Hybrid Encryption and Further Topics

Cryptography (lecture portion)

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Recap

- Symmetric cryptography
  - Key exchange
  - DH(E)
  - AES
- Asymmetric cryptography
  - Public key
  - Private/secret key
  - RSA
- Cryptographic hashes
  - Collision resistance
  - (Second) pre-image resistance
  - SHA-2

Overview

- Hybrid encryption
  - Key exchange revisited (with key derivation)
  - Hybrid encryption scheme
  - Challenge-response scheme
- Examples of combined use of cryptography
  - Secure password storage
  - Transport Layer Security
  - Practical protocols (choice)

Key exchange revisited I

- Diffie-Hellman key exchange
  - Alice and Bob exponentiate random numbers in a modulus (multiplicative group)
  - Rules for exponents give Alice and Bob the same group element
  - Final group element can be used to derive a shared key
  - Eve cannot feasibly compute the shared key (discrete logarithm problem and Diffie-Hellman assumptions)
- Challenges
  - Choosing safe groups
  - Converting the final group element into a key $\rightarrow$ key derivation

Key exchange revisited II

- Key derivation
  - Derive a key k from the final group element f
  - Example: Get 128-bit AES key from 1,024-bit group element
  - Multiple possibilities
- Hashing for key derivation
  - Compute a cryptographic hash: $k := H(f)$
  - → Removes any remaining algebraic structure
  - → Yields a fixed-size result (key)
- Standardized advanced versions, e.g., PBKDF2
  - Repeated use of hashes, e.g., 1,000 iterations
  - → Slows down attackers significantly
  - Use of additional salt (details later)

[1] Kaliski, B.: PKCS #5: Password-Based Cryptography Specification Version 2.0. https://www.ietf.org/rfc/rfc2898.txt (accessed on October 8, 2022), 2000.

Hybrid encryption I

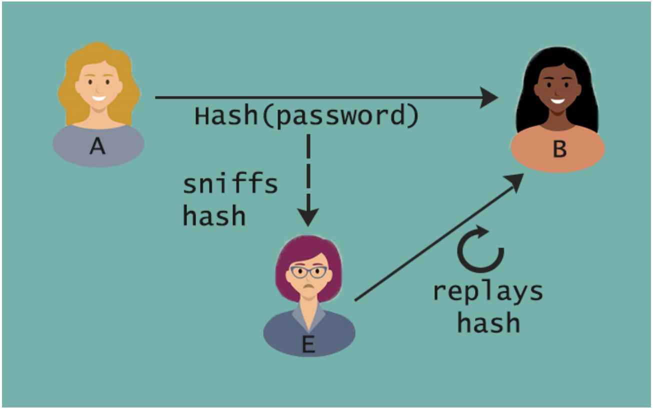
- Alternative to Diffie-Hellman key exchange
- Combine asymmetric and symmetric ciphers
- Assumptions
  - Bob has a public-private key pair $\left(k^A_{public}, k^A_{private}\right)$
  - Alice knows Bob's public key (recall certificates!)
- Key exchange steps:
  1. Alice generates a random key k
  2. Alice encrypts k with Bob's public key: $k_e = E(k^B_{public}, k)$
  3. Alice sends the encrypted key k_e to Bob
  4. Bob decrypts the received key with his secret key: $k = D(k^B_{private}, k_e)$
  5. Alice and Bob can exchange messages with symmetric key k

Hybrid encryption II

- Why not use asymmetric cryptography for all messages?
  - Public key cryptography is much less efficient than secret key cryptography (longer messages require much more expensive computations)
  - RSA keys are much longer than AES keys for the same level of security (recall elliptic curves for a viable alternative!)
- Summary of hybrid encryption
  - Use public key cryptography to exchange the key
  - Use secret key cryptography to exchange messages
  - The symmetric key is practically random
  - Bob's public key must be known in advance for this to work
- Supplement to this scheme: Challenge-response scheme

Challenge and response I

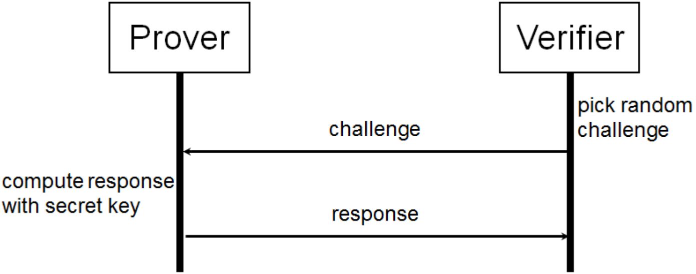
- How to verify that Bob is talking to Alice and not to Eve?
- Risk of replay attacks by Eve



Source: Gibson, D.: Replay Attacks. https://cybersecurityglossary.com/replay-attacks/ (accessed on October 8, 2022), 2020.

Challenge and response II

- How to solve authentication?
  - Certificates (lack liveness, allow for replay attacks)
  - Challenge and response (impedes replay attacks by testing liveness)



Source: Rathgeb, C.: IT-Sicherheit, Kapitel 6 – Authentifikation. https://www.dasec.h-da.de/wp-content/uploads/2014/05/06_authentifikation.pdf (accessed on October 8, 2022), 2014.

[2] Barrett, D. J. and Silverman, R. E.: SSH: The Secure Shell: The Definitive Guide, 1st ed., O'Reilly, 2001.

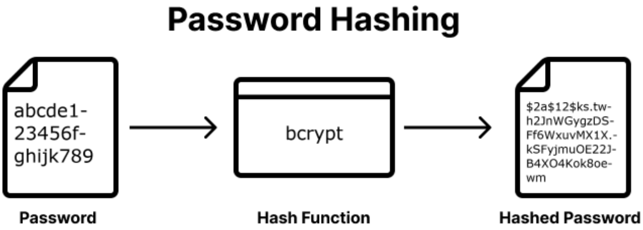
Challenge and response III

- Example: Challenge-response scheme for public-key authentication in the Secure Shell (SSH) protocol (simplified):
  1. Alice sends her public key k_{public} to Bob
  2. Bob generates a random challenge r and encrypts it with Alice's supposed public key: $c := E(k_{public}, r)$
  3. Bob sends the challenge c to Alice
  4. Alice decrypts the supposed challenge c' with her secret key k_{secret}: $r' = D(k_{secret}, c')$
  5. Alice hashes the decrypted challenge r': $h' := H(r')$
  6. Alice sends the hashed response h' to Bob
  7. Bob hashes his random challenge r: $h := H(r)$
  8. Bob checks whether $h = h'$ (if not, he may be talking to Eve)
- Randomness impedes replay attacks
- Hashing is required so that chosen-plaintext attacks are avoided

[2] Barrett, D. J. and Silverman, R. E.: SSH: The Secure Shell: The Definitive Guide, 1st ed., O'Reilly, 2001.

Overview of secure password storage

- How to store (user) passwords?
  - Not as plaintext (obvious)
  - Encrypted? $\rightarrow$ Decryption key yields plaintext passwords
  - Hashed? $\rightarrow$ Identical passwords yield identical hashes
  - In practice: Salted and stretched

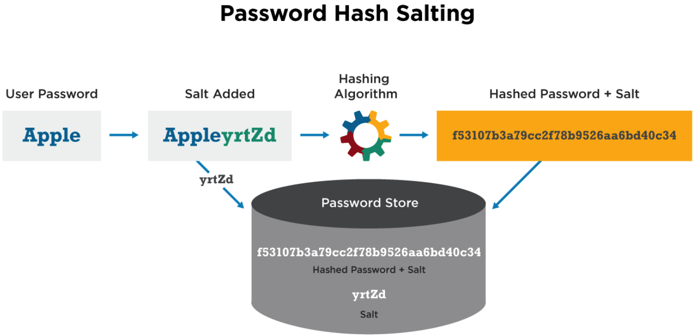


Source: Authgear: Password Hashing and Salting Explained. https://www.authgear.com/post/password-hashing-salting (accessed on October 8, 2022), 2022.

[3] Arias, D.: Adding Salt to Hashing: A Better Way to Store Passwords. https://auth0.com/blog/adding-salt-to-hashing-a-better-way-to-store-passwords/ (accessed on October 8, 2022), 2021.

Salting

- Salt: Random number (stored together with password) **per user**
- Salting: Concatenating the password p with a salt s before hashing
- Salted hashing: $\hat{H}(p, s) := H(p||s)$

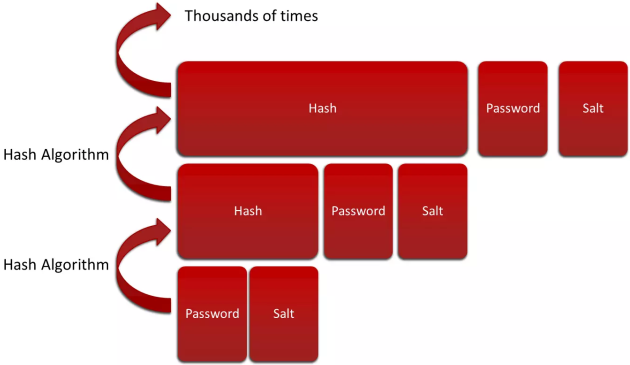


Source: Taylor, C.: Password Salting. `https://cyberhoot.com/cybrary/password-salting/` (accessed on October 8, 2022), 2020.

[3] Arias, D.: Adding Salt to Hashing: A Better Way to Store Passwords. `https://auth0.com/blog/adding-salt-to-hashing-a-better-way-to-store-passwords/` (accessed on October 8, 2022), 2021.

Stretching

- Stretching: Prolonging computation by repeated hashing
- Iterations: $P_1 = \hat{H}(p, s), P_{n>1} = \hat{H}(P_{n-1} || p, s)$
- Stored password hash: P_N for large N, e.g., 10,000



Source: Romero, M. I.: Risks and Challenges of Password Hashing.
https://www.sitepoint.com/risks-challenges-password-hashing/ (accessed on October 8, 2022), 2014.

Attacks on securely stored passwords I

- Rainbow tables (pre-computed hashes when no salts are used)
- Dictionary attack (try a list of common passwords)
- Brute force (try all passwords from a defined set)

Password	p4s5w3rdz	p4s5w3rdz	p4s5w3rdz	p4s5w3rdz
Salt	-	-	et52ed	ye5sf8
Hash	f4c31aa	f4c31aa	lvn49sa	z32i6t0

Adopted from Arias, D.: Adding Salt to Hashing: A Better Way to Store Passwords. `https://auth0.com/blog/adding-salt-to-hashing-a-better-way-to-store-passwords/` (accessed on October 8, 2022), 2021.

[3] Arias, D.: Adding Salt to Hashing: A Better Way to Store Passwords. `https://auth0.com/blog/adding-salt-to-hashing-a-better-way-to-store-passwords/` (accessed on October 8, 2022), 2021.

Attacks on securely stored passwords II

- Brute force attacks depend on the assumed password alphabet
- Example: 8 character-passwords with English alphabet (only upper and lower case): Key space is
  $52^8 > 50^8 = \left(\frac{100}{2}\right)^8 = \frac{(10^2)^8}{2^8} = \frac{10^{16}}{2^8} = 2^2 \cdot \frac{10^{16}}{2^{10}} \approx 4 \cdot \frac{10^{16}}{10^3} = 4 \cdot 10^{13}$
- Dictionary attacks are only successful when the password is contained in the dictionary (otherwise brute force attack required)
- Stretching can slow down dictionary **and** brute force attacks
- Salting makes rainbow tables futile

→ Use salting and stretching (better: standardized algorithms)

→ User recommendation: Use a password manager

[3] Arias, D.: Adding Salt to Hashing: A Better Way to Store Passwords. https://auth0.com/blog/adding-salt-to-hashing-a-better-way-to-store-passwords/ (accessed on October 8, 2022), 2021.

Overview of Transport Layer Security (TLS)

- Based on the now-obsolete Secure Sockets Layer (SSL)
- Protocol to provide a secure channel between Alice and Bob
- Guarantees
  - Authentication (Bob is always authenticated, Alice optionally)
  - Confidentiality (only Alice and Bob can read data, but not an attacker)
  - Integrity (data cannot be changed by an attacker without detection)
- Uses a variety of cryptographic primitives, e.g.,
  - Asymmetric ciphers
  - Symmetric ciphers
  - Cryptographic hashes
  - Digital signatures
  - Digital certificates

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446). https://www.rfc-editor.org/rfc/rfc8446.html (accessed on October 26, 2022), 2018.

Recap: Digital signatures

- Generated and added to a message by the signer/sender
- Can be checked by the receiver (and everybody else)
- Preserve message integrity instead of message privacy
- Guarantees
  - The signed message has not been modified
  - The signed message originates from the signer
  - → Non-repudiation: A signer cannot claim **not** to have signed the message
- Rely on public key cryptography and hashes
  - Signature: Hash of message, encrypted with secret key
  - Signature verification: Compare hash and decrypted signature
  - If the signature check fails, either the message has been tampered with or someone else (a different key) has signed the message

Recap: Digital certificates

- Digital certificate
  - associates a public key with a person/entity
  - contains information about the signer, the person and their key
  - is signed by a trusted party
  - allows verifying signature and thus identity-to-key matching
  - Assumption: Trusted party whose public key is known by all parties
- Certificate authorities (CAs)
  - are trusted to issue certificates
  - check the identity of the owner or entity
  - are assumed to have a known public key
- Certificate authority hierarchies (CA hierarchies)
  - Issuing of certificates is delegated to sub-CA(s)
  - Multi-level certificates from CA to sub-CA(s) to entity

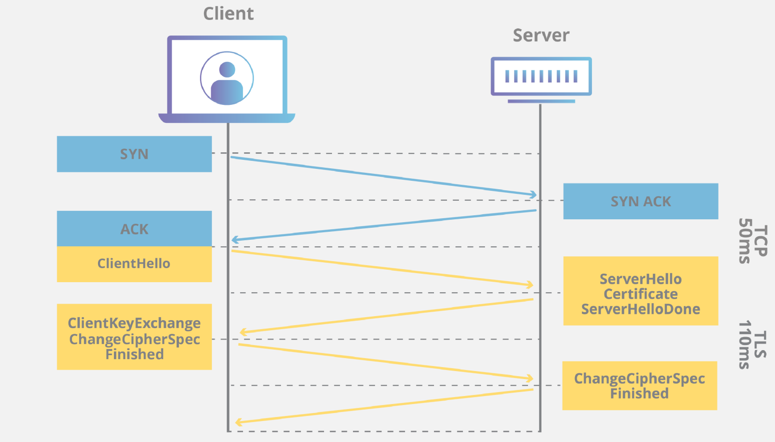
  → Hierarchical trust model
  - Root/top-level CA(s) self-sign their own certificate(s)

Key and cipher agreement I

- TLS relies on transport protocols such as TCP
- Initial handshake
  - Authenticates communicating parties through certificates
  - Negotiates used ciphers (not every party supports every cipher)
  - Performs key exchange with forward secrecy
  - Tamper-resistant even against active attackers (who modify messages)
- Used cryptographic primitives
  - Digital certificates for authentication (simplified)
  - Digital signatures for supported ciphers and certificates
  - (EC)DHE and similar protocols for key exchange
  - Hashes of the transcript (sequence of handshake messages)

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446). https://www.rfc-editor.org/rfc/rfc8446.html (accessed on October 26, 2022), 2018.

Key and cipher agreement II



Source: Cloudflare: What is Transport Layer Security (TLS)?
https://www.cloudflare.com/learning/ssl/transport-layer-security-tls/ (accessed on October 26, 2022), 2022.

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446).
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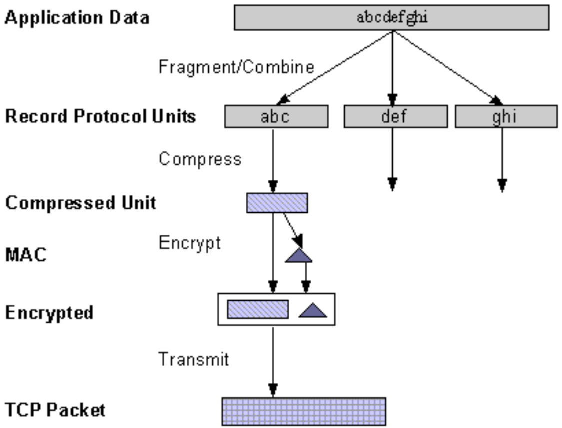
Secure message exchange I

- TLS can exchange messages after finished handshake
- Record protocol
  1. (Alice) Message is split into blocks
  2. (Alice) Blocks (records) are protected
  3. (Alice) Protected records are transmitted
  4. (Bob) Protected records are received
  5. (Bob) Protected records are checked and unprotected
  6. (Bob) Blocks (records) are reassembled into message
- Used cryptographic primitives
  - Symmetric block ciphers in selected modes (without details)
  - Message authentication codes (MACs, similar to hashes, no details)
- Optional compression step (without details)

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446). https://www.rfc-editor.org/rfc/rfc8446.html (accessed on October 26, 2022), 2018.

Secure message exchange II



Source: The Apache Software Foundation: SSL/TLS Strong Encryption: An Introduction. https://httpd.apache.org/docs/2.4/ssl/ssl_intro.html (accessed on October 26, 2022), 2022.

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446). https://www.rfc-editor.org/rfc/rfc8446.html (accessed on October 26, 2022), 2018.

Practical concerns I

- Newer versions of TLS implement new ciphers and features
- SSL and older TLS versions are
  - vulnerable to certain attacks (without details)
  - support broken ciphers/hash algorithms etc.
  - support weak algorithms and key lengths

→ Deprecation or removal of flawed/weak algorithms and protocol parts

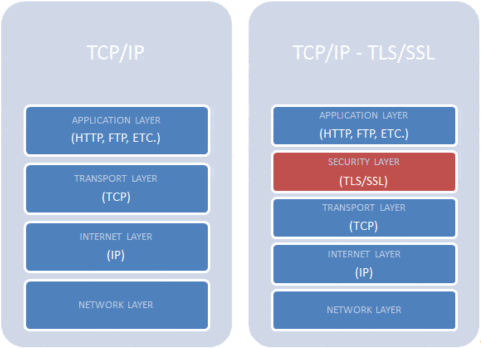
→ Versioning (current: TLS 1.3)

- Byte-by-byte illustration of a TLS 1.3 connection (including handshake): `https://tls13.xargs.org/`

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446). `https://www.rfc-editor.org/rfc/rfc8446.html` (accessed on October 26, 2022), 2018.

Practical concerns II

- TLS is designed to provide extra layer for application(-level) protocols

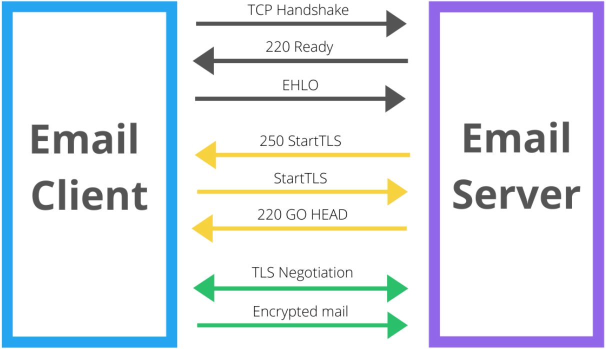


Source: Slaviero, M.: TLS/SSL and .NET Framework 4.0. `https://www.red-gate.com/simple-talk/development/dotnet-development/tlsssl-and-net-framework-4-0/` (accessed on October 26, 2022), 2011.

[4] Rescorla, E.: The Transport Layer Security (TLS) Protocol Version 1.3 (RFC 8446). `https://www.rfc-editor.org/rfc/rfc8446.html` (accessed on October 26, 2022), 2018.

Practical concerns III

- Retrofitting unprotected protocols through STARTTLS command



Source: Griffin, J.: What is StartTLS? `https://sendgrid.com/blog/what-is-starttls/` (accessed on October 26, 2022), 2020.

[5] Griffin, J.: What is StartTLS? `https://sendgrid.com/blog/what-is-starttls/` (accessed on October 26, 2022), 2020.

Practical protocols (choice)

- Practical cryptographic protocols to illustrate combined use of cryptography (choose one):
  - Masking (smart meter data aggregation) [6]
  - Proof of work blockchains (electronic cash) [7]
  - Wi-Fi Protected Access 3 (WPA3, wireless communication) [8, 9]
  - Content protection (video streaming) [10, 11]
  - Further topics (suggestions)

[6] Kursawe, K., Danezis, G. and Kohlweiss, M.: Privacy-friendly Aggregation for the Smart Grid. In PETS 2011: Privacy Enhanced Technology Symposium, pp. 175–191, 2011.
[7] Nakamoto, S.: Bitcoin: A Peer-to-Peer Electronic Cash System. https://bitcoin.org/bitcoin.pdf (accessed on October 26, 2022), 2008.
[8] WiFi Alliance: WPA3™ Specification Version 3.0. https://www.wi-fi.org/downloads-public/WPA3_Specification_v3.0.pdf/35332 (accessed on October 26, 2022), 2020.
[9] WiFi Alliance: Wi-Fi Protected Access® Security Considerations. https://www.wi-fi.org/downloads-public/Security_Considerations_20210511.pdf/36067 (accessed on October 26, 2022), 2021.
[10] European Telecommunications Standards Institute and European Broadcasting Union: Digital Video Broadcasting (DVB); Content Protection and Copy Management (DVB-CPCM); Part 2: CPCM Reference Model (ETSI TS 102 825-2 V1.2.1), 2011.
[11] European Telecommunications Standards Institute and European Broadcasting Union: Digital Video Broadcasting (DVB); Content Protection and Copy Management (DVB-CPCM); Part 5: CPCM Security Toolbox (ETSI TS 102 825-5 V1.2.1), 2011.

Thank you for your attention!

Questions?