SAT-based cryptanalysis of ACORN

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Abstract. The CAESAR competition aims to provide a portfolio of authenticated encryption algorithms. SAT solvers represent powerful tools to verify automatically and efficiently (among others) the confidentiality and the authenticity of information claimed by cryptographic primitives. In this work, we study the security of the CAESAR candidate ACORN against a SAT-based cryptanalysis. We provide the first practical and efficient attacks on the first and the last versions of ACORN. More precisely, we achieve state recovery, key recovery, state collision as well as forgery attacks. All our results demonstrate the usefulness of SAT solvers to cryptanalyse all the candidates of the CAESAR competition, thereby accelerating the "*test of time*".

1 Introduction

Authenticated Encryption (AE) provides (at the same time) message confidentiality and data authentication. Currently, the cryptographic literature provides two ways to obtain secure authenticated encryption primitives: generic composition and dedicated algorithm. The generic composition primitives require the application of two primitives (with two different keys): (1) an encryption primitive providing confidentiality, and (ii) a Message Authentication Code (MAC) primitive providing data authentication. In 2000, Bellare and Namprempre described three different generic composition primitives (namely Encrypt-and-MAC, MAC-then-Encrypt, and Encrypt-then-MAC) and prove that only one generic composition primitive fulfils all the considered security notions [2]. Compared to generic composition, dedicated primitives increase the efficiency (in time and memory) of the authenticated encryption process by executing one primitive (using one key) that provides at the same time confidentiality and data authentication.

The Authenticated Encryption with Associated Data (AEAD) primitives represent a generalisation of AE that (1) authenticate a part of the message called associated data (e.g., routing information in network packets), and (2) encrypt and authenticate another part of the message (e.g., the body data in network packets). The open cryptographic "*Competition for Authenticated Encryption: Security, Applicability, and Robustness*" (CAESAR) [15] was launched by Bernstein in order to find a suitable portfolio of AEAD primitives with security and performance exceeding the current standards AES-GCM [13] and AES-CCM [10]. The call for submissions of CAESAR resulted in 57 first-round candidates. Each proposal relies on different design goals such as high-speed in software and/or hardware devices, low memory footprint as well as side-channel attacks resistances.

The proliferation of international open competitions (including AES, SHA-3 and eSTREAM) boosts the researches in cryptanalysis of cryptographic primitives. However, the impressive increase of submissions to cryptographic competitions reveals a major problem related to the cryptanalytic effort required to provide a suitable analysis[1]: the human verification of the degree of resilience claimed by designers of cryptographic primitives is prone to flaws in particular under time constraints. As a result, it appears clearly that cryptanalysts require automatic tools to assist the analysis of cryptographic primitives in order to formally verify properties related, in the present case, to confidentiality and authenticity as well as to reduce the required (test of) time to analyse each primitive. It is worth to note that automatic tools are also useful for the design of new primitives. More precisely, automatic tools stress the effects of different parameters such as the number of rounds, the nonlinear part as well as the linear layers.

In July 2015, the CAESAR team announced that the 30 selected candidates for the second round include the ACORN proposal [16]. Two months later, the designer of ACORN submitted (to the second round of the CAESAR competition) a tweaked version of the first version of ACORN (denoted ACORN v2). This paper demonstrates the usefulness of our automatic tool by highlighting critical flaws in the first and the last version of ACORN (i.e., ACORN v1 and ACORN v2).

Related Work.

In 2014, Liu *et al.* analysed the existence of slid pairs attacks in the first version of ACORN that provide the same internal state of ACORN from two distinct pairs of key and initialisation vector (IV), up to a clock difference, with probability 1 [7]. They also found slid keys that provide (with probability 1) an identical state up to a clock difference using one key and two distinct IVs. Furthermore, they explored state recovery attacks using guess-and-determine and differential algebraic techniques. The time complexities of the described state recovery attacks are about 2^{180} and 2^{130} CPU cycles (vs. 2^{128} for a brute-force attack).

In 2015, Chaigneau *et al.* provided a key recovery attack under the nonce-reuse setting (i.e., the adversary uses several times a single nonce to encrypt several different plaintexts with the same key) and the decryption-misuse setting (i.e., ACORN releases the plaintext although the tag verification fails) although the designer of ACORN claims no security in these settings [3]. The described attack (on the first version of ACORN) required to have the same associated data field in order to have the same internal state before encrypting the plaintexts. This context enables a state recovery attack followed by a key recovery attack from the extracted state.

Few months later, Salam *et al.* showed the existence of state collision attacks in ACORN v1 that can be exploited in a forgery attack (representing the ability to produce a valid tag for the authentication of the data which has never been queried by the user), i.e. a pair of inputs (plaintext or associated data) that leads to the same state. They assumed that (1) the adversary knows the internal state before the encryption step if the attacker uses the plaintext to generate collisions or (2) the adversary knows the key and the IV if the attacker uses the associated data to generate collisions [12]. According to the authors, the presented attacks can be extended to the second version of ACORN.

In 2015, Josh *et al.* provided some observations on the first version of ACORN. They found that the combination (with the exclusive OR operation) of the first keystream bits (i.e., the stream of bits combined with the plaintext in order to provide the ciphertext) for a fixed key and IV but different associated data becomes the scalar 0 [4].

Contribution.

We explore and demonstrate the capability of our automated search tool to the cryptanalysis of the ACORN primitive. More precisely, our tool is able (1) to recover an arbitrary number of (internal) states (of the

[1] The AES competition received 15 candidates while the eSTREAM competition obtained 34 candidates and the SHA-3 competition had 51 candidates.

stream-based authenticated encryption primitive ACORN) that leads to a given tag, (2) to extract the secret key of ACORN from a recovered state, and (3) to find an arbitrary number of plaintexts (and associated data) leading to the same tag. For the later attack, we discuss fix points and multiple states collisions (which generalise the results of Salam *et al.* [12]).

We exemplify the ability of an adversary to control the content of the messages that lead to the same tag (knowing the key and the IV). Afterwards, we discuss the exploitation of this property in a realistic attack scenario, suggesting that ACORN is not suitable for a wide range of applications. Since our attack does not contradict the claims of ACORN's author, this attack casts some doubt on the necessary security requirements of authenticated encryption schemes.

We also show that all our attacks can be quickly reproduced (1) with an ordinary desktop computer, and (2) without human analysis of the algebraic property of ACORN. All our results are based on a freely available tool called *Cryptosat* (written in R and freely available on our website[2]) using the SAT-solver *Cryptominisat* (version 2.9.5) [14].

Outline.

The rest of the paper is organized as follows. Section 2 details the ACORN authenticated encryption primitive. Section 3 presents the SAT-based analysis of cryptographic primitives with *Cryptosat*. Section 4 shows the results of attacks against ACORN using *Cryptosat*. Section 5 concludes this paper with several perspectives of future works.

2 ACORN

The CAESAR candidates rely (among others) on a secret key $K \in \mathcal{K} = \{0,1\}^k$, a nonce $N \in \mathcal{N} = \{0,1\}^n$, a message payload $P \in \mathcal{P} = \{0,1\}^*$ (requiring both confidentiality and data authentication services) and an associated data $A \in \mathcal{A} = \{0,1\}^*$ (requiring data authentication service). An AEAD primitive maps the message P and the associated data A to a single binary string $C \in \mathcal{C} = \{0,1\}^*$ that contains the encrypted form of P as well as additional message authenticated code called the tag $T \in \mathcal{T} = \{0,1\}^t$ (where t represents the tag length) in order to authenticate P and A, i.e.:

$$\mathsf{AEAD}\colon \mathcal{K} \times \mathcal{N} \times \mathcal{P} \times \mathcal{A} \to \mathcal{C}. \tag{1}$$

The inverse mapping of AEAD (denoted AEAD^{-1}) returns the original message payload P if the user supplies the correct values for K, N, C and A, i.e.:

$$\mathsf{AEAD}^{-1}\colon \mathcal{K} \times \mathcal{N} \times \mathcal{C} \times \mathcal{A} \to \mathcal{P} \cup \perp, \tag{2}$$

where $\perp$ is an error message returned if the tag computed by the receiver does not match the received tag T (in which case AEAD^{-1} releases no plaintext).

ACORN represents a lightweight authenticated encryption primitive based on a stream cipher using a 128-bit key and a 128-bit nonce (also known as initialization vector, or IV in short) with the requirement that the associated data length and the plaintext length are at most 2^{64} bits each. ACORN manipulates a single internal state (denoted S) of 293 bits for encryption and authentication. The state represents the concatenation of 6 Linear Feedback Shift Registers (LFSRs) (of lengths 61, 46, 47, 39, 37 and 59) and one register (of length 4). ACORN executes three different Boolean functions:

[2] https://qualsec.ulb.ac.be/people/frederic-lafitte/cryptosat/

- the function $\mathsf{KSG}_{128}(S_i)$ that generates the keystream bit (i.e., a stream of bits added, bit-wise modulo 2, to the plaintext to form the ciphertext and *vice versa*) from the i-th generated state (denoted $S_i \in \{0,1\}^{293}$),
- the function $\mathsf{FBK}_{128}(S_i, ca_i, cb_i)$ that computes the overall feedback bit using two constants $ca_i \in \{0,1\}$ and $cb_i \in \{0,1\}$ (where ca_i and cb_i represent the i-th bit of vectors ca and cb), and
- the function $\mathsf{StateUpdate}_{128}(S_i, m_i, ca_i, cb_i)$ that updates the state according to the i-th bit of the input message m (denoted m_i), the vector ca and the vector cb.

In more details, Acorn generates the i-th keystream bit ks_i by computing:

$$
\begin{aligned}
ks_i &= \mathsf{KSG}_{128}(S_i) && (3)\\
&= S_{i,12} \oplus S_{i,154} \oplus \mathsf{maj}(S_{i,235}, S_{i,61}, S_{i,193}), && (4)
\end{aligned}
$$

where $\oplus$ is the addition operation modulo 2, $S_{i,j} \in \{0,1\}$ represents the j-th bit of S_i and

$$\mathsf{maj}(x,y,z) = (x \wedge y) \oplus (x \wedge z) \oplus (y \wedge z). \tag{5}$$

Acorn generates the feedback bit (denoted f_i) by computing:

$$
\begin{aligned}
f_i &= \mathsf{FBK}_{128}(S_i, ca_i, cb_i, ks_i) && (6)\\
&= S_{i,0} \oplus \neg S_{i,107} \oplus \mathsf{maj}(S_{i,244}, S_{i,23}, S_{i,160}) && (7)\\
&\oplus \mathsf{ch}(S_{i,230}, S_{i,111}, S_{i,66}) \oplus (ca_i \wedge S_{i,196})\\
&\oplus (cb_i \wedge ks_i),
\end{aligned}
$$

where:

$$\mathsf{ch}(x,y,z) = (x \wedge y) \oplus (\neg x \wedge z). \tag{8}$$

Acorn updates the state by computing the following $\mathsf{StateUpdate}_{128}$ function:

$$
\begin{aligned}
S_{i,289} &= S_{i,289} \oplus S_{i,235} \oplus S_{i,230}, && (9)\\
S_{i,230} &= S_{i,230} \oplus S_{i,196} \oplus S_{i,193}, && (10)\\
S_{i,193} &= S_{i,193} \oplus S_{i,160} \oplus S_{i,154}, && (11)\\
S_{i,154} &= S_{i,154} \oplus S_{i,111} \oplus S_{i,107}, && (12)\\
S_{i,107} &= S_{i,107} \oplus S_{i,66} \oplus S_{i,61}, && (13)\\
S_{i,61} &= S_{i,61} \oplus S_{i,23} \oplus S_{i,0}, && (14)\\
f_i &= \mathsf{FBK}_{128}(S_i, ca_i, cb_i, ks_i) && (15)\\
S_{i+1,j} &= S_{i,j+1} \ \forall j \in \{0,1,...,291\}, && (16)\\
S_{i+1,292} &= f_i \oplus m_i, && (17)
\end{aligned}
$$

as clarified in Figure 1. In the following, for the sake of brevity, we detail only Acorn v2.

Based on the three functions KSG_{128}, FBK_{128} and $\mathsf{StateUpdate}_{128}$, Acorn executes four steps: (1) the initialization, (2) the processing of the associated data, (3) the processing of the plaintext, and (4) the tag generation as illustrated in Figure 2.

More precisely, during the initialization step, Acorn first initializes the state to the vector 0 before executing 1793 times the function $\mathsf{StateUpdate}_{128}$ with the input parameters (related to the secret key and

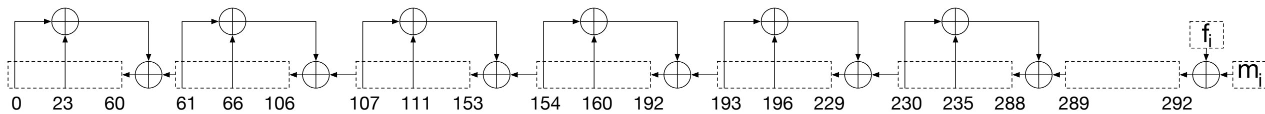


Fig. 1: Concatenation of six LFSRs and a register of four bits. The function f_i represents the overall feedback bit for the i-th step while m_i represents the i-th bit of the input message.

the initialization vector) defined in Table 1. Note that the function $\mathsf{StateUpdate}_{128}$ manipulates one bit at a time from the input parameters.

During the processing of the associated data, ACORN executes $\mathsf{adlen} + 256$ times (where adlen is the bit length of the associated data) the function $\mathsf{StateUpdate}_{128}$ with the input parameters (related to the associated data) defined in Table 2.

During the processing of the plaintext and for each bit of the plaintext, ACORN combines one bit of the plaintext with the keystream (provided by the function KSG_{128}) and updates the state S with the function $\mathsf{StateUpdate}_{128}$ that takes as input the parameters defined in Table 3. ACORN executes this step $\mathsf{pclen} + 256$ times (where pclen represents the bit length of the plaintext).

Finally, during the tag generation step, the function $\mathsf{StateUpdate}_{128}$ takes one bit at a time from three vectors m, ca and cb defined in Table 4, and the tag is given by the $\mathsf{compression}$ function that outputs the last (128) generated keystream bits.

Note that at each of the above steps, ACORN updates the internal state according to the value of the key, the IV, the associated data or the plaintext leading the keystream bits (and eventually the tag) to be related to these values.

vector \ index	0 to 127	128 to 255	256	257 to 1791
m	K	IV	$K_0 \oplus 1$	$K_1, ..., K_{127}, K_0, ..., K_{127}, K_0, ..., K_{127}, ...$
ca	1	1	1	1
cb	1	1	1	1

Table 1: Values of input parameters to the function $\mathsf{StateUpdate}_{128}$ during the initialization step where K_i represents the i-th bit of the key K and IV represents the initialization vector.

3 SAT-based Analysis

Boolean satisfiability, abbreviated SAT, is the problem of deciding whether a given propositional formula $\phi(x_1, \ldots, x_n)$ can be satisfied, i.e. whether there exists a map $v : \{x_1, \ldots, x_n\} \to \{\mathsf{true}, \mathsf{false}\}$ such that $\phi(v(x_1), \ldots, v(x_n))$ is true.

In general, modern SAT solvers are algorithms that aim at answering instances of SAT by attempting to construct a satisfying valuation v. Any algorithm that attempts to solve (random) SAT instances will have

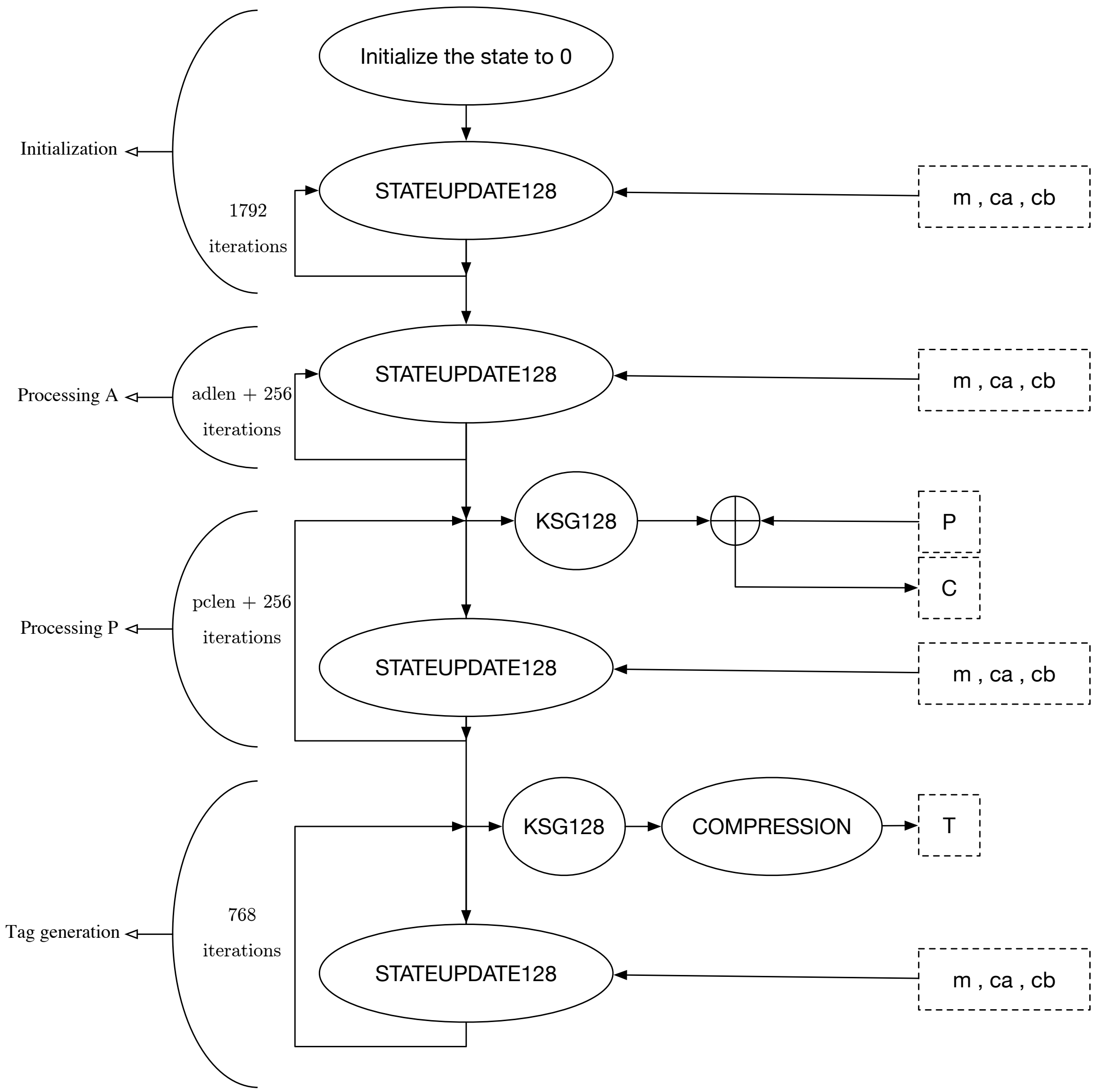


Fig. 2: ACORN executes four phases: (1) the initialization, (2) the processing of the associated data A, (3) the processing of the plaintext P and (4) the tag T generation.

index / vector	0 to $\mathsf{adlen}-1$	adlen	$\mathsf{adlen}+1$ to $\mathsf{adlen}+127$	$\mathsf{adlen}+128$ to $\mathsf{adlen}+255$
m	A	1	0	0
ca	1	1	1	0
cb	1	1	1	1

Table 2: Values of input parameters to the function $\mathsf{StateUpdate}_{128}$ during the processing of the associated data A.

index / vector	0 to $\mathsf{pclen}-1$	pclen	$\mathsf{pclen}+1$ to $\mathsf{pclen}+127$	$\mathsf{pclen}+128$ to $\mathsf{pclen}+255$
m	P	1	0	0
ca	1	1	1	0
cb	0	0	0	0

Table 3: Values of input parameters to the function $\mathsf{StateUpdate}_{128}$ during the processing of the plaintext P.

a worst case exponential complexity. However, modern SAT solvers perform surprisingly well on very large (structured) instances, to the extent that it is often a good strategy to translate a difficult problem into SAT in order to harness the power of modern solvers.

In the following, the formula ϕ is represented in Conjunctive Normal Form (CNF): the formula ϕ contains a logical conjunction ($\wedge$) of clauses, where a clause represents a logical disjunction ($\vee$) of literals, and where a literal denotes a proposition x_i or its negation (denoted $\neg x_i$).

Since 1999, cryptanalysts mention SAT-solvers as useful tools for cryptanalysis (see for example the work of Massacci [8], the work of Massacci and Marraro [9], and the work of Mironov and Zhang [11]). Our SAT-based cryptanalysis tool (called *Cryptosat*) is freely available on our website[3] and allows to easily verify properties of any symmetric key algorithm of the ARX family (+S-boxes and bit-wise Boolean functions). For example, the tool was successfully applied to the analysis of stream ciphers (the ZUC primitive [6] as well as the compression functions of the MD4 and MD5 hash functions or the key schedule of WIDEA and MESH block ciphers [5]). In our experiments, *Cryptosat* uses the SAT-solver *Cryptominisat* (version 2.9.5) [14], leaving the investigation of other SAT-solvers as an interesting scope for further research.

Cryptosat transforms C++ code into a CNF formula thanks to operator overloading. For example, the exclusive-or operation (denoted $\oplus$) between two variables $x_1 \in \{0,1\}$ and $x_2 \in \{0,1\}$ can be represented with the following CNF formula:

$$\phi(x_1, x_2) = (x_1 \vee x_2) \wedge (\neg x_1 \vee \neg x_2). \tag{18}$$

The resulting formula is written in a text file formatted in DIMACS [4] that contains three parts. The first part contains a set of comments beginning with the character c. The second part of the file contains the line p cnf nbvar nbclauses where nbvar indicates the number of variables and nbclauses represents the number of clauses in the formula. Finally, the last part of the file contains one line per clause (ended with the character 0) where a proposition x_i (respectively $\neg x_i$) is represented by the integer i (respectively $-i$). For example,

[3] `https://qualsec.ulb.ac.be/people/frederic-lafitte/cryptosat/`

[4] See `http://www.satcompetition.org/2009/format-benchmarks2009.html` for more details on this format.

vector \ index	0 to 767
m	0
ca	1
cb	1

Table 4: Values of input parameters to the function $\mathsf{StateUpdate}_{128}$ during the tag generation.

the CNF formula representing the exclusive-or operation between two variables $x_1 \in \{0,1\}$ and $x_2 \in \{0,1\}$ can be encoded in DIMACS as follows:

```
c XOR formulated in CNF and encoded in DIMACS
p cnf 2 2
1 2 0
-1 -2 0
```

Cryptosat is used with a timeout: its output is either SAT or UNSAT, depending on the output of *Cryptominisat*, or TIMEOUT when the SAT-solver exceeds the given timeout. In the SAT case, a map v that satisfies the formula ϕ is returned. More precisely, as soon as we encoded in C++ the function $\mathsf{AEAD}(K, N, P, A)$, *Cryptosat* converts the C++ code into a CNF formula (representing the C++ code) in which the propositions correspond to the manipulated bits of $\mathsf{AEAD}(K, N, P, A)$. Afterward, the user of *Cryptosat* substitutes into the formula ϕ known values for N, P, and A in order to obtain a simpler formula $\phi'(K)$ fed to the (*Cryptominisat*) SAT solver in order to extract the secret key K. It is worth to note that *Cryptosat* provides an interface that minimises user effort. Briefly, *Cryptosat* verifies at the same time the degree of resilience of the C++ code and the primitive's design.

4 Experiments

This section demonstrates that ACORN v1 and v2 contain critical weaknesses leading to a state recovery attack (in Section 4.2), a key recovery attack (in Section 4.3), a state collision attack (in Section 4.4) as well as a forgery attack (in Section 4.5). The state recovery attack provides the probability that *Cryptosat* retrieves an internal state from a given fixed tag. The key recovery attack shows the probability that *Cryptosat* extracts the secret key from a known internal state. The state collision attack provides several internal states (manipulated before the tag generation) leading to a same given tag while the forgery attack provides several plaintexts and associated data (in which the values of a subset of bits can be selected by the adversary) leading to a same given tag. We estimate the probabilities and the time complexity of each attack by using $3,000$ (randomly) generated tags or states, depending on the context.

4.1 Experimental setup

The randomness used in all the experiments comes from the default pseudorandom number generator of R (i.e., Mersenne-Twister). In order to apply our attack, we installed *Cryptominisat*, a freely available tool in GitHub[5]. Then, we installed R, a free software environment available in the R Project[6] before importing

[5] https://github.com/msoos/cryptominisat
[6] https://www.r-project.org

our R package *Cryptosat* available in our website[7]. Eventually, we executed a set of R codes provided in the Appendices and referred to in the subsequent sections describing the attacks. Note however that we provide the codes for Acorn v2 but the same attacks can be applied on Acorn v1 by putting the parameters associated to the first version of Acorn. All the presented results can be reproduced with an AMD Opteron 6134 2.3 GHz using 1 core and 4 GB DDR3 ECC RAM 1.333 Ghz.

4.2 State recovery attack

The first experiment provides an intuition on the effectiveness of a SAT-based analysis on a reduced version of Acorn. Figure 3 shows the probability to extract an internal state (from which the tag is produced) of Acorn leading to the tag value as a function of (1) the number of iterations in the generation of the random given tag, and (2) the *timeout* (representing the limit of time before the adversary stops the execution of *Cryptominisat*). The results show that the probability to extract the target value (with a fixed timeout value) depends linearly (with a very small slope) on the number of iterations. Furthermore, the figure demonstrates that reduced versions of Acorn can be attacked in practice without any human analysis of the algebraic properties of the target primitive.

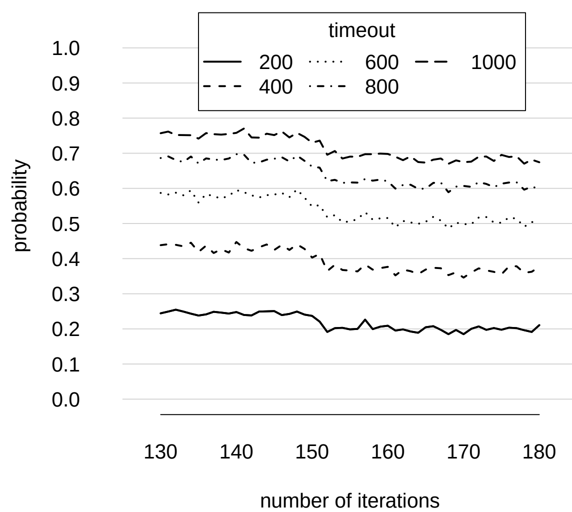


Fig. 3: Estimated probability (with 3,000 randomly generated tags) to recover an internal state leading to the target tag value provided by Acorn as a function of (1) the number of iterations during the generation of the tag and (2) the timeout value (in seconds).

[7] `https://qualsec.ulb.ac.be/people/frederic-lafitte/cryptosat/`

The next experiment estimates the probability of the previously presented state recovery attack on the full version of ACORN v1 and ACORN v2. Recall that ACORN v2 executes 768 iterations during the tag generation while ACORN v1 executes 512 iterations. Table 5 provides the (estimated) probability to extract the (secret) internal state from the tag as a function of the value of the timeout. For example, an adversary extracts an internal state of ACORN v1 leading to a given tag value with probability 0.6240 when the timeout equals to 800 seconds. Surprisingly, our results also point out that an adversary requires the same execution time to extract the secret internal state (leading to the tag value) when targeting the first and the last version of ACORN. Indeed, an adversary recovers an internal state of ACORN v2 leading to the tag value with probability 0.6093 when the timeout equals 800 seconds. The R Code 1.1 (in the Appendix) allows to reproduce the state recovery attack for ACORN v2 from a tag (denoted `TARGETMAC` in the code) with a timeout (denoted `TIMEOUT` in the code) thanks to *Cryptominisat* (located in the path denoted `SOLVER` in the code).

Primitive \ Timeout	200	400	600	800	$1,000$
ACORN v1	0.1903	0.3683	0.5000	0.6240	0.6847
ACORN v2	0.1890	0.3610	0.4907	0.6093	0.7177

Table 5: Estimated probability (with $3,000$ randomly generated tag) to extract the state stored before the tag generation from the tag as a function of the target primitive as well as the timeout value (in seconds).

Note however that the retrieved internal state (with the previously described attack) may differ from the internal state computed by the user of ACORN knowing the key, the IV, the associated data and the plaintext due to the surjectivity propriety of the mapping from the internal state (of 293 bits) to the tag value (of 128 bits), i.e. several internal states lead to the same tag. To fix this issue, we assume in the next experiment that the adversary knows (e.g, from a side-channel) a subset of bits of the target internal state representing the state manipulated when ACORN uses the key, the IV, the associated data and the plaintext. Table 6 provides the probability to extract the (right) internal state as a function of the number of known bits for ACORN v1 and ACORN v2 with a timeout of $1,000$ seconds. The probability to extract the right internal state falls to zero when considering less than 263 known bits of the state with a timeout of $1,000$ seconds. We could increase this probability by increasing the timeout, which constitutes an interesting future work.

Primitive	Number of known bits	Probability
ACORN v1	283	0.1023
	273	0.0137
	263	0.0000
ACORN v2	283	0.0757
	273	0.0517
	263	0.0000

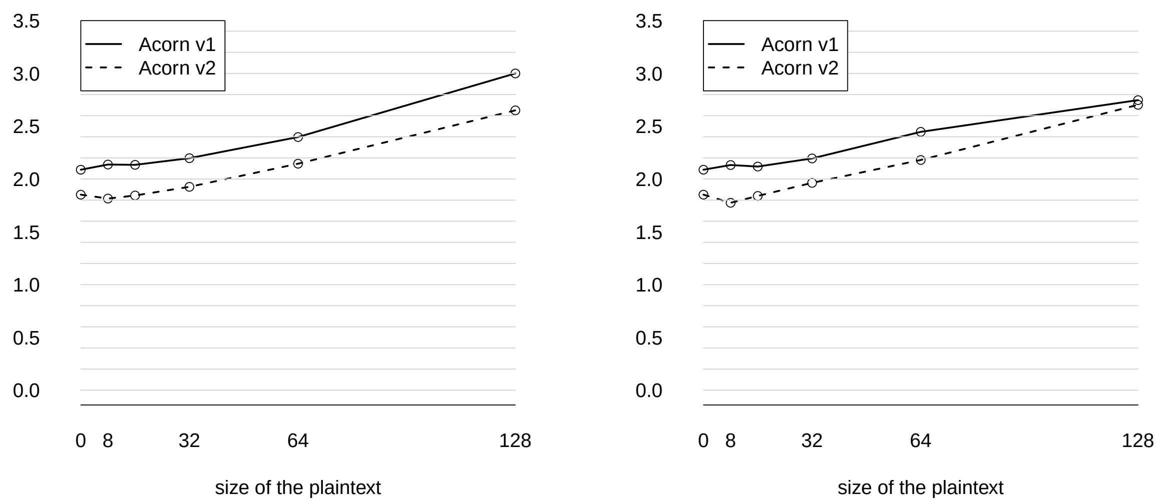
Table 6: Estimated probability (with $3,000$ randomly generated tag) to extract the right state stored before the tag generation from the tag as a function of the target primitive and the number of known bits of the right state with a timeout of $1,000$ seconds.

4.3 Key recovery attack

The next experiment on Acorn v1 and Acorn v2 provides the (average) execution time required by *Cryptosat* to extract the secret key as well as the IV when the adversary knows the internal state, the plaintext and (optionally) the ciphertext. Since Acorn is based on a stream cipher, we expect Acorn to exhibit a similar resistance to this kind of attack (i.e., key-recovery from state is an important criterion for stream ciphers). Figure 4 shows the average execution time (in seconds) to extract the key and the IV with probability 1 as a function of the length of the plaintext.

The experiments show that the secret key and the IV can be (deterministically) derived as soon as the (previously presented) state recovery attack recovers the right internal state, i.e. the state just after processing the associated data and plaintext using that specific key-IV pair; indeed, other states can lead to the same tag. Furthermore, *Cryptosat* requires a (slightly) lower execution time to recover the secret key and the IV from Acorn v2 than from Acorn v1. The reason is that Acorn v1 executes 2560 iterations (before the tag generation step) independently of the size of the message while Acorn v2 executes (i.e., 2304) a lower number of iterations. Note however that, compared to Acorn v2, the cost of the higher number of iterations for Acorn v1 (independently of the size of the message) should vanish when the size of the message increases.

Code 1.2 (in the Appendix) allows to reproduce the key recovery attack on Acorn v2 from a known internal state (denoted `STATE` in the code), using a plaintext (denoted `PLAINTEXT` in the code) as well as the ciphertext (denoted `CIPHERTEXT` in the code).



(a) (b)

Fig. 4: Average execution time (in seconds and estimated with $3,000$ randomly generated tags) to extract the key and the IV from a known state (representing the input state to the tag generation step) for Acorn v1 and Acorn v2 as a function of the size of the plaintext (in bytes) knowing only the plaintext in 4(a), and knowing the plaintext and the ciphertext in 4(b).

4.4 State collision attack

The next experiment generalises the results of Salam *et al.* [12] by providing a multi state collision attack (i.e., several internal states leading to the same tag value) instead of a single collision attack provided by Salam *et al.*

In a technical point of view, in order to obtain several internal states leading to the same tag value, we fix the value of one different bit of the state (to the value 1) for each generated state, leaving *Cryptosat* to select the value of the other bits of the state. Table 7 provides five different states of Acorn v1 as well as five different states of Acorn v2 leading to the same tag. We extract each state of Acorn v1 with an average of 1641.98 seconds and each state of Acorn v2 with an average (over just 5 samples) of 570.736 seconds.

Code 1.3 (in the Appendix) provides the R instructions in order to accomplish in practice a multi-collision attack extracting a number of different states (denoted `NUMBEROFSTATES` in the code) knowing one tag value.

Tag	Primitive	State	Solving time
378ada093afcd068951b4a0f398f098a	Acorn v1	13a412610222dba5cc8855640fdbd65ba02f6 6f50491a7045a3d60bedb4c9ab40848aced39	956.13
		1a3da43fb0973ed7d5b22d7311f637fc57a15 cc4076d7a2cce9112f411d6272c3718aafe47	766.86
		1529bbbedea296669e142454f6b1d5f4a0be4 725e49646e3b3956f3f0a00c717a953a3464d	4649.66
		02d32ee6048530605f541b0ba948cd88b68ea cc8e320e606dd2d1c26d4be857c16bc415541	85.84
		050db2ef7f7d5979fef9df5aed44fc95ef6551 c89b2b84caefb567896a6ce3463d7a169d3c	1751.41
	Acorn v2	116121797d0c34fba3644474d410b04571ca 38f3b2f7f974537f9831c9af513d0763661273	391.52
		0d174afadbe045f699d3776ec82397b5792f5 11ec36d13094145c435347ac4613ac720718f	875.18
		1ce3f50745bbdf1781228a649b76d3430c74 5d4a90fd09d1159cae29781a7d0fffc5322fa6	74.48
		0bf26fc99fd301a6a4949559b0528267c83f0 1a522747f2a34904af8fe3146a207e2fb5e28	491.23
		1357259c0a50e39b86b5603ccae8467b645ed 7272491a687953e27cd4e525b093a50f6d4de	1021.27

Table 7: Execution time (in seconds) to extract the state (showed in hexadecimal) stored before the tag generation of Acorn v1 and Acorn v2 as a function of the tag value (displayed in hexadecimal). Note that the presented states contain 74 symbols representing 296 bits. However, only the (293) least significant bits of the state lead to the same tag.

4.5 Forgery attack

Similarly to the previous experiments, Table 8 provides the tag value when the plaintext is empty as well as four different plaintexts for Acorn v1 and Acorn v2 (extracted by *Cryptosat*) leading to the same tag knowing the key and the IV. Note that the adversary is not required to known the key and the IV if he knows the internal state. *Cryptosat* requires a solving time to extract the plaintext of 517.35 seconds on average for ACORN v1 and of 939.74 seconds on average for ACORN v2. Note that the same attack can be applied on the associated data part. For example, Table 9 provides the same tag generated in the previous experiment but with an empty associated data as well as with four different associated data for ACORN v1 and ACORN v2.

Code 1.4 (in the Appendix) shows the R code allowing to extract several plaintexts (including the plaintext of length zero) leading to the same tag value. More precisely, the variable `NUMBEROFPLAINTEXTS` denotes the number of different plaintexts to extract (including the plaintext of length zero).

Note however that, in the previous experiment, *Cryptosat* produces several plaintexts leading to the same tag value but with possibly different internal states manipulated before the tag generation and after the processing of the plaintext. Table 10 provides several plaintexts leading to the same internal state stored before the tag generation (that leads eventually to the same tag value). There is a significant performance gain by targeting the internal state without the knowledge of the tag value as done in the previous experiment (although all the plaintexts lead to the same tag in this new experiment) since the adversary has access to useful information. Furthermore, this experiment shows that an adversary can extract very quickly a fixed point, i.e. several encrypted plaintexts leading to the same given internal state (in the present case the state obtained with an empty plaintext). An attacker can reiterate this experiment by executing the Code 1.5 available in the Appendix.

We exemplify the forgery attack with a realistic scenario by selecting carefully the plaintext values. More precisely, Table 11 shows 3 different plaintexts (of 64 bytes) representing three informative texts (of 15 or 17 characters depending on the context) encoded in ASCII leading to the same tag for ACORN v1 and ACORN v2. The three (informative) messages are: "*Bob gave 5Euro.*", "*Bob gave 500Euro.*" and "*Eve gave 500Euro.*". The ASCII encoding represents each character with 1 byte, leading the length of each text to be 15 or 17 bytes depending on the context. The unused bytes (i.e., 49 or 47 bytes) are filled by *Cryptosat* in order to get the same tag. *Cryptosat* requires less than 640 seconds to find each plaintext for ACORN v1 and less than 130 seconds to find each plaintext for ACORN v2.

The presented forgery attacks imply that (1) a user (knowing the key and the IV) can easily repudiate the authenticity of the plaintext and of the associated data (i.e., convince the receiver that the sender sent another message), and (2) an (unreliable) communication channel can lose or modify the ciphertext and the associated data without any detection by the receiver (i.e., a data integrity issue).

The forgery attack can also be applied in the context of Cryptographic Key Management Systems (CKMS) [1]. For example, a malicious maintenance personal of the CKMS can produce a secret key for each honest user (in which the metadata indicates the name of the user) that can also be used by a (set of) malicious person(s) on a cryptographic module that verifies the access to the key (of an honest user) from the tag. More precisely, for each (honest) user, the CKMS generates a secret key authenticated with a metadata (indicating the name of the honest user) that leads to the same tag when modifying the metadata with the name(s) of (a set of) malicious person(s). As a result, the cryptographic module cannot reliably distinguish the use of the key between an honest user and a malicious person.

5 Conclusion and perspectives

There have been several efforts for gauging the security provided by ACORN v1 [3, 4, 7, 12]. We presented practical (state recovery, key recovery, state collision and forgery) attacks against the full version of ACORN v1 and ACORN v2. These attacks do no contradict the author's security claims but casts some doubts on the wide applicability of ACORN given the attack from Section 4.5.

Primitive	Tag	Plaintext	Solving time
ACORN v1	7d945f7104c1d29f 52a22b5e3fd2e7f8	∅	
		5676fffd6ac385210838bee69001945034c273e53f9995bb7f6f7382 9a3c017cae498af95a10fb2f93562d4cf82cf0d7c856839e7a43fd69	610.47
		cac11cff235041c798c35ca35fb297c19558b9f055a782b1659937a41 988f1c3226764760586465daacb7360efa0081c898a465827bc86c7	1050.65
		cf6c89f7ff512fe739be01babde2bb7ebd46a85c6ec89ea442096f3b2 1271f2db2d315215b5b173869e12da4c023060d400250f6cb4e85d3	359.25
		570674fe9effd017a1d070d4f5c4a8aa4de72d3b770bd6f810a646645 1d67556358973b8c659fb4d9e005fced9d1d3c1d734e6800417d989	49.02
ACORN v2	607aceb1afc94bfa 7f19a57bf0365304	∅	
		8f38ff07a659eccbe2014e63a2a33c211266fa0663f2939128fa7eeeb9 4b1673bbd832ed080319cb79923def84d0142d51d840665105cb3d	3170.8
		b87390ff2e389c3140ff26cd5f24f164a0f08625bba76c7ef3e573900 583e3450dfc0b446262a4fd24bf431cd74967c2d5b2e3ddb835f4cf	227.95
		28e62845ff7850d63b4a48c343cc017a9b45ab62c42866642e735e90d 0f6edad795254abd1e07261c98585cf8a2aaddbe5dda9340e1db050	258.62
		3abc970d94ffc8c3194e126dfe1cc84d9a553144e9002a6563e9f2c5c2 4983a4beb3445588bb3b5563cb9a60c0a30186519bca2419da0a56	101.6

Table 8: Execution time (in seconds) to extract the plaintext (showed in hexadecimal) leading to the tag (displayed in hexadecimal) produced by ACORN v1 and ACORN v2 knowing the key (equal to 32fd8dc435218dffcde3f439018cfd16 in hexadecimal) and the IV (equal to a25a90cdf57ffc082cca99602c524085 in hexadecimal). The symbol ∅ represents the empty plaintext.

The main advantage of our strategy based on *Cryptosat*, which can be applied to any other target primitive, lies in automation: *Cryptosat* requires no human analysis concerning the (algebraic) properties of the primitive. More generally, all our results highlight the usefulness of our tool in order to verify (quickly and easily) security properties of cryptographic primitives such as the presence of fixed points, time complexity estimations as well as probabilities estimation. All the presented attacks can be reproduced using the scripts given in the Appendix.

We plan three future works. First, we aim to extend our experiments by increasing the number of known tag values by the adversary (instead of the single tag value used during our experiments). Second, we plan to verify each candidate of the CAESAR competition in order to detect (with *Cryptosat*) flawed primitives. Third, in the long term, we aim to justify what makes cryptographic instances resilient to SAT-based attacks.

Primitive	Tag	Associated data	Solving time
Acorn v1	7d945f7104c1d29f 52a22b5e3fd2e7f8	∅	
		9106ff01d140dd3002c08598a6c446b1c717f1ab77171ef94bc434f9f 3f2697114484fcb134362aabed1683ba895d927d7117db1f1c5a2ea	1000.07
		f6606cff1db155b6148a7f6524456a45450a2b0fa587606a90d20896 709468861e98014cea82e94fae037fd7b2fd1e798eb69868886828a4	214.14
		e74a99b5ffd9244d0b2bb7c5854fbaef85ab777bedf6ccd4fac039fb a4b087aec45628e1bfce386033825d081e55e06d1507f5acf2bee954	871.9
		9b81302db0ff07dce3b5bbfef527119845fa6aa22167e78d2a81f7cc2 277a4db17692b7b285869361e9395cc18a4cca8d29602d27ec7eb0d	1402.92
Acorn v2	607aceb1afc94bfa 7f19a57bf0365304	∅	
		29ecff30a5833c4efcf3605ca62bc0a39e0a9c1e90caa7953b5620a5 5b32c8575ee8abf5c9cd103926466ff87e8c4490d8cdf47069c840f1	1695.24
		fe32b3ffd4052863f608467c8b4ddae56fe2487fa21edeb8927ec9ae 1d7665d07b8bdff8fde39d7ed79c6c6e954845cab5c901c1a9e6315c	260.86
		ae563488ff51ea258296337473ed5eff7aaf82c65cf8f53b104536266 49759067a0b06de97cfc776ea6d22b583535052d51ae0c17d1eb87a	170.51
		401b05ed51ffa73346a8d8f681fd0ddce07b0e4ca9622762d1266036 e9ef941d69219381087670f3503307f32076ff52b7aca56828a475bb	67.29

Table 9: Execution time (in seconds) to extract the associated data (showed in hexadecimal) leading to the tag (displayed in hexadecimal) produced by Acorn v1 and Acorn v2 knowing the key (equal to 32fd8dc435218dffcde3f439018cfd16 in hexadecimal) and the IV (equal to a25a90cdf57ffc082cca99602c524085 in hexadecimal). The symbol ∅ represents the empty associated data.

Primitive	Tag	Plaintext	Solving time
Acorn v1	7d945f7104c1d29f 52a22b5e3fd2e7f8	∅	
		ad9ffff616f7cc52268f3330f0e782fc3c4de05161d560d247e1477156 70d1d1ce6b483ad2a97d57776ec8566a317b8921b1e1b02abc32e0	1.53
		e46b69ff3562bca885a76a2c90292d333e423f538af0ee4dd09026ab b87a36de0906b70b2c073ca1769f29309a1642865654ff99c5b732e0	1.54
		819179aeff096df81400dba83ef89bd148c58a658f597470e84c862ca b26a7af851e4d46cccc9cd145c309acb31887d012cc4099c5b732e0	1.58
		d84e7dd01aff98e5343cc5f7aaf8e700e39343fca8a1a6ca996139c17 ce92cabc7684cb112da4862b9eed34968669b132f343de0577f9bc9	1.55
Acorn v2	607aceb1afc94bfa 7f19a57bf0365304	∅	
		481eff77885277051f6f495163915de73ad0acf4b955060510fd44b3 6e922aaa8ef7810823e10ee111d4f6d851f5ff01f66aaabddc990928	1.41
		7212e6ff941a95aea07ec09d6cf35c22a405fed67c5d48edb3a54a45 bd8533b3c6e9e711b9ec7f59fb2a3fcfa9d34d9c9f11e441a1ea1a32	1.41
		6de70b76ffa973e99a878cf377e4de5999a07e6bdc52bb6214c0fef90 91d954312fef067856683a19409b1ac649e5d865ee68e828d8c1832	1.34
		cc4c9dd7bfff9990693d71299dbe9dd09e06fe001a99eb5fe94ca359a 0db7eaa6ec7b6da70788d126f3a3ecfa9d34d9c9f11e441a1ea1a32	1.32

Table 10: Execution time (in seconds) to extract the plaintext (showed in hexadecimal) leading to the same tag (displayed in hexadecimal) as well as the same internal state manipulated before the tag generation produced by Acorn v1 and Acorn v2 knowing the key (equal to 32fd8dc435218dffcde3f439018cfd16 in hexadecimal) and the IV (equal to a25a90cdf57ffc082cca99602c524085 in hexadecimal). The symbol ∅ represents the empty plaintext.

Primitive	Tag	Informative text	Plaintext	Solving time
Acorn v1	1d60abed41a00f19 00a3be8c5e3e4831	Bob gave 5Euro.	*426f6220676176652035457575726f2e*9f73bf75e1b3f b965d6bd1e1e5cff7783bcfae41d08451db91f0f4fd 9a204e77c7de57932442357dcc0dab4f2a8fde20bd	5.99
		Bob gave 500Euro.	*426f62206761766520353030457575726f2e*58c23af4 7c3a4fe4c77f92a8b19d342b8a7e25d9b7ecff3881f d2c7a255888f30ea49d8a29274dee2e54783b8f7f9e	589.21
		Eve gave 500Euro.	*45766520676176652035303045757 5726f2e*4d62ed7d 8d72d2a9af789bfab267cea1db9df0072161642d0b8 c8009929c0ff8a5157fc42d79d171d92584ea81c160	639.86
Acorn v2	f4acf3a1470154a9 99addb1668bfcbef	Bob gave 5Euro.	*426f6220676176652035457575726f2e*46252a2ffd923 14bb6e12146a74a45dacdbe1c2935e321c0c9ca000 ae2ba3644f253cc1595bc94a30a6d50f42710747a13	3.12
		Bob gave 500Euro.	*426f62206761766520353030457575726f2e*059e21b0 e059823c52fb1a1de305745cec07edb2a2474b3a3c8 9add1352e52b63afaad7f038fb8223fac132cbe2dcc	129.34
		Eve gave 500Euro.	*457665206761766520353030457575726f2e*fc4808766 9df93cdd1c7e8556f357ed2a869815d8d53545e9180 e967eb2f05b2ec43b47e821f9d2af487c4ae10d05a	24.54

Table 11: Execution time (in seconds) to extract the plaintext of 64 bytes (showed in hexadecimal) representing an informative text (of length 15 or 17 characters depending on the context) encoded in ASCII leading to the tag (displayed in hexadecimal) produced by Acorn v1 and Acorn v2 knowing the key (equal to 32fd8dc435218dffcde3f439018cfd16 in hexadecimal) and the IV (equal to a25a90cdf57ffc082cca99602c524085 in hexadecimal). The plaintext related to the informative text is showed in italic.

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Appendix A

Code 1.1: R code to execute in order to recover the secret state manipulated by ACORN v2

```
TARGETMAC <- rep("FF", 16) # example of target MAC
SOLVER <- "/cmsat-2.9.5/build/cryptominisat" # the path to Cryptominisat
TIMEOUT <- 1000 # the timeout before to stop the execution of Cryptominisat

library("cryptosat")
target <- ACORNv2()
target$setParameter("keyIVsetup",FALSE)
target$setParameter("printPstate",TRUE)
target$setParameter("Aiterations",0)
target$setParameter("Piterations",0)
instance <- target$generateInstance()
for( i in 0:15 ) {
  varname <- paste("mac[",i,"]",sep="")
  instance$setEqual(varname, TARGETMAC[i+1])
}
for( i in 0:292 ) { # each bit of the STATE is encoded with 1 byte
  varname <- paste("pstate[",i,"]",sep="")
  instance$setEqual(varname, xbits=1:7, y="0000000", yformat="bin")
}
solution <- instance$solveWith(SOLVER,timeout=TIMEOUT)
if(!solution$isSAT()){
    cat("State not recovered\n")
}else{
    cat("State:")
    for(i in c(0:292)){
        cat(solution$getValueOf(paste("pstate[",i,"]",sep="")),"")
   }
}
```

Code 1.2: R code to execute in order to recover the key and the IV knowing the state of ACORN v2 as well as the plaintext and the ciphertext

```
SOLVER <- "/cmsat-2.9.5/build/cryptominisat" # the path to cryptominisat
TIMEOUT <- 200 # the timeout before to stop the execution of cryptominisat
STATE <- sample(c("00","01"),293,replace=T) # example with a random state
PLAINTEXT <- sample(c("00","01"),8,replace=T) # example with random plaintxt
CIPHERTEXT <- sample(c("00","01"),8,replace=T) # example with random ciphertxt

mlen <- length(PLAINTEXT)
library("cryptosat")
target <- ACORNv2()
target$setParameter("mlen",mlen)
target$setParameter("printPstate",TRUE)
target$setParameter("processTag",FALSE)
instance <- target$generateInstance()
if(mlen != 0){
    for( i in 0:c(mlen-1) ) {
        instance$setEqual(paste("m[",i,"]",sep=""), PLAINTEXT[i+1])
        instance$setEqual(paste("c[",i,"]",sep=""), CIPHERTEXT[i+1])
    }
}
for( i in 0:292 ) {
    instance$setEqual(paste("pstate[",i,"]",sep=""), STATE[i+1])
}
solution <- instance$solveWith(SOLVER,timeout=TIMEOUT)

if(solution$isSAT()){
    cat("Key: ",paste(solution$getValueOf("key"),collapse=""),"\n")
    cat("IV:",paste(solution$getValueOf("iv"),collapse=""),"\n")
}
```

Code 1.3: R code to execute in order to recover several states manipulated by ACORN v2

```
TARGETMAC <- rep("FF", 16) # example of target MAC
SOLVER <- "/cmsat-2.9.5/build/cryptominisat" # the path to Cryptominisat
TIMEOUT <- 1000 # the timeout before to stop the execution of Cryptominisat
NUMBEROFSTATES <- 4 # number of different states to recover (max: 294)

library("cryptosat")
target <- ACORNv2()
target$setParameter("keyIVsetup",FALSE)
target$setParameter("printPstate",TRUE)
target$setParameter("Aiterations",0)
target$setParameter("Piterations",0)
instance <- target$generateInstance()
for( i in 0:15 ) {
  varname <- paste("mac[",i,"]",sep="")
  instance$setEqual(varname, TARGETMAC[i+1])
}
for(sample in c(0:(NUMBEROFSTATES-1))) {
    for( i in 0:292 ) { # each bit of the STATE is encoded with 1 byte
        varname <- paste("pstate[",i,"]",sep="")
        if(i== sample-1){
            instance$setEqual(varname, xbits=1:8, y="00000001", yformat="bin")
        }else{
            instance$setEqual(varname, xbits=1:7, y="0000000", yformat="bin")
        }
    }
    solution <- instance$solveWith(SOLVER,timeout=TIMEOUT)
    if(!solution$isSAT()){
        cat("State not recovered\n")
    }
    else{
        cat("State:")
        for(i in c(0:292)){
            cat(solution$getValueOf(paste("pstate[",i,"]",sep=""))," ")
        }
        cat("\n")
    }
}
```

Code 1.4: R code to execute in order to recover several plaintexts leading to the same tag provided by ACORN v2 when there is no plaintext (without exploiting a fixed point in the state transition function)

```
SOLVER <- "/cmsat-2.9.5/build/cryptominisat" # the path to Cryptominisat
NUMBEROFPLAINTEXTS <- 4 # number of different plaintexts to recover (max: 294)
KEY <- rep("FF", 16) # example of key
IV <- rep("FF", 16)  # example of IV
MLEN <- 56 # example of size of the recovered plaintexts

library("cryptosat")
target <- ACORNv2()
target$setParameter("mlen",0)
instance <- target$generateInstance()
for( i in 0:15 ) {
    instance$setEqual(paste("key[",i,"]",sep=""), KEY[i+1])
    instance$setEqual(paste("iv[", i,"]",sep=""),  IV[i+1])
}
solution <- instance$solveWith(SOLVER)
mac <- solution$getValueOf("mac")
cat("MAC: ", paste(mac,collapse=""),"\n")
for(sample in c(2:NUMBEROFPLAINTEXTS)){
    target <- ACORNv2()
    target$setParameter("mlen",MLEN)
    instance <- target$generateInstance()

    for( i in 0:15 ) {
        instance$setEqual(paste("key[",i,"]",sep=""), KEY[i+1])
        instance$setEqual(paste("iv[", i,"]",sep=""),  IV[i+1])
        instance$setEqual(paste("mac[", i,"]",sep=""),  mac[i+1])
    }
    instance$setEqual(paste("m[",sample-2,"]",sep=""), "ff")
    solution <- instance$solveWith(SOLVER,timeout=1000)

    if(solution$isSAT()){
        m <- paste(solution$getValueOf("m"),collapse="")
        cat("Plaintext:",m,"\n")
        cat("MAC:",paste(solution$getValueOf("mac"),collapse=""),"\n")
    }
}
```

Code 1.5: R code to execute in order to recover several plaintexts leading to the same tag provided by ACORN v2 when there is no plaintext (exploiting a fixed point in the state transition function)

```
SOLVER <- "/cmsat-2.9.5/build/cryptominisat" # the path to Cryptominisat
NUMBEROFPLAINTEXTS <- 4 # number of different plaintexts to recover (max: 294)
KEY <- rep("FF", 16) # example of key
IV <- rep("FF", 16)  # example of IV
MLEN <- 56 # example of size of the recovered plaintexts

library("cryptosat")
target <- ACORNv2()
target$setParameter("mlen",0)
target$setParameter("printPstate",TRUE)
instance <- target$generateInstance()
for( i in 0:15 ) {
    instance$setEqual(paste("key[",i,"]",sep=""), KEY[i+1])
    instance$setEqual(paste("iv[", i,"]",sep=""),  IV[i+1])
}
solution <- instance$solveWith(SOLVER)
mac <- solution$getValueOf("mac")
pstate <- solution$getValueOf("pstate")
cat("MAC: ", paste(mac,collapse=""),"\n")
for(sample in c(2:NUMBEROFPLAINTEXTS)){
    target <- ACORNv2()
    target$setParameter("mlen",MLEN)
    target$setParameter("printPstate",TRUE)
    instance <- target$generateInstance()

    for( i in 0:15 ) {
        instance$setEqual(paste("key[",i,"]",sep=""), KEY[i+1])
        instance$setEqual(paste("iv[", i,"]",sep=""),  IV[i+1])
    }
    for( i in 0:292 ) {
        instance$setEqual(paste("pstate[", i,"]",sep=""),  pstate[i+1])
    }
    instance$setEqual(paste("m[",sample-2,"]",sep=""), "ff")
    solution <- instance$solveWith(SOLVER,timeout=1000)

    if(solution$isSAT()){
        m <- paste(solution$getValueOf("m"),collapse="")
        cat("Plaintext:",m,"\n")
        cat("MAC:",paste(solution$getValueOf("mac"),collapse=""),"\n")
    }
}
```