Systems' Security | *Segurança de Sistemas*

Message Authentication Codes

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Overview

Learning Objectives

After this chapter, you should be able to:

1. List and explain the possible attacks that are relevant to message authentication.
2. Define the term message authentication code.
3. List and explain the requirements for a message authentication code.
4. Explain the concept of authenticated encryption.

Introduction

Message Authentication

- one of the most complex areas of cryptography
- one approach is the usage of **Message Authentication Code** (MAC)
    - can be built from cryptographic hash functions
    - or built using a block cipher mode of operation
    - or a new approach known as authenticated encryption

Types of attacks in the context of communications across a network:

- attacks to the confidentiality
  - **Disclosure** – release of message contents to any person or process not possessing the appropriate authorization (by means of a cryptographic key)
  - **Traffic analysis** – discovery of the pattern of traffic between parties (determine the frequency and duration of connections, the number and length of messages between parties)

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  - **Traffic analysis** – discovery of the pattern of traffic between parties (determine the frequency and duration of connections, the number and length of messages between parties)
- attacks to the non-repudiation
  - **Source repudiation** – denial of transmission of message by source
  - **Destination repudiation** – Denial of receipt of message by destination

Types of attacks in the context of communications across a network (continuation):

- attacks to the authentication
  - **Masquerade** – insertion of messages into the network from a fraudulent source (also known as impersonification)
  - **Content modification** – changes to the contents of a message, including insertion, deletion, transposition, and modification
  - **Sequence modification** – any modification to a sequence of messages between parties, including insertion, deletion, and reordering
  - **Timing modification** – delay or replay of messages

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Message Authentication

- is a procedure to verify that received messages come from the alleged source and have not been altered and may also verify sequencing and timeliness.
- a digital signature is an authentication technique that also includes measures to counter repudiation by the source.

Message authentication strategies

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2. **message encryption** – the ciphertext of the entire message serves as its authenticator
3. **message authentication code** (MAC) – a function of the message and a secret key that produces a fixed-length value that serves as the authenticator

Message Encryption as an Authenticator

Symmetric encryption

- $A \rightarrow B : \quad E_k(M)$
- provides confidentiality
- if A and B are the only ones that know the key k, then can we say that the message could only be sent by A?

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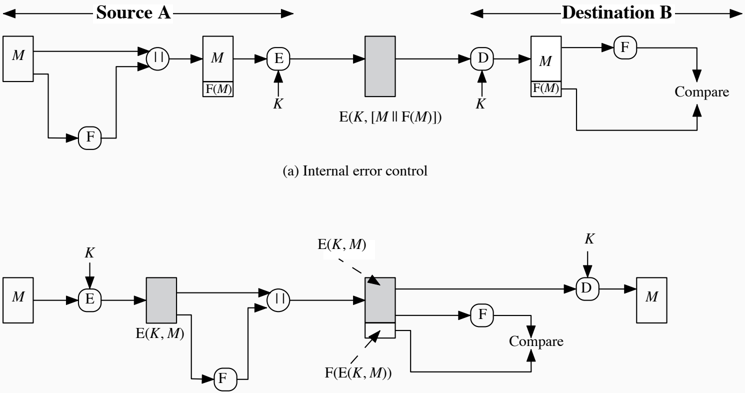
- solution: add some form of error control

Symmetric encryption + error control

- internal error control provides authentication
- external error control, may, or may not, provide authentication depending on the used function



(a) Internal error control

(b) External error control

Public key encryption

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    - for the authentication some form of error control must be added

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  - for the authentication some form of error control must be added
- $A \rightarrow B : \quad E_{PU_B}[E_{PR_A}(M)]$
  - provides confidentiality, authentication and non-repudiation
  - this approach is very slow

Message Authentication Code as an Authenticator

Message Authentication Code (MAC)

- use of a secret key to generate a small fixed-size block of data
- known as a cryptographic checksum or MAC
- this value is appended to the message
- does not provide a digital signature, because both sender and receiver share the same key

$$mac = C_k(M)$$

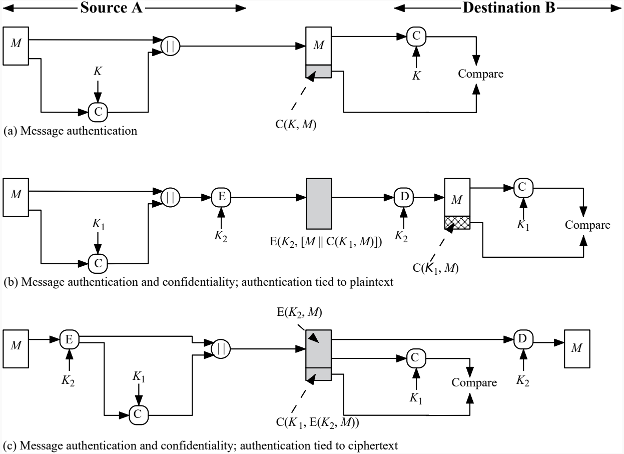
M input message

C MAC function

k shared secret key

mac message authentication code value
also known as *tag*

Message Authentication Code (MAC) – basic uses



Short representations

(a) $A \rightarrow B: \quad M \,\|\, C_k(M)$
without confidentiality

(b) $A \rightarrow B: \quad E_{k_2}[M \,\|\, C_{k_1}(M)]$
internal control

(c) $A \rightarrow B: \quad E_{k_2}(M) \,\|\, C_{k_1}[E_{k_2}(M)]$
external control

Message Authentication Code

Cryptographic requirements

- for any given M, it is computationally infeasible to find $N \neq M$ with $C_k(N) = C_k(M)$
  an attacker should not able to construct a new message to match a given tag without knowing the key

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- the authentication algorithm should not be weaker with respect to certain parts of the message than others. If this were not the case, then an opponent who had M and $C_k(M)$ could attempt variations on M at the known “weak spots” with a likelihood of early success at producing a new message that matched the old tags

Security of MACs

- resistance to brute-force attacks
  - the assessment of strength is similar to that for symmetric encryption algorithms
  - the level of effort for brute-force attack on a MAC algorithm can be expressed as $min(2^k, 2^n)$, $k =$ number of bits of the key and $n =$ number of bits of the tag
  - the key length and tag length should be: $min(k, n) \geqslant 128$ bits

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  - the key length and tag length should be: $min(k, n) \geqslant 128$ bits
- resistance to cryptanalysis
  - there is much more variety in the structure of MACs, so it is not possible to generalize about the cryptanalysis of MACs
  - there are far less works done on studying this type of attacks when compared whit hash functions

MAC Algorithms

There are two types of MACs:

- **block cipher-based** – can use any symmetric encryption algorithm
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- **block cipher-based** – can use any symmetric encryption algorithm
  - traditionally been the most common approach to constructing a MAC
- **hash based** – can use any hash algorithm (also known as keyed hash)
  - generally execute faster in software than symmetric block cipher-based
  - became more popular after the mandatory use of HMAC in IPsec

Hash based MAC algorithms

- hash function such as SHA was not designed for use as a MAC because it does not rely on a secret key
- there are many ways to incorporate a secret key into an existing hash algorithm
- the approach that has received the most support is HMAC

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HMAC

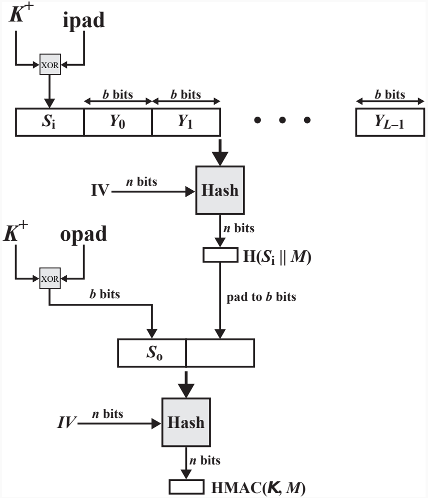
- is the mandatory-to-implement MAC for IP security
- is used in other Internet protocols, such as SSL/TLS
- is publish as RFC 2104 and NIST standard (FIPS 198)

Hash based MAC algorithms

HMAC structure

1. K^+ = append zeros to the left end of k to create a b-bit string (*e.g.*, if K length = 160 bits and $b = 512$, then K will be appended with $(512 - 160) = 352$ bits with zeroes)
2. $S_i = K^+ \oplus ipad$, to produce the b-bit block ($ipad = 00110110$ repeated $b/8$ times)
3. append M to S_i
4. apply hash to the result of step 3: $H(S_i \parallel M)$
5. $S_o = K^+ \oplus opad$, to produce the b-bit block ($opad = 01011100$ repeated $b/8$ times)
6. Append the hash result from step 4 to S_o
7. Apply H to the stream generated in step 6 and output the result

$$HMAC_k(M) = H[K^+ \oplus opad \parallel H(K^+ \oplus ipad) \parallel M]$$



Hash based MAC algorithms

Security of HMAC

- depends on the cryptographic strength of the hash function
- if the security of the embedded hash function were compromised, the security of HMAC could be retained simply by replacing the embedded hash function with a more secure one

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Security of HMAC

- depends on the cryptographic strength of the hash function
- if the security of the embedded hash function were compromised, the security of HMAC could be retained simply by replacing the embedded hash function with a more secure one
- attacking HMAC is harder than attacking a hash function
    - the attacker cannot generate message/code pairs because he does not know k
    - therefore, the attacker must observe a sequence of messages generated by HMAC under the same key
    - for a hash of 128 bits, this requires 2^{64} observed blocks (2^{72} bits) with the same key
    - on a 1 Gbps link, one would need to observe a continuous stream of messages with no change in key for about 150 000 years in order to succeed
    - for that reason the use of MD5 is acceptable inside an HMAC

Block-cipher based MAC algorithms

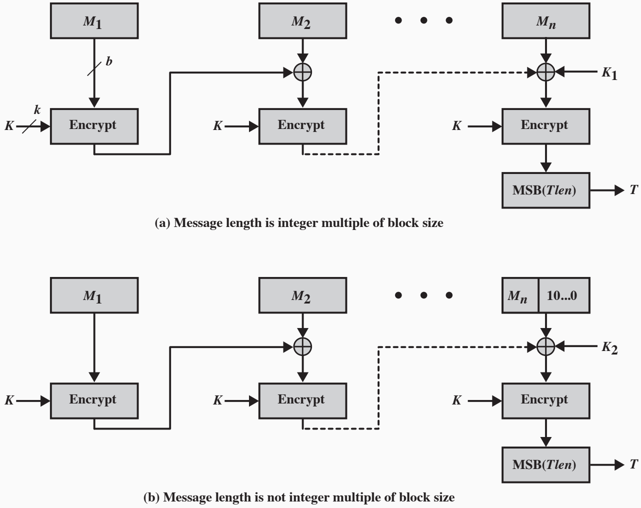
- use a symmetric cipher algorithm as its base
- symmetric cipher algorithms already have a key as input
- used to inside authenticated encryption schemes
- 2 proposals:
  - Data Authentication Algorithm (DAA) – based on DES and no longer safe to use
  - Cipher-based Message Authentication Code (CMAC) – a refinement of DAA, can be used with 3DES and AES

Block-cipher based MAC algorithms

CMAC structure

$$C_1 = E_k(M_1)$$
$$C_2 = E_k(M_2 \oplus C_1)$$
$$C_3 = E_k(M_3 \oplus C_2)$$
...
$$C_n = E_k(M_n \oplus C_{n-1} \oplus k_1)$$
$$T = MSB_{T_{len}}(C_n)$$

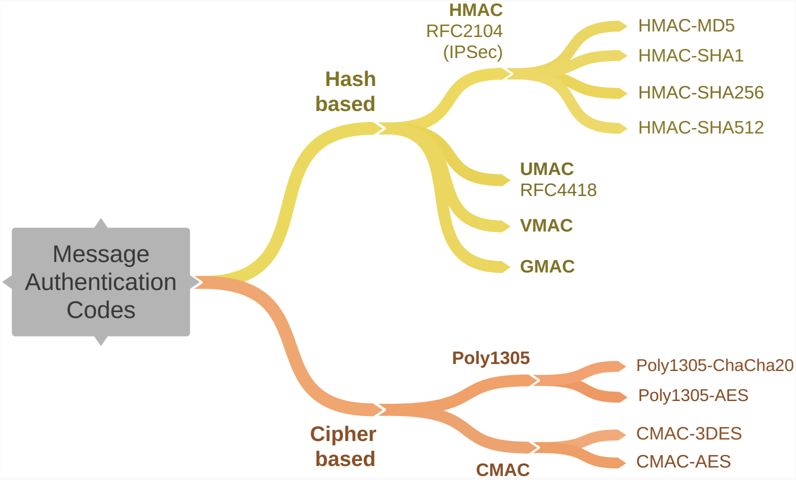
k_1 and k_2 are derivated from k



Block-cipher based MAC algorithms

Poly1305

- created by Daniel J. Bernstein
- the algorithm name is based on the fact that it evaluates the *modulus* of the prime number $2^{130} - 5 = 1\,361\,129\,467\,683\,753\,853\,853\,498\,429\,727\,072\,845\,819$ (40 decimal digits)
- there are several variants:
  - Poly1305-AES
  - Poly1305-Salsa20
  - Poly1305-ChaCha20 – adopted by google for TLS communications (standardized in RFC 7905), can also be used in SSH


Message Authentication Codes
Hash based
HMAC
RFC2104
(IPSec)
HMAC-MD5
HMAC-SHA1
HMAC-SHA256
HMAC-SHA512
UMAC
RFC4418
VMAC
GMAC
Cipher based
Poly1305
Poly1305-ChaCha20
Poly1305-AES
CMAC
CMAC-3DES
CMAC-AES

Authenticated Encryption

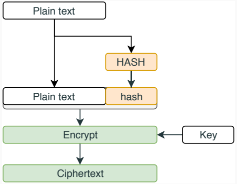
Authenticated encryption (AE)

- is a term used to describe encryption systems that simultaneously protect confidentiality and authenticity (integrity)
- until recently the two services have been designed separately
  - Hashing followed by encryption
  - Independently encrypt and authenticate
  - Authentication followed by encryption
  - Encryption followed by authentication

Traditional approaches

Hash-then-Encrypt

$E_k[M \mid\mid H(M)]$



(used on WiFi WEP)

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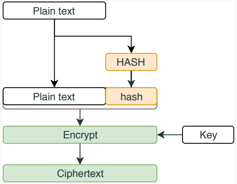

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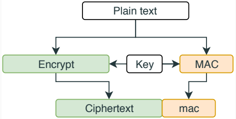
Encrypt-and-MAC

$E_k(M) \parallel C_k(M)$



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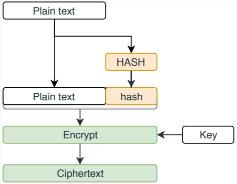

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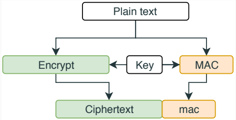

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MAC-then-Encrypt

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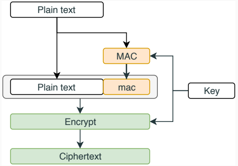

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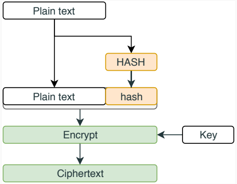

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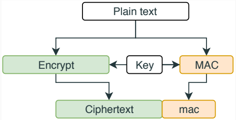

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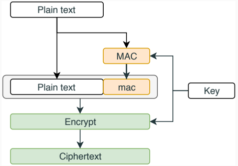
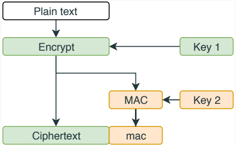


(used on TLS)

Encrypt-then-MAC

$E_{k2}(M) \,||\, C_{k1}[E_{k2}(M)]$



(used on IPsec)

Traditional approaches

- these approaches require two passes through the data being protected (time consuming)
- there are security vulnerabilities with all of them
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Authenticated encryption (AE)

- requires only a single pass through the data being protected (more efficient)
- address the security vulnerabilities of the traditional approaches
- it is possible to authenticate data that is not encrypted:
  - **Authenticated Encryption with Associated Data** (AEAD)

Authenticated Encryption with Associated Data (AEAD):

- allows a recipient to check the integrity of both the **encrypted** and **unencrypted** information in a message
- associated data – is a part of the message that does not requires confidentiality, but must be authentic, *e. g.* network protocol headers

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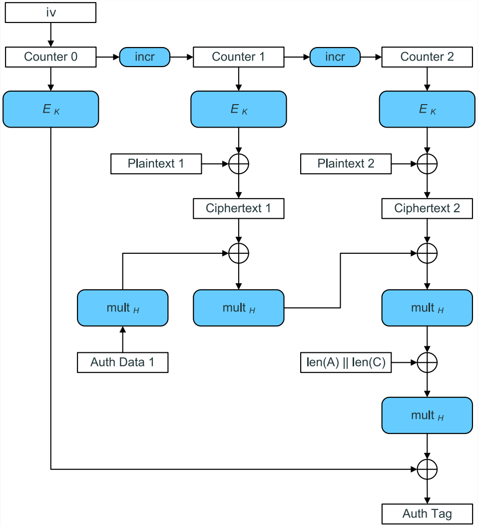
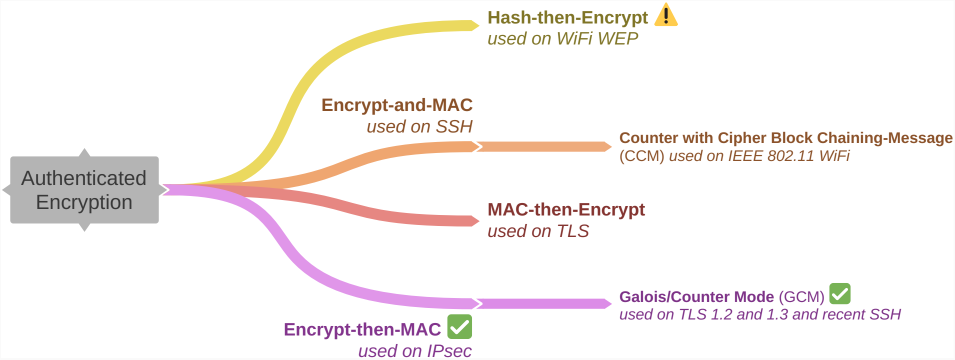
Some Variants:

- **Counter with Cipher Block Chaining-Message** (CCM) – used by IEEE 802.11 WiFi
- **Galois/Counter Mode** (GCM) – mode of operation for symmetric-key cryptographic block ciphers that has been widely adopted because of its performance
  - processes with a single pass over the data
  - supported in the newer versions of IPsec, SSH, TLS 1.2 and TLS 1.3, ...

AUTHENTICATED ENCRYPTION WITH ASSOCIATED DATA – GALOIS/COUNTER MODE (GCM)




Authenticated Encryption
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used on WiFi WEP
Encrypt-and-MAC
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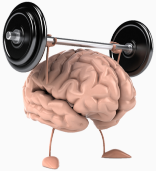
Counter with Cipher Block Chaining-Message
(CCM) used on IEEE 802.11 WiFi
MAC-then-Encrypt
used on TLS
Galois/Counter Mode (GCM)
used on TLS 1.2 and 1.3 and recent SSH
Encrypt-then-MAC
used on IPsec

Table 1: Limitations for an untruncated 128-bit authentication tag

Construction	**Max bytes for a single (key,nonce)**	**Max bytes for a single key**
AES256-GCM [1]	64 GB [2]	$\approx$ 350 GB (for $\approx$16 KB long messages)
ChaCha20-Poly1305 [3]	2^{64} bytes (no pratical limit)	Up to 2^{64} messages (no pratical limit)
ChaCha20-Poly1305-IETF [3]	256 GB [2]	Up to 2^{64} messages (no pratical limit)
XChaCha20-Poly1305-IETF [3,4]	2^{64} bytes (no pratical limit)	Up to 2^{64} messages (no pratical limit)

[1] fastest algorithm due to hardware acceleration introduced by Intel in the Westmere processors (in 2010) and newer
[2] it is possible to overcome the limitation by rekeying: using a new (key,nounce) pair
[3] faster than AES in software only implementations (without AES specific hardware acceleration)
[4] is the safest choice (key = 256 bits, block = 512 bits, nounce = 192 bits), but not wide spread usage

Exercises



1. What types of attacks are addressed by message authentication?
2. What are some approaches to producing message authentication?
3. When a combination of symmetric encryption and an error control code is used for message authentication, in what order must the two functions be performed?
4. What is a message authentication code?
5. What is the difference between a message authentication code and a one-way hash function?

Cryptographic Schemes

Use one, or more, cryptographic algorithm, to achieve new goals. There are four types of cryptographic schemes with hash:

1. Message Authentication Code (MAC) – already addressed
2. Authenticated Encryption – already addressed
3. Key Derivation Functions (KDF) – to store passwords in a non-reversible fashion
4. One-Time Password (OTP) – mainly used as second authentication factor

Key Derivation Functions (KDF)

- designed to securely store passwords without encryption
- like an hash function:
  - the output has fixed length (256, 512, ...) bits
  - non-reversible
- slower than hash functions → harder to brute-force
  - can be parameterized to adjust the required computational effort
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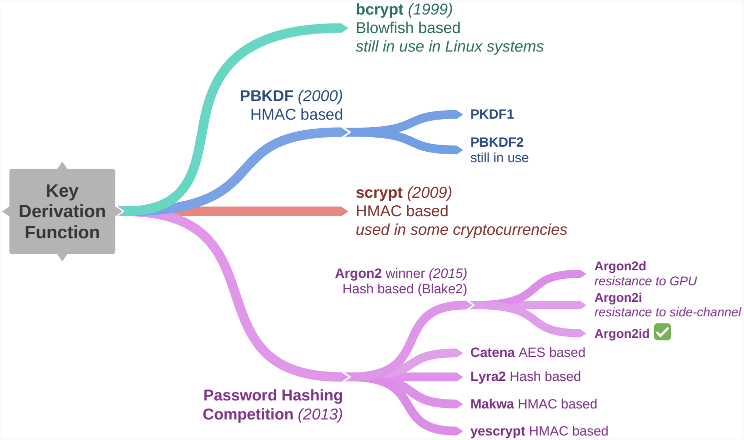
  - can be parameterized to adjust the required computational effort
  - common parameters are: salt, number of iterations, derived key length
- Disadvantages:
  - it is still needed to keep a secret value on the server side
  - people tend to use weak passwords and reuse them (this is a problem with passwords in general)

Key Derivation Functions



Key Derivation Function

Argon2

- based on Blake2b hash
- three versions
    - Argon2d – is faster, suitable for cryptocurrencies, is resistant to GPU accelaration;
    - Argon2i – is slower, preferred for password hashing, is resistant to side-channel attacks;
    - Argon2id – is a hybrid version;

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Parameters:

- primary:
  - **password** – any length from 0 to $2^{32} - 1$ bytes;
  - **number of iterations** – used to tune the running time independently of the memory size;
  - **memory required** – it is a memory-hard function;
  - **parallelism** – how many independent computational chains can be run;
- secondary (default values maybe used):
  - salt – random value, 128 bits is recommended for password hashing;
  - output length – any integer number of bytes from 4 to $2^{32} - 1$
  - secret value – serves as key if necessary, but by default none is used;
  - associated data – optional arbitrary extra data;
  - algorithm type – *d*, *i*, or *id*;

Key Derivation Function

Argon2 example:

- input values:
    - password = `Correct Horse Battery Staple`;
    - memory = `1 GB`
    - iterations = `4`
    - parallelism = `1`
- output:

  `$argon2id$v=19$m=1048576,t=4,p=1$1k8ic3+vS0kDB+4J7bcjQg$ok3jcq9yW7Rw7GuhZfJi0IdcoixCZYWgCcHxp8bny6M`
    - `$argon2id` – the variant of Argon2 being used
    - `$v=19` – the version of Argon2 being used
    - `$m=1048576,t=4,p=1` – the memory (m), iterations (t) and parallelism (p)
    - `$1k8ic3+vS0kDB+4J7bcjQg` – the base64-encoded randomly selected salt
    - `$ok3jcq9yW7Rw7GuhZfJi0IdcoixCZYWgCcHxp8bny6M` – the base64-encoded derived key

Key Derivation Function

Argon2 example:

- input values:
  - password = `Correct Horse Battery Staple`;
  - memory = `1 GB`
  - iterations = `4`
  - parallelism = `1`
- output:
  `$argon2id$v=19$m=1048576,t=4,p=1$1k8ic3+vS0kDB+4J7bcjQg$ok3jcq9yW7Rw7GuhZfJi0IdcoixCZYWgCcHxp8bny6M`
  - `$argon2id` – the variant of Argon2 being used
  - `$v=19` – the version of Argon2 being used
  - `$m=1048576,t=4,p=1` – the memory (m), iterations (t) and parallelism (p)
  - `$1k8ic3+vS0kDB+4J7bcjQg` – the base64-encoded randomly selected salt
  - `$ok3jcq9yW7Rw7GuhZfJi0IdcoixCZYWgCcHxp8bny6M` – the base64-encoded derived key
- time to calculate on my laptop ≈ 2,5 seconds

Key Derivation Function

Argon2 guidelines for choosing the parameters:

1. set **memory** limit to the amount of memory you want to reserve for password hashing
2. then, set **iterations** to 3 and measure the time it takes to hash a password
3. if it is too long for your application, reduce **memory**, but keep **iterations** set to 3

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Use cases:

- for online use (*e. g.* login in on a website), a **1 second** computation is likely to be the acceptable maximum
- for interactive use (*e. g.* a desktop application), a **5 second** pause after having entered a password is acceptable if the password doesn't need to be entered more than once per session
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Note

But the best defense against brute-force password cracking remains using **strong passwords**

One-Time Password (OTP)

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- main disadvantage: vulnerable to man-in-the-middle attacks
- there are two types:
  - based only on a seed (or counter)
  - based on time-synchronization

HMAC-based One-time Password (HOTP)

- based on an increasing counter (C) value and a static symmetric key (k)
- specified in RFC4226
  - uses HMAC-SHA-1
  - $HOTP(k, C) = Truncate(HMAC\_SHA1(k, C))$
  - $Truncate()$ returns a number with a configurable amount of digits from 6 to 10
- used on SMS tokens sent by banks
  - vulnerable to SIM swap scam and fake cell phone towers

Time-based One-Time Password (TOTP) RFC 6238

- is an extension of the HMAC-based One-time Password algorithm
- $TOTP = HTOP(k, T)$, where $T = (Current\_Unix\_time - T0)/X$ and X is the time step
- must validate over a range of time (typically 1 minute) due to latency, both network and human, and unsynchronised clocks

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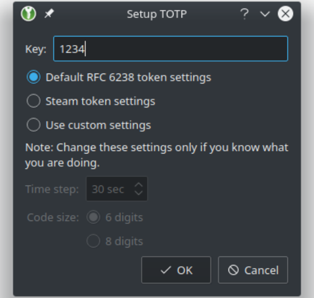
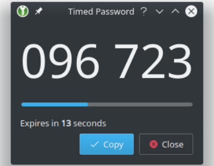
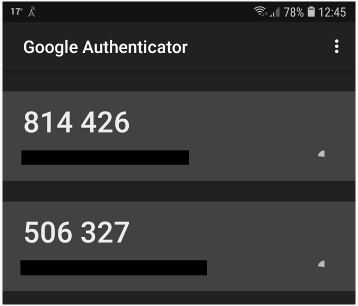
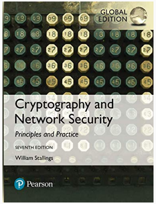
- TOPT apps: Keepass, Google Authenticator, LastPass Authenticator, ...







Questions?



Chapters 12 of

William Stallings, Cryptography and Network Security: Principles and Practice, Global Edition, 2016