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BSI Standards Publication

Information security — Message authentication codes (MACs)

Part 2: Mechanisms using a dedicated hash-function

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National foreword

This British Standard is the UK implementation of ISO/IEC 9797-2:2021, incorporating corrigendum November 2024. It supersedes BS ISO/IEC 9797-2:2011, which is withdrawn.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by ISO/IEC corrigendum November 2024 is indicated in the text by ▌AC1⟩ ⟨AC1▐.

The UK participation in its preparation was entrusted to Technical Committee IST/33/2, Cryptography and Security Mechanisms.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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Information security — Message authentication codes (MACs) —

Part 2: Mechanisms using a dedicated hash-function

Sécurité de l'information — Codes d'authentication de message (MAC) —

Partie 2: Mécanismes utilisant une fonction de hachage dédiée

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives or www.iec.ch/members_experts/refdocs).

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This document was prepared by Joint Technical Committee ISO/IEC JTC 1, *Information technology*, SC 27, *Information security, cybersecurity and privacy protection*.

This third edition cancels and replaces the second edition (ISO/IEC 9797-2:2011), which has been technically revised.

The main changes compared to the previous edition are as follows:

— Using dedicated hash-function 17 for MAC Algorithms 1 and 3 has been added;

— Using dedicated hash-functions 11, 12, 13 to 16, and 17 for MAC Algorithm 2 has been added;

— MAC Algorithm 4 based on Keccak, a primitive in the definition of dedicated hash-functions 13 to 16 has been added.

A list of all parts in the ISO/IEC 9797 series can be found on the ISO and IEC websites.

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Information security — Message authentication codes (MACs) —

Part 2: Mechanisms using a dedicated hash-function

1 Scope

This document specifies MAC algorithms that use a secret key and a hash-function (or its round-function or sponge function) to calculate an *m*-bit MAC. These mechanisms can be used as data integrity mechanisms to verify that data has not been altered in an unauthorized manner.

NOTE A general framework for the provision of integrity services is specified in ISO/IEC 10181-6.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 10118-3, *IT Security techniques — Hash-functions — Part 3: Dedicated hash-functions*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
block
bit-string of length L_1, i.e. the length of the first input to the round-function

[SOURCE: ISO/IEC 10118-3:2018, 3.1]

3.2
entropy
measure of the disorder, randomness or variability in a closed system

Note 1 to entry: The entropy of a random variable X is a mathematical measure of the amount of information provided by an observation of X.

[SOURCE: ISO/IEC 18031:2011, 3.11]

3.3
input data string
string of bits which is the input to a MAC algorithm

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3.4
hash-code
string of bits which is the output of a hash-function

[SOURCE: ISO/IEC 10118-1:2016, 3.3]

3.5
hash-function
function which maps strings of bits of variable (but usually upper bounded) length to fixed-length strings of bits, satisfying the following two properties:

— for a given output, it is computationally infeasible to find an input which maps to this output;

— for a given input, it is computationally infeasible to find a second input which maps to the same output

Note 1 to entry: Computational infeasibility depends on the specific security requirements and environment. Refer to ISO/IEC 10118-1:2016, Annex C.

[SOURCE: ISO/IEC 10118-1:2016, 3.4, modified — "feasability" in Note 1 to entry changed to "infeasability".]

3.6
initializing value
value used in defining the starting point of a hash-function

[SOURCE: ISO/IEC 10118-1:2016, 3.5, modified — Note 1 to entry removed]

3.7
MAC algorithm key
key that controls the operation of a MAC algorithm

[SOURCE: ISO/IEC 9797-1:2011, 3.8]

3.8
message authentication code
MAC
string of bits which is the output of a MAC algorithm

Note 1 to entry: A MAC is sometimes called a cryptographic check value (see for example ISO 7498-2[1]).

[SOURCE: ISO/IEC 9797-1:2011, 3.9]

3.9
message authentication code algorithm
MAC algorithm
algorithm for computing a function which maps strings of bits and a secret key to fixed-length strings of bits, satisfying the following two properties:

— for any key and any input string the function can be computed efficiently;

— for any fixed key, and given no prior knowledge of the key, it is computationally infeasible to compute the function value on any new input string, even given knowledge of the set of input strings and corresponding function values, where the value of the ith input string may have been chosen after observing the value of the first i-1 function values (for integer $i > 1$)

Note 1 to entry: A MAC algorithm is sometimes called a cryptographic check function (see for example ISO 7498-2).

Note 2 to entry: Computational infeasibility depends on the user's specific security requirements and environment.

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[SOURCE: ISO/IEC 9797-1:2011, 3.10 modified — "feasability" in Note 2 to entry changed to "infeasability".]

3.10
output transformation
function that is applied at the end of the MAC algorithm, before the truncation operation

[SOURCE: ISO/IEC 9797-1:2011, 3.12]

3.11
padding
appending extra bits to a data string

[SOURCE: ISO/IEC 10118-1:2016, 3.7]

3.12
round-function
function ϕ (..,..) that transforms two binary strings of lengths L_1 and L_2 to a binary string of length L_2 that is used iteratively as part of a hash-function, where it combines a data string of length L_1 with the previous output of length L_2 or the initializing value

Note 1 to entry: The literature on this subject contains a variety of terms that have the same or similar meaning as round-function. Compression function and iterative function are some examples.

[SOURCE: ISO/IEC 10118-1:2016, 3.8]

3.13
security strength
number associated with the amount of work required to break a cryptographic algorithm or system and specified in bits such that security strength s bits implies the required number of operations is 2^s

Note 1 to entry: Computationally infeasible in 3.2, 3.6 and 3.10 implies the security strength is at least 112 bits. Refer to ISO/IEC 10118-1:2016, Annex C.

3.14
word
string of 32 bits used in dedicated hash-functions 1, 2, 3, 4, 8 and 17 or a string of 64 bits used in dedicated hash-functions 5, 6, 9 and 10 of ISO/IEC 10118-3:2018

[SOURCE: ISO/IEC 10118-3:2018, 3.2, modified — added specific bit lengths, 32 bits or 64 bits, for different dedicated hash-functions.]

4 Symbols and notation

C_i, C'_i	constant words used in the round-functions
D	input data string, i.e. the data string to be input to the MAC algorithm
$\bar{D}$	padded data string
$j \sim X$	string obtained from a string X at least j bits in length by taking the leftmost j bits of X
H	hash-code
H', H''	strings of L_2 bits which are used in the MAC algorithm computation to store an intermediate result
h	hash-function
h'	hash-function h with modified constants and modified IV

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$\bar{h}$ simplified hash-function h without the padding and length appending, and without truncating the round-function output (L_2 bits) to its leftmost L_H bits

NOTE 1 $\bar{h}$ is applied to input strings with a length that is a positive integer multiple of L_1.

NOTE 2 The output of $\bar{h}$ is L_2 bits rather than L_H bits; in particular, in dedicated hash-functions 6 and 8 defined in ISO/IEC 10118-3:2018, L_H is always smaller than L_2.

IV initializing value

IV', IV_1, IV_2 initializing values

k length (in bits) of the MAC algorithm key

K MAC algorithm key

K', K_0, K_1, K_2, $\bar{K}$, $\bar{K}_1$, $\bar{K}_2$ secret keys derived to be used for a MAC algorithm

$K_1[i]$ i^{th} word in the derived key K_1

KT first input string of the function ϕ' used in the output transformation step of MAC Algorithm 1

$\tilde{L}$ bit string encoding the message length in MAC Algorithm 3

L_X length (in bits) of a bit-string X

L_1 length (in bits) of the first of the two input strings to the round-function, ϕ

L_2 length (in bits) of the second of the two input strings to the round-function, ϕ, of the output string from the round-function, ϕ, and of IV

m length (in bits) of the MAC

$OPAD$, $IPAD$ constant strings used in MAC Algorithm 2

q number of blocks in the input data string D after the padding and splitting process

R, S_0, S_1, S_2 constant strings used in the computation of the constants for MAC Algorithm 1 and MAC Algorithm 3

T_0, T_1, T_2, U_0, U_1, U_2 constant strings used in the key derivation for MAC Algorithm 1 and MAC Algorithm 3

w length (in bits) of a word; w is 32 when using dedicated hash-functions 1, 2, 3, 4, 8 and 17 of ISO/IEC 10118-3:2018, and w is 64 when using dedicated hash-functions 5, 6, 9 and 10 of ISO/IEC 10118-3:2018

$X \oplus Y$ bitwise exclusive-or of bit-strings X and Y

$X \| Y$ concatenation of bit-strings X and Y (in that order)

: = symbol denoting the "set equal to" operation used in the procedural specifications of MAC algorithms, where it indicates that the value of the string on the left side of the symbol shall be made equal to the value of the expression on the right side of the symbol

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ϕ round-function, i.e. if X and Y are bit-strings of lengths L_1 and L_2 respectively, then $\phi(X, Y)$ is the string obtained by applying ϕ to X and Y

ϕ' modified round-function with constants different from those used in the original round function

Ψ modulo 2^w addition operation, where w is the number of bits in a word, i.e. if A and B are words, then AΨB is the word obtained by treating A and B as the binary representations of integers and computing their sum modulo 2^w, and the result is constrained to lie between 0 and $2^w - 1$ inclusive

The value of w is 32 in dedicated hash-functions 1, 2, 3, 4, 8 and 17, and 64 in dedicated hash-functions 5, 6, 9 and 10.

AC1 $\lceil x \rceil$ the smallest integer greater than or equal to the real number x AC1

5 Requirements

Users who wish to employ a MAC algorithm from this document shall select:

— a dedicated hash-function from the functions specified in ISO/IEC 10118-3:2018 so that the hash-function and its round-function or its sponge function is implemented or suitable to use; a MAC algorithm amongst those specified in Clauses 6, 7, 8 and 9 which can use the selected hash-function or its round-function or sponge function; and

— the length (in bits) m of the MAC, where m is at least 32.

The use of dedicated hash-functions 7 and 9 to 16 from ISO/IEC 10118-3 with MAC Algorithms 1 and 3 is not specified in this document. The use of dedicated hash-functions 9 and 10 from ISO/IEC 10118-3 with MAC Algorithm 2 is also not specified in this document. MAC Algorithm 4 makes use of the Keccak function, a primitive (known as a sponge function) used in defining dedicated hash-functions 13 to 16 from ISO/IEC 10118-3. The permitted combinations of MAC algorithms and hash-functions are summarized in Table 1.

Table 1 — Permitted combinations of MAC algorithms and dedicated hash-functions

Dedicated hash-function in ISO/IEC 10118-3	MAC Algorithm 1	MAC Algorithm 2	MAC Algorithm 3	MAC Algorithm 4
1 RIPEMD-160	√	√	√	
2 RIPEMD-128	√	√	√	
3 SHA-1	√	√	√	
4 SHA-256	√	√	√	
5 SHA-512	√	√	√	
6 SHA-384	√	√	√	
7 Whirlpool		√		
8 SHA-224	√	√	√	
9 SHA-512/224				
10 SHA-512/256				
11 STREEBOG 512		√		
12 STREEBOG 256		√		
13 SHA3–224		√		√
14 SHA3–256		√		√
15 SHA3–384		√		√
16 SHA3–512		√		√
17 SM3	√	√	√	

Agreement on these choices amongst the users is essential for use of the data integrity mechanism.

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The key K used in a MAC algorithm shall have entropy that meets or exceeds the security strength to be provided by the MAC algorithm.

In every case, the MAC algorithm key K shall be chosen such that every possible key is approximately equally likely to be selected.

For MAC Algorithms 1 and 2, the length m of the MAC is a positive integer less than or equal to the length of the hash-code L_H. For MAC Algorithm 2, the length m of MAC value shall be at least 32 bits. For MAC Algorithm 3, the length m of the MAC is a positive integer less than or equal to half the length of the hash-code, i.e. $m \leq L_H/2$. The length in bits of the input data string may be limited by the dedicated hash-function and/or the MAC algorithm and is discussed for each MAC algorithm. For MAC Algorithm 4, the length in bits of the input data string D shall be at most $2^{2\,040} - 1$. The selection of a specific MAC Algorithm, dedicated hash-function as specified in Table 1, and value for m is beyond the scope of this document.

These choices affect the security level of the MAC algorithm. For a detailed discussion, see Annex C. The key used for calculating and verifying the MAC is the same. If the input data string is also being enciphered, the key used for the calculation of the MAC should be different from that used for encipherment, because it is considered as good cryptographic practice to have independent keys for confidentiality and for data integrity.

Annex A lists the object identifiers which shall be used to identify the mechanisms defined in this document.

Annex B provides numerical examples for the MAC algorithms specified in this document to be used for checking the correctness of implementations.

Annex C describes major attacks and proofs of security for the MAC algorithms specified in this document.

6 MAC Algorithm 1

6.1 General

This clause contains a description of MDx-MAC[10] with dedicated hash-functions 1 to 6, 8 and 17. Table 2 shows the commonly used names of MDx-MAC with individual dedicated hash-functions.

Table 2 — The MDx-MAC algorithm with different dedicated hash-functions

Dedicated hash-function:	The MDx-MAC algorithm is also known as
Dedicated hash-function 1	RIPEMD-160-MAC
Dedicated hash-function 2	RIPEMD-128-MAC
Dedicated hash-function 3	SHA-1-MAC
Dedicated hash-function 4	SHA-256-MAC
Dedicated hash-function 5	SHA-512-MAC
Dedicated hash-function 6	SHA-384-MAC
Dedicated hash-function 8	SHA-224-MAC
Dedicated hash-function 17	SM3-MAC

The use of MAC Algorithm 1 with dedicated hash-functions 7 and 9 to 16 of ISO/IEC 10118-3 is not specified in this document.

MAC Algorithm 1 requires one application of the hash-function to compute a MAC value but requires that the constants in the corresponding round-function be modified. The hash-function shall be selected from dedicated hash-functions 1 to 6, 8 and 17 from ISO/IEC 10118-3. MAC Algorithm 1 can accommodate the maximum of 128 bit key K and therefore provide at most 128 bits security strength. For MAC Algorithm 1, the length in bits of the input data string D shall be at most $2^{64} - 1$ when using

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dedicated hash-functions 1, 2, 3, 4, 8 and 17, and at most $2^{128} - 1$ when using dedicated hash-functions 5 and 6.

6.2 Description of MAC Algorithm 1

6.2.1 General

MAC Algorithm 1 involves the following five steps: key expansion, modification of the constants and the *IV*, hashing operation, output transformation, and truncation.

6.2.2 Step 1 (key expansion)

[AC1] If K is shorter than 128 bits, concatenate K to itself $\lceil 128/k \rceil$ times and select the leftmost 128 bits of the result to form the 128-bit key K': [AC1]

$K' := 128 \sim (K \,||\, K \,||\, \ldots \,||\, K)$. If the length (in bits) of K is greater than or equal to 128, $K' := 128 \sim K$.

Compute the derived keys K_0, K_1, and K_2 as follows:

$K_0 := \bar{h}\,(K' \,||\, U_0 \,||\, K')$

$K_1 := 128 \sim \bar{h}\,(K' \,||\, U_1 \,||\, K')$, when using dedicated hash-functions 1, 2 and 3

$K_1 := 256 \sim \bar{h}\,(K' \,||\, U_1 \,||\, K')$, when using dedicated hash-functions 4, 5, 6, 8 and 17

$K_2 := 128 \sim \bar{h}\,(K' \,||\, U_2 \,||\, K')$

Here $\bar{h}$ is a simplified hash-function h selected from dedicated hash-functions listed in Table 2 and U_0, U_1, and U_2 are 768-bit constants that are defined in 6.4.1.

Padding and length appending can be omitted because in this case the length of the input string is either L_1 bits or $2L_1$ bits.

When deriving K_0, truncation is omitted and the length of K_0 is always L_2 bits.

When using dedicated hash-functions 1, 2, 3, 5 and 6, the derived key K_1 is split into four words denoted by $K_1[i]$ $(0 \le i \le 3)$, i.e.

$K_1 = K_1[0] \,||\, K_1[1] \,||\, K_1[2] \,||\, K_1[3]$

When using dedicated hash-functions 4, 8 and 17, the derived key K_1 is split into eight words denoted by $K_1[i]$ $(0 \le i \le 7)$, i.e:

[AC1] $K_1 = K_1[0] \,||\, K_1[1] \,||\, K_1[2] \,||\, K_1[3] \,||\, K_1[4] \,||\, K_1[5] \,||\, K_1[6] \,||\, K_1[7]$ [AC1]

To convert a string into words, a byte ordering convention is required. The byte ordering convention for this conversion is that which is defined for the selected dedicated hash-functions in ISO/IEC 10118-3.

6.2.3 Step 2 (modification of the constants and the *IV*)

When using dedicated hash-functions 1, 2, 3, 4, 5, 6, 8 and 17, the additive constants used in the round-function are modified by the modulo 2^w addition of a word of K_1, for example:

$C_0 := C_0 \,\Psi\, K_1[0]$

Precisely which word of K_1 is added to each constant depends on the hash-function in use, and is specified in 6.4.

The initializing value, *IV*, of the hash-function is replaced by $IV' := K_0$.

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6.2.4 Step 3 (hashing operation)

The string which is input to the modified hash-function h' is equal to the input data string D, i.e.

$H' := h'(D)$.

6.2.5 Step 4 (output transformation)

The modified round-function ϕ' is applied one additional time, with as first input the string KT (defined below) and as second input the string H' (the result of Step 3), i.e.:

$H'' := \phi'(KT, H')$.

For dedicated hash-functions 1, 2, 3, 4, 8 and 17:

$KT = K_2 \,||\, (K_2 \oplus T_0) \,||\, (K_2 \oplus T_1) \,||\, (K_2 \oplus T_2)$

For dedicated hash-functions 5 and 6:

$KT = K_2 \,||\, (K_2 \oplus T_0) \,||\, (K_2 \oplus T_1) \,||\, (K_2 \oplus T_2) \,||\, K_2 \,||\, (K_2 \oplus T_0) \,||\, (K_2 \oplus T_1) \,||\, (K_2 \oplus T_2)$

Here T_0, T_1, and T_2 are 128-bit strings defined in 6.4 for each dedicated hash-function.

The output transformation corresponds to processing an additional data block derived from K_2 after padding and appending of the length field.

6.2.6 Step 5 (truncation)

The MAC of m bits is derived by taking the leftmost m bits of the string H'', i.e.

$\text{MAC} := m \sim H''$

6.3 Efficiency

If the padded data string (where the padding algorithm depends on the selected hash-function) contains q blocks, then MAC Algorithm 1 requires $q + 7$ applications of the round-function when dedicated hash-functions 1, 2, 3, 4, 8 and 17 are selected, and $q + 4$ applications of the round function when dedicated hash-functions 5 and 6 are selected. This can be reduced to $q + 1$ applications of the round-function by pre-computing the values K_0, K_1 and K_2, and by replacing the initializing value IV by IV' in the application of the hash-function. It is recommended to make this modification to the code of the hash-function together with the mandatory modification required for Step 2. For long input strings, MAC Algorithm 1 has a performance which is comparable to that of the hash-function used.

6.4 Computation of the constants

6.4.1 General

The constants described in 6.4 are used in MAC Algorithms 1 and 3. MAC Algorithm 3 is specified in Clause 8. The strings T_i and U_i are fixed elements in the description of the MAC algorithm. They are computed (only once) using the hash-function; they are different for each of the eight hash-functions. The 128-bit constants T_i and 768-bit constants U_i are defined as follows. The definition of T_i involves the 496-bit constant R = "ab…yzAB…YZ01…89" and 16-bit constants S_0, S_1, S_2, where S_i is the 16-bit string formed by repeating twice the 8-bit representation of i (e.g. the hexadecimal representation of S_1 is 3131). In both cases, ASCII coding is used; this is equivalent to coding using ISO/IEC 646:

for i: = 0 to 2

$T_i := 128 \sim \bar{h}(S_i \,||\, R)$ for dedicated hash-functions 1, 2, 3, 4, 8 and 17

$T_i := 128 \sim \bar{h}(S_i \,||\, R \,||\, 0^{512})$ for dedicated hash-functions 5 and 6, where 0^{512} is 512 zero bits

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for i: = 0 to 2 U_i: = $T_i \,||\, T_{i+1} \,||\, T_{i+2} \,||\, T_i \,||\, T_{i+1} \,||\, T_{i+2}$

where the subscripts in T_i are taken modulo 3. In dedicated hash-functions 1, 2, 3, 4, 5, 6, 8 and 17, for all constants C_i, C'_i and all words $K_1[i]$ the most significant bit corresponds to the leftmost bit. The constants C_i and C'_i are presented using a hexadecimal representation.

6.4.2 Dedicated hash-function 1 (RIPEMD-160)

The 128-bit constant strings T_i for dedicated hash-function 1 are defined as follows (in hexadecimal representation):

T_0 = `1CC7086A046AFA22353AE88F3D3DACEB`

T_1 = `E3FA02710E491D851151CC34E4718D41`

T_2 = `93987557C07B8102BA592949EB638F37`

Two sequences of constant words C_0, C_1, ..., C_{79} and C'_0, C'_1, ..., C'_{79} are used in the round-function of dedicated hash-functions 1. They are defined as follows:

$C_i = K_1[0]$, $(0 \le i \le 15)$

$C_i = K_1[1] \Psi$ `5A827999`, $(16 \le i \le 31)$

$C_i = K_1[2] \Psi$ `6ED9EBA1`, $(32 \le i \le 47)$

$C_i = K_1[3] \Psi$ `8F1BBCDC`, $(48 \le i \le 63)$

$C_i = K_1[0] \Psi$ `A953FD4E`, $(64 \le i \le 79)$

$C'_i = K_1[1] \Psi$ `50A28BE6`, $(0 \le i \le 15)$

$C'_i = K_1[2] \Psi$ `5C4DD124`, $(16 \le i \le 31)$

$C'_i = K_1[3] \Psi$ `6D703EF3`, $(32 \le i \le 47)$

$C'_i = K_1[0] \Psi$ `7A6D76E9`, $(48 \le i \le 63)$

AC1 $C'_i = K_1[1]$ $(64 \le i \le 79)$ AC1

6.4.3 Dedicated hash-function 2 (RIPEMD-128)

The 128-bit constant strings T_i for dedicated hash-function 2 are defined as follows (in hexadecimal representation).

T_0 = `FD7EC18964C36D53FC18C31B72112AAC`

T_1 = `2538B78EC0E273949EE4C4457A77525C`

T_2 = `F5C93ED85BD65F609A7EB182A85BA181`

Two sequences of constant words C_0, C_1, ..., C_{63} and C'_0, C'_1, ..., C'_{63} are used in the round-function of dedicated hash-function 2. They are defined as follows:

$C_i = K_1[0]$, $(0 \le i \le 15)$

$C_i = K_1[1] \Psi$ `5A827999`, $(16 \le i \le 31)$

$C_i = K_1[2] \Psi$ `6ED9EBA1`, $(32 \le i \le 47)$

$C_i = K_1[3] \Psi$ `8F1BBCDC`, $(48 \le i \le 63)$

$C'_i = K_1[0] \Psi$ `50A28BE6`, $(0 \le i \le 15)$

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$C'_i = K_1[1] \Psi$ `5C4DD124`, $(16 \le i \le 31)$

$C'_i = K_1[2] \Psi$ `6D703EF3`, $(32 \le i \le 47)$

[AC1⟩ $C'_i = K_1[3]$ $(48 \le i \le 63)$ ⟨AC1]

6.4.4 Dedicated hash-function 3 (SHA-1)

The 128-bit constant strings T_i for dedicated hash-function 3 are defined as follows (in hexadecimal representation):

T_0 = `1D4CA39FA40417E2AE5A77B49067BBCC`

T_1 = `9318AFEF5D5A5B46EFCA6BEC0E138940`

T_2 = `4544209656E14F97005DAC76868E97A3`

A sequence of constant words C_0, C_1, ..., C_{79} is used in the round-function of dedicated hash-function 3. It is defined as follows.

$C_i = K_1[0] \Psi$ `5A827999`, $(0 \le i \le 19)$

$C_i = K_1[1] \Psi$ `6ED9EBA1`, $(20 \le i \le 39)$

$C_i = K_1[2] \Psi$ `8F1BBCDC`, $(40 \le i \le 59)$

$C_i = K_1[3] \Psi$ `CA62C1D6`, $(60 \le i \le 79)$

6.4.5 Dedicated hash-function 4 (SHA-256)

[AC1⟩ The 128-bit constant strings T_i for dedicated hash-function 4 are defined as follows (in hexadecimal representation): ⟨AC1]

T_0 = `13C10FB018D2C57E189060502F7DB523`

T_1 = `3DD6B5AE05B11977F3BFDC25CB1F35A8`

T_2 = `E31F81250B926FEAD2A82A6F63DD66D5`

A sequence of constant words C_0, C_1, ..., C_{63} is used in the round-function of dedicated hash-function 4. It is defined as follows.

$C_i = K_1[i \bmod 8] \Psi C''_i$ $(0 \le i \le 63)$

where the sequence C''_0, C''_1, ..., C''_{63} in a hexadecimal representation (where the most significant bit corresponds to the leftmost bit) is defined as follows, where the words are listed in the order C''_0, C''_1, ..., C''_{63}.

```
428a2f98 71374491 b5c0fbcf e9b5dba5 3956c25b 59f111f1 923f82a4 ab1c5ed5
d807aa98 12835b01 243185be 550c7dc3 72be5d74 80deb1fe 9bdc06a7 c19bf174
e49b69c1 efbe4786 0fc19dc6 240ca1cc 2de92c6f 4a7484aa 5cb0a9dc 76f988da
983e5152 a831c66d b00327c8 bf597fc7 c6e00bf3 d5a79147 06ca6351 14292967
27b70a85 2e1b2138 4d2c6dfc 53380d13 650a7354 766a0abb 81c2c92e 92722c85
a2bfe8a1 a81a664b c24b8b70 c76c51a3 d192e819 d6990624 f40e3585 106aa070
19a4c116 1e376c08 2748774c 34b0bcb5 391c0cb3 4ed8aa4a 5b9cca4f 682e6ff3
748f82ee 78a5636f 84c87814 8cc70208 90befffa a4506ceb bef9a3f7 c67178f2
```

NOTE These values are the first 32 bits of the fractional parts of the cube roots of the first 64 primes. They are the constant sequence used in SHA-256.

6.4.6 Dedicated hash-function 5 (SHA-512)

[AC1⟩ The 128-bit constant strings T_i for dedicated hash-function 5 are defined as follows (in hexadecimal representation): ⟨AC1]

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T_0 = `85f6e8b28ba014ed11d076ead90412a5`

T_1 = `33a6da6c7aaaf2149104fe4183152828`

T_2 = `7682094a7e45cf6bf27d19c2c7d6cf77`

A sequence of constant words C_0, C_1, ..., C_{79} is used in the round-function of dedicated hash-function 5. It is defined as follows:

$C_i = K_1[i \bmod 4] \Psi C''_i \ (0 \le i \le 79)$,

where the sequence C''_0, C''_1, ..., C''_{79} in a hexadecimal representation (where the most significant bit corresponds to the leftmost bit) is defined as follows, where the words are listed in the order C''_0, C''_1, ..., C''_{79}.

```
428a2f98d728ae22 7137449123ef65cd b5c0fbcfec4d3b2f e9b5dba58189dbbc
3956c25bf348b538 59f111f1b605d019 923f82a4af194f9b ab1c5ed5da6d8118
d807aa98a3030242 12835b0145706fbe 243185be4ee4b28c 550c7dc3d5ffb4e2
72be5d74f27b896f 80deb1fe3b1696b1 9bdc06a725c71235 c19bf174cf692694
e49b69c19ef14ad2 efbe4786384f25e3 0fc19dc68b8cd5b5 240ca1cc77ac9c65
2de92c6f592b0275 4a7484aa6ea6e483 5cb0a9dcbd41fbd4 76f988da831153b5
983e5152ee66dfab a831c66d2db43210 b00327c898fb213f bf597fc7beef0ee4
c6e00bf33da88fc2 d5a79147930aa725 06ca6351e003826f 142929670a0e6e70
27b70a8546d22ffc 2e1b21385c26c926 4d2c6dfc5ac42aed 53380d139d95b3df
650a73548baf63de 766a0abb3c77b2a8 81c2c92e47edaee6 92722c851482353b
a2bfe8a14cf10364 a81a664bbc423001 c24b8b70d0f89791 c76c51a30654be30
d192e819d6ef5218 d69906245565a910 f40e35855771202a 106aa07032bbd1b8
19a4c116b8d2d0c8 1e376c085141ab53 2748774cdf8eeb99 34b0bcb5e19b48a8
391c0cb3c5c95a63 4ed8aa4ae3418acb 5b9cca4f7763e373 682e6ff3d6b2b8a3
748f82ee5defb2fc 78a5636f43172f60 84c87814a1f0ab72 8cc702081a6439ec
90befffa23631e28 a4506cebde82bde9 bef9a3f7b2c67915 c67178f2e372532b
ca273eceea26619c d186b8c721c0c207 eada7dd6cde0eb1e f57d4f7fee6ed178
06f067aa72176fba 0a637dc5a2c898a6 113f9804bef90dae 1b710b35131c471b
28db77f523047d84 32caab7b40c72493 3c9ebe0a15c9bebc 431d67c49c100d4c
4cc5d4becb3e42b6 597f299cfc657e2a 5fcb6fab3ad6faec 6c44198c4a475817
```

These values are the first 64 bits of the fractional parts of the cube roots of the first 80 primes. They are the constant sequence used in SHA-512.

6.4.7 Dedicated hash-function 6 (SHA-384)

[AC1⟩ The 128-bit constant strings T_i for dedicated hash-function 6 are defined as follows (in hexadecimal representation): ⟨AC1]

T_0 = `33bfc7a7db2d833c1fa120f248ea0c68`

T_1 = `0f53e26170ddedf90aa666a58accf8c4`

T_2 = `f9371fddd155caefbd989e1270066c7c`

A sequence of constant words C_0, C_1, ..., C_{79} is used in the round-function of dedicated hash-function 6. It is defined as follows:

$C_i = K_1[i \bmod 4] \Psi C''_i \ (0 \le i \le 79)$

where the sequence C''_0, C''_1, ..., C''_{79} is the same as that for dedicated hash-function 5 of 6.4.6.

6.4.8 Dedicated hash-function 8 (SHA-224)

[AC1⟩ The 128-bit constant strings T_i for dedicated hash-function 8 are defined as follows (in hexadecimal representation): ⟨AC1]

T_0 = `F48D1673DF60BE1B00BACDC816CC3E4A`

T_1 = `A38F38CA4247A2F794F62F3F76460AB7`

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