Existentially unforgeable

- A secure MAC is **existentially unforgeable**: without the key, an attacker cannot create a valid tag on a message
  - David cannot generate MAC(K, M') without K
  collision
  - David cannot find any $M' \neq M$ such that MAC(K, M') = MAC(K, M)

Example: HMAC

~~NIST~~

- issued as RFC 2104 [1]
- has been chosen as the mandatory-to-implement MAC for IP Security
- Used in Transport Layer Security (TLS) and Secure Electronic Transaction (SET)

[1] "HMAC: Keyed-Hashing for Message Authentication", RFC 2104, https://datatracker.ietf.org/doc/html/rfc2104

HTTP, IPsec, DNS, SMTP

HMAC(K, M)

- will produce two keys to increase security
- If key K_1 is longer than the desired size, we can hash it first K^+, but be careful with using keys that are too much smaller, they have to have enough randomness in them
- Output $H[(K^+ \oplus opad) \,||\, H[(K^+ \oplus ipad) \,||\, M]]$

$\underbrace{K^+ \oplus opad}_{K_1}$ $\underbrace{K^+ \oplus ipad}_{K_2}$

Example: HMAC

- HMAC(K, M):
  - Output $H[(K^+ \oplus opad) \,||\, H[(K^+ \oplus ipad) \,||\, M]]$

→ 512 bits

8 bits

- Use K to derive two different keys
  - *opad* (outer pad) is the hard-coded byte **0x5c** repeated until it's the same length as K^+

K_1 & K_2

8 bits

  - *ipad* (inner pad) is the hard-coded byte **0x36** repeated until it's the same length as K^+
  - As long as *opad* and *ipad* are different, you'll get two different keys
  - For paranoia, the designers chose two very different bit patterns, even though they theoretically need only differ in one bit

Coding theory

Euclidean Distance

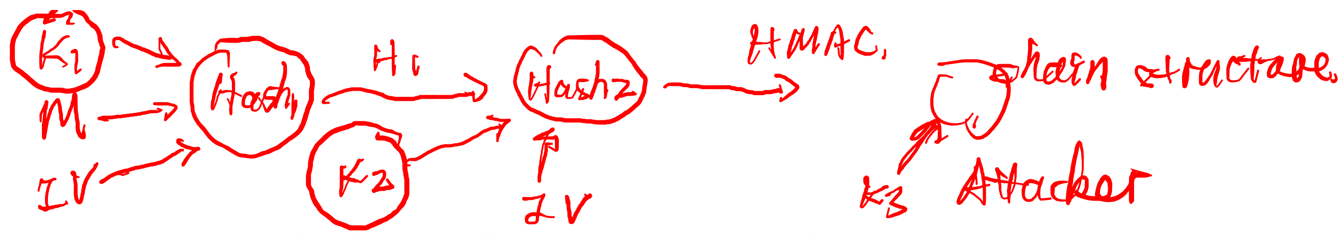
Hamming distances

x, y

$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$

$d_H(x, y) = W_H(x \oplus y)$

HMAC



K1 & K2

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

A	B	A ⊕ B
0	0	0
0	1	1
1	0	1
1	1	0

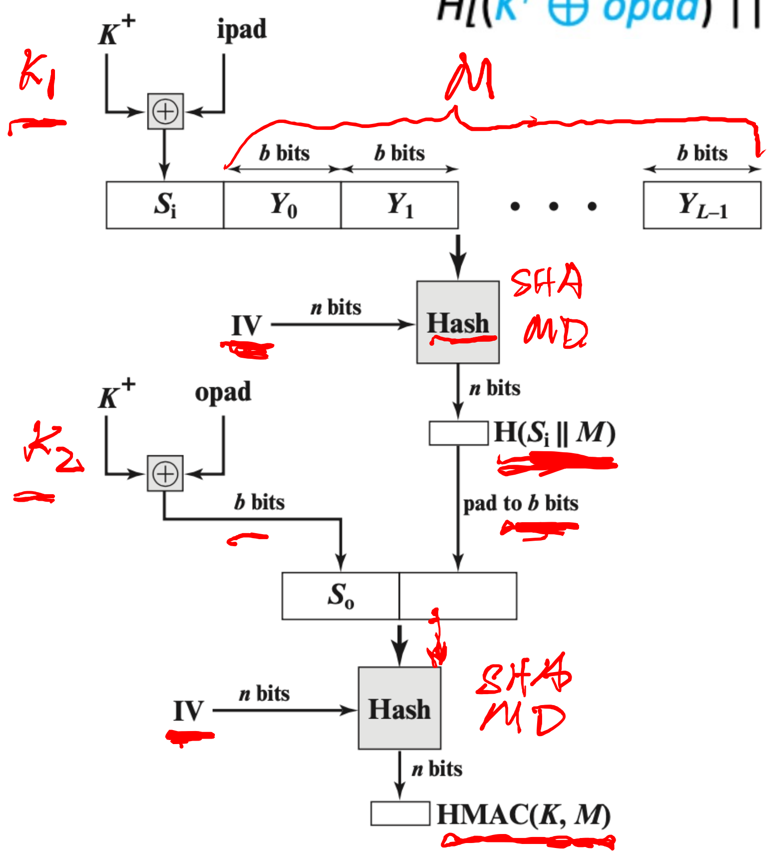


Figure 3.6 HMAC Structure

$$K^+ = \begin{cases} H(K) & K \text{ is larger than block size} \\ K & \text{otherwise} \end{cases}$$

b bits

000…K

ipad = 00110110 , repeat b/8 times

opad = 01011100, repeat b/8 times

HMAC procedure

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

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

HMAC Properties

- HMAC(K, M) = $H[(K^+ \oplus opad) \,||\, H((K^+ \oplus ipad) \,||\, M]]$
- HMAC is a hash function, so it has the properties of the underlying hash too
  - It is collision resistant M' $MAC(K, M) \neq MAC(K, M')$
  - Given HMAC(K, M), an attacker can't learn M – *one way*
  - If the underlying hash is secure, HMAC doesn't reveal M, but it is still deterministic
- You can't verify a tag T if you don't have K
- This means that an attacker can't brute-force the message M without knowing K

MACs: Summary

- Inputs: a secret key and a message
  K.
- Output: a tag on the message
  Replay attack, timestamp & nounce
- A secure MAC is unforgeable: Even if David can trick Alice into creating MACs for messages that David chooses, David cannot create a valid MAC on a message that she hasn't seen before
  K x.
  - Example: HMAC(K, M) = H(($K^+ \oplus opad$) || H(($K^+ \oplus ipad$) || M))
- MACs do not provide confidentiality

① M || MAC.

② Timing Attacks
comparison

1 $M' || MAC(K, M)$

3 change 1 st byte M'
2nd M'

T_2

T_3

Do MACs provide integrity?

- Do MACs provide integrity?

  × key

  - Yes. An attacker cannot tamper with the message without being detected

- Do MACs provide authenticity?

  1. Integrity
  2. Validating of originator
  3. Non-repudiation of origin.

  - It depends on your threat model
  - If only two people have the secret key, MACs provide authenticity: it has a valid MAC, and it's not from me, so it must be from the other person
  - More than one secret key, If a message has a valid MAC, you can be sure it came from *someone with the secret key*, but you can't narrow it down to one person

group key

Authenticated Encryption

Authenticated Encryption: Definition

- **Authenticated encryption** (**AE**): A scheme that simultaneously guarantees confidentiality and integrity (and authenticity, depending on your threat model) on a message
- Two ways of achieving authenticated encryption:
  - Combine schemes that provide confidentiality with schemes that provide integrity → MAC
    ways Encryption
  - Use a scheme that is designed to provide confidentiality and integrity

Scratchpad: Let’s design it together

- You can use:
  - An encryption scheme: Enc(K, M) and Dec(K, M)
  - An unforgeable MAC scheme (e.g. HMAC): MAC(K, M)
- First attempt: Alice sends Enc(K_1, M) and MAC(K_2, M)
  - Integrity? Yes, attacker can’t tamper with the MAC
  - Confidentiality? No, the MAC is not secure
- Idea 1: Let’s compute the MAC on the *ciphertext* instead of the plaintext: Enc(K_1, M) and MAC(k2, Enc(K_1, M))
  - Integrity? Yes, attacker can’t tamper with the MAC
  - Confidentiality? Yes, the MAC might leak info about the ciphertext, but that’s okay
- Idea 2: Let’s encrypt the MAC too: Enc(K_1, M || MAC(K_2, M))
  - Integrity? Yes, attacker can’t tamper with the MAC
  - Confidentiality? Yes, everything is encrypted