PRIMATEs v1

Submission to the CAESAR Competition

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Notation

Set $\mathbf{K} := \{0,1\}^k$, $\mathbf{T} := \{0,1\}^\tau$, $\mathbf{N} := \{0,1\}^\nu$, $\mathbf{R} := \{0,1\}^r$, $\mathbf{C} := \{0,1\}^c$, and $\mathbf{C}^{\frac{1}{2}} := \{0,1\}^{c/2}$. Given the state $X \in \mathbf{R} \times \mathbf{C}$, $X_r \in \mathbf{R}$ denotes its rate part and $X_c \in \mathbf{C}$ its capacity part. We write $0^r \in \mathbf{R}$ for a shorthand of $00\cdots0 \in \mathbf{R}$.

The bitwise XOR operation of the bit strings a_1 and a_2 is denoted by $a_1 \oplus a_2$, and $a_1 \| a_2$ and $a_1 a_2$ both denote the concatenation of the bit strings a_1 and a_2.

An element of $\mathbf{R}$ is called a block. Let $\mathbf{R}^*$ denote the set of strings whose length is a multiple of r, at most $2^{c/2}$ blocks. Similarly, let $\mathbf{R}^+$ denote the set of strings whose length is a positive multiple of r, at most $2^{c/2}$ blocks. Given a plaintext (a message) $M \in \{0,1\}^*$, we divide it into blocks and write $M[1]M[2]\cdots M[w] \leftarrow M$, where each $M[i]$ for $i < w$ is a block and $M[w]$ is a string of length less than or equal to a block. By $\lfloor M \rfloor_n$ we denote the n most significant bits of M (the n leftmost bits). When we write $M\|10^*$, we mean that M is padded with a 1-bit and then zeros until the length of the resulting string is a multiple of r.

Authenticated encryption with associated data (AEAD).

An authenticated encryption algorithm with associated data consists of a key generation $\mathcal{K}$, an encryption $\mathcal{E}$ and decryption $\mathcal{D}$ algorithms. The encryption algorithm $\mathcal{E}$ takes as input a key $K \in \mathbf{K}$, associated data $A \in \mathbf{R}^*$, and a message $M \in \mathbf{R}^+$, and returns a ciphertext $C \in \mathbf{R}^+$ and a tag $T \in \mathbf{T}$, as $(C,T) \leftarrow \mathcal{E}_K(A,M)$. The decryption algorithm $\mathcal{D}$ takes as input a key $K \in \mathbf{K}$, associated data $A \in \mathbf{R}^*$, a ciphertext $C \in \mathbf{R}^+$, and a tag $T \in \mathbf{T}$, and returns either a message $M \in \mathbf{R}^+$ or the reject symbol $\perp$, as $M/\perp \leftarrow \mathcal{D}_K(A,C,T)$. The two functionalities $\mathcal{E}$ and $\mathcal{D}$ are sound, in the sense that whenever we encrypt a message as $(C,T) \leftarrow \mathcal{E}_K(A,M)$, we always get the message back, not $\perp$, via the decryption process $M \leftarrow \mathcal{D}_K(A,C,T)$.

Nonce-based AEAD.

Whenever the AEAD scheme takes an additional nonce $N \in \mathbf{N}$ argument both in encryption and decryption we speak of a nonce-based AEAD. The encryption algorithm is then defined as $(C,T) \leftarrow \mathcal{E}_K(N,A,M)$ and the decryption algorithm as $M/\perp \leftarrow \mathcal{D}_K(N,A,C,T)$ with the soundness condition $M \leftarrow \mathcal{D}_K(N,A,\mathcal{E}_K(N,A,M))$ satisfied.

Nonces.

A nonce $N \in \mathbf{N}$ is an unique non-repeating value, i.e. a counter. The nonces in this work are public values and we alternatively refer to them as public message numbers. We do not use secret message numbers. How the sender and receiver generate and synchronize nonces is left implicit as long as the uniqueness condition is satisfied.

1 Parameters

The authenticated encryption family PRIMATEs is defined by the following two parameters:

1. The security level $s \in \{10, 15\}$ bytes;
2. The mode of operation $Scheme \in \{\mathsf{GIBBON}, \mathsf{HANUMAN}, \mathsf{APE}\}$.

The security level determines: the state size b, where the state consists of a rate part with r and a capacity part with c bits; and the permutation family PRIMATE-s. The PRIMATE-s : $\{0,1\}^b \rightarrow \{0,1\}^b$ family consists of four permutations p_1, p_2 , p_3 and p_4. On the other hand, each mode of operation determines the key length k, the tag length τ, the nonce length ν and the subset of permutations from PRIMATE-s.

1.1 Recommended Parameters

We recommend a security level s of either 10 or 15 bytes for PRIMATEs family with:

	$s = 10$ bytes (80 bits)	$s = 15$ bytes (120 bits)
b (state size)	25 bytes (200 bits)	35 bytes (280 bits)
c (capacity size)	20 bytes (160 bits)	30 bytes (240 bits)
r (rate size)	5 bytes (40 bits)	5 bytes (40 bits)
permutations	PRIMATEs-80	PRIMATEs-120

Below we recommend the respective values for the three modes where *Scheme*-s indicates the mode under $s = 10$ and $s = 15$ bytes respectively. For GIBBON and HANUMAN we have identical values as compared to APE as shown:

	GIBBON-s	HANUMAN-s	APE-s
k (key size)	s	s	$2s$
τ (tag size)	s	s	$2s$
ν (nonce size)	s	s	s
PRIMATE	p_1, p_2, p_3	p_1, p_4	p_1

GIBBON and HANUMAN have a mandatory nonce input while APE supports an optional nonce input. The optional nonce input for APE is of length less or equal to s bytes. The length of plaintext and associated data processing is discussed in Sect. 2. Our recommendation for lightweight authenticated encryption is HANUMAN. For lightweight applications where speed is critical we recommend GIBBON and for lightweight environments where additional security requirements are needed or security is critical we recommend APE. The primary recommended security level is $s = 15$ (120 bit security), whereas we recommend $s = 10$ (80 bit security) for extremely lightweight applications.

Algorithm 1: $\mathcal{E}_K(N, A, M)$

Input: $K \in \mathbf{C}^{\frac{1}{2}}$, $N \in \mathbf{C}^{\frac{1}{2}}$, $A \in \{0,1\}^*$, $M \in \{0,1\}^*$
Output: $C \in \{0,1\}^*$, $T \in \mathbf{C}^{\frac{1}{2}}$

$V \leftarrow p_1(0^r \| N \| K)$
$V \leftarrow V_r \parallel (0^{\frac{c}{2}} \parallel K) \oplus V_c$
if $A \neq \varnothing$ **then**
  $V \leftarrow p_2(V)$
  $A[1]A[2] \cdots A[u] \leftarrow A$
  $A[u] \leftarrow A[u] \| 10^*$
  for $i = 1$ **to** $u - 1$ **do**
    $V \leftarrow p_2(A[i] \oplus V_r \parallel V_c)$
  end
  $V \leftarrow A[u] \oplus V_r \parallel V_c$
end
$M[1]M[2] \cdots M[w] \leftarrow M$
$M[w] \leftarrow M[w] \| 10^*$
$V \leftarrow p_3(V)$
for $i = 1$ **to** w **do**
  $C[i] \leftarrow M[i] \oplus V_r$
  $V \leftarrow p_3(C[i] \parallel V_c)$
end
$V \leftarrow p_1(V_r \parallel (0^{\frac{c}{2}} \parallel K) \oplus V_c)$
$C \leftarrow C[1]C[2] \cdots C[w]$
$T \leftarrow \lfloor V_c \rfloor_{\frac{c}{2}} \oplus K$
return (C, T)

Algorithm 2: $\mathcal{D}_K(N, A, C, T)$

Input: $K \in \mathbf{C}^{\frac{1}{2}}$, $N \in \mathbf{C}^{\frac{1}{2}}$, $A \in \{0,1\}^*$, $C \in \{0,1\}^*$, $T \in \mathbf{C}^{\frac{1}{2}}$
Output: $M \in \{0,1\}^*$ or $\perp$

$V \leftarrow p_1(0^r \| N \| K)$
$V \leftarrow V_r \parallel (0^{\frac{c}{2}} \parallel K) \oplus V_c$
if $A \neq \varnothing$ **then**
  $V \leftarrow p_2(V)$
  $A[1]A[2] \cdots A[u] \leftarrow A$
  $A[u] \leftarrow A[u] \| 10^*$
  for $i = 1$ **to** $u - 1$ **do**
    $V \leftarrow p_2(A[i] \oplus V_r \parallel V_c)$
  end
  $V \leftarrow A[u] \oplus V_r \parallel V_c$
end
$C[1]C[2] \cdots C[w] \leftarrow C$
$V \leftarrow p_3(V)$
for $i = 1$ **to** w **do**
  $M[i] \leftarrow C[i] \oplus V_r$
  $V \leftarrow p_3(C[i] \parallel V_c)$
end
$V \leftarrow p_1(V_r \parallel (0^{\frac{c}{2}} \parallel K) \oplus V_c)$
$M \parallel 10^* \leftarrow M[1]M[2] \cdots M[w]$
$T' \leftarrow \lfloor V_c \rfloor_{\frac{c}{2}} \oplus K$
return $T = T'$? $M : \perp$

Figure 1: The GIBBON encryption $\mathcal{E}_K(N, A, M)$ and decryption $\mathcal{D}_K(N, A, C, T)$ algorithms and without spill over.

2 Specification of PRIMATEs

2.1 GIBBON

The GIBBON algorithm is described in Fig. 1. GIBBON supports variable length associated data and plaintexts. As discussed in Sect. 3 we recommend the associated data and the plaintexts to be of size at most $2^{c/2}$ bits. For GIBBON-80 this is approximately 2^{77} bytes and for GIBBON-120 this is 2^{117} bytes. The algorithm uses three independent permutations, p_1, p_2 and p_3. The key K is used for: 1. a part of the capacity of the initial state; 2. after the initialization (first p_1 iteration); 3. before the finalization (last p_1 iteration); and 4. after the tag truncation. GIBBON works exactly the same in the case of integral and fractional data. The padded input message (resp. associated data) is generated by applying 10^* padding to the original message (resp. associated data). In the case when $|M[w]| = r$ with M of integral message blocks instead of occupying an extra message block for this, the '10^*'-padding spills over into the capacity. This can be seen as an XOR of $10 \cdots 00$ into the capacity part of the state. We recall the reader of the fact that the $\oplus 1$ in the beginning of the function is a shorthand notation for $\oplus 00 \cdots 01$, and hence, these values do not cancel each other out. The encryption procedure of GIBBON is illustrated in Fig. 6.

Algorithm 3: $\mathcal{E}_K(N, A, M)$

Input: $K \in \mathbf{C}^{\frac{1}{2}}$, $N \in \mathbf{C}^{\frac{1}{2}}$, $A \in \{0,1\}^*$, $M \in \{0,1\}^*$
Output: $C \in \{0,1\}^*$, $T \in \mathbf{C}^{\frac{1}{2}}$

$V \leftarrow p_1(0^r \| N \| K)$
if $A \neq \varnothing$ **then**
  $A[1]A[2]\cdots A[u] \leftarrow A$
  $A[u] \leftarrow A[u] \| 10^*$
  for $i = 1$ **to** $u - 1$ **do**
    $V \leftarrow p_4(A[i] \oplus V_r \parallel V_c)$
  end
  $V \leftarrow p_1(A[u] \oplus V_r \parallel V_c)$
end
$M[1]M[2]\cdots M[w] \leftarrow M$
$M[w] \leftarrow M[w] \| 10^*$
for $i = 1$ **to** w **do**
  $C[i] \leftarrow M[i] \oplus V_r$
  $V \leftarrow p_1(C[i] \parallel V_c)$
end
$C \leftarrow C[1]C[2]\cdots C[w]$
$T \leftarrow \lfloor V_c \rfloor_{\frac{c}{2}} \oplus K$
return (C, T)

Algorithm 4: $\mathcal{D}_K(N, A, C, T)$

Input: $K \in \mathbf{C}^{\frac{1}{2}}$, $N \in \mathbf{C}^{\frac{1}{2}}$, $A \in \{0,1\}^*$, $C \in \{0,1\}^*$, $T \in \mathbf{C}^{\frac{1}{2}}$
Output: $M \in \{0,1\}^*$ or $\perp$

$V \leftarrow p_1(0^r \| N \| K)$
if $A \neq \varnothing$ **then**
  $A[1]A[2]\cdots A[u] \leftarrow A$
  $A[u] \leftarrow A[u] \| 10^*$
  for $i = 1$ **to** $u - 1$ **do**
    $V \leftarrow p_4(A[i] \oplus V_r \parallel V_c)$
  end
  $V \leftarrow p_1(A[u] \oplus V_r \parallel V_c)$
end
$C[1]C[2]\cdots C[w] \leftarrow C$
for $i = 1$ **to** w **do**
  $M[i] \leftarrow C[i] \oplus V_r$
  $V \leftarrow p_1(C[i] \parallel V_c)$
end
$M \parallel 10^* \leftarrow M[1]M[2]\cdots M[w]$
$T' \leftarrow \lfloor V_c \rfloor_{\frac{c}{2}} \oplus K$
return $T = T'$? $M : \perp$

Figure 2: The HANUMAN encryption $\mathcal{E}_K(N, A, M)$ and decryption $\mathcal{D}_K(N, A, C, T)$ algorithms and without spill over.

2.2 HANUMAN

The HANUMAN algorithm is described in Fig. 2. HANUMAN supports variable length associated data and plaintexts. As discussed in Sect. 3 we recommend the associated data and the plaintexts to be of size at most $2^{c/2}$ bits. For HANUMAN-80 this is approximately 2^{77} bytes and for HANUMAN-120 this is 2^{117} bytes. The algorithm uses two independent permutations, p_1 and p_4. The key is used twice for: 1. a part of the capacity of the initial state; and 2. after the tag truncation. The padded input message (resp. associated data) is generated by applying 10^* padding to the message (resp. associated data). In the case when $|M[w]| = r$ with M of integral message blocks instead of occupying an extra message block for this, the '10*'-padding spills over into the capacity. This can be seen as an XOR of $10 \cdots 00$ into the capacity part of the state. The encryption procedure of HANUMAN is illustrated in Fig. 7.

2.3 APE

The APE algorithm is described in Fig. 3. We treat the nonce as the first part of the associated data whenever present. This is not explicitly reflected in our APE figures and algorithm where in the presence of nonce $A \leftarrow N \| A$. APE supports variable length associated data and plaintexts. As discussed in Sect. 3 we recommend the associated data and the plaintexts to be of size at most $2^{c/2}$ bits. For APE-80 this is approximately 2^{77} bytes and for APE-120 this is 2^{117} bytes. The algorithm uses the permutation p_1 together with its inverse p_1^{-1} for decryption. The key is used twice for: 1. part of the capacity of the initial state; 2. after the tag generation. The fractional plaintext data cases are dealt with differently in APE (Fig. 9) as compared to the integral data

Algorithm 5: $\mathcal{E}_K(A, M)$

Input: $K \in \mathbf{C}$, $A \in \mathbf{R}^*$, $M \in \mathbf{R}^+$
Output: $C \in \mathbf{R}^+$, $T \in \mathbf{C}$

$V \leftarrow 0^r \parallel K$
if $A \neq \varnothing$ **then**
  $A[1]A[2]\cdots A[u] \leftarrow A$
  $A[u] \leftarrow A[u]\|10^*$
  for $i = 1$ **to** u **do**
    $V \leftarrow p_1\big(A[i] \oplus V_r \parallel V_c\big)$
  end
end
$V \leftarrow V \oplus (0^{b-1} \parallel 1)$
$M[1]M[2]\cdots M[w] \leftarrow M$
$l \leftarrow |M[w]|$
$M[w] \leftarrow M[w]\|10^*$
for $i = 1$ **to** w **do**
  $V \leftarrow p_1\big(M[i] \oplus V_r \parallel V_c\big)$
  $C[i] \leftarrow V_r$
end
$C \leftarrow C[1]C[2]\cdots C[w-2]$
$C \leftarrow C \parallel \lfloor C[w-1] \rfloor_l$
$C \leftarrow C \parallel C[w]$
$T \leftarrow V_c \oplus K$
return (C, T)

Algorithm 6: $\mathcal{D}_K(A, C, T)$

Input: $K \in \mathbf{C}$, $A \in \mathbf{R}^*$, $C \in \mathbf{R}^+$, $T \in \mathbf{C}$
Output: $M \in \mathbf{R}^+$ or $\perp$

$IV \leftarrow 0^r \parallel K$ **if** $A = \varnothing$ **then**
  $A[1]A[2]\cdots A[u] \leftarrow A$
  for $i = 1$ **to** u **do**
    $IV \leftarrow p\big(A[i] \oplus IV_r \parallel IV_c\big)$
  end
end
$C[1]C[2]\cdots C[w] \leftarrow C$
$l \leftarrow |C[w]|$
$C[w] \leftarrow \lceil C[w-1] \rceil_{r-l} \parallel C[w]$
$C[w-1] \leftarrow \lfloor C[w-1] \rfloor_l$
$C[0] \leftarrow IV_r$
$V \leftarrow p^{-1}\big(C[w] \parallel K \oplus T\big)$
$M[w] \leftarrow \lfloor V_r \rfloor_l \oplus C[w-1]$
$V \leftarrow V \oplus M[w]10^*\|0^c$
for $i = w - 1$ **to** 1 **do**
  $V \leftarrow p^{-1}\big(C[i] \parallel V_c\big)$
  $M[i] \leftarrow C[i-1] \oplus V_r$
end
$M \leftarrow M[1]M[2]\cdots M[w]$
if $IV_c = V_c \oplus (0^{c-1} \parallel 1)$ **then**
  return M
else
  return $\perp$
end

Figure 3: The APE encryption $\mathcal{E}_K(A, M)$ and decryption $\mathcal{D}_K(A, C, T)$ algorithms where $w \geq 2$ and without spill over.

(Fig. 8) as elaborated below:

Consider a message M and denote its last block by $M[w]$, where $|M[w]| = |M| \bmod r$. We distinguish among three cases:

- $|M[w]| \leq r - 1$ and $w = 1$. The procedure can be seen left in Fig. 9. Note that the corresponding ciphertext will be of r bits. This is required for decryption to be possible;
- $|M[w]| \leq r - 1$ and $w \geq 2$. The procedure is depicted right in Fig. 9. Note that the ciphertext $C[w-1]$ is of size equal to $M[w]$. The reason we opt for this design property is the following: despite $M[w]$ being smaller than r bits, we require its corresponding ciphertext to be r bits for decryption to be possible. As a consequence ciphertext $C[w-1]$ is of size equal to $M[w]$;
- $|M[w]| = r$. In this special case where M consists of integral message blocks, we nevertheless need a padding. However, instead of occupying an extra message block for this, the '10*'-padding spills over into the capacity. This can be seen as an XOR of $10\cdots00$ into the capacity part of the state.

The adjustments have no influence on the decryption algorithm $\mathcal{D}$, except if $|M| \leq r$ for which a slightly more elaborate function is needed. Note that the spilling of the padding in case $|M[w]| = r$ causes security to degrade by half a bit: intuitively, APE is left with a capacity of $c' = c - 1$ bits. We have opted for this degradation over an efficiency loss due to an additional round.

2.4 PRIMATE Permutation

One round permutation which is called PRIMATE has two different variants, PRIMATE-80 and PRIMATE-120, and is inspired by [8]. They are designed according to the wide trail strategy [11] and their structure is very similar to the Rijndael block cipher [12]. They operate on a 5×8 and a 7×8 state of 5-bit elements, respectively. The first row of the state (5 bytes) is the rate of the state whereas the rest of the state is the capacity for both versions. The state and each individual element possess big-endian encoding. PRIMATE update the internal state by means of the sequence of transformations

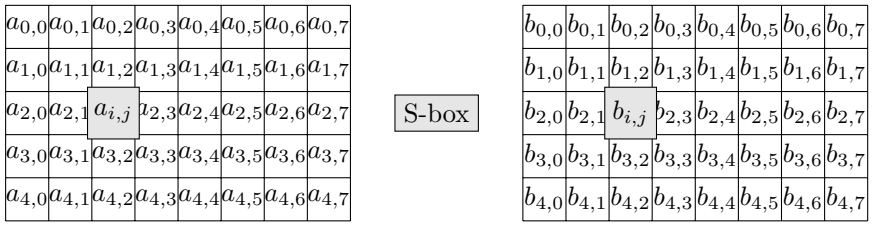
$$\mathsf{CA} \circ \mathsf{MC} \circ \mathsf{SR} \circ \mathsf{SB} \ .$$

The four permutations p_1, p_2, p_3 and p_4 of PRIMATE are defined by means of different round constants, which will be generated by a 5-bit LFSR, and different number of rounds as shown in the following table.

	p_1	p_2	p_3	p_4
Number of rounds	12	6	6	12
Initial value of the LFSR	1	24	30	24

2.4.1 SubBytes (SB).

The SubBytes step is the only non-linear transformation of PRIMATE. It is a permutation consisting of an S-box applied to each element of the state (shown below for PRIMATE-80).



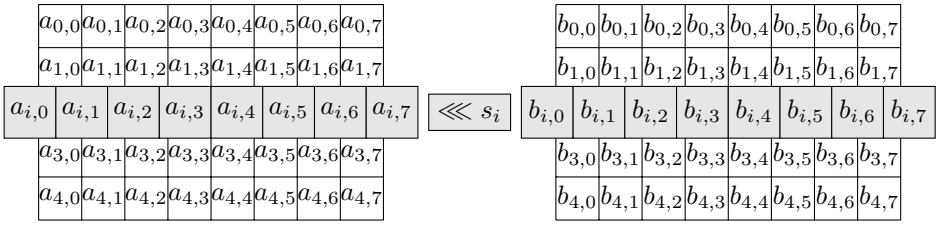
This permutation is an almost bent (AB) permutation as defined in Table 1. The differential and linear probability for this S-box is 2^{-4}, which provides optimum security against linear and differential cryptanalysis [10]. The specific permutation is chosen from the AB permutation set such that the area of both plain and shared implementation provide a good tradeoff.

Table 1: 5-bit S-box.

x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
S(x)	1	0	25	26	17	29	21	27	20	5	4	23	14	18	2	28
x	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
S(x)	15	8	6	3	13	7	24	16	30	9	31	10	22	12	11	19

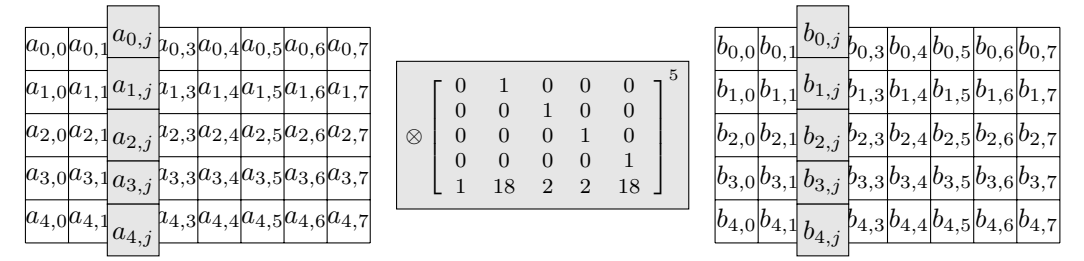
2.4.2 ShiftRows (SR).

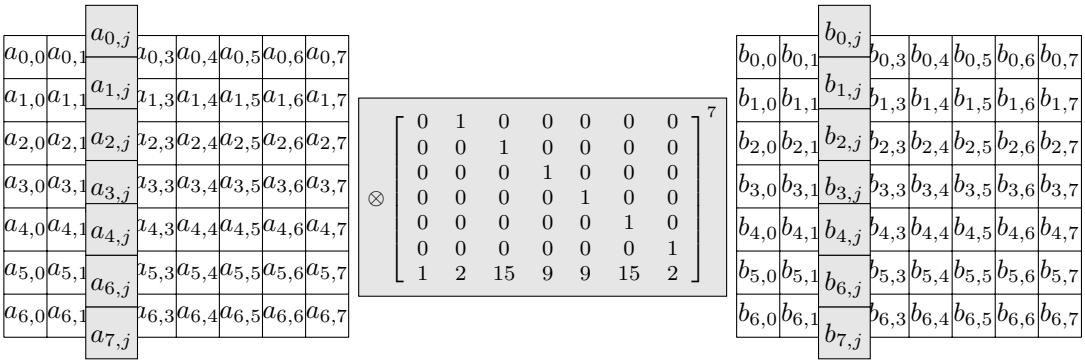
The ShiftRows step is a byte transposition that cyclically shifts the rows of the state over different offsets. Row i is shifted left by $s_i = \{0, 1, 2, 4, 7\}$ positions for PRIMATE-80 (shown below) and by $s_i = \{0, 1, 2, 3, 4, 5, 7\}$ positions for PRIMATE-120. Since ShiftRows is only wiring in hardware, its overall cost is negligible.



2.4.3 MixColumns (MC).

[h] The MixColumns step is operating on the state column by column. To be more precise, it is a left-multiplication by a 5×5 (resp. 7×7) matrix over $\mathbb{F}_{2^5}$ with primitive polynomial $x^5 + x^2 + 1$. The main design goal of the MixColumns transformation is to follow the wide trail strategy and that it can be implemented efficiently. Therefore, we use a recursive approach [3, 21] to generate an MDS matrix that has a maximum (6 and 8 respectively) *branch number* (the smallest nonzero sum of active inputs and outputs of each column).

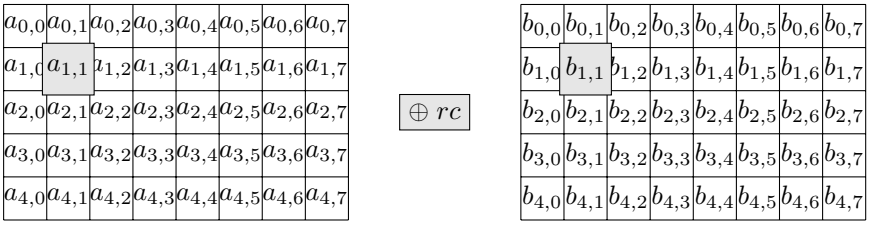




2.4.4 ConstantAddition (CA).

In this transformation the state is modified by combining the second element of the second row with a predefined constant by a bitwise XOR operation. The purpose of

adding round constants is to make each round different and to break the symmetry of the other transformations. Furthermore, it provides a natural opportunity to make the parts for processing associated data and message different from each other. A 5-bit Fibonacci LFSR with taps in the first (i.e. the most significant bit) and fourth bit is used to generate the round constants rc. Therefore, the hardware implementation of ConstantAddition is in fact very cheap.



3 Security Claims

The designers claim that the following levels of security, expressed in bits:

	PRIMATEs-s	PRIMATEs-80	PRIMATEs-120
confidentiality of M	$c/2$	80	120
integrity of M	$c/2$	80	120
integrity of A	$c/2$	80	120
integrity of N	$c/2$	80	120

The claimed security levels correspond to the birthday bound security on the capacity of PRIMATEs-80 and PRIMATEs-120, respectively (see also Sect. 4). The security of GIBBON and HANUMAN depends on the nonce, while for APE the nonce is optional and its security results do not rely on uniqueness of the nonce, hence APE is fully secure against nonce misuse. Technically, this implies that all security results of APE only hold up to common prefix: under the same associated data and nonce, two messages with the same prefix (in r-bit blocks) have the same corresponding ciphertext blocks. We refer to [1] for the technicalities.

The designers claim that APE offers certain additional security benefits. Most importantly, it is secure under the release of unverified plaintext (RUP). This means that APE is still secure if the decryption algorithm is implemented so as to output the decrypted plaintext before successful verification. This scenario arises for example when devices have insufficient memory to store the entire plaintext [13], or when the decrypted plaintext needs to be processed early due to real-time requirements [9, 20]. We refer to [2] for more information on the security under the release of unverified plaintext.

	APE-s	APE-80	APE-120
confidentiality under RUP	$c/2$	80	120
integrity under RUP	$c/2$	80	120

4 Security Analysis

PRIMATEs are indistinguishable from an ideal authenticated encryption scheme up to about $2^{c/2}$ primitive calls; implying that PRIMATEs achieve a security level of $c/2$ bits. This result is proven in the ideal model, where the underlying primitive permutations PRIMATE are assumed to be perfectly random permutations.

4.1 GIBBON

The structure of GIBBON is similar to the MonkeyWrap [5] construction. The scheme generates a stream of a ciphertext and a tag depending on the public message number and the message. Security is achieved as long as the public message number is used only once with the same key. It is also assumed that if the verification step of the algorithm reveals that the ciphertext has been tampered with, then the algorithm returns no information beyond the verification failure. In particular, no plaintext blocks are returned. A state recovery for GIBBON does not lead to trivial key recovery and also does not lead to trivial universal forgery attacks due to the key additions.

4.2 HANUMAN

HANUMAN follows a design similar to that of SpongeWrap [7]. The scheme constructs a keystream which depends on the public message number and message, with which the message is then XORed to produce the ciphertext. As long as the public message number remains unique for each encryption, confidentiality will be achieved since the keystream will be close to uniformly random, assuming the PRIMATE permutations are close to ideal. Note that if a public message number is repeated, then the XOR of the first message blocks can be determined from the XOR of the ciphertexts. Associated data is processed via an independent permutation in order to prevent forgery attacks in which a message is first encrypted as associated data, and then again as plaintext. Attacks can be found if a collision occurs in the capacity, yet this is expected to happen only after roughly $2^{c/2}$ total queries to the underlying permutations. It is also assumed that if the verification step of the algorithm reveals that the ciphertext has been tampered with, then the algorithm returns no information beyond the verification failure.

4.3 APE

The security results for APE can be found in [1]. APE is the first and only misuse resistant permutation based authenticated encryption. The security results for APE apply *both* in the cases when nonces are unique values (full security) and also when nonces are reused (full security up to common prefix, the maximum attainable for single pass schemes). As a mode of operation for a permutation, APE is secure in the ideal model. Considering a distinguisher whose queries are of total length at most m blocks, APE is proven secure in the ideal model up to a bound of $\frac{m^2}{2^{r+c}} + \frac{2m(m+1)}{2^c}$ (for integral data blocks) and $\frac{m^2}{2^{r+c}} + \frac{2m(m+1)}{2^{c-1}}$ (for fractional data blocks) [1].

We can also look at APE as a mode of operation for a block cipher where we replace the operation $(0^r \| K) \oplus p_1 \oplus (0^r \| K)$ with that of a block cipher (see [1] for a more

detailed explanation). This version of APE is secure in the standard model, meaning if the underlying block cipher is a secure strong pseudorandom permutation (SPRP), then APE with a block cipher is secure as well. The bounds from the ideal model also hold in the standard model, up to twice the SPRP security of E_K. We interpret this result to mean that if $(0^r \| K) \oplus p_1 \oplus (0^r \| K)$ with p_1 instantiated by a PRIMATE is a secure SPRP, then APE with a PRIMATE is secure as well.

In the same vein, a formal security proof for APE in the case unverified plaintext is released is given in [2]. In more detail, in this publication a model is introduced to analyze security of authenticated encryption schemes in case of unverified release of plaintext, and APE is proven to meet the security notion with no security loss (compared to the above-mentioned bounds).

Taking $c = 20$ bytes (160 bits), $r = 5$ bytes (40 bits) for APE-80 or $c = 35$ bytes (280 bits), $r = 5$ bytes (40 bits) for APE-120, the security levels approach the ones claimed in Sect. 3, but not exactly. For instance, for APE-80 we claim 80-bit security, while the proven security bound (fractional case) satisfies $\frac{m^2}{2^{r+c}} + \frac{2m(m+1)}{2^c} = \frac{1}{2}$ for $m \approx 2^{79.5}$. Similarly, for the fractional case the security bound equals $\frac{1}{2}$ for $m \approx 2^{79}$. The difference is due to the security model and proof techniques applied.

4.4 PRIMATE

This section shows some known properties of the non-linear permutation PRIMATE.

4.4.1 Differential and Linear Trails

PRIMATE has diffusion properties according to the wide trail design strategy and hence provides good bounds against differential an linear cryptanalysis. We use the technique in [18] to calculate the differential and linear hull probabilities of PRIMATE. Since the five bit S-box of PRIMATE is an almost bent (AB) permutation, the differential and linear probability for this S-box is 2^{-4}, which provides optimum security against linear and differential cryptanalysis [10].

For PRIMATE-80, the branch number of the linear diffusion is 6, differential/linear probability for any two round can be calculated as $16 \cdot (2^{-4})^6 = 2^{-20}$, therefore the differential/linear probability for any four-round is $(2^{-20})^5 = 2^{-100}$. For PRIMATE-120, the branch number of the linear diffusion is 8, therefore the differential/linear probability for any four-round PRIMATE-120 is bounded by $(16 \cdot (2^{-4})^8)^7 = 2^{-196}$. Moreover, for a refined bound of PRIMATE, we refer to [16].

This means that the probability of any twelve-round differential (and linear) of PRIMATE-80 respectively PRIMATE-120 differential, assuming independent rounds, is 2^{-100} respectively 2^{-196}. Therefore, there is only a very small chance that a standard differential or linear attack would lead to a successful attack on PRIMATE.

4.4.2 Collision Producing Trails

Assume we have a certain difference for the message that may result in a zero difference in the state with a high probability after the difference has been injected. Then this can be used in a forgery attack on PRIMATE. Note that a linear trail of a similar shape might be used for a distinguish attack on the keystream of PRIMATE.

However, the simple design of PRIMATE allows to prove also good bounds against this kind of differential and linear attacks. To obtain better bounds for PRIMATE we adopt the mixed-integer linear programming (MILP) technique proposed in [17] to find the minimum number of differentially and linearly active S-boxes of the target ciphers. Using this technique and the optimizer CPLEX [15], we obtained differential and linear bounds of PRIMATE-80 and PRIMATE-120. The results are listed in Table 2.

Table 2: Bounds for collision producing trails in the message processing of PRIMATE.

Round		1	2	3	4	5	6	7	8	9	10	11	12
Active S-box	PRIMATE-80	-	-	-	-	-	84	84	84	84	84	84	84
	PRIMATE-120	-	-	-	-	-	127	127	127	127	127	127	127

For 5 and less rounds of both PRIMATE-80 and PRIMATE-120, there does not exist such trails and for 6 and more rounds only trails with at least 84 respectively 127 active S-boxes can produce a collision. This results in an upper bound for the differential and linear probability of 2^{-336} and 2^{-508}, respectively.

We want to note that these bounds depends on the choice of the injection layer. Therefore, we have tested several different injection layers and choose the one that resulted in the best bound in the design of PRIMATE.

4.4.3 Impossible Differential Cryptanalysis

In this part, we will discuss the application of impossible differential cryptanalysis to PRIMATE. Since the branch number of the PRIMATE-80 and PRIMATE-120 is 6 respectively 8, the number of nonzero element differences in each column before and after the MixColumns operation can never be smaller than these values. Based on this property, we constructed impossible differentials for 6 and 5 rounds of PRIMATE-80 and PRIMATE-120 respectively, which are depicted in Figure 4 and Figure 5 respectively.

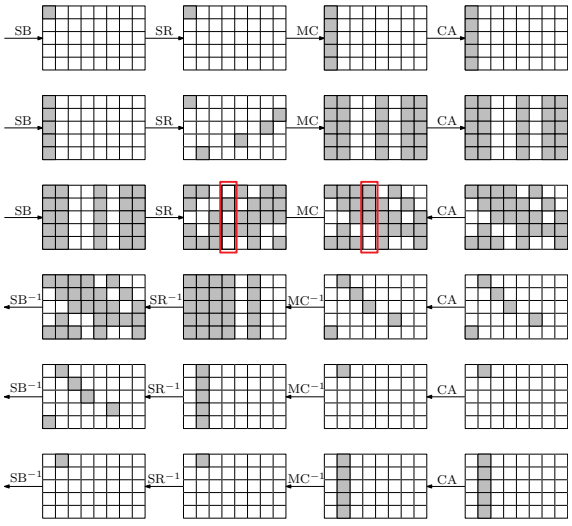


Figure 4: Impossible Differential for 6 rounds of PRIMATE-80.

Taking PRIMATE-80 as an example, assume we start from the first round, if the difference is at position (0,0) of the state, then after 2.5 rounds PRIMATE encryption, the

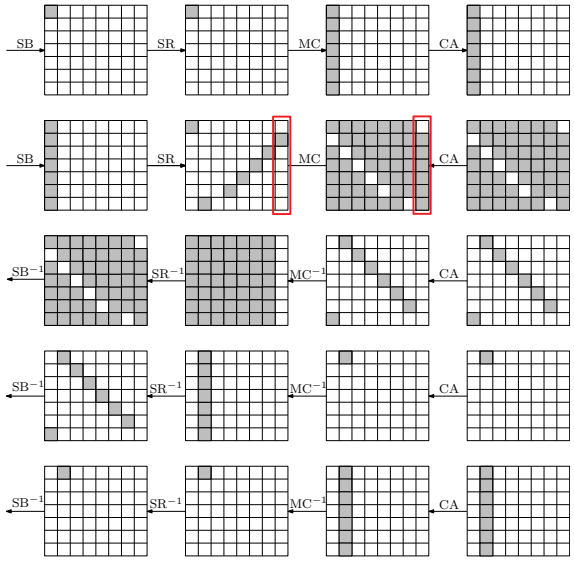


Figure 5: Impossible Differential for 5 rounds of PRIMATE-120.

vector in column 3 before the MixColumns operation in the third round is $(0, *, 0, *, 0)^T$, whereas "*" denotes a nonzero difference. Given one of the 31 differences in column 1 at the bottom of the distinguisher that result in single difference at position (0,1) before MixColumns decrypt 3.5 rounds of PRIMATE, the output vector in column 3 after MixColumns operation in the third round is $(*, *, *, 0, 0)^T$. These columns are depicted in red in Figure 4. This means that $M(0, *, 0, *, 0)^T \rightarrow (*, *, *, 0, 0)^T$, the number of nonzero differences before and after MixColumns is 5, there is an contradiction. Therefore, a 6-round impossible differential has been constructed for PRIMATE-80. Similarly we can obtain a 5-round impossible differential for PRIMATE-120.

Therefore, for PRIMATE-80 and PRIMATE-120, it should be difficult to recover the key using these impossible differentials even if the internal state (right after the state initialization) has been recovered.

5 Features of PRIMATEs

Permutation-based AE for lightweight applications.

The PRIMATEs authenticated encryption family is designed for *lightweight* cryptographic applications. The domain of lightweight cryptography focuses on cryptographic algorithms for extremely constrained hardware devices, where the goal is to implement an efficient cryptographic algorithm using only a very limited number of gates.

At the the core of the PRIMATEs family are the PRIMATE permutations. Since the introduction of the Sponge functions methodology [6], permutation-based cryptographic algorithms are rapidly gaining acceptance due to their efficient implementation properties. Very recently, the sponge-based hash function Keccak [4] was selected as the winner of the NIST SHA-3 competition.

The PRIMATE permutation is a substitution-permutation network using a 5-bit S-box with ideal linear and differential properties, and a recursive MDS matrix, which

leads to a very small and efficient implementation in hardware.

Resistance against hardware side-channel attacks.

When resistance against hardware side-channel attacks is required, the permutation has been designed to offer an efficient threshold implementation to counter first-order DPA attacks, based on glitch-free secret-sharing-based masking.

Online.

All PRIMATEs offer online encryption, thereby allowing the algorithm to output ciphertext blocks without the knowledge of plaintext lengths or the next plaintext blocks. PRIMATEs are inherently sequential. For lightweight applications, this is not an issue: the design goal is to use a very small number of gates, therefore parallelism would not be of any benefit.

Comparison to AES-GCM.

- GCM-AES is a block cipher based design. In comparison, PRIMATEs are smaller than similar AEAD algorithms based on a block cipher (such as AES), as our implementation does not contain a key schedule, uses smaller S-boxes (5 bits instead of 8 bits), and uses a more compact, recursive MDS matrix implementation.
- Unlike in AES-GCM, PRIMATEs handle all nonce lengths in the same way, thereby reducing the complexity of the implementation and simplifying the security analysis.
- The PRIMATEs modes avoid all the attacks that are inherent to AEAD modes based on a universal hash function [14, 19], such as AES-GCM.

Key and Nonce Agility.

Changing the key or nonce has very little overhead for all modes in the PRIMATEs family, requiring only one permutation function call and one XOR for GIBBON, and requires only one permutation function call for HANUMAN. In the case of APE, changing the key also requires one permutation function call. The nonce is optional in APE. If a nonce is used, changing the nonce requires ν/r permutation function calls.

Besides the aforementioned features that hold in general for the PRIMATEs algorithm family, several features make specific modes stand out.

Features Specific to HANUMAN, GIBBON or APE.

- HANUMAN is based on the SpongeWrap [6] design strategy. More concretely, it is the hermetic Sponge design strategy, which means that its underlying permutation should be free of any structural distinguishers.
- GIBBON is intended for lightweight applications where speed is critical and a formal security proof (based on the security of the underlying permutation) is

not required. To achieve high throughput, GIBBON employs reduced-round permutations p_2 and p_3 to process the associated data and message respectively, next to the full-round permutation p_1 used for initialization and finalization.

- APE should be used in applications where additional security is required. Like HANUMAN, APE is provably secure, based on the security of the underlying permutation. Additionally, APE provides resistance against nonce reuse [1], as well as resistance against adversaries that can observe the unverified plaintext during decryption [2]. The price to pay for this additional security is that decryption is performed backwards using the inverse of the permutation.

6 Design Rationale

The PRIMATEs have been designed with lightweight hardware requirements as present in constrained devices in mind. For the mode of operation, they follow the principles of the sponge methodology, more specifically, some of the principles of SpongeWrap and MonkeyDuplex. The modes of operation are generic and free of weaknesses as justified by the formal security proofs. For the underlying permutation(s), the PRIMATEs follow the well-established SPN approach of Rijndael (and its wide-trail design strategy), based on almost bent S-boxes (attaining best possible differential and linear properties) as well as MDS diffusion matrices (achieving best possible differential and linear local diffusion). To favor lightweight implementations of the PRIMATEs, the MDS diffusion matrices are chosen to be recursive and the S-boxes are 5-bit.

The PRIMATEs family includes three modes: GIBBON and HANUMAN are nonce-based, while APE has been designed to maintain security under both nonce reuse and release of unverified plaintext – scenarios which is likely to persist in highly constrained embedded systems. GIBBON does not follow the hermetic sponge-based design approach, while both HANUMAN and APE do. This allows GIBBON to be considerably faster and more energy-efficient. A state recovery for GIBBON does not lead to trivial key recovery and also does not lead to trivial universal forgery attacks due to the key additions.

The designers have not hidden any weaknesses in these ciphers.

7 Intellectual Property

The submitters are not aware of any patent involved in PRIMATEs family. Furthermore, PRIMATEs will not be patented. If any of this information changes, the submitters will promptly (and within at most one month) announce these changes on the `crypto-competitions` mailing list.

8 Consent

The submitter/submitters hereby consent to all decisions of the CAESAR selection committee regarding the selection or non-selection of this submission as a second-round candidate, a third-round candidate, a finalist, a member of the final portfolio, or any

other designation provided by the committee. The submitter/submitters understand that the committee will not comment on the algorithms, except that for each selected algorithm the committee will simply cite the previously published analysis that led to the selection of the algorithm. The submitter/submitters understand that the selection of some algorithms is not a negative comment regarding other algorithms, and that an excellent algorithm might fail to be selected simply because not enough analysis was available at the time of the committee decision. The submitter/submitters acknowledge that the committee decisions reflect the collective expert judgments of the committee members and are not subject to appeal. The submitter/submitters understand that if they disagree with published analysis then they are expected to promptly and publicly respond to those analysis, not to wait for subsequent committee decisions. The submitter/submitters understand that this statement is required as a condition of consideration of this submission by the CAESAR selection committee.

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Diagrams

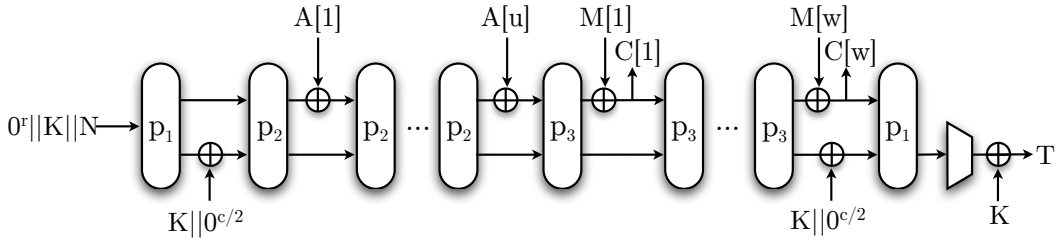

Figure 6: The GIBBON mode of operation.

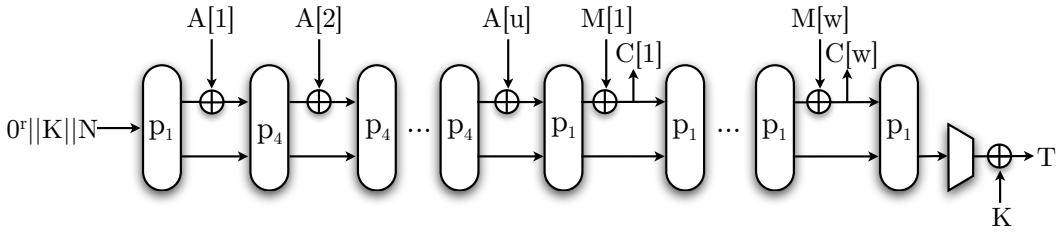

Figure 7: The HANUMAN mode of operation.

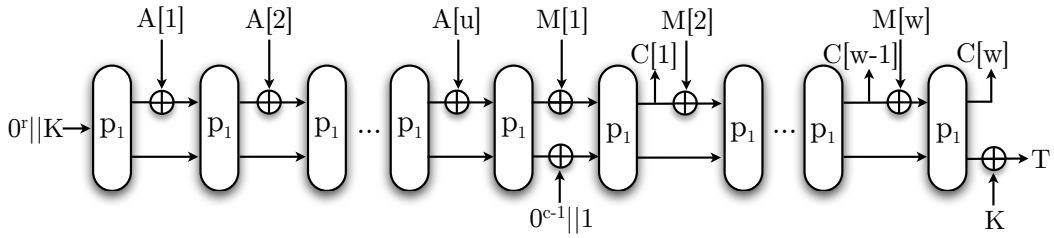

Figure 8: The APE mode of operation (encryption).

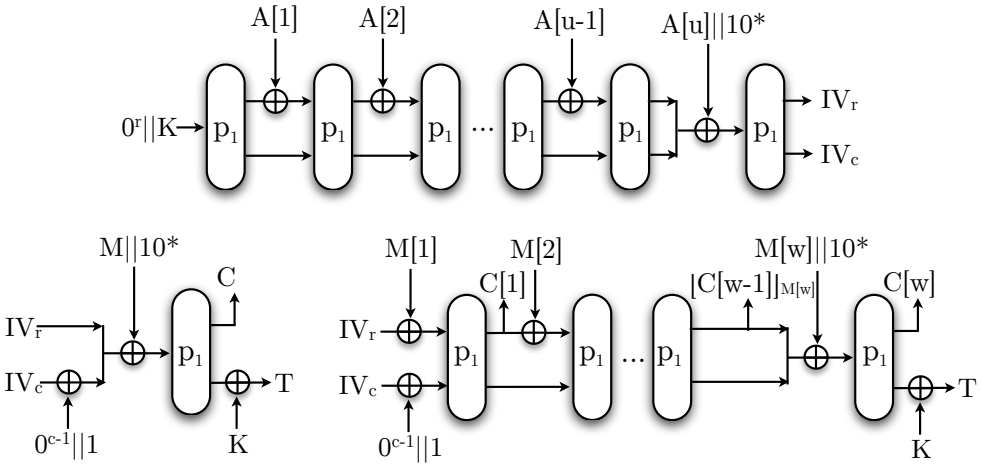

Figure 9: The APE mode of operation (encryption) for fractional data.