LECTURE NOTES
PROGRAMME – BCA VI SEM

CRYPTOGRAPHY

PAPER CODE:- BCA-6044

UNIT IV

Message Authentication & Hash Functions: Message Authentication & Hash Functions: Authentication requirements, authentication functions, message authentication codes, hash function, md5 message digest algorithm, secure hash algorithm (SHA), and digital signatures..

Message Authentication

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. It is intended against the attacks like content modification, sequence modification, timing modification and repudiation. For repudiation, concept of digital signatures is used to counter it. There are three classes by which different types of functions that may be used to produce an authenticator. They re:

- ***Message encryption***–the ciphertext serves as auth nticator
- ***Message authentication code (MAC)***–a public function of the message and a secret key producing a fixed-length value to erve as authenticator. This does not provide a digital signature because A and B share the same key.
- ***Hash function***–a public function mapping an arbitrary length message into a fixed-length hash value to serve as authenticator. This does not provide a digital signature because there is no key.

MESSAGE ENCRYPTION:

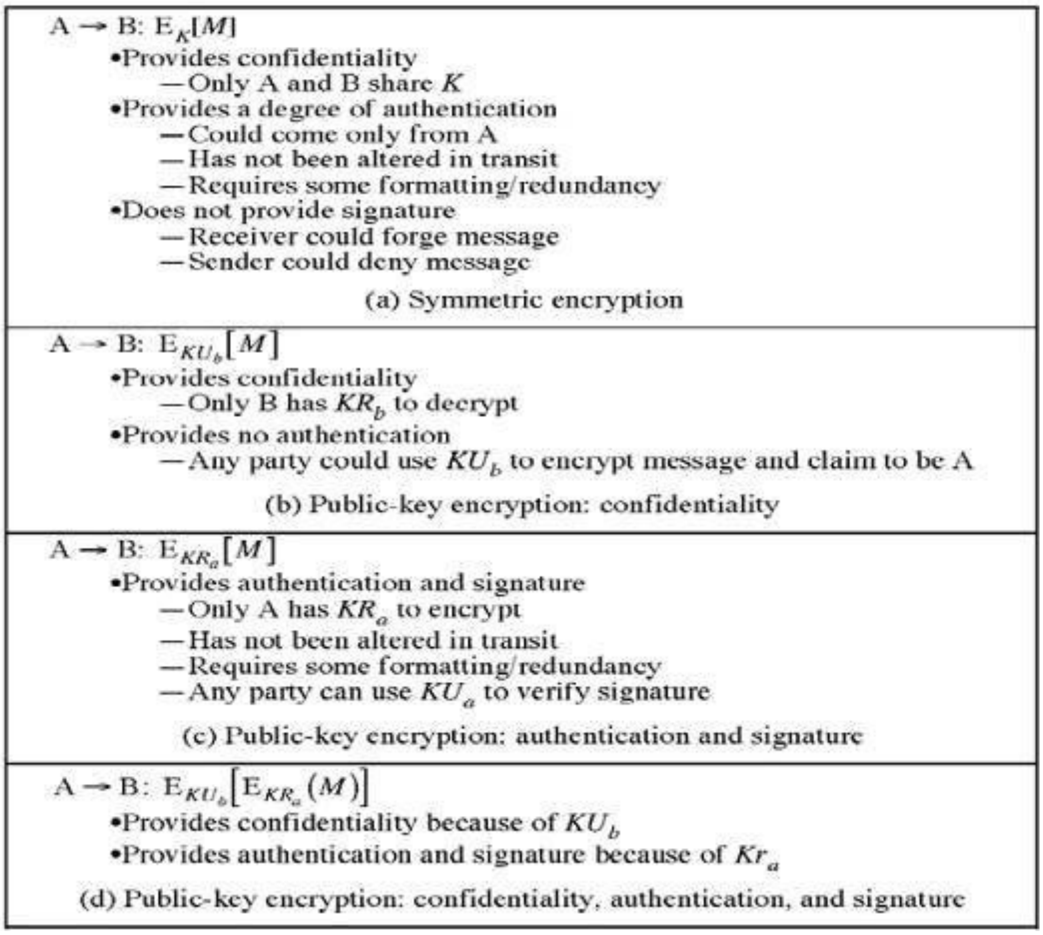
Message encryption by itself can provide a measure of authentication. The analysis differs for conventional and public-key encryption schemes. The message must have come from the sender itself, because the ciphertext can be decrypted using his (secret or public) key. Also, none of the bits in the message have been altered because an opponent does not know how to manipulate the bits of the ciphertext to induce meaningful changes to the plaintext. Often one needs alternative authentication schemes than just encrypting the message.

- Sometimes one needs to avoid encryption of full messages due to legal requirements.

➢ Encryption and authentication may be separated in the system architecture.

The different ways in which message encryption can provide authentication, confidentiality in both symmetric and asymmetric encryption techniques is explained with the table below:

Confidentiality and Authentication Implications of Message Encryption



A → B: $E_K[M]$
- Provides confidentiality
  - —Only A and B share K
- Provides a degree of authentication
  - —Could come only from A
  - —Has not been altered in transit
  - —Requires some formatting/redundancy
- Does not provide signature
  - —Receiver could forge message
  - —Sender could deny message

(a) Symmetric encryption

A → B: $E_{KU_b}[M]$
- Provides confidentiality
  - —Only B has KR_b to decrypt
- Provides no authentication
  - —Any party could use KU_b to encrypt message and claim to be A

(b) Public-key encryption: confidentiality

A → B: $E_{KR_a}[M]$
- Provides authentication and signature
  - —Only A has KR_a to encrypt
  - —Has not been altered in transit
  - —Requires some formatting/redundancy
  - —Any party can use KU_a to verify signature

(c) Public-key encryption: authentication and signature

A → B: $E_{KU_b}[E_{KR_a}(M)]$
- Provides confidentiality because of KU_b
- Provides authentication and signature because of Kr_a

(d) Public-key encryption: confidentiality, authentication, and signature

MESSAGE AUTHENTICATION CODE

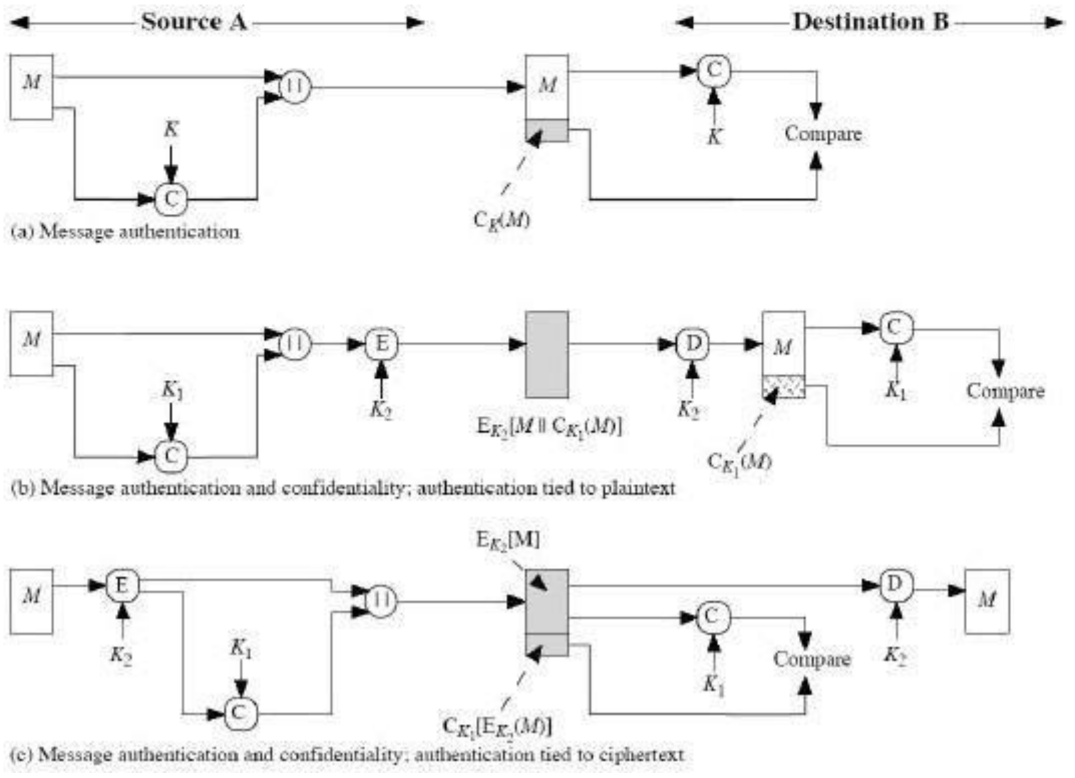
An alternative authentication technique involves the use of a secret key to generate a small fixed-size block of data, known as cryptographic checksum or MAC, which is appended to the message. This technique assumes that both the communicating parties say A and B share a common secret key K. When A has a message to send to B, it calculates MAC as a function C of key and message given as: **MAC=Ck(M)** The message and the MAC are transmitted to the intended recipient, who upon receiving performs the same calculation on the received message, using the same secret key to generate a new MAC. The received MAC is compared to the calculated MAC and only if they match, then:

1. The receiver is assured that the message has not been altered: Any alternations been done the MAC's do not match.

2. The receiver is assured that the message is from the alleged sender: No one except the sender has the secret key and could prepare a message with a proper MAC.

3. If the message includes a sequence number, then receiver is assured of proper sequence as an attacker cannot successfully alter the sequence number.

Basic uses of Message Authentication Code (MAC) are shown in the figure:


Source A
Destination B
M
K
C
||
Compare
$C_K(M)$
(a) Message authentication
K_1
K_2
E
D
$E_{K_2}[M \| C_{K_1}(M)]$
$C_{K_1}(M)$
(b) Message authentication and confidentiality; authentication tied to plaintext
$E_{K_2}[M]$
$C_{K_1}[E_{K_2}(M)]$
(c) Message authentication and confidentiality; authentication tied to ciphertext

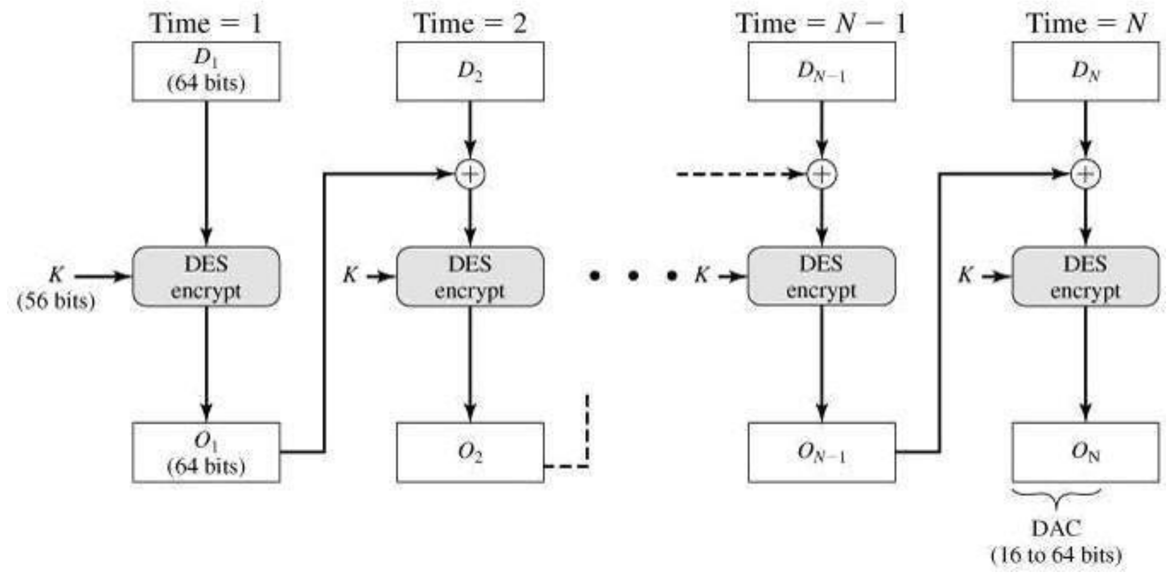
There are three different situations where use of a MAC is desirable:

- If a message is broadcast to several destinations in a network (such as a military control center), then it is cheaper and more reliable to have just one node responsible to evaluate the authenticity –message will be sent in plain with an attached authenticator.
- If one side has a heavy load, it cannot afford to decrypt all messages –it will just check the authenticity of some randomly selected messages.

- Authentication of computer programs in plaintext is very attractive service as they need not be decrypted every time wasting of processor resources. Integrity of the program can always be checked by MAC.

MESSAGE AUTHENTICATION CODE BASED ON DES

The Data Authentication Algorithm, based on DES, has been one of the most widely used MACs for a number of years. The algorithm is both a FIPS publication (FIPS PUB 113) and an ANSI standard (X9.17). But, security weaknesses in this algorithm have been discovered and it is being replaced by newer and stronger algorithms. The algorithm can be defined as using the cipher block chaining (CBC) mode of operation of DES shown below with an initialization vector of zero.



The data (e.g., message, record, file, or program) to be authenticated are grouped into contiguous 64-bit blocks: D1, D2,..., DN. 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:

$O_1 \quad = E(K, D_1)$

$O_2 \quad = E(K, [D_2 \oplus O_1])$

$O_3 \quad = (K, [D_3 \oplus O_2])$

•

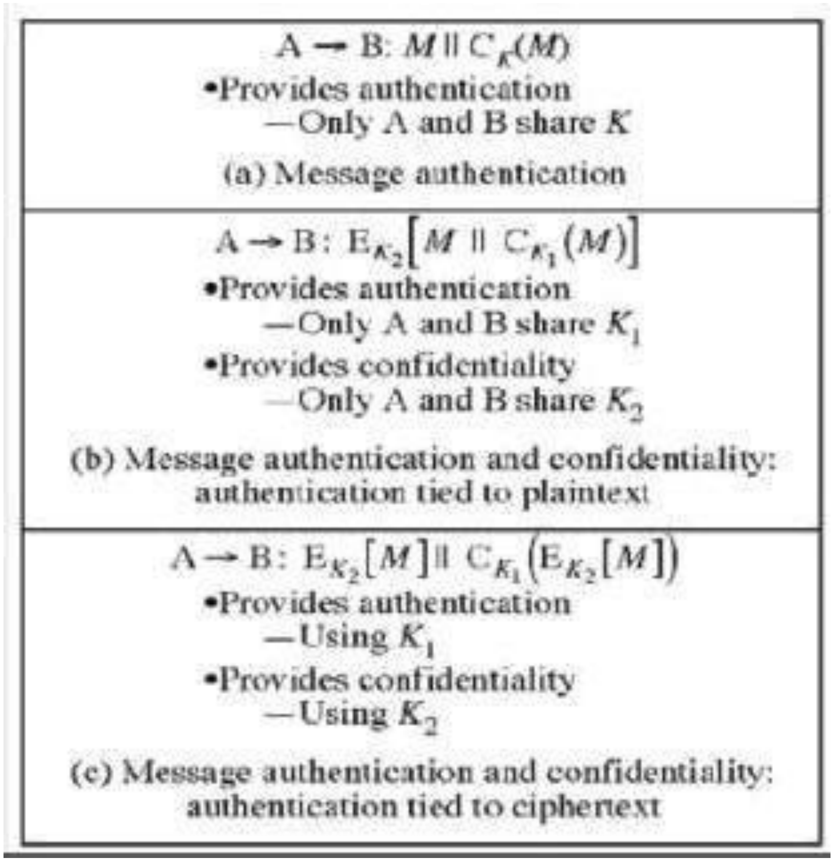
•

•

$O_N \quad = E(K, [D_N \oplus O_{N1}])$

The DAC consists of either the entire block ON or the leftmost M bits of the block, with 16 ≤ M ≤ 64

Use of MAC needs a shared secret key between the communicating parties and also MAC does not provide digital signature. The following table summarizes the confidentiality and authentication implications of the approaches shown above.



$A \rightarrow B: M \| C_K(M)$
- Provides authentication
  - —Only A and B share K

(a) Message authentication

$A \rightarrow B: E_{K_2}\left[M \| C_{K_1}(M)\right]$
- Provides authentication
  - —Only A and B share K_1
- Provides confidentiality
  - —Only A and B share K_2

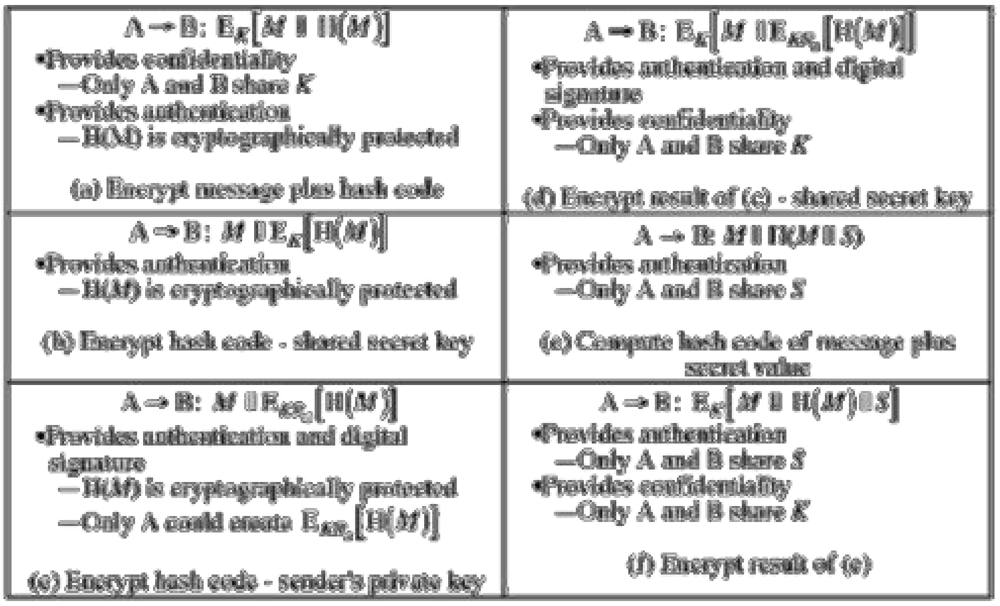
(b) Message authentication and confidentiality: authentication tied to plaintext

$A \rightarrow B: E_{K_2}[M] \| C_{K_1}\left(E_{K_2}[M]\right)$
- Provides authentication
  - —Using K_1
- Provides confidentiality
  - —Using K_2

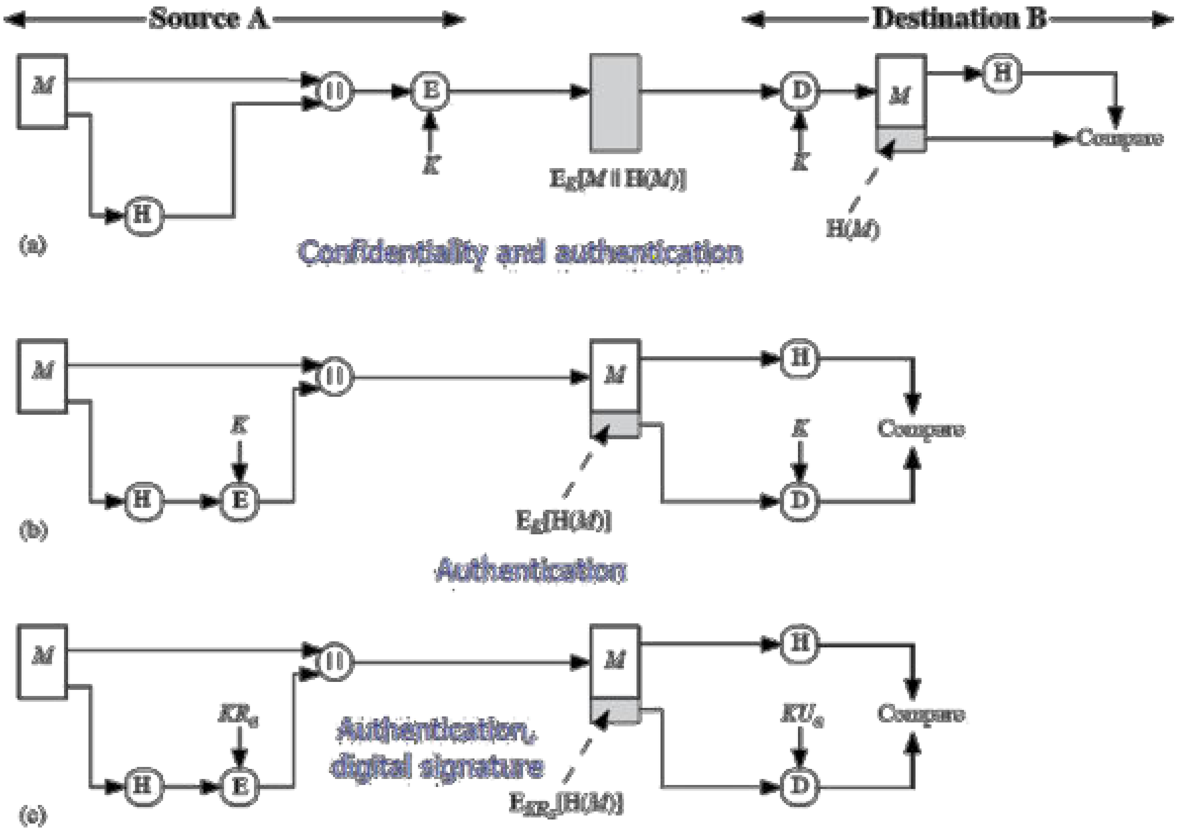
(c) Message authentication and confidentiality: authentication tied to ciphertext

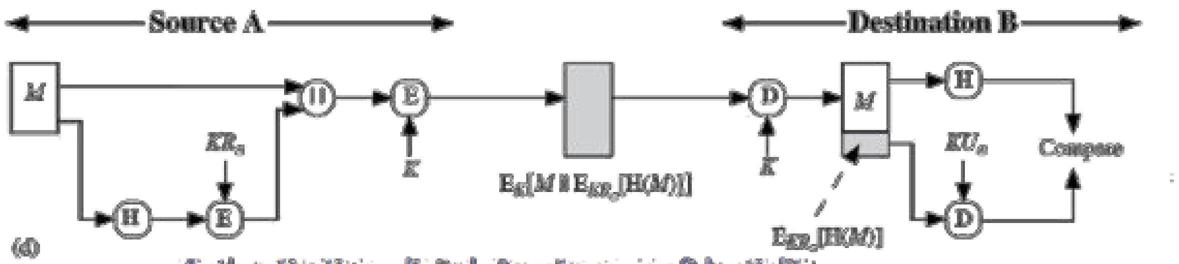
HASH FUNCTION

A variation on the message authentication code is the one-way hash function. As with the message authentication code, the hash function accepts a variable-size message M as input and produces a fixed-size hash code H(M), sometimes called a message digest, as output. The hash code is a function of all bits of the message and provides an error-detection capability: A change to any bit or bits in the message results in a change to the hash code. A variety of ways in which a hash code can be used to provide message authentication is shown below and explained stepwise in the table.

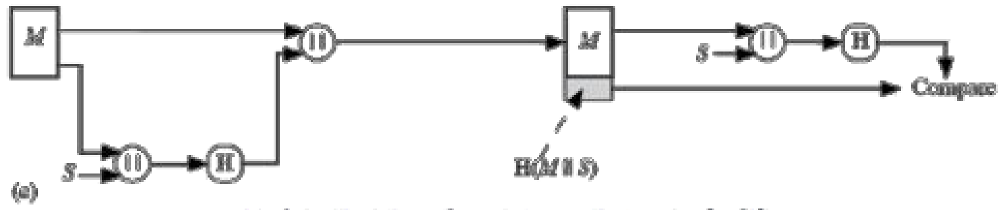


$A \rightarrow B: E_K[M \Vert H(M)]$ •Provides confidentiality —Only A and B share K •Provides authentication —H(M) is cryptographically protected (a) Encrypt message plus hash code	$A \rightarrow B: E_K[M \Vert E_{KR_a}[H(M)]]$ •Provides authentication and digital signature •Provides confidentiality —Only A and B share K (d) Encrypt result of (c) - shared secret key
$A \rightarrow B: M \Vert E_K[H(M)]$ •Provides authentication —H(M) is cryptographically protected (b) Encrypt hash code - shared secret key	$A \rightarrow B: M \Vert H(M \Vert S)$ •Provides authentication —Only A and B share S (e) Compute hash code of message plus secret value
$A \rightarrow B: M \Vert E_{KR_a}[H(M)]$ •Provides authentication and digital signature —H(M) is cryptographically protected —Only A could create $E_{KR_a}[H(M)]$ (c) Encrypt hash code - sender's private key	$A \rightarrow B: E_K[M \Vert H(M) \Vert S]$ •Provides authentication —Only A and B share S •Provides confidentiality —Only A and B share K (f) Encrypt result of (e)

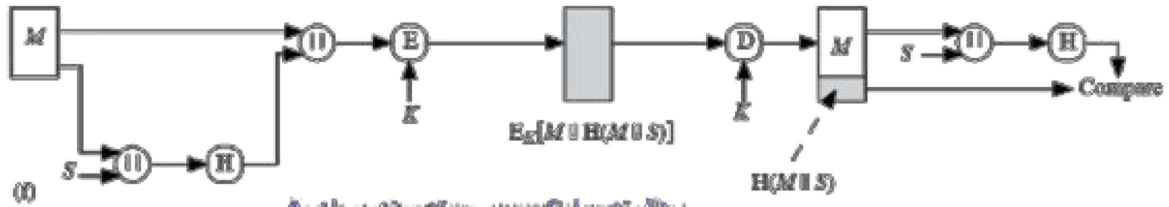




Authentication, digital signature, confidentiality



Authentication (no encryption needed!)



Authentication, confidentiality

In cases where confidentiality is not required, methods b and c have an advantage over those that encrypt the entire message in that less computation is required. Growing interest for techniques that avoid encryption is due to reasons like, Encryption software is quite slow and may be covered by patents. Also encryption hardware costs are not negligible and the algorithms are subject to U.S export control. A fixed-length hash value h is generated by a function H that takes as input a message of arbitrary length**: h=H(M).**

- A sends M and H(M)
- B authenticates the message by computing H(M) and checking the match

Requirements for a hash function: The purpose of a hash function is to produce a “fingerprint” of a file, message, or other block of data. To be used for message authentication, the hash function H must have the following properties

- H can be applied to a message of any size
- H produces fixed-length output
- Computationally easy to compute H(M) for any given M

- Computationally infeasible to find M such that H(M)=h, for a given h, referred to as the *one-way property*
- Computationally infeasible to find M' such that H(M')=H(M), for a given M, referred to as *weak collision resistance*.
- Computationally infeasible to find M,M' with H(M)=H(M') (to resist to birthday attacks), referred to as *strong collision resistance*.

Examples of simple hash functions are:

- Bit-by-bit XOR of plaintext blocks: h= $D1 \oplus D2 \oplus \ldots \oplus DN$
- Rotated XOR –before each addition the hash value is rotated to the left with 1 bit
- Cipher block chaining technique without a secret key.

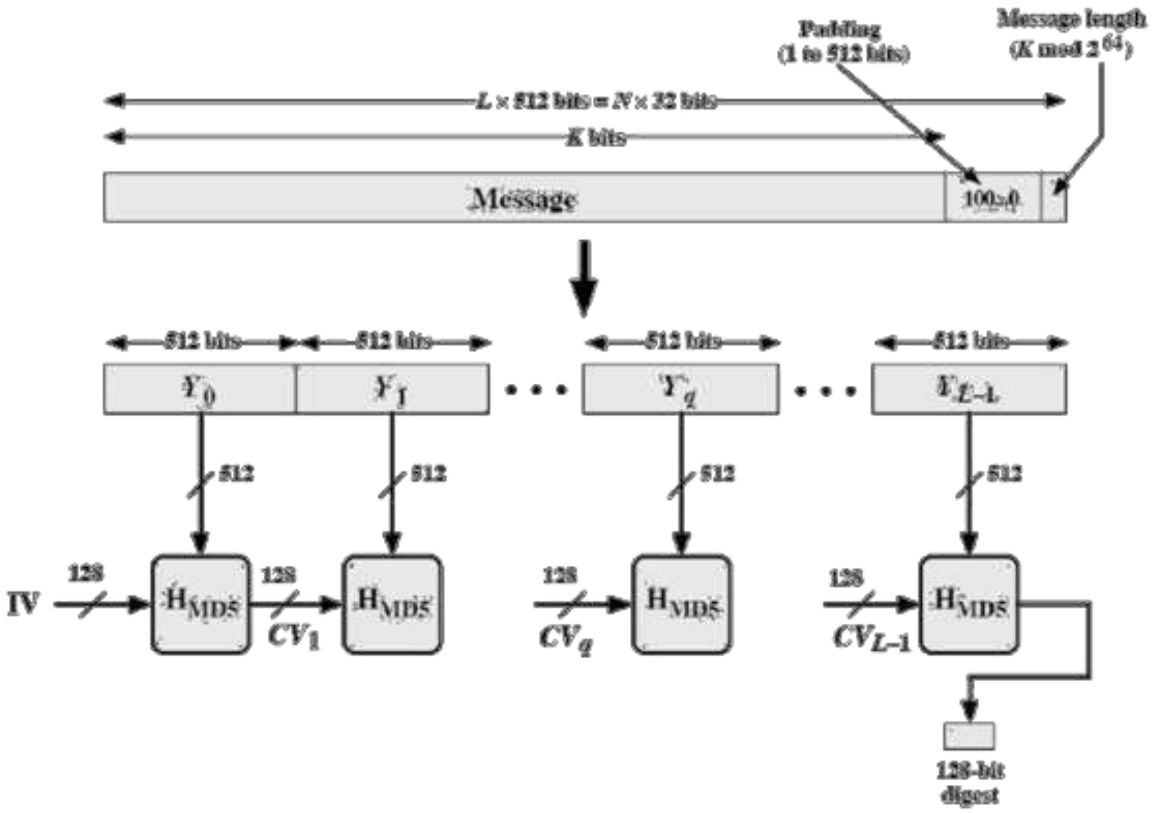
MD5 MESSAGE DIGEST ALGORITHM

The MD5 message-digest algorithm was developed by Ron Rivest at MIT and it remained as the most popular hash algorithm until recently. The algorithm takes as input, a message of arbitrary length and produces as output, 128-bit message digest. The input is processed in 512-bit blocks. The processing consists of the following steps:

1.) *Append Padding bits*: The message is padded so that its length in bits is congruent to 448 modulo 512 i.e. the length of the padded message is 64 bits less than an integer multiple of 512 bits. Padding is always added, even if the message is already of the desired length. Padding consists of a single 1-bit followed by the necessary number of 0-bits.

2.) *Append length*: A 64-bit representation of the length in bits of the original message (before the padding) is appended to the result of step-1. If the length is larger than 264, the 64 least representative bits are taken.

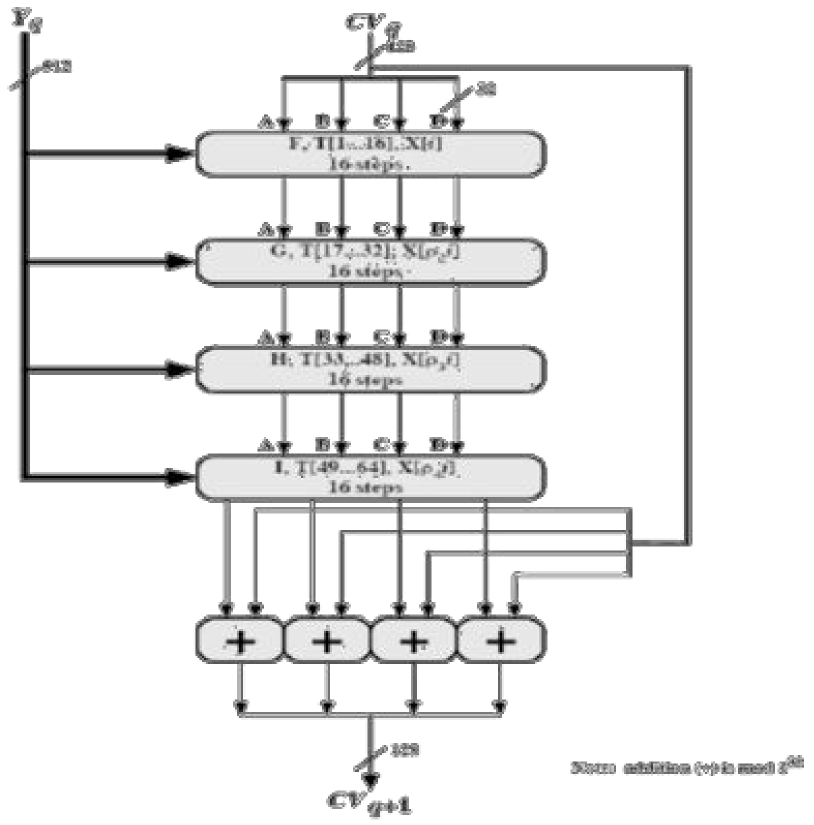
3.) *Initialize MD buffer*: A 128-bit buffer is used to hold intermediate and final results of the hash function. The buffer can be represented as four 32-bit registers (A, B, C, D) and are initialized with A=0x01234567, B=0x89ABCDEF, C=0xFEDCBA98, D=0x76543210 i.e. 32-bit integers (hexadecimal values).



Message Digest Generation Using MD5

4.) *Process Message in 512-bit (16-word) blocks* : The h art of algorithm is the compression function that consists of four rounds of processing and this module is labeled HMD5 in the above figure and logic is illustrated in the following figure. The four rounds have a similar structure, but each uses a different primitive logical function, referred to as F, G, H and I in the specification. Each block takes as input the current 512-bit block being processed Yq and the 128-bit buffer value ABCD and updates the contents of the buffer. Each round also makes use of one-fourth of a 64- element table T*1….64+, constructed

from the sine function. The ith element of T, denoted T[i], has the value equal to the integer part of 232 * abs(sin(i)), where i is in radians. As the value of abs(sin(i)) is a value between 0 and 1, each element of T is an integer that can be represented in 32-bits and would eliminate any regularities in the input data. The output of fourth round is added to the input to the first round (CVq) to produce CVq+1. The addition is done independently for each of the four words in the buffer with each of the corresponding words in CVq, using addition modulo 232. This operation is shown in the figure below:



5.) *Output*: After all L 512-bit blocks have been proc ssed, the output from the Lth stage is the 128- bit message digest. MD5 can be summarized as follows:

$CV0 = IV$ $CV_{q+1} = SUM_{32}(CV_q,RF_IY_qRF_H[Y_q,RF_G[Y_q,RF_F[Y_q,CV_q]]]])$ MD = CV_L Where,

IV = initial value of ABCD buffer, defined in step 3.

Y_q = the q_{th} 512-bit block of the message

L = the number of blocks in the message

CV_q = chaining variable processed with the q_{th} block of the message.

RFx = round function using primitive logical function x.

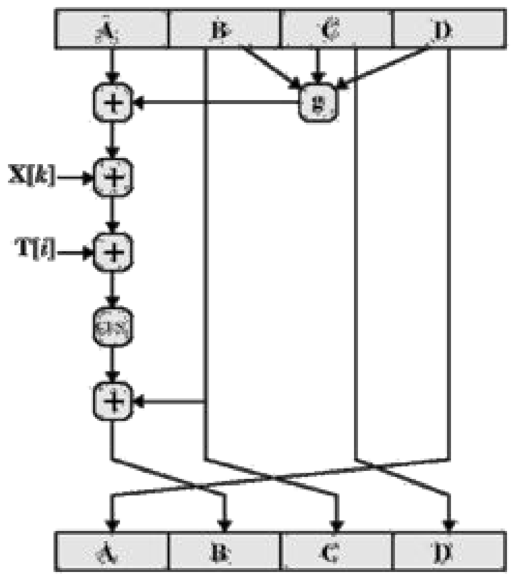
MD = final message digest value

SUM_{32} = Addition modulo 2_{32} performed separately.

MD5 Compression Function:

Each round consists of a sequence of 16 steps operating on the buffer ABCD. Each step is of the form, **a = b+((a+g(b,c,d)+X[k]+T[i])<<<s)**

where a, b, c, d refer to the four words of the buffer but used in varying permutations. After 16 steps, each word is updated 4 times. g(b,c,d) is a different nonlinear function in each round (F,G,H,I). Elementary MD5 operation of a single step is shown below.



The primitive function g of the F,G,H,I is given as:

Round	Primitive function g	g(b, c, d)
1	F(b, c, d)	$(b \wedge c) \vee (b' \wedge d)$
2	G(b, c, d)	$(b \wedge d) \vee (c \wedge d')$
3	H(b, c, d)	$b \oplus c \oplus d$
4	I(b c, d)	$c \oplus (b \vee d')$

Truth table

b	c	d	F	G	H	I
0	0	0	0	0	0	1
0	0	1	1	0	1	0
0	1	0	0	1	1	0
0	1	1	1	0	0	1
1	0	0	0	0	1	1
1	0	1	0	1	0	1
1	1	0	1	1	0	0
1	1	1	1	1	1	0

Where the logical operators (AND, OR, NOT, XOR) are represented by the symbols
(ʌ,v, **~,(+)).**

Each round mixes the buffer input with the next "word" of the message in a complex, non-linear manner. A different non-linear function is used in each of the 4 rounds (but the same function for all 16 steps in a round). The 4 buffer words (a,b,c,d) are rotated from step to step so all are used and updated. g is one of the primitive functions F,G,H,I for the 4 rounds respectively. X[k] is the kth 32-bit word in the current message block. T[i] is the ith entry in the matrix of constants T. The addition of varying constants T and the use of different shifts helps ensure it is extremely difficult to compute collisions. The array of 32-bit words X[0..15] holds the value of current 512-bit input block being processed. Within a round, each of the 16 words of X[i] is used exactly once, during one step. The order in which these words is used varies from round to round. In the first round, the words are used in their original order. For rounds 2 through 4, the following permutations are used

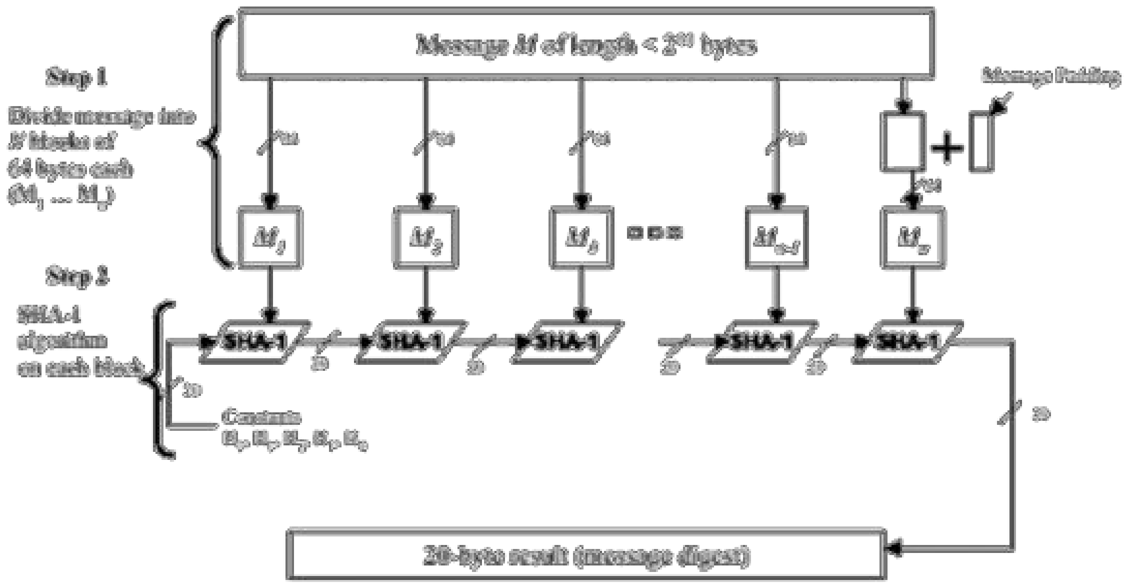
- $p2(i) = (1 + 5i) \bmod 16$
- $p3(i) = (5 + 3i) \bmod 16$
- $p4(I) = 7i \bmod 16$

MD4

- Precursor to MD5
- Design goals of MD4 (which are carried over to MD5)
- Security
- Speed
- Simplicity and compactness
- Favor little-endian architecture
- Main differences between MD5 and MD4
- A fourth round has been added.
- Each step now has a unique additive constant.
- The function g in round 2 was changed from (bc v bd v cd) to (bd v cd’) to make g less symmetric.
- Each step now adds in the result of the previous step. This promotes a faster "avalanche effect".
- The order in which input words are accessed in rounds 2 and 3 is changed, to make these patterns less like each other.
- The shift amounts in each round have been approximately optimized, to yield a faster "avalanche effect." The shifts in different rounds are distinct.

SECURE HASH ALGORITHM

The secure hash algorithm (SHA) was developed by the National Institute of Standards and Technology (NIST). SHA-1 is the best established of the existing SHA hash functions, and is employed in several widely used security applications and protocols. The algorithm takes as input a message with a maximum length of less than 264 bits and produces as output a 160-bit message digest.



Message M of length < 2^64 bytes
Step 1
Divide message into N blocks of 64 bytes each (M1 ... MN)
Message Padding
Step 2
SHA-1 algorithm on each block
SHA-1
Constants
20-byte result (message digest)

The input is processed in 512-bit blocks. The overall processing of a message follows the structure of MD5 with block length of 512 bits and hash length and chaining variable length of 160 bits. The processing consists of following steps:

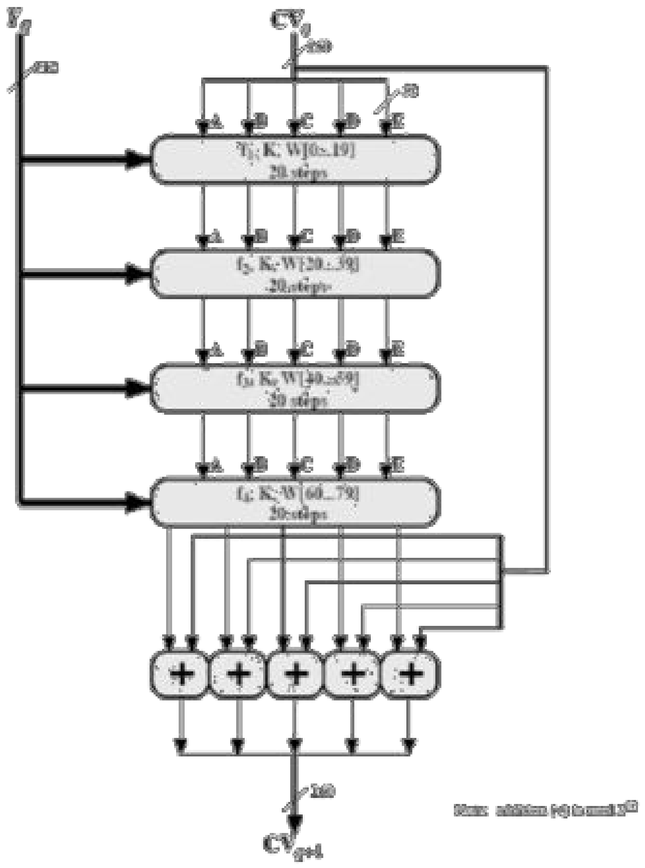
1.) ***Append Padding Bits:*** The message is padded so that length is congruent to 448 modulo 512; padding always added –one bit 1 followed by the necessary number of 0 bits.

2.) ***Append Length:*** a block of 64 bits containing the length of the original message is added.

3.) ***Initialize MD buffer*****:**A160-bitbufferisued to hold intermediate and final results on the hash function. This is formed by 32-bit registers A,B,C,D,E. Initial values: A=0x67452301, B=0xEFCDAB89, C=0x98BADCFE, D=0x10325476, E=C3D2E1F0. Stores in big-endian format i.e. the most significant bit in low address.

4.) ***Process message in bloc 512-bit (16-word) blocks*****:** The processing of a single 512-bit block is shown above. It consists of four rounds of processing of 20 steps each. These four rounds have similar structure, but uses a different primitive logical function, which we refer to as f1, f2, f3 and f4. Each round takes as input the current 512-bit block being processed and the 160-bit buffer value ABCDE and updates the contents of the buffer. Each round also makes use of four distinct additive constants Kt. The output of the fourth round i.e. eightieth step is added to the input to the first round to produce CVq+1.

5.) ***Output:*** After all L 512-bit blocks have been processed, the output from the Lth stage is the 160-bit message digest.

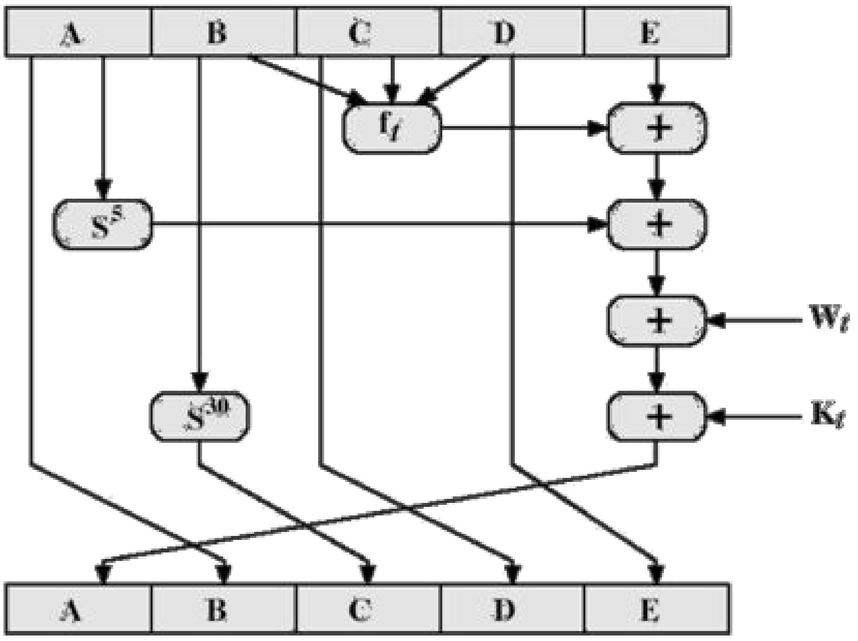


SHA-1 Processing of a Single 512-bit Block
(SHA-1 Compression Function)

The behavior of SHA-1 is as follows: **CV0 = IV CVq+1 = SUM32(CVq, ABCDEq) MD = CVL** Where, IV = initial value of ABCDE buffer ABCDEq = output of last round of processing of qth message block L = number of blocks in the message SUM32 = Addition modulo 232 MD = final message digest value.

SHA-1 Compression Function:

Each round has 20 steps which replaces the 5 buffer words. The logic present in each one of the 80 rounds present is given as **(A,B,C,D,E) <- (E + f(t,B,C,D) + S_5(A)+ Wt+ Kt),A,S_{30}(B),C,D** Where, A, B, C, D, E = the five words of the buffer t = step number; 0< t < 79 f(t,B,C,D) = primitive logical function for step t S_k = circular left shift of the 32-bit argument by k bits Wt **=** a 32-bit word derived from current 512-bit input block. Kt **=** an additive constant; four distinct values are used + = modulo addition.



SHA shares much in common with MD4/5, but with 20 instead of 16 steps in each of the 4 rounds. Note the 4 constants are based on sqrt(2,3,5,10).Note also that instead of just splitting the input block into 32-bit words and using them d recently, SHA-1 shuffles and

mixes them using rotates & XOR's to form more complex input, and greatly increases the difficulty of finding collisions. A sequence of logical functions f_0, f_1,..., f_{79} is used in the SHA-1. Each f_t, 0<=t<=79, operates on three 32-bit words B, C, D and produces a 32-bit word as output. f_t(B,C,D) is defined as follows: for words B, C, D, **f_t(B,C,D) = (B AND C) OR ((NOT B) AND D) (0 <= t <= 19) f_t(B,C,D) = B XOR C XOR D (20 <= t <= 39) f_t(B,C,D) = (B AND C) OR (B AND D) OR (C AND D) (40 <= t <= 59) f_t(B,C,D) = B XOR C XOR D (60 <= t <= 79).**

WHIRLPOOL HA H FUNCTION

• Created by Vincent Rijmen and Paulo S. L. M. Barreto

• Hashes messages of plaintext length 2^256

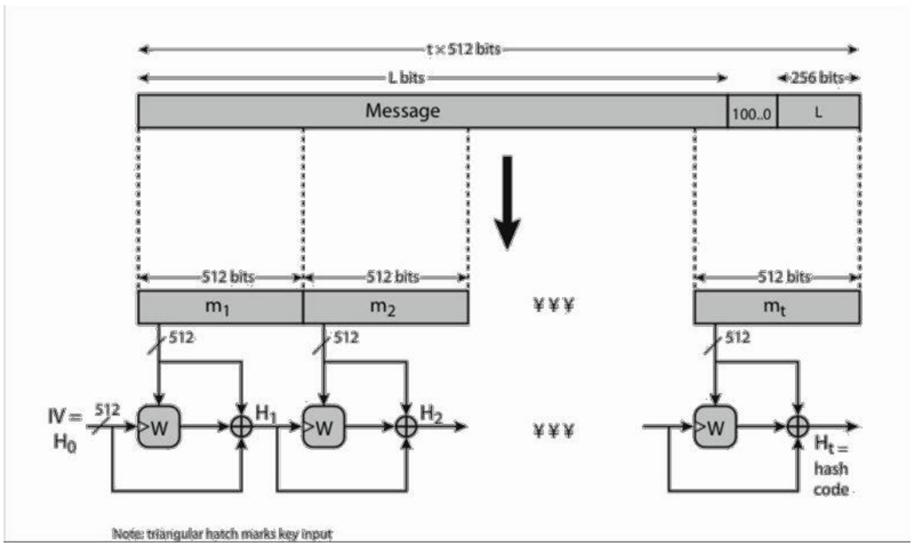
• Result is a 512 bit message

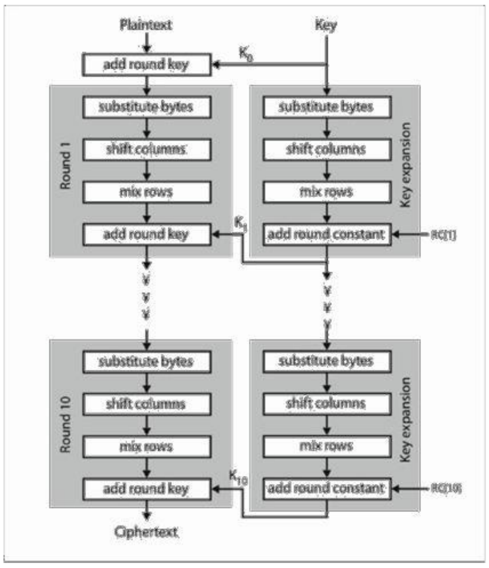
• Three versions have been released – WHIRLPOOL-0 – WHIRLPOOL-T – WHIRLPOOL

- designed specifically for hash function use
- with security and efficiency of AES
- but with 512-bit block size and hence hash
- similar structure & functions as AES but

- input is mapped row wise
- has 10 rounds
- a different primitive polynomial for GF(2^8)
- uses different S-box design & values
- “W” is a 512-bit block cipher
- “m” is the plaintext, split into 512 bit blocks
- “H” is the blocks formed from the hashes

WHIRLPOOL OVERVIEW





- The block cipher W is the core element of the Whirlpool hash function
- It is comprised of 4 steps.
  - – Add Round Key

– Shift Columns

– Mix Rows

– Substitute bytes

Add Round Key

• During the Add Round Key step, the message is XOR'd with the key

• If this is the first message block being run through, the key is a block of all zeros

• If this is any block except the first, the key is the digest of the previous block

Shift Columns

• Starting from left to right, each column gets rotated vertically a number of bytes equal to which number column it is, from top to bottom –

Ex:

• [0,0][0,1][0,2] [0,0][2,1][1,2]

• [1,0][1,1][1,2] ------> [1,0][0,1][2,2]

• [2,0][2,1][2,2] [2,0][1,1][0,2]

Mix Rows

• Each row gets shifted horizontally by the numb r of row it is. Similar to the shift column function, but rotated left to right –

Ex:

• [0,0][0,1][0,2] [0,0][0,1][0,2]

• [1,0][1,1][1,2] ------> [1,2][1,0][1,2]

• [2,0][2,1][2,2] [2,1][2,2][0,2]

Substitute bytes

• Each byte in the message is passed through a set of s-boxes

• The output of this is then set to be the key for the next round

HMAC

Interest in developing a MAC, derived from a cryptographic hash code has been increasing mainly because hash functions are generally faster and are also not limited by export restrictions unlike block ciphers. Additional reason also would be that the library code for cryptographic hash functions is widely available. The original proposal is for incorporation of a secret key into an existing hash algorithm and the approach that received most support is HMAC. HMAC is specified as Internet standard RFC2104. It makes use of the hash function on the given message. Any of MD5, SHA-1, RIPEMD-160 can be used.

HMAC Design Objectives

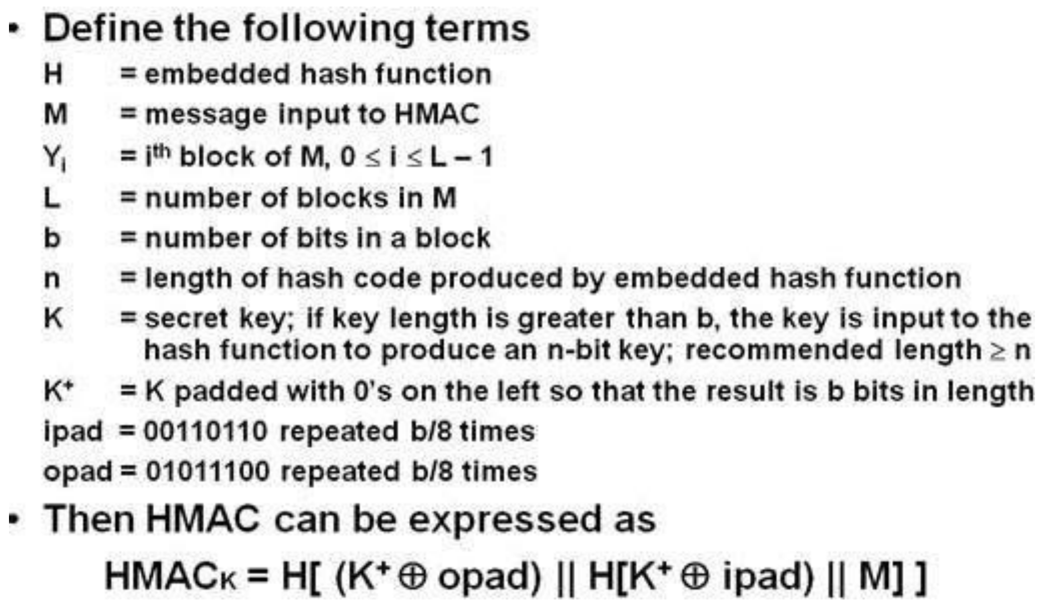
- To use, without modifications, available hash functions
- To allow for easy replaceability of the embedded hash function
- To preserve the original performance of the hash function
- To use and handle keys in a simple way
- To have a well understood cryptographic analysis of the strength of the MAC based on reasonable assumptions on the embedded hash function

The first two objectives are very important for the acceptability of HMAC. HMAC treats the hash function as a “black box”, which has two benefits. First is that an existing implementation of the hash function can be used for implementing HMAC making the bulk of HMAC code readily available without modificat on. Second is that if ever an existing hash function is to be replaced, the existing hash funct on module is removed and new module is dropped in. The last design obj ctive provides the main advantage of HMAC over other proposed hash-based schemes. HMAC can be proven secure provided that the embedded hash function has ome reasonable cryptographic strengths.

Steps involved in HMAC algorithm:

1. Append zeroes to the left end of K to create a b-bit string K_+ (ex: If K is of length 160-bits and b = 512, then K will be appended with 44 zero bytes).
2. XOR(bitwise exclusive-OR) K_+ with ipad to produce the b-bit block S_i.
3. Append M to S_i.
4. Now apply H to the stream generated in step-3
5. XOR K_+ with opad to produce the b-bit block S_0.
6. Append the hash result from step-4 to S_0.
7. Apply H to the stream generated in step-6 and output the result.

HMAC Algorithm



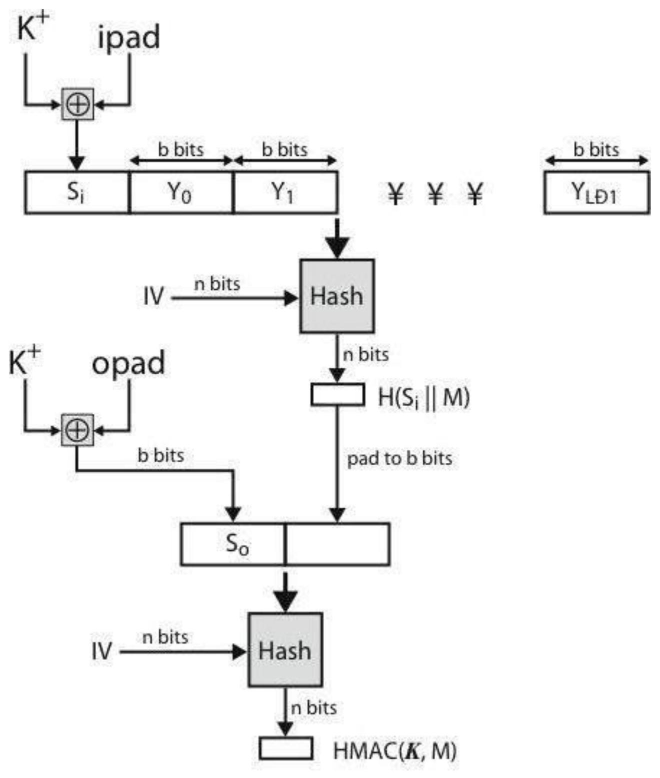
- Define the following terms

H	= embedded hash function
M	= message input to HMAC
Y_i	= ith block of M, $0 \le i \le L - 1$
L	= number of blocks in M
b	= number of bits in a block
n	= length of hash code produced by embedded hash function
K	= secret key; if key length is greater than b, the key is input to the hash function to produce an n-bit key; recommended length $\ge$ n
K^+	= K padded with 0's on the left so that the result is b bits in length
ipad	= 00110110 repeated b/8 times
opad	= 01011100 repeated b/8 times

- Then HMAC can be expressed as

$$HMAC_K = H[\,(K^+ \oplus opad) \,||\, H[K^+ \oplus ipad) \,||\, M]\,]$$

HMAC Structure



The XOR with ipad results in flipping one-half of the bits of K. Similarly, XOR with opad results in flipping one-half of the bits of K, but different set of bits. By passing S_i and S_0 through the compression function of the hash algorithm, we have pseudorandomly generated two keys from K.

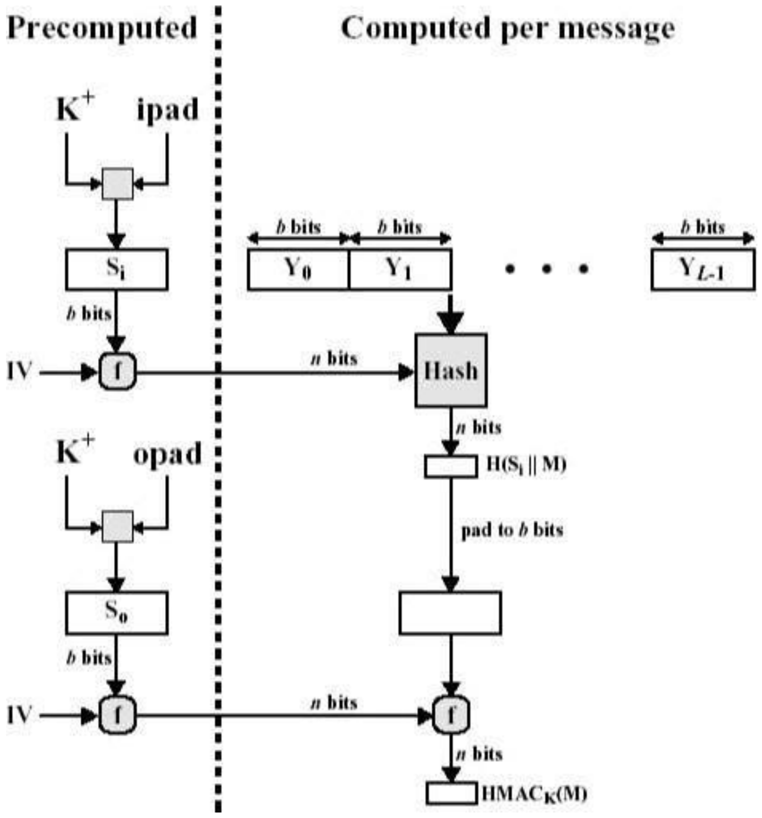
HMAC should execute in approximately the same time as the embedded hash function for long messages. HMAC adds three executions of the hash compression function (for S_0, S_i, and the block produced from the inner hash)

A more efficient implementation is possible. Two quantities are precomputed.

$f(IV, (K^+ \oplus ipad)$

$f(IV, (K^+ \oplus opad)$

where f is the compression function for the hash function which takes as arguments a chaining variable of n bits and a block of b-bits and produces a chaining variable of n bits.



As shown in the above figure, the values are needed to be computed initially and every time a key changes. The precomputed quantities substitute for the initial value (IV) in the hash function. With this implementation, only one additional instance of the compression function is added to the processing normally produced by the hash function. This implementation is worthwhile if most of the messages for which a MAC is computed are short.

Security of HMAC:

The appeal of HMAC is that its designers have been able to prove an exact relationship between the strength of the embedded hash function and the strength of HMAC. The security of a MAC function is generally expressed in terms of the probability of successful forgery with a given amount of time spent by the forger and a given number of message-MAC pairs created with the same key. Have two classes of attacks on the embedded hash function:

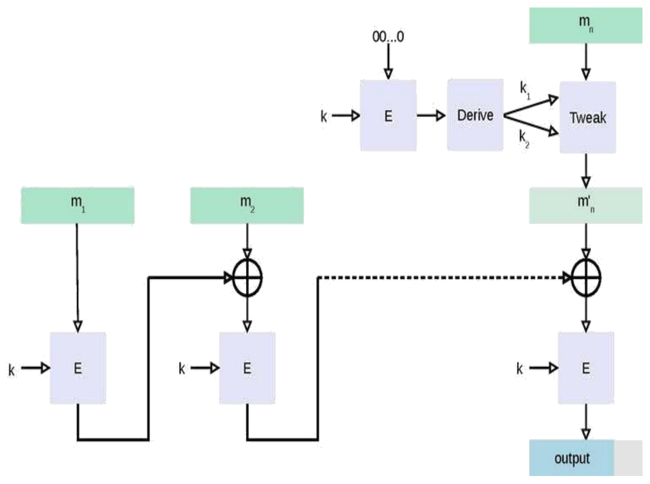
1. The attacker is able to compute an output of the compression function even with an IV that is random, secret and unknown to the attacker.

2. The attacker finds collisions in the hash function even when the IV is random and secret. These attacks are likely to be caused by brute force attack on key used which has work of order 2^n; or a birthday attack which requires work of order $2^{(n/2)}$ - but which requires the attacker to observe 2^n blocks of messages using the same key - very unlikely. So even MD5 is still secure for use in HMAC given these constraints.

CMAC

In cryptography, **CMAC** (Cipher-based Message Authentication Code)[1] is a block cipher-based message authentication code algorithm. It may be used to provide assurance of the authenticity and, hence, the integrity of binary data. This mode of operation fixes security deficiencies of CBC-MAC (CBC-MAC is secure only for fixed-length messages).

The core of the CMAC algorithm is variation of CBC-MAC that Black and Rogaway proposed and analyzed under the name XCBC[2] and submitted to NIST.[3] The XCBC algorithm efficiently addresses the security deficiencies of CBC-MAC, but requires three keys. Iwata and Kurosawa proposed an improvement of XCBC and named the resulting algorithm One-Key CBC-MAC (OMAC) in their papers.[4][5] They later submitted OMAC1[6], a refinement of OMAC, and additional security analysis.[7] The OMAC algorithm reduces the amount of key material required for XCBC. CMAC is equivalent to OMAC1.



To generate an ℓ-bit CMAC tag (t) of a message (m) using a b-bit block cipher (E) and a secret key (k), one first generates two b-bit sub-keys (k_1 and k_2) using the following algorithm (this is equivalent to multiplication by x and x_2 in a finite field GF(2_b)). Let $\ll$ denote the standard left-shift operator and $\oplus$denote exclusive or:

1. Calculate a temporary value $k_0 = E_k(0)$.
2. If msb(k_0) = 0, then $k_1 = k_0 \ll 1$, else $k_1 = (k_0 \ll 1) \oplus C$; where C is a certain constant that depends only on b. (Specifically, C is the non-leading coefficients of the lexicographically first irreducible degree-b binary polynomial with the minimal number of ones.)
3. If msb(k_1) = 0, then $k_2 = k_1 \ll 1$, else $k_2 = (k_1 \ll 1) \oplus C$.
4. Return keys (k_1, k_2) for the MAC generation process.

As a small example, suppose $b = 4$, $C = 0011_2$, and $k_0 = E_k(0) = 0101_2$. Then $k_1 = 1010_2$ and $k_2 = 0100 \oplus 0011 = 0111_2$.

The CMAC tag generation process is as follows:

1. Divide message into b-bit blocks $m = m_1 \parallel ... \parallel m_{n-1} \parallel m_n$ where $m_1, ..., m_{n-1}$ are complete blocks. (The empty me age is treated as 1 incomplete block.)
2. If m_n is a complete block then $m_n' = k_1 \oplus m_n$ else $m_n' = k_2 \oplus (m_n \parallel 10...0_2)$.
3. Let $c_0 = 00\ldots0_2$.
4. For $i = 1, ..., n\text{-}1$, calculate $c_i = E_k(c_{i-1} \oplus m_i)$.
5. $c_n = E_k(c_{n-1} \oplus m_n')$
6. Output $t = \text{msb}_\ell(c_n)$.

The verification process is as follows:

1. Use the above algorithm to generate the tag.
2. Check that the generated tag is equal to the received tag.

DIGITAL SIGNATURE

The most important development from the work on public-key cryptography is the digital signature. Message authentication protects two parties who exchange messages from any third party. However, it does not protect the two parties against each other. A digital signature is analogous to the handwritten signature, and provides a set of security capabilities that would be difficult to implement in any other way. It must have the following properties:

• It must verify the author and the date and time of the signature

• It must to authenticate the contents at the time of the signature • It must be verifiable by third parties, to resolve disputes Thus, the digital signature function includes the authentication function. A variety of approaches has been proposed for the digital signature function. These approaches fall into two categories: direct and arbitrated.

Direct Digital Signature

Direct Digital Signatures involve the direct application of public-key algorithms involving only the communicating parties. A digital signature may be formed by encrypting the entire message with the sender's private key, or by encrypting a hash code of the message with the sender's private key. Confidentiality can be provided by further encrypting the entire message plus signature using either public or private key schemes. It is important to perform the signature function first and then an outer confidentiality function, since in case of dispute, some third party must view the message nd its signature. But these approaches are dependent on the security of the sender's private-key. Will have problems if it is lost/stolen and signatures forged. Need time-stamps and timely key revocation.

Arbitrated Digital Signature

The problems associated with direct digital signatures can be addressed by using an arbiter, in a variety of possible arrangements. The arbiter plays a sensitive and crucial role in this sort of scheme, and all parties must have a great deal of trust that the arbitration mechanism is working properly. These schemes can be implemented with either private or public- ey algorithms, and the arbiter may or may not see the actual message contents. **Using Conventional encryption**

X⍰A : M || E (Kxa ,[IDx || H (M)])

A⍰Y : E(Kay ,[IDx || M || E (Kxa ,[IDx ||H(M))]) || T])

- It is assumed that the sender X and the arbiter A share a secret key Kxa and that A and Y share secret key Kay. X constructs a message M and computes its hash value H(m) . Then X transmits the message plus a signature to A. the signature consists of an identifier IDx of X plus the hash value, all encrypted using Kxa.
- A decrypts the signature and checks the hash value to validate the message. Then A transmits a message to Y, encrypted with Kay. The message includes IDx, the original message from X, the signature, and a timestamp.

- Arbiter sees message
- Problem : the arbiter could form an alliance with sender to deny a signed message, or with the receiver to forge the sender’s signature.

Using Public Key Encryption

X ⍰A : IDx ||E(PRx,[IDx|| E (PUy, E(PRx, M))])

A ⍰Y : E(PRa, [IDx ||E (PUy, E (PRx, M))|| T])

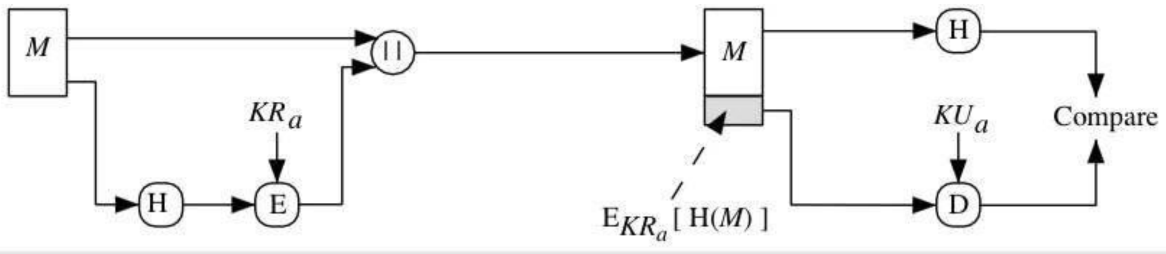
⍰⍰X double encrypts a message M first with X’s private key, PRx, and then with Y’s public key, PUy. This is a signed, secret version of the message. This signed message, together with X’s identifier , is encrypted again with PRx and, together with IDx, is sent to A. The inner, double encrypted message is secure from the arbiter (and everyone else except Y)

- A can decrypt the outer encryption to assure that the message must have come from X (because only X has PRx). Then A transmits a message to Y, encrypted with PRa. The message includes IDx, the double encrypted message, and timestamp.
- Arbiter does not see message

Digital Signature Standard (DSS)

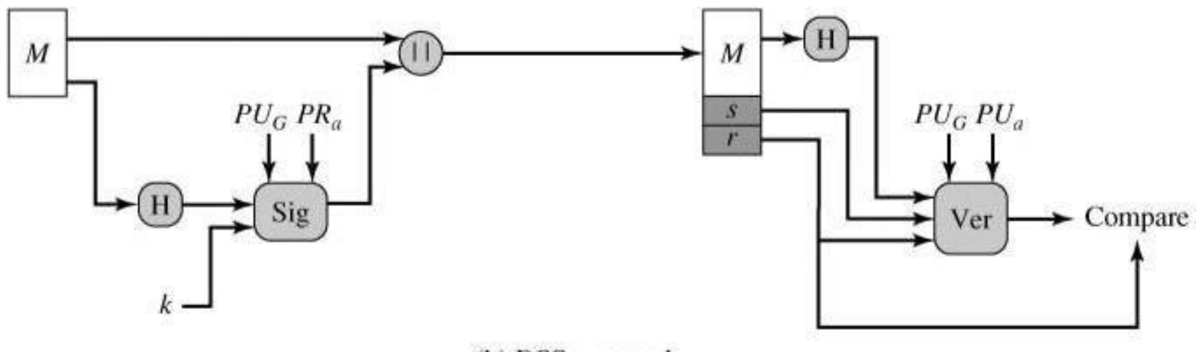
The National Institute of Standards and Technology (NIST) has published Federal Information Processing Standard FIPS 186, known as the Digital Signature Standard (DSS). The DSS makes use of the Secure Ha h Algorithm (SHA) and presents a new digital signature technique, the Digital Signature Algorithm (DSA). The DSS uses an algorithm that is designed to provide only the digital signature function and cannot be used for encryption or key exchange, unlike RSA.

The RSA approach is shown below. The message to be signed is input to a hash function that produces a secure hash code of fixed length. This hash code is then encrypted using the sender's private key to form the signature. Both the message and the signature are then transmitted.



The recipient takes the message and produces a hash code. The recipient also decrypts the signature using the sender's public key. If the calculated hash code matches the decrypted signature, the signature is accepted as valid. Because only the sender knows the private key, only the sender could have produced a valid signature.

The DSS approach also makes use of a hash function. The hash code is provided as input to a signature function along with a random number k generated for this particular signature. The signature function also depends on the sender's private key (PRa) and a set of parameters known to a group of communicating principals. We can consider this set to constitute a global public key (PUG).The result is a signature consisting of two components, labeled s and r.



(b) DSS approach

At the receiving end, the hash code of the incoming message is generated. This plus the signature is input to a verification function. The verification function also depends on the global public key as well as the sender's public key (PUa), which is paired with the sender's private key. The outp t of the verification function is a value that is equal to the signature component r if the signature is valid. The signature function is such that only the sender, with knowledge of the private key, could have produced the valid signature.

KNAPSACK ALGORITHM

Public-Key cryptography was invented in the 1970s by Whitfield Diffie, Martin Hellman and Ralph Merkle.

Public-key cryptography needs two keys. One key tells you how to encrypt (or code) a message and this is "public" so anyone can use it. The other key allows you to decode (or decrypt) the message. This decryption code is kept secret (or private) so only the person who knows the key can decrypt the message. It is also possible for the person with the private key to encrypt a message with the private key, then anyone holding the public key can decrypt the message, although this seems to be of little use if you are trying to keep something secret!

The First General Public-Key Algorithm used what we call the Knapsack Algorithm. Although we now know that this algorithm is not secure we can use it to look at how these types of encryption mechanisms work.

The knapsack algorithm works like this:
Imagine you have a set of different weights which you can use to make any total weight that you need by adding combinations of any of these weights together. Let us look at an example:
Imagine you had a set of weights 1, 6, 8, 15 and 24. To pack a knapsack weighing 30, you could use weights 1, 6, 8 and 15. It would not be possible to p ck a knapsack that weighs 17 but this might not matter.
You might represent the weight 30 by the binary code 11110 (one 1, one 6, one 8, one
15 and no 24).
Example:

Plain text	10011	11010	01011	00000
Knapsack	1 6 8 15 24	1 6 8 15 24	1 68 15 24	1 68 15 24
Cipher text	1 + 15 + 24 = 40	1 + 6 + 15 = 22	6 +15 + 24 = 45	0 =0

What total weights is it possible to make?

So, if someone sends you the code 38 this can only have come from the plain text 01101. When the Knapsack Algorithm is used in public key cryptography, the idea is to create two different knapsack problems. One is easy to solve, the other not. Using the easy knapsack, the hard knapsack is derived from it. The hard knapsack becomes the public key. The easy knapsack is the private key. The public key can be used to encrypt messages, but cannot be used to decrypt messages. The private key decrypts the messages.

The Superincreasing Knapsack Problem

An easy knapsack problem is one in which the weights are in a superincreasing sequence. A superincreasing sequence is one in which the next term of the sequence is greater than the sum of all preceding terms. For example, the set {1, 2, 4, 9, 20, 38} is superincreasing, but the set {1, 2, 3, 9, 10, 24} is not because 10 < 1+2+3+9.

It is easy to solve a superincreasing knapsack. Simply take the total weight of the knapsack and compare it with the largest weight in the sequence. If the total weight is less than the number, then it is not in the knapsack. If the total weight is greater then the number, it is in the knapsack. Subtract the number from the total, and compare with the next highest number. Keep working this way until the total reaches zero. If the total doesn't reach zero, then there is no solution.

So, for example, if you have a knapsack that weighs 23 that has been made from the weights of the superincreasing series {1, 2, 4, 9, 20, 38} then it does not contain the weight 38 (as 38 > 23)
but it does contain the weight 20; leaving 3; which does not contain the weight 9 still leaving 3; which does not contain the weight 4 still leaving 3;
which contains the weight 2, leaving 1; which contains the weight 1.
The binary code is therefore 110010.

It is much harder to decrypt a non-superincreasing knapsack problem. Give a friend a non-super increasing knapsack and a total and see why this is the case.
One algorithm that uses a superincreasing knapsack for the private (easy) key and a non-superincreasing knapsack for the public key was created by Merkle and Hellman They did this by taking a superincreasing knapsack problem and converting it into a non-superincreasing one that could be made public, using modulus arithmetic.

<u>Making the Public Key</u>

To produce a normal knapsack sequence, take a superincreasing sequence; e.g. {1, 2, 4, 10, 20, 40}. Multiply all the values by a number, n, modulo m. The modulus should be a number greater than the sum of all the numbers in the sequence, for example, 110. The multiplier should have no factors in common with the modulus. So let's choose 31. The normal knapsack sequence would be:

1×31 mod(110) = 31

2×31 mod(110) = 62

4×31 mod(110) = 14

10×31 mod(110) = 90

20×31 mod(110) = 70

40×31 mod(110) = 30

So the public key is: {31, 62, 14, 90, 70, 30} and
the private key is {1, 2, 4, 10, 20.40}.

Let's try to send a message that is in binary code:
100100111100101110
The knapsack contains six weights so we need to split the mess ge into groups of six:
100100
111100
101110
This corresponds to three sets of weights with totals as follows
100100 = 31 + 90 = 121
111100 = 31+62+14+90 = 197
101110 = 31+14+90+70 =205
So the coded message is 121 197 205.

Now the receiver has to decode the message...
The person decoding must know the two numbers 110 and 31 (the modulus and the multiplier). Let's call the modulus "m" and the number you multiply by "n".
We need *n*−1, which is a multiplicative inverse of n mod m, i.e. *n*(*n*−1) = 1 mod m
In this case I have calculated *n*−1 to be 71.

All you then have to do is multiply each of the codes 71 mod 110 to find the total in the knapsack which contains {1, 2, 4, 10, 20, 40} and hence to decode the message. The coded message is 121 197 205:

121×71 mod(110) = 11 = 100100
197×71 mod(110) = 17 = 111100
205×71 mod(110) = 35 = 101110

The decoded message is:
100100111100101110.
Just as I thought!

Simple and short knapsack codes are far too easy to break to be of any real use. For a knapsack code to be reasonably secure it would need well over 200 terms each of length 200 bits.

AUTHENTICATION APPLICATIONS

KERBEROS

Kerberos is an authentication service developed as part of Project Athena at MIT. It addresses the threats posed in an o en distributed environment in which users at workstations wish to access services on servers distributed throughout the network. Some of these threats are:

- A user may gain access to a particular workstation and pretend to be another user operating from that workstation.
- A user may alter the network address of a workstation so that the requests sent from the altered workstation appear to come from the impersonated workstation.
- A user may eavesdrop on exchanges and use a replay attack to gain entrance to a server or to disrupt operations.

Two versions of Kerberos are in current use: Version-4 and Version-5. The first published report on Kerberos listed the following requirements:

Secure: A network eavesdropper should not be able to obtain the necessary information to impersonate a user. More generally, Kerberos should be strong enough that a potential opponent does not find it to be the weak link.

Reliable: For all services that rely on Kerberos for access control, lack of availability of the Kerberos service means lack of availability of the supported services. Hence, Kerberos should be highly reliable and should employ a distributed server architecture, with one system able to back up another.

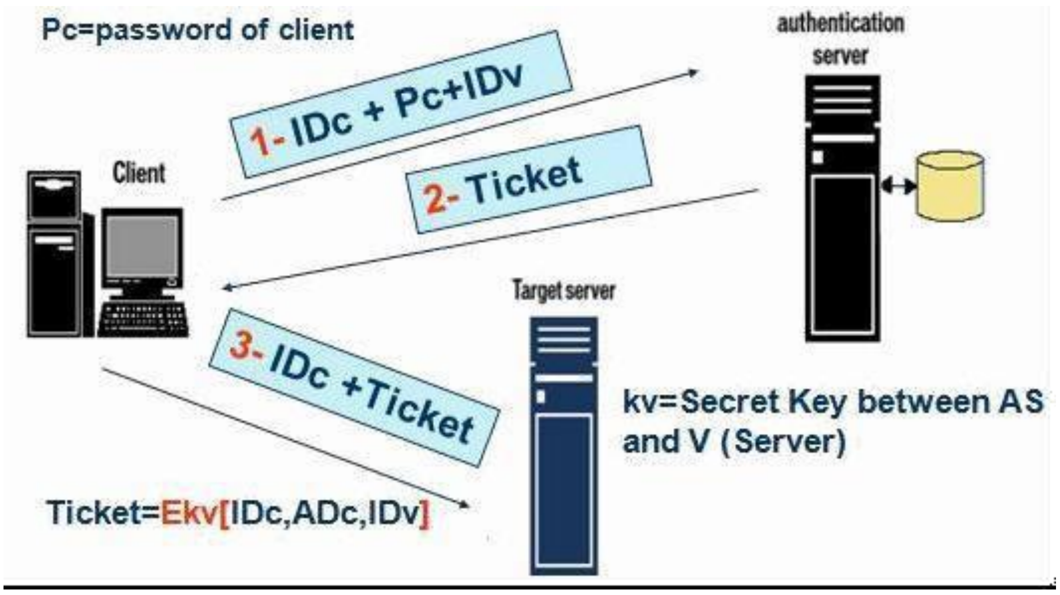
Transparent: Ideally, the user should not be aware that authentication is taking place, beyond the requirement to enter a password.

Scalable: The system should be capable of supporting large numbers of clients and servers. This suggests a modular, distributed architecture

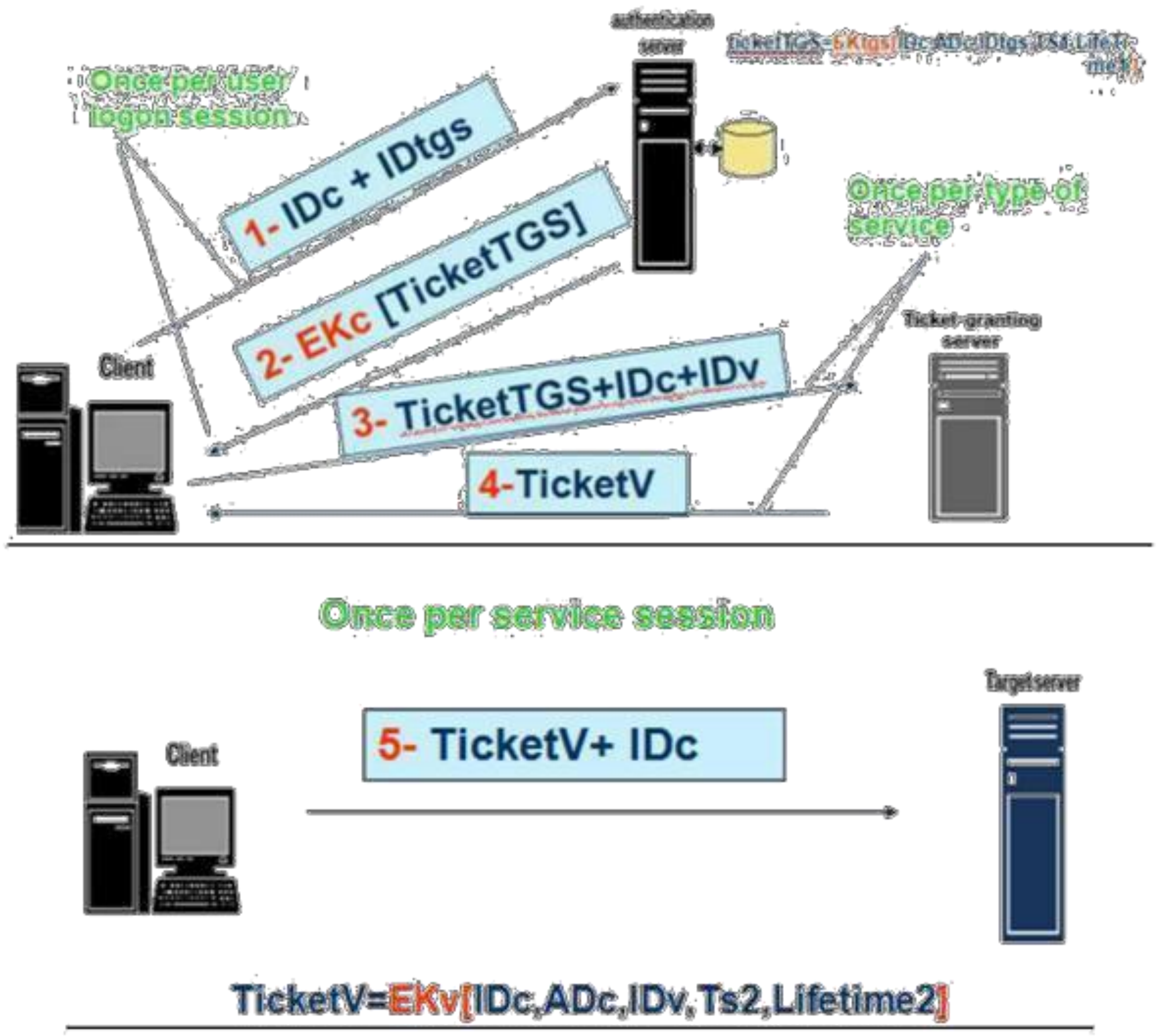
Two versions of Kerberos are in common use: Version 4 is most widely used version. Version 5 corrects some of the security deficiencies of Vers on 4. Version 5 has been issued as a draft Internet Standard (RFC 1510)

KERBEROS VERSION 4

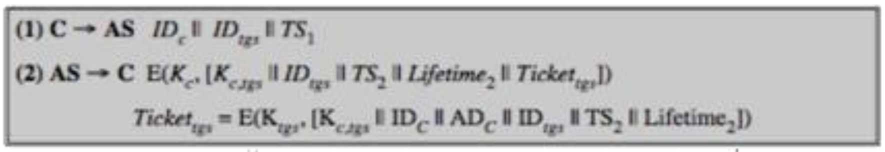
1.) **SIMPLE DIALOGUE**:



MORE SECURE DIALOGUE



The Version 4 Authentication Dialogue The full Kerberos v4 authentication dialogue is shown here divided into 3 phases.

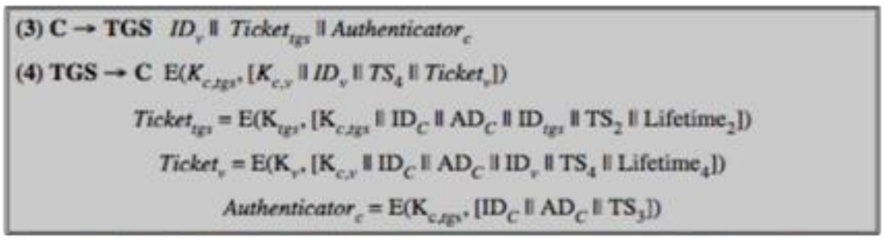


(1) **C → AS** $ID_c \| ID_{tgs} \| TS_1$

(2) **AS → C** $E(K_c, [K_{c,tgs} \| ID_{tgs} \| TS_2 \| Lifetime_2 \| Ticket_{tgs}])$

$Ticket_{tgs} = E(K_{tgs}, [K_{c,tgs} \| ID_C \| AD_C \| ID_{tgs} \| TS_2 \| Lifetime_2])$

(a) Authentication Service Exchange to obtain ticket-granting ticket



(3) **C → TGS** $ID_v \| Ticket_{tgs} \| Authenticator_c$

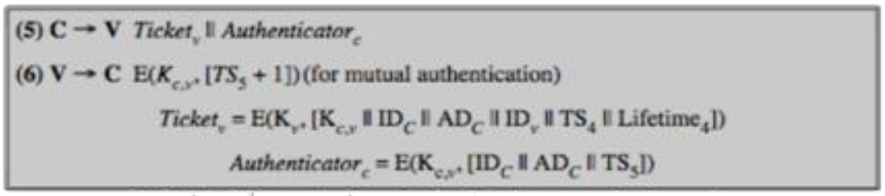
(4) **TGS → C** $E(K_{c,tgs}, [K_{c,v} \| ID_v \| TS_4 \| Ticket_v])$

$Ticket_{tgs} = E(K_{tgs}, [K_{c,tgs} \| ID_C \| AD_C \| ID_{tgs} \| TS_2 \| Lifetime_2])$

$Ticket_v = E(K_v, [K_{c,v} \| ID_C \| AD_C \| ID_v \| TS_4 \| Lifetime_4])$

$Authenticator_c = E(K_{c,tgs}, [ID_C \| AD_C \| TS_3])$

(b) Ticket-Granting Service Exchange to obtain service-granting ticket



(5) **C → V** $Ticket_v \| Authenticator_c$

(6) **V → C** $E(K_{c,v}, [TS_5 + 1])$ (for mutual authentication)

$Ticket_v = E(K_v, [K_{c,v} \| ID_C \| AD_C \| ID_v \| TS_4 \| Lifetime_4])$

$Authenticator_c = E(K_{c,v}, [ID_C \| AD_C \| TS_5])$

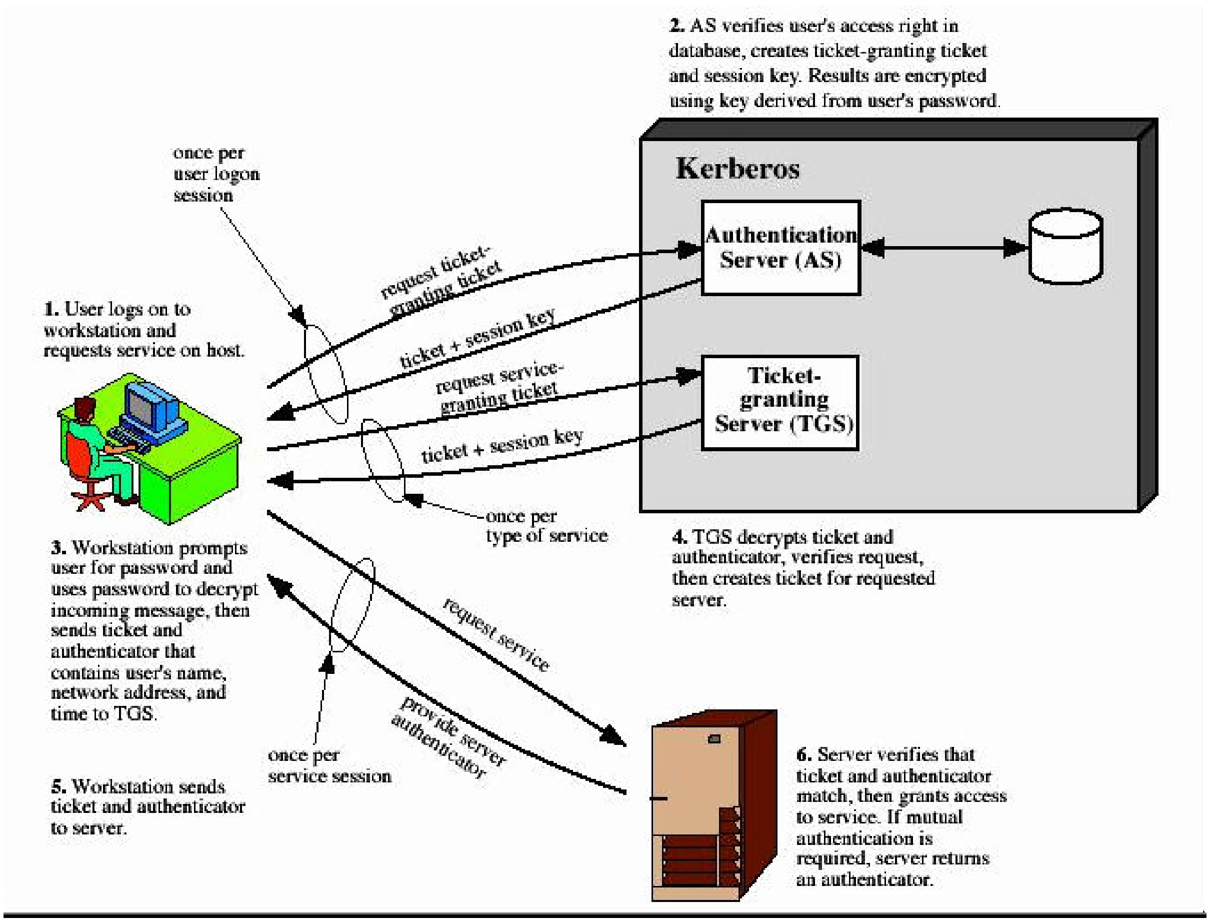
(c) Client/Server Authentication Exchange to obtain service

There is a problem of captured ticket-granting tickets nd the need to determine that the ticket presenter is the same as the client for whom the ticket was issued. An efficient way of doing this is to use a session encryption key to secure information.

Message (1) includes a time stamp, so that the AS knows that the message is timely. Message (2) includes several elements of the ticket in a form accessible to C. This enables C to confirm that this ticket is for the TGS and to learn its expiration time. Note that the ticket does not prove anyone's identity but is a way to distribute keys securely. It is the authenticator that proves the client's identity. Because the authenticator can be used only once and has a short lifetime, the threat of an opponent stealing both the ticket and the authenticator for presentation later is countered. C then sends the TGS a message that includes the ticket plus the ID of the requested service (message 3). The reply from the TGS, in message (4), follows the form of message (2). C now has a reusable service-granting ticket for V. When C presents this ticket, as shown in message (5), it also sends an authenticator.

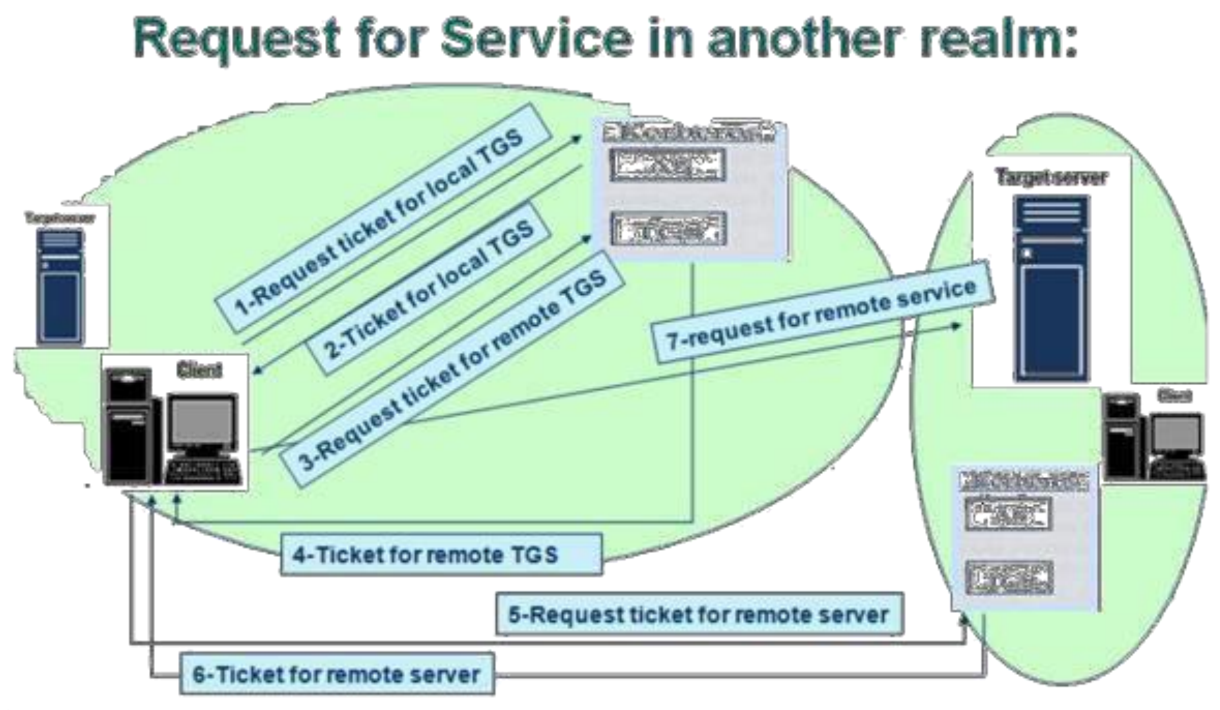
The server can decrypt the ticket, recover the session key, and decrypt the authenticator.If mutual authentication is required, the server can reply as shown in message (6).

Overview of Kerberos


2. AS verifies user's access right in database, creates ticket-granting ticket and session key. Results are encrypted using key derived from user's password.
Kerberos
Authentication Server (AS)
Ticket-granting Server (TGS)
once per user logon session
request ticket-granting ticket
ticket + session key
request service-granting ticket
ticket + session key
1. User logs on to workstation and requests service on host.
once per type of service
3. Workstation prompts user for password and uses password to decrypt incoming message, then sends ticket and authenticator that contains user's name, network address, and time to TGS.
4. TGS decrypts ticket and authenticator, verifies request, then creates ticket for requested server.
request service
provide server authenticator
once per service session
5. Workstation sends ticket and authenticator to server.
6. Server verifies that ticket and authenticator match, then grants access to service. If mutual authentication is required, server returns an authenticator.

Kerberos Realms A full-service Kerberos environment consisting of a Kerberos server, a number of clients, and a number of application servers is referred to as a Kerberos realm. A Kerberos realm is a set of managed nodes that share the same Kerberos database, and are part of the same administrative domain. If have multiple realms, their Kerberos servers must share key and trust each other.

The following figure shows the authentication messages where service is being requested from another domain. The ticket presented to the remote server indicates the realm in which the user was originally authenticated. The server chooses whether to honor the remote request. One problem presented by the foregoing approach is that it does not scale well to many realms, as each pair of realms need to share a key.


Request for Service in another realm:
Target server
Client
1-Request ticket for local TGS
2-Ticket for local TGS
3-Request ticket for remote TGS
4-Ticket for remote TGS
5-Request ticket for remote server
6-Ticket for remote server
7-request for remote service
Kerberos
Target server
Client

The limitations of Kerberos version-4 are categorised into two types:

- Environmental shortcomings of Version 4:

– Encryption system dependence: DES

– Internet protocol dependence

– Ticket lifetime

– Authentication forwarding

➢ Inter-realm authentication Technical

- deficiencies of Version 4:

– Double encryption

– Session Keys

– Password attack

KERBEROS VERSION 5

Kerberos Version 5 is specified in RFC 1510 and provides a number of improvements over version 4 in the areas of environmental shortcomings and technical deficiencies. It includes some new elements such as:

➢ Realm: Indicates realm of the user

➢ Options

➢ Times

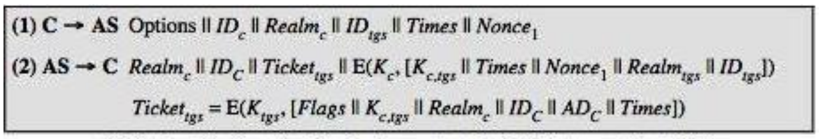
– From: the desired start time for the ticket

– Till: the requested expiration time

– Rtime: requested renew-till time

- Nonce: A random value to assure the response is fresh

The basic Kerberos version 5 authentication dialogue is shown here First, consider the **authentication service exchange.**

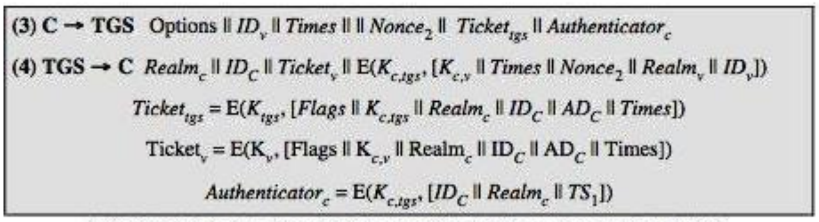


(1) C → AS $\text{Options} \parallel ID_c \parallel Realm_c \parallel ID_{tgs} \parallel Times \parallel Nonce_1$

(2) AS → C $Realm_c \parallel ID_C \parallel Ticket_{tgs} \parallel E(K_c, [K_{c,tgs} \parallel Times \parallel Nonce_1 \parallel Realm_{tgs} \parallel ID_{tgs}])$

$Ticket_{tgs} = E(K_{tgs}, [Flags \parallel K_{c,tgs} \parallel Realm_c \parallel ID_C \parallel AD_C \parallel Times])$

(a) Authentication Service Exchange to obtain ticket-granting ticket



(3) C → TGS $\text{Options} \parallel ID_v \parallel Times \parallel \parallel Nonce_2 \parallel Ticket_{tgs} \parallel Authenticator_c$

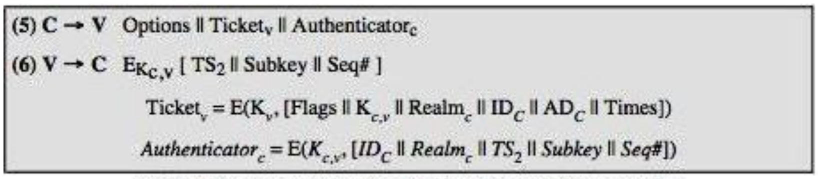
(4) TGS → C $Realm_c \parallel ID_C \parallel Ticket_v \parallel E(K_{c,tgs}, [K_{c,v} \parallel Times \parallel Nonce_2 \parallel Realm_v \parallel ID_v])$

$Ticket_{tgs} = E(K_{tgs}, [Flags \parallel K_{c,tgs} \parallel Realm_c \parallel ID_C \parallel AD_C \parallel Times])$

$\text{Ticket}_v = E(K_v, [\text{Flags} \parallel K_{c,v} \parallel \text{Realm}_c \parallel ID_C \parallel AD_C \parallel \text{Times}])$

$Authenticator_c = E(K_{c,tgs}, [ID_C \parallel Realm_c \parallel TS_1])$

(b) Ticket-Granting Service Exchange to obtain service-granting ticket



(5) C → V $\text{Options} \parallel \text{Ticket}_v \parallel \text{Authenticator}_c$

(6) V → C $E_{K_{c,v}} [\, TS_2 \parallel \text{Subkey} \parallel \text{Seq\#} \,]$

$\text{Ticket}_v = E(K_v, [\text{Flags} \parallel K_{c,v} \parallel \text{Realm}_c \parallel ID_C \parallel AD_C \parallel \text{Times}])$

$Authenticator_c = E(K_{c,v}, [ID_C \parallel Realm_c \parallel TS_2 \parallel Subkey \parallel Seq\#])$

(c) Client/Server Authentication Exchange to obtain service

Message (1) is a client request for a ticket -granting ticket. Message (2) returns a ticket-granting ticket, identifying information for the client, and a block encrypted using the encryption key based on the user's password. This block includes the session key to be used between the client and the TGS. Now compare the **ticket-granting service** exchange for versions 4 and 5. See that message (3) for both versions includes an authenticator, a ticket, and the name of the requested service. In addition, version 5 includes requested times and options for the ticket and a nonce, all with functions similar to those of message (1). The authenticator itself is essentially the same as the one used in version 4. Message (4) has the same structure as message (2), returning a ticket plus information needed by the client, the latter encrypted with the session key now shared by the client and the TGS. Finally, for the client/server authentication exchange, several new features appear in version 5, such as a request for mutual authentication. If required, the server responds with message (6) that includes the timestamp from the authenticator. The flags field included in tickets in version 5 supports expanded functionality compared to that available in version 4.

Advantages of Kerberos:

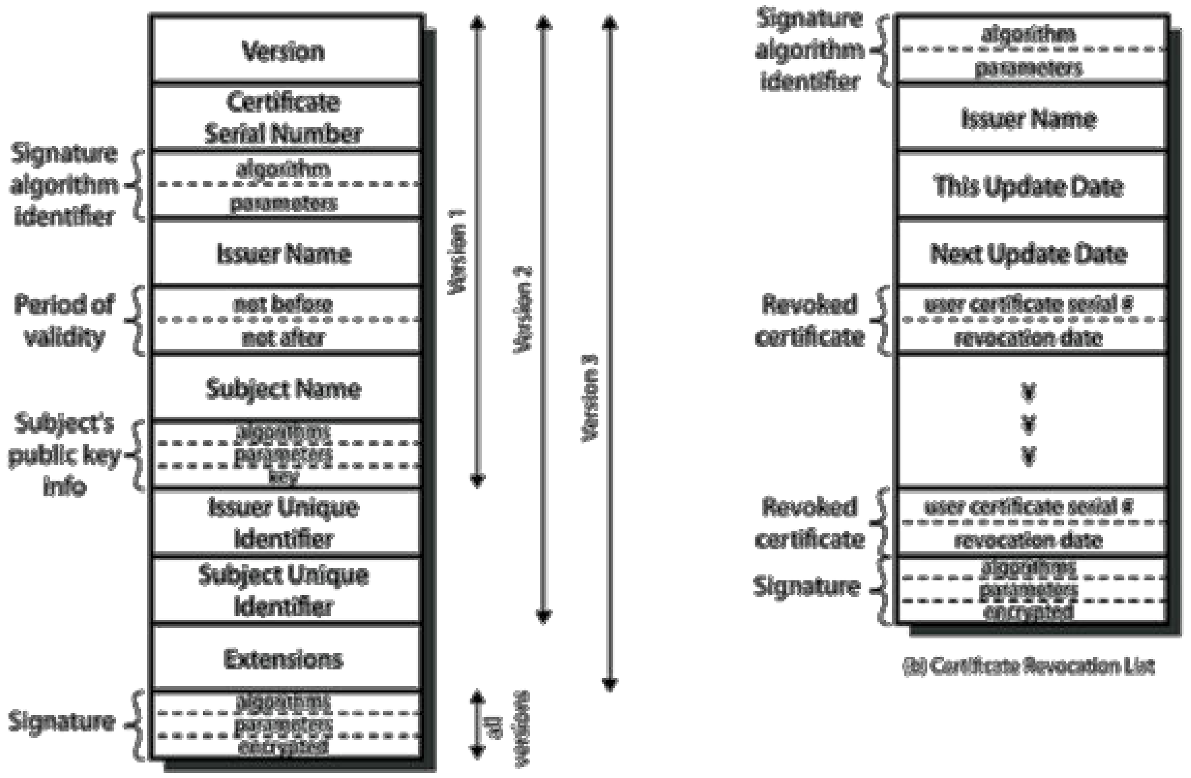
- User's passwords are never sent across the network, encrypted or in plain text
- Secret keys are *only* passed across the network in encrypted form
- Client and server systems mutually authenticate
- It limits the duration of their users' authentication.
- Authentications are **reusable** and **durable**
- Kerberos has been scrutinized by many of the top programmers, cryptologists and security experts in the industry

X.509 AUTHENTICATION SERVICE

ITU-T recommendation X.509 is partMediaoftheX.500series of recommendations that define a directory service. The directory is, in effect, server or distributed set of servers that maintains a database of information about users. The information includes a mapping from user name to network address, as w ll as other attributes and information about the users. X.509 is based on the use of public-key cryptography and digital signatures. The heart of the X.509 scheme is the public-key certificate associated with each user. These user certificates are a umed to be created by some trusted certification authority (CA) and placed in the directory by the CA or by the user. The directory server itself is not responsible for the creation of public keys or for the certification function; it merely provides an easily accessible location for users to obtain certificates.

The general format of a certificate is shown above, which includes the following elements:

- version 1, 2, or 3
- serial number (unique within CA) identifying certificate
- signature algorithm identifier issuer X.500 name (CA)
- period of validity (from - to dates)
- subject X.500 name (name of owner)
- subject public-key info (algorithm, parameters, key)
- issuer unique identifier (v2+)



Media

subject unique identifier (v2+)

extension fields (v3)

signature (of hash of all fields in certificate)

The standard uses the following notation to define certificate:

CA<<A>> = CA {V, SN, AI, CA, TA, A, Ap}

Where Y<<X>>= the certificate of ser X issued by certification authority Y

Y {I} == the signing of I by Y. It consists of I with an encrypted hash code appended

User certificates generated by a CA have the following characteristics:

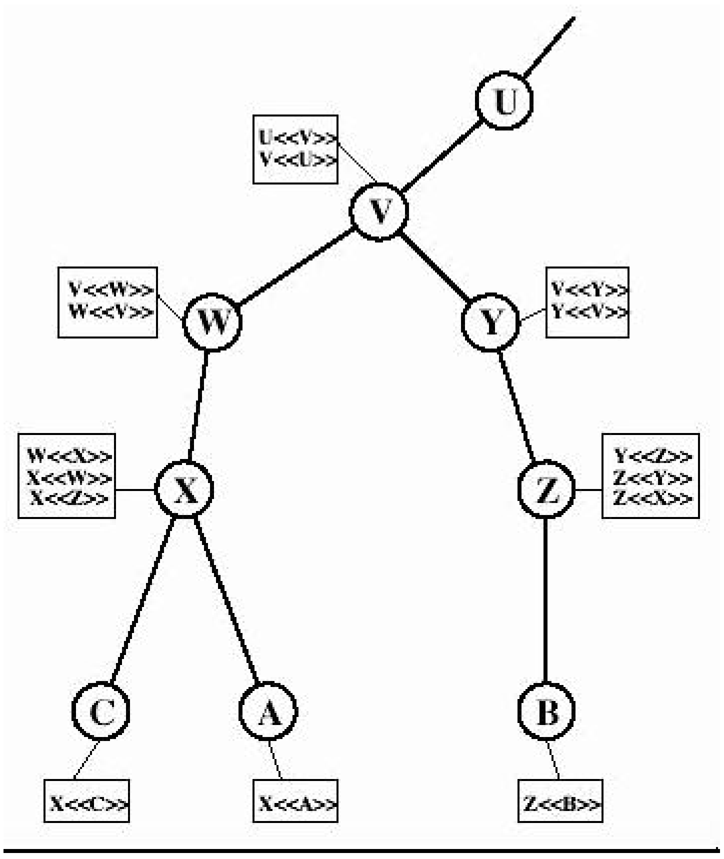
1. Any user with CA's public key can verify the user public key that was certified
2. No party other than the CA can modify the certificate without being detected
3. because they cannot be forged, certificates can be placed in a public directory

Scenario: Obtaining a User Certificate If both users share a common CA then they are assumed to know its public key. Otherwise CA's must form a hierarchy and use certificates linking members of hierarchy to validate other CA's. Each CA has certificates for clients (forward) and parent (backward). Each client trusts parents certificates. It enables verification of any certificate from one CA by users of all other CAs in hierarchy. A has obtained a certificate from the CA X1. B has obtained a certificate from the CA X2. A can read the B’s certificate but cannot verify it. In order to solve the problem , the Solution: **X1<<X2> X2<<B>>.** A obtain the certificate of X2 signed by X1 from directory. obtain X2’s public key. A goes back to directory and obtain the certificate of B signed by X2.

obtain B’s public key securely. The directory entry for each CA includes two types of certificates: Forward certificates: Certificates of X generated by other CAs Reverse certificates: Certificates generated by X that are the certificates of other CAs

X.509 CA Hierarchy

A acquires B certificate using chain:
X<<W>>W<<V>>V<<Y>>Y<<Z>>
Z<<B>> B acquires A certificate using chain:
Z<<Y>>Y<<V>>V<<W>>W<<X>> X<<A>>



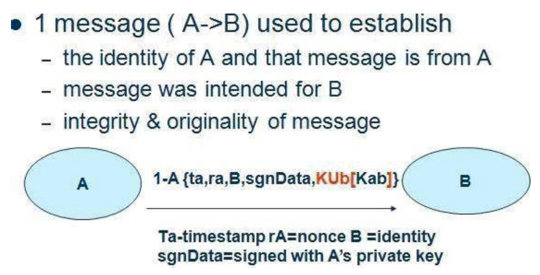
Revocation of Certificates Typically, a new certificate is issued just before the expiration of the old one. In addition, it may be desirable on occasion to revoke a certificate before it expires, for one of the following reasons:

- The user's private key is assumed to be compromised.
- The user is no longer certified by this CA.
- The CA's certificate is assumed to be compromised.

Each CA must maintain a list consisting of all revoked but not expired certificates issued by that CA, including both those issued to users and to other CAs. These lists should also be posted on the directory. Each **certificate revocation list (CRL) posted** to the directory is signed by the issuer and includes the issuer's name, the date the list was created, the date the next CRL is scheduled to be issued, and an entry for each revoked certificate. Each entry consists of the serial number of a certificate and revocation date for that certificate. Because serial numbers are unique within a CA, the serial number is sufficient to identify the certificate.

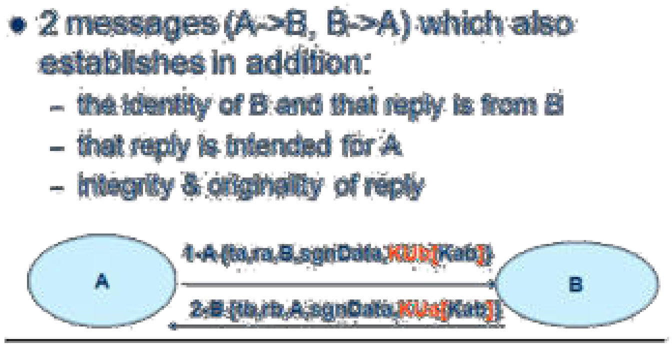
AUTHENTICATION PROCEDURES

X.509 also includes three alternative authentication procedures that are intended for use across a variety of applications. All these procedures make use of public-key signatures. It is assumed that the two parties know each other's public key, there by obtaining each other's certificates from the directory or because the certificate is included in the initial message from each side. 1. One-Way Authentication: One way authentication involves a single transfer of information from one user (A) to another (B), and establishes the details shown above. Note that only the identity of the initiating entity is verified in this process, not that of the responding entity. At a minimum, the message includes a timestamp, a nonce, and the identity of B and is signed with A’s private key. The message may also include information to be conveyed, such as a session ey for B.


- 1 message (A->B) used to establish
  - the identity of A and that message is from A
  - message was intended for B
  - integrity & originality of message

A
1-A {ta,ra,B,sgnData,KUb[Kab]}
B
Ta-timestamp rA=nonce B =identity
sgnData=signed with A’s private key

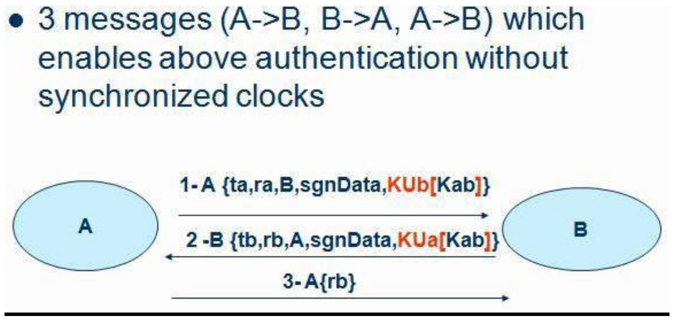
Two-Way Authentication: Two-way authentication thus permits both parties in a communication to verify the identity of the other, thus additionally establishing the above details. The reply message includes the nonce from A, to validate the reply. It also includes a timestamp and nonce generated by B, and possible additional information for A.



- 2 messages (A->B, B->A) which also establishes in addition:
  - the identity of B and that reply is from B
  - that reply is intended for A
  - integrity & originality of reply

A
1-A {ta,ra,B,sgnData,KUb[Kab]}
2-B {tb,rb,A,sgnData,KUa[Kab]}
B

Three-Way Authentication: Three-Way Authentication includes a final message from A to B, which contains a signed copy of the nonce, so that timestamps need not be checked, for use when synchronized clocks are not available.



- 3 messages (A->B, B->A, A->B) which enables above authentication without synchronized clocks

A
1- A {ta,ra,B,sgnData,KUb[Kab]}
2 -B {tb,rb,A,sgnData,KUa[Kab]}
3- A{rb}
B