

Project:

Message Authentication Code

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Abstract

The goal of this project is to perform some personal study in order to acquire the extra knowledge in cryptography while also improving major skills such as writing, collaboration and public presentation. In this project, we intend to have a preliminary understanding of a method of cryptography: Message Authentication Code. MAC is a short piece of information used to authenticate a message, confirming that the message comes from its authenticity and has not been changed^[1].

In this project, we first give the brief introduction to cryptography, message authentication and message authentication code in order. Then in the second chapter, we mainly represent two kinds of MAC: MAC based on block ciphers and MAC based on Hash functions. The third chapter is mainly about the MAC security. We discuss the security by both brute-force attack and cryptanalysis. In the fourth chapter, some applications are mentioned and the major one is pseudo-random number generation. We will discuss both PRNG based on Hash function and PRNG based on MAC function to judge the superiority of MAC.

Cryptography is quite a complex and esoteric subject and there are so many mysteries in the world. We just do a simple and shallow survey on the aspect of MAC. There still remains a large number of interesting and profound problems to be solved. The study of cryptography is still pending.

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I Introduction

1 Introduction to Cryptography

The Concise Oxford Dictionary (2006) defines cryptography as the art of writing or solving codes^[2]. However, in the late 20th century, this picture of cryptography radically changed. A rich theory emerged, enabling the rigorous study of cryptography as a science. Cryptography is now about constructing and analyzing protocols that prevent third parties or the public from reading private messages^[3].

1.1 Classic Cryptography

The main classical cipher types are transposition ciphers, which rearrange the order of letters in a message and substitution ciphers, which systematically replace letters or groups of letters with other letters or groups of letters.

The earliest known use of cryptography is some carved ciphertext on stone in Egypt (ca 1900 BCE), but this may have been done for the amusement of literate observers rather than as a way of concealing information.

1.2 Modern Cryptography

Modern cryptography includes various aspects in information security such as data confidentiality, data integrity, authentication, and non-repudiation^[4]. Applications of modern cryptography exist at the intersection of the disciplines of mathematics, computer science, and electrical engineering.

Here are several chief topics of modern cryptography:

- **Symmetric-key cryptography**
- **Public-key cryptography**
- **Cryptanalysis**
- **Cryptographic primitives**
- **Cryptosystems**

2 Introduction to Message Authentication

Message authentication is a mechanism or service used to verify the integrity of a message. Message authentication assures that data received contain no modification, insertion, deletion, or replay and that the purported identity of the sender is valid^[5].

2.1 Message Authentication Functions

Message authentication does not necessarily include the property of non-repudiation^{[6][7]} and is typically achieved by using message authentication codes (MACs), message encryption (ME) or hash function^[5].

- (1) **Hash function:** A function that maps a message of any length into a fixed-length hash value, which serves as the authenticator
- (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

2.2 Message Authentication Requirements

In the context of communications across a network, message authentication can deal with the following four attacks.

- (1) **Masquerade:** Insertion of messages into the network from a fraudulent source.
- (2) **Content modification:** Changes to the contents of a message.
- (3) **Sequence modification:** Any modification to a sequence of messages between parties.
- (4) **Timing modification:** Delay or replay of messages.

In summary, message authentication is a procedure to verify that received messages come from the alleged source and have not been altered. Message authentication may also verify sequencing and timeliness^[5].

However, there are still a few attacks that message authentication can not deal with. The following are some:

- (1) **Disclosure:** Release of message contents to any person or process not possessing the appropriate cryptographic key.
- (2) **Traffic analysis:** Discovery of the pattern of traffic between parties.

- (3) **Source repudiation:** Denial of transmission of message by source.
- (4) **Destination repudiation:** Denial of receipt of message by destination.

Measures to deal with the first two attacks are in the realm of message confidentiality and are dealt with in Part One. Mechanisms for dealing specifically with item (3) come under the heading of digital signatures. A digital signature is an authentication technique that also includes measures to counter repudiation by the source. Dealing with item (4) may require a combination of the use of digital signatures and a protocol designed to counter this attack.

3 Introduction to Message Authentication Codes

A message authentication code (MAC) is an algorithm that takes a variable-length message and a secret key as input and produces an authentication code. A recipient in possession of the secret key can generate an authentication code to verify the integrity of the message^[1].

There are two means of forming a MAC. One is to combine a cryptographic hash table in some fashion with a secret key. Another is to use a symmetric block cipher in such a way that it produces a fixed-length output for a variable-length input.

3.1 Requirements for Message Authentication Codes

Assume that an opponent knows the MAC function but does not know K . Then the MAC function should satisfy the following requirements.

1. If an opponent observes M and $MAC(K, M)$, it should be computationally infeasible for the opponent to construct a message M' such that

$$MAC(K, M') = MAC(K, M)$$

2. $MAC(K, M)$ should be uniformly distributed in the sense that for randomly chosen messages, M and M' , the probability that $MAC(K, M') = MAC(K, M)$ is 2^{-n} , where n is the number of bits in the tag.

3. Let M' be equal to some known transformation on M . That is, $M' = f(M)$. For example, f may involve inverting one or more specific bits. In that case,

$$Pr[MAC(K, M) = MAC(K, M')] = 2^{-n}$$

The first requirement speaks to the example, in which an opponent is able to construct a new message to match a given tag, even though the opponent does not know and does not learn the key.

The second requirement deals with the need to thwart a brute-force attack based on chosen plaintext.

The final requirement dictates that the authentication algorithm should not be weaker with respect to certain parts or bits of the message than others^[5].

II MAC Classification

1 MAC Based on Block Ciphers

1.1 Definition of DAA

The Data Authentication Algorithm (DAA) is based on DES, and it has been one of the most widely used MACs for a number of years.

The algorithm can be defined as using the cipher block chaining (CBC) mode of operation of DES with an initialization vector of zero. The data to be authenticated are grouped into contiguous 64-bit blocks: D_1, D_2, \dots, D_n . If necessary, the final block is padded on the right with zeroes to form a full 64-bit block. Using the DES encryption algorithm E and a secret key K , a data authentication code (DAC) is calculated as follows

$$\begin{aligned} O_1 &= E(K, D_1) \\ O_2 &= E(K, D_2 \oplus O_1) \\ O_3 &= E(K, D_3 \oplus O_2) \\ &\vdots \\ O_n &= E(K, D_n \oplus O_{n-1}) \end{aligned}$$

And then O_n is the MAC of the data.

However, only messages of one fixed length of mn bits are processed, where n is the cipher block size and m is a fixed positive integer. As a simple example, notice that given the CBC MAC of a one-block message X , say $T = \text{MAC}(K, X)$, the adversary immediately knows the CBC MAC for the two-block message $X \parallel (X \oplus T)$ since this is once again T .

1.2 Definition of CMAC

Black and Rogaway [BLAC00] demonstrated that the limitation of DAA could be overcome using three keys: one key of length K to be used at each step of the

cipher block chaining and two keys of length n , where k is the key length and n is the cipher block length. This proposed construction was refined by Iwata and Kurosawa so that the two n -bit keys could be derived from the encryption key, rather than being provided separately [IWAT03]. This refinement, adopted by NIST, is the Cipher-based Message Authentication Code (CMAC) mode of operation for use with AES and triple DES.

First, let us define the operation of CMAC when the message is an integer multiple n of the cipher block length b . For AES, $b = 128$, and for triple DES, $b = 64$. The message is divided into n blocks (M_1, M_2, \dots, M_n) . The algorithm makes use of a k -bit encryption key K and an n -bit constant, K_1 . For AES, the key size k is 128, 192, or 256 bits; for triple DES, the key size is 112 or 168 bits. CMAC is calculated as follows

$$\begin{aligned} C_1 &= E(K, M_1) \\ C_2 &= E(K, M_2 \oplus C_1) \\ C_3 &= E(K, M_3 \oplus C_2) \\ &\vdots \\ C_n &= E(K, M_n \oplus C_{n-1} \oplus K_1) \\ T &= \text{left most } s \text{ bits of } C_n \end{aligned}$$

And then T (of length s) is the MAC of the data.

If the message is not an integer multiple of the cipher block length, then the final block is padded to the right (least significant bits) with a 1 and as many 0s as necessary so that the final block is also of length b . The CMAC operation then proceeds as before, except that a different n -bit key K_2 is used instead of K_1 .

The two n -bit keys are derived from the k -bit encryption key as follows.

$$\begin{aligned} L &= E(K, 0^n) \\ K_1 &= L \cdot x \\ K_2 &= L \cdot x^2 \end{aligned}$$

where multiplication is done in the finite field $GF(2^n)$ and x and x^2 are first and second order polynomials that are elements of $GF(2^n)$.

2 MAC Based on Hash Functions

2.1 Introduction to HMAC

In recent years, there has been increased interest in developing a MAC derived from a cryptographic hash function. The motivations for this interest are

- (1) cryptographic Hash functions such as MD5 and SHA generally execute faster in software than symmetric block ciphers such as DES and AES.
- (2) Library code for cryptographic hash functions is widely available.

A hash function such as SHA does not rely on a secret key, which means that it cannot be used directly. There have been a number of proposals for the incorporation of a secret key into an existing hash algorithm. The approach that has received the most support is HMAC.

According to RFC 2104^[9], HMAC can be used in combination with any iterated cryptographic hash function. MD5 and SHA-1 are examples of such hash functions. HMAC also uses a secret key for calculation and verification of the message authentication values. The main goals behind this construction are

- (1) To use, without modifications, available hash functions. In particular, hash functions that perform well in software, and for which code is freely and widely available.
- (2) To preserve the original performance of the hash function without incurring a significant degradation.
- (3) To use and handle keys in a simple way.
- (4) To have a well understood cryptographic analysis of the strength of the authentication mechanism based on reasonable assumptions on the underlying hash function.
- (5) To allow for easy replaceability of the underlying hash function in case that faster or more secure hash functions are found or required.

2.2 Definition of HMAC

First, the definition of HMAC requires a cryptographic hash function, which we denote by H . We assume H to be a cryptographic hash function where data is hashed by iterating a basic compression function on blocks of data.

Second, We denote by B the byte-length of such blocks ($B=64$ for MD5 and SHA-1), and by L the byte-length of hash outputs ($L=16$ for MD5, $L=20$ for SHA-1). The authentication key K can be of any length up to B . Applications that use

keys longer than B bytes will first hash the key using H and then use the resultant L byte string as the actual key to HMAC. In any case the minimal recommended length for K is L bytes (as the hash output length).

At last, We define two fixed and different strings $ipad$ and $opad$ as follows (the ‘i’ and ‘o’ are mnemonics for inner and outer):

$ipad = \text{the byte } 0x36 \text{ repeated } B \text{ times}$
 $opad = \text{the byte } 0x5C \text{ repeated } B \text{ times}$

The procedure of HMAC is

- (1) Append zeros to the end of K to create a B byte string (e.g., if K is of length 20 bytes and $B=64$, then K will be appended with 44 zero bytes $0x00$)
- (2) XOR (bitwise exclusive-OR) the B byte string computed in step (1) with $ipad$
- (3) Append the stream of data ‘text’ to the B byte string resulting from step (2)
- (4) Apply H to the stream generated in step (3)
- (5) XOR (bitwise exclusive-OR) the B byte string computed in step (1) with $opad$
- (6) Append the H result from step (4) to the B byte string resulting from step (5)
- (7) Apply H to the stream generated in step (6) and output the result

The pseudo code describing (including the pre-processing of K) is

Input: Hash function H , block length B , Message M , $ipad$ and $opad$

Output: A Hashed string with length L

```

function HMAC( $H, B, M$ )
  if length( $K$ ) >  $B$  then
     $K \leftarrow H(K)$ 
  end if
   $K' \leftarrow K$  with appended zero until it reaches length  $B$ 
   $S_i \leftarrow K' \text{ xor } ipad$ 
   $W_i \leftarrow H(S_i || M)$ 
   $S_o \leftarrow K' \text{ xor } opad$ 
   $W_o \leftarrow H(S_o || W_i)$ 
  return  $W_o$ 
end function

```

HMAC is defined in such a way that the underlying hash function H can be used with no modification to its code. In particular, it uses the function H with the pre-defined initial value IV (a fixed value specified by each iterative hash function to initialize its compression function). However, if desired, a performance improvement can be achieved at the cost of (possibly) modifying the code of H to support variable IV s.

2.3 The Security of HMAC

The security of the message authentication mechanism presented here depends on cryptographic properties of the hash function H : the resistance to collision finding (limited to the case where the initial value is secret and random, and where the output of the function is not explicitly available to the attacker), and the message authentication property of the compression function of H when applied to single blocks (in HMAC these blocks are partially unknown to an attacker as they contain the result of the inner H computation and, in particular, cannot be fully chosen by the attacker).

These properties, and actually stronger ones, are commonly assumed for hash functions of the kind used with HMAC. In particular, a hash function for which the above properties do not hold would become unsuitable for most (probably, all) cryptographic applications, including alternative message authentication schemes based on such functions.

So the probability of successful attack on HMAC is equivalent to one of the following attacks on the embedded hash function.

- (1) The attacker is able to compute an output of the compression function even with an IV that is random, secret, and unknown to the attacker.
- (2) The attacker finds collisions in the hash function even when the IV is random and secret.

3 Authenticated Encryption

Authenticated encryption (AE) is a term used to describe encryption systems that simultaneously protect confidentiality and authenticity (integrity) of communications. Many applications and protocols require both forms of security, but until recently the two services have been designed separately.

There are four common methods in practical use:

- (1) HtE (Hash then Encrypt): First compute $h = H(M)$ and then encrypt $W = E(K, (M || h))$.
- (2) MtE (MAC then Encrypt): First compute $m = MAC(K_1, M)$ and then encrypt $W = E(K_2, (M || m))$.
- (3) EtM (Encrypt then MAC): First encrypt $w = E(K_1, M)$ and then compute $W = MAC(K_2, w)$.
- (4) E&M (Encrypt and MAC): Encrypt $w = E(K_1, M)$ and compute $m = MAC(K_2, M)$ and use these two values to authenticate.

III MAC Security

1 Attacks

Just as with encryption algorithms and hash functions, we can group attacks on MACs into two categories: brute-force attacks and cryptanalysis.

1.1 Brute-Force Attacks

In cryptography, a brute-force attack is that an attacker tries many passwords to guess. The attacker systematically checks all possible passwords until the correct one is found. But as the password's length increases, the amount of time to find the correct password increases exponentially. Thus the resources required for a brute-force attack grow exponentially with increasing key size.

A brute-force attack on a MAC is difficult since it requires known message-tag pairs. We need to state the desired security property of a MAC algorithm, which can be expressed as follows.

- Computation resistance: Given one or more text-MAC pairs $[x_i, \text{MAC}(K, x_i)]$, it is computationally infeasible to compute any text-MAC pair $[x, \text{MAC}(K, x)]$ for any new input $x \neq x_i$.

To do brute-force attack, attacker can have two approaches: attack the key space and attack the MAC value. The former attack is to recover the key and the latter attack is to generate a valid tag for a given message or to find a message that matches a given tag.

For the key space attack, assume that the attacker has one known text-tag pair. Then he can compute the n -bit tag on the known text for all possible keys. At least one key is guaranteed to produce the correct tag. If the key size is k bits, we can find the level of effort is 2^k . However, MAC is a many-to-one mapping so that it has not only one key corresponding to such text-tag pair. Thus additional text-tag pairs must be tested for different correct keys. It shows that the level of effort drops off rapidly with each additional text-MAC pair and The total level of effort keeps 2^k .

For the MAC value attack, the attacker aim to generate a valid tag for a given message or to find a message that matches a given tag but he will require chosen text–tag pairs or knowledge of the key. The level of effort is 2^n .

To sum up, level of effort for the brute-force attack can be expressed as $\min(2^k, 2^n)$ where k is the key size and n is the code size. The assessment of strength satisfies the security. Therefore, MAC have strong resistance on brute-force attack.

1.2 Cryptanalysis

Cryptanalysis is the study of analyzing information systems in order to study the hidden aspects of the systems. It's used to breach cryptographic security systems and gain access to the contents of encrypted messages, even if the cryptographic key is unknown. Nowadays, we have various attack modes such as Mod-n cryptanalysis, attacking cryptographic hash system, side-channel attack and so on^[8].

As with encryption algorithms and hash functions, cryptanalytic attacks on MAC algorithms seek to exploit some property of the algorithm to perform some attack other than an exhaustive search. An ideal MAC algorithm will require a cryptanalytic effort no less than the brute-force effort. However, there is much more variety in the structure of MACs than in hash functions, so it is difficult to generalize about the cryptanalysis of MACs.

IV MAC Application

1 Pseudo-random Number Generation

In this section, we are going to discuss the pseudo-random number generation on the basis of hash function and MAC. A seed value and a deterministic algorithm for generating a stream of pseudo-random bits are two essential elements of any pseudo-random number generator abbreviated as PRNG.

If a required value, such as a session key, is produced by the algorithm which is used as a pseudo-random function (PRF), then only the user of PRF can know the seed value. What's more, if the algorithm is used to produce a stream encryption function such that $C = c_1c_2...c_n = E_{k_1}(m_1)E_{k_2}(m_2)...E_{k_n}(m_n)$ where E are different blocks and $k_1k_2...k_n$ is a key stream, then both the sender and the receiver should know the seed value the seed which plays the role of a secret key.

Since either a hash function or MAC produces an apparently random output, it can serve as the basis of PRNG. Both ISO standard 18031 (Random Bit Generation) and NIST SP 800-90 (Recommendation for Random Number Generation Using Deterministic Random Bit Generators) define an approach for random number generation using a cryptographic hash function. In addition, SP 800-90 defines a random number generator based on HMAC^[1]. We will discuss there two approaches in the following subsections detailedly.

1.1 PRNG Based on Hash Function

For the algorithm based on the hash function, we have some pseudo-code. We need to input the seed V with *seedlen* which is the bit length of V . Notice that $V \geq k + 64$ where k is the security level expressed in bits. We also need to input *outlen* which is the bit length of Hash value and the desired number of bits n for the output. Thus we can get a random number of n bits due to the following Random Generator Function. Through the code we can find the pseudorandom bit stream $w_1 || w_2 || ... || w_m$.

Input:

V = seed
security level k expressed in bits
 $seedlen$ = bit length of $V \geq k + 64$
 $outlen$ = bit length of Hash value
 n = desired number of bits for the output

Output:

a random number of n bits

function RANDOMGENERATOR($V, k, seedlen, n, outlen$)

$m \leftarrow \lceil n/outlen \rceil$

data $\leftarrow V$

W is a null string

for $i = 1$ to m **do**

$W_i \leftarrow H(\text{data})$

$W \leftarrow W \parallel W_i$

data $\leftarrow (\text{data} + 1) \bmod 2^{seedlen}$

end for

return leftmost n bits of W

end function

Here is also a figure for PRNG using cryptographic hash function:

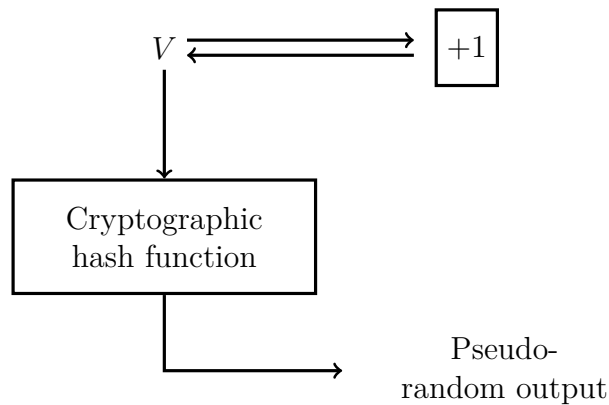


Figure IV.1: PRNG using cryptographic hash function

The SP 800-90 specification also provides for periodically updating V to enhance security. The specification also indicates that there are no known or suspected weaknesses in the hash-based approach for a strong cryptographic hash algorithm, such as SHA-2^[1].

1.2 PRNG Based on MAC Function

In fact, since because HMAC is a widely used standardized MAC function and is implemented in many protocols and applications, HMAC is always used for constructing a MAC-based PRNG rather than the use of a cryptographic hash function for a PRNG. Although HMAC involves two executions of the underlying hash function for each output block, leading to twice longer execution time, it provides a greater degree of confidence in its security.

Here is a figure for PRNG using HMAC:

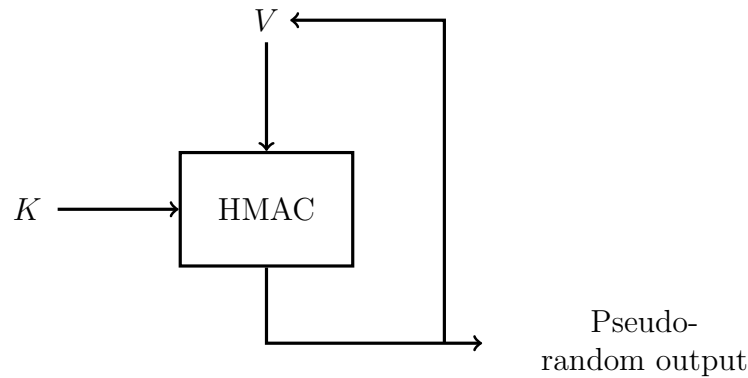


Figure IV.2: PRNG using HMAC

For the MAC-based approach, there are two inputs: a key K and a seed V . Here are some differences among various types of HMAC.

For HMAC NIST SP 800-90:

Input:

V = seed

$outlen$ = bit length of Hash value

n = desired number of bits for the output

Output:

a random number of n bits

function RANDOMGENERATOR($V, k, seedlen, n, outlen$)

$m \leftarrow \lceil n/outlen \rceil$

$w_0 \leftarrow V$

W is a null string

for $i = 1$ to m **do**

$w_i \leftarrow \text{MAC}(K, w_{i-1})$

$W \leftarrow W \parallel w_i$

end for

return leftmost n bits of W

end function

For HMAC IEEE 802.11i:

Input:

V = seed
 $outlen$ = bit length of Hash value
 n = desired number of bits for the output

Output:

a random number of n bits

function RANDOMGENERATOR($V, k, seedlen, n, outlen$)

$m \leftarrow \lceil n/outlen \rceil$

W is a null string

for $i = 1$ to m **do**

$w_i \leftarrow \text{MAC}(K, (V \parallel i))$

$W \leftarrow W \parallel w_i$

end for

return leftmost n bits of W

end function

For HMAC TLS/WTLS:

Input:

V = seed
 $outlen$ = bit length of Hash value
 n = desired number of bits for the output

Output:

a random number of n bits

function RANDOMGENERATOR($V, k, seedlen, n, outlen$)

$m \leftarrow \lceil n/outlen \rceil$

$A(0) \leftarrow V$

W is a null string

for $i = 1$ to m **do**

$A(i) \leftarrow \text{MAC}(K, A(i-1))$

$w_i \leftarrow \text{MAC}(K, (A(i) \parallel V))$

$W \leftarrow W \parallel w_i$

end for

return leftmost n bits of W

end function

In HMAC NIST SP 800-90 the combination of K and V form the overall seed for the PRNG. The key remains the same for each block of output, and the data input for each block is equal to the tag output of the previous block. It provides for periodically updating K and V to enhance security.

In HMAC IEEE 802.11i, the data input consists of the seed concatenated with a counter. The counter is incremented for each block of output. The security is enhanced comparing to HMAC NIST SP 800-90 since the knowledge of the input and output should not be sufficient to recover K and predict future pseudo-random bits.

In HMAC Transport Layer Security protocol and the Wireless Transport Layer Security Protocol abbreviated as TLS/WTLS, for each block of output w_i , it involves invoking HMAC twice. The double use of HMAC doubles the burden, decreases the performance but increases the security overkill.

V Conclusion and Discussion

1 Discussion

In this project, we have searched a lot about the message authentication codes. We found that there are two different types of MACs, one is based on hash functions called HMAC, another is based on block ciphers called CMAC, which replaced DAA. DAA used to be widely adopted in government and industry, but it was abandoned ruthlessly. Thus we can see that everything keeps changing. Maybe one day HMAC or CMAC will be found insecure and we may create a newer and stronger algorithm to replace HMAC or CMAC. Also, we found something interesting called authentication encryption. It belongs to message authentication, just like message authentication codes, so we did extra research on it. In brief, our team learned a lot according to this project, and expand one's horizon on the vast field of cryptography.

2 Conclusion

In this project, we have made the study of MAC in order to acquire the extra knowledge in cryptography. What's more, our major skills such as writing and collaboration haven been improved as well. We have had a preliminary understanding of Message Authentication Code thanks for this subject. We have understood what MAC is, how MAC works, how secure MAC is, and some applications of MAC. The superiority of MAC is represented throughout whole the project. Cryptography is quite a complex and esoteric subject and there are so many mysteries in the world. But we still have enough enthusiasm to explore the secrets in the world of cryptography. The study of cryptography is still pending.

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