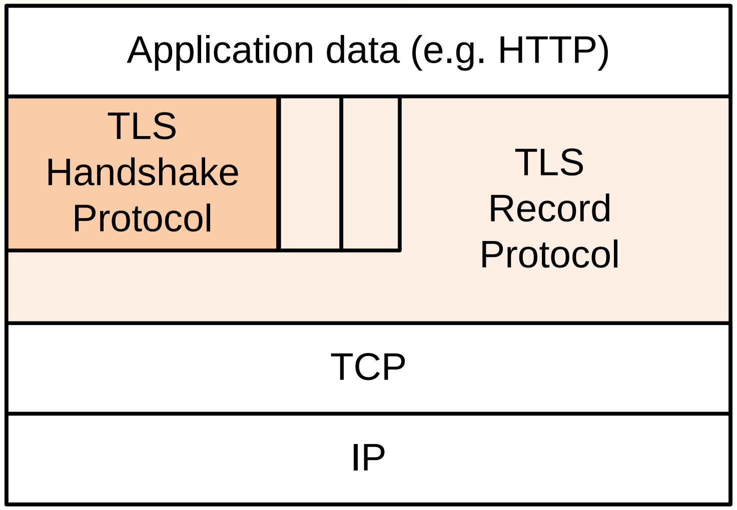
TLS/SSL architecture (1)

- Encryption and authentication layer added to the protocol stack between TCP and applications
- End-to-end security between client and server, usually web browser and server



TLS/SSL architecture (2)

- TLS Handshake Protocol — authenticated key exchange
- TLS Record Protocol — block data delivery



- General architecture of security protocols: authenticated key exchange + session protocol
- TSL specifies separate minor “protocols”:
  - Alert — error messages
  - Change Cipher Spec — turn on encryption or update keys

Cryptography in TLS

- Key-exchange mechanisms and algorithms organized in cipher suites
  - Negotiated in the beginning of the handshake
- Example: TLS_RSA_WITH_3DES_EDE_CBC_SHA
  - RSA = handshake: RSA-based key exchange
  - Key-exchange uses its own MAC composed of SHA-1 and MD5
  - 3DES_EDE_CBC = data encryption with 3DES block cipher in EDE and CBC mode
  - SHA = data authentication with HMAC-SHA-1
- TLS mandatory cipher suites:
  TLS_DHE_DSS_WITH_3DES_EDE_CBC_SHA (TLS 1.0)
  - DHE_DSS = handshake: ephemeral Diffie-Hellman key exchange authenticated with DSS* signatures

  TLS_RSA_WITH_3DES_EDE_CBC_SHA (TLS 1.1)

  TLS_RSA_WITH_AES_128_CBC_SHA (TLS 1.2)
- SHA-1 and MD5 in key exchange replaced with negotiable MAC algorithm in TLS 1.2
- Insecure cipher suites:
  TLS_NULL_WITH_NULL_NULL
  TLS_RSA_EXPORT_WITH_DES40_CBC_SHA

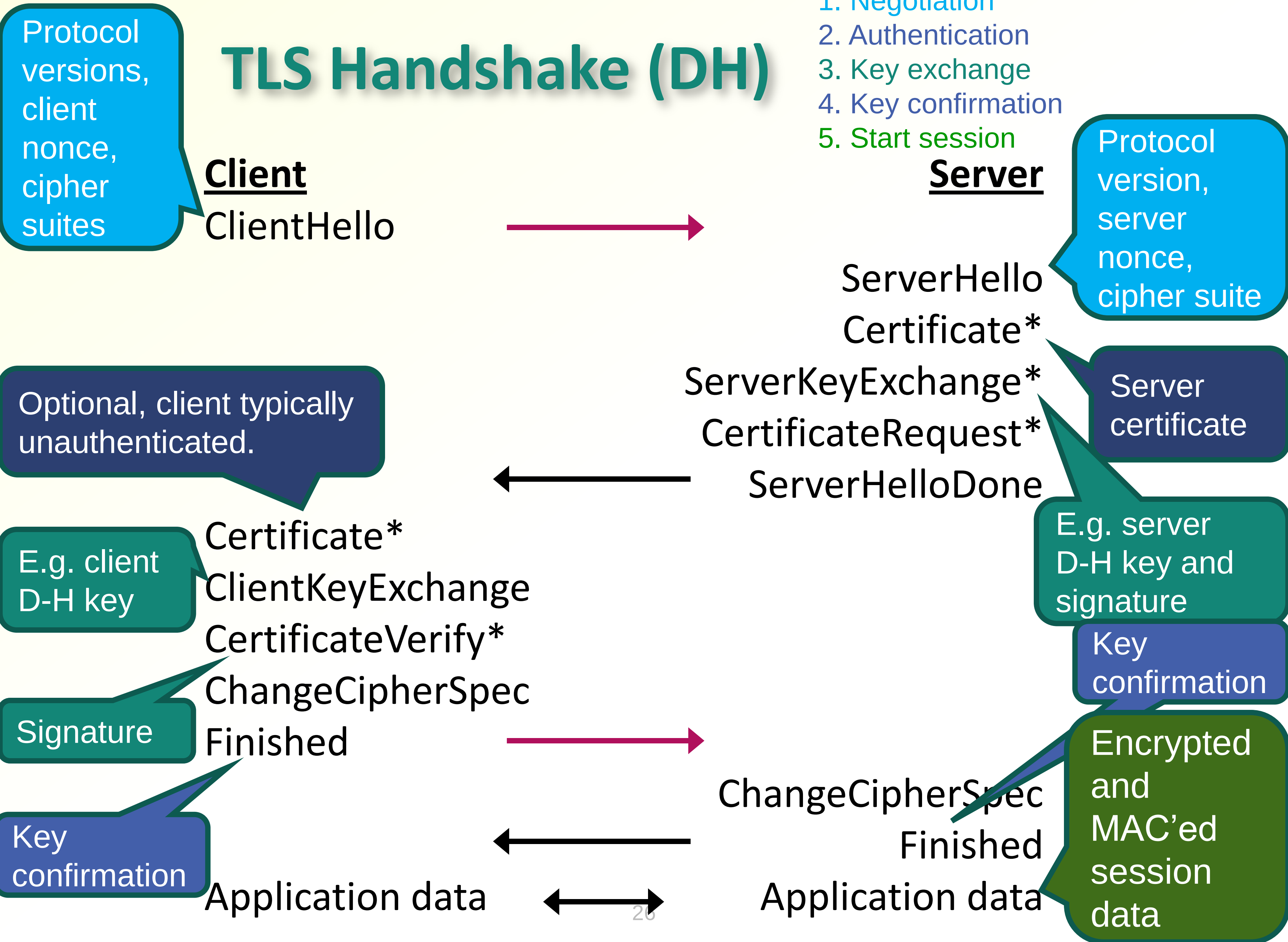
TLS handshake

TLS handshake protocol

- Runs on top of TLS record protocol
- Negotiates protocol version and cipher suite (i.e. cryptographic algorithms)
  - Protocol versions: 3.0 = SSLv3, 3.1 = TLSv1
  - Cipher suite e.g. DHE_RSA_WITH_3DES_EDE_CBC_SHA
- Performs authenticated key exchange
  - Several different key exchange mechanisms supported (typically RSA and DHE)
  - Often only the server is authenticated

TLS Handshake (DH)

1. Negotiation
2. Authentication
3. Key exchange
4. Key confirmation
5. Start session



TLS handshake

1. C → S:	ClientHello
2. S → C:	ServerHello,
	Certificate,
	[ServerKeyExchange],
	[CertificateRequest],
	ServerHelloDone
3. C → S:	[Certificate],
	ClientKeyExchange,
	[CertificateVerify],
	ChangeCipherSpec,
	Finished
4. S → C:	ChangeCipherSpec,
	Finished

- [Brackets] indicate fields needed only for bidirectional authentication

TLS_DHE_DSS handshake

1. C → S: Versions, N_C, SessionId, CipherSuites

2. S → C: Version, N_S, SessionId, CipherSuite
   CertChain_S
   g, n, g^y, $\text{Sign}_S(N_C, N_S, g, n, g^y)$
   [Root CAs]

3. C → S: [CertChain_C]
   g^x
   [Sign_C(all previous messages including N_C, N_S, g, n, g^y, g^x)]
   ChangeCipherSpec
   MAC_{SK} (“client finished”, all previous messages)

4. S → C: ChangeCipherSpec
   MAC_{SK}("server finished“, all previous messages)

1. Negotiation
2. Ephemeral Diffie-Hellman
3. Nonces
4. Signature
5. Certificates
6. Key confirmation and negotiation integrity check

- pre_master_secret = g^{xy}
- master_secret = SK = h(g^{xy}, “master secret”, N_C, N_S)
- The Finished messages are already protected by the new session keys

TLS_RSA handshake

1. $C \rightarrow S$: Versions, N_C, SessionId, CipherSuites
2. $S \rightarrow C$: Version, N_S, SessionId, CipherSuite
   CertChain_S
   [Root CAs]
3. $C \rightarrow S$: [CertChain_C]
   E_S(pre_master_secret),
   [Sign_C(all previous messages including N_C, N_S, $E_S(\ldots)$)]
   ChangeCipherSpec
   MAC_{SK} (“client finished”, all previous messages)
4. $S \rightarrow C$: ChangeCipherSpec
   MAC_{SK}("server finished“, all previous messages)

1. Negotiation
2. RSA
3. Nonces
4. Signature
5. Certificates
6. Key confirmation and negotiation integrity check

- E_S = RSA encryption (PKCS #1 v1.5) with S’s public key from CertChain_S
- pre_master_secret = random number chosen by C
- master_secret = SK = h(pre_master_secret, “master secret”, N_C, N_S)
- *Finished* messages are already protected by the new session keys

Nonces in TLS

- Client and Server Random are nonces
- Concatenation of a real-time clock value and random number:

```
struct {
          uint32 gmt_unix_time;
          opaque random_bytes[28];
} Random;
```

Session vs. connection

- TLS session can span multiple connections
  - Client and server may cache the session state and master_secret
  - Client sends the SessionId of a cached session in Client Hello; otherwise zero
  - Server responds with the same SessionId if session found in server cache; otherwise with a fresh value
- New session keys derived from old master_secret and new nonces
- Change of IP address does not invalidate cached sessions
- Session tickets [RFC 5077]:
  - Server can send the session state data (ticket) to the client
  - Client sends the ticket back to the server when reconnecting
  - Ticket is encrypted and authenticated with a secret key know only to the server → client cannot modify data
  - Not implemented by all browsers

TLS renegotiation attack

- TLS client or server can initiate “renegotiation handshake” i.e. new handshake to refresh session keys
- In 2009, a protocol flaw was found:
  1. MitM attacker intercepts a TLS connection from honest client; lets the client wait executing the next step
  2. Attacker executes a TLS handshake with the honest server and sends some data to the server over this TLS connection
  3. Attacker forwards the (still insecure) connection from the client to the server over its own TLS connection
  4. Honest client executes the TLS handshake with the server; server thinks it is renegotiation; attacker loses ability to decrypt the data after ChangeCipherSpec, but continues to forward the connection
- What did the attacker achieve? Attacker inserted its own data to the beginning of the connection
  - E.g. consider applications where the client sends commands first and finally authorizes them by entering its credentials
- Solved by RFC 5746
- Surprising because TLS/SSL is one of the most analyzed protocols and no major protocol-level flaws have been found since 1995

TLS record protocol

TLS record protocol

- For write (sending):
  1. Take arbitrary-length data blocks from upper layer
  2. Fragment to blocks of ≤ 4096 bytes
  3. Compress the data (optional)
  4. Apply a MAC
  5. Encrypt
  6. Add fragment header (SN, content type, length)
  7. Transmit over TCP server port 443 (https)
- For read (receiving):
  - Receive, decrypt, verify MAC, decompress, defragment, deliver to upper layer

TLS record protocol - abstraction

- Abstract view:
  E_{K1} (data, $HMAC_{K2}$(SN, content type, length, data))
- Different encryption and MAC keys in each direction
  - All keys and IVs are derived from the master_secret
- TLS record protocol uses 64-bit unsigned integers starting from zero for each connection
  - TLS works over TCP, which is reliable and preserves order. Thus, sequence numbers must be received in exact order

TLS Applications

- Originally designed for web browsing
  - Client typically unauthenticated
- New applications:
  - Any TCP connection can be protected with TLS
  - The SOAP remote procedure call (SOAP RPC) protocol uses HTTP as its transport protocol. Thus, SOAP can be protected with TLS
  - TLS-based VPNs
  - EAP-TLS authentication and key exchange in wireless LANs and elsewhere
- Many of the new applications require mutual authentication

Puzzle of the day

- Kerberos is vulnerable to offline password cracking from sniffed network messages
- Question 1: If an online service (e.g. webmail) uses TLS with server-only authentication to protect passwords, is the system vulnerable to offline password cracking?
- Question 2: Are WLAN security protocols vulnerable to offline password cracking?

Related reading

- William Stallings. Network security essentials: applications and standards, 3rd ed.: chapters 7.1-7.2
- William Stallings. Cryptography and Network Security, 4th ed.: chapters 17.1-17.2
- Kaufmann, Perlman, Speciner. Network security, 2nd ed.: chapters 11, 19
- Dieter Gollmann. Computer Security, 2nd ed.: chapter 13.4

Exercises

- Use a network sniffer (e.g. Netmon, Ethereal) to look at TLS/SSL handshakes. Can you spot a full handshake and session reuse? Can you see the lack of identity protection?
- What factors mitigate the lack of identity protection in TLS?
- How would you modify the TLS handshake to improve identity protection? Remember that the certificates are sent as plaintext and SessionId is also a traceable identifier.
- Why do most web servers prefer the RSA handshake?
- Consider removing fields from the TLS DHE and RSA key exchanges. How does each field contribute to security?
- How to implement perfect forward secrecy with RSA?
- Why have the mandatory-to-implement cipher suites changed over time?
- How many round trips between client and server do the TLS DHE and RSA key exchanges require? Consider also the TCP handshake and that certificates may not fit into one IP packet.
- Why is the front page of a web site often insecure (HTTP) even if the password entry and/or later data access are secure (HTTPS)? What security problems can this cause?
- What problems arise if you want to set up multiple secure (HTTPS) web sites behind a NAT or on a virtual servers that share only one IP address? (The server name extension (RFC 6066) provides some help.)