On the security of CBC-MAC schemes

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Purpose of MACs

- Used to protect integrity and guarantee origin of data strings.
- Sender and verifier share a secret key (of ***k*** bits).
- Sender inputs data and key to MAC algorithm – output is MAC (short string of bits) which is sent/stored with data.
- Verifier recomputes MAC using received message and secret key and compares.

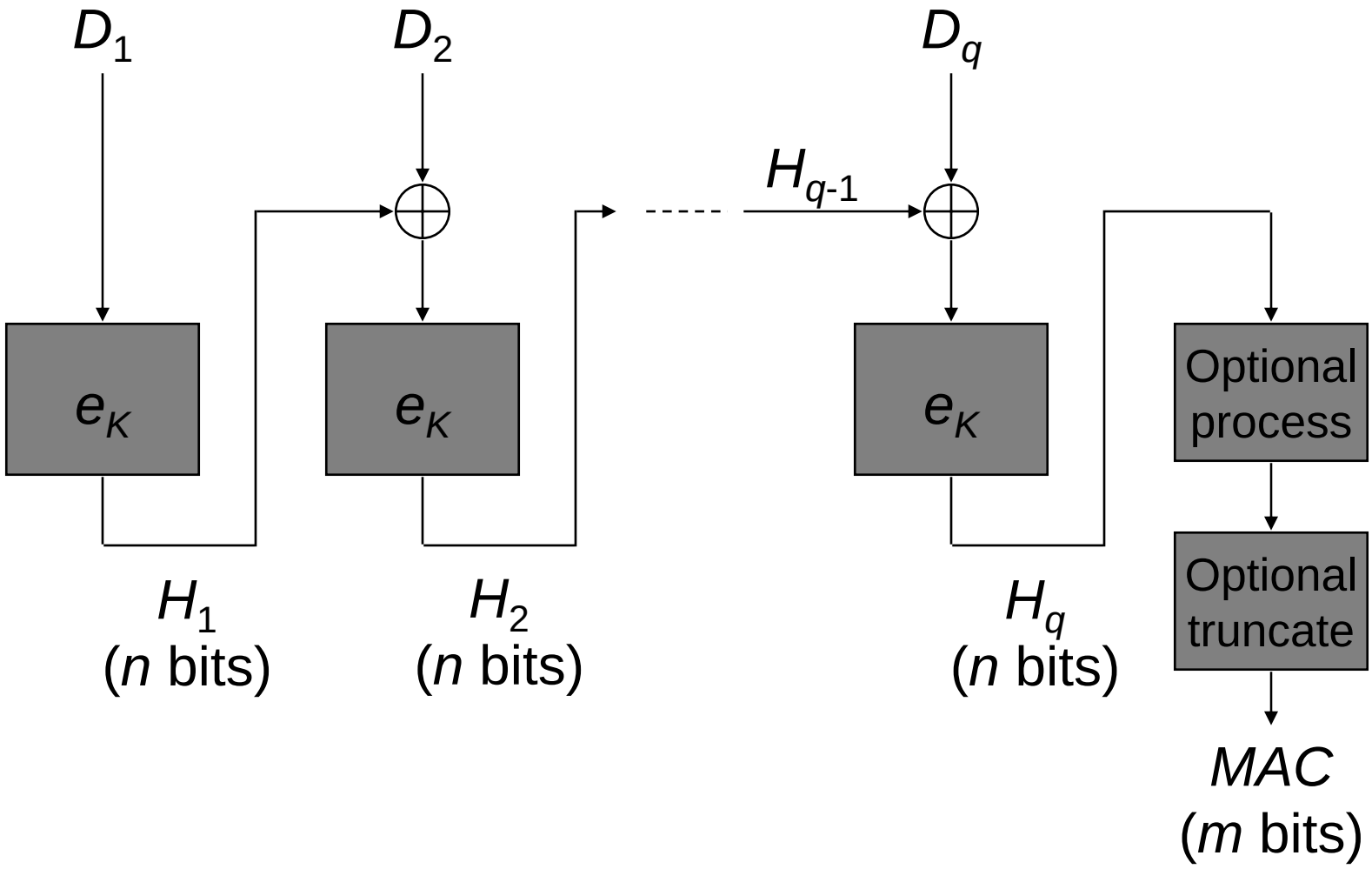
CBC-MACs

- A CBC-MAC is a particular (very popular) type of MAC.
- Computed using a block cipher in CBC (Cipher Block Chaining) mode.
- Write $e_K(P)$ for block cipher encryption of block P (***n*** bits) using secret key K (***k*** bits).
- Similarly, write $d_K(C)$ for block cipher decryption of block C using key K.

CBC-MAC operation

- Divide and pad data to be MACed into n-bit blocks D_1, D_2, …, D_q (n is block length of block cipher, e.g. $n = 64$ for DES).
- The MAC is computed by:
  - put $H_1 = e_K(D_1)$,
  - for $i = 2, 3, ..., q$: put $H_i = e_K(D_i \oplus H_{i-1})$.
- H_q is then subject to an 'optional process' and truncated to m bits to give the MAC.

CBC-MAC calculation



Padding

- Three well known padding methods:
  - **Method 1**: add minimum no. of zeros to make a whole number of blocks.
  - **Method 2**: add single one followed by zeros to make a whole number of blocks.
  - **Method 3**: right-pad with zeros as necessary. Left-pad with extra *n*-bit block containing binary representation of bit-length of unpadded string.
- Padding not sent with MACed message.

Trailing zeros forgeries

- Padding Method 1 allows attacker to add or delete trailing zeros from a message without changing the MAC. **A forgery attack**.
- Arises from fact that Padding Method 1 is not a one-to-one function, i.e. up to *n* unpadded messages map to the same padded message.
- Motive for introduction of Method 2.

Need for optional process

- Suppose a CBC-MAC is computed with no optional process and no truncation (SMAC).
- Suppose we have the MACs for two one-block messages:

$$MAC_1 = eK(D_1), \quad MAC_2 = eK(D_2).$$

- Then MAC_2 is a valid MAC on the two block message: $D_1 \,||\, D_2 \oplus MAC_1$.
- Need to add optional process (or padding method 3) to avoid this ‘cut and paste’ **Forgery attack**.

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Optional processes

- Two well-known optional processes:
  - choose a key K_1 and compute:

$$H_q'' = e_K(d_{K1}(H_q)),$$

  - choose a key K_1 and compute:

$$H_q' = e_{K1}(H_q).$$

- First method results in ANSI Retail MAC (ARMAC) when block cipher = DES
- Second method often called EMAC.

Standard CBC-MACs

- ISO/IEC standard for CBC-MACs (ISO/IEC 9797-1: 1999) contains 6 schemes.
- First three are as follows:
  - Alg. 1 = CBC-MAC with no optional process (SMAC).
  - Alg. 2 = CBC-MAC with optional process as single extra encryption (EMAC).
  - Alg. 3 = CBC-MAC with optional process as extra decryption and encryption (i.e., triple encrypt last block) (ARMAC).

EMAC security

- EMAC has a proof of security (Petrank & Rackoff, 2000).
- For block ciphers with large enough *n* and *k* (128 or more), EMAC is sound choice – with padding method 2 or 3.
- For block ciphers with small *k* (e.g. DES: *k*=56), EMAC insecure, because of simple meet-in-the-middle key recovery attack.
- Attack complexity: $O(2^k)$ encryptions with 1 known MAC.

ARMAC security

- Problems with EMAC (and SMAC), combined with desire to use DES, motivates design of ARMAC.
- ARMAC seems much more resistant to key recovery attacks than EMAC (no proof however).
- Key recovery attack either requires triple DES break (2^k encryptions + 2^k storage) or large number ($2^{n/2}$) of known MACs combined with single DES break (2^k encryptions).

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Rationale

- The standardisation of a block cipher (AES) with larger *n* and *k*, means that it seems appropriate to re-examine ways in which we use block ciphers.
- Modes of operation and commonly used CBC-MAC schemes are quite ‘old’ designs.
- Can we do better?

NIST process

- NIST has an ongoing project to produce new ‘modes’ standards for DES.
- ***Objective***: produce combined encryption + integrity mode (proposal for review in NIST Special Publication 800-38C, September 2003).
- ***Objective***: CBC-MAC standard for AES.
- NIST activity mirrored in ISO, where ISO/IEC 9797-1 currently under review, and Data Encapsulation Mechanisms (DEMs) work just starting (DEM = combined encryption/integrity).

Candidate schemes

- A number of candidate CBC-MAC schemes have been proposed, including:
  - RMAC (Jaulmes, Joux and Valette, 2002),
  - XCBC (Black and Rogaway, 2000), and
  - TMAC and OMAC (Iwata and Kurosawa, 2003).

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RMAC

- RMAC operates as follows.
- Two block cipher keys required (K, K_1).
- To generate a MAC first generate a random salt R (of k bits).
- Then, using the model previously described, RMAC involves the optional process:

$$H_q' = e_{K_1 \oplus \mathrm{R}}(H_q).$$

Rationale of RMAC

- Typically, a CBC-MAC scheme will be subject to forgery attacks requiring $O(2^{n/2})$ known/chosen MACs (based on ‘birthday paradox’ probability).
- For ‘short block’ block ciphers (e.g. 3DES, IDEA, … with $n = 64$) this is sometimes a little ‘close’ to what is possible.
- RMAC objective is to offer greater resistance to ‘birthday’ forgery attacks.

NIST draft

- RMAC was included in NIST special publication 800-38B (November 2002) – essentially a draft standard.
- At that time RMAC was clearly the leading candidate for standardisation.

Reaction to 800-38B

- The release of NIST SP 800-38B provoked a large number of negative comments.
- The result is that RMAC is no longer being seriously considered for NIST adoption.
- The original SP 800-38B and the main comments are available for download at the NIST website.

A simple observation

- Suppose know one RMAC (*M* say) for data *D* (using salt *R*, say).
- Request another MAC (*M′* say) for the same data *D* (uses salt *R′* say).
- Then immediately know that:

  $d_{K_1 \oplus R}(M) = d_{K_1 \oplus R'}(M')$.

- Enables exhaustive search for K_1 with complexity 2^k (and just 2 known MACs).
- This contradicts claims in SP 800-38B.

Some attacks on RMAC

- In (Knudsen & Mitchell, J. Crypt., to appear) a series of *partial key recovery* attacks on RMAC are presented.
- Enable one of the two RMAC keys (K_1) to be recovered with much less than 2^k work.
- Once K_1 is known, very simple forgery attacks become possible (based on ‘cut and paste’ attack).

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XCBC

- XCBC, another CBC-MAC scheme, was proposed by Black & Rogaway in 2000.
- Objective was to define a provably secure CBC-MAC which minimises number of block cipher encryptions/decryptions.
- Address fact that EMAC + pad method 2 can involve 2 ‘extra’ encryptions by comparison with SMAC + pad method 1.

XCBC operation I

- XCBC does not quite fit the general CBC-MAC model presented earlier.
- Use padding method 2 if data string needs padding; otherwise do not pad.
- Avoid ambiguity problems by computing MAC differently depending on whether or not padding was performed.
- Three keys: K, K_1 and K_2 (K has k bits, & K_1, K_2 have n bits).

XCBC operation II

- If no padding then exor K_1 with D_q (last data block).
- If padding used then exor K_2 with D_q.
- Then compute SMAC on (modified) data using key K.

XCBC properties

- Same number of encryptions as SMAC with padding method 1, yet forgery problems removed.
- Proof of security exists.
- Hence optimally efficient with respect to block cipher operations, BUT largish key (384 bits for AES).

TMAC

- To reduce key size, Kurosawa and Iwata (2003) proposed TMAC (T for ‘two key’) using keys K (of k bits) and K' of n bits.
- Derive K_1 and K_2 from K' by putting $K_2 = K'$ and $K_1 = u.K'$ where multiplication takes place in GF(2^n).
- Compute MAC as for XCBC.
- TMAC still has a proof of security.

OMAC

- Iwata and Kurosawa (2003) have recently proposed OMAC (O for ‘one-key’) using just one key K (of k bits).
- Derive K' from K by setting $K' = e_K(0^n)$.
- Then derive K_1 and K_2 from K' as for TMAC.
- Finally, compute MAC as for XCBC.
- OMAC again has a proof of security.

NIST statement

- NIST have not yet published a new draft on CBC-MACs, but have indicated that they are leaning towards OMAC.
- There is also an ‘open call’ for comments on all CBC-MAC schemes.
- Some comments exist on NIST website.
- Thus, now is the time to provide input to NIST!

Partial key recovery attack on TMAC

- Sung, Hong & Lee (2003) described attack against TMAC which allows recovery of K' given $O(2^{n/2})$ known/chosen MACs and trivial computation (no key search).
- Recovering K still requires 2^k work, and proof of security not challenged.
- However, knowing K' does make very trivial forgeries possible.

OMAC attacks

- The TMAC attack works against OMAC, as does a further (different) attack, both allowing recovery of *K‘* given $O(2^{n/2})$ known/chosen MACs.
- As Iwata has pointed out, this is no longer a partial key recovery attack, since *K'* is not part of the key (but is derived from it) – unlike TMAC.
- Nevertheless, recovery of *K'* would allow very trivial forgeries.

What does it mean?

- These attacks do not contradict proofs of security for OMAC and TMAC.
- None of the proofs say anything about security once an attacker has $O(2^{n/2})$ known MACs.
- However, it is arguable that one should still be concerned about what happens at the ‘boundaries’ of the security proof.

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Where next?

- The main choice right now (for NIST) would appear to be between EMAC and OMAC.
- Both have similar provable security.
- OMAC is more efficient.
- However EMAC appears stronger just outside envelope of security proof.
- Views are needed, both for NIST and in near future for ISO.