General Overview of the Authenticated Schemes for the First Round of the CAESAR Competition

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Abstract. The ongoing CAESAR competition aims at finding authenticated encryption schemes that offer advantages over AES-GCM and are suitable for widespread adoption. At the moment, 48 remaining first-round submissions are going through an intensive review, analysis and comparison process. While the cryptographic community benefits greatly from the manifold different submission designs, their pure number implies a challenging amount of study. As part of a remedy, this paper provides an easy-to-grasp overview over functional aspects, security parameters, and robustness offerings of the CAESAR candidates, clustered by their underlying designs (block-cipher-, stream-cipher-, permutation-/sponge-, compression-function-based, dedicated).

Keywords: authenticated encryption, CAESAR competition, symmetric cryptography.

1 Introduction

Confidential messages that shall be submitted over an insecure channel usually require protection of not only their privacy, but also of the authenticity of their respective sender. Authenticated encryption (AE) schemes are key-based cryptographic algorithms that try to provide both goals simultaneously. The notion of AE was introduced by the seminal work by Bellare and Namprempre around 2000 [20,21], and further evolved during the past decade [112,114,117].

There are a few approaches of how to design an AE scheme: The classical way is the so-called generic composition, which considers authentication and encryption as two separate goals. Following this approach, authenticated encryption is realized by the composition of two building blocks: a secure message authentication code (MAC) and a secure block cipher. While generic composition allows that each component can analyzed and exchanged individually, it always suffered from being neither very efficient nor very robust to implementation errors (see, e.g., [51]).

Around 2000, a series of papers [55,75,77,116] demonstrated that AE schemes can be constructed more efficiently than generic composition in a block-cipher mode of operation. These works paved the way towards an understanding of modern authenticated encryption as a cryptographic building block on its own rather than as the mere combination of two. In the previous decade, many more schemes have been developed in this way—among them two NIST-recommended modes (CCM [48] and AES-GCM [91]), and the ISO standard AES-OCB2 [67]. There are several further approaches to construct AE schemes, e.g., based on a keyless permutation [27], a stream cipher [4], a hash or compression function [54], or by designing dedicated schemes, where the message is used to update a larger internal state [32,52,134].

Despite the variety of available designs, at the beginning of 2013, a large amount of SSL/TLS servers still employ RC4 [110]—most likely due to the performance reasons or as a backup strategy against attacks [6,47]. Moreover, GCM lost part of its trustworthiness after cryptanalytical efforts [109,121] which identified considerable groups of weak keys. At the FSE 2013 [22], Bernstein outlined the most obvious needs on AE schemes: Can one construct AE schemes that offer a higher level of security than GCM with similar performance; or such that are faster than GCM with a similar level of security. Moreover, the community derived many further desirable features from practical needs: Can AE schemes be designed to be fast in hard- and software, to detect forgery attempts fast, to provide robustness against nonce misuse or against leakage of invalid plaintexts, and etc. So, there still seems to be an enormous gap that motivates a concentrated research on novel designs.

The CAESAR (Competition for Authenticated Encryption: Security, Applicability, and Robustness) contest aims at filling this gap for AE. At January 2013, Bernstein called for submissions that should "*(1) offer advantages over AES-GCM and (2) are suitable for widespread adoption*" [23]. His call was responded by 57 submissions in total – many of which proposed several recommendations for their primitives, or even multiple different instantiations. While analysts and designers can learn lots from the heterogeneous field of candidates, their pure number implies a challenging amount of study for submitters and analysts to keep track of every scheme's individual advantages and drawbacks.

Contribution. As part of a remedy, in this paper, we (as a first group) try to provide a comprehensive overview on the first-round CAESAR candidates, inspired by the preliminary summary by Bart Preneel at the Dagstuhl Seminar 14021 [13]. We propose an intuitive classification of the candidates according to their design approaches (block-cipher-based, stream-cipher-based, permutation-/sponge-based, compression-function-based, dedicated). After spending decent amount of times on large number of candidates and their voluminous documentation, we could provide easy-to-grasp tables to compare their individual functional features (parallelizability, onlineness, inverse-freeness, support for intermediate tags, and incrementality), their security parameters (for privacy and integrity), as well as their robustness offering (nonce- and decryption-misuse). We need to mention that, for the most of the candidates, our finding for the features and security is not stated in the design specification, so we needed to go through all candidates to educe all these features.

Note that we consider only recommended parameter sets for those candidates that have not been withdrawn from the competition, which is the case for 49 out of the 57 submissions. At the time, we exclude AES-COBRA [10], Calico [128], CBEAM [119], FASER [37], HKC [63], Marble [59], McMambo [81], PAES [142], and PANDA [143]. Furthermore, we explicitly do not consider performance measures since the SUPERCOP framework and website [24] provide the better platform for this purpose.

Outline. The remainder of this paper is organized as follows: Section 2 lists the functional characteristics of authenticated encryption schemes. Section 3 briefly recalls the relevant security and robustness notions and criteria. The general overview of attacks on candidates is explained in Section 4. In the last section, Section 5, the schemes are compared in a table for functional features and security parameters, .

2 Design Classification

In this section, we first define authenticated encryption scheme which supports associated data, then we explain the underlying primitives which candidates are constructed based on.

Authenticated Encryption Scheme (with Associated Data). Let $k, \nu, t \geq 1$, $K \in \{0,1\}^k$ denote a secret key, $N \in \{0,1\}^\nu$ a nonce, $H \in \{0,1\}^*$ a header (associated data, hereafter), $M \in \{0,1\}^*$ a message, $T \in \{0,1\}^t$ an authentication tag, and $C \in \{0,1\}^*$ a ciphertext. An authenticated encryption scheme with associated data is a triple $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$, with a key-generation procedure $\mathcal{K}$ that returns a randomly chosen key K, a deterministic encryption algorithm $\mathcal{E}_{\mathcal{K}}(N, H, M)$, and its inverse decryption algorithm $\mathcal{D}_{\mathcal{K}}(N, H, C, T)$. $\mathcal{E}$ always outputs a ciphertext-tag pair $(C,\ T)$, and $\mathcal{D}$ outputs either the plaintext M that corresponds to C, or the bot symbol $\perp$ if the tag is invalid:

$$\mathcal{E} : \{0,1\}^k \times \{0,1\}^\nu \times \{0,1\}^* \times \{0,1\}^* \to \{0,1\}^* \times \{0,1\}^t$$
$$\mathcal{D} : \{0,1\}^k \times \{0,1\}^\nu \times \{0,1\}^* \times \{0,1\}^* \times \{0,1\}^t \to \{0,1\}^* \cup \{\perp\}.$$

We use these notions in the remainder of this paper. Note that the CAESAR call for submissions demanded a slightly different API, where the nonce is split into a public and a secret message number (PNM, SNM).

2.1 Underlying Constructions

This section briefly recalls the constructions that appear as base of the CAESAR submissions.

Block Cipher. A block cipher is a keyed family of n-bit permutations $E : \{0,1\}^k \times \{0,1\}^n \rightarrow \{0,1\}^n$, which takes a k-bit key K and an n-bit message M, and outputs an n-bit ciphertext C.

AES-Based. Most of the schemes are based on AES, since during the years, major efforts have been put on analysing AES where they help to investigate its design in detail and trust it for high level of security. Moreover, starting with Intel's Westmere microarchitecture in 2011, current processors provide native AES instructions that allow fast constant-time encryption and decryption. Hence, AE schemes that build upon standardized primitives can benefit from the available instruction sets and existing cryptanalysis.

Stream Cipher. A stream cipher is a symmetric pseudo-random bit generator (PRBG) that takes a fixed-length secret key and generates a keystream of variable length. Like block ciphers, stream ciphers can be used as a core primitive in authenticated encryption scheme to achieve both confidentiality and integrity as long as the cipher is secure [52].

Key-Less Permutation. A key-less permutation is a bijective mapping on fixed-length strings. Permutations received a high level of attention during the SHA-3 competition[1] – last but not least due to its winner [26]. Quite a number of CAESAR submissions use a key-less permutation as their underlying primitive. The most famous keyless permutation is the sponge construction [25], which is an iterated function with variable-length in- and outputs from a permutation (or transformation) that itself operates on a fixed-length state. Literally, the sponge is said to *absorb* its inputs block by block first before it processes and *squeezes* it out afterwards.
Duplex constructions are closely related to sponges [27]. Unlike sponges, which are stateless between calls, a duplex accept calls that take an input string and return an output string which depends on all previous inputs.

Hash Function/Compression Function. A hash function maps strings of arbitrary length to fixed-length outputs. For cryptographic hash functions, it is not feasible to find a collision, preimage and second preimage. A compression function is defined similarly as a hash function, but it compresses two fixed-length inputs to a single fixed-length output.

Dedicated. The structure of a few CAESAR candidates is similar to that of Type-3 Feistel schemes [147]. Such schemes maintain a multi-block state $S_0, \ldots, S_n$, which is updated by feeding in one message block (e.g., $S_0 = S_0 \oplus M$) and updating each state with the result of its neighbor state block, processed by a round function: $S_i = S_i \oplus f(S_{i-1})$.

2.2 Underlying Modes and Masking Methods

Encryption Modes. An algorithm which uses block cipher to provide security for confidentiality and authenticity is called mode of operation. Mode of operation is usually used for secure transformation of data larger than a block. So, for block-cipher-based candidates, we explicitly state which encryption

[1] http://competitions.cr.yp.to/sha3.html

mode(s) they inherit from. Moreover, we also list the underlying modes for some non-block-cipher-based submissions, when this is the case. The following modes adopted by the CAESAR submissions, and use the following acronyms:

CFB	Ciphertext feedback mode [105].
CTR	Counter mode [105].
ECB	Electronic codebook mode [105].
EME	Encrypt-Mix-Encrypt mode [61,60].
iFeed	iFeed mode [146].
JHAE	JH-based mode for authenticated encryption [70].
LEX	Leakage extraction mode [30].
OFB	Output-feedback mode [105].
OTR	Two-branch two-round Feistel [95].
PFB	Plaintext feedback mode.
PPAE	Parallelizable permutation-based authenticated encryption [5].
SIV	Synthetic initialization vector mode [117].
TAE	Tweakable authenticated encryption [86,87].
XEX	XOR-encrypt-XOR (Even-Mansour) [113].

Masking Methods. Many modern block-cipher-based schemes mask in- and outputs to the block cipher to prevent them from being under control of adversaries. From our finding, following approaches are used for the masking:

AX	Addition and XOR.
Doubling	XOR with a key-dependent variable that is incremented by doubling it in Galois Field [113].
GFM	Multiplication with a key-dependent variable in Galois-Field.
AES	XORing an AES-processed chaining value [2].

2.3 Functional Characteristics

Parallelizable. Various block-cipher modes for authenticated encryption are inherently sequential, some to satisfy stricter notions of security, some others to achieve lightweight implementations. We call an encryption operation parallelizable if the processing of the i-th input block does not depend on the output of processing the j-th block, for any $i \neq j$. As a slightly weaker kind of this feature, we call an AE scheme *pipelineable* if the encryption (and likewise the decryption) can be decomposed into operations $f \circ g$, such that the first operation $g(M_i)$ can be already performed for the i-th block before the encryption of the previous blocks have finished. Note that we regard parallelizable encryption and decryption separately.

Online. A cipher is called online if the encryption of the i-th input block M_i depends only on the blocks $M_1, \ldots, M_{i-1}$ and only constant size-state is used from the processing of one block to the next. We call an AEAD scheme $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ online if $\mathcal{E}$ is an online cipher and $\mathcal{D}$ its inverse operation. Schemes that are not online are called offline or two-pass.

Inverse-Free. AE schemes that employ only an encryption *or* decryption function can save precious memory and area resources. Wlog., we call an AE scheme inverse-free if it does not require either its underlying primitive's forward or inverse operation, e.g., as does require the block cipher's decryption function.

Incremental Authenticated Encryption. AE schemes are frequently used to encrypt lots of data, wherein subsequent messages differ only by a fraction (e.g., a single block) from each other. An AE scheme is said to provide *incremental authenticated encryption*, if, given a previous authenticated ciphertext and tag (C, T) for a message M, encrypting and authenticating a message M' that differs from M only in a fraction can be computed in proportional time and not the same as simply encrypting and authenticating a message M. Then recomputation of changed data will be significantly faster. Incrementality is essentially a practical concern because it is measure of efficiency. Therefore, incremental scheme have this advantage over standard one specially for larger message size. In this paper, we assume that recomputation requires only the costs for processing the changed blocks and tag derivation.
Note that some schemes may provide this property under the requirement of reusing the nonce. We consider nonce misuse to be an *erroneous* usage which should not be encouraged to obtain a nice "feature". Hence, we denote scheme to provide incremental authenticated encryption only if the nonce is used only once and never is repeated.

Incremental Associated Data. This property is similar to incremental AE. Suppose, an intermediate result of a previous associated data processing is cached, and the current associated data changes only in a fraction. We say a scheme provides incremental associated data if only the changed blocks and a finalization step need to be recomputed.

Fixed Associated Data Reuse. Some applications use the same or slightly modified associated data values for subsequent messages [124]. Schemes that can cache and reuse the result of processing the associated data of the previous encrypted message may allow for a considerable speed-ups. We say that such schemes provide associated-data reuse. Note that this implies that the nonce is not part or appended to the associated data.

Intermediate Tags. Intermediate tags [27] allow the receiver to detect early if parts of a decrypted message are invalid, which saves computations when authenticating large messages. Such information can be integrated easily into weak non-malleability of online cipher by adding well-formed redundancy, such as fixed constants or checksums [3]. Hence, we say that an AE scheme provides this property, if it is online and non-malleable (OPRP-CCA-secure). By non-malleability, we mean that if adversary manipulates the i-th ciphertext block, then she cannot distinguish between the $(i+1), (i+2)$, ... ciphertext blocks of online cipher and random one. The scheme with support of intermediate tag can be well-suited for low-latency environments such as optical transport network (OTN), where messages usually contains of multiple TCP/IP packages with small integrated checksums.

3 Security

In this section, we give general overview of security notion for AE schemes and online AE schemes. The security aim of AE is ensuring both privacy and authenticity for encrypted messages at the same time. For our purpose, we consider some general security notion and CCA3 security by Rogeway and Shrimpton [118] which includes IND-CPA and INT-CTXT notions. We also consider these notions for online ciphers: OCCA3 and OPRP-CPA.
Following the notions by Bellare et al. [20], we consider an authenticated encryption scheme secure (in the CCA3 sense) iff it provides data privacy (in the sense of indistinguishablity from an ideal authenticated encryption against chosen-plaintext attacks, IND-CPA) and ciphertext integrity against forgery attacks (INT-CTXT). More formally, we call an AE scheme $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ secure iff the IND-CPA + INT-CTXT-advantage is negligible for any nonce-respecting adversary. We define an online authenticated encryption scheme Π to be secure (in the OCCA3 sense) iff it provides OPRP-CPA and INT-CTXT security. We recall the notions in brief in the following subsection.

3.1 General Security Notions.

Definition 1 (IND-CPA-Security). *Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an authenticated encryption scheme. Then, the* IND-CPA*-advantage of a computationally bounded adversary $\mathcal{A}$ for Π is defined as*

$$\mathbf{Adv}_{\Pi}^{\textsf{IND-CPA}}(\mathcal{A}) \leq \left| \Pr\left[K \xleftarrow{\$} \mathcal{K} : \mathcal{A}^{\mathcal{E}(\cdot,\cdot)} \Rightarrow 1 \right] - \Pr\left[\mathcal{A}^{\$(\cdot,\cdot)} \Rightarrow 1 \right] \right|.$$

We define $\mathbf{Adv}_{\Pi}^{\textsf{IND-CPA}}(q, \ell, t)$ as the maximum advantage over all IND-CPA*-adversaries $\mathcal{A}$ on Π that run in time at most t, and make at most q queries of total length ℓ to the available oracles.*

Let $\mathcal{A}^{\mathcal{O}}$ be a computationally bounded adversary with access to an oracle $\mathcal{O}$, which responds with either real encryptions using $\mathcal{E}$ or a random permutation π, as given in Definition 1. In the beginning, the oracle tosses a fair coin to obtain a bit b. Thereupon, $\mathcal{A}$ can query messages to $\mathcal{O}$. Depending on b, $\mathcal{A}$ obtains either "real" encryptions for the messages it sends, or just the "random" outputs. Hence, the challenge for $\mathcal{A}$ is to guess b. We write $ to indicate that every value is chosen uniformly at random.

Definition 2 (INT-CTXT-Security). *Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an authenticated encryption scheme. Then, the* INT-CTXT*-advantage of a computationally bounded adversary $\mathcal{A}$ for Π is defined as*

$$\mathbf{Adv}_{\Pi}^{\textsf{IND-CPA}}(\mathcal{A}) \leq \Pr\left[K \xleftarrow{\$} \mathcal{K} : \mathcal{A}^{\mathcal{E}(\cdot,\cdot),\mathcal{D}(\cdot,\cdot)} \Rightarrow \textit{ forges} \right]$$

We define $\mathbf{Adv}_{\Pi}^{\textsf{INT-CTXT}}(q, \ell, t)$ as the maximum advantage over all INT-CTXT*-adversaries $\mathcal{A}$ on Π that run in time at most t, and make at most q queries of total length ℓ to the available oracles.*

For the definitions and security notions regarding online ciphers, please see Bellare et al. [19].

Definition 3 (CCA3-Security). *Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an authenticated encryption scheme. Then, the* CCA3*-advantage of a computationally bounded adversary $\mathcal{A}$ is defined as*

$$\mathbf{Adv}_{\Pi}^{\textsf{CCA3}}(\mathcal{A}) = \left| \Pr\left[K \xleftarrow{\$} \mathcal{K} : \mathcal{A}^{\mathcal{E}_K(\cdot,\cdot),\mathcal{D}_K(\cdot,\cdot,\cdot)} \Rightarrow 1 \right] - \Pr\left[\mathcal{A}^{\$(\cdot,\cdot),\perp(\cdot,\cdot,\cdot)} \Rightarrow 1 \right] \right|.$$

The CCA3 notion states that $\mathcal{A}$ has access to an oracle $\mathcal{O}$, which provides $\mathcal{A}$ with an encryption and a decryption functions. At the beginning, $\mathcal{O}$ tosses a fair coin; depending on the result of the coin toss, $\mathcal{O}$ uses the *real* encryption $\mathcal{E}_K(\cdot,\cdot)$ and decryption $\mathcal{D}_K(\cdot,\cdot,\cdot)$ functions, or a *random* function $\$(\cdot,\cdot)$ for the encryption and a $\perp$ function for $\perp(\cdot,\cdot,\cdot)$, which returns $\perp$ on every input, for the decryption queries of $\mathcal{A}$. Wlog., we assume that $\mathcal{A}$ never asks a query to which it already knows the answer. The goal of $\mathcal{A}$ in this scenario is to determine the result of the coin toss, i.e., to distinguish between the real encryptions with Π and random one.

Relation to Privacy and Integrity Notions. Bellare and Namprempre showed in [20] that the CCA3 advantage of an adversary on an AE scheme Π can be upper bounded by the sum of the maximal advantage of an adversary on the integrity of Π, and the maximal advantage of a chosen-plaintext adversary on the privacy of Π. Then CCA3-advantage over all adversaries $\mathcal{A}$ that run in time at most t, ask at most q queries of a total length at most ℓ to the available oracles is given by:

$$\mathbf{Adv}_{\Pi}^{\textsf{CCA3}}(q, t, \ell) \leq \mathbf{Adv}_{\Pi}^{\textsf{IND-CPA}}(q, t, \ell) + \mathbf{Adv}_{\Pi}^{\textsf{INT-CTXT}}(q, t, \ell).$$

3.2 Security Notions for On-Line AE Schemes

Definition 4 (OCCA3-Security). *Let $\Pi = (\mathcal{K}, \mathcal{E}, \mathcal{D})$ be an on-line authenticated encryption scheme. Then, the OCCA3-advantage of an adversary $\mathcal{A}$ is upper bounded by*

$$\mathbf{Adv}_{\Pi}^{\mathsf{OCCA3}}(\mathcal{A}) \leq \mathbf{Adv}_{\Pi}^{\mathsf{OPRP\text{-}CPA}}(q, \ell, t) + \mathbf{Adv}_{\Pi}^{\mathsf{INT\text{-}CTXT}}(q, \ell, t).$$

The OCCA3-advantage of Π, $\mathbf{Adv}_{\Pi}^{\mathsf{OCCA3}}(q, \ell, t)$, is then defined by the maximum advantage of all OCCA3-adversaries $\mathcal{A}$ that run in time at most t, and make at most q queries of total length ℓ to the available oracles.

Based on the definition above, an on-line authenticated encryption scheme Π is OCCA3-secure if it provides both OPRP-CPA-security *and* INT-CTXT-security.

Definition 5 (OPRP-CCA-Security). *Let K be a k-bit key, P a random on-line permutation, and $\Gamma : \{0,1\}^k \times (\{0,1\}^n)^* \to (\{0,1\}^n)^*$ an on-line cipher. Then, we define the OPRP-CCA-advantage of an adversary $\mathcal{A}$ by*

$$\mathbf{Adv}_{\Gamma}^{\mathsf{OPRP\text{-}CCA}}(\mathcal{A}) = \left| \Pr\left[\mathcal{A}^{\Gamma_K(\cdot), \Gamma_K^{-1}(\cdot)} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{P(\cdot), P^{-1}(\cdot)} \Rightarrow 1\right] \right|,$$

where the probabilities are taken over $K \xleftarrow{\$} \mathcal{K}$ and $P \xleftarrow{\$} \mathsf{OPerm}_n$. Further, we define $\mathbf{Adv}_{\Gamma}^{\mathsf{OPRP\text{-}CCA}}(q, \ell, t)$ as the maximum advantage over all OPRP-CCA-adversaries $\mathcal{A}$ that run in time at most t, and make at most q queries of total length ℓ to the available oracles.

Quantitative Security Statements. The CAESAR call demanded quantitative claims of security of each submission for privacy and integrity. For the sake of clarity, we employ two complexities for each notion: query and time complexity. The query complexity q represents the logarithm base-2 of the number of blocks that an adversary has to query in order to violate the claimed security goals with probability of 1/2 or greater. The time complexity t reflects the log base-2 of the number of calls to the underlying primitive function that any adversary has to perform in order to break a goal with probability of 1/2 or higher, if it has only a small ($\ll q$) plaintext-ciphertext pairs.

Provable Security. We indicate which schemes provide a security proof under well-established assumptions, e.g., abstracting their underlying primitive by a random PRF/PRP.

3.3 Robustness

An AE scheme is called robust if it provides CCA3/OCCA3 and additional security against more general adversaries. Note that security proofs for AE schemes used to rely on two common assumptions: (1) nonce-respecting adversaries, and (2) secure underlying primitives. While both aspects are well-understood in theory, they are hard to guarantee in practice. Thus, security issues have been overlooked or ignored in various cases and security applications have been put at high risk. We consider two robustness notions in the established security definitions: resistance against nonce-ignoring adversaries and against leakage of would-be plaintexts. Like before, we distinguish between online and off-line (two-pass) schemes.

Security Against Nonce-Ignoring Adversaries. In a robust setting for nonce-misuse, the nonce is used more than once without harming a security. For a scheme to be robust, there is an ongoing discussion about suitable definition of robust AE.
Rogaway and Shrimpton [117] follow a strict interpretation of (nonce-)misuse-resistant AE (MRAE). According to their notion, an MRAE-secure scheme lets adversaries gain no advantage when a nonce

repeats, except for noticing when the same message was encrypted multiple times. Clearly, following this interpretation implies that MRAE-secure schemes can not be online.
In contrast, the notion of nonce-misuse resistance by Fleischmann et al. [53] exclusively targeted online ciphers; the authors considered a nonce repetition as an erroneous usage that resistant schemes should provide as a second line of defense against. Following their definition, an online AE scheme is called secure against nonce-ignoring adversaries if all an adversary can learn from repeating nonces is the longest common prefix of messages. Thus, the privacy protection transformed from PRP-CPA to OPRP-CPA security in this case.
To respect both views, we opt for a two-way strategy: for two-pass schemes we indicate nonce-misuse resistance iff they provide MRAE (which is equivalent to PRP-CPA and INT-CTXT) security [117]; for online schemes, we indicate nonce-misuse resistance iff they provide OPRP-CPA and INT-CTXT security.

Security Against Plaintext-Aware Adversaries. An unverified plaintext is the message that results from decrypting an unauthentic ciphertext. The security arguments for AE schemes usually require that adversaries never learn anything about such unverified plaintexts. However, for larger data streams or in real-time environments, it may be hard or even impossible to buffer the decryption until the tag is verified. In this setting, decryption algorithm is allowed to return both $\perp$ and an arbitrary piece of sidelong information for the case of invalid ciphertext. The output of decryption algorithm does not matter as long as sidelong information are invalid and independent of encryption algorithm.
Again, (at least) two views exist on this problem. It was first concerned by Abed et al. [3] in their notion of decryption-misuse resistance for online AE schemes. Their notion follows from online chosen-ciphertext security (OPRP-CCA-security), which is the strongest form of non-malleability and decryption-misuse resistance that an *online cipher* can provide, i.e., an adversary that manipulates the i-th block will obtain garbled pseudorandom outputs starting from that block.
Later, in [11], Andreeva et al. formalized and generalized this view. They provided several security definitions meant to capture the requirement that, for an invalid ciphertext and a repeated nonce, decryption algorithm releases only harmless information. They introduced two notions of plaintext awareness (PA1, PA2) for privacy and the INT-RUP notion for integrity. Their definitions reflect that no adversary can gain any advantage by having access to a decryption oracle which always returns a plaintext from any ciphertext input.
As for nonce-misuse case, we opt for a two-way strategy. For two-pass schemes we indicate decryption-misuse resistance iff they provide PRP-CCA security; for online schemes, we indicate decryption-misuse resistance if they offer OPRP-CCA security.

Definition 6 (INT-RUP Advantage). *Let $\Pi = (\mathcal{E}, \mathcal{D}, \mathcal{V})$ be an authenticated encryption scheme with separate decryption and verification. Then, the INT-RUP advantage of a computationally bounded adversary $\mathcal{A}$ that never queries $\mathcal{E}_{\mathcal{K}} \rightarrow \mathcal{V}_{\mathcal{K}}$,for Π is defined as*

$$\mathbf{Adv}_{\Pi}^{\textsf{INT-RUP}}(\mathcal{A}) := \Pr\left[\mathcal{A}^{\mathcal{E}_{\mathcal{K}}, \mathcal{D}_{\mathcal{K}}, \mathcal{V}_{\mathcal{K}}} \textit{ forges}\right],$$

where the probability is defined over the key $\mathcal{K}$ and random coins of $\mathcal{A}$. Forges means the event of verification oracle that returns $\top$ to the adversary.

4 General Overview of Attacks on Candidates.

In this section, we first give general explanation of broken candidates and their analysis. Then we consider analysis and observation of existing candidates.

4.1 Broken Candidates.

57 candidates are submitted for the CAESAR competition. At the time of writing this paper, 9 candidates are considered broken and withdrawn from the competition.

AES-COBRA. AES-COBRA is an authenticated encryption mode based on AES block cipher with the claim of 64-bit security for both privacy and integrity, and 128-bit for both key recovery and tag guessing attacks. But Nandi [99] showed a forgery attack on n-bit blockcipher with only $\mathcal{O}(n)$ queries and success probability about 1/2 which violated the security claim made by the designers.

Calico. Calico is a family of lightweight authenticated encryption with support of associated data. It is basically based on stream cipher ChaCha-14 and 20, MAC function Siphash-2-4, and hash function BLAKE2. The designer claimed 127 bits of security for the confidentiality of plaintext, erased old keys in stream modes, and 63 bits of security for the integrity. Christoph Dobraunig et al. [44] showed a forgery and key recovery attacks which requires 2^{64} online queries with the success probability of 1 to recover 128-bit key of the MAC.

CBEAM. CBEAM is algorithm for the authenticated encryption which supports associated data. It uses sponge permutation construction. The designer claimed 127-bit of security for privacy and 63-bit for the privacy but Minaud [92] showed a differential attack on the sponge permutation of CBEAM which can be exploited for a forgery with success probability of 2^{-43} which is contrary to 2^{-63}.

FASER. FASER is an authenticated encryption scheme which supports two different versions including 128 and 256-bit. The designers claimed full security for the privacy and 64 and 96-bit of security for the integrity for 128 and 256-bit versions, respectively. Xu et al [141] found a correlation attack on FASER-128 with time complexity of 2^{36} and 2^{12} keystream words. They had also distinguishing attack on FASER-128 and 256-bit versions by only 16 and 64 keystream words. Moreover, Feng et al [50] showed that a real-time key recovery attack is possible on the FASER-128 with only 64 key words to recover all possible keys in real-time in PC.

HKC. HKC is a authenticated encryption scheme which is based on stream cipher. It has a built in MAC routine which provides encrypt then MAC procedures. The designers claimed full security of 256-bit for both privacy and integrity but Saarinen [122] showed that, by taking advantage of linear update function, message forgery attack is trivial and security claim will not hold.

Marble. Marble is an authenticated encryption algorithm which supports associated data. The designer claimed full security of 128-bit for both privacy and integrity even for decryption misuse setting, but Fuhr et al [**?**] showed a simple forgery attack on mode of operation of Marble by using only 2^{64} chosen plaintext queries which violate the security claim made by the designer. They could also recover secret key by using 2^{32} additional decryption queries in the decryption misuse setting. After this attack, the designer modified the mask process but then Lu [89] showed that the modified version is still vulnerable to both forgery and key-recovery attacks.

McMambo. McMambo is a block-cipher mode of operation based on Mambo cipher. The designer claimed 128-bit of security for the privacy and 64-bit for the integrity. The designer claimed that Mambo block cipher is indistinguishable from the random oracle with a fixed key, but Neves [102] showed that there is a iterative differential with probability of 2^{-2} over the full double round of McMambo that can lead to a forgery attack with probability of 2^{-24} which is contrary to the security claim made by the designer.

PAES. PAES is an authenticated encryption algorithm which has two versions of 4 and 8. The designer claimed 128-bit of security for both privacy and integrity for either version in nonce-respecting model, and only 128-bit for integrity of PAES-8 in nonce-ignoring setting, but Sasaki et al [126] showed a practical universal forgery attack on PAES-8 in nonce-ignoring setting with only 2^{11} encryption queries and computational cost.

PANDA. PANDA is a family of authenticated ciphers which has two versions of PANDA-s and PANDA-b. Designers claimed 128-bit of security for both privacy and integrity in nonce-respecting setting, and 128-bit for PANDA-b in nonce-ignoring setting but only 128-bit of security for privacy of PANDA-s with no privacy. Sasaki et al [125] showed a forgery attack in nonce-ignoring setting of PANDA-s with 2^{64} computational cost and negligible memory. Also Feng et al [140] showed another practical forgery and state recovery attack on PANDA-s with time complexity of 2^{41} under known-plaintext-attack with only 137 pairs and negligible memory. Both attacks by Sasaki and Feng violate the security claim of the designers.

4.2 Second Round Candidates.

Recently the committee member of CAESAR announced the second round candidates. From there, 30 out of 48 non-broken candidates could make to the second round. 13 out of 30 candidates are based on block cipher as shown in Table 2, 3 dedicated scheme, 3 stream cipher, 2 permutation, 8 sponge, and one compression function-base, as shown in Table 3.

4.3 Third-Party Cryptanalysis of Non-broken Candidates.

In this section we summarize all external analysis and observations of candidates which are made until the time of writing this paper.

Construction	Candidate	Cryptanalysis	Reference
Block-cipher-based	++AE	Forgery	[131]
	AES-COPA	Universal Forgery	[89,100]
	AES-JAMBU	Distinguish	[107,108]
	AES-CMCC	Distinguish, Forgery	[15,18]
	AVALANCHE	Forgery, Key Recovery	[16,33]
	CBA	Distinguish	[46]
	Julius-ECB	Forgery	[74]
	iFeed	Forgery, Subkey Recovery	[135]
	LAC	Differential Forgery	[83]
	POET	Weak Keys, Forgery on POET-G	[1,98]
	iSCREAM	Forgery, Weak Keys, Key Recovery	[82,127]
	Silver	Forgery, Key Recovery	
	[76]		
Stream-cipher-based	ACORN	State Recovery, Key Recovery	[88,39]
	Sablier	Key Recovery	[49]
	Wheesht	Distinguish, Key Recovery, Forgery	[35,101]
	Raviyoyla	Distinguish, Forgery	[29,103]
Sponge-based	ICEPOLE	State Recovery, Forgery	[66,42]
	π-cipher	Tag second-preimage, Forgery	[84,85]
	PRIMATEs	Forgery, Fault Attack, Key Recovery Cube Attack on PRIMATE-APE	[129,123,93,115]
	NORX	Distinguish	[40]
Permutation-based	Prøst-OTR	Forgery	[43]

Table 1: External Analysis of Candidates.

5 Overview

In the following, we give an overview over the functional and security properties of the remaining CAESAR submissions. Tables 2-7 list the properties and parameters of block-cipher- and non-block-cipher-based AE schemes.

Candidate	Mode	Masking	Primitive	Features						Security			2nd-round
				Parallelizable Enc/Dec	*Online*	*Inverse-Free*	*Incremental AD/AE*	*Fixed AD reuse*	*Intermediate Tags*	*Security proof*	*Nonce-MR*	*Decryption-MR*	
++AE [111]	ECB	AX	AES	•/•	•	–	–/–	–	–	–	•	–	–
AES-CMCC [130]	CBC	–	AES	–/•	–	•	–/–	–	–	•	•	–	–
AES-COPA [12]	EME	Doubling	AES	•/•	•	•	•/–	•	–	•	•	–	•
AES-CPFB [96]	CTR,PFB	–	AES	•/–	•	•	–/–	–	–	•	–	–	–
AES-JAMBU [137]	OFB	–	AES	–/–	•	•	–/–	–	–	–	•	–	•
AES-OTR [94]	OTR	Doubling	AES	•/•	•	•	•/–	•	–	•	–	–	•
AEZ [64]	OTR	–	AES-4	•/•	–	•	•/–	•	–	•	•	•	•
AVALANCHE [8]	ECB	–	AES	•/•	•	•	–/–	–	–	•	–	–	–
CBA [65]	ECB	Doubling	AES	•/•	•	•	•/–	•	–	–	–	–	–
CLOC [68]	CFB	–	AES*	–/–	•	•	–/–	•	–	•	–	–	•
Deoxys$^{\neq}$ [71]	TAE	–	Deoxys-BC,AES	•/•	•	–	–/–	–	–	•	–	–	•
Deoxys$^{=}$ [71]	EME	–	Deoxys-BC,AES	•/•	•	–	–/–	–	–	•	•	–	•
ELmD [41]	EME	Doubling	AES	•/•	•	–	–/–	–	•	•	•	–	•
iFeed[AES] [146]	iFeed	Doubling	AES	•/–	•	•	•/–	•	•	•	–	–	–
iSCREAM [57]	TAE	–	iSCREAM, SPN	•/•	•	•	–/–	–	–	–	–	–	–
Joltik$^{\neq}$ [72]	TAE	–	Joltik-BC,AES	•/•	•	–	–/–	–	–	•	–	–	•
Joltik$^{=}$ [72]	EME	–	Joltik-BC,AES	•/•	•	–	–/–	–	–	•	•	–	•
Julius-CTR [17]	CTR	GFM	AES	•/•	–	•	–/–	–	–	•	–	–	–
Julius-ECB [17]	ECB	GFM	AES	•/•	–	–	–/–	–	–	•	•	–	–
KIASU$^{\neq}$ [73]	TAE	–	KIASU-BC,AES	•/•	•	–	–/–	–	–	•	–	–	–
KIASU$^{=}$ [73]	EME	–	KIASU-BC,AES	•/•	•	–	–/–	–	–	•	•	–	–
LAC [145]	LEX	–	L-Block	•/•	•	–	–/–	–	–	–	–	–	–
OCB [80]	XEX	Doubling	AES	•/•	•	–	–/–	–	–	•	–	–	•
POET [2]	ECB	AES-4/10	AES	◦/◦	•	•	•/–	•	•	•	•	•	•
SCREAM [57]	TAE	–	SCREAM,SPN	•/•	•	•	–/–	–	–	–	–	–	•
SHELL [133]	EME	CTR,Doubling	AES	•/•	•	–	–/–	–	–	•	•	–	•
SILC [69]	CFB	–	AES*	–/•	•	•	–/–	–	–	•	–	–	•
Silver [106]	TAE	–	MAES	•/•	•	–	–/–	–	–	•	–	–	–
YAES [34]	CTR	–	AES	•/•	•	•	•/–	•	–	–	–	–	–

Table 2: Block-cipher-based candidates. * = Primary recommendation is AES-based, • = Provides feature, – = Seems not to provide feature, ◦ = Pipelineable.

Construction	Candidate	Design	Primitive	*Parallelizable Enc/Dec*	*Online*	*Inverse-Free*	*Incremental AD/AE*	*Fixed AD reuse*	*Intermediate Tags*	*Security proof*	*Nonce-MR*	*Decryption-MR*	2nd-round
				Features						**Security**			
Dedicated	AES-AEGIS [139]	AES	AES-round	•/–	•	•	–/–	–	–	–	–	–	•
	MORUS [138]	LRX	MORUS	–/–	•	•	–/–	–	–	–	–	–	•
	Tiaoxin [104]	AES [1]	AES-round	•/•	•	•	–/–	–	–	–	–	–	•
Stream-cipher-based	ACORN [136]	LFSR	ACORN	•/•	•	•	–/–	–	–	–	–	–	•
	Enchilada [62]	–	ChaCha, Rijndael	•/•	•	•	•/–	•	–	•	–	–	–
	HS1-SIV [79]	SIV	ChaCha, Poly1305	–/–	–	•	–/–	–	–	•	•	–	•
	Raviyoyla [132]	–	MAGv2	–/–	•	•	–/–	–	–	–	–	–	–
	Sablier [144]	LFSR	Sablier	•/•	•	•	•/–	•	–	–	–	–	–
	TriviA-ck [36]	–	Trivia-SC	•/•	–	•	–/–	–	•	•	–	–	•
	Wheesht [90]	ARX	Wheesht	–/–	•	•	–/–	–	–	–	–	–	–
CF-based	OMD [38]	–	SHA-256/512	–/–	•	•	•/–	•	–	•	–	–	•
Permutation-based	Minalpher [124]	SPN,XEX	Minalpher-P	•/•	•	–	–/–	–	–	•	•	•	•
	PAEQ [31]	PPAE	AESQ	•/•	•	•	•/•	•	–	•	•	–	•
	Prøst-COPA [78]	SPN,EME	Prøst	•/•	•	•	•/–	•	–	•	•	–	–
	Prøst-OTR [78]	SPN,OTR	Prøst	•/•	•	•	•/–	•	–	•	–	–	–
Sponge-based	Artemia [7]	SPN	JHAE	–/–	•	•	–/–	–	–	•	–	–	–
	Ascon [45]	SPN,Duplex	Ascon	–/–	•	•	–/–	–	–	•	•	–	•
	ICEPOLE [97]	Duplex	Keccak-like	•/•	•	•	–/–	–	•	•	•	–	•
	Ketje [28]	Duplex	Keccak-f	–/–	•	•	–/–	–	•	•	–	–	•
	Keyak [58]	Duplex	Keccak-f	•/•	•	•	–/–	–	•	•	–	–	•
	NORX [14]	LRX,Duplex	n.n.	•/•	•	•	–/–	–	–	•	–	–	•
	π-cipher [56]	ARX,Duplex	n.n.	•/•	•	•	–/–	–	–	–	–	–	•
	PRIMATEs-GIBBON [9]	SPN,Duplex	PRIMATE	–/–	•	•	–/–	–	–	•	–	–	•
	PRIMATEs-HANUMAN [9]	SPN,Duplex	PRIMATE	–/–	•	•	–/–	–	–	•	–	–	•
	PRIMATEs-APE [9]	SPN,Duplex	PRIMATE	–/–	•	–	•/–	•	–	•	•	•	•
	Prøst-APE [78]	SPN,Duplex	Prøst	–/–	•	–	•/–	•	–	–	•	•	–
	STRIBOB [120]	Duplex	Streebog	–/–	•	•	–/–	–	–	•	–	–	•

Table 3: Candidates based on dedicated, stream ciphers, compression functions, (non-sponge) permutations, and sponges in particular. n.n. = Unnamed custom primitive, • = Provides feature, – = Seems not to provide feature.

Candidate	Parameters			Privacy	Integrity
	k	ν	t	q/t	q/t
++AE	128	64	128	64/128	64/126.75
AES-CMCC-32-64	128	32*	64	64/128	64/128
AES-CMCC-32-32	128	32*	32	64/128	32/128
AES-CMCC-16-32	128	16*	32	64/128	16/128
AES-CMCC-32-16	128	32*	16	64/128	32/128
AES-CMCC-16-16	128	16*	16	64/128	16/128
AES-COPA	128	128	128	64/128	64/128
AES-CPFB	128	96	128	64/128	64/128
AES-JAMBU	128	64	64	64/128	64/128
AES-OTR-128	128	96	128	64/128	128/128
AES-OTR-256	256	96	128	64/256	128/256
AEZ	128	96	128	61/128	128/128
AVALANCHE-512	512	160	128	103/256	127/256
AVALANCHE-448	448	128	128	71/192	127/192
AVALANCHE-384	384	80	128	55/128	127/128
CBA-128-32	128	96	32	47/128	47/128
CBA-128-64	128	96	64	63/128	63/128
CBA-128-96	128	96	96	63/128	63/128
CBA-192-64	192	96	64	47/192	47/192
CBA-256-96	256	96	96	63/256	63/256
CLOC-AES-12	128	96	64	64/128	64/128
CLOC-AES-8	128	64	64	64/128	64/128
CLOC-TWINE-6	80	48	32	32/ 80	32/ 80
Deoxys$^{\neq}$-128-128	128	64	128	64/128	128/128
Deoxys$^{\neq}$-256-128	256	64	128	128/256	128/256
Deoxys$^{=}$-128-128	128	64	128	64/128	64/128
Deoxys$^{=}$-256-128	256	64	128	64/256	64/256
ELmD-0-f	128	64	128	62.8/128	62.4/128
ELmD-127-f	128	64	128-255	62.8/128	62.3/128
iFeed[AES]-128-96	128	96	128	64/128	128/128
iFeed[AES]-128-104	128	104	128	64/128	128/128

Table 4: Parameter sets for block-cipher-based candidates. * = 128-bit SNM optional.

Candidate	Parameters			Privacy	Integrity
	k	ν	t	q/t	q/t
Joltik$^{\neq}$-64-64	64	32	64	32/ 64	64/ 64
Joltik$^{\neq}$-80-48	80	24	64	24/ 80	64/ 80
Joltik$^{\neq}$-96-96	96	48	64	48/ 96	64/ 96
Joltik$^{\neq}$-128-64	128	32	64	32/128	64/128
Joltik$^{=}$-64-64	64	32	64	32/ 64	32/ 32
Joltik$^{=}$-80-48	80	24	64	24/ 80	24/ 32
Joltik$^{=}$-96-96	96	48	64	48/ 96	48/ 32
Joltik$^{=}$-128-64	128	32	64	32/128	32/ 32
Julius-ECB-R.	128	96	128	64/128	128/128
Julius-ECB-C.	128	64	128	64/128	64/128
Julius-CTR-R.	128	96	128	64/128	64/128
Julius-CTR-C.	128	64	128	64/128	64/128
KIASU$^{\neq}$	128	32	128	64/128	64/128
KIASU$^{=}$	128	32	128	64/128	64/128
LAC	80	64	64	40/ 80	64/ 80
Marble	128	0	128	128/128	128/128
OCB-128-64	128	128	64	64/128	64/ 64
OCB-128-96	128	128	96	64/128	64/ 96
OCB-128-128	128	128	128	64/128	64/128
OCB-192-64	192	128	64	64/192	64/ 64
OCB-192-96	192	128	96	64/192	64/ 96
OCB-192-128	192	128	128	64/192	64/128
OCB-256-64	256	128	64	64/256	64/ 64
OCB-256-96	256	128	96	64/256	64/ 96
OCB-256-128	256	128	128	64/256	64/128
POET-4	128	128	128	64/128	55/128
POET-10	128	128	128	64/128	64/128
SCREAM	128	96	128	64/128	64/128
SHELL-128-64	128	64	128	55/ 80	55/ 80
SHELL-128-80	128	80	128	55/ 80	55/ 80
SILC/AES-8	128	64	64	64/128	64/128
SILC/AES-12	128	96	64	64/128	64/128
SILC/PRESENT	80	48	32	32/ 80	32/ 80
SILC/LED	80	48	32	32/ 80	32/ 80
Silver	128	128	128	64/128	128/128
YAES	128	127	128	48/ 64	55/128

Table 5: Parameter sets for block-cipher-based candidates. ECB-R. = ECB-Regular, ECB-C. = ECB-Compact, CTR-R. = CTR-Regular, CTR-C. = CTR-Compact.

Candidate	Parameters			Privacy	Integrity
	k	ν	t	q/t	q/t
AES-AEGIS-128	128	128	128	64/128	64/128
AES-AEGIS-256	256	256	128	128/256	128/128
MORUS-640	128	128	128	128/128	128/128
MORUS-1280	256	128	128	256/256	128/256
Tiaoxin	128	128	128	128/128	128/128
ACORN-128	128	128	128	64/128	64/128
Enchilada-128	256	64	128	128/128	128/128
Enchilada-256	256	64	128	128/255	128/255
HS1-SIV-Lo	256	96	64	56/256	56/256
HS1-SIV	256	96	128	112/256	112/256
HS1-SIV-Hi	256	96	256	168/256	168/256
Raviyoyla	256	128	128	128/256	128/256
Sablier	80	80	32	40/ 80	32/128
TriviA-ck	128	64	128	64/128	128/128
Wheesht	512	128*	256	128/256	128/256
OMD	256	256	32-256	127/256	127/256
Minalpher	256	104	128	64/128	128/256
PAEQ-64	64	64	64	64/ 64	64/ 64
PAEQ-80	80	80	80	80/ 80	80/ 80
PAEQ-128	128	96	128	128/128	128/128
PAEQ-160	160	128	160	160/160	160/160
PAEQ-t-128	128	128	512	128/128	128/128
PAEQ-tnm-128	128	256	512	128/128	128/128
Prøst-COPA-128	128	128	256	64/128	64/128
Prøst-COPA-256	256	256	256	128/256	128/256
Prøst-OTR-128	128	64	128	64/128	64/128
Prøst/OTR-256	256	256	256	128/256	128/256

Table 6: Parameter sets for dedicated, stream-cipher-based, compression-function-based, and permutation-based candidates (from top to bottom). * = 128-bit SNM.

Candidate	Parameters			Privacy	Integrity
	k	ν	t	q/t	q/t
Artemia-128	128	128	128	64/128	64/128
Artemia-256	256	256	256	64/128	128/128
Ascon-128	128	128	128	64/128	64/128
Ascon-96	96	96	96	96/ 96	96/ 96
ICEPOLE-128	128	128*	128	126/128	128/128
ICEPOLE-128a	128	128	128	126/128	128/128
ICEPOLE-256a	256	96	128	62/128	128/128
Ketje/JR	96	80	96	96/128	96/128
Ketje/SR	128	128	128	128/128	128/128
Keyak	128	128	128	123/128	128/128
NORX/32-4-1	128	64	128	64/128	64/128
NORX/64-4-1	256	128	256	128/256	256/256
NORX/32-6-1	128	64	128	64/128	64/128
NORX/64-6-1	256	128	256	128/256	256/256
NORX/64-4-4	256	128	256	64/256	128/256
π-cipher/16-96	96	32*	128	48/ 96	96/ 96
π-cipher/16-128	128	32*	128	64/128	128/128
π-cipher/32-128	128	128†	256	64/128	128/128
π-cipher/32-256	256	128†	256	128/256	256/256
π-cipher/64-128	128	128‡	512	64/128	128/128
π-cipher/64-256	256	128‡	512	128/256	256/512
Pr.-HANUMAN-10	80	80	80	80/ 80	80/ 80
Pr.-HANUMAN-15	120	120	120	120/120	120/120
Pr.-GIBBON-10	80	80	80	80/ 80	80/ 80
Pr.-GIBBON-15	120	120	120	120/120	120/120
Pr.-APE-10	160	80	160	80/ 80	80/ 80
Pr.-APE-15	240	120	240	120/120	120/240
Prøst/APE-128	128	64	128	64/128	64/128
Prøst/APE-256	256	128	256	128/256	128/256
STRIBOB	192	128	128	64/191	127/128

Table 7: Parameter sets for sponge-based candidates. Pr. = PRIMATEs, */†/‡ = 128/256/512-bit SNM.

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