

# STRIBOB: Authenticated Encryption from GOST R 34.11-2012 LPS Permutation (*Extended Abstract*)

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**Abstract.** Authenticated encryption algorithms protect both the confidentiality and integrity of messages in a single processing pass. In this note we show how to utilize the  $L \circ P \circ S$  transform of the Russian GOST R 34.11-2012 standard hash “Streebog” to build an efficient, lightweight algorithm for Authenticated Encryption with Associated Data (AEAD) via the Sponge construction and BLNK padding. The proposed algorithm “StriBob” has attractive security properties, is faster than the Streebog hash alone, twice as fast as the GOST 28147-89 encryption algorithm, and requires only a modest amount of running-time memory. StriBob is a Round 1 candidate in the CAESAR competition.

**Keywords:** StriBob, Authenticated Encryption, GOST R 34.11-2012, Streebog, Sponge Construction, DuplexWrap, BLNK Padding, CAESAR.

## 1 Introduction

Since January 1, 2013, the Russian Federation has mandated the use of new GOST R 34.11-2012 hash algorithm in digital signatures [12, 15]. This hash (Figure 1) was apparently designed in response to cryptographic weaknesses reported in the previous hash standard GOST R 34.11-94 [14, 22]. The 2012 standard, dubbed STREEBOG, has superficial similarities to the old 1994 standard but also features clearly AES-inspired design elements [10, 16, 24].

In contrast to the Russian approach, the U.S. NIST selected a novel Sponge-based design, KECCAK, as the basis of future SHA-3 hash function standard [4, 9]. Sponge hashes diverge from more traditional Davies-Mayer [21] (SHA) and derived HAIFA [7] (STREEBOG) constructions in that they are based on a single keyless permutation  $\pi$  rather on a keyed permutation which can be seen as a special-purpose block cipher.

Furthermore, Sponge permutations can be used to achieve Authenticated Encryption in straightforward manner (see Figure 5) [3, 5]. Here both the confidentiality and integrity of

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a message can be guaranteed with a single processing pass, without the use of a separate encryption algorithm such as GOST 28147-89 [13] and a hash-based Message Authentication Code such as HMAC-Streebog [25]. This has clear advantages for performance and implementation footprint, which are especially useful in limited-resource applications. Even full-featured secure communications suites can be constructed from a single permutation [27].

In this note we show how to construct a modern lightweight AEAD algorithm from the core of the GOST R 34.11-2012 STREEBOG hash. Our proposal, “STRIBOB” is faster than the STREEBOG hash alone, has good security arguments, and runs on low-resource platforms. The proposal is a first round candidate in the U.S. NIST - funded CAESAR Competition [26, 28].

## 2 Structure of GOST R 34.11-2012

STREEBOG produces either 256-bit or 512-bit hash from a bit string of arbitrary size using the Merkle-Damgård [11, 23] iterative method (without randomization). Figure 1 gives an overview of the hashing process.

Padded message  $M$  is processed in 512-bit blocks  $M = m_0 | m_1 | \dots | m_n$  by a compression function  $h' = g_N(h, m_i)$ . The chaining variable  $h$  also has 512 bits and  $N$  denotes the index bit offset of the input block. After the last message block, there are finalization steps involving two invocations of the compression function, first on the total bit length of input, and then on checksum  $\epsilon$ , which is computed over all input blocks mod  $2^{512}$ .

### 2.1 STREEBOG Compression Function $g_N(h, m)$

The compression function  $h' = g_N(h, m)$  takes in a chaining variable  $h$ , message block  $m$ , a position index variable  $N$ , and produces a new chaining value  $h'$ . The compression function is built from a keyless 512-bit nonlinear permutation LPS and 512-bit vector XOR operations. The compression function has 12 rounds and a performs a total of 25 invocations of LPS :

$$\begin{aligned}
 [K_1, X_1] &= [ \text{LPS}(h \oplus N), m ] \\
 [K_{i+1}, X_{i+1}] &= [ \text{LPS}(K_i \oplus C_i), \text{LPS}(X_i \oplus K_i) ] \text{ for } 1 \leq i \leq 12 \\
 g_N(h, m) &= K_{13} \oplus X_{13} \oplus h \oplus m.
 \end{aligned}$$

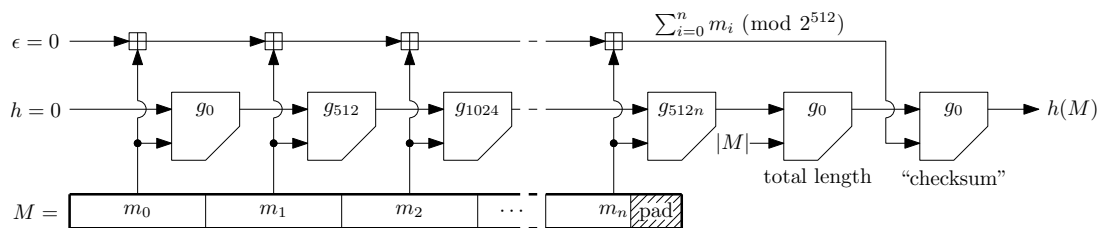


Figure 1: Operation of STREEBOG with 512-bit output. For 256-bit hashes, the initial  $h$  value is changed to  $0 \times 010101 \dots 01$  and the output  $h(M)$  is truncated to 256 bits.

Figure 2 shows the structure of  $g$ . We can view it as a two-track substitution-permutation network where input value  $h \oplus N$  and a set of 12 round constants  $C_i$  is used to key (via  $K_i$ ) another substitution-permutation network operating on  $h$ . The outputs of the two tracks are finally XOR'ed together with original values of  $h$  and  $m$ . We note that  $h$  together with offset  $N$  uniquely defines all  $K_i$  subkey values for each invocation of  $g$ .

Computation of  $g_N(h, m)$  requires at least  $3 \times 512$  bits or 192 bytes of temporary storage, which may be preventive for ultra light-weight applications. Furthermore the  $\text{mod } 2^{512}$  summation for  $\epsilon$  must be performed concurrently to the compression function.

## 2.2 The LPS Transform

The LPS transform (Figure 3) is a 512-bit keyless permutation, and forms the cryptographic core of STREEBOG and STRIBOB. It depicted in Figure 3. and consists of three stages. We abbreviate the composite function  $L(P(S(x))) = (L \circ P \circ S)(x)$  as LPS. The components are:

$S$  Nonlinear substitution. A  $8 \times 8$  - bit S-Box is first applied to each of the 64 bytes of data.

$P$  Permutation. A byte transpose where the  $8 \times 8$  byte matrix is reflected over its main diagonal (rows written as columns or columns written as rows).

$L$  Linear transform. Finally the eight 64-bit words are individually subjected to a vector-matrix multiplication with a  $64 \times 64$  - bit matrix in  $\mathbb{F}_2$

LPS is closely related to the WhirlPool [2], which also uses 512-bit permutations. If we use the original AES-style notation,  $S$  is equivalent to `SubBytes`,  $P$  corresponds to `ShiftColumns`, and  $L$  to `MixRows`.

## 2.3 Security of LPS

STREEBOG gets all of its nonlinearity from 8-bit S-box  $S$ , which seems to have been designed to offer resistance against classical methods of cryptanalysis. Its differential bound [8] is  $P = \frac{8}{256}$  and best linear approximation [20] holds with  $P = \frac{28}{128}$ .

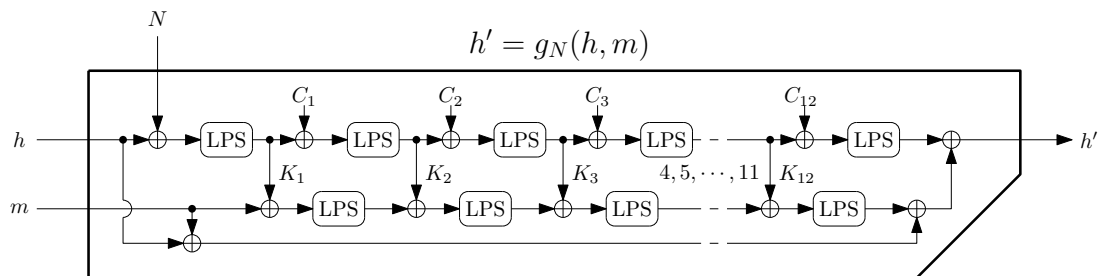


Figure 2: STREEBOG compression function. All data paths, inputs, and outputs are 512-bit vectors. Here the  $\oplus$  symbol denotes the XOR operation between two 512-bit vectors.

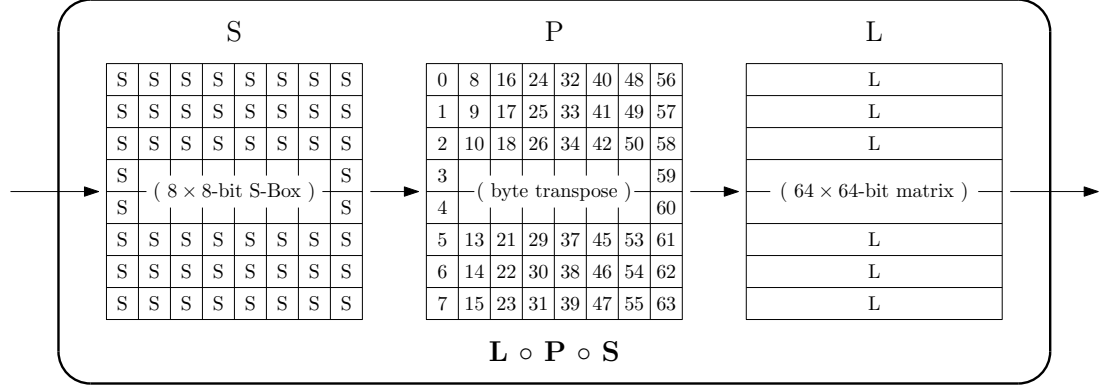


Figure 3: LPS consists of a byte substitution layer  $S$ , byte transpose  $P$ , and a linear layer  $L$ .  $L$  can be alternatively expressed as a  $8 \times 8$  - byte matrix in  $\mathbb{GF}(2^8)$ .

The linear transform  $L$  is not randomly constructed even though it is expressed without explanation as a  $64 \times 64$  binary matrix in [15].  $L$  in fact has a byte-oriented structure as an MDS matrix with  $\mathbb{F}_{2^8}$  arithmetic in a similar fashion as AES, even though this is not mentioned in the standard specification [16, 24].  $S$  and  $L$  are effective in mixing the bits of the eight 64-bit rows.  $P$  swaps rows and columns and after two rounds each input bit affects each output bit of the 512-bit state. LPS has similar per-round avalanche to AES and similar resistance to Square attacks [17].

We note that structurally similar Whirlpool has been attacked with Rebound Distinguishers [18, 19]. However, these attacks can only barely reach 10 rounds of Whirlpool, and not 12 rounds used in the present construction.

### 3 Authenticated Encryption Algorithm STRIBOB

In a sponge function only a single keyless permutation  $\pi$  is required. We utilize the LPS transform and twelve round constants  $C_i$  of GOST R 34.11-2012 in our new design. For some vector of twelve 512-bit subkeys  $C_i$  we define a 512-bit permutation  $\pi_C(X_1) = X_{13}$  with iteration

$$x_{i+1} = \text{LPS}(X_i \oplus C_i) \text{ for } 1 \leq i \leq 12.$$

Figure 4 shows the operation of the  $\pi$  function. We assume that  $\pi_C$  and  $\pi_K$  are equally strong since both  $C$  and  $K$  consist of an essentially random set of subkeys. There is a straightforward

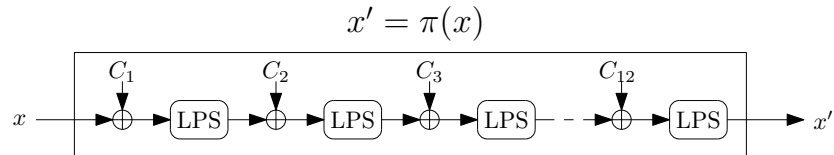


Figure 4: The 512-bit permutation  $\pi$  used by STRIBOB.

intuitive security relation between  $\pi_K$  and a single instance of the full compression function  $g$ . We note that for the very first message block  $m$ , the subkeys  $K_i$  are always constant as they depend on the initial constant  $h = 0$  alone. We can therefore write for first block:

$$h' = g_0(0, m) = \pi_K(m) \oplus m.$$

The output truncation after the last invocation of  $g$  of STREEBOG-256 indicates that collision resistance is expected of half of the output as well, which is exactly what we need in a  $r = 256$  Sponge mode (Section 3.1).

After careful analysis, we conjecture that the  $\pi_C$  permutation offers *no structural distinguishers* that are not based on some trivial property such as a priori knowledge of output value of  $\pi_C(x)$  for some particular  $x$ . We use  $\pi_C$  alone in our final construction.

### 3.1 Sponge Mode and Security Parameters

The sponge function  $\pi$  is operated in a MULTIPLEX - like mode in order to achieve maximum flexibility [27]. This way STRIBOB can be used for plain hashing, PRNG generation and in two-party protocols in addition to Authenticated Encryption with Associated Data (AEAD).

**Theorem 1.** *The DUPLEXWRAP and MULTIPLEX authenticated encryption modes satisfy the following privacy and authentication security bounds:*

$$\begin{aligned} \text{Adv}_{\text{sbob}}^{\text{priv}}(\mathcal{A}) &< \frac{D + T}{2^k} + \frac{D^2 + 4DT}{2^{c+1}} \\ \text{Adv}_{\text{sbob}}^{\text{auth}}(\mathcal{A}) &< \frac{D + T}{2^k} + \frac{D^2 + 4DT}{2^{c+1}} + \frac{D}{2^t}. \end{aligned}$$

against any single adversary  $\mathcal{A}$  if  $K \xleftarrow{\$} \{0, 1\}^k$ , tags of  $t$  bits are used,  $\pi$  is a randomly chosen permutation,  $D$  is the data complexity (number of queries to target), and  $T$  is the offline attack time complexity.

*Proof.* See Theorem 4 of [6] and related work [1, 3]. □

Since  $b = 512$ , we choose a Sponge rate of  $r = 256$  bits, which leaves capacity  $c = b - r = 256$ . We choose key size  $k = 192$  and limit  $N < 2^{60}$ . As our capacity is  $c \approx 254$  (couple of effective capacity bits are lost due to domain separation [27]), a 192-bit security level is comfortably reached.

### 3.2 Padding Example

STRIBOB uses BLNK padding, which is a variant of [27]. The “payload rate bytes” are the first 32 bytes of the state and byte 32 is used as padding and domain indicator. Each element is padded with a  $0 \times 01$  byte and zeros to full  $r$ -bit block length so that  $\pi$  is called between different domains. If the domain data length is an exact multiple of  $r$ , BLNK\_END is set at the domain indicator byte. The domain flags used in the CAESAR implementation are:

| Flag name | Value | Padding bit or Domain identifier      |
|-----------|-------|---------------------------------------|
| BLNK_END  | 0x01  | Padding marker bit                    |
| BLNK_FIN  | 0x02  | Data element final block marker bit   |
| BLNK_KEY  | 0x10  | Secret key (in)                       |
| BLNK_NPUB | 0x20  | Public sequence number (in)           |
| BLNK_NSEC | 0x30  | Secret sequence number (in / out)     |
| BLNK_AAD  | 0x40  | Authenticated Associated Data (in)    |
| BLNK_MSG  | 0x50  | Confidential Message Payload (in/out) |
| BLNK_MAC  | 0x60  | Message Authentication Code (out)     |

**Example.** To illustrate the operation with CAESAR parameters, we use the 192-bit secret key "192-bit Secret Key value" and public nonce "Nonces Used Once" (16 bytes) to authenticate Associated Data "AAD Test Vector Exact Block 32 B" (32 bytes) and to encrypt plaintext "This is a Test Vector for sribob192r1" (38 bytes).

S1 STRIBOB uses an all-zero initial state. The first input to  $\pi$  is the padded secret key value:  
3139322D62697420536563726574204B65792076616C7565**01**0000000000000000**12**00...00

S2 Nonce is XORed into the state before second  $\pi$ :  
4E6F6E6365732055736564204F6E6365**01**000000000000000000000000000000**22**00...00

S3 Associated data length equals rate (32 bytes) so padding is in domain separation byte:  
414144205465737420566563746F7220457861637420426C6F636B2033322042**43**00...00

*Info.* The state before encryption is:

39E876FD1FA6DB05FC681ECAC803A2A48B6CB30E6B47D9FEC94FE1E8CB3E02D4  
734803FB16F36A5653DEFEB7012C28C949172CAEC1274E19A7C5132AFE58EAC

S4 Padded plaintext blocks for  $\pi$  invocations 4 and 5:  
546869732069732061205465737420566563746F7220666F722073747269626F**50**00...00  
623139327231**01**00**52**00...00

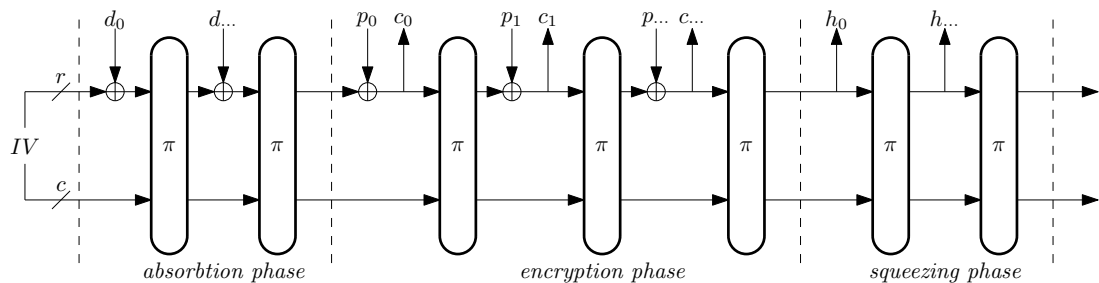


Figure 5: A simplified view of a Sponge-based AEAD. First the padded Secret Key, Nonce, and Authenticated Associated Data - all represented by  $d_u$  words - are “absorbed” or mixed into the Sponge state. The  $\pi$  permutation is then used to also encrypt data  $p_i$  into ciphertext  $c_i$  (or vice versa) and finally to “squeeze” out a Message Authentication Code  $h_i$ .

Corresponding ciphertext bytes:

```
6D801F8E3FCFA8259D484AAFBB7782F2EE0FC7611967BF91BB6F929CB95760BB  
A808DE292F8B
```

S5 Authentication tag extraction, 128 bits. No need for state after this with CAESAR.

```
165BD9D62B3C7B7D6DC423446BE76082
```

## 4 Implementation and Performance Notes

Since the new construct requires 12 invocations of LPS per 256 bits processed in comparison to 25 invocations per 512 bits with STREEBOG, we see that the new construct is faster. Furthermore, the operational memory requirement is shrunk to approximately 25 % of the original.

**Low-resource software platforms.** For a software implementation on a low-resource 8 or 16-bit CPUs and SoCs (e.g. RFID, Smart Card, Sensor, Ubiquitous / IoT category systems) it is advantageous to realize the linear layer  $L$  as a matrix multiplication in  $\mathbb{F}_{2^8}$ . Multiplication in a small finite field can be implemented via discrete logarithm and exponentiation tables:  $AB = \exp(\log A + \log B)$ . Note that STREEBOG and therefore STRIBOB uses a special bit-inverted representation for field elements [16].

One can combine the S-Box lookup and discrete logarithm table into a single  $8 \times 8$  - bit lookup table  $\log(S(x))$ . The  $8 \times 8$  matrix over  $\mathbb{F}_{2^8}$   $M$  (representing  $L$ ) can be stored in log form. Required addition  $x + y \pmod{2^8 - 1}$  can be implemented by adding carry bit  $\lfloor \frac{x+y}{2^8} \rfloor$  of addition  $x + y \pmod{2^8}$  to the 8-bit sum itself – set  $\exp(255) = \exp(0)$  in this case.

As the transpose  $P$  can be coded into the loops (switching the column and row indexes), the implementation of LPS requires a total of  $256 + 256 + 8 \times 8 = 576$  bytes for storage. Unfortunately  $C_i$  round constants still require  $12 \times 64 = 768$  bytes. One may consider a variant that uses a fast pseudorandom generator such as some Fibonacci-based sequence or linear congruential generator instead of a truly random  $C$  to further compress the implementation.

**Medium- to high-resource software platforms.** A software implementation on system with a medium- or high-performance CPUs (e.g. server, desktop, laptop, or tablet category systems) can utilize  $8 \times 8 \times 64$  - bit lookup tables that combine  $S$  and  $L$ , requiring a total of 16 kB and 768 B for round constants. The compression function code itself is very compact.

Results of wall-clock throughput measurements on a typical desktop system: <sup>1</sup>

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<sup>1</sup>Measurements were made on a single core of an Intel Core i7 860 @ 2.80 GHz system running Ubuntu Linux 13.10 (amd64) with gcc 4.8.1. The AES, SHA, GOST 28147-89 and R 34.11-1994 timings with were measured with Ubuntu default OpenSSL (1.0.1e). A. Degtyarev's implementation (0.11) was used for the GOST 34.11-2012 benchmark. The STRIBOB reference implementation is by author.

| Algorithm             | Throughput               |
|-----------------------|--------------------------|
| AES - 128 / 192 / 256 | 109.2 / 90.9 / 77.9 MB/s |
| SHA - 256 / 512       | 212.7 / 328.3 MB/s       |
| GOST 28147-89         | 53.3 MB/s                |
| GOST R 34.11-1994     | 20.8 MB/s                |
| GOST R 34.11-2012     | 109.4 MB/s               |
| STRIBOB               | 115.7 MB/s               |

**Hardware.** Use of AES instruction set significantly boosts AES performance, but so would similar hardware optimizations for STREEBOG and STRIBOB. Since the rate of STRIBOB is twice that of AES and there are 12 rounds (indicating roughly equivalent critical path), we can expect STRIBOB hardware implementations to be significantly faster than AES.

## 5 Conclusions

We propose STRIBOB, an Authenticated Encryption with Associated Data (AEAD) algorithm based on the GOST R 34.11-2012 hash standard. The new algorithm is faster than the hash standard alone, twice as fast as the GOST 27147-89 encryption algorithm, and is competitive against AES. STRIBOB is a first round candidate in the CAESAR competition of the U.S. National Institute of Standardization and Technology [26, 28].

A strong security relation exists between STRIBOB's  $\pi$  function to the compression function  $g$  of GOST R 34.11-2012, giving us a significant level of confidence in its security. Furthermore the underlying Sponge mode of operation is provably secure. We feel that our proposal offers a viable alternative to present GOST standards.

## References

- [1] ANDREEVA, E., MENNINK, B., AND PRENEEL, B. Security reductions of the second round SHA-3 candidates. IACR ePrint 2010/381, [eprint.iacr.org/2010/381](http://eprint.iacr.org/2010/381), July 2010.
- [2] BARRETO, P. S. L. M., AND RIJMEN, V. The Whirlpool hashing function. NESSIE Algorithm Specification [www.larc.usp.br/~pbarreto/WhirlpoolPage.html](http://www.larc.usp.br/~pbarreto/WhirlpoolPage.html), 2000, Revised May 2003.
- [3] BERTONI, G., DAEMEN, J., PEETERS, M., AND ASSCHE, G. V. Duplexing the sponge: Single-pass authenticated encryption and other applications. In *SAC 2011 (2011)*, A. Miri and S. Vaudenay, Eds., vol. 7118 of *LNCS*, Springer, pp. 320–337.
- [4] BERTONI, G., DAEMEN, J., PEETERS, M., AND ASSCHE, G. V. The Keccak reference, version 3.0. NIST SHA3 Submission Document, January 2011.



- [5] BERTONI, G., DAEMEN, J., PEETERS, M., AND ASSCHE, G. V. Permutation-based encryption, authentication and authenticated encryption. In *DIAC 2012* (2012). [keccak.noekeon.org/KeccakDIAC2012.pdf](http://keccak.noekeon.org/KeccakDIAC2012.pdf).
- [6] BERTONI, G., DAEMEN, J., PEETERS, M., ASSCHE, G. V., AND KEER, R. V. CAESAR submission: Keyak v1. [competitions.cr.ypt.to/round1/keyakv1.pdf](http://competitions.cr.ypt.to/round1/keyakv1.pdf), March 2014.
- [7] BIHAM, E., AND DUNKELMAN, O. A framework for iterative hash functions - HAIFA. IACR ePrint 2007/278, [eprint.iacr.org/2007/278](http://eprint.iacr.org/2007/278), July 2007.
- [8] BIHAM, E., AND SHAMIR, A. *Differential Cryptanalysis of the Data Encryption Standard*. Springer, 1993.
- [9] CHANG, S., R. PERLNER, BURR, W. E., TURAN, M. S., KELSEY, J. M., PAUL, S., AND BASSHAM, L. E. Third-round report of the SHA-3 cryptographic hash algorithm competition. Tech. Rep. NISTIR 7896, National Institute of Standards and Technology, November 2012.
- [10] DAEMEN, J., AND RIJMEN, V. *The Design of Rijndael: AES - the Advanced Encryption Standard*. Springer, 2002.
- [11] DAMGÅRD, I. A design principle for hash functions. In *CRYPTO '89* (1989), G. Brassard, Ed., vol. 435 of *LNCS*, Springer, pp. 416–427.
- [12] DOLMATOV, V., AND DEGTYAREV, A. GOST R 34.11-2012: Hash Function. IETF RFC 6986, August 2013.
- [13] GOST. Cryptographic protection for data processing system. GOST 28147-89, 1989. (In Russian).
- [14] GOST. Cryptographic protection of information, hash function. GOST R 34.11-94, 1994. (In Russian).
- [15] GOST. Information technology. cryptographic protection of information, hash function. GOST R 34.11-2012, 2012. (In Russian).
- [16] KAZYMYROV, O., AND KAZYMYROVA, V. Algebraic aspects of the Russian hash standard GOST R 34.11-2012. In *CTCrypt '13, June 23-24, 2013, Ekaterinburg, Russia* (2013). IACR ePrint 2013/556 [eprint.iacr.org/2013/556](http://eprint.iacr.org/2013/556).
- [17] KNUDSEN, L., AND WAGNER, D. Integral cryptanalysis (extended abstract). In *FSE 2002* (2002), J. Daemen and V. Rijmen, Eds., vol. 2365 of *LNCS*, Springer, pp. 112–127.
- [18] LAMBERGER, M., MENDEL, F., RECHBERGER, C., RIJMEN, V., AND SCHLÄFFER, M. Rebound distinguishers: Results on the full whirlpool compression function. In *ASIACRYPT '09* (2009), M. Matsui, Ed., vol. 5912 of *LNCS*, Springer, pp. 126–143.

- [19] LAMBERGER, M., MENDEL, F., SCHLÄFFER, M., RECHBERGER, C., AND RIJMEN, V. The rebound attack and subspace distinguishers: Application to Whirlpool. *J. Cryptology* (2013). DOI: 10.1007/s00145-013-9166-5.
- [20] MATSUI, M. Linear cryptanalysis method for DES cipher. In *EUROCRYPT '93* (1994), T. Hellesest, Ed., vol. 765 of *LNCS*, Springer, pp. 386–397.
- [21] MATYAS, S., MEYER, C., AND OSSAS, J. Generating strong one-way functions with cryptographic algorithm. *IBM Technical Disclosure Bulletin*, 27 (1985), 5658–5659.
- [22] MENDEL, F., PRAMSTALLER, N., RECHBERGER, C., KONTAK, M., AND SZMIDT, J. Cryptanalysis of the GOST hash function. In *CRYPTO 2008* (2008), D. Wagner, Ed., vol. 5157 of *LNCS*, Springer, pp. 162–128.
- [23] MERKLE, R. *Secrecy, Authentication, and public key systems*. PhD thesis, Stanford University, 1979.
- [24] NIST. Advanced Encryption Standard (AES). FIPS 197, 2001.
- [25] NIST. The keyed-hash message authentication code (HMAC). FIPS 198-1, July 2008.
- [26] NIST, AND BERNSTEIN, D. CAESAR call for submissions. `competitions.cryp.to/caesar-call.html`, January 2014.
- [27] SAARINEN, M.-J. O. Beyond modes: Building a secure record protocol from a cryptographic sponge permutation. In *CT-RSA 2014* (2014), J. Benaloh, Ed., vol. 8366 of *LNCS*, Springer, pp. 270–285.
- [28] SAARINEN, M.-J. O. The STRIBOBr1 authenticated encryption algorithm. CAESAR, 1st Round `www.stribob.com`, March 2014.