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Hash and MAC functions

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Course of Network Security, Spring 2014

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Hash Function

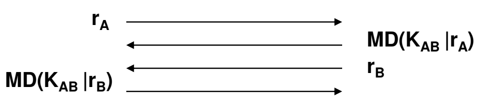
- Also known as Message Digest
- it is a function that takes an input message and produce an output (hash value, or message digest)
- the input can be a variable-length bit string, the output is a fixed-length bit string (e.g. 128 bits)
- It is a one-way function
  - **it is not practical to figure out which input corresponds to a given output**

$$h=H(m)$$

- e.g. MD2, MD5 (RFC1321), SHA-1, SHA-2

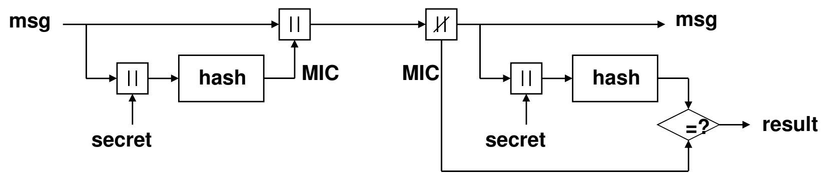
What doing with a Hash

- Message fingerprint
  - **maintaining a copy of a message digest of some data/program in place of the copy of the entire data (for integrity check)**
- Password Hashing
  - **a system may know/store just the hash of a passwd**
- Digital signature
  - **Signing the MD of a message instead of the entire message**
    - for efficiency (MDs are easier to compute than public-key algorithms)
- Authentication
  - **similar to secret key cryptography**



What doing with a Hash

- Computing a MIC (Message Integrity Check) or MAC
  - **the obvious thought is that H(m) is a MIC for m, but it isn't; anyone can compute H(m)**
  - **the way is to send also a (shared) secret (pwd or key)**



What doing with a Hash

- Encryption
  - **encryption should be easy with H, but what about decryption?**
  - **one-time pad**
    - just as OFB, generating a pseudorandom bit stream and encrypting the message just by a simple ⊕
    - the pseudorandom stream is generated starting from a hash of a secret: $o_1=H(K_{AB}|IV)$, $o_2=H(K_{AB}|o_1)$, .. , $o_{k+1}=H(K_{AB}|o_k)$
    - same problems as OFB
  - **mixing in the plaintext**
    - as in CFB, the plaintext is mixed in the bit stream generation
    - $b_1=H(K_{AB}|IV)$, $b_2=H(K_{AB}|c_1)$, .. , $b_{k+1}=H(K_{AB}|c_k)$
    - $c_1=m_1 \oplus b_1$, $c_2=m_2 \oplus b_2$, .. , $c_k=m_k \oplus b_k$

Hash function properties

- Input message *m* of any size
- Output data *h* of fixed size
- The transformation *H(m)* is one-way
- It reduces data size, "summarizing" the characteristics of the message
  - **allows the detection of possible modifications/errors**
- Fast calculation of *h=H(m)*
  - **requires low processing resources**
- The message digest should look "randomly generated"
- It must be computationally infeasible to find a message with a given prespecified message digest
- It should be impossible to two find two messages that has the same digest (although the function is not one-to-one)

About the hash function

- Message digest functions are like alchemy
  - **It's a bunch of steps that each mangle the message more and more**
  - **A plausible way of constructing a message digest function is to combine lots of "perverse" operations**
  - **however the message digest should remain easy to compute**
- Often, hash function uses constants (magic numbers)
  - **Often the algorithm designers specify how they chose a particular number (to prevent suspects on particular properties of the chosen number)**
    - π
    - Published books with random numbers
      (A book has been published in 1939)

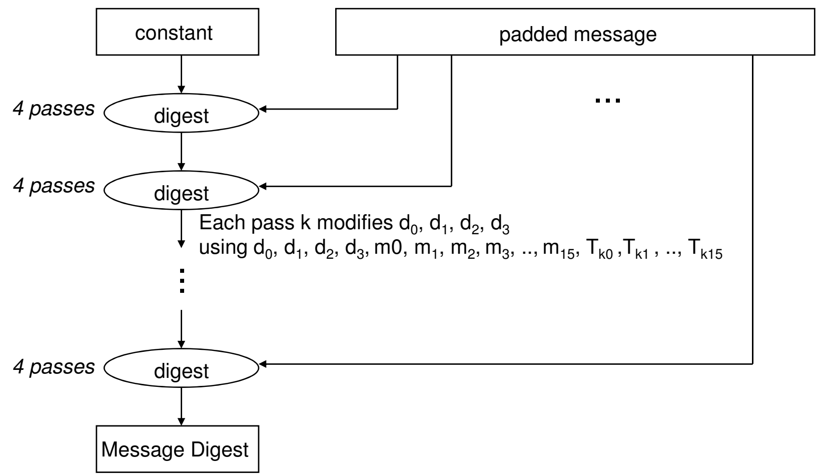
How many bits should the output have?

- How many bits should the output have in order to prevent someone from being able to find two message with the same hash?
- If the message digest has m bits, then it would take $2^{m/2}$ messages chosen at random (Birthday Paradox)
  - **this is why message digest functions have output of at least 128 or more bits (in place of just 64 as for symmetric cryptography)**
  - **however sometime it is not sufficient for an attacker to find out just two messages with the same hash; in such case, a brute-force attack requires 2^m searches**

MD5

- Designed by Ronald L. Rivest of MIT
- Can handle message with an arbitrary number of bits
- Produce a 128-bit hash (32-bit-word oriented, 128 bit = 4 words)
- Message padding
  - **the message must be a multiple of 512 bits (16 words);**
  - **the message is padded by adding one "1" bit and**
  - **padded with "0"s until bit Nx512-64**
  - **the remaining 64 bit represent the number of unpadded message bits, mod 2^{64}**
- Message processed in 512-bit blocks (16 words)
- For each message block, makes 4 passes over the 128-bit block
  - **each pass consists of 16 steps with a given function g() and constants T_{ki}**

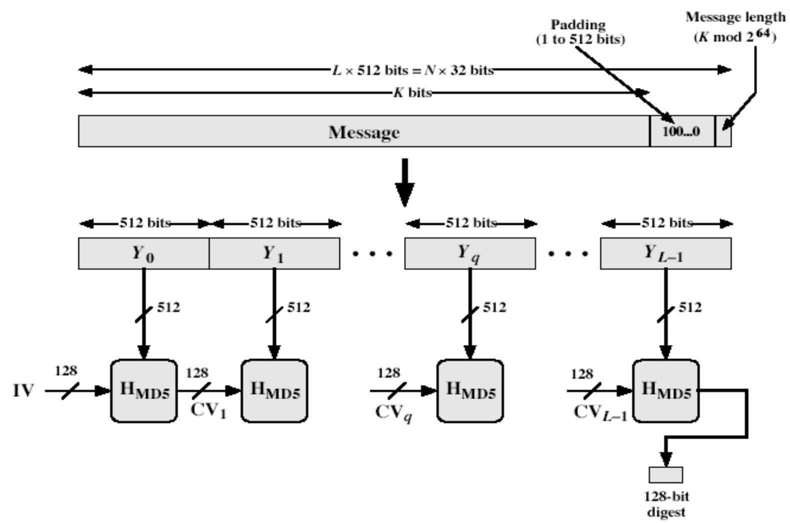
MD5 scheme



MD5 initialization

- Padding
  - **Input message needs to be padded in order to make the length module 512 equal to 448 bit**
    - total length (including padding) becomes 512 minus 64 bit
    - added from 1 to 512 bit as needed
    - padding bits are one "1" followed by zeros
  - **then, 64 bit (512-448) are appended, reporting the message length module 2^{64}**
    - resulting total length becomes 512
- The 128 bit MD buffer, formed by four 32 bit words (A, B, C, D), is initialized to:
  - `A= 01 23 45 67`
  - `B= 89 AB CD EF`
  - `C= FE DC BA 98`
  - `D= 76 54 32 10`

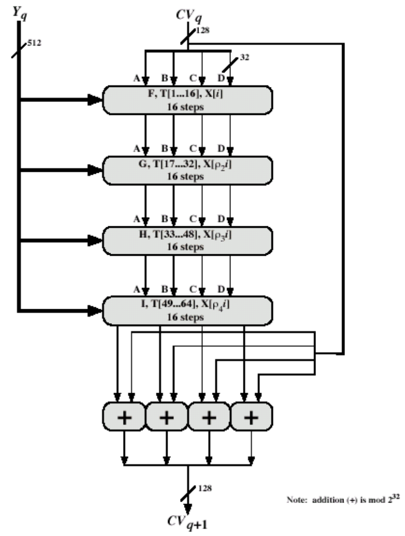
MD5 padding and processing



MD5 processing

- Message is processed in blocks of size 512 bit (16 word)
- Starting from the initial buffer, 4 processing phases (passes) for each block are executed
- For each phase, a different function is used, referred as F, G, H and I
- Each function uses as input:
  - **the buffer ABCD of size 128 bit,**
  - **the current message block Y_q of size 512 bit,**
  - **1/4 of a table T[1..64] with 64 values, obtained from the sin() function**
- The output of the fourth is added to the input (module 32), word by word
- The output of the last operation is the resulting message digest

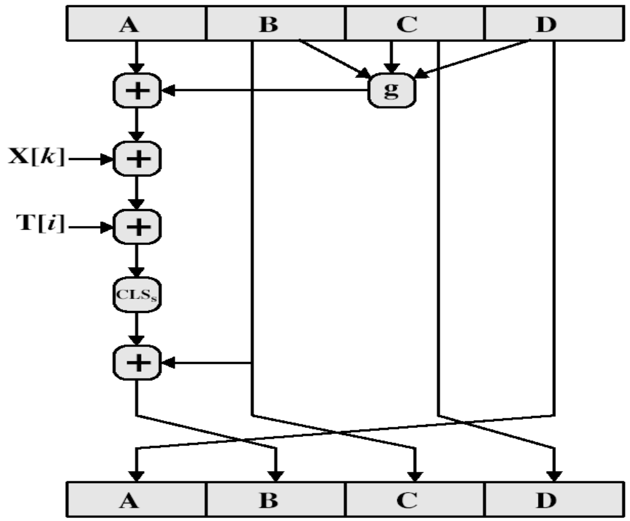
MD5 processing



MD5 processing (4 passes)

- A = B+((A+g(B,C,D)+X[k]+T[i]<<<s)
- Pass 1 (16 steps)
  g(x,y,z) = F(x,y,z)
- Pass 2 (16 steps)
  - **g(x,y,z) = G(x,y,z)**
- Pass 3 (16 steps)
  - **g(x,y,z) = H(x,y,z)**
- Pass 4 (16 steps)
  - **g(x,y,z) = I(x,y,z)**
- with:
  - **F(X,Y,Z) = XY v not(X) Z**
  - **G(X,Y,Z) = XZ v Y not(Z)**
  - **H(X,Y,Z) = X xor Y xor Z**
  - **I(X,Y,Z) = Y xor (X v not(Z))**

MD5 processing (16 steps)



Secure Hash Standard (SHS/SHA)

- Set of cryptographically secure hash algorithms specified by NIST as message digest functions
- The original specification of the algorithm was published in 1993 as the Secure Hash Standard, FIPS PUB 180, by NIST (SHA-0)
  - **Secure Hash Algorithm (SHA)**
- Successively revised by the following standards
  - **SHA-1, SHA-224, SHA-256, SHA-384, and SHA-512**
  - **the latter four variants are sometimes collectively referred to as SHA-2**
  - **SHA-1 (and SHA) produces a message digest that is 160 bits long**
  - **the other algorithms produce digests that are respectively 224, 256, 384, 512 bits long**
- SHA-1 is employed in several widely used security applications and protocols
  - **TLS/SSL, PGP, SSH, S/MIME, IPsec, etc.**

SHA standards

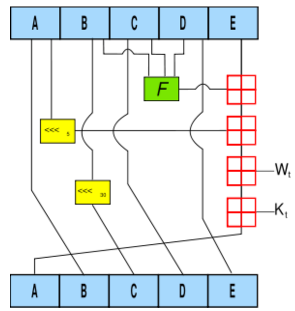
Algoritmo e variante		Dimensione dell'output (bit)	Dimensione dello stato interno (bit)	Dimensione del blocco (bit)	Max. dimensione del messaggio (bit)	Dimensione della *word* (bit)
SHA-0		160	160	512	$2^{64} - 1$	32
SHA-1		160	160	512	$2^{64} - 1$	32
SHA-2	*SHA-256/224*	256/224	256	512	$2^{64} - 1$	32
	SHA-512/384	512/384	512	1024	$2^{128} - 1$	64

SHA-1

- SHA-0 was superseded by the revised version SHA-1, published in 1995
  - **SHA-1 differs from SHA-0 only by a single bitwise rotation in the message schedule of its compression function**
  - **this was done, according to the NSA, to correct a flaw in the original algorithm which reduced its cryptographic security**
- SHA-1 (as well as SHA-0) produces a 160-bit (5-word blocks) digest from a message with a maximum length of (2^{64} - 1) bits
  - **the limitation to 2^{64} - 1 bits is not a problem, since it would take several hundred years to transmit such a long message at 10Gb/s and it would take even longer (hundreds of centuries) to compute SHA-1 at 100MIPS**

SHA-1 (cont.)

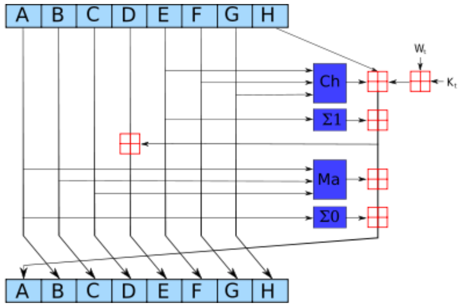
- Based on principles similar to those used by MD5 message digest algorithms Pad the message as in MD5 (except that the message is limited to 2^{64} bits)
- Operates in stages (as MD5)
  - **Makes 5 passes for each block of data (4 in MD5)**
  - **Uses a different 160-bit mangle function in each stage**



- Little slower than MD5 and (presumably) little more secure

SHA-2

- SHA-224, SHA-256, SHA-384, and SHA-512
  - **FIPS PUB 180-2 standard in 2002 (SHA-224 variant in 2004)**
- SHA-256 and SHA-512 are computed with 32- and 64-bit words, respectively
  - **use different shift amounts and additive constants**
  - **different number of rounds**
- SHA-224 and SHA-384 are simply truncated versions of the first two, computed with different initial values

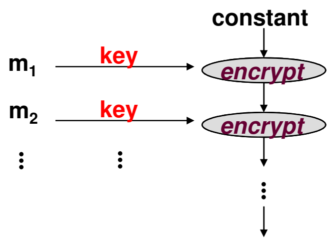


Future of SHA

- SHA-1 has been compromised
- SHA-2 security is not yet as well-established
  - **not received as much scrutiny as SHA-1**
  - **although no attacks have yet been reported, SHA-2 is algorithmically similar to SHA-1**
- An open competition for a new SHA-3 function has been started by NIST on November 2, 2007
  - **similar to the development process for AES**
  - **submissions was due October 31, 2008**
  - **On October 2, 2012, NIST selected the Keccak algorithm as SHA-3 competition winner**

Using secret key algorithm as Hash Function

- A hash algorithm can be replaced by a block ciphers
  - **using H_0=0 and zero-pad of final block**
  - **compute: $H_i = E_{M_i} [H_{i-1}]$**
  - **and use final block as the hash value**
  - **similar to CBC but without a key**
- resulting hash can be too small (64-bit)
- not very fast to compute



Using secret key algorithm as Hash Function

- Example: the orginal UNIX password hash (crypt function)
  - **first convert the passwd (the message) into a "secret key"**
    - the 7bit ASCII codes of the first 8 chars form the 56bit key
  - **the key is used to encrypt the number 0 with a modified DES**
    - 25 DES passes are performed
    - the modified DES is used to prevent HW accelerators designed to DES to be used to reverse the passwd hash
    - the modified algorithm uses a 12-bit random number (salt)
  - **the salt and the final ciphertext are base64-encoded into a printable string stored in the password or shadow file**
- Currently, the most common crypt function used by Unix/Linux systems supports both the original DES-based and hash-based algorithms (e.g. MD5-crypt function), where common hash function such as MD5 or SHA-1 are used
  - **such functions generally allow users to have any length password (> 8bytes), and do not limit the password to ASCII (7-bit) text**

Unix password hashing

- The MD5-crypt function is really not a straight implementation of MD5
  - **first the password and salt are MD5 hashed together in a first digest**
  - **then 1000 iteration loops continuously remix the password, salt and intermediate digest values**
  - **the output of the last of these rounds is the resulting hash**
- A typical output of the stored password together with username, salt, and other information is:

alice:1BZftq3sP$xEeZmr2fGEnKjVAxzjQo68:12747:0:99999:7:::

  - **where 1 indicates the use of MD5-crypt, while BZftq3sP is the base-64 encoding of the salt and xEeZmr2fGEnKjVAxzjQo68 is the password hash**

Message Authentication

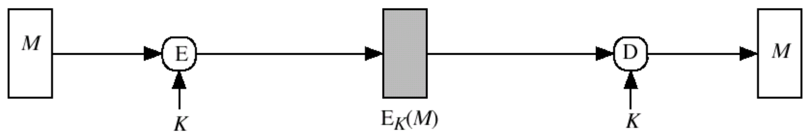
(data origin authentication, integrity check)

Message Authentication

- Message authentication is concerned with:
  - **protecting the integrity of a message**
  - **validating identity of originator**
  - **non-repudiation of origin (dispute resolution)**
- Three alternative approaches:
  - **use of secret or public key encryption algorithms**
  - **use of encryption and hash algorithms**
  - **use of ad-hoc (secret key based) Message Authentication Code (MAC) algorithms**

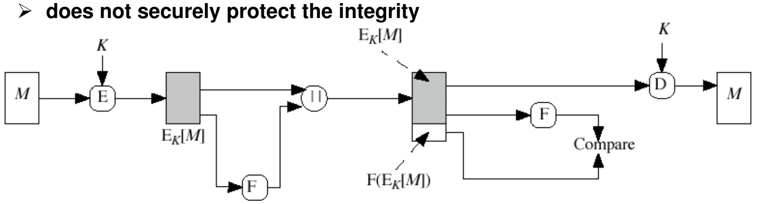
Msg. Auth. - Secret-key Encryption

- Symmetric encryption:
  - **encryption provides both confidentiality and origin authentication**
  - **however, need to recognize corrupted messages (based on the received message or with an explicit MIC)**

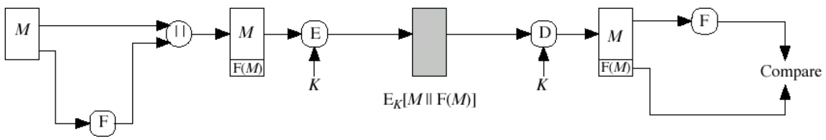


Msg. Auth. - Secret-key Encryption + Hash

- External error control (checksum):
  - **does not securely protect the integrity**



- Message Integrity Check (MIC):
  - **example through internal error control - Manipulation Detection Code (MDC)**

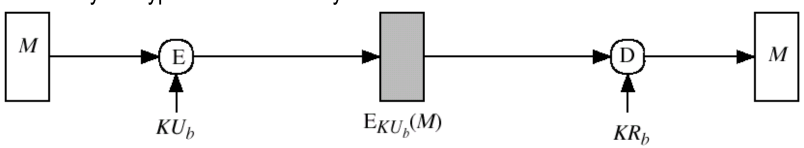


Msg. Auth. - Asymmetric Cryptography

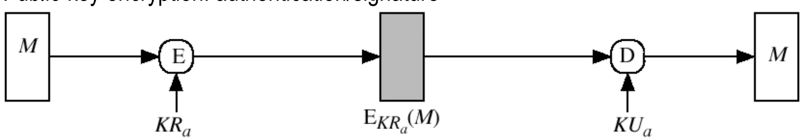
- if public-key encryption is used
  - **encryption with public key provides no proof of sender (no sender authentication)**
    - since anyone potentially knows public-key
  - **both secrecy and authentication if**
    - sender "signs" message using their private-key
    - then encrypts with recipients public key
  - **problems**
    - the result is the same cost of two public-key encryption
    - need to recognize corrupted messages for integrity check

Msg. Auth. - Asymmetric Cryptography (cont.)

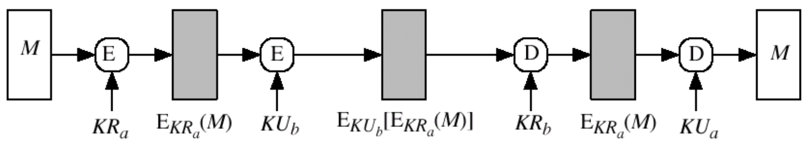
Public-key encryption: confidentiality



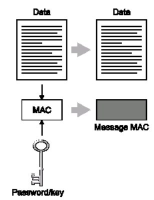
Public-key encryption: authentication/signature

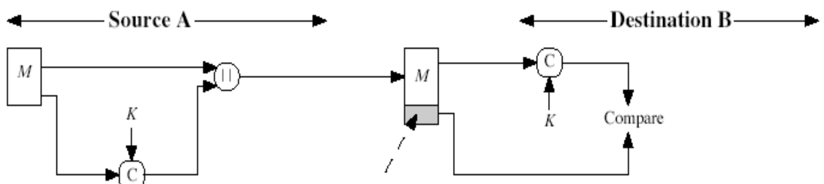


Public-key encryption: confidentiality + authentication/signature



Message Authentication Code (MAC)





(a) Message authentication

Message Authentication Code (MAC)

- a MAC is a cryptographic checksum, generated by an algorithm that creates a small fixed-sized block
  - **depending on both message and a secret key K**
    - MAC = $C_K(M)$
  - **condenses a variable-length message M to a fixed-sized authenticator**
    - it needs not be reversible
    - is a many-to-one function
      - potentially many messages have same MAC
      - but finding these needs to be very difficult
- appended to message as a **signature**
- receiver performs same computation on message and checks it matches the MAC
- provides assurance that message is unaltered and comes from sender

Message Authentication Code (cont.)

- In case secrecy is also required
  - **use of encryption with separate key**
  - **can compute MAC either before or after encryption**
  - **is generally regarded as better done before**
- why use a MAC?
  - **sometimes only authentication is needed**
  - **sometimes need authentication to persist longer than the encryption (eg. archival use)**
- MAC is similar but not equal to digital signature

Requirements for MACs

- MAC functions have to satisfy the following requirements:
  - **knowing a message and MAC, is infeasible to find another message with same MAC**
  - **is infeasible to find two messages with same MAC**
  - **MACs should be uniformly distributed**
  - **MAC should depend equally on all bits of the message**

Using Symmetric Ciphers for MACs

- Can use any block cipher chaining mode and use final block as a MAC
- Data Authentication Algorithm (DAA) is a widely used MAC based on DES-CBC
  - **using IV=0 and zero-pad of final block**
  - **encrypt message using DES in CBC mode**
  - **and send just the final block as the MAC**
    - or the leftmost M bits of final block
- But final MAC is now too small for security (≤64bit)

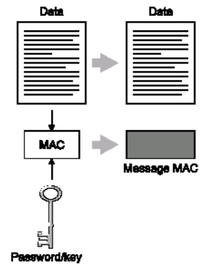
MAC Security

- Cryptanalytic attacks
- Like block ciphers, brute-force attacks are the best alternative
- Transient effect
  - **message authentication, as opposed to encryption, has a "transient" effect**
  - **a published breaking of a message authentication scheme would lead to the replacement of that scheme, but would have no adversarial effect on information authenticated in the past**
  - **this is in contrast with encryption, where information encrypted today may suffer from exposure in the future if, and when, the encryption algorithm is broken**

Hash Message Authenication Code (H-MAC)

H-MAC (RFC 2104)

- Mechanism for message authentication using cryptographic hash functions in combination with a secret shared key
  - **only who knows the secret key can compute the hash**
- HMAC can be used with any iterative cryptographic hash function, e.g., MD5, SHA-1
  - **the cryptographic strength of HMAC depends on the properties of the underlying hash function**



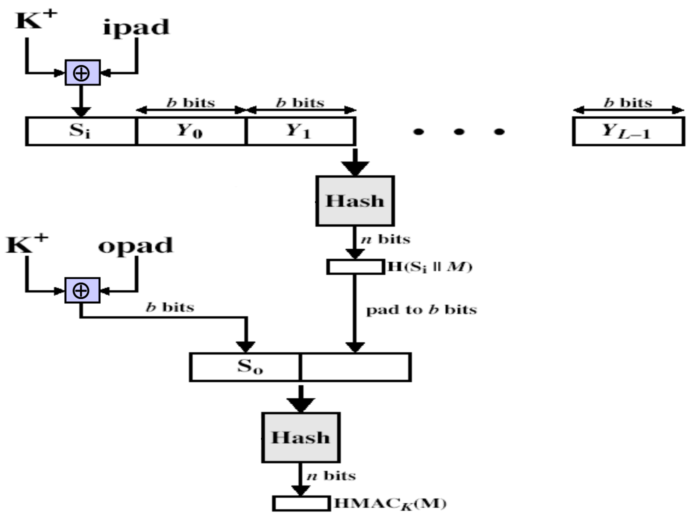
HMAC

- Specified as Internet standard RFC2104
- Uses hash function on the message:

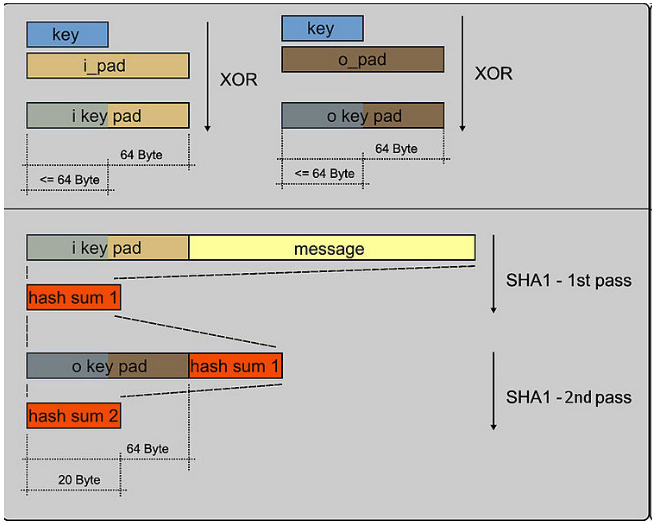
  $\mathrm{HMAC}_K = \mathrm{Hash}[(K^+ \text{ XOR } opad) \,||\, \mathrm{Hash}[(K^+ \text{ XOR } ipad) \,||\, M)]]$

  - **where K+ is the key 0-padded out to size B**
    - B is the size of the processing block
    - if K is longer than B bytes it is first hashed using H
  - **and opad, ipad are specified padding constants**
    - ipad = the byte 0x36 repeated B times
    - opad = the byte 0x5C repeated B times
- Overhead is just 3 more hash calculations than the message needs alone
- Any of MD5, SHA-1, RIPEMD-160 can be used

HMAC



Example - SHA-1 HMAC



Truncated HMAC

- A well-known practice with MACs is to truncate the output of the MAC and output only part of the bits
  - **advantages: less information on the hash result available to an attacker**
  - **disadvantages less bits to predict for the attacker**
- It is recommended to let the output length t be not less than half the length of the hash output and not less than 80 bits
- Sometimes HMAC that uses a hash function H with t bits of output is denoted as HMAC-H-t
  - **example, HMAC-SHA1-80 denotes HMAC computed using the SHA-1 function and with the output truncated to 80 bits**