SHAvite-3: Secure, Efficient, and Flexible Hash Function Proposal

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Outline

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SHAvite-3 (SHAvite-Shalosh)

- A SHA-3 candidate designed to be secure, efficient, and suitable for all environments.
- SHAvite-3_{256} is used for digests up to 256 bits, and SHAvite-3_{512} is used for digests of 257 to 512 bits.
- The compression functions are iterated using HAIFA.
- Supports salts (nonces/randomized hashing), variable digest length, while maintaining full security.
- The compression function is designed using known and understood components: Feistel structure, AES-round, and LFSRs.

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    - where each round function is composed of three AES rounds.
    - The message expansion combines both AES rounds and LFSRs.

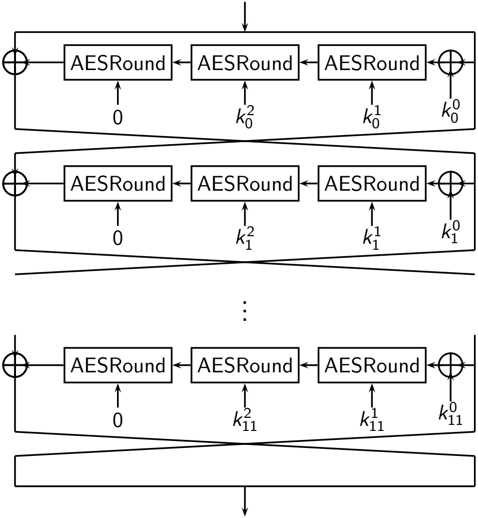
Advanced Encryption Standard

- AES was selected at the end of a similar process to the SHA-3 process by NIST in 2000.
- The selected algorithm, Rijndael, was selected from 15 submissions, of which 5 became known the AES finalists.
- Thoroughly analyzed in many cryptographic settings, and so far withstood all cryptanalytic attempts.
- Best known attack: $7/10$ rounds for 128-bit keys, $8/12$ rounds for 192-bit, and $8/14$ rounds for 256-bit keys (in the related-key model, the results are $7/9/10$ rounds, respectively).

E^{256} — the Underlying Block Cipher

- Accepts a 256-bit plaintext (chaining value).
- Accepts a key (message block, bit counter, and a salt) of 832 bits in total.
- The round function is composed of 3 rounds of AES (with an AddRoundKey operation before the first round, last AddRoundKey operation omitted).
- The message expansion generates 36 128-bit subkeys (12 rounds of E^{256}, each uses 3 round of AES).

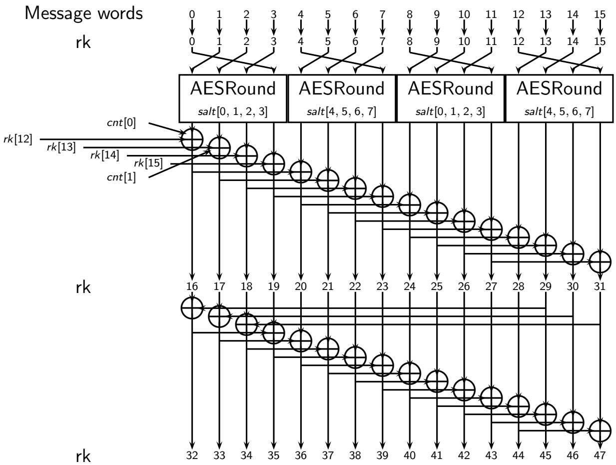
E^{256} — the Underlying Block Cipher (cont.)



The Message Expansion (E^{256} Key Schedule)

- Accepts 832-bit key: 512-bit block, 256-bit salt, 64-bit counter.
- Not all bits are treated equally.
- A combination of an LFSR (for diffusion), and AES rounds (for maximal "confusion" and nonlinearity).

The Message Expansion (E^{256} Key Schedule) (cont.)



The Message Expansion (E^{256} Key Schedule) (cont.)

- The key (message block, counter, and salt) is expanded into 144 32-bit words.
- The first 16 32-bit words are the message words.
- The following process is repeated four times:
  1. 16 words are generated by applying AES round (where the salt is XORed before the round) and some XORs.
  2. 16 words are generated using an LFSR operation.
- The counter words are mixed into 8 of the 144 words, to ensure that the counter affects the encryption process.

Final Touches — SHAvite-3_{256}

- In order to hash the message M into an m-bit digest, for $m \leq 256$, compute IV_m which is

$$h_0 = IV_m = C_{256}(MIV_{256}, m, 0, 0),$$

- Let $|M|$ be the length of M before padding, measured in bits. Pad the message M according to the padding scheme of HAIFA:
  1. Pad a single bit of 1.
  2. Pad as many 0 bits as needed such that the length of the padded message (with the 1 bit and the 0's) is congruent modulo 512 to 432.
  3. Pad $|M|$ encoded in 64 bits.
  4. Pad m encoded in 16 bits.
- Divide the padded message $pad(M)$ into 512-bit blocks, $pad(M) = M_1||M_2||\ldots||M_l$,

Final Touches — SHAvite-3$_{256}$

- Set $\#bits \leftarrow 0$.
- Set $h_0 \leftarrow IV_m$.
- For $i = 1, \ldots, \lfloor |M|/512 \rfloor$:
  - Set $\#bits \leftarrow \#bits + 512$.
  - Compute $h_i = C_{256}(h_{i-1}, M_i, \#bits, salt)$.
-
  - If $|M| = 0 \bmod 512$, compute $h_l = C_{256}(h_{l-1}, M_l, 0, salt)$, else
  - If $|M| \bmod 512 \le 431$, compute $h_l = C_{256}(h_{l-1}, M_l, |M|, salt)$, else
  - Compute $h_{l-1} = C_{256}(h_{l-2}, M_{l-1}, |M|, salt)$, and then compute $h_l = C_{256}(h_{l-1}, M_l, 0, salt)$.
- Output $truncate_m(h_l)$, where $truncate_m(x)$ outputs the m leftmost bits of x, i.e., $x[0]||x[1]|| \ldots$.

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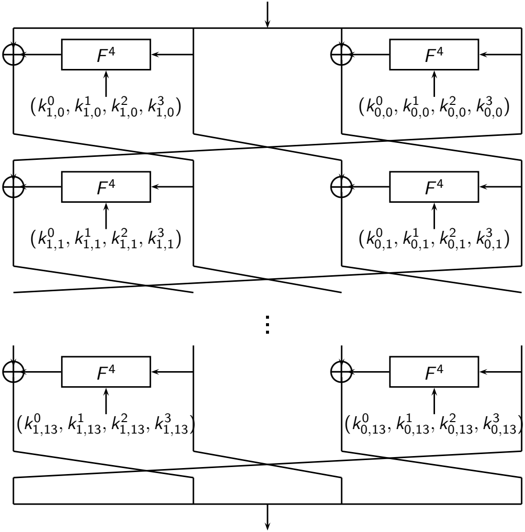
E^{512} — the Underlying Block Cipher

- Accepts a 512-bit plaintext (chaining value), and 1664-bit key (message block, counter, and salt).
- The block cipher has a Generalized Feistel structure.
- The plaintext is divided into four words of 128 bits each.
- In each of the 14 rounds, two words enter (separately) the round function.
- After XORing the output of the round function with the two remaining words, the words are rotated.

E^{512} — the Underlying Block Cipher (cont.)



How to Pronounce SHAvite-3

SHA-vite SHA-losh

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- shavit means “comet” in Hebrew
- A follower of Shiva, god of destruction, is called Shavite.
- shalosh means 3 in Hebrew.

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Is the Block Cipher E^{256} Secure?

- Of course!

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- The maximal expected differential probability of three round AES is at most 2^{-49}.
- Analysis reveals that there are no 2-round iterative characteristics, 3-round iterative characteristics of probability higher than 2^{-98}, ..., 9-round characteristics with probability higher than 2^{-294}.
- Similar results hold for linear cryptanalysis/boomerang attacks.
- Longest known impossible differential is of 5 rounds.
- Longest known SQUARE is of 3 rounds.
- Slide/Related-key attacks — counter protects against these.
- Algebraic attacks: equations reach full degree after 4 rounds.

Is the Block Cipher E^{512} Secure?

- The maximal expected differential probability of four round AES is at most 2^{-113}.
- Analysis reveals that there are no 2-round iterative characteristics, 3-round iterative characteristics of probability higher than 2^{-113}, ..., 9-round characteristics with probability higher than 2^{-678}.
- Similar results hold for linear cryptanalysis/boomerang attacks.
- Longest known impossible differential is of 9 rounds.
- Longest known SQUARE is of 3 rounds.
- Slide/Related-key attacks — counter protects against these.
- Algebraic attacks: equations reach full degree after 4 rounds.

Extending the Block Cipher Security Results

First Attempt

Computing the maximal expected differential probability of related-key attacks.

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First Attempt Fails (2)

The attacker controls the keys, he can make sure some differential transitions do happen.

Extending the Security Results — 2nd Attempt

What to do

Consider differentials through the message expansion.

- For a fixed salt, the message expansion can be treated as a block cipher.
- Compute the probability of differentials of it.
- Count how many active S-boxes there are in the message expansion.
- Assume that the attacker can use message modification to increase the probability of the differential (fixing 8 bits of the message/salt/counter can "eliminate" the cost of one active S-box).
- Results: No good differentials. The message expansion makes sure there are no high probability differentials through the message expansion.

A 3rd Attempt (TBD)

- Collision-producing differentials need to go both through the message expansion and the block cipher.
- Each probabilistic event in any of the two should "cost":
  1. Each active byte that enters the actual compression data-path costs at least 8 bits of control.
  2. Each transition of difference column through the MDS matrix in the message expansion — costs control according to the hamming weights.
  3. Each XOR in the message expansion that cancels a difference — costs control.
- Too large of a search space, but gives a very strong upper bound.

Theoretical Notions of Security

- HAIFA offers a prefix-free encoding:
  - If the compression function is a random oracle the hash function is indifferentiable from random oracle (up to the birthday bound).
  - Maintaining the salt secret leads to an efficient and secure PRF (MAC).
- If the compression function is a random oracle, the second preimage resistance can be proved to be $O(2^n)$.

Outline

Software Implementation

Hash Function	32-Bit	64-Bit
MD5	7.4	8.8
SHA-1	9.8	9.5
SHA-256	28.8	25.3
SHA-512	77.8	16.9
SHAvite-3_{256} (measured)	35.3	26.7
SHAvite-3_{256} (conjectured)	26.6	18.6
SHAvite-3_{256} (with AES inst.)	< 8	
SHAvite-3_{512} (measured)	55.0	38.2
SHAvite-3_{512} (conjectured)	35.3	28.4
SHAvite-3_{512} (with AES inst.)	< 12	

Expect 1–1.5 cycles per byte improvement if no salts are used.

Hardware Implementation (Estimations)

- We looked at four hardware optimizations for AES: FPGA/ASIC, fastest/smallest.

Digest Size	Technology	Size	Throughput
256	ASIC	10.3 Kgates	7.6 Mbps
		55.0 Kgates	604.4 Mbps
	FPGA	510 Slices	1.7 Mbps
		3585 Slices	872.3 Mbps
512	ASIC	18.5 Kgates	4.7 Mbps
		81 Kgates	907.7 Mbps
	FPGA	895 Slices	1.0 Mbps
		7170 Slices	1.12 Gbps

These are estimates based on AES implementations from 2005. Expect real figures to be much better.

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The SHAvite-3-MAC

- With HAIFA, one can define

$$\text{HAIFA-MAC}_k^C(M) = \text{HAIFA}_k^C(M).$$

- As HAIFA is PRF-preserving, then the above MAC is secure.

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- With HAIFA, one can define

$$\text{HAIFA-MAC}_k^C(M) = \text{HAIFA}_k^C(M).$$

- As HAIFA is PRF-preserving, then the above MAC is secure.
- SHAvite-3 is secure, and thus we define

$$\text{SHAvite-3-MAC}_k(M) = \text{SHAvite-3}_k(M).$$

- Of course, the user needs to keep the key secret!

Comparison with HMAC

- More efficient — most of the time, one compression function less than HMAC.
- More efficient — one less initialization than HMAC.
- Better foundations for the security analysis.

Number of compression function calls:

Construction	0 Bytes	1500 Bytes	n Bytes
SHA-256	1	24	$\lceil (n+8)/64 \rceil$
HMAC-SHA-256	2	25	$1 + \lceil (n+8)/64 \rceil$
SHAvite-3	1	24	$\lceil (n+10)/64 \rceil$
SHAvite-3-MAC	1	24	$\lceil (n+10)/64 \rceil$

Questions?

Thank you for your attention!

http://www.cs.technion.ac.il/∼orrd/SHAvite-3/