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Modification in Hash Function from Md4 to Sha-3

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Abstract:

A hash function modify the input as by providing a fixed size output. Cryptography hash functions are generally used for securing the various applications. The hash functions main use is to create various algorithms and protocol mechanisms. Constructing a hash function, required two main fundamental parts. First is a compression function and the second is a domain extender. Two major classifications of hash functions are: dedicated hash functions, and block cipher-based hash functions. I am analyzing the modification done in the logics that are done in the hash function .the modifications from MD4 to SHA-256 is in detail and SHA-3 construction has been briefed in this paper. In this framework, discussions on attacks on hash functions have been excluded to limit the scope of this paper.

Keywords: Hash Function, Merkle-Damgård Design, MD4, SHA-2, SHA-3

I. INTRODUCTION

We know that an ancient approach for identifying a person uniquely is to take the left or right thumb impression of that person. Similarly it is of great help if we work with a small message which represents a much longer message uniquely. Hash function provides us this facility. A hash function maps a variable-length input message into a fixed-length output message. This hash function output can be treated as a fingerprint of the input data [20]. A very simple example of hash function is modulo operation. Hash functions have been used in many fields of computer science such as hash table in data structure, checksum algorithms for error detection, digital signature in information security etc. They all depend on the fundamental property that different input values would produce different fingerprints in most of the cases. The hash functions that are used in the information security related applications are referred as cryptographic hash functions. A cryptographic hash function h takes a message with arbitrary length as input, and deterministically maps it to a bit-string with fixed length as output. That is

h: {0,1}* {0,1}n **1.1**

This output bit-string of the hash function is commonly referred as "message digest" or simply "digest", or just "hash". Here onwards, we use the term hash function to mean cryptographic hash function.

Hash functions are being used as building blocks of many complex cryptographic mechanisms and protocols. One such usage is in digital signature. Digital Signature Standard (DSS) is used for authentication, as well as for non-repudiation of data. Hash function is also used in authentication protocols such as Kerberos. Kerberos offers authentication, eavesdropping prevention, and integrity of data in client-server architecture. Secure communication protocols such as IPSec, SSL, or SSH also use hash functions. Internet Key Exchange (IKE) protocols in IPSec use hash functions as pseudo-random functions. The handshaking protocol in SSL uses a hash function to create a message authentication code. PGP and S/MIME also use hash function to ensure the integrity of e-mail messages.

The organization of this paper is as follows. The basic properties of a hash functions have been introduced in section 2. Next section briefly introduces various components or building blocks of hash function design. Section 4 discusses dedicated hash functions. This includes Merkle-Damgård construction, Merkle-Damgård alternatives, concept of domain extenders, and detail descriptions of two hash functions in the MD4 family: MD4, and SHA-256. The block cipher based hash function designs have been discussed in section 5. Section 6 discusses SHA-3 hash function.

II. PROPERTIES OF CRYPTOGRAPHIC HASH FUNCTIONS

The properties of hash functions differ depending upon the usage of hash functions. To introduce the three properties a hash function should possess, we recollect the terms image, and preimage. Consider a function f(x) = y that maps x to the image y. The x is said to be preimage of y. Now the three properties of hash functions are as in the following [21]:

1. Preimage Resistance: Given a digest y of n-bit length, it is computationally infeasible to find a message x that hashes to y. That is, computational cost of finding the input x must be $\geq 2n$, where h(x) = y and |y| = n. The notation |x| represents the size of x in bits.

2. Second Preimage Resistance: Given a message x, it is computationally infeasible to find a different message x', such that both messages hash to the same digest. That is, computational cost of finding the input x' ($\neq$ x) must be $\geq 2n$, where h(x') = y, h(x) = y, and |y|=n.

3. Collision Resistance: It is computationally infeasible to find two different messages, which hash to the same digest. That is, computational cost of finding an input pair x and x' such that h(x) = h(x') must be $\geq 2n/2$. Here n is the length of message digest.

Preimage resistance property can be expressed as the inability to learn about the contents of input data from its digest. Second preimage resistance property can be interpreted as the inability to learn about second preimage from the given first preimage such that both of these preimages have same digest. Collision resistance property signifies that the digests are almost unique for each given message. If input message is altered, almost always the hash changes as well. The word almost is to be noted. Because when a function maps from a larger domain to a smaller range, collisions necessarily exist. If we properly design cryptographic hash functions with digests of sufficient length then probability that one can obtain two different messages with identical hashes is too small to be bothered in all practical applications. These three properties - preimage resistance, second preimage resistance, and collision resistance are also known as one-way, weak collision resistance, and strong collision resistance properties respectively. If a hash function satisfies the first two properties then it is referred as one-way hash function (OWHF). Whereas the hash function, that satisfies all the three properties, is referred as collision resistant hash function (CRHF) [12].

A hash function with an output of n bits can only offer a security level of 2n operations for pre-image and second pre-image attacks and 2n/2 operations against finding collisions. While a security level of 128-bits is typical for main stream applications, 80-bit security is often a reasonable target for RFID tag-based applications [6]. Here onwards the abbreviation HF has been used to mean hash function in this paper.

III. COMPONENTS OF HASH FUNCTION

To process arbitrary long input data, HFs are generally designed by reusing small and fixed-length input functions under some composition method. The composition method a HF goes through is arbitrary-length domain extender of underlying building blocks with a fixed domain size. Such building blocks are known as *compression functions*. Thus, construction of a HF consists of two components. First component is a *compression function* that maps a fixed-length input to a fixed-length output. The size of original input to HF must be greater equal to this "fixed-length input" of compression function. Second component is a *domain extender* that uses a compression function and produces a function with arbitrary-length input and fixed-length output. The design of a compression function is the key component in constructing a HF. The various HF design philosophies try to build the compression functions from different angles. Although most of the existing HFs can be described as being based on a block cipher, these block cipher based HFs can be further classified into two categories. First category is the *block cipher-based hash functions* that use HFs based on an existing block cipher designed for encryption/decryption purpose such as DES, AES etc. Second category is the HFs that use block ciphers but these block ciphers have been designed particularly for use in HFs. HFs designed using the compression functions constructed only for HFs are called *dedicated hash functions*. A striking feature of about these block ciphers, which have been designed exclusively for use in HFs, is that they are not necessarily secure and hence may be unsuitable for exclusive encryption/decryption purposes. It may be pointed out here that people have used stream cipher like RC4 instead of traditional approach of using block cipher in designing a HF instead of block ciphers [7]. Compare to block-cipher-based hashes, the stream-cipher-based hashes have smaller block size and more number of rounds.

In brief, the general framework for iterated HF to process padded input message $M=m_1m_2\cdots m_n$ can be described as follows: $H_0 = IV\ ,\ H_i = f(H_{i-1}, m_i)\ \ for\ i = 1,2,\cdots,n.\ \ h(x) = g(H_n)$. Here IV is *initial vector* or *initial value*. Function f is called *round function* or *compression function*. H_i is called *chaining variable*. Result of the HF is denoted with h(x). Function g is called *output transformation*. In many cases, use of output transformation is not mentioned explicitly. In that case, g is simply the identity function. That is, $g(H_n) = H_n$. In this case output length is equal to the length of the chaining variable. Role of an output transformation is to further reduce the length of hash result.

IV. DEDICATED HASH FUNCTIONS

The most adopted approach to design HFs is to use a *domain extender* on top of a *compression function* in an *iterative* manner. Iterative structures allow for a sequential message processing. One of the first examples of an iterative HF is the Rabin hash [28]. In 1989, Merkle [22] and Damgård [9] independently introduced the concept of systematic iterative hash construction known as the *Merkle-Damgård construction*.

4.1 MERKLE-DAMGÅRD CONSTRUCTION

The compression function, $f : \{0, 1\}^n \times \{0, 1\}^b \rightarrow \{0, 1\}^n$ that accepts input - a chaining or state variable *h* of n-bits size and a message block m of b-bits size, and produces n-bits updated chaining variable as output, is the building block of Merkle-Damgård construction.

Padding Rules: Message padding mechanism appends sufficient bits to the original message to make its length a multiple of the input size of compression function f. This padding function for Merkle-Damgård construction is *suffix-free*. The suggested suffix-free padding functions proposed by Merkle, and the one proposed independently by Damgård differ. Merkle's padding rule restricts the size of the processed message to maximum 2^{64} bits, but this is not a problem for practical message sizes. On the other hand, adding a single bit per message block as per the padding of Damgård makes it less efficient due to the overhead of bit manipulations. This disadvantage of Damgård's padding has made the way for Merkle's mechanism to be established as the standard padding rule for Merkle-Damgård construction.
Merkle-Damgård design accepts an additional input parameter, *initial value* IV. IV is a fixed constant. This inclusion of the initialization vector and the Merkle suffix-free padding to the Merkle-Damgård iterative domain extender has been referred as the Merkle-Damgård *strengthening* by Lai and Massey [16]. Now Merkle-Damgård construction is stated as follows:
Given: (i) Compression function $f: \{0, 1\}^n \times \{0, 1\}^m \rightarrow \{0, 1\}^n$ and

(ii) n-bit constant (Initialization Vector) IV.

Input: Message M

1. Append 1 followed by a string of 0's to make total appended input length becomes multiple of m, where m is a pre-fixed block length. Also append the m-bit binary encoding of |M|.
2. Divide the padded message M' into $m_1, m_2, m_3, \cdots, m_k$

2. Initialize $h_0 = IV$;
3. For i = 1 to k

Compute $h_i = f(h_{i-1}, m_i)$;

Output: Message digest of M is h_k.
So, Merkle-Damgård construction iterates the compression function f. The output of f at i^{th} round is h_i. This h_i and the next message block m_{i+1} are the input to the next $i+1^{st}$ round of f. Hash of last block, which contains encoding of message length, is the hash of complete message. The temporary storage of the compression function's output, h_i, is referred as chaining variable or internal state. So to design a HF we have to first *choose a collision-resistant compression function*. Second, *use a padding procedure*. Next, *choose an initial vector*. There is no constraint on choosing an initial vector, IV. The only point is that IV should be fixed.
The main advantage of dedicated has function constructions is their high speed and low resource consumption in the software as well as hardware implementations. This is the reason behind the popularity of this class of cryptographic HFs. Examples include such famous functions as MD5 as well as NIST standards SHA-1 and SHA-2.

4.2 DOMAIN EXTENDERS

Domain extenders can be classified as either Merkle-Damgård-based domain extenders or non-Merkle-Damgård-based domain extenders. In both categories there are several domain extenders. A superb discussion on domain extenders can be found in the thesis by Andreeva [1]. Two major design choices for Merkle-Damgård-based domain extenders are:

(i) Wide-Pipe or Narrow-Pipe design,
(ii) Keyed or Keyless design.

***Wide-Pipe Versus Narrow-Pipe Domain Extenders*:** The original wide pipe construction was introduced by Lucks et al [18]. It is characterized by keeping a full large (>2*n*) internal state in the iterative Merkle-Damgård portion. As final step, a distinct output transformation is employed on this "wide" state to compress it to the desired output hash length, which is shorter than internal state size. JH and Keccak are examples in third round SHA-3 competition that have adopted the wide-pipe strategy. Narrow-pipe constructions, in contrast, are designed by iterating a state as large as the output hash value. BLAKE is the example in third round SHA-3 competition that has adopted the narrow-pipe design.

Keyed Versus Keyless Domain Extenders: Another separation of domain extenders is based on the presence or lack of an explicit key input. When the key is unique for every message, it is termed as *salt*. Keyed designs are often less efficient than keyless ones but provide more security guarantees.

4.3 A SUMMARY OF MERKLE-DAMGÅRD ALTERNATIVES

Prefix-Free Merkle-Damgård: The basic prefix-free Merkle-Damgård designs are narrow-pipe, keyless iterative domain extenders that apply a prefix-free padding function [8]. A padding rule is called *prefix-free*, if for any distinct M, M_0, there

exists no bit string X such that pad(M_0) = pad(M)||X. If the prefix-free designs are not additionally suffix-free, then they do not preserve the main collision security property.

***Enveloped Merkle-Damgård*:** This design was proposed by Bellare and Ristenpart [3]. It is a narrow-pipe, keyless domain extender that uses two fixed initialization vectors IV and IV_0. First vector, IV is applied in a Merkle-Damgård style as input to the first compression function. Second vector, IV_0 is provided as input to the final compression function together with chaining variable and final input message bits and this step is known as the *enveloping* step of the construction.

***Merkle-Damgård With Permutation*:** This construction is a narrow-pipe, keyless variant of the original Merkle-Damgård design [15]. The difference with the Merkle-Damgård construction is that a permutation is applied before the processing of the last message block.

Linear Hash: It is narrow-pipe, keyed Merkle-Damgård iteration [4]. The only difference with Merkle-Damgård design is that it accepts an additional key input in every call of the iteration. Moreover, each key is distinct. This approach ensures a domain separation of the underlying compression function.

***Linear XOR*:** It is a narrow-pipe, keyed Merkle-Damgård iteration [4]. It adds a linear number of keys by XOR-ing these with the chaining values in a Merkle-Damgård style iterative HF. The first key is XOR-ed with initialization vector IV and the final key is XOR-ed with final intermediate chaining value, while the final hash result is left unmodified.

***Shoup's Hash*:** The Shoup's hash function [33] derives from the linear XOR hash function and optimizes it in terms of the number of keys. It uses logarithmic rather than linear number of keys, following a specific sequence.

***HAIFA*:** The HAsh Iterative FrAmework (HAIFA), designed by Biham and Dunkelman, is a narrow-pipe hash function [10]. HAIFA modifies Merkle-Damgård by introducing extra input parameters to the compression function: a bit counter, and an optional salt value. The bit counter keeps track of the number of bits hashed so far. The salt value is used as a key to create families of HFs. Salt is set to 0 if only one HF is required.

***Sponge*:** Sponge design supports variable length outputs. If the output length is fixed, the Sponge construction is roughly classified as a keyless, wide-pipe, non-strengthened Merkle-Damgård construction [11]. Sponge operates on a fixed-length state $b = \{0, 1\}^{r+c}$ through transformation or permutation function $p: \{0, 1\}^{r+c} \rightarrow \{0, 1\}^{r+c}$. Here *r* is the bit rate and *c* is the capacity of the sponge. It consists of an absorbing phase and a squeezing phase. In the absorbing phase, the (padded) message is divided into r-bit blocks and each block is XOR-ed with the r part of b (initially, $b = 0^{r+c}$), p then iteratively processes b until all blocks are finished. In the squeezing phase, the state continues to be transformed / permuted by p but this time the r parts of the states are returned at each iteration as output blocks. A well-known sponge construction is SHA-3.

4.4 Other Domain Extenders
Several non-Merkle-Damgård alternative designs are there that often give twofold incentives: increasing the efficiency and/or the security guarantees.

***Tree-Based Hash Functions*:** These constructions, in contrast to the Merkle-Damgård based designs, allow for parallelism. An early tree-based mode of operation was proposed by Damgård [9]. Tree constructions split the message into blocks which could be processed by independent processors or machines and the final result is combined to produce the hash value.
Few other non-Merkle-Damgård alternative designs are *multi-pass domain extender* and *multi-pipe domain extender*. A *multi-pass* domain extender processes the data in more than one pass. A *multi-pipe* domain extender allows for processing the message in multiple pipes without the need to store the message.

4.5 Examples and Description of Dedicated Hash Functions
MD4, MD5, SHA are some examples of dedicated HF. The term "MD4 family" is used for HFs whose design principles are influenced by MD4 up to much extent. Apart from MD4, the other members of the family are HFs such as MD5, SHA-0, SHA-1, SHA-2 etc.

4.5.1 MD4
Famous cryptographer Rivest was motivated by the works of Merkle's and Damgård's at Crypto 1989 and proposed MD4 in next year [29]. MD4 is a very efficient HF based on the principles by Merkle and Damgård. Cryptanalysis of MD4 revealed certain unexpected properties raising concerns about its security. Rivest then proposed the successor MD5 in 1992 [30]. MD5 is based on MD4 and shares many design ideas of MD4. Focus of MD5 is much more on security than on efficiency. MD4 compresses any arbitrary bit-length message into a 128-bit hash. MD4 consists of the following five steps.

***Step 1: Append Padding Bits*:** Input message is padded so that its bit-length is congruent to 448, modulo 512. That is, the message is extended so that it is exactly 64 bits short of being a multiple of 512 bits long. A single "1" bit followed by zero or more "0" bits are appended so that the length in bits of this message becomes congruent to 448, modulo 512. At least a single bit and at most 512 bits are appended. Padding operation is to be done always, even if the length of the message is already congruent to 448, modulo 512.

***Step 2: Append Length*:** Next, 64-bit representation of input message is appended to make the resultant message exactly multiple of 512-bits. If length of message is greater than 64-bits then only the low-order 64 bits of input message length are used.

***Step 3: Initialize MD Buffer*:** The initial value is IV = A||B||C||D where A = 0x67452301, B = 0xEFCDAB89, C = 0x98BADCFE, and D = 0x10325476.

Step 4: Process Message in 16-Word Blocks: Each message block of 512-bits is processed by a compression function. The compression function consists of three rounds, each of which has sixteen steps. The 512-bit message block is broken up in sixteen words of 32-bits and exactly one of these words is used in every step. In each round, a separate ordering of message words is used. Each of i^{th} round uses different nonlinear Boolean function F_i defined as follows:

$F_0(x, y, z) = (x \wedge y) \vee (\neg x \wedge z)$, $F_1(x, y, z) = (x \wedge y) \vee (x \wedge z) \vee (y \wedge z)$, $F_2(x, y, z) = x \oplus y \oplus z$. Here x, y, z are 32-bit words.

Let m_i be the i^{th} message word, $0 \leq i \leq 15$. Then, in round 0, the message words appear in the order $m_0, m_1, \cdots, m_{15}$. In round 1, the message words appear in the order $m_0, m_4, m_8, m_{12}, m_1, m_5, m_9, m_{13}, m_2, m_6, m_{10}, m_{14}, m_3, m_7, m_{11}, m_{15}$. In round 2, the message words appear in the order $m_0, m_8, m_4, m_{12}, m_2, m_{10}, m_6, m_{14}, m_1, m_9, m_5, m_{13}, m_3, m_{11}, m_7, m_{15}$. The expanded message word W_i serves as input for the i^{th} step in the step operation part.

A rotation operation is the circular shift of the bits in a word. The notation $x^{<<<n}$ is used to represent the operation left-rotation of x by n bit positions. The value n varies depending on the step number and round number. The value of n is 3, 7, 11, 19, $\cdots$ (recurring four times) in round-0, and 0, 3, 5, 9, 13, $\cdots$ (recurring four times) in round-1, and 3, 9, 11, 15, $\cdots$ (recurring four times) in round-2.

The step update function modifies the four registers A, B, C, and D into A', B', C', and D' as follows: $B' \leftarrow (A + F_i(B, C, D) + W + k_i)^{<<<n} \equiv 2^{32}$, $C' \leftarrow B$, $D' \leftarrow C$, and $A' \leftarrow D$. After a 512-bit message block is compressed, the variables A, B, C, and D are updated as follows: $A \leftarrow A + A'$, $B \leftarrow B + B'$, $C \leftarrow C + C'$, and $D \leftarrow D + D'$. And then remaining 512-bits message blocks are processed similarly.

***Step 5: Output*:** The message digest of the input message is generated by concatenating all the 32-bit register values of A, B, C, and D after we process all the input message blocks. This concatenation is done from the low-order byte of A, followed by B, C, and D in the same way.

4.5.2 SHA

NIST published the *Secure Hash Standard* in 1993. The HF underlying the standard was named the *Secure Hash Algorithm* (SHA). At present, it is commonly referred to as SHA-0 [24]. SHA-0 has been developed following the same principles as MD4. SHA-0 is a 160-bit HF, with five registers in the state: A, B, C, D, and E. The initial value, IV = 67452301 EFCDAB89 98BADCFE 10325476 C3D2E1F0.Padding is the same as in MD4, and the chaining input is fed forward in the same way, but all SHA functions assume a big-endian byte ordering (i.e., the sequence 00 01 02 03 of bytes will be read as a single 32-bit word 00010203). The message expansion is more complex than in MD4, and there are four rounds of 20 steps each. The four Boolean functions are defined as follows.

$F_0(x,y,z) = (x \wedge y) \vee (\neg x \wedge z)$, $F_1(x,y,z) = F_3(x,y,z) = x \oplus y \oplus z$, $F_2(x,y,z) = (x \wedge y) \vee (x \wedge z) \vee (y \wedge z)$.

Four constants are used, one for each round: k_0 = 0x5A827999, k_1 = 0x6ED9EBA1, k_2 = 0x8F1BBCDC, and k_3 = 0xCA62C1D6. The message expansion works as follows. Let $m_0, m_1, \cdots, m_{15}$ be the sixteen input words of 32-bits. The 80 words wi, $0 \leq i \leq 79$, in the expanded message are defined as: $w_i = m_i$ for $0 \leq i \leq 15$, $w_i = (m_{i-3} \oplus m_{i-8} \oplus m_{i-14} \oplus m_{i-16})$ for $16 \leq i \leq 79$.

A SHA-0 step consists of the following operations: $A' \leftarrow A^{<<<5} + F_i(B, C, D) + E + w_i + k_i$, $B' \leftarrow A$, $C' \leftarrow B^{<<<30}$, $D' \leftarrow C$, and $E' \leftarrow D$.

4.5.3 SHA-1

SHA-0 was replaced by SHA-1 in 1995 [25]. SHA-1 has been widely used as cryptographic HF. SHA-1 is a minor modification of SHA-0. The only difference between the two HFs is the additional rotation operation in the message expansion of SHA-1, which is supposed to provide more security. This is described as: $w_i = m_i$ for $0 \leq i \leq 15$, $w_i = (m_{i-3} + m_{i-8} + m_{i-14} + m_{i-16})^{<<<1}$ for $16 \leq i \leq 79$. The four round constants k_i are first 32 bits of the decimal places of the square root of 2, 3, 5 and 10.

4.5.4 SHA-2

As *Advanced Encryption Standard* (AES) came in 2001, the need of new HFs with larger output sizes was felt to match the key sizes in the AES. This led to the development of three new HFs, SHA-256, SHA-384, and SHA-512, collectively termed SHA-2, published in 2002 [26]. In 2004, another HF, SHA-224, was added to the list of SHA-2 family. Message expansion is much more complicated than earlier versions of SHA, and two registers are updated in each step. SHA-224 and SHA-256 are constructed in the same way, but they use different IVs, and in SHA-224, a 256-bit state is truncated to 224 bits at the end. Similar differences exist between SHA-384 and SHA-512. SHA-256 and SHA-512 differ in word size; SHA-256 uses 32-bit words, whereas it is 64-bits word in SHA-512. Number of steps in SHA-256 and SHA-512 are 64 and 80 respectively. Also, there are few more minor differences.

Here, only SHA-256 is to be described in detail. SHA-256 uses the same padding technique as MD4, and the compression function is a block cipher in Davies-Meyer mode. The initial value of SHA-256, IV = 0x 6A09E667 BB67AE85 3C6EF372 A54FF53A 510E527F 9B05688C 1F83D9AB 5BE0CD19. These values are the first 32-bits of fractional parts of square roots of first eight prime numbers. SHA-256 uses a number of Boolean functions. First, the following two functions applied on a single 32-bit word are used in the message expansion:

$\sigma_0(x) = x^{>>>2} \oplus x^{>>>13} \oplus x^{>>22}$, $\sigma_1(x) = x^{>>>6} \oplus x^{>>>11} \oplus x^{>>25}$. Here, $x^{>>n}$ means shift right by n bits (not circular shift). The n most significant bits are filled with zero bits. Two other functions operating on a single 32-bit word are the following:

$\Sigma_0(x) = x^{>>>2} \oplus x^{>>>13} \oplus x^{>>>22}$, and $\Sigma_1(x) = x^{>>>6} \oplus x^{>>>11} \oplus x^{>>>25}$.

The Boolean functions F_0 and F_2 are the same as defined in SHA-0 and SHA-1. The SHA-256 compression function takes a 512-bit message (sixteen words $m_0, m_1, \cdots, m_{15}$ of 32-bits each) and expands it into a 2048-bit message (sixty four words $w_0, w_1, \ldots, w_{63}$ of 32-bits each) as :

$w_i = m_i$ for $0 \le i \le 15$, $w_i = \sigma_1(m_{i-2}) + m_{i-7} + \sigma_1(m_{i-15}) + m_{i-16}$ for $16 \le i \le 63$. This message expansion introduces more *diffusion* than the SHA-0 and SHA-1. SHA-256 maintains a state of eight registers of 32-bits length. The state is updated through sixty four steps. Two registers are updated via a function of a number of other registers. Each step involves a distinct constant k_j, $0 \le i \le 63$. These constants are the first 32-bits of the fractional parts of the cube roots of the first sixty four prime numbers. In each of sixty four steps, following operations are performed sequentially (t_1 and t_2 are temporary variables, and A, B, ... , H are the eight registers of the state): $t_1 = \sum_0(A) + F_2(A,B,C)$, $t_2 = \sum_1(E) + F_0(E,F,G) + H + w_i + k_i$, H = G, G = F, F = E, E = D + t_2, D = C, C = B, B = A, and A = t_1 + t_2.

After a message block is compressed, the variables A, B, $\cdots$, H are updated similar to the update of chaining variables in MD4. After all the message blocks are compressed in this fashion, the message digest input message in SHA-256 is concatenation of final values of chaining variables i.e., A||B||C||D||E||F||G||H.

V. BLOCK CIPHER BASED HASH FUNCTIONS

Simon, in his seminal work, [34] suggested that CRHFs cannot be constructed based on one-way functions. Instead CRHFs can be designed based on another very well known cryptographic primitive – Block Cipher. This idea of reducing the security of the hash to the security of a block cipher has its own advantages and disadvantages. The main advantage is that using a block cipher as a primitive of HF gives us the security based on the proven security of block ciphers. Another advantage is that existing implementations can be reused. On the other hand, relying on just one primitive may be counter productive. A disadvantage is that HF based on a block cipher is less efficient than the dedicated proposals.

Block cipher is a popular encryption-decryption primitive. To encrypt, the block cipher accepts a key K and a plaintext block x as input, and produces a cipher text block c = E(K, x), also written as $c = E_K(x)$. The function E is invertible when K is known. The cipher text can be decrypted to obtain plain text $x = E_k^{-1}(c)$. It is to be noted that $|m| = |c|$, e.g., $|m| = n$. If we assume that $|K| = n$ or $|K| = m$ then a block cipher, in encryption mode, can be seen as compressing the $2n$ (or $n+m$) bits constituting the key and the plaintext block to n bits of cipher text.

Essentially all modern HFs are built by iterating a compression function following Merkle-Damgård paradigm or its variation, as mentioned earlier. Again, these compression functions are almost always built from a block cipher. Even so-called "dedicated" hashing primitives like MD5 and SHA-1 can be treated as block cipher [13]. Later on this suggestion of treating SHA-1 as block cipher was termed as SHACAL-1. SHACAL-1 is a 160-bit block cipher that takes variable length (0-512 bits key) and 80 rounds [14].

The earliest hash function from block ciphers was constructed by Rabin and DES block cipher was used [28]. He proposed to hash a message $X = x_1 x_2 \cdots x_n$ by fixing an initial value h_0 and computing $H(M) = DESx_n(DESx_{n-1}(\cdots (DESx_1(h_0)) \cdots))$. Here the input message X is divided into message blocks $x_1, x_2, x_3, \cdots, x_n$. This is in effect a Merkle-Damgård construction with block cipher based compression function $f(h_{i-1}, x_i) = Ex_i(h_{i-1})$.

The general framework of iterated constructions with compression functions is of the form $f(h_{i-1}, x_i) = E_a(b) \oplus c$ where a, b, c ϵ $\{h_{i-1}, x_i, h_{i-1} \oplus x_i, V\}$ for some fixed constant vector V. Generally, the value of V is considered to be zero. H_0 is equal to the initial value, IV. So, by choosing different possibilities of a, b, and c, we can have total 4^3 number of possibilities for round function f to choose a particular block-cipher to be used in HF. That is, there are $4^3 = 64$ different ways a block cipher can be used in compression function.

Preneel et al investigated in detail about different ways a block cipher can be used as a primitive for constructing compression function [27]. They have shown that only twelve simple constructions based on a block cipher result in collision-resistant compression functions. The following lists these compression functions. The notations used in this list are: x_i is the i^{th} message-block, h_i is the compression function used at i^{th} iteration, and E_k is the block cipher with key k.

$$f_1: \quad E_{h_{i-1}}(m_i) \oplus m_i \;, f_2: \quad E_{h_{i-1}}(w_i) \oplus w_i \quad , f_3: \quad E_{h_{i-1}}(m_i) \oplus w_i \quad , f_4: \quad E_{h_{i-1}}(w_i) \oplus m_i ,$$

$$f_5: \quad E_{m_1}(h_{i-1}) \oplus h_{i-1} \quad , f_6: \quad E_{m_1}(w_i) \oplus w_i \quad , f_7: \quad E_{m_1}(h_{i-1}) \oplus w_i \quad , f_8: \quad E_{m_1}(w_i) \oplus h_{i-1} ,$$

$$f_9: \quad E_{w_1}(m_i) \oplus m_i \quad , f_{10}: \quad E_{w_1}(h_{i-1}) \oplus h_{i-1} \quad , f_{11}: \quad E_{w_1}(m_i) \oplus h_{i-1} \quad , f_{12}: \quad E_{w_1}(h_{i-1}) \oplus m_i .$$

Here w_i means $m_i \oplus h_{i-1}$. Black, Rogaway, and Srimpton showed that an additional eight of the sixty four schemes are just as collision resistant (up to a small constant) as the first group of schemes [5].

$$f_{13}: \quad E_{w_1}(m_i) \oplus v \;, f_{14}: \quad E_{w_1}(m_i) \oplus w_i \;, f_{15}: \quad E_{m_1}(h_{i-1}) \oplus v \;, f_{16}: \quad E_{w_1}(h_{i-1}) \oplus v$$

$$f_{17}: \quad E_{m_1}(h_{i-1}) \oplus m_i \;, f_{18}: \quad E_{w_1}(h_{i-1}) \oplus w_i \;, f_{19}: \quad E_{m_1}(w_i) \oplus v \;, f_{20}: \quad E_{m_1}(w_i) \oplus m_i .$$

Here v denotes constant vector. From the perspective of collision resistance, one can choose any particular scheme from f_1, f_2, $\cdots$, f_{20}. Among these collision-resistant compression functions the well known functions are Matyas-Meyer-Oseas (f_1), Miyaguchi-Preneel (f_3), and Davies-Meyer (f_5) [12]. Among these constructions Matyas-Meyer-Oseas and Davies-Meyer are dual constructions. In each iteration step of the hash computation, the present value of the chaining variable (h_i) and the input block to be processed (x_i) serve as key and plaintext of the encryption function (or vice versa for its dual). The plaintext input is then added with the output of encryption function, which constitutes a feed-forward operation. The result of the feed-forward serves as the new chaining value for the next iteration. They do not use an output transformation. Therefore the length of the chaining variable is equal to the output length. The feed-forward operation is based on modulo 2 addition (i.e., exclusive-OR), and its purpose is to make the compression function un-invertible.

Although these twenty schemes are provably secure, they could be viewed as inefficient from practical usability point of view. In each of these schemes, the block cipher key is changed every round. For all conventional block ciphers, changing the key in each round is not desirable. Because scheduling a new key causes a significant computational cost. Fix a small, non-empty set of block cipher keys K. A block cipher-based HF is said to be highly-efficient if its compression function uses exactly one call to a block cipher (i.e., it is of rate 1), and if the block cipher uses only keys from K. Since one can preschedule each key in K, a significant performance gain can be achieved: key scheduling reduces to looking up a precomputed permutation.

***Double Block Length Constructions*:** Most of the block cipher based schemes result in HFs with an output length that is too short from collision-resistance point of view. An alternative is the use of double block length HFs, which produces a hash result with length equal to twice the block length of the cipher [32]. This means that DES will yield a 128-bit HF, and AES to have a 256-bit HF. Currently block cipher based HFs are classified into single block length (SBL) HFs and double block length (DBL) HFs. For SBL hash functions, the length of output is equal to that of the block cipher, while for DBL hash functions, the length of the output is twice larger than that of the underlined block cipher. An important parameter describing the efficiency of these constructions is the rate of the block cipher based HF. The rate is defined as the number of b-bit input blocks that can be processed with a single encryption.

One extension of basic MD construction is *dithering*. It is the technique of adding an iteration-dependent input (the dither) to the compression function to defeat certain generic attacks [31]. Aumasson et al identified methods for dithering block cipher based HFs [2].

***Permutation Based Design*:** Recently there have been efforts by researchers to explore in building compression functions from fixed key block ciphers, where only a small number of constants are used as keys. As each key of a block cipher defines an independent random permutation in the ideal cipher model, *such compression functions are often called permutation-based* [17, 19, and 23]. Permutation-based compression functions have an advantage over conventional block cipher based ones, since fixing the keys allows to save computational overload for key scheduling. These designs are characterized by the fact that the key input to the cipher depends on the input values. This implies that the key schedule has to be strong and that it needs to be executed for every encryption (or for every second encryption), which needs a substantial computational cost. An alternative approach is to fix one or more keys, and restrict the HF to use the block cipher for these keys only. The usage of fixed-key block ciphers, or alternatively permutations, causes benefit that one does not need to implement an entire block cipher but only a limited number of instantiations of it. In the five finalists of the SHA-3 competition, two of them (BLAKE, and Skein) are *block cipher-based design*, the other three (Grøstl, JH, and Keccak) are *permutation-based design*.

VI. SHA-3 HASH FUNCTION

NIST announced a public competition in 2007 to develop a new cryptographic hash algorithm, to choose "SHA-3". Five finalists of this SHA-3 competition were *BLAKE, Grøstl, JH, Keccak,* and *Skein*. Keccak has been declared as the winner of SHA-3 HF competition on 2nd October 2012 and hence Keccak [35] is now referred as SHA-3.

SHA-3 is a family of HFs that has been modeled on the sponge functions that use sponge construction, and avails all its advantages such as variable-length output, permutation-based structure and security. Sponge functions have been used to generalize HFs that produces message digest with arbitrary output lengths. Sponge construction is a repetitive construction to construct a function F. The function F accepts a variable-length input and produces arbitrary-length output based on a fixed-length permutation f. The permutation f operates on a fixed number of b-bits, which is referred as width. The sponge construction operates on a state of b = r + c bits, where r is the bit-rate and c is capacity. Higher value of r improves speed, and higher value of c improves its security level. The sponge construction proceeds in the following steps:

(i) First, all the state-bits are initialized to zero.

(ii) Next, the input message is padded so that its length is a multiple of r bits. This padded message is chopped into blocks of r-bits.

(iii) Absorbing phase: All r-bit input blocks are successively sent to sponge construction in two steps – the r bits of each block are XOR-ed with the first r bits of state, and then followed by an application of the permutation f.

(iv) Squeezing phase: When all the blocks have been processed in the absorbing phase, then the first r bits of the state are obtained as output block. If the user requests more output blocks of r-bits then each round of f will provide the required r-bit output blocks.

There are seven HFs in the SHA-3 family. They are denoted by SHA-3_f[b], where b $\in$ {25, 50, 100, 200, 400, 800, 1600} is the bit-width of the underlying permutation, which is also the width of the state in sponge construction. The state is organized as an array of 5 × 5 lanes, each of length w-bits, w ∈ {1, 2, 4, 8, 16, 32, 64}. The SHA-3[r, c, d] sponge function is obtained by using the sponge construction to SHA-3_f[r + c]. The pseudo-code of SHA-3_f is given below:

```
SHA-3_f[b](A)    {
 for i = 0 to (nr – 1)
        A = Round[b](A, RC[i])
 Return A
 }
Round[b](A, RC) {
    C[x] = A[x, 0] ⊕ A[x, 1] ⊕ A[x, 2] ⊕ A[x, 3] ⊕ A[x, 4] , ∀ x in 0 to 4
    D[x] = C[x-1] ⊕ ROT(C[x+1], 1), ∀ x in 0 to 4
    A[x, y] = A[x, y] ⊕ D[x], ∀ (x, y)  in (0 to 4, 0 to 4)
    B[y, 2x+3y] = ROT(A[x, y], r[x, y]),  ∀ (x, y)  in (0 to 4, 0 to 4)
    A[x, y] = B[x, y] ⊕ ((NOT B[x+1, y]) AND B[x+2, y),  ∀ (x, y) in (0 to 4, 0 to 4)
    A[0, 0] = A[0, 0] ⊕ RC
 Return A
 }
```

The pseudo-code of SHA-3[r, c, d] is given below:

```
SHA-3[r, c, d](M)          {
 /*  Initalize and Padding */
        S[x, y] = 0, ∀ (x, y) in (0 to 4, 0 to 4)
        P = M || 0x01 || byte(d) || byte(r/8) || 0x01 || 0x00 || … || 0x00
/* Absorb Phase */
                ∀ block Pi in P
                        S[x, y] = S[x, y] ⊕ P[x+5y], ∀ (x, y)  such that (x+5y) < (r/w)
                        S = SHA-3_f[r+c](S)
 /* Squeezing Phase */
        Z = empty string
        While output is being requested
                Z = Z || S[x, y], ∀ (x, y) such that (x+5y) < (r/w)
                S = SHA-3_f[r+c](S)
        Return Z
 }
```


VII. CONCLUSION

An effort has been made to understand the prominent design rationale behind various cryptographic HFs. The focus of discussion was on dedicated HFs and block cipher based HFs. Nonetheless there are other design philosophies to construct HFs. One such approach is to construct HFs that are provably secure in a sense that the problem of breaking it is related to some known computational problem considered very difficult. With the rising use of sensor devices in many security sensitive applications, few lightweight HFs have been proposed and many more to come in near future. This paper aims to serve in understanding the prominent design philosophies of HFs up to SHA-3.

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