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The AES-CMAC Algorithm

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Abstract

The National Institute of Standards and Technology (NIST) has recently specified the Cipher-based Message Authentication Code (CMAC), which is equivalent to the One-Key CBC MAC1 (OMAC1) submitted by Iwata and Kurosawa. This memo specifies an authentication algorithm based on CMAC with the 128-bit Advanced Encryption Standard (AES). This new authentication algorithm is named AES-CMAC. The purpose of this document is to make the AES-CMAC algorithm conveniently available to the Internet Community.

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1. Introduction

The National Institute of Standards and Technology (NIST) has recently specified the Cipher-based Message Authentication Code (CMAC). CMAC [NIST-CMAC] is a keyed hash function that is based on a symmetric key block cipher, such as the Advanced Encryption Standard [NIST-AES]. CMAC is equivalent to the One-Key CBC MAC1 (OMAC1) submitted by Iwata and Kurosawa [OMAC1a, OMAC1b]. OMAC1 is an improvement of the eXtended Cipher Block Chaining mode (XCBC) submitted by Black and Rogaway [XCBCa, XCBCb], which itself is an improvement of the basic Cipher Block Chaining-Message Authentication Code (CBC-MAC). XCBC efficiently addresses the security deficiencies of CBC-MAC, and OMAC1 efficiently reduces the key size of XCBC.

AES-CMAC provides stronger assurance of data integrity than a checksum or an error-detecting code. The verification of a checksum or an error-detecting code detects only accidental modifications of the data, while CMAC is designed to detect intentional, unauthorized modifications of the data, as well as accidental modifications.

AES-CMAC achieves a security goal similar to that of HMAC [RFC-HMAC]. Since AES-CMAC is based on a symmetric key block cipher, AES, and HMAC is based on a hash function, such as SHA-1, AES-CMAC is appropriate for information systems in which AES is more readily available than a hash function.

This memo specifies the authentication algorithm based on CMAC with AES-128. This new authentication algorithm is named AES-CMAC.

2. Specification of AES-CMAC

2.1. Basic Definitions

The following table describes the basic definitions necessary to explain the specification of AES-CMAC.

<table>
<tr><th></th><th></th></tr>
<tr><td>x || y</td><td>Concatenation.
x || y is the string x concatenated with the string y.
0000 || 1111 is 00001111.</td></tr>
<tr><td>x XOR y</td><td>Exclusive-OR operation.
For two equal length strings, x and y,
x XOR y is their bit-wise exclusive-OR.</td></tr>
<tr><td>ceil(x)</td><td>Ceiling function.
The smallest integer no smaller than x.
ceil(3.5) is 4. ceil(5) is 5.</td></tr>
<tr><td>x << 1</td><td>Left-shift of the string x by 1 bit.
The most significant bit disappears, and a zero comes into the least significant bit.
10010001 << 1 is 00100010.</td></tr>
<tr><td>0^n</td><td>The string that consists of n zero-bits.
0^3 means 000 in binary format.
10^4 means 10000 in binary format.
10^i means 1 followed by i-times repeated zeros.</td></tr>
<tr><td>MSB(x)</td><td>The most-significant bit of the string x.
MSB(10010000) means 1.</td></tr>
<tr><td>padding(x)</td><td>10^i padded output of input x.
It is described in detail in section 2.4.</td></tr>
<tr><td>Key</td><td>128-bit (16-octet) long key for AES-128.
Denoted by K.</td></tr>
<tr><td>First subkey</td><td>128-bit (16-octet) long first subkey, derived through the subkey generation algorithm from the key K.
Denoted by K1.</td></tr>
</table>

Second subkey	128-bit (16-octet) long second subkey, derived through the subkey generation algorithm from the key K. Denoted by K2.
Message	A message to be authenticated. Denoted by M. The message can be null, which means that the length of M is 0.
Message length	The length of the message M in octets. Denoted by len. The minimum value of the length can be 0. The maximum value of the length is not specified in this document.
AES-128(K,M)	AES-128(K,M) is the 128-bit ciphertext of AES-128 for a 128-bit key, K, and a 128-bit message, M.
MAC	A 128-bit string that is the output of AES-CMAC. Denoted by T. Validating the MAC provides assurance of the integrity and authenticity of the message from the source.
MAC length	By default, the length of the output of AES-CMAC is 128 bits. It is possible to truncate the MAC. The result of the truncation should be taken in most significant bits first order. The MAC length must be specified before the communication starts, and it must not be changed during the lifetime of the key.

2.2. Overview

AES-CMAC uses the Advanced Encryption Standard [NIST-AES] as a building block. To generate a MAC, AES-CMAC takes a secret key, a message of variable length, and the length of the message in octets as inputs and returns a fixed-bit string called a MAC.

The core of AES-CMAC is the basic CBC-MAC. For a message, M, to be authenticated, the CBC-MAC is applied to M. There are two cases of operation in CMAC. Figure 2.1 illustrates the operation of CBC-MAC in both cases. If the size of the input message block is equal to a positive multiple of the block size (namely, 128 bits), the last block shall be exclusive-OR’ed with K1 before processing. Otherwise, the last block shall be padded with 10^i (notation is described in section 2.1) and exclusive-OR’ed with K2. The result of the previous process will be the input of the last encryption. The output of AES-CMAC provides data integrity of the whole input message.

```
 +-----+     +-----+     +-----+     +-----+     +-----+     +---+----+
 | M_1 |     | M_2 |     | M_n |     | M_1 |     | M_2 |     |M_n|10^i|
 +-----+     +-----+     +-----+     +-----+     +-----+     +---+----+
    |           |           |   +--+    |           |           |   +--+
    |     +--->(+)    +--->(+)<-|K1|    |     +--->(+)    +--->(+)<-|K2|
    |     |     |     |     |   +--+    |     |     |     |     |   +--+
 +-----+  |  +-----+  |  +-----+     +-----+  |  +-----+  |  +-----+
 |AES_K|  |  |AES_K|  |  |AES_K|     |AES_K|  |  |AES_K|  |  |AES_K|
 +-----+  |  +-----+  |  +-----+     +-----+  |  +-----+  |  +-----+
    |     |     |     |     |           |     |     |     |     |
    +-----+     +-----+     |           +-----+     +-----+     |
                            |                                   |
                         +-----+                              +-----+
                         |  T  |                              |  T  |
                         +-----+                              +-----+

             (a) positive multiple block length         (b) otherwise
```

Figure 2.1. Illustration of the two cases of AES-CMAC

AES_K is AES-128 with key K.
The message M is divided into blocks M_1,...,M_n,
where M_i is the i-th message block.
The length of M_i is 128 bits for i = 1,...,n-1, and
the length of the last block, M_n, is less than or equal to 128 bits.
K1 is the subkey for the case (a), and
K2 is the subkey for the case (b).
K1 and K2 are generated by the subkey generation algorithm
described in section 2.3.

2.3. Subkey Generation Algorithm

The subkey generation algorithm, Generate_Subkey(), takes a secret key, K, which is just the key for AES-128.

The outputs of the subkey generation algorithm are two subkeys, K1 and K2. We write (K1,K2) := Generate_Subkey(K).

Subkeys K1 and K2 are used in both MAC generation and MAC verification algorithms. K1 is used for the case where the length of the last block is equal to the block length. K2 is used for the case where the length of the last block is less than the block length.

Figure 2.2 specifies the subkey generation algorithm.

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                    Algorithm Generate_Subkey                      +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                                                                   +
+   Input    : K (128-bit key)                                      +
+   Output   : K1 (128-bit first subkey)                            +
+              K2 (128-bit second subkey)                           +
+-------------------------------------------------------------------+
+                                                                   +
+   Constants: const_Zero is 0x00000000000000000000000000000000     +
+              const_Rb   is 0x00000000000000000000000000000087     +
+   Variables: L          for output of AES-128 applied to 0^128    +
+                                                                   +
+   Step 1.  L := AES-128(K, const_Zero);                           +
+   Step 2.  if MSB(L) is equal to 0                                +
+            then    K1 := L << 1;                                  +
+            else    K1 := (L << 1) XOR const_Rb;                   +
+   Step 3.  if MSB(K1) is equal to 0                               +
+            then    K2 := K1 << 1;                                 +
+            else    K2 := (K1 << 1) XOR const_Rb;                  +
+   Step 4.  return K1, K2;                                         +
+                                                                   +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Figure 2.2. Algorithm Generate_Subkey

In step 1, AES-128 with key K is applied to an all-zero input block.

In step 2, K1 is derived through the following operation:

If the most significant bit of L is equal to 0, K1 is the left-shift of L by 1 bit.

Otherwise, K1 is the exclusive-OR of const_Rb and the left-shift of L by 1 bit.

In step 3, K2 is derived through the following operation:

If the most significant bit of K1 is equal to 0, K2 is the left-shift of K1 by 1 bit.

Otherwise, K2 is the exclusive-OR of const_Rb and the left-shift of K1 by 1 bit.

In step 4, (K1,K2) := Generate_Subkey(K) is returned.

The mathematical meaning of the procedures in steps 2 and 3, including const_Rb, can be found in [OMAC1a].

2.4. MAC Generation Algorithm

The MAC generation algorithm, AES-CMAC(), takes three inputs, a secret key, a message, and the length of the message in octets. The secret key, denoted by K, is just the key for AES-128. The message and its length in octets are denoted by M and len, respectively. The message M is denoted by the sequence of M_i, where M_i is the i-th message block. That is, if M consists of n blocks, then M is written as

- M = M_1 || M_2 || ... || M_{n-1} || M_n

The length of M_i is 128 bits for i = 1,...,n-1, and the length of the last block M_n is less than or equal to 128 bits.

The output of the MAC generation algorithm is a 128-bit string, called a MAC, which is used to validate the input message. The MAC is denoted by T, and we write T := AES-CMAC(K,M,len). Validating the MAC provides assurance of the integrity and authenticity of the message from the source.

It is possible to truncate the MAC. According to [NIST-CMAC], at least a 64-bit MAC should be used as protection against guessing attacks. The result of truncation should be taken in most significant bits first order.

The block length of AES-128 is 128 bits (16 octets). There is a special treatment if the length of the message is not a positive multiple of the block length. The special treatment is to pad M with the bit-string 10^i to adjust the length of the last block up to the block length.

For an input string x of r-octets, where 0 <= r < 16, the padding function, padding(x), is defined as follows:

- padding(x) = x || 10^i   where i is 128-8*r-1

That is, padding(x) is the concatenation of x and a single ’1’, followed by the minimum number of ’0’s, so that the total length is equal to 128 bits.

Figure 2.3 describes the MAC generation algorithm.

```
   +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
   +                   Algorithm AES-CMAC                              +
   +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
   +                                                                   +
   +   Input    : K    ( 128-bit key )                                 +
   +            : M    ( message to be authenticated )                 +
   +            : len  ( length of the message in octets )             +
   +   Output   : T    ( message authentication code )                 +
   +                                                                   +
   +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
   +   Constants: const_Zero is 0x00000000000000000000000000000000     +
   +              const_Bsize is 16                                    +
   +                                                                   +
   +   Variables: K1, K2 for 128-bit subkeys                           +
   +              M_i is the i-th block (i=1..ceil(len/const_Bsize))   +
   +              M_last is the last block xor-ed with K1 or K2        +
   +              n      for number of blocks to be processed          +
   +              r      for number of octets of last block            +
   +              flag   for denoting if last block is complete or not +
   +                                                                   +
   +   Step 1.  (K1,K2) := Generate_Subkey(K);                         +
   +   Step 2.  n := ceil(len/const_Bsize);                            +
   +   Step 3.  if n = 0                                               +
   +            then                                                   +
   +                 n := 1;                                           +
   +                 flag := false;                                    +
   +            else                                                   +
   +                 if len mod const_Bsize is 0                       +
   +                 then flag := true;                                +
   +                 else flag := false;                               +
   +                                                                   +
   +   Step 4.  if flag is true                                        +
   +            then M_last := M_n XOR K1;                             +
   +            else M_last := padding(M_n) XOR K2;                    +
   +   Step 5.  X := const_Zero;                                       +
   +   Step 6.  for i := 1 to n-1 do                                   +
   +                begin                                              +
   +                  Y := X XOR M_i;                                  +
   +                  X := AES-128(K,Y);                               +
   +                end                                                +
   +            Y := M_last XOR X;                                     +
   +            T := AES-128(K,Y);                                     +
   +   Step 7.  return T;                                              +
   +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Figure 2.3. Algorithm AES-CMAC

In step 1, subkeys K1 and K2 are derived from K through the subkey generation algorithm.

In step 2, the number of blocks, n, is calculated. The number of blocks is the smallest integer value greater than or equal to the quotient determined by dividing the length parameter by the block length, 16 octets.

In step 3, the length of the input message is checked. If the input length is 0 (null), the number of blocks to be processed shall be 1, and the flag shall be marked as not-complete-block (false). Otherwise, if the last block length is 128 bits, the flag is marked as complete-block (true); else mark the flag as not-complete-block (false).

In step 4, M_last is calculated by exclusive-OR'ing M_n and one of the previously calculated subkeys. If the last block is a complete block (true), then M_last is the exclusive-OR of M_n and K1. Otherwise, M_last is the exclusive-OR of padding(M_n) and K2.

In step 5, the variable X is initialized.

In step 6, the basic CBC-MAC is applied to M_1,...,M_{n-1},M_last.

In step 7, the 128-bit MAC, T := AES-CMAC(K,M,len), is returned.

If necessary, the MAC is truncated before it is returned.

2.5. MAC Verification Algorithm

The verification of the MAC is simply done by a MAC recomputation. We use the MAC generation algorithm, which is described in section 2.4.

The MAC verification algorithm, Verify_MAC(), takes four inputs, a secret key, a message, the length of the message in octets, and the received MAC. These are denoted by K, M, len, and T', respectively.

The output of the MAC verification algorithm is either INVALID or VALID.

Figure 2.4 describes the MAC verification algorithm.

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                      Algorithm Verify_MAC                         +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                                                                   +
+   Input    : K    ( 128-bit Key )                                 +
+            : M    ( message to be verified )                      +
+            : len  ( length of the message in octets )             +
+            : T’   ( the received MAC to be verified )             +
+   Output   : INVALID or VALID                                     +
+                                                                   +
+-------------------------------------------------------------------+
+                                                                   +
+   Step 1.  T* := AES-CMAC(K,M,len);                               +
+   Step 2.  if T* is equal to T’                                   +
+            then                                                   +
+                 return VALID;                                     +
+            else                                                   +
+                 return INVALID;                                   +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Figure 2.4. Algorithm Verify_MAC

In step 1, T* is derived from K, M, and len through the MAC generation algorithm.

In step 2, T* and T’ are compared. If T* is equal to T’, then return VALID; otherwise return INVALID.

If the output is INVALID, then the message is definitely not authentic, i.e., it did not originate from a source that executed the generation process on the message to produce the purported MAC.

If the output is VALID, then the design of the AES-CMAC provides assurance that the message is authentic and, hence, was not corrupted in transit; however, this assurance, as for any MAC algorithm, is not absolute.

3. Security Considerations

The security provided by AES-CMAC is built on the strong cryptographic algorithm AES. However, as is true with any cryptographic algorithm, part of its strength lies in the secret key, K, and the correctness of the implementation in all of the participating systems. If the secret key is compromised or inappropriately shared, it guarantees neither authentication nor integrity of message at all. The secret key shall be generated in a way that meets the pseudo randomness requirement of RFC 4086 [RFC4086] and should be kept safe. If and only if AES-CMAC is used properly it provides the authentication and integrity that meet the best current practice of message authentication.

4. Test Vectors

The following test vectors are the same as those of [NIST-CMAC]. The following vectors are also the output of the test program in Appendix A.

```
--------------------------------------------------
Subkey Generation
K              2b7e1516 28aed2a6 abf71588 09cf4f3c
AES-128(key,0) 7df76b0c 1ab899b3 3e42f047 b91b546f
K1             fbeed618 35713366 7c85e08f 7236a8de
K2             f7ddac30 6ae266cc f90bc11e e46d513b
--------------------------------------------------

--------------------------------------------------
Example 1: len = 0
M              <empty string>
AES-CMAC       bb1d6929 e9593728 7fa37d12 9b756746
--------------------------------------------------

Example 2: len = 16
M              6bc1bee2 2e409f96 e93d7e11 7393172a
AES-CMAC       070a16b4 6b4d4144 f79bdd9d d04a287c
--------------------------------------------------

Example 3: len = 40
M              6bc1bee2 2e409f96 e93d7e11 7393172a
               ae2d8a57 1e03ac9c 9eb76fac 45af8e51
               30c81c46 a35ce411
AES-CMAC       dfa66747 de9ae630 30ca3261 1497c827
--------------------------------------------------

Example 4: len = 64
M              6bc1bee2 2e409f96 e93d7e11 7393172a
               ae2d8a57 1e03ac9c 9eb76fac 45af8e51
               30c81c46 a35ce411 e5fbc119 1a0a52ef
               f69f2445 df4f9b17 ad2b417b e66c3710
AES-CMAC       51f0bebf 7e3b9d92 fc497417 79363cfe
--------------------------------------------------
```

5. Acknowledgement

Portions of the text herein are borrowed from [NIST-CMAC]. We appreciate the OMAC1 authors, the SP 800-38B author, and Russ Housley for his useful comments and guidance, which have been incorporated herein. We also thank Alfred Hoenes for many useful comments. This memo was prepared while Tetsu Iwata was at Ibaraki University, Japan.

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6. References

6.1. Normative References

[NIST-CMAC] NIST, Special Publication 800-38B, "Recommendation for Block Cipher Modes of Operation: The CMAC Mode for Authentication", May 2005.

[NIST-AES] NIST, FIPS 197, "Advanced Encryption Standard (AES)", November 2001. http://csrc.nist.gov/publications/fips/fips197/fips-197.pdf

[RFC4086] Eastlake, D., 3rd, Schiller, J., and S. Crocker, "Randomness Requirements for Security", BCP 106, RFC 4086, June 2005.

6.2. Informative References

[RFC-HMAC] Krawczyk, H., Bellare, M., and R. Canetti, "HMAC: Keyed-Hashing for Message Authentication", RFC 2104, February 1997.

[OMAC1a] Tetsu Iwata and Kaoru Kurosawa, "OMAC: One-Key CBC MAC", Fast Software Encryption, FSE 2003, LNCS 2887, pp. 129-153, Springer-Verlag, 2003.

[OMAC1b] Tetsu Iwata and Kaoru Kurosawa, "OMAC: One-Key CBC MAC", Submission to NIST, December 2002. Available from the NIST modes of operation web site at http://csrc.nist.gov/CryptoToolkit/modes/proposedmodes/omac/omac-spec.pdf

[XCBCa]	John Black and Phillip Rogaway, "A Suggestion for Handling Arbitrary-Length Messages with the CBC MAC", NIST Second Modes of Operation Workshop, August 2001. Available from the NIST modes of operation web site at http://csrc.nist.gov/CryptoToolkit/modes/proposedmodes/xcbc-mac/xcbc-mac-spec.pdf
[XCBCb]	John Black and Phillip Rogaway, "CBC MACs for Arbitrary-Length Messages: The Three-Key Constructions", Journal of Cryptology, Vol. 18, No. 2, pp. 111-132, Springer-Verlag, Spring 2005.

Appendix A. Test Code

This C source is designed to generate the test vectors that appear in this memo to verify correctness of the algorithm. The source code is not intended for use in commercial products.

```
/****************************************************************/
/* AES-CMAC with AES-128 bit                                    */
/* CMAC     Algorithm described in SP800-38B                    */
/* Author: Junhyuk Song (junhyuk.song@samsung.com)              */
/*         Jicheol Lee  (jicheol.lee@samsung.com)               */
/****************************************************************/

#include <stdio.h>

/* For CMAC Calculation */
unsigned char const_Rb[16] = {
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x87
};
unsigned char const_Zero[16] = {
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00
};

/* Basic Functions */

void xor_128(unsigned char *a, unsigned char *b, unsigned char *out)
{
    int i;
    for (i=0;i<16; i++)
    {
        out[i] = a[i] ^ b[i];
    }
}

void print_hex(char *str, unsigned char *buf, int len)
{
    int     i;

    for ( i=0; i<len; i++ ) {
        if ( (i % 16) == 0 && i != 0 ) printf(str);
        printf("%02x", buf[i]);
        if ( (i % 4) == 3 ) printf(" ");
        if ( (i % 16) == 15 ) printf("\n");
    }
    if ( (i % 16) != 0 ) printf("\n");
}
```

```
   void print128(unsigned char *bytes)
   {
       int         j;
       for (j=0; j<16;j++) {
           printf("%02x",bytes[j]);
           if ( (j%4) == 3 ) printf(" ");
       }
   }

   void print96(unsigned char *bytes)
   {
       int         j;
       for (j=0; j<12;j++) {
           printf("%02x",bytes[j]);
           if ( (j%4) == 3 ) printf(" ");
       }
   }

   /* AES-CMAC Generation Function */

   void leftshift_onebit(unsigned char *input,unsigned char *output)
   {
       int         i;
       unsigned char overflow = 0;

       for ( i=15; i>=0; i-- ) {
           output[i] = input[i] << 1;
           output[i] |= overflow;
           overflow = (input[i] & 0x80)?1:0;
       }
       return;
   }

   void generate_subkey(unsigned char *key, unsigned char *K1, unsigned
                        char *K2)
   {
       unsigned char L[16];
       unsigned char Z[16];
       unsigned char tmp[16];
       int i;

       for ( i=0; i<16; i++ ) Z[i] = 0;

       AES_128(key,Z,L);

       if ( (L[0] & 0x80) == 0 ) { /* If MSB(L) = 0, then K1 = L << 1 */
           leftshift_onebit(L,K1);
       } else {    /* Else K1 = ( L << 1 ) (+) Rb */
```

```
          leftshift_onebit(L,tmp);
          xor_128(tmp,const_Rb,K1);
      }

      if ( (K1[0] & 0x80) == 0 ) {
          leftshift_onebit(K1,K2);
      } else {
          leftshift_onebit(K1,tmp);
          xor_128(tmp,const_Rb,K2);
      }
      return;
  }

  void padding ( unsigned char *lastb, unsigned char *pad, int length )
  {
      int         j;

      /* original last block */
      for ( j=0; j<16; j++ ) {
          if ( j < length ) {
              pad[j] = lastb[j];
          } else if ( j == length ) {
              pad[j] = 0x80;
          } else {
              pad[j] = 0x00;
          }
      }
  }

  void AES_CMAC ( unsigned char *key, unsigned char *input, int length,
                  unsigned char *mac )
  {
      unsigned char       X[16],Y[16], M_last[16], padded[16];
      unsigned char       K1[16], K2[16];
      int         n, i, flag;
      generate_subkey(key,K1,K2);

      n = (length+15) / 16;       /* n is number of rounds */

      if ( n == 0 ) {
          n = 1;
          flag = 0;
      } else {
          if ( (length%16) == 0 ) { /* last block is a complete block */
              flag = 1;
          } else { /* last block is not complete block */
              flag = 0;
          }
```

```
      }

      if ( flag ) { /* last block is complete block */
          xor_128(&input[16*(n-1)],K1,M_last);
      } else {
          padding(&input[16*(n-1)],padded,length%16);
          xor_128(padded,K2,M_last);
      }

      for ( i=0; i<16; i++ ) X[i] = 0;
      for ( i=0; i<n-1; i++ ) {
          xor_128(X,&input[16*i],Y); /* Y := Mi (+) X  */
          AES_128(key,Y,X);      /* X := AES-128(KEY, Y); */
      }

      xor_128(X,M_last,Y);
      AES_128(key,Y,X);

      for ( i=0; i<16; i++ ) {
          mac[i] = X[i];
      }
  }

  int main()
  {
      unsigned char L[16], K1[16], K2[16], T[16], TT[12];
      unsigned char M[64] = {
          0x6b, 0xc1, 0xbe, 0xe2, 0x2e, 0x40, 0x9f, 0x96,
          0xe9, 0x3d, 0x7e, 0x11, 0x73, 0x93, 0x17, 0x2a,
          0xae, 0x2d, 0x8a, 0x57, 0x1e, 0x03, 0xac, 0x9c,
          0x9e, 0xb7, 0x6f, 0xac, 0x45, 0xaf, 0x8e, 0x51,
          0x30, 0xc8, 0x1c, 0x46, 0xa3, 0x5c, 0xe4, 0x11,
          0xe5, 0xfb, 0xc1, 0x19, 0x1a, 0x0a, 0x52, 0xef,
          0xf6, 0x9f, 0x24, 0x45, 0xdf, 0x4f, 0x9b, 0x17,
          0xad, 0x2b, 0x41, 0x7b, 0xe6, 0x6c, 0x37, 0x10
      };
      unsigned char key[16] = {
          0x2b, 0x7e, 0x15, 0x16, 0x28, 0xae, 0xd2, 0xa6,
          0xab, 0xf7, 0x15, 0x88, 0x09, 0xcf, 0x4f, 0x3c
      };

      printf("--------------------------------------------------\n");
      printf("K              "); print128(key); printf("\n");

      printf("\nSubkey Generation\n");
      AES_128(key,const_Zero,L);
      printf("AES_128(key,0) "); print128(L); printf("\n");
      generate_subkey(key,K1,K2);
```

```
      printf("K1             "); print128(K1); printf("\n");
      printf("K2             "); print128(K2); printf("\n");

      printf("\nExample 1: len = 0\n");
      printf("M              "); printf("<empty string>\n");

      AES_CMAC(key,M,0,T);
      printf("AES_CMAC       "); print128(T); printf("\n");

      printf("\nExample 2: len = 16\n");
      printf("M              "); print_hex("                ",M,16);
      AES_CMAC(key,M,16,T);
      printf("AES_CMAC       "); print128(T); printf("\n");
      printf("\nExample 3: len = 40\n");
      printf("M              "); print_hex("               ",M,40);
      AES_CMAC(key,M,40,T);
      printf("AES_CMAC       "); print128(T); printf("\n");

      printf("\nExample 4: len = 64\n");
      printf("M              "); print_hex("               ",M,64);
      AES_CMAC(key,M,64,T);
      printf("AES_CMAC       "); print128(T); printf("\n");

      printf("--------------------------------------------------\n");

      return 0;
  }
```

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