# SHA-3 proposal BLAKE*

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*This document is a revised version of the supporting documentation submitted to NIST on October 31, 2008. As such, it does not cite all relevant references published from that date. The hash functions specified are the "tweaked" versions, as submitted for the final of the SHA-3 competition. The original submitted functions were called BLAKE-28, BLAKE-32,BLAKE-48, and BLAKE-64; the tweaked versions are BLAKE-224, BLAKE-256, BLAKE-384, and BLAKE-512.

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# 1 Introduction

In 1993, NIST published the first Secure Hash Standard SHA-0, which two years later was superseded by SHA-1 to improve the original design. SHA-1 was still deemed secure by the end of the millenium, when researchers' attention turned to block ciphers through the AES competition. Shortly after an avalanche of results on hash functions culminated with collision attacks for MD5 and SHA-1. Meanwhile NIST had introduced the SHA-2 family, unbroken until now. Some years later NIST announced the SHA-3 program, calling for proposals for a hash function that will augment the SHA-2 standard.

BLAKE is our candidate for SHA-3. We did not reinvent the wheel; BLAKE is built on previously studied components, chosen for their complementarity. The heritage of BLAKE is threefold:

- BLAKE's **iteration mode** is HAIFA, an improved version of the Merkle-Damgård paradigm proposed by Biham and Dunkelman. It provides resistance to long-message second preimage attacks, and explicitly handles hashing with a salt.
- BLAKE's **internal structure** is the local wide-pipe, which we already used with the LAKE hash function. It makes local collisions impossible in the BLAKE hash functions, a result that doesn't rely on any intractability assumption.
- BLAKE's **compression algorithm** is a modified version of Bernstein's stream cipher ChaCha, whose security has been intensively analyzed and performance is excellent, and which is strongly parallelizable.

The iteration mode HAIFA would significantly benefit to the new hash standard, for it provides randomized hashing and structural resistance to second-preimage attacks. The LAKE local wide-pipe structure is a straightforward way to give strong security guarantees against collision attacks. Finally, the choice of borrowing from the stream cipher ChaCha comes from our experience in cryptanalysis of Salsa20 and ChaCha [3], when we got convinced of their remarkable combination of simplicity and security.

### Content of this document

The present chapter contains design principles, a short description of BLAKE, and security claims. Chapter 2 gives a complete specification of the BLAKE hash functions. Chapter 3 reports performance in FPGA, ASIC, 8-bit microcontroller, and 32- and 64-bit processor. Chapter 4 explains how to use BLAKE, detailing construction of HMAC, UMAC, and PRF ensembles. Chapter 5 gives elements of analysis, including attacks on simplified versions. We conclude with acknowledgments, references, and appendices containing source code and intermediate values.

## 1.1 Design principles

The BLAKE hash functions were designed to meet all NIST criteria for SHA-3, including:

- message digests of 224, 256, 384, and 512 bits
- same parameter sizes as SHA-2
- one-pass streaming mode
- maximum message length of at least $2^{64} - 1$ bits

In addition, we imposed BLAKE to:

- explicitly handle hashing with a salt
- be parallelizable
- allow performance trade-offs
- be suitable for lightweight environments

We briefly justify these choices: First, a built-in salt simplifies a lot of things; it provides an interface for an extra input, avoids insecure homemade modes, and encourages the use of randomized hashing. Parallelism is a big advantage for hardware implementations, which can also be exploited by certain large microprocessors. In addition, BLAKE allows a trade-off throughput/area to adapt the implementation to the hardware available.

Oppositely, we excluded the following goals:

- have a reduction to a supposedly hard problem
- have homomorphic or incremental properties
- have a scalable design
- have a specification for variable length hashing

We justify these choices: The relative unsuccess of provably secure hash functions stresses the limitations of the approach: though of theoretical interest, such designs tend to be inefficient, and their highly structured constructions expose them to attacks with respect to notions other than the proved one. The few advantages of homomorphic and incremental hash functions are not worth their cost; more importantly, these properties are undesirable in many applications. Scalability of the design to various parameter sizes has no real advantage in practice, and the security of scalable designs is difficult to assess. Finally, we deemed unnecessary to complicate the function with variable-length features, for users can just truncate the hash values for shorter hashes, and there is no demand for hash values of more than 512 bits.

To summarize, we made our candidate as simple as possible, and combined well-known and trustable building blocks so that BLAKE already looks familiar to cryptanalysts. We avoided superfluous features, and just provide what users really need or will need in the future (like hashing with a salt). It was essential for us to build on previous knowledge—be it about security or implementation—in order to adapt our proposal to the low resources available for analyzing the SHA-3 candidates.

## 1.2 BLAKE in a nutshell

BLAKE is a family of four hash functions: BLAKE-224, BLAKE-256, BLAKE-384, and BLAKE-512 (see Table 1.1). As SHA-2, BLAKE has a 32-bit version (BLAKE-256) and a 64-bit one (BLAKE-512), from which other instances are derived using different initial values, different padding, and truncated output.

| Algorithm | Word | Message | Block | Digest | Salt |
|---|---|---|---|---|---|
| BLAKE-224 | 32 | $<2^{64}$ | 512 | 224 | 128 |
| BLAKE-256 | 32 | $<2^{64}$ | 512 | 256 | 128 |
| BLAKE-384 | 64 | $<2^{128}$ | 1024 | 384 | 256 |
| BLAKE-512 | 64 | $<2^{128}$ | 1024 | 512 | 256 |

Table 1.1: Properties of the BLAKE hash functions (sizes in bits).

The BLAKE hash functions follow the HAIFA iteration mode [10]: the compression function depends on a *salt*[1] and the *number of bits hashed so far* (counter), to compress each message block with a distinct function. The structure of BLAKE's compression function is inherited from LAKE [4] (see Fig. 1.1): a large inner state is initialized from the initial value, the salt, and the counter. Then it is injectively updated by message-dependent *rounds*, and it is finally compressed to return the next chain value. This strategy was called *local wide-pipe* in [4], and is inspired by the wide-pipe iteration mode [32].

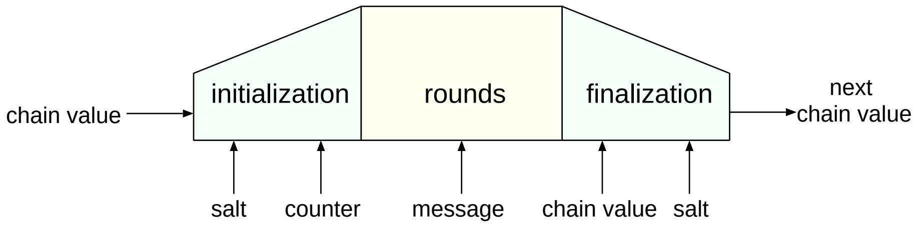


Figure 1.1: The local wide-pipe construction of BLAKE's compression function.

The inner state of the compression function is represented as a $4{\times}4$ matrix of words. A round of BLAKE-256 is a modified "double-round" of the stream cipher ChaCha: first, all four columns are updated independently, and thereafter four disjoint diagonals. In the update of each column or diagonal, two message words are input according to a round-dependent permutation. Each round is parametrized by distinct constants to minimize self-similarity. After the sequence of rounds, the state is reduced to half its length with feedforward of the initial value and the salt.

An implementation of BLAKE requires low resources, and is fast in both software and hardware environments. In 180 nm ASIC, BLAKE-256 can be implemented with about 13 500 gates, and can reach a throughput of more than 4 Gbps; BLAKE-512 can be implemented with about X Y gates, and can reach a throughput of more than 6 Gbps. On an Intel Core 2 Duo, BLAKE-256 can hash at about 15 cycles/byte, and BLAKE-512 at about 10 cycles/byte.

[1] A value that parametrizes the function, and can be either public or secret.

## 1.3 Expected strength

For all BLAKE hash functions, there should be no attack significantly more efficient than standard bruteforce methods for

- finding collisions, with same or distinct salt
- finding (second) preimages, with arbitrary salt

BLAKE should also be secure for randomized hashing, with respect to the experiment described by NIST in [37, 4.A.ii]. It should be impossible to distinguish a BLAKE instance with an unknown salt (that is, uniformly chosen at random) from a PRF, given blackbox access to the function; more precisely, it shouldn't cost significantly less than $2^{|s|}$ queries to the box, where $|s|$ is the bit length of the salt. BLAKE should have no property that makes its use significantly less secure than an ideal function for any concrete application. (These claims concern the proposed functions with the *recommended* number of rounds, not reduced or modified versions.)

## 1.4 Advantages and limitations

We summarize the advantages and limitations of BLAKE:

#### Advantages

Design

- simplicity of the algorithm
- interface for hashing with a salt

Performance

- fast in both software and hardware
- parallelism and throughput/area trade-off for hardware implementation
- simple speed/confidence trade-off with the tunable number of rounds

Security

- based on an intensively analyzed component (ChaCha)
- resistant to generic second-preimage attacks
- resistant to side-channel attacks
- resistant to length-extension

#### Limitations

- message length limited to respectively $2^{64}$ and $2^{128}$ for BLAKE-256 and BLAKE-512
- resistance to Joux's multicollisions similar to that of SHA-2
- fixed-points found in less time than for an ideal function (but not efficiently)

## 1.5 Notations

Hexadecimal numbers are written in `typewriter` style (for example $\texttt{F0} = 240$). A *word* is either a 32-bit or a 64-bit string, depending on the context. We use the same conventions of big-endianness as NIST does in the SHA-2 specification [35, §3]. In particular, we use (unsigned) big-endian representation for expressing integers, and, e.g. converting data streams into word arrays. Table 1.2 summarizes the basic operations used.

| Symbol | Meaning |
|---|---|
| $\leftarrow$ | variable assignment |
| $+$ | addition modulo $2^{32}$ or (modulo $2^{64}$) |
| $\oplus$ | Boolean exclusive OR (XOR) |
| $\ggg k$ | rotation of $k$ bits towards less significant bits |
| $\lll k$ | rotation of $k$ bits towards more significant bits |
| $\langle \ell \rangle_k$ | encoding of the integer $\ell$ over $k$ bits |

Table 1.2: Operations symbols used in this document.

If $p$ is a bit string, we view it as a sequence of words and $p_i$ denotes its $i^{\text{th}}$ word component; thus $p = p_0 \| p_1 \| \ldots$ For a message $m$, $m^i$ denotes its $i^{\text{th}}$ 16-word block, thus $m^i_j$ is the $j^{\text{th}}$ word of the $i^{\text{th}}$ block of $m$. Indices start from zero, for example a $N$-block message $m$ is decomposed as $m = m^0 m^1 \ldots m^{N-1}$, and the block $m^0$ is composed of words $m^0_0, m^0_1, m^0_2, \ldots, m^0_{15}$.

The adjective *random* here means uniformly random with respect to the relevant probability space. For example a "random salt" of BLAKE-256 is a random variable uniformly distributed over $\{0,1\}^{128}$, and may also mean "uniformly chosen at random". The *initial value* is written IV; intermediate hash values in the iterated hash are called *chain values*, and the last one is the *hash value*, or just *hash*.

# 2 Specification

This chapter defines the hash functions BLAKE-256, BLAKE-512, BLAKE-224, and BLAKE-384.

## 2.1 BLAKE-256

The hash function BLAKE-256 operates on 32-bit words and returns a 32-byte hash value. This section defines BLAKE-256, going from its constant parameters to its compression function, then to its iteration mode.

### 2.1.1 Constants

BLAKE-256 starts hashing from the same initial value as SHA-256:

$$
\begin{aligned}
\mathrm{IV}_0 &= \texttt{6A09E667} & \mathrm{IV}_1 &= \texttt{BB67AE85}\\
\mathrm{IV}_2 &= \texttt{3C6EF372} & \mathrm{IV}_3 &= \texttt{A54FF53A}\\
\mathrm{IV}_4 &= \texttt{510E527F} & \mathrm{IV}_5 &= \texttt{9B05688C}\\
\mathrm{IV}_6 &= \texttt{1F83D9AB} & \mathrm{IV}_7 &= \texttt{5BE0CD19}
\end{aligned}
$$

BLAKE-256 uses 16 constants[1]

$$
\begin{aligned}
c_0 &= \texttt{243F6A88} & c_1 &= \texttt{85A308D3}\\
c_2 &= \texttt{13198A2E} & c_3 &= \texttt{03707344}\\
c_4 &= \texttt{A4093822} & c_5 &= \texttt{299F31D0}\\
c_6 &= \texttt{082EFA98} & c_7 &= \texttt{EC4E6C89}\\
c_8 &= \texttt{452821E6} & c_9 &= \texttt{38D01377}\\
c_{10} &= \texttt{BE5466CF} & c_{11} &= \texttt{34E90C6C}\\
c_{12} &= \texttt{C0AC29B7} & c_{13} &= \texttt{C97C50DD}\\
c_{14} &= \texttt{3F84D5B5} & c_{15} &= \texttt{B5470917}
\end{aligned}
$$

Ten permutations of $\{0, \dots, 15\}$ are used by all BLAKE functions, defined in Table 2.1.

### 2.1.2 Compression function

The compression function of BLAKE-256 takes as input four values:

- a chain value $h = h_0, \dots, h_7$
- a message block $m = m_0, \dots, m_{15}$
- a salt $s = s_0, \dots, s_3$

[1] First digits of $\pi$.

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\sigma_0$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $\sigma_1$ | 14 | 10 | 4 | 8 | 9 | 15 | 13 | 6 | 1 | 12 | 0 | 2 | 11 | 7 | 5 | 3 |
| $\sigma_2$ | 11 | 8 | 12 | 0 | 5 | 2 | 15 | 13 | 10 | 14 | 3 | 6 | 7 | 1 | 9 | 4 |
| $\sigma_3$ | 7 | 9 | 3 | 1 | 13 | 12 | 11 | 14 | 2 | 6 | 5 | 10 | 4 | 0 | 15 | 8 |
| $\sigma_4$ | 9 | 0 | 5 | 7 | 2 | 4 | 10 | 15 | 14 | 1 | 11 | 12 | 6 | 8 | 3 | 13 |
| $\sigma_5$ | 2 | 12 | 6 | 10 | 0 | 11 | 8 | 3 | 4 | 13 | 7 | 5 | 15 | 14 | 1 | 9 |
| $\sigma_6$ | 12 | 5 | 1 | 15 | 14 | 13 | 4 | 10 | 0 | 7 | 6 | 3 | 9 | 2 | 8 | 11 |
| $\sigma_7$ | 13 | 11 | 7 | 14 | 12 | 1 | 3 | 9 | 5 | 0 | 15 | 4 | 8 | 6 | 2 | 10 |
| $\sigma_8$ | 6 | 15 | 14 | 9 | 11 | 3 | 0 | 8 | 12 | 2 | 13 | 7 | 1 | 4 | 10 | 5 |
| $\sigma_9$ | 10 | 2 | 8 | 4 | 7 | 6 | 1 | 5 | 15 | 11 | 9 | 14 | 3 | 12 | 13 | 0 |

Table 2.1: Permutations of $\{0, \ldots, 15\}$ used by the BLAKE functions.

- a counter $t = t_0, t_1$

These four inputs represent 30 words in total (i.e., 120 bytes = 960 bits). The output of the function is a new chain value $h' = h'_0, \ldots, h'_7$ of eight words (i.e., 32 bytes = 256 bits). We write the compression of $h, m, s, t$ to $h'$ as

$$h' = \textbf{compress}(h, m, s, t)$$

### Initialization

A 16-word state $v_0, \ldots, v_{15}$ is initialized such that different inputs produce different initial states. The state is represented as a 4×4 matrix, and filled as follows:

$$\begin{pmatrix} v_0 & v_1 & v_2 & v_3 \\ v_4 & v_5 & v_6 & v_7 \\ v_8 & v_9 & v_{10} & v_{11} \\ v_{12} & v_{13} & v_{14} & v_{15} \end{pmatrix} \leftarrow \begin{pmatrix} h_0 & h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 & h_7 \\ s_0 \oplus c_0 & s_1 \oplus c_1 & s_2 \oplus c_2 & s_3 \oplus c_3 \\ t_0 \oplus c_4 & t_0 \oplus c_5 & t_1 \oplus c_6 & t_1 \oplus c_7 \end{pmatrix}$$

### Round function

Once the state $v$ is initialized, the compression function iterates a series of 14 rounds. A round is a transformation of the state $v$ that computes

$$\begin{array}{llll} G_0(v_0, v_4, v_8, v_{12}) & G_1(v_1, v_5, v_9, v_{13}) & G_2(v_2, v_6, v_{10}, v_{14}) & G_3(v_3, v_7, v_{11}, v_{15}) \\ G_4(v_0, v_5, v_{10}, v_{15}) & G_5(v_1, v_6, v_{11}, v_{12}) & G_6(v_2, v_7, v_8, v_{13}) & G_7(v_3, v_4, v_9, v_{14}) \end{array}$$

where, at round $r$, $G_i(a, b, c, d)$ sets[2]

$$\begin{array}{rcl} a & \leftarrow & a + b + (m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)}) \\ d & \leftarrow & (d \oplus a) \ggg 16 \\ c & \leftarrow & c + d \\ b & \leftarrow & (b \oplus c) \ggg 12 \\ a & \leftarrow & a + b + (m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)}) \\ d & \leftarrow & (d \oplus a) \ggg 8 \\ c & \leftarrow & c + d \\ b & \leftarrow & (b \oplus c) \ggg 7 \end{array}$$

[2]In the rest of the paper, for statements that don't depend on the index $i$ we shall omit the subscript and write simply G.

The first four calls $G_0, \dots, G_3$ can be computed in parallel, because each of them updates a distinct column of the matrix. We call the procedure of computing $G_0, \dots, G_3$ a *column step*. Similarly, the last four calls $G_4, \dots, G_7$ update distinct diagonals thus can be parallelized as well, which we call a *diagonal step*. At round $r > 9$, the permutation used is $\sigma_{r \bmod 10}$ (for example, in the last round $r = 13$ and the permutation $\sigma_{13 \bmod 10} = \sigma_3$ is used).

Figures 2.1 and 2.2 illustrate $G_i$, the column step, and the diagonal step. An example of computation is given in Appendix A.

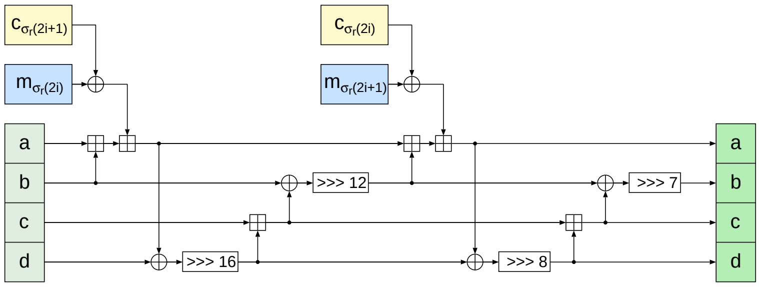


Figure 2.1: The $G_i$ function.

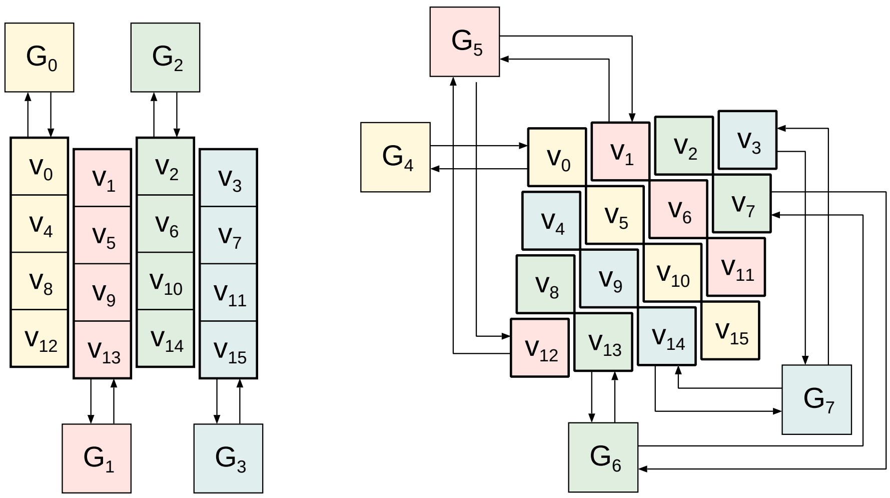


Figure 2.2: Column step and diagonal step.

### Finalization

After the rounds sequence, the new chain value $h'_0, \dots, h'_7$ is extracted from the state $v_0, \dots, v_{15}$ with input of the initial chain value $h_0, \dots, h_7$ and the salt $s_0, \dots, s_3$:

$$\begin{aligned}
h'_0 &\leftarrow h_0 \oplus s_0 \oplus v_0 \oplus v_8 \\
h'_1 &\leftarrow h_1 \oplus s_1 \oplus v_1 \oplus v_9 \\
h'_2 &\leftarrow h_2 \oplus s_2 \oplus v_2 \oplus v_{10} \\
h'_3 &\leftarrow h_3 \oplus s_3 \oplus v_3 \oplus v_{11} \\
h'_4 &\leftarrow h_4 \oplus s_0 \oplus v_4 \oplus v_{12} \\
h'_5 &\leftarrow h_5 \oplus s_1 \oplus v_5 \oplus v_{13} \\
h'_6 &\leftarrow h_6 \oplus s_2 \oplus v_6 \oplus v_{14} \\
h'_7 &\leftarrow h_7 \oplus s_3 \oplus v_7 \oplus v_{15}
\end{aligned}$$

## 2.1.3 Hashing a message

We now describe the procedure for hashing a message $m$ of bit length $\ell < 2^{64}$. As it is usual for iterated hash functions, the message is first *padded* (BLAKE uses a padding rule very similar to that of HAIFA), then it is processed block per block by the compression function.

### Padding

First the message is extended so that its length is congruent to 447 modulo 512. Length extension is performed by appending a bit 1 followed by a sufficient number of 0 bits. At least one bit and at most 512 are appended. Then a bit 1 is added, followed by a 64-bit unsigned big-endian representation of $\ell$. Padding can be represented as

$$m \leftarrow m \| 1000 \dots 0001 \langle \ell \rangle_{64}$$

This procedure guarantees that the bit length of the padded message is a multiple of 512.

### Iterated hash

To proceed to the iterated hash, the padded message is split into 16-word blocks $m^0, \dots, m^{N-1}$. We let $\ell^i$ be the number of message bits in $m^0, \dots, m^i$, that is, excluding the bits added by the padding. For example, if the original (non-padded) message is 600-bit long, then the padded message has two blocks, and $\ell^0 = 512$, $\ell^1 = 600$. A particular case occurs when the last block contains *no original message bit*; for example a 1020-bit message leads to a padded message with three blocks (which contain respectively 512, 508, and 0 message bits), and we set $\ell^0 = 512$, $\ell^1 = 1020$, $\ell^2 = 0$. The general rule is: if the last block contains no bit from the original message, then the counter is set to zero; this guarantees that if $i \neq j$, then $\ell_i \neq \ell_j$.

The salt $s$ is chosen by the user, and set to the null value when no salt is required (i.e., $s_0 = s_1 = s_2 = s_3 = 0$). The hash of the padded message $m$ is then computed as follows:

$h^0 \leftarrow \mathrm{IV}$
**for** $i = 0, \dots, N-1$
  $h^{i+1} \leftarrow$ **compress**$(h^i, m^i, s, \ell^i)$
**return** $h^N$

The procedure of hashing $m$ with BLAKE-256 is aliased BLAKE-256$(m, s) = h^N$, where $m$ is the (non-padded) message, and $s$ is the salt. The notation BLAKE-256$(m)$ denotes the hash of $m$ when no salt is used (i.e., $s = 0$).

## 2.2 BLAKE-512

BLAKE-512 operates on 64-bit words and returns a 64-byte hash value. All lengths of variables are doubled compared to BLAKE-256: chain values are 512-bit, message blocks are 1024-bit, salt is 256-bit, counter is 128-bit.

### 2.2.1 Constants

The initial value of BLAKE-512 is the same as for SHA-512:

$$
\begin{aligned}
\mathsf{IV}_0 &= \texttt{6A09E667F3BCC908} & \mathsf{IV}_1 &= \texttt{BB67AE8584CAA73B} \\
\mathsf{IV}_2 &= \texttt{3C6EF372FE94F82B} & \mathsf{IV}_3 &= \texttt{A54FF53A5F1D36F1} \\
\mathsf{IV}_4 &= \texttt{510E527FADE682D1} & \mathsf{IV}_5 &= \texttt{9B05688C2B3E6C1F} \\
\mathsf{IV}_6 &= \texttt{1F83D9ABFB41BD6B} & \mathsf{IV}_7 &= \texttt{5BE0CD19137E2179}
\end{aligned}
$$

BLAKE-512 uses the constants[3]

$$
\begin{aligned}
c_0 &= \texttt{243F6A8885A308D3} & c_1 &= \texttt{13198A2E03707344} \\
c_2 &= \texttt{A4093822299F31D0} & c_3 &= \texttt{082EFA98EC4E6C89} \\
c_4 &= \texttt{452821E638D01377} & c_5 &= \texttt{BE5466CF34E90C6C} \\
c_6 &= \texttt{C0AC29B7C97C50DD} & c_7 &= \texttt{3F84D5B5B5470917} \\
c_8 &= \texttt{9216D5D98979FB1B} & c_9 &= \texttt{D1310BA698DFB5AC} \\
c_{10} &= \texttt{2FFD72DBD01ADFB7} & c_{11} &= \texttt{B8E1AFED6A267E96} \\
c_{12} &= \texttt{BA7C9045F12C7F99} & c_{13} &= \texttt{24A19947B3916CF7} \\
c_{14} &= \texttt{0801F2E2858EFC16} & c_{15} &= \texttt{636920D871574E69}
\end{aligned}
$$

Permutations are the same as for BLAKE-256 (see Table 2.1).

### 2.2.2 Compression function

The compression function of BLAKE-512 is similar to that of BLAKE-256 except that it makes 16 rounds instead of 14, and that $\mathsf{G}_i(a, b, c, d)$ computes

$$
\begin{aligned}
a &\leftarrow a + b + (m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)}) \\
d &\leftarrow (d \oplus a) \ggg 32 \\
c &\leftarrow c + d \\
b &\leftarrow (b \oplus c) \ggg 25 \\
a &\leftarrow a + b + (m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)}) \\
d &\leftarrow (d \oplus a) \ggg 16 \\
c &\leftarrow c + d \\
b &\leftarrow (b \oplus c) \ggg 11
\end{aligned}
$$

The only differences with BLAKE-256's $\mathsf{G}_i$ are the word length (64 bits instead of 32) and the rotation distances. At round $r > 9$, the permutation used is $\sigma_{r \bmod 10}$ (for example, in the last round $r = 15$ and the permutation $\sigma_{15 \bmod 10} = \sigma_5$ is used).

[3] First digits of $\pi$.

### 2.2.3 Hashing a message

For BLAKE-512, message padding goes as follows: append a bit 1 and as many 0 bits until the message bit length is congruent to 895 modulo 1024. Then append a bit 1, and a 128-bit unsigned big-endian representation of the message bit length:

$$m \leftarrow m \| 1000\ldots0001\langle\ell\rangle_{128}$$

This procedure guarantees that the length of the padded message is a multiple of 1024.

The algorithm for iterated hash is identical to that of BLAKE-256.

## 2.3 BLAKE-224

BLAKE-224 is similar to BLAKE-256, except that

- it uses the initial value of SHA-224:

$$\begin{array}{ll} \mathsf{IV}_0 = \texttt{C1059ED8} & \mathsf{IV}_1 = \texttt{367CD507} \\ \mathsf{IV}_2 = \texttt{3070DD17} & \mathsf{IV}_3 = \texttt{F70E5939} \\ \mathsf{IV}_4 = \texttt{FFC00B31} & \mathsf{IV}_5 = \texttt{68581511} \\ \mathsf{IV}_6 = \texttt{64F98FA7} & \mathsf{IV}_7 = \texttt{BEFA4FA4} \end{array}$$

- in the padded data, the 1 bit preceding the message length is replaced by a 0 bit:

$$m \leftarrow m \| 1000\ldots0000\langle\ell\rangle_{64}$$

- the output is truncated to its first 224 bits, that is, the iterated hash returns $h_0^N, \ldots, h_6^N$ instead of $h^N = h_0^N, \ldots, h_7^N$

## 2.4 BLAKE-384

BLAKE-384 is similar to BLAKE-512, except that

- it uses the initial value of SHA-384:

$$\begin{array}{ll} \mathsf{IV}_0 = \texttt{CBBB9D5DC1059ED8} & \mathsf{IV}_1 = \texttt{629A292A367CD507} \\ \mathsf{IV}_2 = \texttt{9159015A3070DD17} & \mathsf{IV}_3 = \texttt{152FECD8F70E5939} \\ \mathsf{IV}_4 = \texttt{67332667FFC00B31} & \mathsf{IV}_5 = \texttt{8EB44A8768581511} \\ \mathsf{IV}_6 = \texttt{DB0C2E0D64F98FA7} & \mathsf{IV}_7 = \texttt{47B5481DBEFA4FA4} \end{array}$$

- in the padded data, the 1 bit preceding the message length is replaced by a 0 bit:

$$m \leftarrow m \| 1000\ldots0000\langle\ell\rangle_{128}$$

- the output is truncated to its first 384 bits, that is, the iterated hash returns $h_0^N, \ldots, h_5^N$ instead of $h^N = h_0^N, \ldots, h_7^N$

## 2.5 Alternative descriptions

The round function of BLAKE described in §2.1.2 operates first on columns of the matrix state, second on diagonals (see Fig. 2.2). Another way to view this transformation is

1. make a column-step
2. rotate the $i^{\text{th}}$ column up by $i$ positions, for $i = 0, \ldots, 3$
3. make a *row-step* (see Fig. 2.3), that is,

$$G_4(v_0, v_1, v_2, v_3) \quad G_5(v_4, v_5, v_6, v_7) \quad G_6(v_8, v_9, v_{10}, v_{11}) \quad G_7(v_{12}, v_{13}, v_{14}, v_{15})$$

A similar description was used for the stream cipher Salsa20 [8].

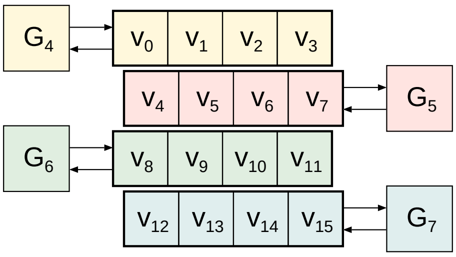


Figure 2.3: Row step of the alternative description.

Similarly, the transformation could be viewed as follows:

1. make a column-step
2. rotate the $i^{\text{th}}$ row by $i$ positions left, for $i = 0, \ldots, 3$
3. make a column-step again

Finally, another equivalent definition of a round is

$$\begin{array}{llll} G_0\ (v_0, v_4, v_8, v_{12}) & G_2\ (v_1, v_5, v_9, v_{13}) & G_4\ (v_2, v_6, v_{10}, v_{14}) & G_6\ (v_3, v_7, v_{11}, v_{15}) \\ G_8\ (v_0, v_5, v_{10}, v_{15}) & G_{10}(v_1, v_6, v_{11}, v_{12}) & G_{12}(v_2, v_7, v_8, v_{13}) & G_{14}(v_3, v_4, v_9, v_{14}) \end{array}$$

where $G_i(a, b, c, d)$ is redefined to

$$\begin{aligned} a &\leftarrow a + b + (m_{\sigma_r(i)} \oplus c_{\sigma_r(i+1)}) \\ d &\leftarrow (d \oplus a) \ggg 16 \\ c &\leftarrow c + d \\ b &\leftarrow (b \oplus c) \ggg 12 \\ a &\leftarrow a + b + (m_{\sigma_r(i+1)} \oplus c_{\sigma_r(i)}) \\ d &\leftarrow (d \oplus a) \ggg 8 \\ c &\leftarrow c + d \\ b &\leftarrow (b \oplus c) \ggg 7 \end{aligned}$$

This definition may speed up implementations by saving the doublings.

## 2.6 Tunable parameter

In its call for a new hash function [37], NIST encourages the description of a parameter that allows speed/confidence trade-offs. For BLAKE this parameter is the *number of rounds*. We recommend 14 rounds for BLAKE-224 and BLAKE-256, and we recommend 16 rounds for BLAKE-384 and BLAKE-512. Rationale behind these choices appear in Chapter 5.

# 3 Performance

We implemented BLAKE in several environments (software and hardware). This chapter reports results from our implementations.

### IMPORTANT REMARK

Implementations reported in this chapter in §3.2–3.4 refer to the original version of BLAKE (i.e., the original functions called BLAKE-32, with 10 rounds, and BLAKE-64, with 14 rounds). The speed results reported thus do not correspond to the latest version of BLAKE. However, memory, and hardware area values remain valid. For up-to-date benchmarks (as of 2011) we refer the reader to the SHA-3 Zoo [23], XBX [41], and eBASH [9], respectively for hardware, low-end software, and high-end software performance.

## 3.1 Generalities

This section gives general facts about the complexity of BLAKE, independently of any implementation.

### 3.1.1 Complexity

#### Number of operations

A single G makes 6 XOR's, 6 additions and 4 rotations, so 16 arithmetic operations in total. Hence a round makes 48 XOR's, 48 additions and 32 rotations, so 128 operations. BLAKE-256's compression function thus counts 672 XOR's, 672 additions, 448 rotations, plus 4 XOR's for the initialization and 24 XOR's for the finalization, thus a total of 1820 operations. BLAKE-512's compression function counts 768 XOR's, 768 additions, 512 rotations, plus 4 XOR's and 24 XOR's, thus a total of 2076 operations. We omit the overhead for initializing the hash structure, padding the message, etc., whose cost is negligible compared to that of a compression function.

#### Memory

BLAKE-256 needs to store in ROM 64 bytes for the constants, and at least 80 bytes to describe the permutations (144 bytes in total). In RAM, the storage $m, h, s, t$ and $v$ requires 184 bytes. In practice, however, more space might be required. For example, our implementation on the PIC18F2525 microcontroller (see §3.3) stores the 8-bit addresses of the permutation elements, not the 4-bit elements directly, thus using 160 bytes for storing the 80 bytes of information of the message permutations.

### 3.1.2 Memory/speed tradeoffs

A memory/speed tradeoff for a hash function implementation consists in storing some additional data in memory in order to reduce the number of computation steps. This is relevant, for example, for hash functions that use a a large set of constants generated from a smaller set of constants. BLAKE, however, requires a fixed and small set of constants, which is not trivially compressible. Therefore, the algorithm of BLAKE admits no memory/speed tradeoff; the implementations reported in §3.2, 3.3, and 3.4 thus do not consider memory/speed tradeoffs. The tradeoffs made in the hardware implementations (§3.2) are rather space/speed than memory/speed.

### 3.1.3 Parallelism

When hashing a message, most of the time spent by the computing unit will be devoted to computing rounds of the compression function. Each round is composed of eight calls to the G function: $G_0, G_1, \dots, G_7$. Simplifying:

- on a *serial* machine, the speed of a round is about eight times the speed of a G
- on a *parallel* machine, $G_0, G_1, G_2$ and $G_3$ can be computed in four parallel branches, and then $G_4, G_5, G_6$ and $G_7$ can be computed in four branches again. The speed of a round is thus about twice the speed of a G

Since parallelism is generally a trade-off, the gain in speed may increase the consumption of other resources (area, etc.). An example of trade-off is to split a round into two branches, resulting in a speed of four times that of a G.

## 3.2 ASIC and FPGA

We propose four hardware architectures of the BLAKE compression function and report the performances of the corresponding ASIC and FPGA implementations. Similar architectures have been considered by Henzen et al. for VLSI implementations of ChaCha, in [26].

More efficient implementations of BLAKE can be found in [27].

### 3.2.1 Architectures

The HAIFA iteration mode forces a straightforward hardware implementation of the BLAKE compression function based on a single round unit and a memory to store the internal state variables $v_0, v_1, \dots, v_{15}$. No pipeline circuits have been designed, due to the enormous resource requirements of such solutions. Nonetheless, several architectures of the compression function have been investigated to evaluate the relation between speed and area. Every implemented circuit reports to the basic block diagram of Fig 3.1.

Besides memory, the four main block components of BLAKE are

- the *initialization* and *finalization* blocks, which are pure combinational logic; initialization contains eight 32/64-bit XOR logic gates to compute the initial state $v$, while finalization consists of 24 XOR gates to generate the next chain value.
- the *round function*, which is essentially one or more G functions; G is composed of six modulo $2^{32}/2^{64}$ adders and six XOR gates. Rotations are implemented as a straight rerouting of the internal word bits without any additional logic and without affecting the propagation delay of the circuit.

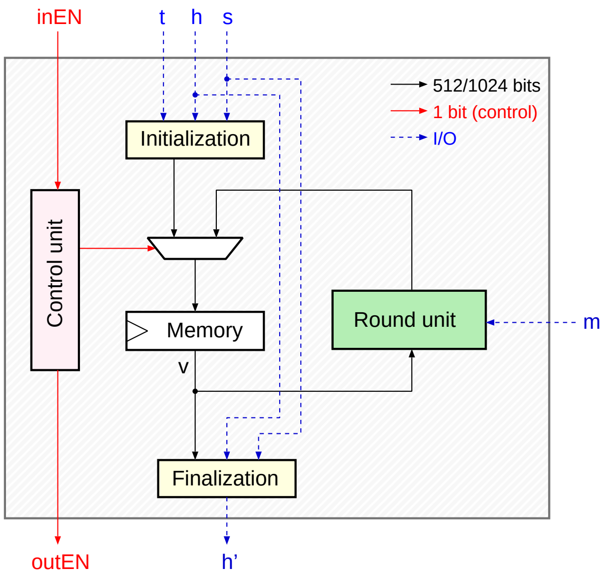


Figure 3.1: Block diagram of the BLAKE compression function. The signals `inEn` and `outEN` define the input and output enables.

- the *control unit*, which controls the computation of the compression function, aided by IO enable signals.

Four architectures with different round units have been investigated:

- [8G]-BLAKE: This design corresponds to the isomorphic implementation of the round function. Eight G function units are instantiated; the first four units work in parallel to compute the column step, while the last four compute the diagonal step.

- [4G]-BLAKE: The round module consists of four parallel G units, which, at a given cycle, compute either the column step or the diagonal step.

- [1G]-BLAKE: The iterative decomposition of the compression function leads to the implementation of a single G function. Thus, one G unit processes the full round in eight cycles.

- [$\frac{1}{2}$G]-BLAKE: This lightweight implementation consists of a single half G unit. During one cycle, only a single update of the inputs $a$, $b$, $c$, $d$ is processed (i.e., half a G).

In the last three architectures, additional multiplexers and demultiplexers driven by the control unit preserve the functionality of the algorithm, selecting the correct $v$ elements inside and outside the round unit.

### 3.2.2 Implementation results

Based on functional VHDL coding (see Appendix B.1), the four designs have been synthesized using a 0.18 µm CMOS technology with the aid of the Synopsys Design Compiler Tool.

Table 3.1 summarizes the final values of area, frequency, and throughput[1]. In addition, the hardware efficiency computes the ratio between speed and area of the circuits. The [8G] and [4G]-BLAKE architectures maximize the throughput, so they were synthesized with speed optimization options at the maximal clock frequency. The target applications of [1G] and [$\frac{1}{2}$G]-BLAKE are resource-restricted environments, where a compact chip size is the main constraint. Hence, these designs have been synthesized at low frequencies to achieve minimum-area requirements.

| Arch. | Function | Area [kGE] | Freq. [MHz] | Latency [cycles] | Throughput [Mbps] | Efficiency [Kbps/GE] |
|---|---|---|---|---|---|---|
| [8G] | BLAKE-32 | 58.30 | 114 | 11 | 5295 | 90.8 |
| | BLAKE-64 | 132.47 | 87 | 15 | 5910 | 44.6 |
| [4G] | BLAKE-32 | 41.31 | 170 | 21 | 4153 | 100.5 |
| | BLAKE-64 | 82.73 | 136 | 29 | 4810 | 58.1 |
| [1G] | BLAKE-32 | 10.54 | 40 | 81 | 253 | 24.0 |
| | BLAKE-64 | 20.61 | 20 | 113 | 181 | 8.8 |
| [$\frac{1}{2}$G] | BLAKE-32 | 9.89 | 40 | 161 | 127 | 12.9 |
| | BLAKE-64 | 19.46 | 20 | 225 | 91 | 4.7 |

Table 3.1: ASIC synthesis results. One gate equivalent (GE) corresponds to the area of a two-input drive-one NAND gate of size 9.7 $\mu m^2$.

Three architectures have been implemented on FPGA silicon devices: the Xilinx Virtex-5, Virtex-4, and Virtex-II Pro[2]. We used SynplifyPro and Xilinx ISE for synthesis and place & route. Table 3.2 reports resulting circuit performances.

For the ASIC and the FPGA implementations, the memory of the internal state consists of 16 32/64-bit registers, which are updated every round with the output words of the round unit. No RAM or ROM macro cells are used to store the 16 constants $c_0, \ldots, c_{15}$. In the same way, the ten permutations $\sigma_0, \ldots, \sigma_9$ have been hard-coded in VHDL. In ASIC, this choice has been motivated by the insufficient memory requirement of these variables. In FPGA, constants and permutations can be stored in dedicated block RAMs. This solution decreases slightly the number of slices needed, but does not speed-up the circuits.

A complete implementation of BLAKE (to include memory storing intermediate values, counter, and circuits to finalize the message, etc.) leads to an increase of about 1.8 kGE or 197 slices for ASIC and FPGA, respectively.

### Minimizing the area

An ASIC architecture even smaller than [$\frac{1}{2}$G] can be reached, by making a circuit only for a quarter (rather than a half) of the G function, and serializing the finalization block. Latency and throughput deteriorate much, but we can reach an area of 8.4 kGE. We omit an extensive description of this architecture because the area reduction from [$\frac{1}{2}$G] is not worth its cost, in general.

[1] The unit Gbps means Gigabits per second, where a Gigabit is $1000^3$ bits, not $1024^3$. Similar rule applies to Mbps and Kbps in Tables 3.1 and 3.2.

[2] Data sheets available at `http://www.xilinx.com/support/documentation/`

| | XC2VP50 | | | XC4VLX100 | | | XC5VLX110 | | |
|---|---|---|---|---|---|---|---|---|---|
| Function | Area [slices] | Freq. [MHz] | Thr. [Mbps] | Area [slices] | Freq. [MHz] | Thr. [Mbps] | Area [slices] | Freq. [MHz] | Thr. [Mbps] |
| [8G]-BLAKE architecture | | | | | | | | | |
| BLAKE-32 | 3091 | 37 | 1724 | 3087 | 48 | 2235 | 1694 | 67 | 3103 |
| BLAKE-64 | 11122 | 17 | 1177 | 11483 | 25 | 1707 | 4329 | 35 | 2389 |
| [4G]-BLAKE architecture | | | | | | | | | |
| BLAKE-32 | 2805 | 53 | 1292 | 2754 | 70 | 1705 | 1217 | 100 | 2438 |
| BLAKE-64 | 6812 | 31 | 1104 | 6054 | 40 | 1413 | 2389 | 50 | 1766 |
| [1G]-BLAKE architecture | | | | | | | | | |
| BLAKE-32 | 958 | 59 | 371 | 960 | 68 | 430 | 390 | 91 | 575 |
| BLAKE-64 | 1802 | 36 | 326 | 1856 | 42 | 381 | 939 | 59 | 533 |

Table 3.2: FPGA post place & route results [overall effort level: standard]. A single Virtex-5 slice contains twice the number of LUTs and FFs.

### 3.2.3 Evaluation

The scalable structure of the round function allows the implementation of distinct architectures, where the trade-off between area and speed differs. Fast circuits are able to achieve throughput about 6 Gbps in ASIC and 3 Gbps in modern FPGA chips, while lightweight architectures require less than 10 kGE or 1000 Slices. BLAKE turns out to be an extremely flexible function, that can be integrated in a wide range of applications, from modern high-speed communication security protocols to low-area RFID systems.

## 3.3 8-bit microcontroller

The compression function of BLAKE-32 was implemented in a PIC18F2525 microcontroller. About 1800 assembly lines were written, using Microchip's MPLAB Integrated Development Environment v7.6. This section reports results of this implementation, starting with a presentation of the device used. Sample assembly code computing the round function is given in Appendix B.2.

### 3.3.1 The PIC18F2525

The PIC18F2525 is a member of the PIC family of microcontrollers made by Microchip Technology. PIC's are very popular for embedded systems (more than 6 billions sold). The PIC18F2525 works with 8-bit words, but has an instruction width of 16 bits; it makes up to 10 millions of instructions per second (MIPS).

Following the Harvard architecture, the PIC18F2525 separates program memory and data memory:

- *program memory* is where the program resides, and can store 48 Kb in flash memory (that is, 24576 instructions)

- *data memory* is reserved to the data used by the program. It can store 3986 bytes in RAM and 1024 bytes in EEPROM.

Program memory will contain the code of our BLAKE implementation, including the permutations' look-up tables, while variables will be stored in the data memory.

Our PIC processor runs at up to 40 MHz, and a single-cycle instruction takes four clock cycles (10 MIPS). In the following we give cost estimates in terms of instruction cycles, not clock cycles.

| | |
|---|---|
| Operating frequency | DC – 40 MHz |
| Program memory (bytes) | 49152 |
| Program memory (instructions) | 24576 |
| Data memory (bytes) | 3968 |
| Data EEPROM (bytes) | 1024 |
| Interrupt sources | 19 |
| I/O ports | Ports A, B, C, (E) |
| Timers | 4 |
| Serial communication | MSSP, enhanced USART |
| Parallel communications | no |
| Instruction set | 75 instructions (83 with extended IS) |

Table 3.3: Main features of the PIC18F2525

Features of the PIC18F2525 are summarized in Table 3.3. All details can be found on Wikpedia[3] and in Microchip's datasheet[4].

### 3.3.2 Memory management

Our implementation requires 2470 bytes of program memory (including the look-up tables for the permutations), out of 48 Kb available. Data memory stores 274 bytes in RAM for the input variables, constants, and temporary variables, that is:

- message block $m$ (64 bytes)
- chain value $h$ (32 bytes)
- salt $s$ (16 bytes)
- counter $t$ (8 bytes)
- constants $c_0, \dots, c_{15}$ (64 bytes)
- internal state $v$ (64 bytes)
- temporary variables $(a, b, c, d)$ for G (16 bytes)
- other temporary variables (10 bytes)

To summarize, BLAKE-32 uses 5% of the program memory, 7% of the RAM, and no EEPROM.

[3] `http://en.wikipedia.org/wiki/PIC_micro`
[4] `http://ww1.microchip.com/downloads/en/DeviceDoc/39626b.pdf`

### 3.3.3 Speed

BLAKE-32 only uses the three operations XOR, 32-bit integer addition, and 32-bit rotation. In the PIC18F2525 the basic unit is a byte, not a 32-bit word, hence 32-bit operations have to be simulated with 8-bit instructions:

- 32-bit XOR is simulated by four independent 8-bit XOR's
- 32-bit addition is simulated by four 8-bit additions with manual transfer of the carry between each addition
- 32-bit rotation is simulated using byte swaps and 1-bit rotate instructions

Rotations are the most complicated operations to implement, because a different code has to be written for each rotation distance; rotation of 8 or 16 positions requires no rotate instruction, while one is needed for 7-bit rotation, and four for 12-bit rotation. For example, the code for a 8-bit rotation of x=x_hi‖x_mh‖x_ml‖x_lo looks like

```
movFF x_hi,tmp
movFF x_mh,x_hi
movFF x_ml,x_mh
movFF x_lo,x_ml
movFF tmp,x_lo
```

while the code for a 7-bit rotation looks like

```
bcf STATUS, C
btfsc x_lo,0
bsf STATUS, C
rrcF x_hi
rrcF x_mh
rrcF x_ml
rrcF x_lo
movFF x_lo,tmp
movFF x_hi,x_lo
movFF x_mh,x_hi
movFF x_ml,x_mh
movFF tmp,x_ml
```

In terms of cycles, counting all the instructions needed (rotate, move, etc.), we have that

- $\ggg$ 16 needs 6 cycles
- $\ggg$ 12 needs 22 cycles
- $\ggg$ 8 needs 5 cycles
- $\ggg$ 7 needs 12 cycles

Below we detail the maximum cost of each line of the $G_i$ function:

$$\begin{array}{lrcl}
\text{(76 cycles)} & a & \leftarrow & a+b+(m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)}) \\
\text{(24 cycles)} & d & \leftarrow & (d \oplus a) \ggg 16 \\
\text{(24 cycles)} & c & \leftarrow & c+d \\
\text{(34 cycles)} & b & \leftarrow & (b \oplus c) \ggg 12 \\
\text{(67 cycles)} & a & \leftarrow & a+b+(m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)}) \\
\text{(22 cycles)} & d & \leftarrow & (d \oplus a) \ggg 8 \\
\text{(24 cycles)} & c & \leftarrow & c+d \\
\text{(29 cycles)} & b & \leftarrow & (b \oplus c) \ggg 7
\end{array}$$

The cycle count is different for $(b \oplus c) \ggg 12$ and $(b \oplus c) \ggg 7$ because of the different rotation distances. The fifth line needs fewer cycles than the first because of the proximity of the indices (though not of the addresses).

In addition, preparing $G_i$'s inputs costs 18 cycles, and calling it 4 cycles, thus in total 322 cycles are needed for computing a $G_i$. Counting the initialization of $v$ (at most 161 cycles) and the overhead of 8 cycles per round, the compression function needs 26001 cycles (that is, 406 cycles per byte). With a 32 MHz processor (8 MIPS), it takes about 3.250 ms to hash a single message block (a single instruction is 125 ns long); with a 40 MHz processor (10 MIPS), it takes about 2.6 ms.

No precomputation is required to set up the algorithm (BLAKE does not require building internal tables before hashing a message, neither it requires the initialization of a particular data structure, for example). On the PIC18F2525, the only setup cost is for preparing the device, i.e. loading data into the data memory; this cost cannot be expressed (solely) in terms of clock cycles, because of interrupt routines and waiting time, which depend on the data source considered.

For sufficiently large messages (say, a few blocks), the cost of preparing the device and of padding the message is negligible, compared to the cost of computing the compression functions. In this case, generating one message digest with BLAKE-28 or BLAKE-32 on a PIC18F2525 requires about 406 cycles per byte.

## 3.4 Large processors

BLAKE is easily implemented on 32- and 64-bit processors: it works on words of 32 or 64 bits, and only makes wordwise operations (XOR, rotation, addition) that are implemented in most of the processors. It is based on ChaCha, one of the fastest stream ciphers. The speed-critical code portion is short and thus is relatively easy to optimize. Because the core of BLAKE is just the G function (16 operations), implementations are simple and compact.

As requested by NIST, we wrote a reference implementation and optimized implementations in ANSI C. Here we report speed benchmarks based on the optimized implementation, which will be used by NIST for comparing BLAKE with other candidates. On specific processors, faster implementations can be obtained by programming BLAKE in assembly; one may directly reuse the assembly programs of ChaCha available[5].

We compiled our program with `gcc 4.1.0` with options `-O3 -fomit-frame-pointer -Wall -ansi`. We report speeds for various lengths of (aligned) messages, and give the median measurement over a hundred trials. We measured the time of a call to the function `Hash` specified in NIST's API, which includes

[5] See `http://cr.yp.to/chacha.html`

1. function `Init`: initialization of the function parameters, copy of the instance's IV
2. function `Update`: iterated hash of the message
3. function `Final`: padding of the message, compression (at most two) of the remaining data

Table 3.4 reports the number of clock cycles required to generate one message digest with the full versions of BLAKE-32 and BLAKE-64 and for reduced-round versions, depending on the message length. BLAKE-224 and BLAKE-384 show performance similar to BLAKE-32 and BLAKE-64, respectively. The "Core 2 Duo" platform corresponds to the *NIST SHA-3 Reference Platform*, except that our computer was running Linux instead of Windows Vista.

For any digest length, a negligible number of cycles is required to setup the algorithm. This is because no precomputation is necessary, and the only preparation consists in loading data in memory.

| Data length [bytes] | 10 | 100 | 1000 | 10000 |
|---|---|---|---|---|
| Celeron M (32-bit mode) | | | | |
| BLAKE-32 (10 rounds) | ≈1500 | 50.1 | 24.5 | 22.2 |
| BLAKE-32 (8 rounds) | ≈1500 | 56.5 | 21.7 | 18.5 |
| BLAKE-32 (5 rounds) | ≈1500 | 43.2 | 13.9 | 12.5 |
| BLAKE-64 (14 rounds) | ≈2000 | 126.4 | 64.4 | 58.8 |
| BLAKE-64 (10 rounds) | ≈2000 | 99.7 | 47.7 | 43.1 |
| BLAKE-64 (7 rounds) | ≈2000 | 93.5 | 32.5 | 30.8 |
| Core 2 Duo (32-bit mode) | | | | |
| BLAKE-32 (10 rounds) | ≈2900 | 51.5 | 27.4 | 28.3 |
| BLAKE-32 (8 rounds) | ≈2900 | 45.2 | 22.6 | 24.2 |
| BLAKE-32 (5 rounds) | ≈2900 | 35.0 | 15.9 | 14.0 |
| BLAKE-64 (14 rounds) | ≈4400 | 94.0 | 61.3 | 61.7 |
| BLAKE-64 (10 rounds) | ≈4400 | 74.0 | 45.4 | 57.6 |
| BLAKE-64 (7 rounds) | ≈4400 | 58.9 | 32.5 | 41.0 |
| Core 2 Duo (64-bit mode) | | | | |
| BLAKE-32 (10 rounds) | ≈1600 | 36.4 | 18.4 | 16.7 |
| BLAKE-32 (8 rounds) | ≈1600 | 32.2 | 15.4 | 13.8 |
| BLAKE-32 (5 rounds) | ≈1600 | 26.9 | 10.9 | 9.6 |
| BLAKE-64 (14 rounds) | ≈1900 | 33.7 | 13.8 | 12.3 |
| BLAKE-64 (10 rounds) | ≈1900 | 29.9 | 11.6 | 9.3 |
| BLAKE-64 (7 rounds) | ≈1900 | 26.8 | 8.5 | 7.2 |

Table 3.4: Performance of our optimized C implementation of BLAKE (in cycles/byte), on a 900 MHz Intel Celeron M and a 2.4 GHz Intel Core 2 Duo.

In terms of bytes-per-second, the top speed is achieved by BLAKE-64 in 64-bit mode, with about 317 Mbps. For very small messages (10 bytes) the overhead is due to the compression of 64 (respectively 128) bytes, and to the cost of initializing and padding the message. The cost per byte quickly decreases, and stabilizes after 1000-byte messages. Although different processors were used, our estimates can be compared with the fastest C implementation of SHA-256, by Gladman[6]: in 64-bit mode on a AMD processor, SHA-256 runs at 20.4 cycles-per-byte, and SHA-512 at 13.4 cycles-per-byte.

[6] `http://fp.gladman.plus.com/cryptography_technology/sha/index.htm`

# 4 Using BLAKE

BLAKE is intended to replace SHA-2 with a minimal engineering effort, and to be used wherever SHA-2 is. BLAKE provides the same interface as SHA-2, with the optional input of a salt. BLAKE is suitable whenever a cryptographic hash function is needed, be it for digital signatures, MAC's, commitment, password storage, key derivation, etc.

This chapter explains how the salt input should (not) be used, and construction details based on BLAKE for HMAC and UMAC, PRF ensembles, and randomized hashing.

## 4.1 Hashing with a salt

The BLAKE hash functions take as input a message and a salt. The aim of hashing with distinct salts is to hash with different functions but using the same algorithm. Depending on the application, the salt can be chosen randomly (thus reusing a same salt twice can occur, though with small probability), or derived from a counter (nonce).

For applications in which no salt is required, it is set to the null value ($s = 0$). In this case the initialization of the state $v$ simplifies to

$$\begin{pmatrix} v_0 & v_1 & v_2 & v_3 \\ v_4 & v_5 & v_6 & v_7 \\ v_8 & v_9 & v_{10} & v_{11} \\ v_{12} & v_{13} & v_{14} & v_{15} \end{pmatrix} \leftarrow \begin{pmatrix} h_0 & h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 & h_7 \\ c_0 & c_1 & c_2 & c_3 \\ t_0 \oplus c_4 & t_0 \oplus c_5 & t_1 \oplus c_6 & t_1 \oplus c_7 \end{pmatrix}$$

and the finalization of the compression function becomes

$$\begin{aligned} h'_0 &\leftarrow h_0 \oplus v_0 \oplus v_8 \\ h'_1 &\leftarrow h_1 \oplus v_1 \oplus v_9 \\ h'_2 &\leftarrow h_2 \oplus v_2 \oplus v_{10} \\ h'_3 &\leftarrow h_3 \oplus v_3 \oplus v_{11} \\ h'_4 &\leftarrow h_4 \oplus v_4 \oplus v_{12} \\ h'_5 &\leftarrow h_5 \oplus v_5 \oplus v_{13} \\ h'_6 &\leftarrow h_6 \oplus v_6 \oplus v_{14} \\ h'_7 &\leftarrow h_7 \oplus v_7 \oplus v_{15} \end{aligned}$$

The salt input may contain a nonce or a random seed, for example. A typical application is for password storage. However, the salt input is not intended to contain the secret key for a MAC construction. We recommend using HMAC or UMAC for MAC functionality, which are much more efficient.

## 4.2 HMAC and UMAC

HMAC [5] can be built on BLAKE similarly to SHA-2. The salt input is not required, and should thus be set to zero (see 4.1). BLAKE has no property that limits its use for HMAC, compared to SHA-2. For example, HMAC based on BLAKE-256 takes as input a key $k$ and a message $m$ and computes

$$\text{HMAC}_k(m) = \text{BLAKE-256}\big(k \oplus \text{opad} \| \text{BLAKE-256}(k \oplus \text{ipad} \| m)\big).$$

All details on the HMAC construction are given in the NIST standardization report [36] or in the original publication [5].

UMAC is a MAC construction "faster but more complex" [13] than HMAC: it is based on the "$\text{PRF}(\text{hash}, \text{nonce})$" approach, where the value "hash" is a universal hash of the message authenticated. UMAC authors propose to instanciate the PRF with HMAC based on SHA-1, computing $\text{HMAC}_k(\text{nonce}\|\text{hash})$.

For combining BLAKE with UMAC, the same approach can be used, namely using HMAC based on BLAKE. It is however more efficient to use BLAKE's salt, and thus compute $\text{HMAC}(\text{hash})$ with $s = \text{nonce}$:

$$\text{HMAC}_k(\text{hash}) = \text{BLAKE-256}\big(k \oplus \text{opad} \| \text{BLAKE-256}(k \oplus \text{ipad} \| \text{hash}, \text{nonce}), \text{nonce}\big)$$

In the best case, setting $s = \text{nonce}$ saves one compression compared to the original construction, while in the worst case performance is unchanged. UMAC authors suggest a nonce of 64 bits [13], which fits in the salt input of all BLAKE functions. We recommend this construction for UMAC based on BLAKE.

## 4.3 PRF ensembles

To construct pseudorandom functions (PRF) ensembles from hash functions, a common practice is to append or prepend the index data to the message. For example, for an arbitrary message $m$ one can define the $i^{\text{th}}$ function of the ensemble as

$$\text{BLAKE-256}(m\|i) \text{ or } \text{BLAKE-256}(i\|m)$$

where $i$ is encoded over a fixed number of bits. These techniques pose no problem specific to BLAKE. The second construction is even more secure than with SHA-2, because it makes some length-extension attacks impossible (cf. [5, §6] and §5.6.1).

Another technique proposed for constructing PRF ensembles is to modify the IV according to the index data. That is, the $i^{\text{th}}$ function of the ensemble has an IV equal to (some representation of) $i$. A concrete construction that exploits this technique is NMAC [5], which computes a MAC as

$$\text{NMAC}_{k_1\|k_2}(m) = H_{k_1}\big(H_{k_2}(m)\big)$$

where $H_k$ is a hash function with initial value $k$.

For combining BLAKE with NMAC, we recommend not to set directly $\text{IV} \leftarrow k_i$, $i = 1, 2$, but instead $\text{IV} \leftarrow \textbf{compress}(\text{IV}, i, 0, 0)$, starting from the IV specific to the function used. This makes the effective IV dependent on the function instance (cf. §2.1 and §2.3).

A last choice for constructing PRF's based on BLAKE is to use the salt for the index data, giving ensembles of $2^{128}$ and $2^{256}$ for BLAKE-256 and BLAKE-512, respectively.

## 4.4 Randomized hashing

Randomized hashing is mainly used for digital signatures (cf. [24, 38]): instead of sending the signature $\mathsf{Sign}(\mathsf{H}(m))$, the signer picks a random $r$ and sends $(\mathsf{Sign}(\mathsf{H}_r(m)), r)$ to the verifier. The advantage of randomized hashing is that it relaxes the security requirements of the hash function [24]. In practice, random data is either appended/prepended to the message or combined with the message; for example the RMX transform [24], given a random $r$, hashes $m$ to the value

$$\mathsf{H}\big(r\|(m^1 \oplus r)\| \ldots \|(m^{N-1} \oplus r)\big).$$

BLAKE offers a dedicated interface for randomized hashing, not a modification of a non-randomized mode: the input $s$, 128 or 256 bits long, should be dedicated for the salt of randomized hashing. This avoids the potential computation overhead of other methods, and allows the use of the function as a blackbox, rather than a special mode of operation of a classical hash function. BLAKE remains compatible with previous generic constructions, including RMX.

# 5 Elements of analysis

This chapter presents a preliminary analysis of BLAKE, with a focus on BLAKE-256. We study properties of the function's components, resistance to generic attacks, and dedicated attack strategies.

## 5.1 Permutations

The permutations $\sigma_0, \ldots, \sigma_9$ were chosen to match several security criteria: First we ensure that a same input difference doesn't appear twice at the same place (to complicate "correction" of differences in the state). Second, for a random message all values $(m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)})$ and $(m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)})$ should be distinct with high probability. For chosen messages, this guarantees that each message word will be XOR'd with different constants, and thus apply distinct transformations to the state through rounds. It also implies that no pair $(m_i, m_j)$ is input twice in the same $G_i$. Finally, the position of the inputs should be balanced: in a round, a given message word is input either in a column step or in a diagonal step, and appears either first or second in the computation of $G_i$. We ensure that each message word appears as many times in a column step as in a diagonal step, and as many times first as second within a step. To summarize:

1. no message word should be input twice at the same point
2. no message word should be XOR'd twice with the same constant
3. each message word should appear exactly 5 times in a column step and 5 times in a diagonal step
4. each message word should appear exactly 5 times in first position in G and 5 times in second position

This is equivalent to say that, in the representation of permutations in §2.1.1 (also see Table 5.1):

1. for all $i = 0, \ldots, 15$, there should exist no distinct permutations $\sigma, \sigma'$ such that $\sigma(i) = \sigma'(i)$
2. no pair $(i, j)$ should appear twice at an offset of the form $(2k, 2k+1)$, for all $k = 0, \ldots, 7$
3. for all $i = 0, \ldots, 15$, there should be 5 distinct permutations $\sigma$ such that $\sigma(i) < 8$, and 5 such that $\sigma(i) > 8$
4. for all $i = 0, \ldots, 15$, there should be 5 distinct permutations $\sigma$ such that $\sigma(i)$ is even, and 5 such that $\sigma(i)$ is odd

| Round | $G_0$ | | $G_1$ | | $G_2$ | | $G_3$ | | $G_4$ | | $G_5$ | | $G_6$ | | $G_7$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 14 | 10 | 4 | 8 | 9 | 15 | 13 | 6 | 1 | 12 | 0 | 2 | 11 | 7 | 5 | 3 |
| 2 | 11 | 8 | 12 | 0 | 5 | 2 | 15 | 13 | 10 | 14 | 3 | 6 | 7 | 1 | 9 | 4 |
| 3 | 7 | 9 | 3 | 1 | 13 | 12 | 11 | 14 | 2 | 6 | 5 | 10 | 4 | 0 | 15 | 8 |
| 4 | 9 | 0 | 5 | 7 | 2 | 4 | 10 | 15 | 14 | 1 | 11 | 12 | 6 | 8 | 3 | 13 |
| 5 | 2 | 12 | 6 | 10 | 0 | 11 | 8 | 3 | 4 | 13 | 7 | 5 | 15 | 14 | 1 | 9 |
| 6 | 12 | 5 | 1 | 15 | 14 | 13 | 4 | 10 | 0 | 7 | 6 | 3 | 9 | 2 | 8 | 11 |
| 7 | 13 | 11 | 7 | 14 | 12 | 1 | 3 | 9 | 5 | 0 | 15 | 4 | 8 | 6 | 2 | 10 |
| 8 | 6 | 15 | 14 | 9 | 11 | 3 | 0 | 8 | 12 | 2 | 13 | 7 | 1 | 4 | 10 | 5 |
| 9 | 10 | 2 | 8 | 4 | 7 | 6 | 1 | 5 | 15 | 11 | 9 | 14 | 3 | 12 | 13 | 0 |

Table 5.1: Input of message words.

## 5.2 Compression function

This section reports a bottom-up analysis of BLAKE's compression function.

### 5.2.1 G **function**

Given $(a, b, c, d)$ and message block(s) $m_j$, $j \in \{0, \dots, 15\}$; a function $G_i$ computes

$$
\begin{aligned}
a &\leftarrow a + b + (m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)}) \\
d &\leftarrow (d \oplus a) \ggg 16 \\
c &\leftarrow c + d \\
b &\leftarrow (b \oplus c) \ggg 12 \\
a &\leftarrow a + b + (m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)}) \\
d &\leftarrow (d \oplus a) \ggg 8 \\
c &\leftarrow c + d \\
b &\leftarrow (b \oplus c) \ggg 7
\end{aligned}
$$

The G function is inspired from the "quarter-round" function of the stream cipher ChaCha, which transforms $(a, b, c, d)$ as follows:

$$
\begin{aligned}
a &\leftarrow a + b \\
d &\leftarrow (d \oplus a) \lll 16 \\
c &\leftarrow c + d \\
b &\leftarrow (b \oplus c) \lll 12 \\
a &\leftarrow a + b \\
d &\leftarrow (d \oplus a) \lll 8 \\
c &\leftarrow c + d \\
b &\leftarrow (b \oplus c) \lll 7
\end{aligned}
$$

To build BLAKE's compression function based on this algorithm, we add input of two message words and constants, and let the function be otherwise unchanged. We keep the rotation distances of ChaCha, which provide a good trade-off security/efficiency: 16- and 8-bit rotations preserve byte alignment, so are fast on 8-bit processors (no rotate instruction is needed), while 12- and 7-bit rotations break up the byte structure, and are reasonably fast.

ChaCha's function is itself an improvement of the "quarter round" of the stream cipher Salsa20. The idea of a 4×4 state with four parallel mappings for rows and columns goes back to the cipher Square [18], and was then successfuly used in Rijndael [19], Salsa20 and ChaCha. Detailed design rationale and preliminary analysis of ChaCha and Salsa20 can be found in [6, 8], and cryptanalysis in [3, 17, 28, 40].

### Bijectivity

Given a message $m$, and a round index $r$, the inverse function of $G_i$ is defined as follows:

$$\begin{array}{rcl} b & \leftarrow & c \oplus (b \lll 7) \\ c & \leftarrow & c - d \\ d & \leftarrow & a \oplus (d \lll 8) \\ a & \leftarrow & a - b - (m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)}) \\ b & \leftarrow & c \oplus (b \lll 12) \\ c & \leftarrow & c - d \\ d & \leftarrow & a \oplus (d \lll 16) \\ a & \leftarrow & a - b - (m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)}) \end{array}$$

Hence for any $(a', b', c', d')$, one can efficiently compute the unique $(a, b, c, d)$ such that $G_i(a, b, c, d) = (a', b', c', d')$, given $i$ and $m$. In other words, $G_i$ is a permutation of $\{0, 1\}^{128}$.

### Linear approximations

We found several linear approximations of differentials; the notation $(\Delta_0, \Delta_1, \Delta_2, \Delta_3) \mapsto (\Delta'_0, \Delta'_1, \Delta'_2, \Delta'_3)$ means that the two inputs with the leftmost difference lead to outputs with the rightmost difference, when $(m_{\sigma_r(2i+1)} \oplus c_{\sigma_r(2i)}) = (m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)}) = 0$. For random inputs we have for example

- $(80000000, 00000000, 80000000, 80008000) \mapsto (80000000, 0, 0, 0)$ with probability 1
- $(00000800, 80000800, 80000000, 80000000) \mapsto (0, 0, 80000000, 0)$, with probability 1/2
- $(80000000, 80000000, 80000080, 00800000) \mapsto (0, 0, 0, 80000000)$, with probability 1/2

Many high probability differentials can be identified for G, and one can use standard message modification techniques (linearization, neutral bits) to identify a subset of inputs for which the probability is much higher than for the whole domain. Similar linear differentials exist in the Salsa20 function, and were exploited [3] to attack the compression function Rumba [7], breaking 3 rounds out of 20.

Particular properties of G are

1. the only fixed-point in G is the zero input
2. no preservation of differences can be obtained by linearization

The first observation is straightforward when writing the corresponding equations. The second point means that there exist no pair of inputs whose difference (according to XOR) is preserved in the corresponding pair of outputs, in the linearized model. This follows from the fact that, if an input difference gives the same difference in the output, then this difference must be a fixed-point for G; since the only fixed-point is the null value, there exists no such difference.

### Diffusion

Diffusion is the ability of the function to quickly spread a small change in the input through the whole internal state. For example, G inputs message words such that any difference in a message word affects the four words output. Tables 5.2.1 and 5.3 give the average number of bits modified by G, given a random one-bit difference in the input, for each input word.

| in\out | $a$ | $b$ | $c$ | $d$ |
|---|---|---|---|---|
| $a$ | 4.6 | 11.7 | 10.0 | 6.5 |
| $b$ | 6.6 | 14.0 | 11.5 | 8.4 |
| $c$ | 2.4 | 6.6 | 4.8 | 2.4 |
| $d$ | 2.4 | 8.4 | 6.7 | 3.4 |

Table 5.2: Average number of changes in each output word given a random bit flip in each input word.

| in\out | $a$ | $b$ | $c$ | $d$ |
|---|---|---|---|---|
| $a$ | 4.4 | 9.9 | 8.2 | 6.3 |
| $b$ | 6.3 | 12.4 | 9.8 | 8.1 |
| $c$ | 1.9 | 3.9 | 2.9 | 1.9 |
| $d$ | 1.9 | 4.9 | 3.9 | 2.9 |

Table 5.3: Average number of changes in each output word given a random bit flip in each input word, in the XOR-linearized model.

## 5.2.2 Round function

The round function of BLAKE is

$$\begin{array}{llll} G_0(v_0\ , v_4\ , v_8\ , v_{12}) & G_1(v_1\ , v_5\ , v_9\ , v_{13}) & G_2(v_2\ , v_6\ , v_{10}, v_{14}) & G_3(v_3\ , v_7\ , v_{11}, v_{15}) \\ G_4(v_0\ , v_5\ , v_{10}, v_{15}) & G_5(v_1\ , v_6\ , v_{11}, v_{12}) & G_6(v_2\ , v_7\ , v_8\ , v_{13}) & G_7(v_3\ , v_4\ , v_9\ , v_{14}) \end{array}$$

### Bijectivity

Because G is a permutation, a round is a permutation of the inner state $v$ for any fixed message. In other words, given a message and the value of $v$ after $r$ rounds, one can determine the value of $v$ at rounds $r-1$, $r-2$, etc., and thus the initial value of $v$. Therefore, for a same initial state a sequence of rounds is a permutation of the message. That is, one cannot find two messages that produce the same internal state, after any number of rounds.

### Diffusion and low-weight differences

After one round, all 16 words are affected by a modification of one bit in the input (be it the message, the salt, or the chain value). Here we illustrate diffusion through rounds with a concrete example, for the *null message* and the *null initial state*. The matrices displayed below represent the *differences* in the state after each step of the first two rounds (column step, diagonal step, column step, diagonal step), for a difference in the least significant bit of $v_0$:

$$\text{column step}\quad \begin{pmatrix} \texttt{00000037} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{E06E0216} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{37010B00} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{37000700} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \end{pmatrix} \quad (\text{weight } 34)$$

$$\text{diagonal step}\quad \begin{pmatrix} \texttt{0000027F} & \texttt{10039015} & \texttt{5002B070} & \texttt{C418A7D4} \\ \texttt{66918CC7} & \texttt{1CBEEE25} & \texttt{F1A8535F} & \texttt{C111AD29} \\ \texttt{F8D104F0} & \texttt{6F08C6F9} & \texttt{5F77131E} & \texttt{E4291FE7} \\ \texttt{151703A7} & \texttt{705002B0} & \texttt{F2C22207} & \texttt{7F001702} \end{pmatrix} \quad (\text{weight } 219)$$

$$\text{column step}\quad \begin{pmatrix} \texttt{944F85FD} & \texttt{A044CCB3} & \texttt{9476A6BC} & \texttt{24B6ADAC} \\ \texttt{A729BBE9} & \texttt{6549BC3D} & \texttt{3A330361} & \texttt{7318B20D} \\ \texttt{7BF5F768} & \texttt{7831614B} & \texttt{CF44C968} & \texttt{53D886E2} \\ \texttt{5A1642B3} & \texttt{41B00EA0} & \texttt{A7115A95} & \texttt{7AC791D1} \end{pmatrix} \quad (\text{weight } 249)$$

$$\text{diagonal step}\quad \begin{pmatrix} \texttt{DFC2D878} & \texttt{F9FAAE7A} & \texttt{2D804D9A} & \texttt{3EF58B7F} \\ \texttt{FC91AF81} & \texttt{D78E2315} & \texttt{55048021} & \texttt{0811CC46} \\ \texttt{FB98AF71} & \texttt{DC27330E} & \texttt{47A19B59} & \texttt{EDDE442E} \\ \texttt{F042BB72} & \texttt{1C7A59AB} & \texttt{AC2EFFA4} & \texttt{2E76390B} \end{pmatrix} \quad (\text{weight } 264)$$

In comparison, in the linearized model (i.e., where all additions are replaced by XOR's), we have:

$$\text{column step}\quad \begin{pmatrix} \texttt{00000011} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{20220202} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{11010100} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{11000100} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \end{pmatrix} \quad (\text{weight } 14)$$

$$\text{diagonal step}\quad \begin{pmatrix} \texttt{00000101} & \texttt{10001001} & \texttt{10011010} & \texttt{02202000} \\ \texttt{40040040} & \texttt{22022220} & \texttt{00202202} & \texttt{00222020} \\ \texttt{01110010} & \texttt{20020222} & \texttt{01111101} & \texttt{00111101} \\ \texttt{01110001} & \texttt{10100110} & \texttt{22002200} & \texttt{01001101} \end{pmatrix} \quad (\text{weight } 65)$$

$$\text{column step}\quad \begin{pmatrix} \texttt{54500415} & \texttt{13012131} & \texttt{02002022} & \texttt{20331103} \\ \texttt{2828A0A8} & \texttt{46222006} & \texttt{04006046} & \texttt{64646022} \\ \texttt{00045140} & \texttt{30131033} & \texttt{12113132} & \texttt{10010011} \\ \texttt{00551045} & \texttt{23203003} & \texttt{03121212} & \texttt{01311212} \end{pmatrix} \quad (\text{weight } 125)$$

$$\text{diagonal step}\quad \begin{pmatrix} \texttt{35040733} & \texttt{67351240} & \texttt{24050637} & \texttt{B1300980} \\ \texttt{27472654} & \texttt{8AE6CA08} & \texttt{EE4A6286} & \texttt{E08264A8} \\ \texttt{03531247} & \texttt{1AB89238} & \texttt{54132765} & \texttt{55051040} \\ \texttt{14360705} & \texttt{73540643} & \texttt{89128902} & \texttt{70030514} \end{pmatrix} \quad (\text{weight } 186)$$

The higher weight in the original model is due to the addition carries induced by the constants $c_0, \dots, c_{15}$. A technique to avoid carries at the first round and get a low-weight output difference is to choose a message such that $m_0 = c_0, \dots, m_{15} = c_{15}$. At the subsequent rounds, however, nonzero words are introduced because of the different permutations.

Diffusion can be delayed a few steps by combining high-probability and low-weight differentials of G, using initial conditions, neutral bits, etc. For example, applying directly the differential

$$(80000000, 00000000, 80000000, 80008000) \mapsto (80000000, 0, 0, 0)$$

the diffusion is delayed one step, as illustrated below:

$$\text{column step} \quad \begin{pmatrix} \texttt{80000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \end{pmatrix} \quad (\text{weight } 1)$$

$$\text{diagonal step} \quad \begin{pmatrix} \texttt{800003E8} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{0B573F03} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{AB9F819D} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{E8800083} \end{pmatrix} \quad (\text{weight } 49)$$

$$\text{column step} \quad \begin{pmatrix} \texttt{8007E4A0} & \texttt{2075B261} & \texttt{18E78828} & \texttt{9800099E} \\ \texttt{5944FE53} & \texttt{F178A22F} & \texttt{86B0A65B} & \texttt{936C73CB} \\ \texttt{A27F0D24} & \texttt{98D6929A} & \texttt{4088A5FB} & \texttt{2E39EDA3} \\ \texttt{A08FFF64} & \texttt{2AD374B7} & \texttt{2818E788} & \texttt{1E9883E1} \end{pmatrix} \quad (\text{weight } 236)$$

$$\text{diagonal step} \quad \begin{pmatrix} \texttt{4B3CBDD2} & \texttt{0290847F} & \texttt{B4FF78F9} & \texttt{F1E71BA3} \\ \texttt{3A023C96} & \texttt{49908E86} & \texttt{F13BC1D7} & \texttt{ADC2020A} \\ \texttt{9DCA344A} & \texttt{827BF1E5} & \texttt{B20A8825} & \texttt{FE575BE3} \\ \texttt{FC81FE81} & \texttt{D676FFC9} & \texttt{80740480} & \texttt{52570CB2} \end{pmatrix} \quad (\text{weight } 252)$$

In comparison, for a same input difference in the linearized model we have

$$\text{column step} \quad \begin{pmatrix} \texttt{80000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \end{pmatrix} \quad (\text{weight } 1)$$

$$\text{diagonal step} \quad \begin{pmatrix} \texttt{80000018} & \texttt{00000000} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{10310101} & \texttt{00000000} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{18808080} & \texttt{00000000} \\ \texttt{00000000} & \texttt{00000000} & \texttt{00000000} & \texttt{18800080} \end{pmatrix} \quad (\text{weight } 18)$$

$$\text{column step} \quad \begin{pmatrix} \texttt{80000690} & \texttt{E1101206} & \texttt{0801B818} & \texttt{B8000803} \\ \texttt{1D217176} & \texttt{600FC064} & \texttt{60111212} & \texttt{22167121} \\ \texttt{90B8B886} & \texttt{16E12133} & \texttt{00888138} & \texttt{83389890} \\ \texttt{90803886} & \texttt{17E01122} & \texttt{180801B8} & \texttt{83B88010} \end{pmatrix} \quad (\text{weight } 155)$$

$$\text{diagonal step} \quad \begin{pmatrix} \texttt{44E4E456} & \texttt{133468BD} & \texttt{DBBDA164} & \texttt{0F649833} \\ \texttt{4E20F629} & \texttt{563A9099} & \texttt{A62F3969} & \texttt{7773C0BE} \\ \texttt{FEB6F508} & \texttt{AABDCBF9} & \texttt{3262E291} & \texttt{87A10D6A} \\ \texttt{3C2B867B} & \texttt{B603B05C} & \texttt{DA695123} & \texttt{F88E8007} \end{pmatrix} \quad (\text{weight } 251)$$

These examples show that even in the linearized model, after two rounds about half of the state bits have changed when different initial states are used (similar figures can be given for a difference in the message). Using clever combinations of low-weight differentials and message modifications one may attack reduced versions with two or three rounds. However, differences after more than four steps seem very difficult to control.

### 5.2.3 Compression function

BLAKE's compression function is the combination of an initialization, a sequence of rounds, and a finalization. Contrary to ChaCha, BLAKE breaks self-similarity by using a round-dependent permutation of the message and the constants. This prevents attacks that exploit the similarity among round functions (cf. slide attacks in §5.7.3). Particular properties of the compression function are summarized below.

### Initialization

At the initialization stage, constants and redundancy of $t$ impose a nonzero initial state (and a non "all-one" state). The disposition of inputs implies that after the first column step the initial value $h$ is directly mixed with the salt $s$ and the counter $t$.

The double input of $t_0$ and $t_1$ in the initial state suggests the notion of *valid* initial state: we shall call an initial state $v_0, \dots, v_{15}$ valid if and only there exists $t_0, t_1$ such that $v_{12} = t_0 \oplus c_4$ and $v_{13} = t_0 \oplus c_5$, and $v_{14} = t_1 \oplus c_6$ and $v_{15} = t_1 \oplus c_7$. Non-valid states are thus impossible initial states.

### Number of rounds

The original submission document wrote

*"The choice of 10 rounds for BLAKE-32 was determined by*

1. *the cryptanalytic results on Salsa20, ChaCha, and Rumba (one BLAKE-32 round is essentially two ChaCha rounds, so the initial conservative choice of 20 rounds for ChaCha corresponds to 10 rounds for BLAKE-32): truncated differentials were observed for up to 4 Salsa20 rounds and 3 ChaCha rounds, and the Rumba compression function has shortcut attacks for up to 3 rounds; the eSTREAM project chose a version of Salsa20 with 12 rounds in its portfolio, and 12-round ChaCha is arguably as strong as 12-round Salsa20.*

2. *our results on early versions of BLAKE, which had similar high-level structure, but a round function different from the present one: for the worst version, we could find collisions for up to 5 rounds.*

3. *our results on the final BLAKE: full diffusion is achieved after two rounds, and the best differentials found can be used to attack two rounds only.*

*BLAKE-64 has 14 rounds, i.e., 4 more than BLAKE-32; this is because the larger state requires more rounds for achieving similar security (in comparison, SHA-512 has 1.25 times more rounds than SHA-256).*

*We believe that the choice of 10 and 14 rounds provides a high security margin, without sacrificing performance. The number of rounds may later be adjusted according to the future results on BLAKE (for example, 8 rounds for BLAKE-32 may be fine if the best attack breaks 4 rounds, while 12 rounds may be chosen if an attack breaks, say, 6 rounds)."*

For the final, we chose to "tweak" BLAKE, as allowed by NIST. The tweak consists in a modified number of rounds: 14 for BLAKE-28 and BLAKE-32, 16 for BLAKE-48 and BLAKE-64. The new versions are called BLAKE-224, BLAKE-256, BLAKE-384, and BLAKE-512, respectively.

The choice of a more conservative security margin was motivated by the implementation and cryptanalysis results published as of December 2010. In particular:

- Optimized implementations BLAKE is fast, and often faster than SHA-2. As security has utmost priority for us, we chose an increased number of rounds so that BLAKE has a very conservative security margin and yet in such a way that it remains faster than SHA-2 on a number of platforms.

- The number of rounds affects throughput but not the amount of memory of or hardware gates necessary for an implementation of BLAKE. As the two latter metrics are generally the limiting factors in embedded systems, more rounds will not affect BLAKE's good suitability for those systems). Energy consumption slightly increases, but at most of a factor 14/10 and 16/14.

- Known cryptanalysis results against reduced versions remain valid, so the understanding of BLAKE's security continues to benefit from these public scrutiny and third party analysis.

As of December 2010, the best attack on the (reduced) BLAKE hash functions that we are aware of is a preimage attack on 2.5 rounds [29] with complexity $2^{209}$ for BLAKE-256 and $2^{481}$ for BLAKE-512. A high-complexity distinguisher for 7 middle rounds of the compression function of BLAKE-256 has been reported to us.

### Finalization

At the finalization stage, the state is compressed to half its length, in a way similar to that of the cipher Rabbit [14]. The feedforward of $h$ and $s$ makes each word of the hash value dependent on two words of the inner state, one word of the initial value, and one word of the salt. The goal is to make the function non-invertible when the initial value and/or the salt are unknown.

Our approach of "permutation plus feedforward" is similar to that of SHA-2, and can be seen as a particular case of Davies-Meyer-like constructions: denoting E the blockcipher defined by the round sequence, BLAKE's compression function computes

$$\mathsf{E}_{m\|s}(h) \oplus h \oplus (s\|s)$$

which, for a null salt, gives the Davies-Meyer construction $\mathsf{E}_m(h) \oplus h$. We use XOR's and not additions (as in SHA-2), because here additions don't increase security, and are much more expensive in circuits and 8-bit processors.

If the salt $s$ was unknown and not fedforward, then one would be able to recover it given a one-block message, its hash value, and the IV. This would be a critical property. The counter $t$ is not input in the finalization, because its value is always known and never chosen by the users.

### Local collisions

A *local collision* happens when, for two distinct messages, the internal states after a same number of rounds are identical. For BLAKE hash functions, there exists no local collisions for a same initial state (i.e., same IV, salt, and counter). This result directly follows from the fact that the round function is a permutation of the message, for fixed initial state $v$ (and so different inputs lead to different outputs). This property generalizes to any number of rounds. The requirement of a same initial state does not limit much the result: for most of the applications, no salt is used, and a collision on the hash function implies a collision on the compression function with same initial state [10].

### Full diffusion

Full diffusion is achieved when each input bit has a chance to affect each output bit. BLAKE-256 and BLAKE-512 achieve full diffusion after two rounds, given a difference in the IV, $m$, or $s$.

### 5.2.4 Fixed-points

A fixed-point for BLAKE's compression function is a tuple $(m, h, s, t)$ such that

$$\textbf{compress}(m, h, s, t) = h$$

Functions of the form $E_m(h) \oplus h$ (like SHA-2) allow the finding of fixed-points for chosen messages by computing $h = E^{-1}(0)$, which gives $E_m(h) \oplus h = h$.

BLAKE's structure is a particular case of the Davies-Meyer-like constructions mentioned in §5.2.3; consider the case when no salt is used ($s = 0$), without loss of generality; for finding fixed-points, we have to choose the final $v$ such that

$$\begin{array}{rcl} h_0 & = & h_0 \oplus v_0 \oplus v_8 \\ h_1 & = & h_1 \oplus v_1 \oplus v_9 \\ h_2 & = & h_2 \oplus v_2 \oplus v_{10} \\ h_3 & = & h_3 \oplus v_3 \oplus v_{11} \\ h_4 & = & h_4 \oplus v_4 \oplus v_{12} \\ h_5 & = & h_5 \oplus v_5 \oplus v_{13} \\ h_6 & = & h_6 \oplus v_6 \oplus v_{14} \\ h_7 & = & h_7 \oplus v_7 \oplus v_{15} \end{array}$$

That is, we need $v_0 = v_8, v_1 = v_9, \dots, v_7 = v_{15}$, so there are $2^{256}$ possible choices for $v$. From this $v$ we compute the round function backward to get the initial state, and we find a fixed-point when

- the third line of the state is $c_0, \dots, c_3$, and
- the fourth line of the state is valid, that is, $v_{12} = v_{13} \oplus c_4 \oplus c_5$ and $v_{14} = v_{15} \oplus c_6 \oplus c_7$

Thus we find a fixed-point with effort $2^{128} \times 2^{64} = 2^{192}$, instead of $2^{256}$ ideally. This technique also allows to find several fixed-points for a same message (up to $2^{64}$ per message) in less time than expected for an ideal function.

BLAKE's fixed-point properties do not give a distinguisher between BLAKE and a PRF, because we use here the internal mechanisms of the compression function, and not blackbox queries.

#### Fixed-point collisions

A fixed-point collision for BLAKE is a tuple $(m, m', h, s, s', t, t')$ such that

$$\textbf{compress}(m, h, s, t) = \textbf{compress}(m', h, s', t') = h,$$

that is, a pair of fixed-points for the same hash value. This notion was introduced in [2], which shows that fixed-point collisions can be used to build multicollisions at a reduced cost. For BLAKE-256, however, a fixed-point collision costs about $2^{192} \times 2^{128} = 2^{320}$ trials, which is too high to exploit for an attack.

## 5.3 Iteration mode (HAIFA)

HAIFA [10, 22] is a general iteration mode for hash functions, which can be seen as "Merkle-Damgård with a salt and a counter". HAIFA offers an interface for input of the salt and the counter, and provides resistance to several generic attacks (herding, long-message second preimages, length extension). HAIFA was used for the LAKE hash functions [4], and analyzed in [1, 15].

Below we comment on BLAKE's use of HAIFA:

- HAIFA has originally a single IV for a family of functions, and computes the effective IV of a specific instance with $k$-bit hashes by setting IV $\leftarrow$ **compress**$(\mathsf{IV}, k, 0, 0)$. This allows variable-length hashing, but complicates the function and requires an additional compression. BLAKE has only two different instances for each function, so we directly specify their proper IV to simplify the definition. Each instance has a distinct effective IV, but no extra compression is needed.

- HAIFA defines a padding data that includes the encoding of the hash value length; again, because we only have two different lengths, one bit suffices to encode the identity of the instance (i.e., 1 encodes 256, and 0 encodes 224). We preserve the instance-dependent padding, but reduce the data overhead, and in the best case save one call to the compression function. Padding the binary encoding of the hash bit length wouldn't increase security.

### On the role of the counter

We will highlight some facts that underlie HAIFA's resistance to length extension and second preimage attacks. Suppose that **compress**$(\cdot, \cdot, \cdot, t)$ defines a family of pseudorandom functions (PRF's); to make clear the abstraction we'll write $\{F_t\}_t$ the PRF family, such that $F_t(m, h, s) = h'$, i.e. F is an ideal compression function, and $F_t$ an ideal compression function with counter set to $t$. In the process of iteratively hashing a message, all compression functions $F_t$ are different, because the counter is different at each compression. For example, when hashing a 1020-bit message with BLAKE-256, we first use $F_{512}$, then $F_{1020}$, and finally $F_0$.

Now observe that the family $\{F_t\}$ can be split into two disjoint sets (considering BLAKE-256's parameters):

1. the *intermediate* compressions, called to compress message blocks containing no padding data (only original message bits):

$$\mathcal{I} = \{F_t, \exists k \in \mathbb{N}^\star, t = 512 \cdot k \leq 2^{64} - 512\}$$

2. the *final* compressions, called to compress message blocks containing padding data:

$$\mathcal{F} = \{F_0\} \cup \{F_t, \exists k \in \mathbb{N}^\star, p \in \{1, \ldots, 511\}, t = 512 \cdot k + p < 2^{64}\}$$

A function in $\mathcal{I}$ is never the last in a chain of iterations. A function in $\mathcal{F}$ appears either in last or penultimate position, and its inputs are restricted to message blocks with consistent padding (for example $F_{10}$ in BLAKE-256 needs messages of the form $\langle$10 bits$\rangle 10\ldots01\langle 10\rangle_{64}$). Clearly, $|\mathcal{I}| = 2^{55} - 1$ and $|\mathcal{F}| = 511 \cdot |\mathcal{I}|$. Functions in $\mathcal{F}$ can be seen as playing a role of output filter, in the same spirit as the NMAC hash construction [16].

The above structure is behind the original security properties of HAIFA, including its resistance to second-preimage attacks [22].

## 5.4 Pseudorandomness

One expects from a good hash function to “look like a random function”. Notions of indistinguishability, unpredictability, indifferentiability [33] and seed-incompressibility [25] define precise notions related to “randomness” for hash functions, and are used to evaluate generic constructions or dedicated designs. However they give no clue on how to construct primitives’ algorithms.

Roughly speaking, the algorithm of the compression function should simulate a “complicated function”, with no apparent structure—i.e., it should have no property that a random function has not. In terms of structure, “complicated” means for example that the algebraic normal form (ANF) of the function, as a vector of Boolean functions, should contain each possible monomial with probability 1/2; generalizing, it means that when any part of the input is random, then the ANF obtained by fixing this input is also (uniform) random. Put differently, the truth table of the hash function when part of the input is random should “look like” a random bit string. In terms of input/output, “complicated” means for example that a small difference in the input doesn’t imply a small difference in the input; more generally, any difference or relation between two inputs should be statistically independent of any relation of the corresponding outputs.

Pseudorandomness is particularly critical for stream ciphers, and no distinguishing attack—or any other non-randomness property—has been identified on Salsa20 or ChaCha. These ciphers construct a complicated function by making a long chain of simple operations. Non-randomness was observed for reduced versions with up to three ChaCha rounds (which correspond to one and a half BLAKE round). BLAKE inherits ChaCha’s pseudorandomness, and in addition avoids the self-similarity of the function by having round-dependent constants. Although there is no formal reduction of BLAKE’s security to ChaCha’s, we can reasonably conjecture that BLAKE’s compression function is “complicated enough” with respect to pseudorandomness.

## 5.5 Indifferentiability

The counter input to each compression function of BLAKE simulates distinct functions for each message block hashed. In particular, the value of the counter input at the last compression is never input for an intermediate compression. It follows that the inputs of the BLAKE’s iteration mode are *prefix-free*, which guarantees [16] that BLAKE is indifferentiable from a random oracle when its compression function is assumed ideal.

This result guarantees that if “something goes wrong” in BLAKE, then its compression function should be blamed. In other words, the iterated hash mode induces no loss of security.

## 5.6 Generic attacks

This section reports on the resistance of BLAKE to the most important generic attacks, that is, attacks that exploit to broad class of functions: for example a generic attack can exploit the iteration mode, or weak algebraic properties of the compression function.

### 5.6.1 Length extension

Length extension is a forgery attack against MAC’s of the form $H_k(m)$ or $H(k\|m)$, i.e. where the key $k$ is respectively used as the IV or prepended to the message. The attack can be applied when H is an iterated hash with "MD-strengthening" padding: given $h = H_k(m)$ and $m$, determine the padding data $p$, and compute $v' = H_h(m')$, for an arbitrary $m'$. It follows from the iterated construction that $v' = H_k(m\|p\|m')$. That is, the adversary forged a MAC of the message $m\|p\|m'$.

The length extension attack doesn't apply to BLAKE, because of the input of the number of bits hashed so far to the compression function, which simulates a specific output function for the last message block (cf. §5.3). For example, let $m$ be a 1020-bit message; after padding, the message is composed of three blocks $m^0, m^1, m^2$; the final chain value will be $h^3 = \textbf{compress}(h^2, m^2, s, 0)$, because counter values are respectively 512, 1020, and 0 (see §2.1.3). If we extend the message with a block $m^3$, with convenient padding bits, and hash $m^0\|m^1\|m^2\|m^3$, then the chain value between $m^2$ and $m^3$ will be $\textbf{compress}(h^2, m^2, s, 1024)$, and thus be different from $\textbf{compress}(h^2, m^2, s, 0)$. The knowledge of BLAKE-256$(m^0\|m^1\|m^2)$ cannot be used to compute the hash of $m^0\|m^1\|m^2\|m^3$.

### 5.6.2 Collision multiplication

We coin the term "collision multiplication" to define the ability, given a collision $(m, m')$, to derive an arbitrary number of other collisions. For example, Merkle-Damgård hash functions allow to derive collisions of the form $(m\|p\|u, m'\|p'\|u)$, where $p$ and $p'$ are the padding data, and $u$ an arbitrary string; this technique can be seen as a kind of length extension attack. And for the same reasons that BLAKE resists length extension, it also resists this type of collision multiplication, when given a collision of minimal size (that is, when the collision only occurs for the hash value, not for intermediate chain values).

### 5.6.3 Multicollisions

A multicollision is a set of messages that map to the same hash value. We speak of a $k$-collision when $k$ distinct colliding messages are known.

#### Joux's technique

The technique proposed by Joux [30] finds a $k$-collision for Merkle-Damgård hash functions with $n$-bit hash values in $\lceil \log_2 k \rceil \cdot 2^{n/2}$ calls to the compression function (see Fig. 5.1). The colliding messages are long of $\lceil \log_2 k \rceil$ blocks. This technique applies as well for the BLAKE hash functions, and to all hash functions based on HAIFA. For example, a 32-collision for BLAKE-256 can be found within $2^{133}$ compressions.

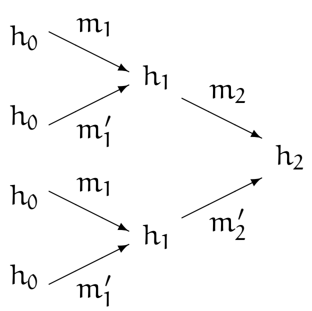


Figure 5.1: Illustration of Joux's technique for 2-collisions, where $\textbf{compress}(h_0, m_1) = \textbf{compress}(h_0, m_1') = h_1$, etc. This technique can apply to BLAKE.

Joux's attack is clearly not a concrete threat, which is demonstrated *ad absurdum*: to be applicable, it requires the knowledge of at least two collisions, but any function (resistant or not to Joux's attack) for which collisions can be found is broken anyway. Hence this attack only damages non-collision-resistant hash functions.

#### Kelsey/Schneier's technique

The technique presented by Kelsey and Schneier [31] works only when the compression function admits easily found fixed-points. An advantage over Joux's attack is that the cost of finding a $k$-collision no longer depends on $k$. Specifically, for a Merkle-Damgård hash function with $n$-bit hash values, it makes $3 \cdot 2^{n/2}$ compressions and needs storage for $2^{n/2}$ message blocks (see Fig. 5.2). Colliding messages are long of $k$ blocks. This technique does not apply to BLAKE, because fixed-points cannot be found efficiently, and the counter $t$ foils fixed-point repetition.

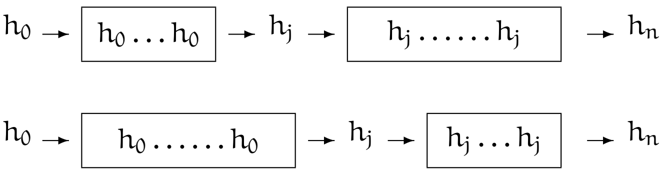


Figure 5.2: Schematic view of the Kelsey/Schneier multicollision attack on Merkle-Damgård functions. This technique does not apply to BLAKE.

#### Faster multicollisions

When an iterated hash admits fixed-points and the IV is chosen by the attacker, this technique [2] finds a $k$-collision in time $2^{n/2}$ and negligible memory, with colliding messages of size $\lceil \log_2 k \rceil$ (see Fig. 5.3. Like the Kelsey/Schneier technique, it is based on the repetition of fixed-points, thus does not apply to BLAKE.

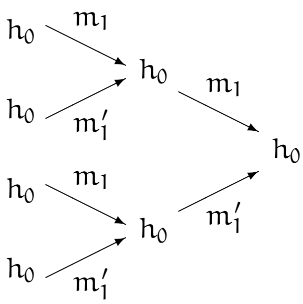


Figure 5.3: Illustration of the faster multicollision, for 2-collisions on Merkle-Damgård hash functions. This technique does not apply to BLAKE.

### 5.6.4 Second preimages

Dean [21, §5.6.3] and subsequently Kelsey and Schneier [31] showed generic attacks on $n$-bit iterated hashes that find second preimages in significantly less than $2^n$ compressions. HAIFA was proven to be resistant to these attacks [22], assuming a strong compression function; this result applies to BLAKE, as a HAIFA-based design. Therefore, no attack on $n$-bit BLAKE can find second-preimages in less than $2^n$ trials, unless exploiting the structure of the compression function.

### 5.6.5 Side channels

All operations in the BLAKE functions are independent of the input and can be implemented to run in constant time on all platforms (and still be fast). The ChaCha core function was designed to be immune to all kind of side-channel attacks (timing, power analysis, etc.), and BLAKE inherits this property. Side-channel analysis of the eSTREAM finalists also suggests that Salsa20 and ChaCha are immune to side-channel attacks [42].

### 5.6.6 SAT solvers

Attacks using SAT-solvers consist in describing a security problem in terms of a SAT instance, then solving this instance with an efficient solver. These attacks were used for finding collisions [34] and preimages for (reduced) for MD4 and MD5 [20]. The high complexity of BLAKE and the absence of SAT-solver-based attacks on ChaCha and Salsa20 argues for the resistance of BLAKE to these methods.

### 5.6.7 Algebraic attacks

Algebraic attacks consist in reducing a security problem to solving a system of equations, then solving this system. The approach is similar to that of SAT-solver attacks, and for similar reasons is unlikely to break BLAKE.

## 5.7 Dedicated attacks

This section describes several strategies for attacking BLAKE, and justifies their limitations.

### 5.7.1 Symmetric differences

A sufficient (but not necessary) condition to find a collision on BLAKE is to find two message blocks for which, given same IV's and salts, the corresponding internal states $v$ and $v'$ after the sequence of rounds satisfy the relation

$$v_i \oplus v_{i+8} = v'_i \oplus v'_{i+8},\ i = 0, \ldots, 7.$$

Put differently, it suffices to find a message difference that leads after the rounds sequence to a difference of the form

$$\begin{pmatrix} v_0 \oplus v'_0 & v_1 \oplus v'_1 & v_2 \oplus v'_2 & v_3 \oplus v'_3 \\ v_4 \oplus v'_4 & v_5 \oplus v'_5 & v_6 \oplus v'_6 & v_7 \oplus v'_7 \\ v_8 \oplus v'_8 & v_9 \oplus v'_9 & v_{10} \oplus v'_{10} & v_{11} \oplus v'_{11} \\ v_{12} \oplus v'_{12} & v_{13} \oplus v'_{13} & v_{14} \oplus v'_{14} & v_{15} \oplus v'_{15} \end{pmatrix} = \begin{pmatrix} \Delta_0 & \Delta_1 & \Delta_2 & \Delta_3 \\ \Delta_4 & \Delta_5 & \Delta_6 & \Delta_7 \\ \Delta_0 & \Delta_1 & \Delta_2 & \Delta_3 \\ \Delta_4 & \Delta_5 & \Delta_6 & \Delta_7 \end{pmatrix}.$$

We say that the state has *symmetric* differences. This condition is not necessary for collisions, because there may exist collisions for different salts.

### Birthday attack

A birthday attack on $v$ can be used to find two messages with symmetric differences, that is, a collision for the "top" and "bottom" differences. Since for each pair of messages the collision occurs with probability $2^{-256}$, a birthday attack requires about $2^{128}$ messages. This approach is likely to be a bit faster than a direct birthday attack on the hash function, because here one never computes the finalization of the compression function. The attack may be improved if one finds message differences that give, for example, $v_0 \oplus v_0' = v_8 \oplus v_8'$ with probability noticeably higher than $2^{-32}$ (for BLAKE-256). Such correlations between differences are however very unlikely with the recommended number of rounds.

### Backward attack

One can pick two random $v$ and $v'$ having symmetric differences, and compute rounds backward for two arbitrary distinct messages. In the end the initial states obtained need

1. to have an IV and salt satisfying $h_i \oplus s_{i \bmod 4} = h_i' \oplus s_{i \bmod 4}'$, for $i = 0, \ldots, 7$, which occurs with probability $2^{-256}$
2. to be valid initial states for a counter $0 < t \leq 512$, which occurs with probability $2^{-128}$

Using a birthday strategy, running this attack requires about $2^{256}$ trials, and finds collisions with different IV's and different salts. If we allow different counters of arbitrary values, then the initial state obtained is valid with probability $2^{-64}$, and the attacks runs within $2^{128} \times 2^{64} = 2^{192}$ trials, which is still slower than a direct birthday attack.

## 5.7.2 Differential attack

BLAKE functions can be attacked if one finds a message difference that gives certain output difference with significantly higher probability than ideally expected. A typical differential attack uses high-probability differentials for the sequence of round functions. An argument against the existence of such differentials is that BLAKE's round function is essentially ChaCha's "double-round", whose differential behavior has been intensively studied without real success; in [3].

Attacks on ChaCha are based on the existence of truncated differentials after three steps (that is, one and a half BLAKE round) [3]. These differentials have a 1-bit input difference and a 1-bit output difference; namely, flipping certain bits gives non-negligible biases in certain output bits. No truncated differential was found through four steps (two BLAKE rounds). This suggests that differentials in BLAKE with input difference in the IV or the salt cannot be found for more than two rounds. An input difference in the message spreads even more, because the difference affects the state through each round of the function.

Rumba [7] is a compression function based on the stream cipher Salsa20; contrary to BLAKE, the message is put in the initial state and no data is input during the rounds iteration. Attacks on Rumba in [3] are based on the identification of a linear approximation through three steps, and the use of message modification techniques to increase the probability of finding compliant messages. Rumba is based on Salsa20, not on ChaCha, and thus such differentials are likely to have much lower probability with ChaCha. With its ten rounds (20 steps), BLAKE is very unlikely to be attacked with such techniques.

### 5.7.3 Slide attack

Slide attacks were originally proposed to attack block ciphers [11,12], and recently were applied in some sense to hash functions [39]. Here we show how to apply the idea to attack a modified variant of BLAKE's compression function.

Suppose all the permutations $\sigma_i$ are equal (to, say, the identity). Then for a message such that $m_0 = \cdots = m_{15}$, the sequence of rounds is a repeated application of the same permutation on the internal state, because for each $G_i$, the value $(m_{\sigma_r(2i)} \oplus c_{\sigma_r(2i+1)})$ is now independent of the round index $r$. The idea of the attack is to use 256 bits of freedom of the message to have, after one round, an internal state $v'$ such that $h_i \oplus s_{i \bmod 4} = h'_i \oplus s'_{i \bmod 4}$, for $h'$ and $s'$ derived from $v'$ according to the initialization rule. The state obtained will be valid with probability $2^{-64}$. Then, for the same message and the $(r-1)$-round function, we get a collision after the finalization process, with different IV, salt, and counter. Runtime is $2^{64}$ trials, to find collisions with two different versions of the compression function. For the full version (with nontrivial permutations), this attack cannot work for more than two rounds.

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# A Round function example

We give an example of computation by the BLAKE-256 round function.

At the first round $G_0(v_0, v_4, v_8, v_{12})$ computes

$$\begin{aligned}
v_0 &\leftarrow v_0 + v_4 + (m_0 \oplus \texttt{85A308D3}) \\
v_{12} &\leftarrow (v_{12} \oplus v_0) \ggg 16 \\
v_8 &\leftarrow v_8 + v_{12} \\
v_4 &\leftarrow (v_4 \oplus v_8) \ggg 12 \\
v_0 &\leftarrow v_0 + v_4 + (m_1 \oplus \texttt{243F6A88}) \\
v_{12} &\leftarrow (v_{12} \oplus v_0) \ggg 8 \\
v_8 &\leftarrow v_8 + v_{12} \\
v_4 &\leftarrow (v_4 \oplus v_8) \ggg 7
\end{aligned}$$

where $\texttt{85A308D3} = c_{\sigma_0(2\times 0+1)} = c_1$ and $\texttt{243F6A88} = c_{\sigma_0(2\times 0)} = c_0$.

Then $G_1(v_1, v_5, v_9, v_{13})$ computes

$$\begin{aligned}
v_1 &\leftarrow v_1 + v_5 + (m_2 \oplus \texttt{03707344}) \\
v_{13} &\leftarrow (v_{13} \oplus v_1) \ggg 16 \\
v_9 &\leftarrow v_9 + v_{13} \\
v_5 &\leftarrow (v_5 \oplus v_9) \ggg 12 \\
v_1 &\leftarrow v_1 + v_5 + (m_3 \oplus \texttt{13198A2E}) \\
v_{13} &\leftarrow (v_{13} \oplus v_1) \ggg 8 \\
v_9 &\leftarrow v_9 + v_{13} \\
v_5 &\leftarrow (v_5 \oplus v_9) \ggg 7
\end{aligned}$$

and so on until $G_7(v_3, v_4, v_9, v_{14})$, which computes

$$\begin{aligned}
v_3 &\leftarrow v_3 + v_4 + (m_{14} \oplus \texttt{B5470917}) \\
v_{14} &\leftarrow (v_{14} \oplus v_3) \ggg 16 \\
v_9 &\leftarrow v_9 + v_{14} \\
v_4 &\leftarrow (v_4 \oplus v_9) \ggg 12 \\
v_3 &\leftarrow v_3 + v_4 + (m_{15} \oplus \texttt{3F84D5B5}) \\
v_{14} &\leftarrow (v_{14} \oplus v_3) \ggg 8 \\
v_9 &\leftarrow v_9 + v_{14} \\
v_4 &\leftarrow (v_4 \oplus v_9) \ggg 7
\end{aligned}$$

After $G_7(v_3, v_4, v_9, v_{14})$, the second round starts. Because of the round-dependent permutations, $G_0(v_0, v_4, v_8, v_{12})$ now uses the permutation $\sigma_1$ instead of $\sigma_0$, and thus computes

$$\begin{aligned}
v_0 &\leftarrow v_0 + v_4 + (m_{14} \oplus \texttt{BE5466CF}) \\
v_{12} &\leftarrow (v_{12} \oplus v_0) \ggg 16 \\
v_8 &\leftarrow v_8 + v_{12} \\
v_4 &\leftarrow (v_4 \oplus v_8) \ggg 12 \\
v_0 &\leftarrow v_0 + v_4 + (m_{10} \oplus \texttt{3F84D5B5}) \\
v_{12} &\leftarrow (v_{12} \oplus v_0) \ggg 8 \\
v_8 &\leftarrow v_8 + v_{12} \\
v_4 &\leftarrow (v_4 \oplus v_8) \ggg 7
\end{aligned}$$

Above, $14 = \sigma_1(2\times 0) = \sigma_1(0)$, $10 = \sigma_1(2\times 0+1) = \sigma_1(1)$, $\texttt{BE5466CF} = c_{10}$, and $\texttt{3F84D5B5} = c_{14}$. Applying similar rules, column steps and diagonal steps continue until the tenth round, which uses the permutation $\sigma_9$.

# B Source code

## B.1 VHDL

We give our VHDL code computing the compression function of BLAKE-256 with the [8G] architecture. We split the implementation into 7 `vhd` files: `blake256`, `blake256Pkg`, `initialization`, `roundreg`, `gcomp`, `finalization`, and `controller`:

File `blake256.vhd`

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;
use work.blake256Pkg.all;

entity blake256 is
    port (
      CLKxCI : in std_logic;
      RSTxRBI : in std_logic;
      MxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
      HxDI : in std_logic_vector(WWIDTH*8-1 downto 0);
      SxDI : in std_logic_vector(WWIDTH*4-1 downto 0);
      TxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
      HxDO : out std_logic_vector(WWIDTH*8-1 downto 0);
      InENxSI : in std_logic;
      OutENxSO : out std_logic
      );
end blake256;

architecture hash of blake256 is
    component controller
      port (
        CLKxCI : in std_logic;
        RSTxRBI : in std_logic;
        VALIDINxSI : in std_logic;
        VALIDOUTxSO : out std_logic;
        ROUNDxSO : out unsigned(3 downto 0)
        );
    end component;

    component initialization
      port (
        HxDI : in std_logic_vector(WWIDTH*8-1 downto 0);
        SxDI : in std_logic_vector(WWIDTH*4-1 downto 0);
        TxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
        VxDO : out std_logic_vector(WWIDTH*16-1 downto 0)
        );
    end component;

    component roundreg
```

```
      port (
        CLKxCI : in std_logic;
        RSTxRBI : in std_logic;
        WEIxSI : in std_logic;
        ROUNDxSI : in unsigned(3 downto 0);
        VxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
        MxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
        VxDO : out std_logic_vector(WWIDTH*16-1 downto 0)
        );
    end component;

    component finalization
      port (
        VxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
        HxDI : in std_logic_vector(WWIDTH*8-1 downto 0);
        SxDI : in std_logic_vector(WWIDTH*4-1 downto 0);
        HxDO : out std_logic_vector(WWIDTH*8-1 downto 0)
        );
    end component;

    signal VxD, VFINALxD : std_logic_vector(WWIDTH*16-1 downto 0);
    signal ROUNDxS : unsigned(3 downto 0);

begin -- hash
    -----------------------------------------------------------------------------
    -- CONTROLLER
    -----------------------------------------------------------------------------
    u_controller:  controller
      port map (
        CLKxCI => CLKxCI,
        RSTxRBI => RSTxRBI,
        VALIDINxSI => InENxSI,
        VALIDOUTxSO => OutENxSO,
        ROUNDxSO => ROUNDxS
        );

    -----------------------------------------------------------------------------
    -- INITIALIZATION
    -----------------------------------------------------------------------------
    u_initialization:  initialization
      port map (
        HxDI => HxDI,
        SxDI => SxDI,
        TxDI => TxDI,
        VxDO => VxD
        );

    -----------------------------------------------------------------------------
    -- ROUND
    -----------------------------------------------------------------------------
    u_roundreg:  roundreg
      port map (
        CLKxCI => CLKxCI,
        RSTxRBI => RSTxRBI,
        WEIxSI => InENxSI,
        ROUNDxSI => ROUNDxS,
        VxDI => VxD,
        MxDI => MxDI,
        VxDO => VFINALxD
        );

    -----------------------------------------------------------------------------
    -- FINALIZATION
```

```
    ----------------------------------------------------------------------------
    u_finalization:  finalization
      port map (
        VxDI => VFINALxD,
        HxDI => HxDI,
        SxDI => SxDI,
        HxDO => HxDO
        );

end hash;
```

### File blake256Pkg.vhd

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;

package blake256Pkg is

    constant WWIDTH : integer := 32; -- WORD WIDTH
    constant NROUND : integer := 14; -- ROUND NUMBER

    ----------------------------------------------------------------------------
    -- c Constants
    ----------------------------------------------------------------------------
    type c_const is array (0 to 15) of std_logic_vector(31 downto 0);

    constant C : c_const :=  ((x"243F6A88"), (x"85A308D3"),
                              (x"13198A2E"), (x"03707344"),
                              (x"A4093822"), (x"299F31D0"),
                              (x"082EFA98"), (x"EC4E6C89"),
                              (x"452821E6"), (x"38D01377"),
                              (x"BE5466CF"), (x"34E90C6C"),
                              (x"C0AC29B7"), (x"C97C50DD"),
                              (x"3F84D5B5"), (x"B5470917"));

    ----------------------------------------------------------------------------
    -- o Permutations
    ----------------------------------------------------------------------------
    type perm is array (0 to 9, 0 to 15) of integer;

    constant PMATRIX : perm :=  ((0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15),
                                 (14, 10, 4, 8, 9, 15, 13, 6, 1, 12, 0, 2, 11, 7, 5, 3),
                                 (11, 8, 12, 0, 5, 2, 15, 13, 10, 14, 3, 6, 7, 1, 9, 4),
                                 (7, 9, 3, 1, 13, 12, 11, 14, 2, 6, 5, 10, 4, 0, 15, 8),
                                 (9, 0, 5, 7, 2, 4, 10, 15, 14, 1, 11, 12, 6, 8, 3, 13),
                                 (2, 12, 6, 10, 0, 11, 8, 3, 4, 13, 7, 5, 15, 14, 1, 9),
                                 (12, 5, 1, 15, 14, 13, 4, 10, 0, 7, 6, 3, 9, 2, 8, 11),
                                 (13, 11, 7, 14, 12, 1, 3, 9, 5, 0, 15, 4, 8, 6, 2, 10),
                                 (6, 15, 14, 9, 11, 3, 0, 8, 12, 2, 13, 7, 1, 4, 10, 5),
                                 (10, 2, 8, 4, 7, 6, 1, 5, 15, 11, 9, 14, 3, 12, 13, 0),
                                 (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15),
                                 (14, 10, 4, 8, 9, 15, 13, 6, 1, 12, 0, 2, 11, 7, 5, 3),
                                 (11, 8, 12, 0, 5, 2, 15, 13, 10, 14, 3, 6, 7, 1, 9, 4),
                                 (7, 9, 3, 1, 13, 12, 11, 14, 2, 6, 5, 10, 4, 0, 15, 8));

end blake256Pkg;
```

### File initialization.vhd

```
library ieee;
use ieee.std_logic_1164.all;
```

```
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;
use work.blake256Pkg.all;

entity initialization is
  port (
    HxDI : in std_logic_vector(WWIDTH*8-1 downto 0);
    SxDI : in std_logic_vector(WWIDTH*4-1 downto 0);
    TxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
    VxDO : out std_logic_vector(WWIDTH*16-1 downto 0)
    );
end initialization;

architecture hash of initialization is

begin -- hash

  VxDO(WWIDTH*16-1 downto WWIDTH*8) <= HxDI;

  VxDO(WWIDTH*8-1 downto WWIDTH*7) <= SxDI(WWIDTH*4-1 downto WWIDTH*3) xor C(0);
  VxDO(WWIDTH*7-1 downto WWIDTH*6) <= SxDI(WWIDTH*3-1 downto WWIDTH*2) xor C(1);
  VxDO(WWIDTH*6-1 downto WWIDTH*5) <= SxDI(WWIDTH*2-1 downto WWIDTH) xor C(2);
  VxDO(WWIDTH*5-1 downto WWIDTH*4) <= SxDI(WWIDTH-1 downto 0) xor C(3);

  VxDO(WWIDTH*4-1 downto WWIDTH*3) <= TxDI(WWIDTH*2-1 downto WWIDTH) xor C(4);
  VxDO(WWIDTH*3-1 downto WWIDTH*2) <= TxDI(WWIDTH*2-1 downto WWIDTH) xor C(5);
  VxDO(WWIDTH*2-1 downto WWIDTH) <= TxDI(WWIDTH-1 downto 0) xor C(6);
  VxDO(WWIDTH-1 downto 0) <= TxDI(WWIDTH-1 downto 0) xor C(7);

end hash;
```

### File `roundreg.vhd`

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;
use work.blake256Pkg.all;

entity roundreg is
  port (
    CLKxCI : in std_logic;
    RSTxRBI : in std_logic;
    WEIxSI : in std_logic;
    ROUNDxSI : in unsigned(3 downto 0);
    VxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
    MxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
    VxDO : out std_logic_vector(WWIDTH*16-1 downto 0)
    );
end roundreg;

architecture hash of roundreg is

  component gcomp
    port (
      AxDI : in std_logic_vector(WWIDTH-1 downto 0);
      BxDI : in std_logic_vector(WWIDTH-1 downto 0);
      CxDI : in std_logic_vector(WWIDTH-1 downto 0);
      DxDI : in std_logic_vector(WWIDTH-1 downto 0);
      MxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
      KxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
      AxDO : out std_logic_vector(WWIDTH-1 downto 0);
      BxDO : out std_logic_vector(WWIDTH-1 downto 0);
```

```
      CxDO : out std_logic_vector(WWIDTH-1 downto 0);
      DxDO : out std_logic_vector(WWIDTH-1 downto 0)
      );
  end component;

  type SUBT16 is array (15 downto 0) of std_logic_vector(WWIDTH-1 downto 0);

  signal VxDN, VxDP, MxD : SUBT16;

  signal G0MxD, G0KxD, G4MxD, G4KxD : std_logic_vector(WWIDTH*2-1 downto 0);
  signal G1MxD, G1KxD, G5MxD, G5KxD : std_logic_vector(WWIDTH*2-1 downto 0);
  signal G2MxD, G2KxD, G6MxD, G6KxD : std_logic_vector(WWIDTH*2-1 downto 0);
  signal G3MxD, G3KxD, G7MxD, G7KxD : std_logic_vector(WWIDTH*2-1 downto 0);

  signal G0AOxD, G0BOxD, G0COxD, G0DOxD : std_logic_vector(WWIDTH-1 downto 0);
  signal G1AOxD, G1BOxD, G1COxD, G1DOxD : std_logic_vector(WWIDTH-1 downto 0);
  signal G2AOxD, G2BOxD, G2COxD, G2DOxD : std_logic_vector(WWIDTH-1 downto 0);
  signal G3AOxD, G3BOxD, G3COxD, G3DOxD : std_logic_vector(WWIDTH-1 downto 0);

  signal G4AOxD, G4BOxD, G4COxD, G4DOxD : std_logic_vector(WWIDTH-1 downto 0);
  signal G5AOxD, G5BOxD, G5COxD, G5DOxD : std_logic_vector(WWIDTH-1 downto 0);
  signal G6AOxD, G6BOxD, G6COxD, G6DOxD : std_logic_vector(WWIDTH-1 downto 0);
  signal G7AOxD, G7BOxD, G7COxD, G7DOxD : std_logic_vector(WWIDTH-1 downto 0);

begin -- hash

  p_unform:  for i in 15 downto 0 generate
    MxD(15-i) <= MxDI(WWIDTH*(i+1)-1 downto WWIDTH*i);
  end generate p_unform;

  VxDO <= VxDP(0) &  VxDP(1) & VxDP(2) & VxDP(3) &
           VxDP(4) & VxDP(5) & VxDP(6) & VxDP(7) &
           VxDP(8) & VxDP(9) & VxDP(10) & VxDP(11) &
           VxDP(12) & VxDP(13) & VxDP(14) & VxDP(15);

  -----------------------------------------------------------------------------
  -- MEMORY INPUTS
  -----------------------------------------------------------------------------
  p_inmem:  process ( G4AOxD, G4BOxD, G4COxD, G4DOxD, G5AOxD, G5BOxD, G5COxD,
                      G5DOxD, G6AOxD, G6BOxD, G6COxD, G6DOxD, G7AOxD, G7BOxD,
                      G7COxD, G7DOxD, VxDI, VxDP, WEIxSI)
  begin -- process p_inmem

    VxDN <= VxDP;

    if WEIxSI = '1' then
      for i in 15 downto 0 loop
        VxDN(15-i) <= VxDI(WWIDTH*(i+1)-1 downto WWIDTH*i);

      end loop;

    else
      VxDN(0) <= G4AOxD;
      VxDN(5) <= G4BOxD;
      VxDN(10) <= G4COxD;
      VxDN(15) <= G4DOxD;

      VxDN(1) <= G5AOxD;
      VxDN(6) <= G5BOxD;
      VxDN(11) <= G5COxD;
      VxDN(12) <= G5DOxD;

      VxDN(2) <= G6AOxD;
      VxDN(7) <= G6BOxD;
      VxDN(8) <= G6COxD;
      VxDN(13) <= G6DOxD;

      VxDN(3) <= G7AOxD;
```

```
    VxDN(4) <= G7BOxD;
    VxDN(9) <= G7COxD;
    VxDN(14) <= G7DOxD;

  end if;
end process p_inmem;

-----------------------------------------------------------------------------
-- G INPUTS
-----------------------------------------------------------------------------
p_outmem:  process (MxD, ROUNDxSI)
begin -- process p_outmem

  G0MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 0)) & MxD(PMATRIX(to_integer(ROUNDxSI), 1));
  G1MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 2)) & MxD(PMATRIX(to_integer(ROUNDxSI), 3));
  G2MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 4)) & MxD(PMATRIX(to_integer(ROUNDxSI), 5));
  G3MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 6)) & MxD(PMATRIX(to_integer(ROUNDxSI), 7));
  G4MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 8)) & MxD(PMATRIX(to_integer(ROUNDxSI), 9));
  G5MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 10)) & MxD(PMATRIX(to_integer(ROUNDxSI), 11));
  G6MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 12)) & MxD(PMATRIX(to_integer(ROUNDxSI), 13));
  G7MxD <= MxD(PMATRIX(to_integer(ROUNDxSI), 14)) & MxD(PMATRIX(to_integer(ROUNDxSI), 15));

  G0KxD <= C(PMATRIX(to_integer(ROUNDxSI), 1)) & C(PMATRIX(to_integer(ROUNDxSI), 0));
  G1KxD <= C(PMATRIX(to_integer(ROUNDxSI), 3)) & C(PMATRIX(to_integer(ROUNDxSI), 2));
  G2KxD <= C(PMATRIX(to_integer(ROUNDxSI), 5)) & C(PMATRIX(to_integer(ROUNDxSI), 4));
  G3KxD <= C(PMATRIX(to_integer(ROUNDxSI), 7)) & C(PMATRIX(to_integer(ROUNDxSI), 6));
  G4KxD <= C(PMATRIX(to_integer(ROUNDxSI), 9)) & C(PMATRIX(to_integer(ROUNDxSI), 8));
  G5KxD <= C(PMATRIX(to_integer(ROUNDxSI), 11)) & C(PMATRIX(to_integer(ROUNDxSI), 10));
  G6KxD <= C(PMATRIX(to_integer(ROUNDxSI), 13)) & C(PMATRIX(to_integer(ROUNDxSI), 12));
  G7KxD <= C(PMATRIX(to_integer(ROUNDxSI), 15)) & C(PMATRIX(to_integer(ROUNDxSI), 14));

end process p_outmem;

-----------------------------------------------------------------------------
-- G BLOCKS
-----------------------------------------------------------------------------
u_gcomp0:  gcomp
  port map (
    AxDI => VxDP(0), BxDI => VxDP(4), CxDI => VxDP(8), DxDI => VxDP(12), MxDI => G0MxD,
    KxDI => G0KxD, AxDO => G0AOxD, BxDO => G0BOxD, CxDO => G0COxD, DxDO => G0DOxD
    );

u_gcomp1:  gcomp
  port map (
    AxDI => VxDP(1), BxDI => VxDP(5), CxDI => VxDP(9), DxDI => VxDP(13), MxDI => G1MxD,
    KxDI => G1KxD, AxDO => G1AOxD, BxDO => G1BOxD, CxDO => G1COxD, DxDO => G1DOxD
    );

u_gcomp2:  gcomp
  port map (
    AxDI => VxDP(2), BxDI => VxDP(6), CxDI => VxDP(10), DxDI => VxDP(14), MxDI => G2MxD,
    KxDI => G2KxD, AxDO => G2AOxD, BxDO => G2BOxD, CxDO => G2COxD, DxDO => G2DOxD
    );

u_gcomp3:  gcomp
  port map (
    AxDI => VxDP(3), BxDI => VxDP(7), CxDI => VxDP(11), DxDI => VxDP(15), MxDI => G3MxD,
    KxDI => G3KxD, AxDO => G3AOxD, BxDO => G3BOxD, CxDO => G3COxD, DxDO => G3DOxD
    );

----------------------

u_gcomp4:  gcomp
  port map (
    AxDI => G0AOxD, BxDI => G1BOxD, CxDI => G2COxD, DxDI => G3DOxD, MxDI => G4MxD,
    KxDI => G4KxD, AxDO => G4AOxD, BxDO => G4BOxD, CxDO => G4COxD, DxDO => G4DOxD
```

```
      );

  u_gcomp5: gcomp
    port map (
      AxDI => G1AOxD, BxDI => G2BOxD, CxDI => G3COxD, DxDI => G0DOxD, MxDI => G5MxD,
      KxDI => G5KxD, AxDO => G5AOxD, BxDO => G5BOxD, CxDO => G5COxD, DxDO => G5DOxD
      );

  u_gcomp6: gcomp
    port map (
      AxDI => G2AOxD, BxDI => G3BOxD, CxDI => G0COxD, DxDI => G1DOxD, MxDI => G6MxD,
      KxDI => G6KxD, AxDO => G6AOxD, BxDO => G6BOxD, CxDO => G6COxD, DxDO => G6DOxD
      );

  u_gcomp7: gcomp
    port map (
      AxDI => G3AOxD, BxDI => G0BOxD, CxDI => G1COxD, DxDI => G2DOxD, MxDI => G7MxD,
      KxDI => G7KxD, AxDO => G7AOxD, BxDO => G7BOxD, CxDO => G7COxD, DxDO => G7DOxD
      );

  -----------------------------------------------------------------------------
  -- v MEMORY
  -----------------------------------------------------------------------------
  p_mem: process (CLKxCI, RSTxRBI)
  begin -- process p_vmem
    if RSTxRBI = '0' then -- asynchronous reset (active low)
      VxDP <= (others => (others => '0'));

    elsif CLKxCI'event and CLKxCI = '1' then -- rising clock edge
      VxDP <= VxDN;

    end if;
  end process p_mem;

end hash;
```

### File gcomp.vhd

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;
use work.blake256Pkg.all;

entity gcomp is
  port (
    AxDI : in std_logic_vector(WWIDTH-1 downto 0);
    BxDI : in std_logic_vector(WWIDTH-1 downto 0);
    CxDI : in std_logic_vector(WWIDTH-1 downto 0);
    DxDI : in std_logic_vector(WWIDTH-1 downto 0);
    MxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
    KxDI : in std_logic_vector(WWIDTH*2-1 downto 0);
    AxDO : out std_logic_vector(WWIDTH-1 downto 0);
    BxDO : out std_logic_vector(WWIDTH-1 downto 0);
    CxDO : out std_logic_vector(WWIDTH-1 downto 0);
    DxDO : out std_logic_vector(WWIDTH-1 downto 0)
    );
end gcomp;

architecture hash of gcomp is

  signal T1, T4, T7, T10 : unsigned(WWIDTH-1 downto 0);
  signal T2, T3, T5, T6 : std_logic_vector(WWIDTH-1 downto 0);
  signal T8, T9, T11, T12 : std_logic_vector(WWIDTH-1 downto 0);
```

```
    signal TK1, TK2 :  std_logic_vector(WWIDTH-1 downto 0);

begin -- hash

    TK1 <= MxDI(WWIDTH*2-1 downto WWIDTH) xor KxDI(WWIDTH*2-1 downto WWIDTH);
    T1 <= unsigned(AxDI) + unsigned(BxDI) + unsigned(TK1);
    T2 <= std_logic_vector(T1) xor DxDI;
    T3 <= T2(15 downto 0) & T2(WWIDTH-1 downto 16);

    T4 <= unsigned(CxDI) + unsigned(T3);
    T5 <= std_logic_vector(T4) xor BxDI;
    T6 <= T5(11 downto 0) & T5(WWIDTH-1 downto 12);

    ---------------------------------------------------------------------------

    TK2 <= MxDI(WWIDTH-1 downto 0) xor KxDI(WWIDTH-1 downto 0);
    T7 <= T1 + unsigned(T6) + unsigned(TK2);
    T8 <= std_logic_vector(T7) xor T3;
    T9 <= T8(7 downto 0) & T8(WWIDTH-1 downto 8);

    T10 <= T4 + unsigned(T9);
    T11 <= std_logic_vector(T10) xor T6;
    T12 <= T11(6 downto 0) & T11(WWIDTH-1 downto 7);

    AxDO <= std_logic_vector(T7);
    BxDO <= T12;
    CxDO <= std_logic_vector(T10);
    DxDO <= T9;

end hash;
```

### File finalization.vhd

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;
use work.blake256Pkg.all;

entity finalization is
    port (
      VxDI : in std_logic_vector(WWIDTH*16-1 downto 0);
      HxDI : in std_logic_vector(WWIDTH*8-1 downto 0);
      SxDI : in std_logic_vector(WWIDTH*4-1 downto 0);
      HxDO : out std_logic_vector(WWIDTH*8-1 downto 0)
      );
end finalization;

architecture hash of finalization is

    type SUB4 is array (3 downto 0) of std_logic_vector(WWIDTH-1 downto 0);
    type SUB8 is array (7 downto 0) of std_logic_vector(WWIDTH-1 downto 0);
    type SUB16 is array (15 downto 0) of std_logic_vector(WWIDTH-1 downto 0);

    signal SINxD : SUB4;
    signal HINxD, HOUTxD : SUB8;
    signal VxD : SUB16;

begin -- hash

    p_unform4:  for i in 0 to 3 generate
      SINxD(i) <= SxDI(WWIDTH*(i+1)-1 downto WWIDTH*i);
    end generate p_unform4;

    p_unform8:  for i in 0 to 7 generate
      HINxD(i) <= HxDI(WWIDTH*(i+1)-1 downto WWIDTH*i);
```

```
      HxDO(WWIDTH*(i+1)-1 downto WWIDTH*i) <= HOUTxD(i);
    end generate p_unform8;

    p_unform16:  for i in 0 to 15 generate
      VxD(i) <= VxDI(WWIDTH*(i+1)-1 downto WWIDTH*i);
    end generate p_unform16;

    HOUTxD(0) <= HINxD(0) xor VxD(0) xor VxD(8) xor SINxD(0);
    HOUTxD(1) <= HINxD(1) xor VxD(1) xor VxD(9) xor SINxD(1);
    HOUTxD(2) <= HINxD(2) xor VxD(2) xor VxD(10) xor SINxD(2);
    HOUTxD(3) <= HINxD(3) xor VxD(3) xor VxD(11) xor SINxD(3);
    HOUTxD(4) <= HINxD(4) xor VxD(4) xor VxD(12) xor SINxD(0);
    HOUTxD(5) <= HINxD(5) xor VxD(5) xor VxD(13) xor SINxD(1);
    HOUTxD(6) <= HINxD(6) xor VxD(6) xor VxD(14) xor SINxD(2);
    HOUTxD(7) <= HINxD(7) xor VxD(7) xor VxD(15) xor SINxD(3);

end hash;
```

### File controller.vhd

```
library ieee;
use ieee.std_logic_1164.all;
use ieee.numeric_std.all;
use std.textio.all;
use ieee.std_logic_textio.all;
use work.blake256Pkg.all;

    entity controller is
    port (
      CLKxCI : in std_logic;
      RSTxRBI : in std_logic;
      VALIDINxSI : in std_logic;
      VALIDOUTxSO : out std_logic;
      ROUNDxSO : out unsigned(3 downto 0)
      );
end controller;

architecture hash of controller is

    type state is (idle, round, fin);

    signal STATExDP, STATExDN : state;
    signal ROUNDxDP, ROUNDxDN : unsigned(3 downto 0);

begin -- hash

    ROUNDxSO <= ROUNDxDP;

    fsm:  process (ROUNDxDP, STATExDP, VALIDINxSI)
    begin -- process fsm

      VALIDOUTxSO <= '0';
      ROUNDxDN <= (others => '0');

      case STATExDP is

        -------------------------------------------------------------------------
        when idle =>

          if VALIDINxSI = '1' then
            STATExDN <= round;

          else
            STATExDN <= idle;

          end if;

        -------------------------------------------------------------------------
```

```
        when round =>

          if ROUNDxDP < NROUND-1 then
            ROUNDxDN <= ROUNDxDP + 1;
            STATExDN <= round;

          else
            STATExDN <= fin;

          end if;
        -------------------------------------------------------------------------
        when fin =>

          VALIDOUTxSO <= '1';
          STATExDN <= idle;

        -------------------------------------------------------------------------
        when others =>

          STATExDN <= idle;

        end case;

    end process fsm;

    process (CLKxCI, RSTxRBI)
    begin -- process
      if RSTxRBI = '0' then -- asynchronous reset (active low)
        STATExDP <= idle;
        ROUNDxDP <= (others => '0');

      elsif CLKxCI'event and CLKxCI = '1' then -- rising clock edge
        STATExDP <= STATExDN;
        ROUNDxDP <= ROUNDxDN;

        end if;
    end process;

end hash;
```

## B.2 PIC assembly

We give the assembly code computing the round function of BLAKE-256.

```
                                    ; round function of BLAKE32
                                    ; indirect adress register FSR0 used for accessing m
                                    ; FSR1 used for accessing c
do_Gi
                clrf FSR1H          ; stays zero al the time
                                    ; only lower adress range is used for cts address
                movlw h'01'         ; table m starts at equ H'110'
                movWF FSR0H         ; so using FSR0 we need to set highbyte correct
                movFF i,pointer2mc  ; use i
                bcf STATUS, C       ; prepare CARRYbit for *2
                rlcF pointer2mc     ; 2*i
                movF pointer2mc     ; load pointer into w
                addWF r,w           ; ADD r (permutation offset in table)
                movWF pointer2mc    ; ..save it back, is now r(2i)
                movlw high permut_table_m  ; ..and use it here to find adress of current m
                movwf TBLPTRH
                rlncf pointer2mc, w
                movwf TBLPTRL
                tblrd*              ; table read here into TABLAT
                movff TABLAT, FSR0L ; move adress to pointer
                movFF INDF0,tmpXOR_lo     ; access content of m signum_r(2i) low byte loaded
                movFF PREINC0,tmpXOR_ml   ; preincrement pointer, access midlowbyte
                movFF PREINC0,tmpXOR_mh   ; preincrement pointer, access midhighbyte
                movFF PREINC0,tmpXOR_hi   ; preincrement pointer, access highbyte

term_a1_lowbyte
                incF pointer2mc     ; pointer now (2i+1)
                movF pointer2mc     ; load pointer into w
                movlw high permut_table_c  ; find c signum_r (2i+1)lowbyte adress
                movwf TBLPTRH
                rlncf pointer2mc, w
                movwf TBLPTRL
                tblrd*              ; table read here into TABLAT
                movff TABLAT, FSR1L ; move adress to pointer

                movF INDF1          ; content of c signum_r(2i+1) now in working reg
                xorWF tmpXOR_lo,w   ; lowest byte [m signum_r (2i) XOR c signum_r (2i+1)]

                addWFC b_lo,w       ; ADD b with carry
                btfsc STATUS, C     ; IF carrybit =1 ...
                incF tmpXOR_ml      ; then ...  add carry
                btfsc STATUS, C     ; IF carrybit =1 ...
                incF tmpXOR_mh      ; then ...  add carry
                btfsc STATUS, C     ; IF carrybit =1 ...
                incF tmpXOR_hi      ; then ...  add carry

                addWFC a_lo,f       ; ADD a, place result in a
                btfsc STATUS, C     ; IF carrybit =1 ...
                incF tmpXOR_ml      ; then ...  add carry
                btfsc STATUS, C     ; IF carrybit =1 ...
                incF tmpXOR_mh      ; then ...  add carry
                btfsc STATUS, C     ; IF carrybit =1 ...
                incF tmpXOR_hi      ; then ...  add carry
```

```
term_a1_midlowbyte
                    movF PREINC1            ; content of c signum_r (2i+1) midlow byte loaded in w
                    xorWF tmpXOR_ml,w       ; midlow byte [m signum_r (2i) XOR c signum_r (2i+1)]
                    addWFC b_ml,w           ; ADD b with carry
                    btfsc STATUS, C         ; IF carrybit =1 ...
                    incF tmpXOR_mh          ; then ...  add carry
                    btfsc STATUS, C         ; IF carrybit =1 ...
                    incF tmpXOR_hi          ; then ...  add carry


                    addWFC a_ml,f           ; ADD a, place result in a
                    btfsc STATUS, C         ; IF carrybit =1 ...
                    incF tmpXOR_mh          ; then ...  add carry
                    btfsc STATUS, C         ; IF carrybit =1 ...
                    incF tmpXOR_hi          ; then ...  add carry

term_a1_midhighbyte
                    movF PREINC1            ; content of c signum_r (2i+1) midhigh byte loaded in w
                    xorWF tmpXOR_mh,w       ; midhigh byte [m signum (2i) XOR c signum (2i+1)]
                    addWFC b_mh,w           ; ADD b with carry
                    btfsc STATUS, C         ; IF carrybit =1 ...
                    incF tmpXOR_hi          ; then ...  add carry

                    addWFC a_mh,f           ; ADD a, place result in a
                    btfsc STATUS, C         ; IF carrybit =1 ...
                    incF tmpXOR_hi          ; then ...  add carry

term_a1_highbyte
                    movF PREINC1            ; content of c signum_r (2i+1) high byte loaded in w
                    xorWF tmpXOR_hi,w       ; highest byte [m signum (2i) XOR c signum (2i+1)]
                    addWFC b_hi,w           ; ADD b with carry, but carry disapears in black hole
                    addWFC a_hi,f           ; ADD a, place result in a

term_d1                                     ;...  next is d = d xor a <<< 16
                    call compute_dxora
                    movFF d_hi,tmpXOR_hi    ; rotate 16 is actually only swapping
                    movFF d_ml,d_hi
                    movFF tmpXOR_hi,d_ml
                    movFF d_mh,tmpXOR_mh
                    movFF d_lo,d_mh
                    movFF tmpXOR_mh,d_lo

term_c1
                    call compute_c
```

```
term_b1                                 ;...  next is b = b xor c <<< 12
            call compute_bxorc
                                        ; now rotate left 12 positions
            bcf STATUS, C               ; prepare Carry flag with 0
            btfsc b_ml,7                ; IF bit 7 of ml-byte
            bsf STATUS, C               ; THEN prepare Carry with 1
            rlcF b_hi
            rlcF b_ml
            rlcF b_hi
            rlcF b_ml
            rlcF b_hi
            rlcF b_ml
            rlcF b_hi
            rlcF b_ml
            bcf STATUS, C               ; prepare Carry flag with 0
            btfsc b_lo,7                ; IF bit 7 of ml-byte
            bsf STATUS, C               ; THEN prepare Carry with 1
            rlcF b_mh
            rlcF b_lo
            rlcF b_mh
            rlcF b_lo
            rlcF b_mh
            rlcF b_lo
            rlcF b_mh
            rlcF b_lo

term_a2
            movF pointer2mc             ; load pointer into w [now (2i+1)]
            movlw high permut_table_m   ; ..and use it here to find adress of current m
            movwf TBLPTRH
            rlncf pointer2mc, w
            movwf TBLPTRL
            tblrd*                      ; table read here into TABLAT
            movff TABLAT, FSR0L         ; move adress to pointer

            movFF INDF0,tmpXOR_lo       ; access content of m signum_r(2i) low byte loaded
            movFF PREINC0,tmpXOR_ml     ; preincrement pointer, access midlowbyte
            movFF PREINC0,tmpXOR_mh     ; preincrement pointer, access midhighbyte
            movFF PREINC0,tmpXOR_hi     ; preincrement pointer, access highbyte
```

```
term_a2_lowbyte
                decF pointer2mc           ; pointer now (2i)
                movF pointer2mc           ; load pointer into w
                movlw high permut_table_c ; find c signum_r (2i)lowbyte adress
                movwf TBLPTRH
                rlncf pointer2mc, w
                movwf TBLPTRL
                tblrd*                    ; table read here into TABLAT
                movff TABLAT, FSR1L       ; move adress to pointer, points now to c signum_r(2i)

                movF INDF1                ; content of c signum_r(2i+1) now in working reg


                xorWF tmpXOR_lo,w         ; lowest byte [m signum_r (2i+1) XOR c signum_r (2i)]

                addWFC b_lo,w             ; ADD b with carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_ml            ; then ...  add carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_mh            ; then ...  add carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_hi            ; then ...  add carry

                addWFC a_lo,f             ; ADD a, place result in a
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_ml            ; then ...  add carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_mh            ; then ...  add carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_hi            ; then ...  add carry

term_a2_midlowbyte
                movF PREINC1              ; content of c signum_r (2i) midlow byte loaded in w
                xorWF tmpXOR_ml,w         ; midlow byte [m signum_r (2i+1) XOR c signum_r (2i)]

                addWFC b_ml,w             ; ADD b with carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_mh            ; then ...  add carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_hi            ; then ...  add carry

                addWFC a_ml,f             ; ADD a, place result in a
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_mh            ; then ...  add carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_hi            ; then ...  add carry

term_a2_midhighbyte
                movF PREINC1              ; content of c signum_r (2i) midhigh byte loaded in w
                xorWF tmpXOR_mh,w         ; midhigh byte [m signum_r (2i+1) XOR c signum_r (2i)]

                addWFC b_mh,w             ; ADD b with carry
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_hi            ; then ...  add carry

                addWFC a_mh,f             ; ADD a, place result in a
                btfsc STATUS, C           ; IF carrybit =1 ...
                incF tmpXOR_hi            ; then ...  add carry
```

```
term_a2_highbyte
                  movF PREINC1            ; content of c signum_r (2i) high byte loaded in w
                  xorWF tmpXOR_hi,w       ; highest byte [m signum_r (2i+1) XOR c signum_r (2i)]
                  addWFC b_hi,w           ; ADD b with carry, but carry disapears in black hole
                  addWFC a_hi,f           ; ADD a, place result in a

term_d2                                   ;...  next is d = d xor a ⋘ 8
                  call compute_dxora
                  movFF d_hi,tmpXOR_hi    ; rotate 8 is actually swapping
                  movFF d_mh,d_hi
                  movFF d_ml,d_mh
                  movFF d_lo,d_ml
                  movFF tmpXOR_hi,d_lo

term_c2
call compute_c

term_b2                                   ;...  next is b = b xor c ⋘ 7
                  call compute_bxorc
                                          ; now rotate left 7 positions
                                          ; which can be seen as rotate right 1 and byte-wapping
                  bcf STATUS, C           ; prepare Carry flag with 0
                  btfsc b_lo,0            ; IF bit 0 of lo-byte
                  bsf STATUS, C           ; THEN prepare Carry with 1
                  rrcF b_hi               ; rotate through carry
                  rrcF b_mh
                  rrcF b_ml
                  rrcF b_lo
                  movFF b_lo,tmpXOR_lo    ; temporarly save low
                  movFF b_hi,b_lo         ; swap byte high -> low
                  movFF b_mh,b_hi         ; midhigh to high
                  movFF b_ml,b_mh         ; midlow to midhigh
                  movFF tmpXOR_lo,b_ml    ; low to midlow

                  return

                                          ; function d <- d XOR a
compute_dxora
                  movF a_lo               ; load a
                  xorWF d_lo,f            ; d XOR a, result in d
                  movF a_ml
                  xorWF d_ml,f
                  movF a_mh
                  xorWF d_mh,f
                  movF a_hi
                  xorWF d_hi,f
                  return
```

```
                                        ; function c <- c + d
compute_c
                    movF d_lo           ; load d
                    addWFC c_lo,f       ; ADD c, place result in c
                    btfsc STATUS, C     ; IF carrybit =1 ...
                    incF d_ml           ; then ...  add carry
                    btfsc STATUS, C     ; IF carrybit =1 ...
                    incF d_mh           ; then ...  add carry
                    btfsc STATUS, C     ; IF carrybit =1 ...
                    incF d_hi           ; then ...  add carry

                    movF d_ml
                    addWFC c_ml,f
                    btfsc STATUS, C
                    incF d_mh
                    btfsc STATUS, C
                    incF d_hi

                    movF d_mh
                    addWFC c_mh,f
                    btfsc STATUS, C
                    incF d_hi

                    movF d_hi
                    addWFC c_hi,f

                    return

                                        ; function b <- b XOR c
compute_bxorc
                    movF c_lo           ; load c
                    xorWF b_lo,f        ; b XOR c, result in b
                    movF c_ml
                    xorWF b_ml,f
                    movF c_mh
                    xorWF b_mh,f
                    movF c_hi
                    xorWF b_hi,f
                    return
```

## B.3 ANSI C

In the C code provided with the submission, we added a function `AddSalt( hashState * state, const BitSequence * salt)`, whose arguments are:

- an initialized state (`state`)
- a salt (`salt`) of type `BitSequence`, long of 128 bits for BLAKE-224 and BLAKE-256, and long of 256 bits for BLAKE-384 or BLAKE-512

The function `AddSalt` extends the initialization of the hash state by adding a salt as extra parameter. Calling `AddSalt` is not compulsory; applications that don't use a salt should not call `AddSalt`. When a salt is required, `AddSalt` should be called after the call `Init`, and before any call to `Update`.

We give our optimized C code computing the compression function of BLAKE-256.

```
static HashReturn compress32( hashState * state, const BitSequence * datablock ) {
#define ROT32(x,n) (((x)<<(32-n))|( (x)>>(n)))
#define ADD32(x,y) ((u32)((x) + (y)))
#define XOR32(x,y) ((u32)((x) ^ (y)))
#define G32(a,b,c,d,i) do {\
      v[a] = XOR32(m[sigma[round][i]], c32[sigma[round][i+1]])+ADD32(v[a],v[b]);\
      v[d] = ROT32(XOR32(v[d],v[a]),16);\
      v[c] = ADD32(v[c],v[d]);\
      v[b] = ROT32(XOR32(v[b],v[c]),12);\
      v[a] = XOR32(m[sigma[round][i+1]], c32[sigma[round][i]])+ADD32(v[a],v[b]);\
      v[d] = ROT32(XOR32(v[d],v[a]), 8);\
      v[c] = ADD32(v[c],v[d]);\
      v[b] = ROT32(XOR32(v[b],v[c]), 7);\
    } while (0)

    u32 v[16];
    u32 m[16];
    int round;

    /* get message */
    m[ 0] = U8TO32_BE(datablock + 0);
    m[ 1] = U8TO32_BE(datablock + 4);
    m[ 2] = U8TO32_BE(datablock + 8);
    m[ 3] = U8TO32_BE(datablock +12);
    m[ 4] = U8TO32_BE(datablock +16);
    m[ 5] = U8TO32_BE(datablock +20);
    m[ 6] = U8TO32_BE(datablock +24);
    m[ 7] = U8TO32_BE(datablock +28);
    m[ 8] = U8TO32_BE(datablock +32);
    m[ 9] = U8TO32_BE(datablock +36);
    m[10] = U8TO32_BE(datablock +40);
    m[11] = U8TO32_BE(datablock +44);
    m[12] = U8TO32_BE(datablock +48);
    m[13] = U8TO32_BE(datablock +52);
    m[14] = U8TO32_BE(datablock +56);
    m[15] = U8TO32_BE(datablock +60);

    /* initialization */
    v[ 0] = state->h32[0];
    v[ 1] = state->h32[1];
    v[ 2] = state->h32[2];
    v[ 3] = state->h32[3];
    v[ 4] = state->h32[4];
    v[ 5] = state->h32[5];
    v[ 6] = state->h32[6];
    v[ 7] = state->h32[7];
    v[ 8] = state->salt32[0];
    v[ 8] ^= 0x243F6A88;
    v[ 9] = state->salt32[1];
    v[ 9] ^= 0x85A308D3;
    v[10] = state->salt32[2];
    v[10] ^= 0x13198A2E;
    v[11] = state->salt32[3];
    v[11] ^= 0x03707344;
    v[12] = 0xA4093822;
    v[13] = 0x299F31D0;
    v[14] = 0x082EFA98;
    v[15] = 0xEC4E6C89;

    if (state->nullt == 0) {
      v[12] ^= state->t32[0];
      v[13] ^= state->t32[0];
```

```
  v[14] ^= state->t32[1];
  v[15] ^= state->t32[1];
}

for(round=0; round<14; ++round) {

  G32( 0, 4, 8,12, 0);
  G32( 1, 5, 9,13, 2);
  G32( 2, 6,10,14, 4);
  G32( 3, 7,11,15, 6);

  G32( 3, 4, 9,14,14);
  G32( 2, 7, 8,13,12);
  G32( 0, 5,10,15, 8);
  G32( 1, 6,11,12,10);
}

state->h32[0] ^= v[ 0];
state->h32[1] ^= v[ 1];
state->h32[2] ^= v[ 2];
state->h32[3] ^= v[ 3];
state->h32[4] ^= v[ 4];
state->h32[5] ^= v[ 5];
state->h32[6] ^= v[ 6];
state->h32[7] ^= v[ 7];
state->h32[0] ^= v[ 8];
state->h32[1] ^= v[ 9];
state->h32[2] ^= v[10];
state->h32[3] ^= v[11];
state->h32[4] ^= v[12];
state->h32[5] ^= v[13];
state->h32[6] ^= v[14];
state->h32[7] ^= v[15];
state->h32[0] ^= state->salt32[0];
state->h32[1] ^= state->salt32[1];
state->h32[2] ^= state->salt32[2];
state->h32[3] ^= state->salt32[3];
state->h32[4] ^= state->salt32[0];
state->h32[5] ^= state->salt32[1];
state->h32[6] ^= state->salt32[2];
state->h32[7] ^= state->salt32[3];

return SUCCESS;
}
```

# C Intermediate values

As required by NIST, we provide intermediate values for hashing a one-block and a two-block message, for each of the required message sizes. For the one-block case, we hash the 8-bit message 00000000. For the two-block case we hash the 576-bit message 000...000 with BLAKE-256 and BLAKE-224, and we hash the 1152-bit message 000...000 with BLAKE-512 and BLAKE-384. Values are given left to right, top to bottom. For example

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00800000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000001 | 00000000 | 00000008 |

represents

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $m_0$ | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_5$ | $m_6$ | $m_7$ |
| $m_8$ | $m_9$ | $m_{10}$ | $m_{11}$ | $m_{12}$ | $m_{13}$ | $m_{14}$ | $m_{15}$ |

## C.1 BLAKE-256

### One-block message

IV:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6A09E667 | BB67AE85 | 3C6EF372 | A54FF53A | 510E527F | 9B05688C | 1F83D9AB | 5BE0CD19 |

Message block after padding:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00800000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000001 | 00000000 | 00000008 |

Salt and counter

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | | | 00000008 | 00000000 |

Initial state of $v$:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6A09E667 | BB67AE85 | 3C6EF372 | A54FF53A | 510E527F | 9B05688C | 1F83D9AB | 5BE0CD19 |
| 243F6A88 | 85A308D3 | 13198A2E | 03707344 | A409382A | 299F31D8 | 082EFA98 | EC4E6C89 |

State $v$ after 1 round:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| E78B8DFE | 150054E7 | CABC8992 | D15E8984 | 0669DF2A | 084E66E3 | A516C4B3 | 339DED5B |
| 26051FB7 | 09D18B27 | 3A2E8FA8 | 488C6059 | 13E513E6 | B37ED53E | 16CAC7B9 | 75AF6DF6 |

State $v$ after 2 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9DE875FD | 8286272E | ADD20174 | F1B0F1B7 | 37A1A6D3 | CF90583A | B67E00D2 | 943A1F4F |
| E5294126 | 43BD06BF | B81ECBA2 | 6AF5CEAF | 4FEB3A1F | 0D6CA73C | 5EE50B3E | DC88DF91 |

State $v$ after 5 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5AF61049 | FD4A2ADC | 5C1DBBD8 | 5BA19232 | 9A685791 | 2B3DD795 | A84DF8D6 | A1D50A83 |
| E3C8D94A | 86CCC20A | B4000CA4 | 596AC140 | 9D159377 | A6374FFA | F00C4787 | 767CE962 |

State $v$ after 10 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| BC04B9A6 | C340C7AC | 4AA36DAA | FDB53079 | 0D85D1BE | 14500FCD | E8A133E1 | 788F54AE |
| 07EEC484 | 0505399D | 837CCC3F | 19AD3EE7 | 9D3FA079 | FA1C772A | F0DFD074 | 5C25729F |

State $v$ after 14 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7A07E519 | 4C7E2BAC | 28ACF9EC | A5ADB385 | F201E161 | 06B69682 | B290A439 | 232A0956 |
| 1CE6D791 | BACE48A4 | 761DD447 | D40FF618 | D7A1D95F | 0F298AD4 | 8E03E31D | 69D958C8 |

Hash value output:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0CE8D4EF | 4DD7CD8D | 62DFDED9 | D4EDB0A7 | 74AE6A41 | 929A74DA | 23109E8F | 11139C87 |

**Two-block message**

IV:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6A09E667 | BB67AE85 | 3C6EF372 | A54FF53A | 510E527F | 9B05688C | 1F83D9AB | 5BE0CD19 |

**First compression** Message block after padding:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |

Salt and counter

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | | | 00000200 | 00000000 |

Initial state of $v$:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6A09E667 | BB67AE85 | 3C6EF372 | A54FF53A | 510E527F | 9B05688C | 1F83D9AB | 5BE0CD19 |
| 243F6A88 | 85A308D3 | 13198A2E | 03707344 | A4093A22 | 299F33D0 | 082EFA98 | EC4E6C89 |

State $v$ after 1 round:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CC8704B8 | 14AF5E97 | 448BD7A4 | 7D5ED80F | 88D88192 | 8DF5C28F | B11E631F | 0AC6CEAB |
| 01A455BA | 43BAAEC3 | C07C7DEC | 4C912C63 | 6F8CDFEC | 87FD02E0 | D969B7B1 | B74125B6 |

State $v$ after 2 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D7ED8FC3 | CC0A55F2 | 24014945 | 38A9D033 | 8DA19E93 | 9B91D76A | 18E0448C | C10A0DF6 |
| FB350B3C | D894B64E | F1B35175 | D0DFF837 | 54E0DF8F | B3131C53 | 64BCB7A4 | 819FDFEA |

State $v$ after 5 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6BB8EAA1 | FB2D35B9 | F1C87115 | 8CCED083 | C3CCF47F | EC295B60 | 18CF9A21 | DC2AC833 |
| 1F87FBA1 | 759AE5F0 | EE2F791D | 11410F9F | 46C442D0 | EC5BE440 | DC9ED226 | 97E6E8BC |

State $v$ after 10 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 58B76F7A | 24300259 | EA5BAEE6 | 7ABECB5C | BEAA0C3C | 38251BB6 | F0D337AF | FF985D99 |
| 527E3C0C | 4EBFC5FA | BF73D485 | 8B538346 | 03C56421 | D1B9147E | 63662E6C | 70E9E8B2 |

State $v$ after 14 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 730FC16C | 4EC65CF3 | 8CBF360F | D0D11F4F | 8E062A2D | 07E1DC39 | B87B1478 | D1E60507 |
| ACB995F2 | E16E3E15 | 088D91E1 | BC2AF23B | B8D7BE9C | B50D24FE | 72662A9D | 70AF0E4D |

Intermediate hash value

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| B5BFB2F9 | 14CFCC63 | B85C549C | C9B4184E | 67DFC6CE | 29E9904B | D59EE74E | FAA9C653 |

**Second compression** Message block after padding:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 80000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000001 | 00000000 | 00000240 |

Salt and counter

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | | | 00000240 | 00000000 |

Initial state of $v$:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| B5BFB2F9 | 14CFCC63 | B85C549C | C9B4184E | 67DFC6CE | 29E9904B | D59EE74E | FAA9C653 |
| 243F6A88 | 85A308D3 | 13198A2E | 03707344 | A4093A62 | 299F3390 | 082EFA98 | EC4E6C89 |

State $v$ after 1 round:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CDB79DEF | 93A4ECB5 | 7565BDDF | 6A981300 | DDC59D39 | 1C31C834 | 2733AC31 | DF5F9C73 |
| B0F52F8A | 6EE197F0 | B9C02368 | BE5FD351 | F28C1CA7 | 7C045278 | 350C6A3F | 831429FB |

State $v$ after 2 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| A860DA64 | 9F0316A8 | D4EA6EF7 | 306B3189 | E8FF54B6 | C44EF07F | 47AA4DC5 | B1861FE9 |
| 654BF44C | 63CA0C35 | 499E7310 | 38B9FA52 | 161D18F7 | E8F59C12 | 2A8F9427 | 9A77E537 |

State $v$ after 5 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1FD187B1 | 5CC01F1F | 498FD157 | 56161CC5 | D27C3FE9 | A6B47936 | D34BAA06 | DC1B2684 |
| 4F4A4639 | 06FDD62E | 3B9EB4BB | 0F749E2C | 257B233B | F3BF6D70 | 88155286 | 574A5FC8 |

State $v$ after 10 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 082D579C | D41F4DF3 | 973DB87A | 653D77E5 | 1FA637C8 | F4BDAA22 | 5DBC0EAC | D3E836A8 |
| 1E7CF1E0 | 5F1C9C3B | 13CD8444 | 79C5ABFB | 4802A70C | 82A926E5 | 4A781534 | 6B4BD102 |

State $v$ after 14 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4DA680DC | 9B42342C | B18EDAA2 | 65461D92 | 33289EF3 | 88C7594D | EDA0117E | 3A412197 |
| 2C0088F6 | A2DDB7F8 | DD9FC832 | EE375CE3 | B1B3A271 | B2732537 | DA252F9B | 1C2ACA85 |

Hash value output:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D419BAD3 | 2D504FB7 | D44D460C | 42C5593F | E544FA4C | 135DEC31 | E21BD9AB | DCC22D41 |

## C.2 BLAKE-224

### One-block message

IV:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C1059ED8 | 367CD507 | 3070DD17 | F70E5939 | FFC00B31 | 68581511 | 64F98FA7 | BEFA4FA4 |

Message block after padding:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00800000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000008 |

Salt and counter

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | | | 00000008 | 00000000 |

Initial state of $v$:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C1059ED8 | 367CD507 | 3070DD17 | F70E5939 | FFC00B31 | 68581511 | 64F98FA7 | BEFA4FA4 |
| 243F6A88 | 85A308D3 | 13198A2E | 03707344 | A409382A | 299F31D8 | 082EFA98 | EC4E6C89 |

State $v$ after 1 round:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 04027914 | 24CFDD6B | 7D33F394 | 12CBCC67 | 2DE38C62 | 6664F3D3 | 1D8D68FC | D6CD0B0B |
| 481423A7 | 2F45B4F9 | 21C35492 | 50FB35FE | 1255AE24 | DFF2A626 | 9240D453 | E8530B9D |

State $v$ after 2 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9FB36742 | 31BC5AC2 | 064D4095 | 4A2260B2 | C12165D2 | 00D0EE58 | AD1D8245 | 4F7B0F17 |
| 36EF0086 | 38DFA9E5 | A67CC4B5 | 20963EEB | F2821838 | D01907D2 | 7D15E12D | 9B9EF864 |

State $v$ after 5 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| AAB629F7 | 16DE3E4A | 5E78A622 | 257EBE3C | 8669EA65 | 99D687FD | A632EA5E | 511B1C46 |
| 93068AB9 | 67EA727C | 5EC4C9A9 | 7212CD6A | 7F90526F | 6E8952F4 | 70E30791 | 16C1EBD8 |

State $v$ after 10 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C9E1652F | BA9E5BDE | 660E702E | 67FC6579 | BE6B4C7F | F5F0749A | 1DFE158F | 3B49131F |
| 62A1B43D | E2D6F00A | 67AAA716 | E006A66D | 95556F38 | 8145A426 | 1EC4DE7E | FC75FF74 |

State $v$ after 14 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CE6B0120 | 7F7831C3 | 6C4AD4F1 | 145018AF | E6FC08D7 | 3796581B | 04D73114 | ACCE45BE |
| 4A6A54FB | 5DFFCE8B | 2653278F | 8D163884 | E703278E | A1FF6179 | C5093076 | D4125387 |

Hash value output:

| | | | | | | |
|---|---|---|---|---|---|---|
| 4504CB03 | 14FB2A4F | 7A692E69 | 6E487912 | FE3F2468 | FE312C73 | A5278EC5 |

**Two-block message**

IV:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C1059ED8 | 367CD507 | 3070DD17 | F70E5939 | FFC00B31 | 68581511 | 64F98FA7 | BEFA4FA4 |

**First compression** Message block after padding:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |

Salt and counter

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | | | 00000200 | 00000000 |

Initial state of $v$:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C1059ED8 | 367CD507 | 3070DD17 | F70E5939 | FFC00B31 | 68581511 | 64F98FA7 | BEFA4FA4 |
| 243F6A88 | 85A308D3 | 13198A2E | 03707344 | A4093A22 | 299F33D0 | 082EFA98 | EC4E6C89 |

State $v$ after 1 round:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| E5B52991 | 1FBB7ECB | F7350E64 | 0C8D11C6 | 148B1E94 | 7C688FED | C8FEEE1B | 4046AC6E |
| 8BC4F63C | C1C7FE8C | 1FA6AE53 | EE4DC034 | 87863887 | 2D70805B | 4FA9A232 | D9860F12 |

State $v$ after 2 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2F3A90E3 | EBBBC331 | 5737A2D1 | 6480F282 | DB471183 | 43014ABD | 88924F03 | 5160CB72 |
| 6E8F7EEB | 115D1FD6 | 43387C5F | FFB59797 | F8663D1A | D5FA0EC9 | 0C0ED9E5 | 8579D4A6 |

State $v$ after 5 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| F729608D | 8119B461 | E62F4D54 | 7889D045 | 838FBD7D | 1A1E5618 | 8728C02B | E973E337 |
| 06F32665 | 23B502C7 | FEDC26FC | CEFD14A6 | DAD6B58F | 4DCA0D19 | 31D904CB | 3C7E2160 |

State $v$ after 10 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D3465C90 | 9AF58DB6 | 77044D06 | 8782E7B8 | F5C3F50A | 78A3A751 | D7923EF6 | 647B8D32 |
| 7B80826F | 21577A7A | CE253568 | 1B6A082B | D5E512E2 | E213D8E0 | F39651A7 | F9FDAE6E |

State $v$ after 14 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8CEF86C7 | A53FE03F | C1CF9E13 | 92912AB7 | E666B2CE | 50E0C7B4 | DFCD83E6 | 99AAAAB2 |
| 5A8C1DB8 | C5DF5DA5 | 5252A472 | 02964CE7 | 64F7CC82 | 6737018C | DB48674D | B0D3F7D2 |

Intermediate hash value

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 176605A7 | 569C689D | A3EDE776 | 67093F69 | 7D51757D | 5F8FD329 | 607C6B0C | 978312C4 |

**Second compression** Message block after padding:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 80000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 |
| 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000000 | 00000240 |

Salt and counter

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 00000000 | 00000000 | 00000000 | 00000000 | | | 00000240 | 00000000 |

Initial state of $v$:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 176605A7 | 569C689D | A3EDE776 | 67093F69 | 7D51757D | 5F8FD329 | 607C6B0C | 978312C4 |
| 243F6A88 | 85A308D3 | 13198A2E | 03707344 | A4093A62 | 299F3390 | 082EFA98 | EC4E6C89 |

State $v$ after 1 round:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 78B24F69 | DD359E3B | 7C75E05E | 779A4316 | 3D2BFBEE | EA479686 | DE701096 | E01398E5 |
| 8907B84D | 855FB196 | D682ED6C | 5487D95E | CAEE46BB | 33A39BBD | 9C28F332 | 5FF502F1 |

State $v$ after 2 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| BC5A4C4C | AD7D995A | 00BBA35D | 0BEA4495 | D6C0F1CF | 891ECA54 | 8EB95E77 | D1614112 |
| 73E586AB | 40CAEBC9 | 19C689DD | 624BC7B7 | 7729314C | 0FC7B802 | E269ED89 | B4C40DD1 |

State $v$ after 5 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9664B1E6 | C7329A7A | 37DB4880 | 779D1981 | B05ECAFD | 49F78A02 | 16983441 | 80C80AB1 |
| 601C3551 | 0DB868EC | 7AD02138 | 691FC82E | 118C8093 | BE617947 | 42DDDA59 | 8862B2F2 |

State $v$ after 10 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| AD49264A | F50B2055 | 29C2EC7B | F8398ABB | FB6BBA47 | C9FC2626 | 1CD31E08 | E3E75A78 |
| 144A402C | ECDA2A07 | 1CCAEED0 | B73AC43B | 2BB70FBB | 71A9E691 | 4F9C2E99 | 8B78FC0E |

State $v$ after 14 rounds:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| A1E9FEE4 | 99180B3C | 8F8629E3 | C825F8DE | 48E8AF2E | 712C0633 | 87373EEA | 4E0CE59F |
| 4325FB9E | D33C2442 | 3868BC3A | D4708103 | BD34589B | EE0AC28B | DBB008E2 | FAE58BB1 |

Hash value output:

| | | | | | | |
|---|---|---|---|---|---|---|
| F5AA00DD | 1CB847E3 | 140372AF | 7B5C46B4 | 888D82C8 | C0A91791 | 3CFB5D04 |

## C.3 BLAKE-512

### One-block message

Message block after padding:

| | | | |
|---|---|---|---|
| 0080000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000001 | 0000000000000000 | 0000000000000008 |

IV:

| | | | |
|---|---|---|---|
| 6A09E667F3BCC908 | BB67AE8584CAA73B | 3C6EF372FE94F82B | A54FF53A5F1D36F1 |
| 510E527FADE682D1 | 9B05688C2B3E6C1F | 1F83D9ABFB41BD6B | 5BE0CD19137E2179 |

Salt and counter

| | | | |
|---|---|---|---|
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000008 | 0000000000000000 | | |

Initial state of $v$:

| | | | |
|---|---|---|---|
| 6A09E667F3BCC908 | BB67AE8584CAA73B | 3C6EF372FE94F82B | A54FF53A5F1D36F1 |
| 510E527FADE682D1 | 9B05688C2B3E6C1F | 1F83D9ABFB41BD6B | 5BE0CD19137E2179 |
| 243F6A8885A308D3 | 13198A2E03707344 | A4093822299F31D0 | 082EFA98EC4E6C89 |
| 452821E638D0137F | BE5466CF34E90C64 | C0AC29B7C97C50DD | 3F84D5B5B5470917 |

State $v$ after 1 round:

| | | | |
|---|---|---|---|
| 98957863D61905B3 | 2064357139454E43 | 391FB64BD757FB63 | A77C0E00BBE362B5 |
| 86D4B6C41F60C7E1 | 823F30053BEB147C | 68E6FC038D3B0B70 | D93165F3477733DF |
| DED9D48A51DDE68F | 3B73BB8B500C22B1 | 03F92332A668036B | E2F0B698EA636BB9 |
| A40103908A3FD2AE | 016613AD1A47C604 | BFBC229C63E28B76 | 02A5DDF1AFF95A3A |

State $v$ after 2 rounds:

| | | | |
|---|---|---|---|
| 84DAC4B310F8B76B | 01CE15A3AA8D8B2E | F12C708C9D10A8B0 | 778C288779642198 |
| 13D4F878F30C3F5E | 5B049744B1932015 | 0FCFC0DEE2C0F4A0 | 80B67926A85E5AD8 |
| 8D0E3FB6C987BE2B | A1E68630BE9171C7 | 06D755881837E80F | B8729CFE5D112FA0 |
| 9226C2A7D8AD1F76 | 8265C86D8C126BC1 | C0BFC6FEE0CFF19B | E48FA8828EEC436A |

State $v$ after 5 rounds:

| | | | |
|---|---|---|---|
| EFD689A66BDC0A95 | 2253DDE0CB058FFC | 886B8A405AE244FA | CA317DFE42522691 |
| FB5123461DF359E7 | 17EFB7C5FD09F586 | 8E07FE0BD4918C29 | E3AE0ACDF25D6303 |
| 6D4719E51F4A0833 | 27218B65BD7D4BC0 | 9227B3EA1497AD64 | 72B2C922552B72F9 |
| 855C5D1C44DD57A4 | FC1340AE55773E39 | 03B57F827BE2F1CD | B43F42F4AA368791 |

State $v$ after 14 rounds:

| | | | |
|---|---|---|---|
| 1C803AADBC03622B | 055EB72E5A0615B3 | 4624E5B1391E8A33 | 7B2A7AA93E27710A |
| F7EA864E4D591DF7 | 34E2FF788DBD71A7 | 01D13A3673488668 | 390D346D5CB82ECF |
| 00D6AC4E1B3D8DE0 | 58CD6E304B8AD357 | 33E864217D9C1147 | C9C686A43790D49F |
| 8C76318C3B9E3C07 | 20952009E26AE7A1 | E63865AEC6B7E10C | 2FAFFDCB74ADE2DE |

State $v$ after 16 rounds:

| | | | |
|---|---|---|---|
| A4C49432D99D5E8D | E90F2891ABD6B4A6 | 49C0415E4A303C04 | 0411BECCA4309EA7 |
| D84C660093C4CABD | 1DA7328A685C8535 | AF04DB28C411CFE1 | 148FACBCAF9CD9FE |
| 595B67D2DCF8E77F | E805A26C2B41F54C | 8F13BB9AAE41CD1D | A413194AD2FEB3B2 |
| 76D336C6C8BC63D1 | 3E99BB3B08FEEF23 | AED8A237B480F33C | 7B6AEA4550AB4634 |

Hash value output:

| | | | |
|---|---|---|---|
| 97961587F6D970FA | BA6D2478045DE6D1 | FABD09B61AE50932 | 054D52BC29D31BE4 |
| FF9102B9F69E2BBD | B83BE13D4B9C0609 | 1E5FA0B48BD081B6 | 34058BE0EC49BEB3 |

### Two-block message

IV:

| | | | |
|---|---|---|---|
| 6A09E667F3BCC908 | BB67AE8584CAA73B | 3C6EF372FE94F82B | A54FF53A5F1D36F1 |
| 510E527FADE682D1 | 9B05688C2B3E6C1F | 1F83D9ABFB41BD6B | 5BE0CD19137E2179 |

**First compression** Message block after padding:

| | | | |
|---|---|---|---|
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |

Salt and counter

| | | | |
|---|---|---|---|
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000400 | 0000000000000000 | | |

Initial state of $v$:

| | | | |
|---|---|---|---|
| 6A09E667F3BCC908 | BB67AE8584CAA73B | 3C6EF372FE94F82B | A54FF53A5F1D36F1 |
| 510E527FADE682D1 | 9B05688C2B3E6C1F | 1F83D9ABFB41BD6B | 5BE0CD19137E2179 |
| 243F6A8885A308D3 | 13198A2E03707344 | A4093822299F31D0 | 082EFA98EC4E6C89 |
| 452821E638D01777 | BE5466CF34E9086C | C0AC29B7C97C50DD | 3F84D5B5B5470917 |

State $v$ after 1 round:

| | | | |
|---|---|---|---|
| 1BE45837F23BAEE5 | 2111F54A79AD333D | F51F6F4BDBDACC64 | BFD3AF47522BA647 |
| 3CBD1A03BABEE0B1 | 4C1679E18847BED0 | 65375DDA217AF370 | FC804555EA9C61C0 |
| 13DCA8E50FCBEEA2 | A028A1030A7F2907 | A8486683A019458C | 6F50BBC1BAAD52D1 |
| 26FF0C474E8A8E46 | 3661DBA5D8ADCE89 | FB6E1530F3FA0CD2 | 29F3D982476D1C5B |

State $v$ after 2 rounds:

| | | | |
|---|---|---|---|
| 078A7F4AB38B51A3 | 3CC938D334F088AE | C9688433013EB5F4 | 963A2028D731F262 |
| A2E4F2F9127A623E | 7DF540DFFEC115F7 | 539403CCFF3E7EDA | 4039A268638B91E7 |
| 6DE0D9BF908EF408 | D9747550EADAF1B2 | 5CBEB17148553D5C | CC40FD3E15DD6C42 |
| 528F6D54B521156E | CE320314E7255341 | C374721DDC0FEEB2 | F64047D64AED39A9 |

State $v$ after 5 rounds:

| | | | |
|---|---|---|---|
| 7CE663EFB2F3997D | CA831A13AE1ADEA2 | 1B489B08D9C77613 | 8449E1F48BF74A4A |
| D7F36F5DAD19B6F0 | 1B79A03B9DADCC93 | 0C5A6120750E5B4A | 4D74C0055FEA4D29 |
| 91ECB03DDFB95F46 | D12929425D257265 | 4436F30BA8FDA059 | 8F5EA5D22A3CFC07 |
| 1591886653094950 | A98739E101B44D3A | 78556C535F2905F2 | E5BC8EDDAC0176DF |

State $v$ after 14 rounds:

| | | | |
|---|---|---|---|
| BAE5B20438EBD1AE | FB9EB556D67BE6CD | 1DD32AA12CB2C411 | 42374BFECE90FA65 |
| 807E55B199234ECC | 7FC73B526FADC9D8 | 760B6B884BA1B098 | B77D0E14CCB094DD |
| FB079B4D09CDA172 | EE56FD3B622F28AC | A4C9C6924B60C4B9 | 244E57A15B596644 |
| 7C86CAACE54A8E3E | 71782EF1771E5ABA | 5FCE8F0139CBA368 | D3F1A57A2BD841F4 |

State $v$ after 16 rounds:

| | | | |
|---|---|---|---|
| 8ACE4588105EF7E8 | 1CC36907319943BE | 40E0AC4199C96848 | D758207628A2FCB1 |
| 0DA86B4B6F335C80 | 40CDA4C168A9570B | 1A58BBB86DFE6BAF | C95C785976A6B38F |
| 9C9DC23D05EE6893 | 933B75529E2BE1FE | 11B14581561A7CCC | 288DF0A868B9453D |
| E96AB70C1614870C | 6437BA76484C940F | 835FC973C1218EC7 | 63A773992264BD92 |

Intermediate hash value:

| | | | |
|---|---|---|---|
| 7C5A61D2E60C5673 | 349FB2D02B78057B | 6D3F1AB23147ECAF | 5A9A25E41F068F7D |
| B5CC8E38D4C1595D | BFFF763B0BDBAF1B | 8684AB60579E5803 | F11BC6D947BC2F64 |

**Second compression** Message block after padding:

| | | | |
|---|---|---|---|
| 0000000000000000 | 0000000000000000 | 8000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000001 | 0000000000000000 | 0000000000000480 |

Salt and counter

| | | | |
|---|---|---|---|
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000480 | 0000000000000000 | | |

Initial state of $v$:

| | | | |
|---|---|---|---|
| 7C5A61D2E60C5673 | 349FB2D02B78057B | 6D3F1AB23147ECAF | 5A9A25E41F068F7D |
| B5CC8E38D4C1595D | BFFF763B0BDBAF1B | 8684AB60579E5803 | F11BC6D947BC2F64 |
| 243F6A8885A308D3 | 13198A2E03707344 | A4093822299F31D0 | 082EFA98EC4E6C89 |
| 452821E638D017F7 | BE5466CF34E908EC | C0AC29B7C97C50DD | 3F84D5B5B5470917 |

State $v$ after 1 round:

| | | | |
|---|---|---|---|
| 7DC6E2217B190BD3 | 2D69C6D6AEDA0572 | C445CFA1EE378343 | 8761913893DAC34F |
| D7AB98024A5DE598 | DD3C50178BA6CFE0 | 26AC7F783C286112 | AF357137BF5B27FA |
| 537A754E12075D1E | 08AE7D22952E350F | 892B8373958F8500 | EDC023EF5FC2B9C3 |
| 3CEE042F8E124FA5 | EBCCEA756D5DDBDC | 44EEF37D26631B07 | CBB87F4CC2DD2D13 |

State $v$ after 2 rounds:

| | | | |
|---|---|---|---|
| CC056856C518D859 | 7344ABCD0D8A6950 | CA67E04FB09D817B | 1D8C4E9DAAEA72D1 |
| E6B340711ECA08BF | 73C3FF68CF47F1F1 | D2207FE16ABA76E7 | FA938A0BC99E8B07 |
| 1D18CC99351E737E | 8FE782CA928829FF | 02BB3600E4FDF376 | B8C00D91EA6C13EA |
| 3F91B8F1E4A84E64 | CC0F5B8510B363B5 | 44B84D4F9533710E | 65E10F27E5E5BFFA |

State $v$ after 5 rounds:

| | | | |
|---|---|---|---|
| 93C53A007170B925 | 1A2FDD068C9D5F6E | 00AC49AE15AB9892 | 037C2596C191739D |
| 4AB00AC40C224583 | 335D1755FE36617F | C5563C085F95A304 | 5186037E4BC146B7 |
| 413BDF4A9610B8AE | 8B00F63774A69126 | 423466AF367F81AE | B07234DA1883CD37 |
| 83DC32EC57DC0C0B | E51C59511CFFA5E1 | 38B2F87608EC0ED5 | B77E9446582F3042 |

State $v$ after 14 rounds:

| | | | |
|---|---|---|---|
| 23897E7C9EAB8A3F | 34125E009632AB3B | 07FFB519E17E078D | 7F488875753A238E |
| 91E58ECF92563D9F | C246847E756F98B3 | 2DD4F6BF4750BB17 | 07CE0E79086F7852 |
| 79103890FB73058D | 53AAC95C31B3B84E | 64EE88C4FB103B29 | C68ED0A58B94204F |
| CA2842EA101CF14B | 251E178D430A7E37 | C3E3C40FE82F826B | F90D61B845D1C180 |

State $v$ after 16 rounds:

| | | | |
|---|---|---|---|
| C2961E406275C096 | 1B37A68DBEE2ABD6 | 4F8F5B9710A90B23 | 315BDA6D8A014764 |
| 0837CD44DD4E7025 | F773FBC58D201D97 | E2AE133356ABB427 | 6D44168B6B9D94B9 |
| 8FFB68448C905990 | A2630AED65596132 | E3E0F3F02115D479 | 7793504008324236 |
| AE8FFBDF8235500C | AF7A62874C4ADDAE | AA34DCCE6F3441B1 | 159DC3567175E603 |

Hash value output:

| | | | |
|---|---|---|---|
| 313717D608E9CF75 | 8DCB1EB0F0C3CF9F | C150B2D500FB33F5 | 1C52AFC99D358A2F |
| 1374B8A38BBA7974 | E7F6EF79CAB16F22 | CE1E649D6E01AD95 | 89C213045D545DDE |

## C.4 BLAKE-384

### One-block message

Message block after padding:

| | | | |
|---|---|---|---|
| 0080000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000008 |

IV:

```
CBBB9D5DC1059ED8  629A292A367CD507  9159015A3070DD17  152FECD8F70E5939
67332667FFC00B31  8EB44A8768581511  DB0C2E0D64F98FA7  47B5481DBEFA4FA4
```

Salt and counter

```
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000008  0000000000000000
```

Initial state of $v$:

```
CBBB9D5DC1059ED8  629A292A367CD507  9159015A3070DD17  152FECD8F70E5939
67332667FFC00B31  8EB44A8768581511  DB0C2E0D64F98FA7  47B5481DBEFA4FA4
243F6A8885A308D3  13198A2E03707344  A4093822299F31D0  082EFA98EC4E6C89
452821E638D0137F  BE5466CF34E90C64  C0AC29B7C97C50DD  3F84D5B5B5470917
```

State $v$ after 1 round:

```
5B063A05F1A479BB  82CA717B7A4F6F94  4F58DFBDAB593FFB  F826C578573BEC7E
C0836949C0FA750A  99FD9AA2E726BF09  32F52E2CBFC45A64  80686C4AE126CDA9
5EB10A738BF891EE  3DF23E84618C549F  F2C230E414F34299  9191632BEE7EE45E
C83CF461EDC79B6D  8FF3FB919A781656  9BE2FD02DFE1B98A  5B64934E1FE8370D
```

State $v$ after 2 rounds:

```
5B2B57C1586FEEA6  7413D0FE48C32BE2  535CA6F699C38D80  BBEE0C0CBD530269
9E3CD39F1C1868DA  A4D8C74D2A7AA0F5  7524F4211494EF12  A94A548795A319EC
B9F9689AFC6AEDA6  EBC0E49C45A1E9AA  260D24A2D818CB43  BA3914617A2D98EC
F7BA66DC1AEB284C  9C362FBCE59789D9  74B3B2650C513D2C  D53EB118A489C053
```

State $v$ after 5 rounds:

```
4292009F26C4CAA5  17DF7CF80E7A6542  24CA7FE6607B8393  C91DDCA2AFECD146
7ECAF3B6BC20CFD7  00D47510478C61B9  F1A2F95870EAF7B0  52AD845DA7D26918
A0E941F5B18548FA  BFCB96FC91F31717  4B9F4584075D75C4  BF9C0EE7E53657FF
CB09E853BA91C13D  FD46E7FE45AA85E3  CE6E1C891FFAAEF9  2C9E50427598264A
```

State $v$ after 14 rounds:

```
1DD69F386C168B30  EB4B1AD311C7C265  42044AA20151C2A0  1BD8CBE637DFB25D
94ABF0918D4B9749  6A59118B73AB159B  56EE21C11395B066  00BB340A4C94C03B
2EC5D56650765851  B84BF78188E22A8D  5149DF33128FAAC1  8E52CD242ADB8EA8
88EA30691A1873AA  DABF685D0556D4AF  51168CA096930C62  E42652FFB6D559CF
```

State $v$ after 16 rounds:

```
36512BF3E39351F8  9477606C71836A24  0EFCB83C910DEED8  23CC167714D245A0
71D6F1D7F5ADA777  19B7C2F855B20B15  14CEB36724144E05  D8AE8C3EBBA6CF13
EDC2A9C9C3A3262A  1E05CB635DCAEA33  38BC8F1C767F147E  01D7C4B422FE1DC5
3FDCC9354FD88B6B  84A44AF8A049C603  85CF0F5D20038E18  2FB4FD1F72850C85
```

Hash value output:

```
10281F67E135E90A  E8E882251A355510                    A719367AD70227B1  37343E1BC122015C
29391E8545B5272D  13A7C2879DA3D807
```

### Two-block message

IV:

```
CBBB9D5DC1059ED8  629A292A367CD507  9159015A3070DD17  152FECD8F70E5939
67332667FFC00B31  8EB44A8768581511  DB0C2E0D64F98FA7  47B5481DBEFA4FA4
```

**First compression** Message block after padding:

```
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000000  0000000000000000  0000000000000000  0000000000000000
```

Salt and counter

```
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000400  0000000000000000
```

Initial state of $v$:

```
CBBB9D5DC1059ED8  629A292A367CD507  9159015A3070DD17  152FECD8F70E5939
67332667FFC00B31  8EB44A8768581511  DB0C2E0D64F98FA7  47B5481DBEFA4FA4
243F6A8885A308D3  13198A2E03707344  A4093822299F31D0  082EFA98EC4E6C89
452821E638D01777  BE5466CF34E9086C  C0AC29B7C97C50DD  3F84D5B5B5470917
```

State $v$ after 1 round:

```
3BBF567D6D8E7C9A  826AB1796F4B2F2A  D3589AB1A73A76FB  7FFB66FFAAA078B4
1F7BFE2284B78162  E1F997F6B243CD2A  70B6BA23B832F52D  B5418F66EC6D2031
ADA82F0DD0769947  C23086272083F261  F6A871C70393F9FA  8D515B125606EADA
C802F0CF294F6269  C6F36399DF7E1E35  8F20EDDF0BA7D74A  DE4472F1D1506E6F
```

State $v$ after 2 rounds:

```
EA85A242A7F6CFCE  89A54C23487CA8BF  5C8893D38EF63BF3  46B087AA28D56BE5
5D085C4433F1929C  8134381EEE29381F  36505EC762DAB50C  D71519E8814D4E39
F4A2235795910F0F  58AD370D224CB9B0  47D1E79A61966B91  0563F8E3BA681DBD
48D6E244313C9D0C  D079DE27CBA8F3C8  DD134C5A6384EFAC  7E27A4AC04CF472D
```

State $v$ after 5 rounds:

```
802C1F2E2198AE80  EE5B58BB836A1D70  8157B2DA7FB7781D  9295E0C42DC728FC
D88DF0E4BFC0ADAB  7871BB15B4555CAB  F89864B706E11F5F  F01F54F3CB2B4E5F
014C1C71F0918E4D  EA826F742DAA21D0  33C03F7DFB0166DC  11442F58CFC88765
0D2FB5DCD1ADE0AE  7C972BBFEF957FB5  7D874F206DD2E3FB  8CFE8958C6233803
```

State $v$ after 14 rounds:

```
48D2ABEEC2D71CC5  453ACF7BB753BBF1  8AD951B5121E15F2  6D70D249D39A715A
AF9FDE1EE3CAD40D  C661F45A89950ADC  843A9EE5D8169BD5  C74BC1121B511E1A
12D0217D0E74E5B1  CC7BD5E254C52B17  8636BF1D9B6E636B  E5FDF466195146E0
16DAC45878471174  CDAE5B050C98E92A  121004668DBAB665  AEF35F816CEA29F2
```

State $v$ after 16 rounds:

```
3712B6E9CB7B63F2  37AF7025586B6460  257ED91309EB62A0  C8E2F10F4C47949F
2A4A05037B5CDDFA  B5E117FF1E5A553E  E1695E955CC18FE4  3100B996720399C7
B547462AECF8B55E  DB5BD016009287B3  A1E6CDA8E4D58AAB  F25A251EC5A5DA6E
CC6204CFC9023E98  9939A01E93E2EBDC  6D666072608B942F  5D6505E5B9649428
```

Intermediate hash value:

```
49EE6D9EE6864874  8E6E89196E8536D4  15C115E1DD4E351C  2F9738C97EEC17C8
811B27AB4D9EE853  A26CFD66E5E0ABF3  570310EA58B3946C  2BD0F46E759D424B
```

**Second compression** Message block after padding:

```
0000000000000000  0000000000000000  8000000000000000  0000000000000000
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000000  0000000000000000  0000000000000000  0000000000000000
0000000000000000  0000000000000000  0000000000000000  0000000000000480
```

Salt and counter

| | | | |
|---|---|---|---|
| 0000000000000000 | 0000000000000000 | 0000000000000000 | 0000000000000000 |
| 0000000000000480 | 0000000000000000 | | |

Initial state of $v$:

| | | | |
|---|---|---|---|
| 49EE6D9EE6864874 | 8E6E89196E8536D4 | 15C115E1DD4E351C | 2F9738C97EEC17C8 |
| 811B27AB4D9EE853 | A26CFD66E5E0ABF3 | 570310EA58B3946C | 2BD0F46E759D424B |
| 243F6A8885A308D3 | 13198A2E03707344 | A4093822299F31D0 | 082EFA98EC4E6C89 |
| 452821E638D017F7 | BE5466CF34E908EC | C0AC29B7C97C50DD | 3F84D5B5B5470917 |

State $v$ after 1 round:

| | | | |
|---|---|---|---|
| 006BE95A66625251 | 79F3D0100619FE3F | C0AC9991BBCFB7CD | 8B84444C9AD96764 |
| 4F171AD0F3A3DEA9 | B1C7F7E6C97AFFF5 | 2E13AB4E1EBABB9F | 49EB4A1D9E1F91F6 |
| 517D276924FEFC3B | CA0EE442F7580C9B | 621CD230958BFF1B | 964C1F3A7F395AC4 |
| 86A45A4C3D9A424C | 0B2D58EC8066608C | 491952B97A0292CD | 0FD9F18EB607B1F2 |

State $v$ after 2 rounds:

| | | | |
|---|---|---|---|
| 9BBA5065D0DDF6BD | 18E52994739A91E0 | 72CD02F348C9BA19 | A258F47A2F3E0A96 |
| 374E2DDCC60DF1EF | 0C442933AC2EB70E | C4AEFCDCABAECFB0 | 44965DA93D4CC1A6 |
| F2EDE0AC437259F6 | 560175CB6A65F093 | 9755239E63B2D96A | 51691777590CB37A |
| 0D44F5E2447E7879 | 535F8292919E08E6 | E47B361174C3D2F3 | 692FC37673F90E04 |

State $v$ after 5 rounds:

| | | | |
|---|---|---|---|
| 9775064D5300CB4D | C8DC04C98F8EEB4F | F262D279CEE88953 | 1D6822F8DE090DDD |
| A86EB858C7914981 | 4257B029F13117A2 | 80BB47E2DC61FBDD | 89F13F71786CDEC3 |
| 0CCFACD927C99DA8 | 22E7BEE29F3FD1D5 | AE62DC2965F57EE4 | 703573F8124518A0 |
| 683890980C63D04B | F95D5141B985AEDD | 45A265F29715CFC7 | FD9664F57FAD2407 |

State $v$ after 14 rounds:

| | | | |
|---|---|---|---|
| 4542B3975A2C224D | 9046DE63F984B8E6 | 75CD7A39321AEDE6 | 56C1820DB8185B88 |
| C63697063579DDFC | 7C24C051F35BBBC4 | DA28EF56D97B2AE0 | 99BBF8B121EC6AD4 |
| FE1E0776A0DF6BB7 | 726DE26C49F7939A | 4C13939D3CA296D7 | EB2D11499200EF0B |
| 6A7C50324336DE37 | 8B06973E8E5A5560 | 90097FD9BC7C9E8C | F9F031F90127D78F |

State $v$ after 16 rounds:

| | | | |
|---|---|---|---|
| A075E77B2D789059 | 694A9DFCECC350DA | BDDD2A4EDB40816A | 2350B07555E4584B |
| 317F8A79881AA9A8 | E56EB3614A02D706 | 358C9DBB7621380E | 66A32913135D8ED9 |
| E203CF38896BBEE0 | 4C533F44179417E1 | 56313DBEF76725A1 | 6A7DFC286CCD8266 |
| D91CA6FF6FE28549 | 63A0A229F2EB6BB9 | 48DF2388CCDE1001 | FB66BFB8E1939963 |

Hash value output:

| | | | |
|---|---|---|---|
| 0B9845DD429566CD | AB772BA195D271EF | FE2D0211F16991D7 | 66BA749447C5CDE5 |
| 69780B2DAA66C4B2 | 24A2EC2E5D09174C | | |