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

Orr Dunkelman

Département d'Informatique
École Normale Supérieure

France Telecom Chaire

Joint work with Eli Biham

# Outline

# Outline

# 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.

# SHAvite $3_{256}$

Based on the $C_{256}$ compression function,

# SHAvite $3_{256}$

Based on the $C_{256}$ compression function,

- which is a Davies-Meyer transformation of the block cipher $E^{256}$,

# SHAvite $3_{256}$

Based on the $C_{256}$ compression function,

- which is a Davies-Meyer transformation of the block cipher $E^{256}$,
  - which is a 12-round Feistel block cipher,

# SHAvite $3_{256}$

Based on the $C_{256}$ compression function,

- which is a Davies-Meyer transformation of the block cipher $E^{256}$,
  - which is a 12-round Feistel block cipher,
    - where each round function is composed of three AES rounds.
    - The message expansion combines both AES rounds and LFSRs.

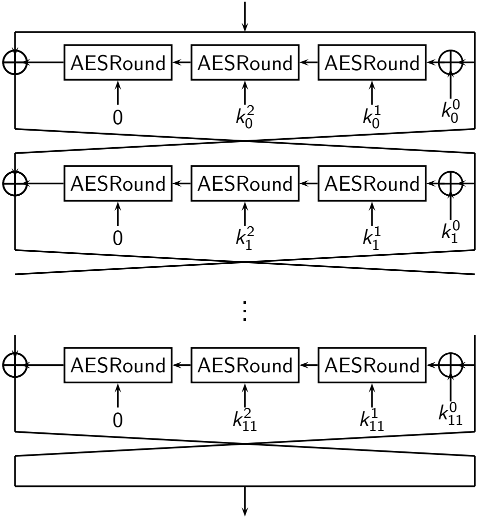
# Advanced Encryption Standard

- 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).

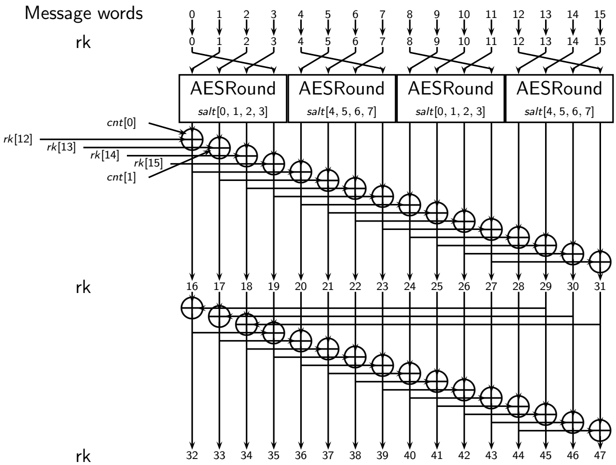
# $E^{256}$ the Underlying Block Cipher (cont.)



# 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 $|M| \bmod 512 \leq 431$, 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., $x[0]||x[1]||\ldots$.

# SHAvite $3_{512}$

Based on the $C_{512}$ compression function,

# SHAvite $3_{512}$

Based on the $C_{512}$ compression function,

- which is a Davies-Meyer transformation of the block cipher $E^{512}$,

# SHAvite $3_{512}$

Based on the $C_{512}$ compression function,

- which is a Davies-Meyer transformation of the block cipher $E^{512}$,
  - which is a 14-round Generalized Feistel block cipher,

# SHAvite $3_{512}$

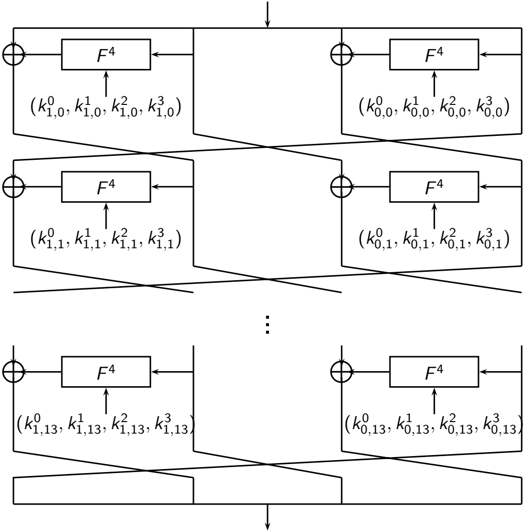
Based on the $C_{512}$ compression function,

- which is a Davies-Meyer transformation of the block cipher $E^{512}$,
  - which is a 14-round Generalized Feistel block cipher,
    - where each round function is composed of four AES rounds.

# $E^{512}$ 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

# What Does it Mean?

- SHA + vite — fast secure hash algorithm.

# What Does it Mean?

- SHA + vite — fast secure hash algorithm.
- shavit means “comet” in Hebrew

# What Does it Mean?

- SHA + vite — fast secure hash algorithm.
- shavit means “comet” in Hebrew
- A follower of Shiva, god of destruction, is called Shavite.

# What Does it Mean?

- SHA + vite — fast secure hash algorithm.
- shavit means “comet” in Hebrew
- A follower of Shiva, god of destruction, is called Shavite.
- shalosh means 3 in Hebrew.

# Outline

# Is the Block Cipher $E^{256}$ Secure?

- Of course!

# Is the Block Cipher $E^{256}$ Secure?

- Of course!
- 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.

# Extending the Block Cipher Security Results

## First Attempt

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

## First Attempt Fails

No good methodology for that.

# Extending the Block Cipher Security Results

## First Attempt

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

## First Attempt Fails

No good methodology for that.

## 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 |
|---|---|
| MD5 | 7.4 |
| SHA-1 | 9.8 |
| SHA-256 | 28.8 |
| SHA-512 | 77.8 |
| SHAvite-$3_{256}$ (measured) | 35.3 |
| SHAvite-$3_{256}$ (conjectured) | 26.6 |
| SHAvite-$3_{256}$ (with AES inst.) | |
| SHAvite-$3_{512}$ (measured) | 55.0 |
| SHAvite-$3_{512}$ (conjectured) | 35.3 |
| SHAvite-$3_{512}$ (with AES inst.) | |

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 |
| | | | 604.4 Mbps |
| | | 510 Slices | 1.7 Mbps |
| | | | 872.3 Mbps |
| 512 | ASIC | 18.5 Kgates | 4.7 Mbps |
| | | | 907.7 Mbps |
| | | 895 Slices | 1.0 Mbps |
| | | | 1.12 Gbps |

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

# Outline

# 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.

# 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.
- 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/**